CDF/ANAL/HEAVY_FLAVOR/GROUP/1184
DRAFT VERSION 0.2

Measuring the b-quark production cross section

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July 17, 1990

Abstract

The production of b-quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV is studied using the CDF detector at the Fermilab Tevatron. B hadrons are detected using the decay channel $B \to J/\psi\, X$, where the J/ψ is identified by its $\mu^+\mu^-$ final state. Separation of J/ψ production mechanisms is discussed, with emphasis on production via $B \to J/\psi\, X$. The differential cross section for J/ψ production and the fraction of J/ψ produced through B decay are used to extrapolate values for the B meson and b-quark total cross sections. Comparison is made with $\mathcal{O}(\alpha_s^3)$ calculations.

1 Introduction

The production properties of heavy quarks in general and b-quarks in particular are thought to be describable by perturbative QCD. The recent calculation by Nason, Dawson, and Ellis [1,2] of the one particle inclusive double differential cross section for b-quark production, $d^2\sigma/dy\, dp_T$, complete to $\mathcal{O}(\alpha_s^3)$, allows us to test the validity of perturbative QCD for b-quark production. We can constrain the theory by measuring the total cross section for b-quark production, $\sigma(p\bar{p} \to b+X)$, and comparing it to these predictions. The b-quark cross section can provide important information on the gluon structure of the proton, and is also important as an "engineering" number, needed to make rate predictions for the SSC and high-sensitivity B experiments and to judge the feasability of proposed experiments.

Proton-antiproton colliders produce b-quarks at a much higher rate than e^+e^- colliders (which are the conventional instruments with which to study B physics) but the backgrounds in $p\bar{p}$ collisions are much larger due to the beam fragments (the 'underlying event'). It therefore becomes necessary to tag the b-quark through its decay products and to use topological event features to separate b-quark events from the background. This has been done at UA1 using leptons, dileptons, and J/ψ as tags [3], and is currently being attempted by several fixed target experiments at FNAL [4] by means of secondary vertex triggers. Exclusive decays of B mesons can provide a much cleaner sample separation; however, the statistics are small in these channels [5,6].

CDF has several data samples which can be used to study b-quark production. The inclusive electron sample is an example of a sample which is believed to contain a large fraction of b-quark events. This assumption can be tested by looking for charmed particles accompanying the electron; the electron is assumed to come from the semi-leptonic decay of the b-quark to a c-quark, with the c-quark fragmenting into a charmed meson. This has been studied by Barry Wicklund and Fumi Ukegawa; they see a clear signal for D^0 mesons in the inclusive electron sample. Such an analysis holds great promise for measuring the b-quark production cross section for b-quarks with $p_T > 20$ GeV/c (the inclusive electron sample has electrons with $p_T > 12$ GeV/c, requiring the parent b-quark to have a much larger p_T) [7]. Likewise, the inclusive muon sample now under construction [8] should provide a similar opportunity to study high-p_T b-quark production.

Since the characteristic p_T of the b-quarks is on the order of the b-quark mass, the inclusive leptons are not sensistive to most of the b-quark cross section. Comparison between theory and experiment can thus be made only for a small fraction of the produced b-quarks. In this note we make use of the extremely clean $J/\psi \rightarrow \mu^+\mu^-$ signal as a sample of events which we believe are enriched with B hadrons. The J/ψ signal extends down to J/ψ p_T of 6 GeV/c, roughly corresponding to a parent b-quark p_T of ≥ 8 GeV/c. The cross section in this channel is larger than in the inclusive leptons and is sensitive to more of the produced b-quarks. Theory predicts the *shape* of the b-quark cross section as a function of p_T much more reliably than the *magnitude* of the cross section. A method we can use to determine this shape from the data is to measure the total cross section for b-quark production for b-quarks with $p_T > p_T^{min}$, for several values of p_T^{min}. The theoretical calculation of this quantity for CDF's region of sensitivity is shown in Figure 1.

The problem we face then comes down to determining how many of these J/ψ were produced via B decay and how many were produced via other mechanisms.

2 Theory

2.1 Sources of J/ψ

There are several sources of J/ψ's in $p\bar{p}$ collisions. One process, which we shall call direct, produces charmonium in the hard-scatter of the constituent partons of the proton and anti-proton. The other process, which we call indirect, produces charmonium through the weak decay of a b-quark to a c-quark via W boson emission. The W must in turn decay to a $\bar{c}$-quark and an s-quark, and the c and $\bar{c}$ must form a bound state.

2.1.1 Direct Production of Charmonium

The Feynman diagrams for direct production of charmonium in $p\bar{p}$ collisions are shown in Figure 2. The leading order, $\mathcal{O}(\alpha_s^2)$, diagram can produce χ_c and η_c but not J/ψ (the

J/ψ must couple to three gluons, while the χ_c and η_c can couple to two). Although the χ_c can decay to a J/ψ , charmonium produced via this diagram has no appreciable p_T hence does not contribute to the J/ψ signal seen in the CDF detector (the daughter muons do not have enough energy to traverse the calorimeters). The next-to-leading order, $\mathcal{O}(\alpha_s^3)$, diagrams produce prompt J/ψ 's and prompt χ_c which can radiatively decay into J/ψ . These processes can produce J/ψ 's with large p_T because the J/ψ 's are recoiling off a gluon. Production of J/ψ from radiative χ_c decays is the dominant production mechanism at the Tevatron; production of prompt J/ψ is negligable by comparison [9,10]. The relative rates of direct J/ψ production as calculated for the Tevatron are shown in Figure 3 for prompt J/ψ and for J/ψ from the radiative decay of the three χ_c states. The calculations use the matrix elements for these diagrams in conjunction with a non-relativistic potential model (Wisconsin Potential) [11] to model the quarkonium. This model reproduces ISR data and UA1 data? A K-factor of 2, determined by normalizing predictions to ISR data (where direct production is the only mechanism which yields charmonium [12]), was used in this calculation. This K-factor is similar in magnitude to the K-factor needed to describe Drell-Yan production, and is presumably needed because c-quarks are too light to be properly treated at $\mathcal{O}(\alpha_s^3)$ in perturbative QCD.

