Fermi National Accelerator Laboratory

FERMILAB-Conf-96/110-E
CDF

Onia and Heavy Flavor Production at the Tevatron Collider

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May 1996

Submitted to the *Les Rencontres de la Vallee d'Aosta,*
La Thuile, Italy, March 3-9, 1996

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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CDF/PUB/BOTTOM/PUBLIC/3676

ONIA AND HEAVY FLAVOR PRODUCTION AT THE TEVATRON COLLIDER

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Abstract

Selected results from the CDF and DØ collaborations on onia and heavy flavor production are presented. Topics include charmonium, bottomonium, and Λ_b production and a search for $B_c \rightarrow J/\psi\pi$.

1 Introduction

The Fermilab Tevatron provides an excellent environment for the study of charm and bottom physics. The CDF [1] and DØ [2] experiments have exploited the large production cross sections present at the Tevatron to make a wide range of measurements. This paper discusses selected topics in onia and heavy flavor production. Measurements by both CDF and DØ of charmonium and bottomonium production are described. Recent results from CDF on Λ_b production and a search for the B_c meson are also discussed.

2 Charmonium Production

There has been considerable interest recently in the production of charmonium in high energy collisions [3]. At the Tevatron there are a number of contributions to J/ψ production. Prompt J/ψ's are produced directly or from the decay of directly produced χ_c and $\psi(2S)$. Initial calculations of direct charmonium production considered leading order gluon-gluon fusion diagrams to be the most important process [4]. It was later noted that at large p_t the contribution from fragmentation processes should be dominant [5]. Recently, fragmentation calculations have been performed for direct J/ψ, $\psi(2S)$, and χ_c production [6, 7, 8]. These calculations indicate that radiative χ_c decay is the most important component of prompt J/ψ production. In addition to the processes described above, J/ψ's are also produced from the decay $B \rightarrow J/\psi X$ [9], corresponding to non-prompt production. Unlike the J/ψ, prompt $\psi(2S)$'s are only expected to arise from direct production since the $\psi(2S)$ is above the χ_c. Thus B decay was considered to be the dominant source of $\psi(2S)$ [10].

2.1 DØ J/ψ Results

The DØ collaboration has published results [11] on J/ψ production in the psuedorapidity region $|\eta^{J/\psi}| < 0.6$. In this analysis candidate J/ψ events are reconstructed from the decay $J/\psi \rightarrow \mu^+\mu^-$ using a 6.6 pb^{-1} data sample. The transverse momentum of the dimuon is required to be greater than 8 GeV/c. The resulting dimuon invariant mass distribution in the central region $|\eta^{J/\psi}| < 0.6$ is shown in Fig. 1(a). In addition to J/ψ production several other processes contribute to this spectrum. These include $b\bar{b}$ and $c\bar{c}$ events where both quarks decay semileptonically or with a sequential semileptonic decay, and events where one muon arises from b or c decay and the other muon comes from π or

