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CDF

Production of Heavy Quark States at CDF

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ABSTRACT

In this paper we present results on quarkonia production, B-meson production and $b\bar{b}$ correlations in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. These results were obtained from data taken with the CDF detector at Fermilab. We cover recently completed analyses of the 1992-95 collider run. Prospects for the near and more distant future are also discussed.

1. INTRODUCTION

Quarkonia production and Beauty production in hadronic collisions is fundamental for the study of perturbative QCD. The comparison of the experimental data with the QCD predictions provides a necessary check of the ingredients entering the evaluation of hadronic processes, and allows us to determine if they can be used to extrapolate the calculations to higher energies. The B-meson and b-quark cross section measurements at 1.8 TeV are also an important benchmark to establish the feasibility of CP violation measurements at high energy hadron colliders. This paper is organized as follows. In section 2 we describe briefly the CDF detector; in section 3 we present our studies on Quarkonia production; in section 4 we describe our studies on Beauty production and in section 5 we discuss the future prospects.

2. THE CDF DETECTOR

Our data have been taken with the CDF detector which has been described in detail elsewhere [1, 2]. The components relevant for this presentation are briefly described here. The central tracking chamber (CTC) is in a 1.4 T axial magnetic field and consists of nine superlayers, four of which give stereo information. A Silicon Vertex Detector (SVX) provides high-resolution $r-\phi$ tracking information near the interaction region. The SVX detector covers the luminous region of $|z| < 26$ cm along the beam line and consists of four layers of DC coupled, single sided, silicon microstrip detectors with an innermost radius of 2.9 cm. The momentum resolution for tracks detected by both the CTC and SVX systems is $\delta P_t/P_t = \sqrt{(0.0009P_t)^2 + (0.0066)^2}$. Surrounding the CTC are electromagnetic calorimeters, electromagnetic strip chambers and hadronic calorimeters providing five absorption lengths of material before the Central Muon Chambers (CMU). The CMU chambers, at a radius of 3.5 m from the beam axis, cover the pseudorapidity region $|\eta| < 0.6$. These chambers are complemented by the central muon upgrade system (CMP) which consists of four layers of drift tubes behind 2 feet of steel. Use of the CMP considerably reduces hadronic punch-through backgrounds to the muon signal.

CDF collected approximately $\sim 20\ pb^{-1}$ of data during the 1992-93 collider run (Run Ia) and keeps accumulating data during the 1994-95 run (Run Ib).

3. QUARKONIA PRODUCTION

In this section we will describe our studies on the production of J/ψ's, $\psi(2S)$'s, χ_c's and Υ'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. The χ_c mesons are produced directly or from the decay of b hadrons and finally Υ's are produced directly or from the decay of higher mass χ_b states.

Using $\sim$15.5(18) pb^{-1} of data taken with the CDF detector during Run Ia we measured the differential and integrated production cross sections for $J/\psi(\psi(2S))$[3]. The two charmonium states are reconstructed in the dimuon channel in the kinematic range $P_T > 4$ GeV/c and $|\eta| < 0.6$ and the mesurements were based on 26,533$\pm$175 J/ψ's and 896$\pm$94 $\psi(2S)$'s. Using information from the SVX to reconstruct the decay vertices of the charmonium states, we distinguish between charmonia from b decays and from other production mechanisms. We find that for the kinematic region $P_T > 4$ GeV/c and $|\eta| < 0.6$, (19.6$\pm$1.5)% of J/ψ's and (22.8$\pm$3.5)% of $\psi(2S)$'s come from the decay of b hadrons. In Fig. 1 we compare our differential production cross section measurements with the theoretical predictions. The direct production model includes contributions from charm fragmentation as well as gluon fragmentation from color-singlet diagrams [4]. The observed yield for charmonia from b hadron decays is consistent with the theoretical predictions within their uncertainties. The observed yield though for charmonia not originating from b decays is found to be much larger than the theoretical expectation. The disagreement with the theory is much more prominent in the $\psi(2S)$ state (a factor of $\sim$ 50) and it has created intense theoretical interest [4, 5, 6, 7, 8]. 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[9, 10] and for the first time the color-octet fragmentation diagrams were considered as a possible solution for the J/ψ and $\psi(2S)$ anomalies. We note however, that only the shape of the color-octet contribution as a function of P_T is known from first principles. The long distance matrix element for each color-octet contribution is determined using fits to our data [3, 9, 11].