The calculated cross sections are sensitive to gluon structure functions at small x (typically, $\frac{2 \cdot p_T}{\sqrt{s}} \approx .006 - .011$) since gluon-gluon interactions dominate production and since small x is where all the gluons are, as seen in Figure 4. The production mechanisms involve calculation of three-gluon vertices, so an experimental test of these calculations tests the non-Abelian nature of QCD.

The transitions among the various charmonium levels are illustrated in Figure 5. Note that since the ψ'' decays to open charm we do not have to consider the production or decay of this state in the present analysis.

2.1.2 Indirect Production of Charmonium

Decays of B hadrons can also produce J/ψ 's [13]. Some of the Feynman diagrams for b-quark production are shown in Figure 6 for the $\mathcal{O}(\alpha_s^2)$ processes and in Figure 7 for the $\mathcal{O}(\alpha_s^3)$ processes. Theory predicts directly the rate of b-quark inclusive production [1]. Matrix elements for the $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$ diagrams are taken from Ellis and Sexton [14]. The Monte Carlo, using parametrizations of data, relates the b-quark production to the B meson production and decay via Field-Feynman [15] fragmentation, Peterson *et al.* parametrization of the fragmentation function [16], and etc from CLEO and MARK J and ARGUS.

To model the fragmentation of heavy quarks, ISAJET uses the Peterson *et al.* parametrization of the fragmentation function, which is consistent with b and c quark data.

Discuss relation of b-quark p_T to B p_T to J/ψ p_T , as can be seen in Figure 16. The theoretical uncertainty must thus contain resonable variations in the Peterson ϵ parameter for b-quark as well as etc. We used $\epsilon_c = 0.07$ (gives $< z >= 0.69$) and $\epsilon_b = 0.015$ (gives $< z >= 0.78$). The best fits to the data are shown in Figure 8. Also, since the one-loop corrections are not included in the $\mathcal{O}(\alpha_s^3)$ calculations, a non-physical cutoff must be imposed to regulate collinear divergences. This cutoff was of the form $p_T(q\bar{q}) > \epsilon\, M(q\bar{q})$ where ϵ was chosen to be 0.2. The magnitude of b-quark production cross section was relatively insensitive to the choice of cutoff. The shape as a function of p_T and η was unchanged by the cutoff.

2.2 Sources of ψ'

B hadron decays are thought to be the only significant source of ψ' . The number of J/ψ which come from B is much larger for us than it is for UA1, as will be shown in Section 6. Assume for the sake of argument that 40% of J/ψ come from either χ_c or direct production, and that 1/10 of this is direct J/ψ . Direct ψ' is .45 of direct J/ψ (ratio of wave functions) and $\mathrm{Br}(\psi' \to \mu^+\mu^-)/\mathrm{Br}(J/\psi \to \mu^+\mu^-) = 1/8$. So $.4 \times .1 \times .45 \times .125 \approx .17\% \times (\#J/\psi \to \mu^+\mu^-) = \#$ direct $\psi' \to \mu^+\mu^- = 3$ out of 70 total $\psi' \to \mu^+\mu^-$. I think this is an overestimate, but certainly less than 5% of the ψ' are produced directly. We have a big advantage in that we can reconstruct the χ_c directly and check to see that the $B \to J/\psi$ plus $\chi_c \to J/\psi$ accounts for all the J/ψ . Within errors it does, so the direct production is "below threshold".

3 Monte Carlo

We choose to measure the J/ψ cross section for a limited region of acceptance then extrapolate to the b-quark and B hadron total cross sections using theoretical predictions of the y and p_T distributions of the b-quark. To make this extrapolation we must depend on the Monte Carlo to model the b-quark fragmentation and B meson decays. Additionally, to determine what fraction of J/ψ come from B decay we must rely on topological features of the events which can only be modeled through use of the Monte Carlo. The Monte Carlo modeling turns out to be the dominant source of systematic uncertainty in this analysis.

We have used ISAJET to model J/ψ production via both the direct and indirect processes. ISAJET is described in detail in Reference [17]. Modifications to ISAJET were needed in order to do this properly. Below, we describe how ISAJET generates events and what we have done to ensure that J/ψ production is adequately simulated. A second Monte Carlo, using Glover's method [10], was used mainly in order to verify theoretical predictions. The elements of this second Monte Carlo have already been described in Section 2. EURODEC, a program which provides fragmentation of partons and decays of particles, was used to interface the Nason *et al.* predictions to the measured J/ψ cross section. Each of these Monte Carlo programs is described below.

3.1 ISACHI

ISAJET does not provide a mechanism with which to generate χ_c ; to simulate correctly the production properties of J/ψ production from radiative χ_c decay we should use the calculated χ_c production matrix elements and allow the χ_c to decay in the Monte Carlo. UA1 has modified ISAJET to produce χ_c 's by including the matrix elements for direct χ_c production [18,19]. ISACHI is implemented as a modification to the TWOJET process; the matrix elements for jet production are replaced by the matrix elements for χ_c production. The evolution of the initial and final state partons, the hadronization and then fragmentation of the final state partons, and the generation of the underlying event (from the beam jets) is all done in the standard way by ISAJET. The assumptions are that ISAJET is mostly right in what it does and that the matrix elements accurately describe the χ_c production. We will not address the first assumption; the second can be verified both through the use of the theoretical predictions in comparison with the measured properties of χ_c production from other experiments [20] as well as with the Υ signals in the CDF data sample.