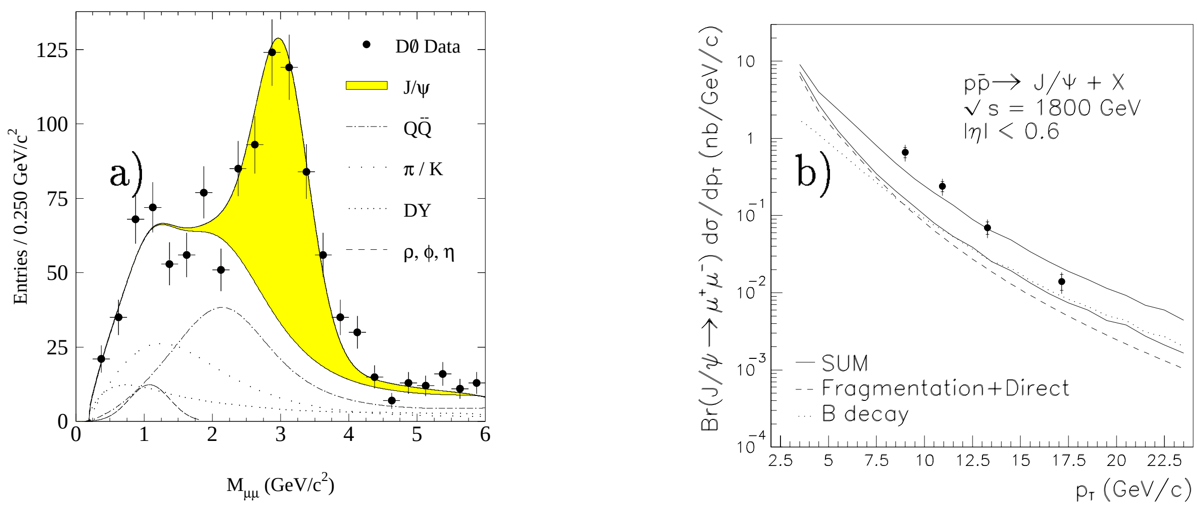

Figure 1: a) DØ dimuon invariant mass distribution for $|\eta^{J/\psi}| < 0.6$. b) DØ inclusive J/ψ cross section result along with theoretical predictions.

K decay. Other contributions come from the Drell–Yan process and decays of light quark mesons such as ρ, ϕ, and η.

In order to determine the contribution from J/ψ production, a maximum likelihood fit is performed to separate the various components. Three pieces of information are used in the fit: the dimuon invariant mass, the dimuon momentum transverse to the associated jet axis, and the isolation of the more energetic muon. A sample of Monte Carlo events is generated for each of the dimuon processes and used as input to the fit. The result of the fit for each component is shown in Fig 1(a). The number of J/ψ signal events extracted from the fit is 407 $\pm$ 28 (stat) $\pm$ 55 (sys).

The inclusive J/ψ cross section as a function of transverse momentum, corrected for acceptance and efficiency, is shown in Fig. 1(b) along with theoretical predictions. The integrated cross section result is $\sigma(J/\psi)\cdot BR(J/\psi \to \mu^+\mu^-) = 2.08 \pm 0.17\,(\mathrm{stat}) \pm 0.46\,(\mathrm{sys})\,\mathrm{nb}$ ($p_t^{J/\psi} > 8\,\mathrm{GeV/c}$, $|\,\eta^{J/\psi}\,| < 0.6$).

The DØ experiment has also measured the fraction f_b of J/ψ events arising from B meson decays using the distribution of the impact parameter of the muons relative to the event vertex in the transverse plane. A simultaneous fit of invariant mass and impact parameter yields the result $f_b = 0.35 \pm 0.09\,(\mathrm{stat}) \pm 0.10\,(\mathrm{sys})$ for $p_t^{J/\psi} > 8$ GeV/c. The integrated b quark cross section, derived using this value, is shown in Fig. 2 along with other DØ cross section results [12]. The measurements are in reasonable agreement with

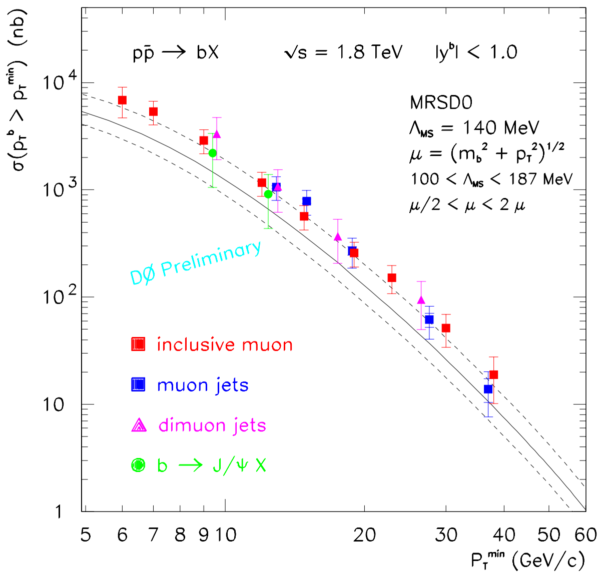

Figure 2: DØ b-quark cross section results.

the QCD NLO prediction [13].