At CDF we reconstruct the χ_c mesons through the decay chain $\chi_c \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu^+\mu^-$. We detect the photon with two different methods, by using either calorimeter or tracking information. In the first 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 $\sim$ 18 pb^{-1} of Run Ia data we reconstructed $1,230 \pm 72$ χ_c's (see Fig. 2) and we 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 $f_\chi^{J/\psi} = 28.3 \pm 1.6(stat) \pm 6.8(syst)$%. We have found as well that the fraction of J/ψ's from χ_c's not including contributions from $B \rightarrow J/\psi X$ and $B \rightarrow \chi_c X$ decays is $f(Nob)_\chi^{J/\psi} = 32.3 \pm 2.0(stat) \pm 8.5(syst)$%. In Fig. 2 we present the fraction $f(Nob)_\chi^{J/\psi}$ as a function of $P_T^{J/\psi}$. We find that the production from χ_c's is not the dominant production mechanism of prompt J/ψ's, in disagreement with current theoretical predictions (see Fig. 3). In the second method we can reconstruct the χ_c signal through the detection of conversion photons. Using 75 pb^{-1} of Run Ia and Run Ib data, we have 46.4 ± 7.2 prompt χ_{c1}'s and 23.2 ± 6.4 prompt χ_{c2}'s (see Fig. 3). The prompt component is isolated from any b background by imposing the requirement that the proper lifetime, λ, of the $J/\psi - \gamma$ system is less than 100 μm. We have measured $\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})+\sigma(\chi_{c2})} = 0.47 \pm 0.08(\text{stat}) \pm 0.02(\text{syst.})$

We report as well on the measurements of the differential and integrated production

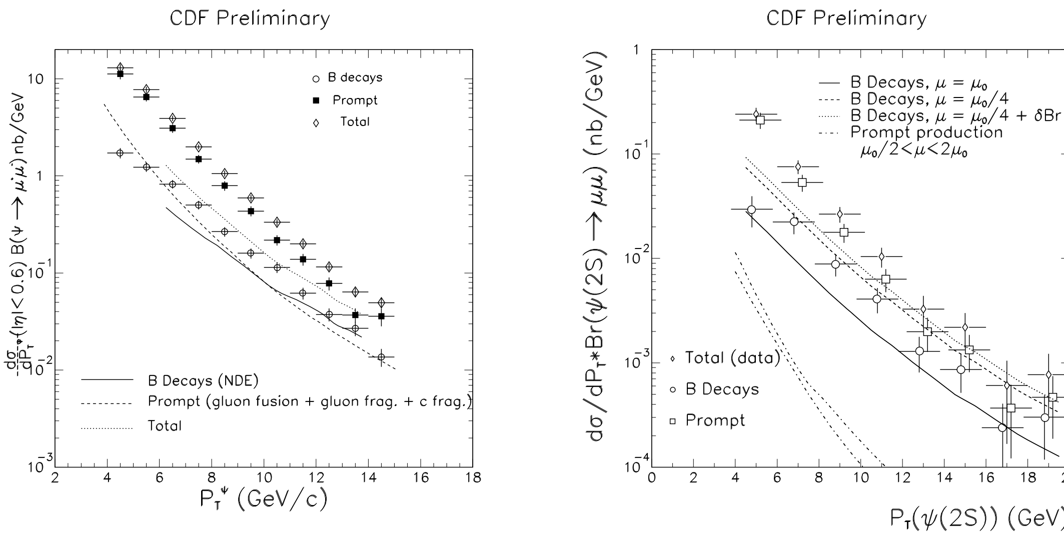

Figure 1: Differential cross sections of J/ψ as a function of $P_T^{J/\psi}$ (left) and of $\psi(2S)$ as a function of $P_T^{\psi(2S)}$ (right).