3.2 ISAPSI

In order to measure the fraction, $\mathcal{F}$, of J/ψ which come from B hadron decays, we must use a Monte Carlo which preserves the correlations between the two b-quarks ; the default ISAJET generation is insufficient for this purpose. The generation of $b\bar{b}$ pairs in ISAJET via TWOJET $\rightarrow b\bar{b}$ only produces only the $2 \rightarrow 2$ diagrams for $q\bar{q}$,$gg \rightarrow b\bar{b}$ and *not* the $2 \rightarrow 3$ diagrams for gluon fusion or flavor excitation. To get those contributions, we implemented a modification to ISAJET which we call ISAPSI. In ISAPSI, events are generated using the TWOJET process with no restrictions on the flavor of the partons involved in the hard scatter. These events were then evolved in the normal way by ISAJET and tested for the presence of a b-quark in the final state. This evolution is ISAJET's way to simulate the higher-order processes. If a b-quark is not found, ISAPSI tries again to make an event. If a b-quark is found, the fragmentation is iterated until a final state J/ψ is found which has a p_T greater than a user threshold (5 GeV/c in our case). This procedure is identicle to that used in the familiar ISAJET modification called ISALEP; a description of and justification for using ISALEP can be found in CDF note 931 [21].

3.3 EURODEC

EURODEC [22] is a Monte Carlo package designed to provide a set of routines for the fragmentation of partons and the subsequent decay of the resulting particles. It is intended to provide an easy interface between parton-level generators (typically, the output of a theoretical calculation) and detector-level simulations (which require a complete list of particles with their associated 4-momenta and properties). EURODEC is used in this analysis because it provides a quick and convenient way to interface the theoretical calculation of Nason *et al.* to the measured J/ψ cross section. EURODEC treats the fragmentation of quarks using Field-Feynman fragmentation and the Peterson *et al.* parametrization for the B meson fragmentation function. The decay tables are derived from recent data on B 's using CLEO and ARGUS data. This type of a Monte Carlo is especially useful in cases like this where theoretical calculations produce the parton distributions; EURODEC provides a standard manner to interface these calculations to the final-state particles which are actually detected. PAPAGENO is an example of a matrix-element generator which produces parton distributions yet provides no means of fragmenting or decaying particles. Hence, PAPAGENO is not useful a a Monte Carlo tool in many cases. Easily adaptable to the CDF environment (although not yet done) since it produces a table of particles and their properties very similar to GENP — the only conversion needed is the particle codes (EURODEC has routines to generate the PDG-standard codes from the EURODEC-standard codes). Note that the fragmentation and decay can be well-modeled by any Monte Carlo since there is plenty of data and the theory has been shown to adequately describe the data. [23,24] EURODEC provides features not present in ISAJET, such as:

- Complete decay table, including $B \to \psi'$, $\psi' \to J/\psi\ \pi^+\pi^-$, etc.
- $B \to \chi_c X$, $\chi_c \to J/\psi\ \gamma$.
- Baryons containing b-quarks .
- Intrinsic widths for particles like K^{0*}.
- Angular distributions in decays

In principle, ISAJET can also be used. However, it has been shown that ISAJET does not have the same p_T and y distributions of the b-quarks as in the calculations by Nason *et al.* [25,26]. Therefore, it is wrong to use an ISAJET cross section to derive a result which is intended to be compared with the Nason *et al.* cross section; the comparison would then be between the two models. We have no way to tune the ISAJET b-quark p_T spectrum, therefore the only choice is to use another Monte Carlo. In addition, the ISAJET decay table is incomplete; many particles and decays which are relevant to this analysis are not included in ISAJET and can not be included without major modifications. In particular, the treatment of B meson decays in ISAJET is incomplete and insufficient for our purposes.

4 Inclusive Dimuon sample

The analysis presented here use the J/ψ data sample described in a separate note [27]. Briefly, events were selected from the MUO04 production output stream by requiring that they pass the DIMUON_CENTRAL_3 trigger and contain two or more CMUO banks. All combinations of opposite-sign CMUO banks are formed; those events containing at least one combination with an invariant mass in the range 3.050 GeV/c^2 to 3.140 GeV/c^2 were called J/ψ candidate events. This window is roughly $\pm 2\sigma$ around the world average value for the J/ψ mass of 3.0969 GeV/c^2 . Events containing at least one combination with an invariant mass in the range 2.800 GeV/c^2 to 2.900 GeV/c^2 or 3.300 GeV/c^2 to 3.400 GeV/c^2 (J/ψ sidebands) were used as a control sample to study the non-J/ψ background in the signal window. No quality cuts were made on the CMUO

Parameter	Low value	Central value	High value	Contribution to systematic error
Luminosity	2.79 pb^{-1}	3.03 pb^{-1}	3.27 pb^{-1}	$\approx 8\%$
Statistics				$< 10\%$
Trigger Efficiency	0.70	0.90	1.00	$\approx 15\%$
Polarization				$< 20\%$
$Br(J/\psi \to \mu^+\mu^-)$	0.060	0.069	.078	$< 13\%$
Total				$\approx 31\%$

Table 1: Uncertainties in the J/ψ production cross section which contribute to the systematic errors on the b-quark cross section.

banks to define good muons because the backround under the J/ψ peak is small. The total integrated luminosity in our data sample after correction for event builder losses is about 3.03 pb^{-1} . The definitions of the J/ψ signal and sideband regions are shown in Figure 9, superimposed on the invariant mass distribution for CMUO pairs in this sample. A J/ψ at rest does not trigger because its daughter muons do not have sufficient momentum to penetrate the iron in the calorimeter. As a result, all the J/ψ in our sample have substantial transverse momentum as can be seen in Figure 10.

5 J/ψ differential cross section

The detailed calculation of the J/ψ differential cross section and the J/ψ total cross section for J/ψ with $p_T > 6$ GeV/c and $\eta < 0.5$ can be found in Reference [27]. In this note we confine ourselves to quoting the results. Shown in Figure 11 is the measured $d\sigma/dp_T$ for J/ψ from all sources. Integrating this, we find the total J/ψ cross section to be:

$$\boxed{\sigma(J/\psi \to \mu^+\mu^-) = xx \pm xx(\text{stat.}) \pm xx(\text{syst.})}$$

for

$$\begin{aligned} p_T(J/\psi) &> 6.0 \text{ GeV}/c \\ |\eta(J/\psi)| &< 0.5 \end{aligned}$$

and

$$\boxed{\sigma(J/\psi \to \mu^+\mu^-) = xx0 \pm xx(\text{stat.}) \pm xx(\text{syst.})}$$

for

$$\begin{aligned} p_T(J/\psi) &> 8.0 \text{ GeV}/c \\ |\eta(J/\psi)| &< 0.5 \end{aligned}$$

The sources of the systematic and statistical errors are presented in Table 1.