To determine the fraction f_χ of J/ψ events which originate from χ_c decays, the decay $\chi_c \rightarrow J/\psi\gamma$ is fully reconstructed. The measured fraction is $f_\chi = 0.32 \pm 0.07(\text{stat}) \pm 0.07(\text{sys})$. This result suggests, contrary to theoretical expectations, that J/ψ production is not primarily from χ_c decay. Combining the f_χ and f_b values and accounting for the contribution from $B \rightarrow \chi_c$, DØ finds that 0.42 ± 0.17 J/ψ events do not originate from B or χ_c decays.

The DØ experiment has also made preliminary measurements of the J/ψ cross section in the forward region $2.6 < |\eta^{\mu\mu}| < 3.4$ using a 6.3 pb^{-1} data sample. A sample of 567 $\pm$ 57 J/ψ events is used to determine the differential cross section shown in Fig. 3(a). Results in the forward direction are combined with measurements made in the central region to determine the rapidity dependence of the J/ψ cross section shown in Fig. 3(b). Data in the intermediate region is currently begin analyzed.

2.2 CDF J/ψ and $\psi(2S)$ Results

The CDF collaboration has separately reconstructed J/ψ and $\psi(2S)$ events in the central region $|\eta^{J/\psi}| < 0.6$ with $p_t^{J/\psi} > 4$ GeV/c [14]. The J/ψ invariant mass distribution, from

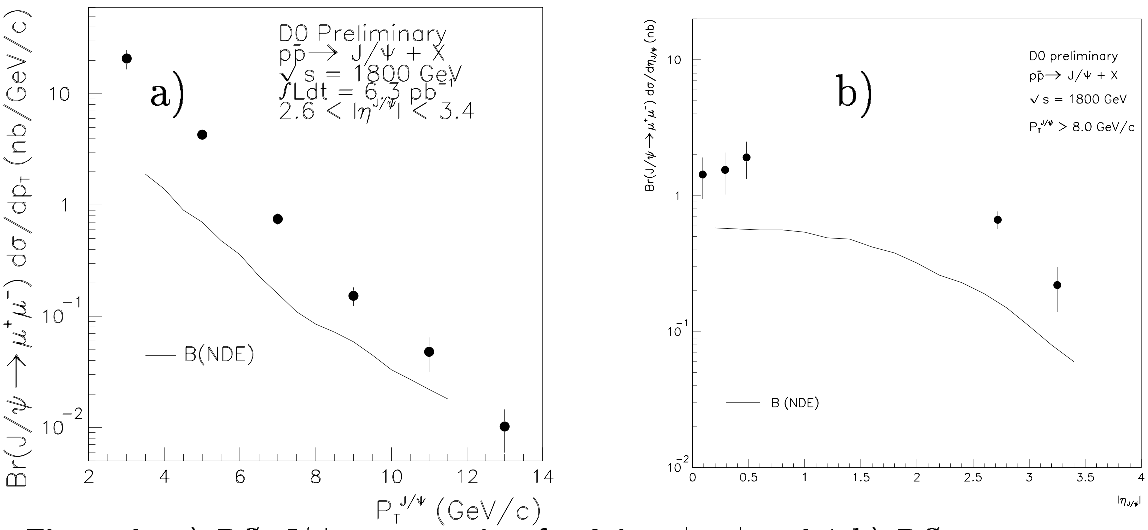

Figure 3: a) DØ J/ψ cross section for $2.6 < |\eta^{\mu\mu}| < 3.4$ b) DØ measurement of the rapidity dependence of the J/ψ cross section

a 15.4 pb$^-$1 data sample, is shown in Fig. 4(a). A fit to this distribution yields 26533 $\pm$ 175 J/ψ events. Fig. 4(b) shows the $\psi(2S)$ invariant mass spectrum, corresponding to 896 $\pm$ 94 events, reconstructed from 17.8 pb^{-1} of data. The integrated cross sections are determined to be $\sigma(J/\psi) \cdot BR(J/\psi \to \mu^+\mu^-) = 29.10 \pm 0.19\,(\mathrm{stat})^{+3.05}_{-2.84}\,(\mathrm{sys})$ nb and $\sigma(\psi(2S)) \cdot BR(\psi(2S) \to \mu^+\mu^-) = 0.721 \pm 0.058\,(\mathrm{stat}) \pm 0.072\,(\mathrm{sys})$ nb $(p_t^{J/\psi} > 4\,\mathrm{GeV/c}, |\eta^{J/\psi}| < 0.6)$.