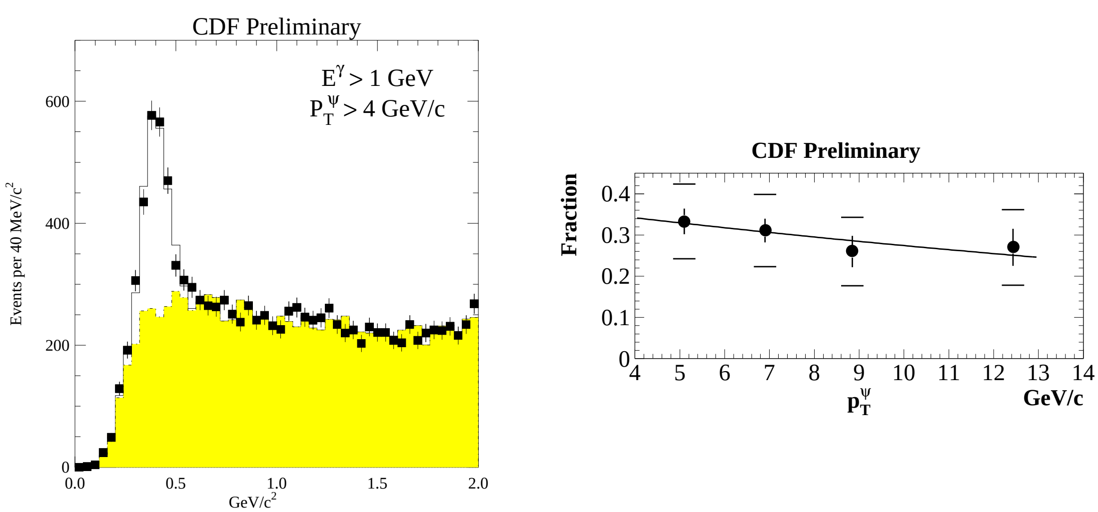

Figure 2: On the left, the mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for the J/ψ signal region. On the right, the fraction of J/ψ from χ_c as a function of $P_T^{J/\psi}$ with the contribution from b's removed. For both plots calorimeter information is used for the detection of the photon, and $P_T^{\gamma} > 1\ GeV/c$.