6 Separating Production Mechanisms

How can we determine the fraction, $\mathcal{F}$, of J/ψ which come from B decays? We have attempted to measure this fraction in several ways. We will rely on the few ways which give us small systematic and statistical uncertainties — the remainder serve as a check on the final result. Many of our assumptions about the direct production mechanism can be tested in the Υ system; the Υ are produced through the exact same diagrams and decays as the J/ψ 's except that Υ cannot come from B decay. Thus, bottomonium gives us a separate, uncluttered system in which to test the theory and Monte Carlo. In particular, the theory can predict the ratio of the cross sections for the various Υ states, the ratio of the J/ψ cross section relative to the $\Upsilon(1S)$ cross section.

We try to separate B events from direct charmonium events using event topologies, and also by attempting to tag a second b-quark in the event. Note that all the methods discussed below provide a clean separation between direct and indirect production. $B \rightarrow \chi_c X$ will appear as indirect production because the events are 'B -like'. Subtraction of background is done using the dimuon events in the near sidebands of the J/ψ invariant mass distribution. The fitting procedure used to extract $\mathcal{F}$ from each method is described in detail in Appendix A.

6.1 $(\Delta R)^2$

$(\Delta R)^2$, the square of the distance in η-ϕ space between the J/ψ and a given track, is calculated for all tracks with $p_T \geq 1$ GeV in each J/ψ event. The resulting distributions are shown in Figure 13 for the ISAPSI and ISACHI Monte Carlos and for the data. There are obvious differences in the distributions from the two Monte Carlos; $b \rightarrow J/\psi$ events have many tracks near the J/ψ from the b-quark fragmentation and from $B \rightarrow J/\psi\ X$ decay products, while $\chi_c \rightarrow J/\psi\ \gamma$ events have few tracks near the J/ψ . All activity (excluding underlying event) in the χ_c events is back-to-back with the χ_c in the parton-parton center of mass frame. The underlying event is approximately flat in this variable, assuming no correlation of the underlying event and the hard scatter. A p_T cut of 1 GeV on tracks used to make this distribution reduces the dependance on the underlying event. This method has no significant statistical uncertainty since the number of tracks in each J/ψ event is large. The statistical uncertainty quoted comes from the likelihood fit. The assumed shape of the $(\Delta R)^2$ distribution for b production depends on what fraction of direct $b\bar{b}$ vs. gluon splitting vs. flavor excitation used by the Monte Carlo. The systematic uncertainty is determined by varying these processes in the fit. All systematics result from the Monte Carlo model.

$$\boxed{\mathcal{F} = 40\% \pm 2\%(\text{stat.}) \pm \%?(\text{syst.})}$$

6.2 $\Delta\phi$

We can use jets in the J/ψ events to tag partons from the hard scatter. Jet finding is performed using a fixed-cone ($\Delta R = 0.7$) clustering algorithm in Production V5.1

(MUO04 output stream). All JETS banks from ETHAT CLUSTERING are checked. $\Delta\phi$ is measured between the leading (highest E_T) jet and the J/ψ , provided that the leading jet has $E_T \geq 10$ GeV and has $\eta \leq 2.3$. The resulting distributions are shown in Figure 14 for the ISAPSI and ISACHI Monte Carlos and for the data. Again, the two production mechanisms are distinct in terms of this variable; b-quark events can contain several jets — back-to-back in ϕ for the $2 \rightarrow 2$ processes and same-side or not quite back-to-back for the $2 \rightarrow 3$ processes (gluon splitting, flavor excitation) — while $\chi_c \rightarrow J/\psi\ \gamma$ should have a jet back-to-back in ϕ with the J/ψ (modulo fragmentation effects). We require the jet E_T to be ≥ 10 GeV because the underlying event should have no jets with $E_T \geq 10$ GeV and because above this energy we understand the jet clustering and energy scale. The forward calorimeter ($\eta > 2.3$) is excluded from this analysis since we do not understand the systematics of jet reconstruction in this region.
Statistical uncertainties:

- The number of J/ψ events with a jet ≥ 10 GeV is a small fraction of the total number of J/ψ events.

Systematic uncertainties:

- The J/ψ p_T is biased high for the sample with a jet above 10 GeV. Thus, this method measures the fraction for a different p_T range than other methods. We expect the fraction to change as a function of J/ψ p_T , so we must be careful interpreting the results from this method.

- The $\Delta\phi$ distribution for b production depends on what fraction of direct $b\bar{b}$ vs. gluon splitting vs. flavor excitation used by the Monte Carlo. The systematic uncertainty is determined by varying these processes in the fit.

$$\boxed{\mathcal{F} = 60\% \pm 6\%(\text{stat.}) \pm \%?(\text{syst.})}$$

6.3 $\sigma(J/\psi\ )/\sigma(\psi'\ )$

The ratio of the J/ψ cross section to the ψ' cross section in principle will yield a very good estimate of the fraction of J/ψ coming from B decay. The kinematics, acceptance, and efficiency for the ψ' are virtually identical to those for the J/ψ , and ψ' are known to come almost exclusively from B decay. Using the CLEO measurements [28] of $\sigma \cdot$Br for $B \rightarrow J/\psi\ X \rightarrow \mu^+\mu^-\ X$ and $B \rightarrow \psi'\ X \rightarrow \mu^+\mu^-\ X$, the large uncertainties in the branching ratios do not enter into our determination of $\mathcal{F}$. Additionally, the systematic errors in both CDF data and CLEO data cancel in the ratio, so we are limited by CLEO statistics only. The dimuon peak in the ψ' region is shown in Figure 12.