CDF determines the fraction of J/ψ and $\psi(2S)$ which come from B decay by measuring the vertex flight distance [15]. The results are $f_b^{J/\psi} = 0.196 \pm 0.015$ and $f_b^{\psi(2S)} = 0.228 \pm 0.038$ for $p_t > 4$ GeV/c. The fraction of J/ψ which come from radiative χ_c decay, determined by fully reconstructing $\chi_c \to J/\psi\gamma$ events, is $f_\chi = 0.283 \pm 0.016(\mathrm{stat}) \pm 0.068(\mathrm{sys})$ for $p_t > 4$ GeV/c. As with the DØ measurements, these results indicate that the dominant contribution to prompt J/ψ production does not come from χ_c decay.

The J/ψ differential cross section is shown in Fig. 5 with the prompt and B hadron components indicated separately along with their sum. Also shown are the theoretical predictions. Fig. 6(a) shows the B component of the $\psi(2S)$ cross section which is in reasonable agreement with the NLO QCD calculation [13]. Fig. 6(b) shows the prompt component of $\psi(2S)$ production along with the theoretical prediction [8]. Several proposals have been made to explain the large discrepancy between data and theory for prompt $\psi(2S)$ production. It has been suggested that the excess might be caused by the presence of new charmonium states above the $D\bar{D}$ threshold [16]. However, in order to explain the data, these states must decay into $\psi(2S)$ at rates which are difficult to explain the-

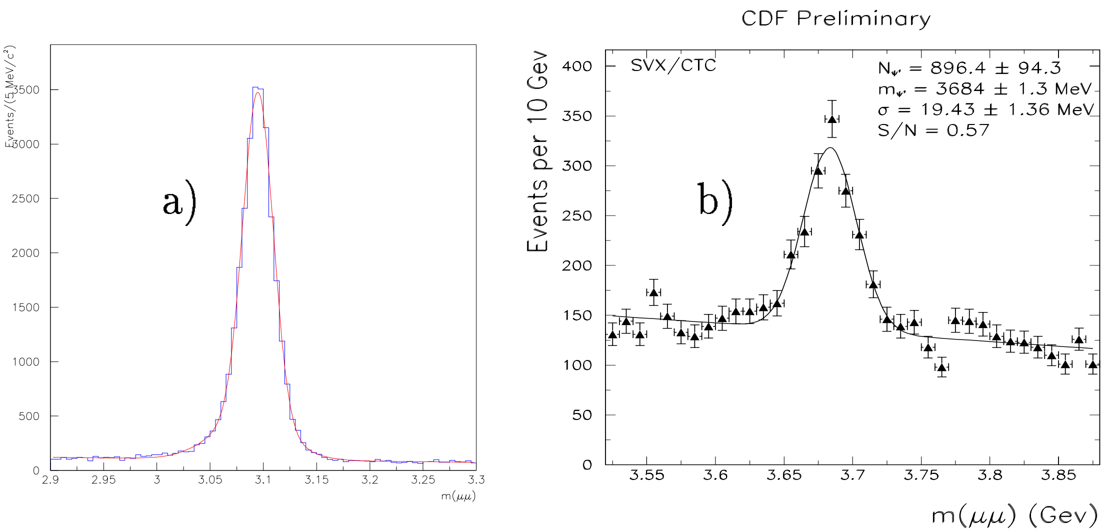

Figure 4: a) CDF J/ψ invariant mass distribution b) CDF $\psi(2S)$ invariant mass distribution.

oretically [17]. Others have suggested that "color-octet" diagrams [18, 19] may play an important role. This latter proposal also may help explain the excess of J/ψ which do not come from χ_c.