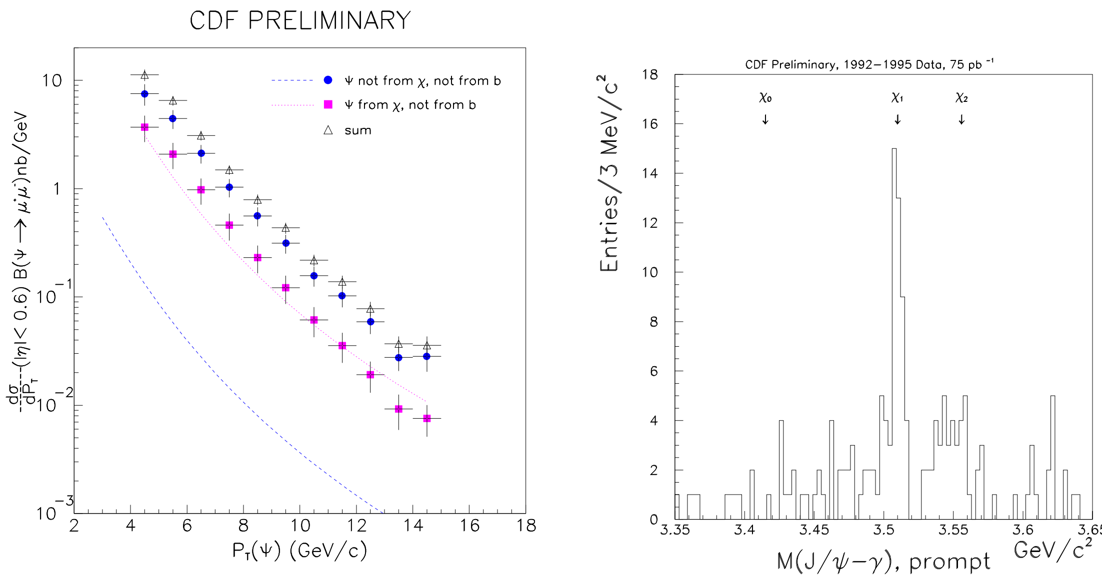

Figure 3: On the left, differential cross sections of prompt J/ψ as a function of $P_T^{J/\psi}$. On the right, the mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for the J/ψ signal region and for $P_T^{\gamma} > 1\ GeV/c$, where tracking information is used for the detection of the photon.

cross sections of the Υ(1S), Υ(2S) and Υ(3S) states by studying the reaction $p\bar{p} \rightarrow \Upsilon X \rightarrow \mu^+\mu^- X$. To reduce hadronic punch-through backgrounds, at least one of the two muons was identified by both the CMU and CMP systems. We have reconstructed 1,248 Υ(1S), 300 Υ(2S) and 203 Υ(3S) events in 16.6 pb^{-1} of data from Run Ia and in the Υ rapidity range $|y| < 0.4$ (see Fig. 4). We find that the rates are higher than the theoretical predictions by a factor of $\sim$ 3 for the Υ(1S), Υ(2S) and by a factor of $\sim$ 10 for the Υ(3S) state. The theoretical calculations include contributions from direct production and from χ_b(1P), χ_b(2P) decays for the Υ(1S); from direct production and from χ_b(2P) decays for the Υ(2S); from direct production only for the Υ(3S). While a factor of 3 descrepancy can be partly accomodated by the inclusion of higher order corrections and possible new production mechanisms [4, 11], the discrepancy for the Υ(3S) state may suggest that there are additional χ_b states below the $B\bar{B}$ threshold that contribute to the Υ(3S) production. In fact, in Ref. 11 there is an attempt to include in the Υ(3S) production cross section a contribution from the radiative decay χ_b(3P) $\rightarrow \Upsilon$(3S)γ. Although this introduces several uncertainties, the agreement with the data seems better.

4. BEAUTY PRODUCTION

In this section we will describe our studies on B-meson production cross sections,