The ratio of the production of ψ' to J/ψ from B decays alone can be extracted from CLEO, however the recent discovery of J/ψ which come from the Υ and *not* from the B complicates this [29].

As discussed in Section 2, the only significant source of ψ' is from B meson decay; direct production of ψ' should be negligable (as is direct production of J/ψ) and ψ' does not result from χ_c decay.

	$\#J/\psi$	$\#\psi'$	Ratio
CLEO	183 ± 16	12.5 ± 4.5	14.64 ± 5.42
CDF(v.c.)	1462 ± 37	61 ± 15	23.97 ± 5.93
CDF(no v.c.)	1659 ± 39	72 ± 17	23.04 ± 5.47

Table 2: Fraction using $\sigma(J/\psi)/\sigma(\psi')$.

- J/ψ are produced through B meson decay and through other processes.
- e^+e^- machines sitting on the $\Upsilon(4S)$ produce J/ψ and ψ' only from B meson decay.
- $\sigma(J/\psi)/\sigma(\psi')$ at CDF is *larger* than the same ratio on the $\Upsilon(4S)$, indicating that some of CDF's J/ψ are produced through sources other than B meson decay.
- This method has nothing to say about processes other than B meson decay, other than that they must account for the excess J/ψ production.
- Systematic errors entirely due to the CLEO error on $\sigma(J/\psi)/\sigma(\psi')$ and to the "Observation of $\Upsilon(4S)$ decays into non-$B\bar{B}$ final states containing ψ mesons".[29]

$$\mathcal{F} = \frac{14.64 \pm 5.42}{23.04 \pm 5.47} = 64\% \pm 28\%(\text{stat.}) \pm 5\%?(\text{syst.})$$

6.4 Isolation

A variable $\mathcal{I}$ can be defined such that $\mathcal{I} =$ the sum of the momenta of all charged tracks within a cone about the J/ψ direction (excluding the J/ψ muons). This variable is similar to calorimeter isolation, but is not sensitive to the extra photon emitted in χ_c decays to J/ψ . This extra photon can systematically increase the calorimeter energy in a cone about the J/ψ , but will not affect $\mathcal{I}$. The sum is made for those charged tracks with momenta ≥ 1 GeV. This variable is very similar to the $(\Delta R)^2$ variable for a restricted cone about the J/ψ .

- $b \rightarrow J/\psi$ events have *many* tracks near the J/ψ from b-quark fragmentation and from $B \rightarrow J/\psi\ X$ decay products.
- $\chi_c \rightarrow J/\psi\ \gamma$ events have *few* tracks near the J/ψ . All activity (excluding underlying event) is back-to-back with the χ_c in the parton-parton center of mass frame.
- Underlying event contributes only a small amount; a p_T cut of 1 GeV on the tracks used to compute $\mathcal{I}$ reduces the dependance on the underlying event.
- This method is insensitive to the angular correlation between the two b-quarks in the event, hence ISAPSI is not needed to model this variable properly.

Statistical uncertainties:

- This method has no significant statistical uncertainty since the number of tracks in each J/ψ event is large.

Systematic uncertainties:

- $\mathcal{I}$ for b production depends on the fragmentation of the b-quark , the underlying event, and the overlap between the b-quark and the $\bar{b}$-quark (for example, in gluon splitting). The systematic uncertainty is determined by varying these parameters in the Monte Carlo. All systematics errors result from the Monte Carlo model.

$$\boxed{\mathcal{F} \ = \% \pm \%(\text{stat.}) \pm \%?(\text{syst.})}$$

6.5 Impact parameter

Evidence that some of the J/ψ come from the decay of long lived objects, presumably B hadrons, can be found in the non-zero mean of the signed impact parameter distribution of the J/ψ daughter muons. The signed impact parameter is the projection of the (possibly finite) flight path of the J/ψ . This method for detecting effects of the B lifetime is more robust than decay length measurements in that the unknown systematics in the determination of the primary and secondary vertex cannot cause a net positive impact parameter, but they can cause a net finite decay length. This analysis is described in detail elsewhere [5]. The impact parameter distribution in the data is fit to a sum of two distributions; a distribution centered on zero (J/ψ from χ_c and prompt J/ψ both decay at the production point), and a distribution centered at the value expected using the nominal B hadron lifetime. The contribution needed from each of these two distributions indicates the fraction of J/ψ coming from B decay in our data. The small number of J/ψ events is the source of the statistical uncertainty in this fit. The measured B hadron lifetime, the assumed mixture of B mesons to B baryons, and the Monte Carlo model of the signed impact parameter for 100% B hadrons contribute to the systematic uncertainty in this measurement. If B_c or Λ_b have shorter lifetimes than B_u or B_d then the shift predicted by the Monte Carlo will be too large, affecting our measurement of the fraction.

$$\boxed{\mathcal{F} \ = 33\% \pm 5\%(\text{stat.}) \pm 10\%?(\text{syst.})}$$

6.6 K^0_S

In the weak decay of a b-quark to a J/ψ , a strange quark is left over. A large number of these will form K^0_S mesons which we can tag at CDF via their decay to two charged pions. Direct J/ψ production, or J/ψ production via χ_c decays, has a gluon jet opposite (in ϕ) the J/ψ which has only a small probability of fragmenting into a K^0_S (compared to b-quark events, where there is *always* a strange quark). This channel is both clean and relatively high in statistics. The need for K^0_S finding complicates the analysis since a proper calculation of the K^0_S finding efficiency in $B\bar{B}$ events is very involved. Additionally, the K^0_S could come from the decay of either of the two B mesons, or from the gluon present in direct charmonium production or from the underlying event. Using the Monte Carlo methods we described in Section 3, we expect 3% of the J/ψ events have a K^0_S if they are all direct, 8% if they are all from B 's and we see 6% in data, implying a B fraction of 60%.