3 Bottomonium Production

Both CDF and DØ have investigated Υ production at the Tevatron. These measurements are important for the investigation of $b\bar{b}$ bound state production mechanisms [4, 7, 19, 20]. Since, as discussed above, there are large discrepancies between data and theory in the charmonium sector, it is interesting to carry out similar comparisons for the Υ particles.

3.1 DØ Υ Results

DØ reconstructs Υ events through the decay $\Upsilon \rightarrow \mu^+\mu^-$ from a data sample of 6.6 pb^{-1}. The DØ measurements are summed over the Υ(1S), Υ(2S), and Υ(3S) resonances. Both integrated and differential cross sections are measured [21] in the rapidity region $|y^{\Upsilon}| < 0.7$. The integrated cross section result divided by the rapidity bin width is $d\sigma/dy|_{y=0}(\Upsilon) \times BR(\Upsilon \rightarrow \mu^+\mu^-) = 768 \pm 81(\mathrm{stat}) \pm 152(\mathrm{sys})$ pb ($p_t^{\Upsilon} < 25$ GeV/c). For $p_t^{\Upsilon} > 5$ GeV/c the $\mathcal{O}(\alpha_s^3)$ prediction [22] is a factor of 5 lower than the data.

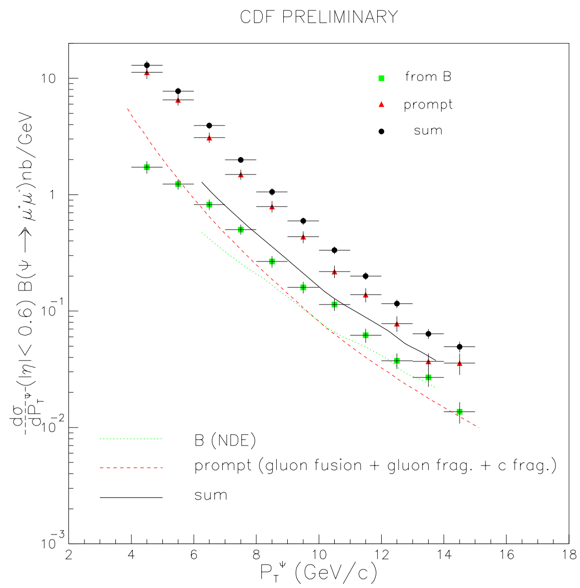

Figure 5: CDF J/ψ differential cross section.

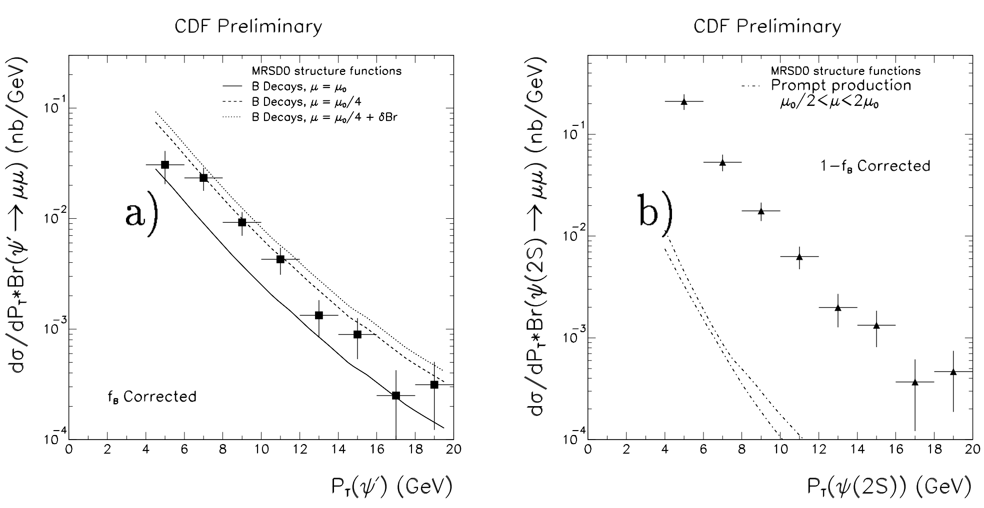

Figure 6: a) CDF $\psi(2S)$ cross section from B decay b) CDF cross section from prompt $\psi(2S)$ production.