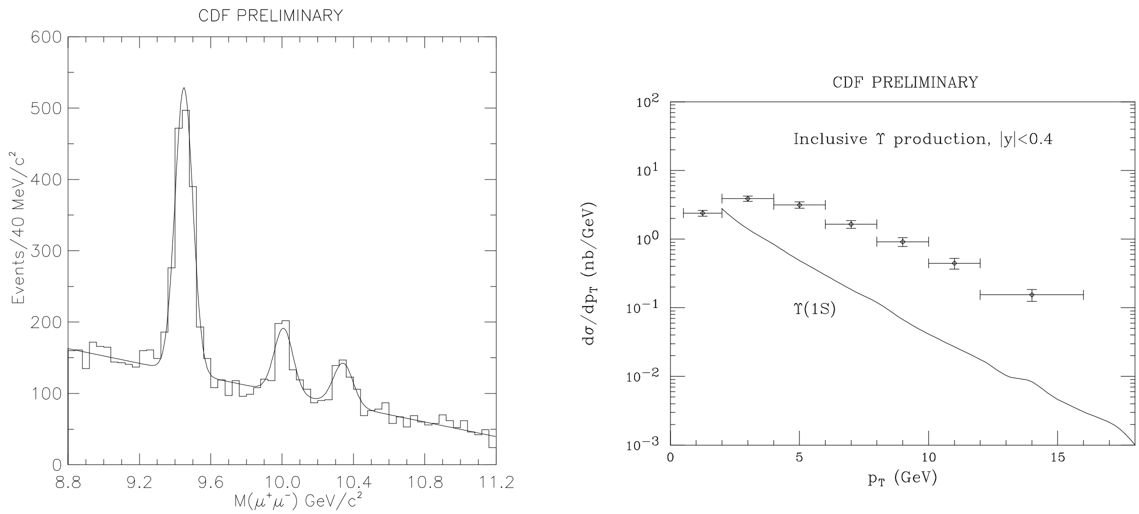

Figure 4: On the left, the invariant mass distribution for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. On the right, the differential cross section as a function of P_T for the $\Upsilon(1S)$ state. Both plots are for $|y| < 0.4$. The theoretical curve on the right corresponds to a leading order calculation and was generated using MRSD0 PDF and scale $\mu^2 = P_T^2 + m_\Upsilon^2$.

on correlated $b\bar{b}$ cross sections and on B_c production.

The B-meson production cross sections from the exclusive decay channels $B \rightarrow J/\psi K^{\pm}$ and $B \rightarrow J/\psi K^{*0}$, $K^{*0} \rightarrow K^+\pi^-$ were based on 19.3 pb^{-1} from the Run Ia data[12]. We reconstructed 72±12, 42±9, 35±7 and 31±6 charged and neutral B-mesons in the P_T^B range of 6-9 GeV/c, 9-12 GeV/c, 12-15 GeV/c and greater than 15 GeV/c respectively. The corresponding B-meson cross sections we derived are shown in Fig. 5, represented by the triangles. The B-meson cross sections from $B \rightarrow \mu X$ decays are based on 17.9 pb^{-1} from the Run Ia data[13] and are also shown in Fig. 5, represented by the diamonds and the squares. These measurements are based on 459±69 $B \rightarrow D^0\mu X$, $D^0 \rightarrow K\pi$ decays and 153±20 $B \rightarrow D^{*+}\mu X$, $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K\pi$ decays. The CDF differential B-meson cross section measurements from the Run Ia data are compared to a NLO calculation by Nason, Dawson and Ellis [14] convoluted with Peterson fragmentation [15]. The uncertainty in the predictions arising from choices of the renormalization scale μ, the b-quark mass and the Peterson parameter ϵ are also shown. The experimental cross sections lie approximately a factor of 2 above the central theory curves.

We are reporting as well on the measurement of correlated b-quark cross sections in the process $p\bar{p} \rightarrow b\bar{b}X$, based on 15.1 pb^{-1} from the Run Ia data. Here, one b is detected from a good quality muon with $P_T > 9$ GeV/c from semileptonic decay and