6.6.1 Vertexing algorithm

The beam position in the transverse plane was determined on a run-by-run basis using tracking information from all tracks in each event in a given run. The scatterplot of impact parameter vs. ϕ_0 was fit to determine the x–y offset of the beam to a precision of $\pm$ 1 μm , with a beam spread of $\pm$ 50 μm [30].

Tracks were identified as possible secondaries by imposing a cut of 1 mm on the impact paramter of the track. A geometrical χ^2 fit was performed on all pairs of opposite-sign track passing this cut to determine if they have a common secondary vertex. The $\chi^2/N_{\rm dof}$ was required to be less than 5 for this fit and the secondary vertex was required to be at least 1 cm away from the primary vertex. In order to improve the mass resolution, the two tracks in each pair were then constrained to originate from this secondary vertex, and the pair was re-fit allowing the track parameters to be steered according to the covariance matrix. Again, $\chi^2/N_{\rm dof}$ was required to be less than 5. The invariant mass was calculated for each track pair satisfying these requirements by assuming both tracks to be charged pions. Additionally, the 3-momentum of the track pair was required to point back to the primary vertex to within 2 cm in 3-space.

Tracks were required to pass the TRKSEL quality cuts, which are:

1. The track must be three-dimensional.
2. Greater than n axial segments, where a segment is 8 out of 12 possible hits in an axial superlayer.
3. Greater than n stereo segments, where a segment is 4 out of 6 possible hits in a stereo superlayer.
4. The track must have hits from at least 50% of the wires it passes.

This procedure applied to minimum bias events defines for us the K^0_S mass and width which are subsequently used in this analysis to define K^0_S candidates as those events within a window of $\pm 2\sigma$ of this measured K^0_S mass.

$$\boxed{\mathcal{F} = 60\% \pm \%(\text{stat.}) \pm \%?(\text{syst.})}$$

6.7 Exclusive decays

The fraction of J/ψ originating from B decays or from χ_c decays can be determined by reconstructing exclusive decay modes of these two particles into J/ψ mesons and using the Monte Carlo to determine the efficiency of this reconstruction.

6.7.1 $B \to J/\psi\ K$ and $B \to J/\psi\ K^{0*}$

This analysis is described in detail elsewhere [5].
Statistical uncertainties:

- The number of reconstructed events is very small, and not known very well due to the modeling of the background in the fit to the invariant mass bump.

Systematic uncertainties:

- We know the Monte Carlo does not simulate tracking properly. Additionally, it is very difficult to compute the efficiency of the vertexing code using Monte Carlo. Additional uncertainties are due to the angular distribution of the decay products and the (unknown) polarization of the decay products.

$$\boxed{\mathcal{F} \ = 63\% \pm 32\%(\text{stat.}) \pm 15\%?(\text{syst.})}$$

6.7.2 $\chi_c \to J/\psi\ \gamma$

This exclusive decay has been reconstructed at CDF [31]. This reconstruction, coupled with the previous one, is especially nice because it verifies our assumptions about what the "other" mechanisms are for J/ψ production. Note that in this analysis cuts have been made which reject χ_c coming from B meson decay, so the fraction quoted below truly represents the contribution from direct production.
Statistical uncertainties:

- The number of reconstructed events is very small, and not known very well due to the modeling of the background in the fit to the invariant mass bump.

Systematic uncertainties:

- The fragmentation of the b-quark and the underlying event both affect the acceptance for signal and background due to the cut on isolation. Checks are made on these effects by varying parameters in Monte Carlo and by anti-selecting on isolation to verify that the number of reconstructed χ_c is consistent with the computed acceptance in the two regions. A limit on the fraction of χ_c coming from B decays can be made with this technique.

$$\boxed{100\% - \mathcal{F} \ = 36\% \pm 11\%(\text{stat.}) \pm \%?(\text{syst.})}$$

6.8 3rd lepton

In events where J/ψ are produced via b-quark decay, we can look for evidence of the presence of the other b-quark . The detection of a third lepton in a J/ψ event (in addition to the two muons from the J/ψ decay) can be used to flag the weak decay of a heavy quark, hence allow separation of heavy-flavor induced J/ψ from directly produced J/ψ . We are counting on the fact that a gluon almost never fragments to a lepton and that we can correctly model the production and detection of low-momentum leptons from heavy flavor.

Statistical uncertainties:

- As in the $\Delta\phi$ method, there are very few J/ψ events with a third lepton.

Systematic uncertainties:

The largest background in this channel comes from fake single muons accompanying a prompt J/ψ . These fake muons can be interacting or non-interacting punchthrough or they can be real muons from charged pion or kaon decays-in-flight. Using our estimates of punchthrough/decay-in-flight we find...[32,33].

- If the third lepton is a muon, it is most likely punchthrough. This limits the usefulness of this technique.
- Punchthrough can be a problem since J/ψ production via χ_c decay or B decay involves a jet opposite to the J/ψ . Punchthrough probability is given roughly by 1/165 for pions above 2 GeV/c .

$$\boxed{\mathcal{F} = \% \pm \%(\text{stat.}) \pm \%?(\text{syst.})}$$

6.9 J/ψ p_T

Theory predicts the p_T spectrum of J/ψ from B and the p_T spectrum of J/ψ from χ_c . The two slopes are significantly different. The resulting distributions are shown in Figure 15 for the ISAPSI and ISACHI Monte Carlos and for the data.

Statistical uncertainties:

- Small since number of J/ψ is large.