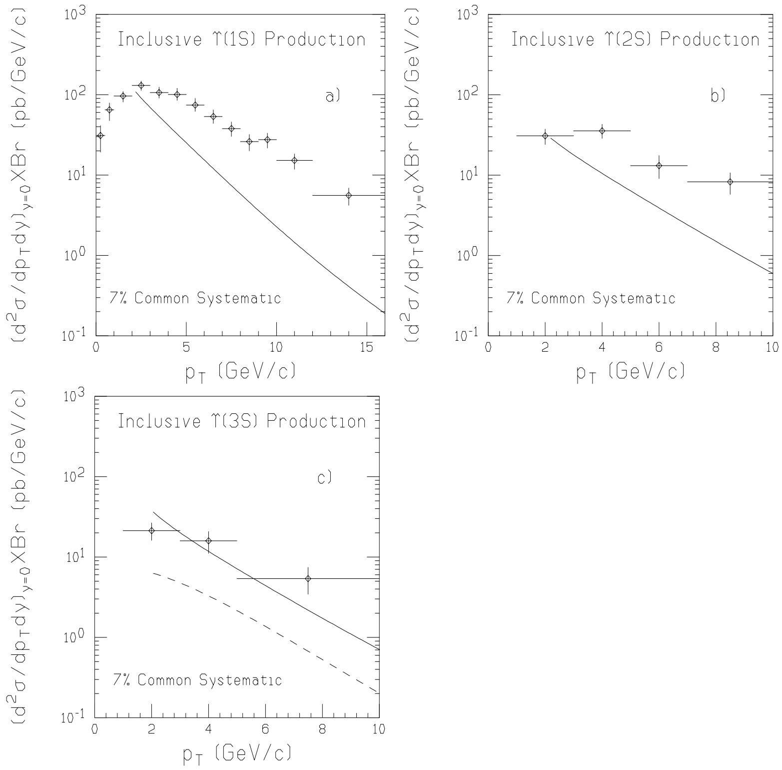

Figure 7: CDF differential Υ cross section results for the Υ(1S), Υ(2S), and Υ(3S). The solid curves in (a) and (b) represent the color-singlet calculations. The dashed curve in (c) represents the color-singlet prediction and the solid curve corresponds the sum of the predicted contributions from direct production and the decay of the unobserved $\chi_b(3P)$ state.

3.2 CDF Υ Results

CDF has also measured the Υ differential and integrated cross sections [23] from $\Upsilon \to \mu^+\mu^-$ decays using a data sample of 16.6 pb^{-1}. The CDF detector resolution allows the separation of the individual Υ resonances. The differential cross section results for each resonance for the rapidity region $|y^\Upsilon| < 0.4$ are shown in Fig. 7. Theoretical predictions [19] are also shown in the figure. The solid curves in the Υ(1S) and Υ(2S) plots represent the color-singlet calculations. The dashed curve in the Υ(3S) figure represents the color-singlet prediction and the solid curve corresponds the sum of the predicted contributions from direct production and the decay of the unobserved $\chi_b(3P)$ state. The integrated cross section results divided by the rapidity bin width are

$$d\sigma/dy|_{y=0}(\Upsilon(1S)) \times BR(\Upsilon \to \mu^+\mu^-) = 753 \pm 29(\text{stat}) \pm 72(\text{sys})\ \text{pb};\ \ 0 < p_t^\Upsilon < 16\ \text{GeV/c},$$
$$d\sigma/dy|_{y=0}(\Upsilon(2S)) \times BR(\Upsilon \to \mu^+\mu^-) = 183 \pm 18(\text{stat}) \pm 24(\text{sys})\ \text{pb};\ \ 1 < p_t^\Upsilon < 10\ \text{GeV/c},$$
$$d\sigma/dy|_{y=0}(\Upsilon(3S)) \times BR(\Upsilon \to \mu^+\mu^-) = 101 \pm 15(\text{stat}) \pm 13(\text{sys})\ \text{pb};\ \ 1 < p_t^\Upsilon < 10\ \text{GeV/c}.$$