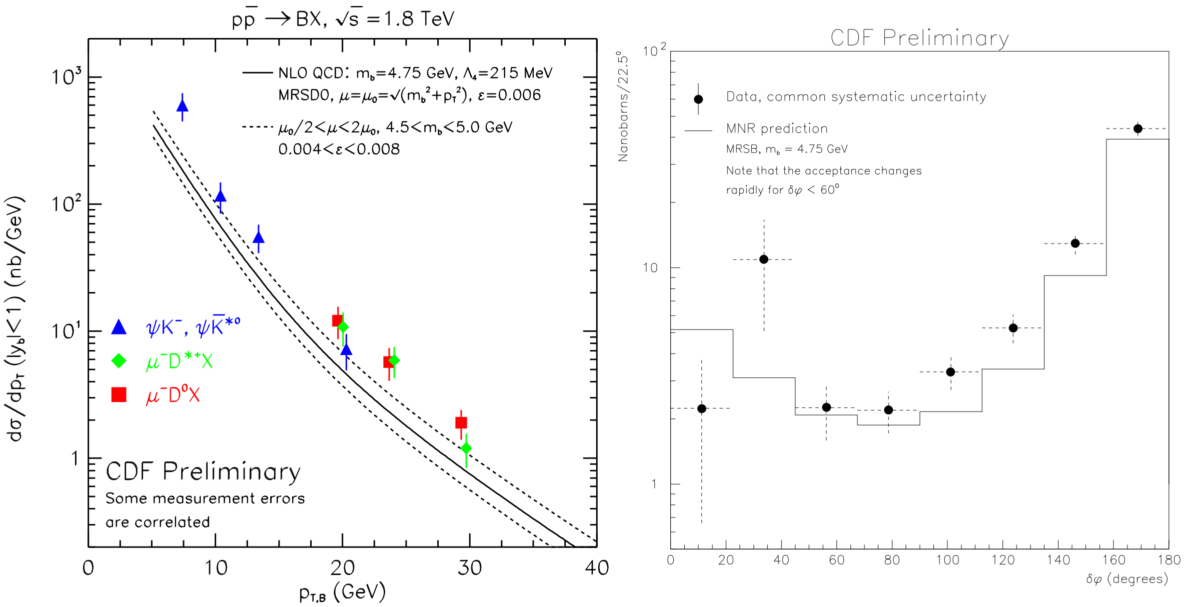

Figure 5: On the left, the B-meson differential cross section. On the right, the measured differential cross section, $d\sigma_{\bar{b}}/d(\delta\phi)$, as a function of the azimuthal angle between the jet and the muon.

the second b ($\bar{b}$) is detected with secondary vertex techniques. To identify the $\bar{b}$ we require that the event contains at least one jet with $E_T > 10$ GeV, $|\eta| <1.5$ and at least two good tracks. In Fig. 5 we show the measured $d\sigma_{\bar{b}}/d(\delta\phi)$ distribution, together with the Mangano-Nason-Ridolfi (MNR) calculation [16]. ϕ is the azimuthal angle between the jet and the muon. The shapes of the theoretical prediction and the experimental data agree well, especially for $\delta\phi > \pi/2$, but the overall normalization of the data is about a factor of 1.3 higher than predicted.

We also present a search for the B_c meson in the decay channel $B_c^{\pm} \rightarrow J/\psi\pi^{\pm}$. This search is guided by a control sample of $B_u^{\pm} \rightarrow J/\psi K^{\pm}$ decays. In Fig. 6 we show 95% confidence level limits on $\sigma \times BR(B_c^{\pm} \rightarrow J/\psi\pi^{\pm})/\ \sigma \times BR(B_u^{\pm} \rightarrow J/\psi K^{\pm})$ as a function of the unknown and not well predicted B_c lifetime. The search is done in the invariant mass range $6.1 < m(B_c) < 6.4$ GeV/c^2.

Finally, in Fig. 6 we also show the B^0 mass distribution of the world's largest sample of reconstructed B mesons through the decay chain $B^0 \rightarrow J/\psi K_s$, $J/\psi \rightarrow \mu^+\mu^-$, $K_s \rightarrow \pi^+\pi^-$. This distribution is based on 60 pb^{-1} from Run Ia and Run Ib data. The sample of events was collected with a dimuon trigger that required both muons to