Systematic uncertainties:

Entirely dependant upon the Monte Carlo to predict the shape of the J/ψ p_T correctly. There is evidence that the Monte Carlo does not do this, so the fraction determined by this method is suspect.

$$\boxed{\mathcal{F} = \% \pm \%(\text{stat.}) \pm \%?(\text{syst.})}$$

7 Extrapolation to the b-quark and B meson cross sections

Once we have made the experimental measurements of the J/ψ cross section and of the fraction, $\mathcal{F}$, of J/ψ which are produced from B decays, an estimate of the b-quark production cross section can be made using Monte Carlo. The extrapolation from these measured quantities to the unmeasured quantity of theoretical interest (the b-quark cross

Method	$\mathcal{F} \pm (\text{stat.}) \pm (\text{syst.})$
$(\Delta R)^2$	$40\% \pm 2\% \pm xx\%$
$\Delta\phi$	$60\% \pm 6\% \pm xx\%$
$\sigma(J/\psi)/\sigma(\psi')$	$64\% \pm 28\% \pm 5\%$
Isolation	$xx\% \pm xx\% \pm xx\%$
Impact parameter	$33\% \pm 5\% \pm 10\%$
K^0_S	$60\% \pm xx\% \pm xx\%$
Exclusive B decays	$63\% \pm 32\% \pm 15\%$
Exclusive χ_c decays	$64\% \pm 11\% \pm xx\%$
3rd lepton	$xx\% \pm xx\% \pm xx\%$
J/ψ p_T	$xx\% \pm xx\% \pm xx\%$
Weighted mean	$xx\% \pm xx\% \pm xx\%$

Table 3: Summary of methods for measuring $\mathcal{F}$, along with the results of each method

section) relies only on the Monte Carlo and not on the detector used since all the detector-related quantities have been accounted for in the J/ψ cross section.

We have choosen to measure the J/ψ cross section for a limited region of acceptance then extrapolate to the b-quark total cross section using theoretical predictions of the y and p_T distributions of the b-quark . To make this extrapolation we must depend on the Monte Carlo. The largest systematic uncertainties in our mesurement results from this extrapolation, which is why we clearly separate the measured quantites (J/ψ cross section and fraction) from this extrapolation.

Using the parametrizations of the b-quark p_T and y distributions from Nason, Dawson, and Ellis [1], we generate b-quarks in the rapidity range $|y| < 1.0$ and then fragment and decay these b-quarks using the Monte Carlo program EURODEC (described in Section 3). The b-quark cross section is then extracted using the following formula:

$$\sigma(p\bar{p} \to b + X) = \sigma(J/\psi) \times \mathcal{F} \times \frac{\sigma_{MC}(p\bar{p} \to b + X)}{\sigma_{MC}(J/\psi)}$$

where

$$\begin{aligned} p_T(b) &> 6.0 \text{ GeV/c} \\ |y(b)| &< 1.0 \\ p_T(J/\psi) &> 6.0 \text{ GeV/c} \\ |\eta(J/\psi)| &< 0.5 \end{aligned}$$

We emphasize again that this part of the analysis is purely Monte Carlo. Parameters in the Monte Carlo are set to match data; comparisons presented in Reference [22] show that EURODEC reproduces well the J/ψ p_T in the B meson rest frame and the inclusive lepton spectrum from B decays. The Monte Carlo reproduces those elements of the data thought to be important for this analysis, so the systematic errors from the Monte Carlo reduce to the sum, in quadrature, of the systematic errors on the determination of these parameters. In Table 4 we list the parameters which affect this extrapolation, the central value used by EURODEC, the low and high variation of these parameters, and

Parameter	Low value	Central value	High value	Contribution to systematic error
ϵ_b	0.005	0.015	0.045	$\approx 10\%$
$\mathrm{Br}(B \rightarrow J/\psi\ X)$	.0094	.0112	.0130	$\approx 16\%$
Meson fraction	0.70	.90	1.00	$\approx 15\%$
Shape of p_T (b) curve				$\approx 20\%$
Total				$\approx 31\%$

Table 4: Systematic Uncertainties in extracting the b-quark production cross section from the measured values of $\sigma(J/\psi)$ and $\mathcal{F}$.

the resulting systematic uncertainty determined by this variation. Listed below are a description of each of these uncertainties along with an evaluation of their importance.

- The systematic uncertainty arising from the Monte Carlo parametrization of the b-quark fragmentation is accounted for by varying the Peterson parameter ϵ_b by a factor of three up and down; the effect of this variation is to harden or soften the p_T spectrum of the B mesons and hence J/ψ 's from B decay, the shape of the J/ψ p_T and η distributions are essentially unchanged. This amount of variation is large with respect to what we know about b-quark fragmentation, so the assigned systematic error is conservatively large.

- The branching ratio of $B \rightarrow J/\psi\ X$ is not known to within 16%, and the uncertainty on this number includes the uncertainty in the branching ratio of $J/\psi \rightarrow \mu^+\mu^-$. A change in this number affects the b-quark cross section by the same percentage change.

- Nobody knows how much of the time the b-quark fragments to mesons as opposed to baryons, but we have a good guess based on mesurements on c-quark fragmentation etc. We assume that a b-quark forms a B meson 90% of the time, but vary this fraction between 70% and 100%. Again, we believe this variation to be a conservative estimate of the systematic error.

- The magnitude of the b-quark cross section as predicted by Nason *et al.* does not affect our measurement of the cross section; only the shape of the p_T and η distributions matter. We conservatively vary these shapes as much as possible within the theoretical error bars (Ellis claims that the theory actually allows very little variation in the shape since the error bars are highly correlated from point-to-point).