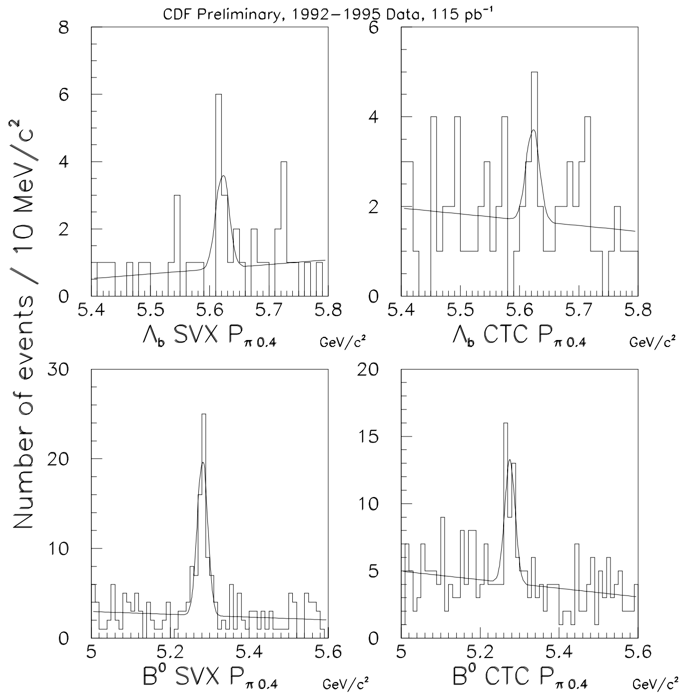

Figure 8: Λ_b and B^0 invariant mass distributions from CDF.

In general the rate of Υ product is found to be higher than leading order QCD predictions. It is possible that the inclusion of color-octet diagrams may help explain the discrepancies between data and theory in Υ production as well [19].

4 Λ_b and B_c Production

The CDF collaboration has fully reconstructed the decay $\Lambda_b \to J/\psi\Lambda$ ($\Lambda \to p\pi, J/\psi \to \mu\mu$) using a data sample of 115 pb^{-1}. The transverse flight distance of the Λ is required to be greater than 1.0 cm and the transverse momentum of the Λ_b must be larger than 6 GeV/c. Events where both muons are measured in the silicon vertex detector (termed SVX candidates) are required to have proper lifetime $c\tau > 100\mu$m. All other events (termed CTC candidates) are required to have $c\tau > 0\mu$m. Figure 8 shows the reconstructed Λ_b invariant mass for the two classes of events. Also shown is the result of the reconstructing the kinematically similar decay $B^0 \to J/\psi K_s^0$ ($K_s^0 \to \pi\pi, J/\psi \to \mu\mu$) used as a reference signal.

For the purposes of a cross section measurement, only the SVX candidates are used. The result of fits to the mass peaks yields 8.04 ± 3.63 Λ_b events and 57.02 ± 8.54 B^0 events.

Using these values along with corrections for the relative efficiencies and branching ratios leads to the result $\sigma_{\Lambda_b} Br(\Lambda_b \to J/\psi\Lambda)/\sigma_{B_d} Br(B_d \to J/\psi K_s^0) = 0.31 \pm 0.15$ (stat) $\pm$ 0.06 (sys). Assuming $\sigma_{\Lambda_b}/\sigma_{B_d} = 0.1/0.375$ and $Br(B_d \to J/\psi K_s^0) = 3.7 \times 10^{-4}$ the branching ratio result $Br(B_d \to J/\psi\Lambda) = 4.3 \pm 2.1$ (stat) $\pm$ 0.8 (sys) $\times 10^{-4}$ is obtained.