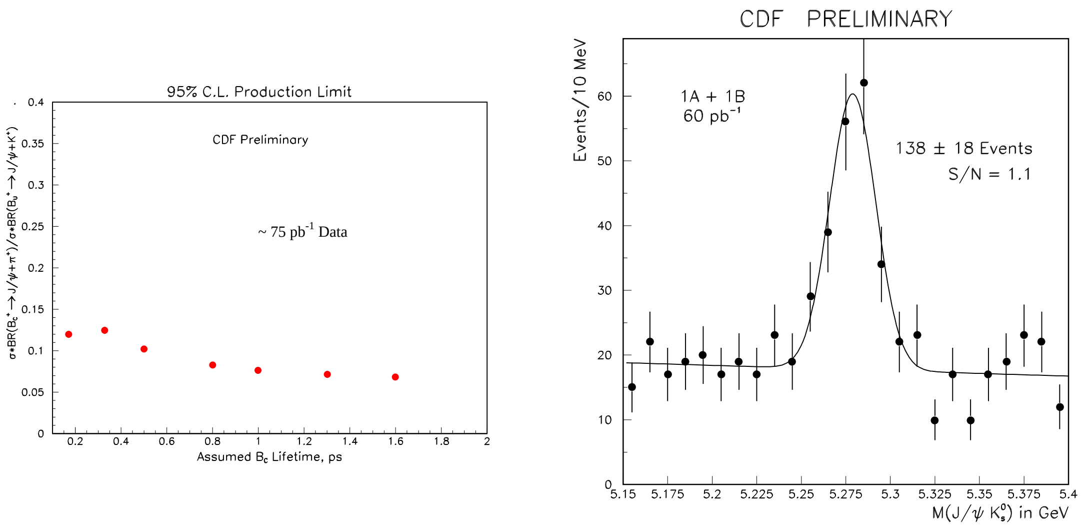

Figure 6: On the left, 95% C.L. limit on the production of $B_c \rightarrow J/\psi\pi$ relative to $B_u \rightarrow J/\psi K$ as a function of the B_c lifetime. On the right, reconstructed $B^0 \rightarrow J/\psi K_s$ mass from 60 pb^{-1} of the 1992-95 data.

have transverse momentum greater than 2 GeV/c. SVX track information is used if available. It was required that $P_T^{K_s} > 1.0(1.5)$ GeV/c and $P_T^B > 6.0(7.0)$ GeV/c if both muons from the J/ψ decay are detected by the SVX (otherwise). The $B^0 \rightarrow J/\psi K_s$ decay mode is the mode most frequently cited in the literature for the measurement of $sin(2\beta)$ and the observation of CP violation.

5. PROSPECTS

By the end of the 1992-95 run ($\approx$ 120 pb^{-1}) we expect to have more than 500,000 J/ψ's, approximately 1,000 B_u's in the $J/\psi K^{\pm}$ mode, 600 B_d's in the $J/\psi K^{*0}$ mode, 200 B_s's in the $J/\psi\phi$ mode and 300 B_d's in the $J/\psi K_s$ mode. We also expect to have approximately 10^6 inclusive single leptons from B decays and 10^4 partially reconstructed events with a lepton and c-hadron in the decay products. Such a sample will lead to a rich B physics program and will allow direct measurements of most of the key ingredients needed to evaluate the capability of an experiment in hadron collisions to perform delicate measurements such as CP violation and B$_s$ mixing. This physics program will become even more interesting after we collect $\approx$ 2 fb^{-1} of data by the end of Run II.

With the Run I data we hope to shed more light on the quarkonia production mechanisms. The increase of statistics will be particularly useful for the $\psi(2S)$, χ_{c1},

χ_{c2}, Υ(2S) and Υ(3S) states. The measurement of the spin alignment of the J/ψ, $\psi(2S)$, χ_{c1} and χ_{c2} states will also produce very valuable information on the production mechanisms[10]. 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. We will produce as well a whole new set of differential and integrated measurements of B-meson and b-quark production cross sections and we will study $b\bar{b}$ production through the observation of $b\bar{b}$ correlations using several different techniques to detect the b-quarks. In addition, we plan to study further the exclusively reconstructed decays $B_s \rightarrow J/\psi\phi$ and $\Lambda_b \rightarrow J/\psi\Lambda$ and to search for the B_c meson through the decays $B_c \rightarrow J/\psi\pi$ and $B_c \rightarrow J/\psi l\nu X$. As far as CP violation studies are concerned, with the Run I statistics and our currently established tagging efficiency (ϵD^2) of 2%, the uncertainty on $sin(2\beta)$, $\delta(sin(2\beta))$, will be about 1.0 [17] by the end of the run. The observation of CP violation in the B system will be the most important goal of our Run II B Physics program. A conservative extrapolation based on a) our current $J/\psi K_s$ signal and modest dilepton trigger improvements (expected signal of 20,000 $B^0 \rightarrow J/\psi K_s$ decays) and b) our currently established tagging efficiency of 2%, results in an uncertainty on $sin(2\beta)$ of 0.14. This number could be improved to $\delta(sin(2\beta))$=0.07 if we acheive $\epsilon D^2 = 8\%$ [18].

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