The semileptonic decay of the Λ_b has also been observed through the decay $\Lambda_b \to \Lambda_c^+ e^- \bar{\nu}_e X$ ($\Lambda_c^+ \to pK^-\pi^+$) The Λ_c is fully reconstructed and required to have the correct charge relationship with respect to the electron. A 19.3 pb^{-1} data sample yields a signal of 33.7 $\pm$ 9.0 Λ_b events leading to the result $f(b \to \Lambda_b)Br(\Lambda_b \to \Lambda_c^+ e^- \overline{\nu}_e X)Br(\Lambda_c \to pK^-\pi^+) = \left(9.5 \pm 2.5\,(\text{stat})^{+4.4}_{-4.0}(\text{sys})\right)$ where $f(b \to \Lambda_b)$ is the fraction of b quarks that fragment into Λ_b. This result uses the CDF b quark cross section measurement $\sigma_b(p_t^b > 10.5\ GeV/c, |y| < 1) = 1.99 \pm 0.30 \pm 0.38\ \mu b$ [24].

In addition CDF has conducted a search for the decay $\Lambda_b \to J/\psi\Lambda(1520)$ ($\Lambda(1520) \to pK, J/\psi \to \mu\mu$). No significant signal is observed in a data sample of approximately 70 pb^{-1}. The corresponding limit is $f(b \to \Lambda_b)BR(\Lambda_b \to \Lambda(1520)) < 2.8 \times 10^{-4}$ (90% C.L.) for $p_t^{\Lambda(1520)} > 2$ GeV.

The CDF collaboration has also searched for the decay $B_c \to J/\psi\pi$. The reconstruction requirements include $p_t^{\pi} > 2.5$ GeV/c and $p_t^{B_c} > 6$ GeV/c. The B_c result is quoted relative to the kinematically similar decay $B^+ \to J/\psi K^+$ and is a function of the assumed B_c lifetime. The limit of $\sigma(B_c^+)BR(B_c^+ \to J/\psi\pi^+)/\sigma(B_u^+)BR(B_u^+ \to J/\psi K^+)$, determined from a data sample of approximately 110 pb^{-1}, is shown in Fig. 9 along with a theoretical estimate.

5 Conclusions

In conclusion both CDF and DØ have made measurements of charmonium and bottomonium production which are in disagreement with conventional theoretical expectations. The introduction of color-octet diagrams may help explain these discrepancies. More theoretical and experimental investigations will be necessary, however, to determine if the production of quarkonia in high energy collisions is truly understood. CDF has also measured Λ_b production rates in both exclusive and semileptonic decays. Finally, CDF has placed a new limit on the decay $B_c^+ \to J/\psi\pi^+$ which is approaching theoretical expectations.

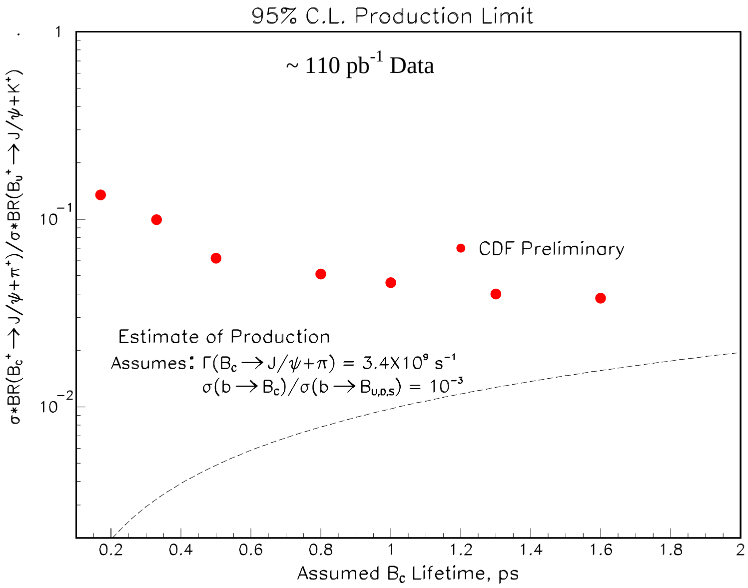

Figure 9: Limit on B_c production from CDF.

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