7.1 The b-quark cross section

Using the central values for the quantities in Table 4, we obtain the ratio as detailed in Table 5. With the systematic errors as presented in Table 4, our result for the multiplicative factor from the Monte Carlo is:

	Multiplicative factor	Number of events
Generated b-quarks $p_T > 6.0$ GeV/c		
b-quark $y < 1.0$		1 000 000
B		899 854
B $\eta < 1.0$		899 798
B $p_T > 6.0$ GeV/c		534 903
J/ψ		10 845
J/ψ $\eta < 0.5$		5 941
J/ψ $p_T > 6.0$ GeV/c		1 273
$Br(B \to J/\psi\ )$	1.12/1.2	1 188
$Br(J/\psi \to \mu^+\mu^-\ )$	0.069	82
Factor of 2	2	164
$\frac{\sigma_{MC}(p\bar{p}\to b+X)}{\sigma_{MC}(J/\psi)}$	1 000 000 / 164	
$\frac{\sigma_{MC}(p\bar{p}\to B+X)}{\sigma_{MC}(J/\psi)}$	899 854 / 164	

Table 5: Summary of factors contributing to the measurement of the ratio $\frac{\sigma_{MC}(p\bar{p}\to b+X)}{\sigma_{MC}(J/\psi)}$

$$\boxed{\frac{\sigma_{MC}(p\bar{p}\to b+X)}{\sigma_{MC}(J/\psi)} = 6098 \pm 476(\text{stat.}) \pm 1890(\text{syst.})}$$

The branching ratio factor 1.12/1.20 is needed because the EURODEC decay table uses 1.2% for the branching ratio of $B \to J/\psi\ X$ while the PDG value is 1.12%. The 'Factor of two' accounts for the fact that $\sigma(J/\psi\ )$ includes J/ψ coming from the decay of both b-quarks and from $\bar{b}$-quarks , while the theory provides us with just $\sigma(p\bar{p} \to b + X)$.

$$\begin{aligned}
\sigma(p\bar{p} \to b + X) &= \sigma(J/\psi\ ) \times \mathcal{F}\ \times \frac{\sigma_{MC}(p\bar{p}\to b+X)}{\sigma_{MC}(J/\psi)} \\
&= \left(xx\text{nb}^{-1}\ \pm xx \pm xx\right) \times (0.65 \pm xx \pm xx) \times (6098 \pm 476 \pm 1890) \\
&\approx 15\mu\text{b}^{-1}\ \pm\pm
\end{aligned}$$

$$\boxed{\sigma(p\bar{p} \to b + X) = \pm(\text{stat.}) \pm (\text{syst.})}$$

for

$$\begin{aligned}
p_T(b) &> 6.0 \text{ GeV}/c \\
|y(b)| &< 1.0
\end{aligned}$$

7.2 The B meson cross section

$$\boxed{\frac{\sigma_{MC}(p\bar{p}\to B+X)}{\sigma_{MC}(J/\psi)} = 5487 \pm 428(\text{stat.}) \pm 1701(\text{syst.})}$$

for

$$\begin{aligned}
p_T(B) &> 6.0 \text{ GeV}/c \\
|y(B)| &< 1.0
\end{aligned}$$

so

$$\begin{aligned}\sigma(p\bar{p} \to B+X) &= \sigma(J/\psi\ ) \times \mathcal{F}\ \times \tfrac{\sigma_{MC}(p\bar{p}\to B+X)}{\sigma_{MC}(J/\psi)} \\ &= \left(xx\mathrm{nb}^{-1}\ \pm xx \pm xx\right) \times (0.65 \pm xx \pm xx) \times (5487 \pm 428 \pm 1701) \\ &\approx 13.5\mu\mathrm{b}^{-1}\ \pm\pm\end{aligned}$$

8 Conclusions

We have presented a measurement of the b-quark production cross section at CDF which was obtained through the measurement of the J/ψ differential cross sections and through the investigation of the sources of J/ψ production. There is still work to do to understand the systematics. The numbers we quote here however, with their conservatively large assigned systematic errors, represent good preliminary mesurements.

This analysis has relied on the input of many people, and would not have been possible without their help. In particular we would like to thank Nigel Glover for his help with the theoretical calculations of J/ψ production, Ian Kenyon and Nick Ellis for providing the UA1 modifications to ISAJET for χ_c production, Avi Yagil for his work to reconstruct radiative χ_c decays, and Pekka Sinervo for many useful discussions.

A Fitting

The fitting to the fraction in all cases is done using a binned maximum likelihood method. The distribution in question is modeled separately by Monte Carlos for B production and for χ_c production. The Monte Carlo distributions are assumed to be ideal (no statistical errors) and the data is fit to a sum of the two Monte Carlo distributions. The statistical error on the fitted fraction comes entirely from the data. The key point to remember with this fit is that we are using only the shapes of the distributions from the direct and indirect production mechanisms to model the data; the relative normalizations are left floating. This removes us from Monte Carlo and theoretical uncertainties in the scale of the J/ψ production via the two mechanisms. We depend only on the shapes, which are much less uncertain. Since the Monte Carlo shapes are assumed to be perfect we require high statistics in the Monte Carlo sample, and we must also smooth the Monte Carlo data so as to reduce dependance on statistical fluctuations. The smoothing procedure consists of parametrizing the Monte Carlo with physics-based curves. This procedure only works if we can show that we *require* contributions from the two different processes in order to adequately describe the data. If the shapes are too similar, the relative normalizations derived from the fit will be meaningless.

The form of the fitted function is

$$\frac{dN}{d(\Delta\mathrm{R})^2} = (1-\mathcal{F}\,)D((\Delta\mathrm{R})^2\,) + \mathcal{F}\,I((\Delta\mathrm{R})^2\,)$$

where $\mathrm{D}((\Delta\mathrm{R})^2\,)$ and $\mathrm{I}((\Delta\mathrm{R})^2\,)$ are the theoretical $(\Delta\mathrm{R})^2$ distributions for direct and indirect production, respectively, and the coefficient $\mathcal{F}$ is determined by the fit. ISAPSI and the Glover Monte Carlo programs plus CDFSIM, the full detector simulation, were used to determine the functions $\mathrm{D}((\Delta\mathrm{R})^2\,)$ and $\mathrm{I}((\Delta\mathrm{R})^2\,)$. For fitting purposes these functions have been normalized to the luminosity of the real data (3.030 pb^{-1}). This way the coefficients α and β can be easily interpreted as the fraction of the predicted amount of bottom and direct production in the data. Specifically, if directly produced and indirectly produced J/ψ were present in the data with the rates predicted by the Monte Carlo programs, α and β will both be equal to one. The program MINUIT [34] was used to fit these distributions and to extract $\mathcal{F}$.

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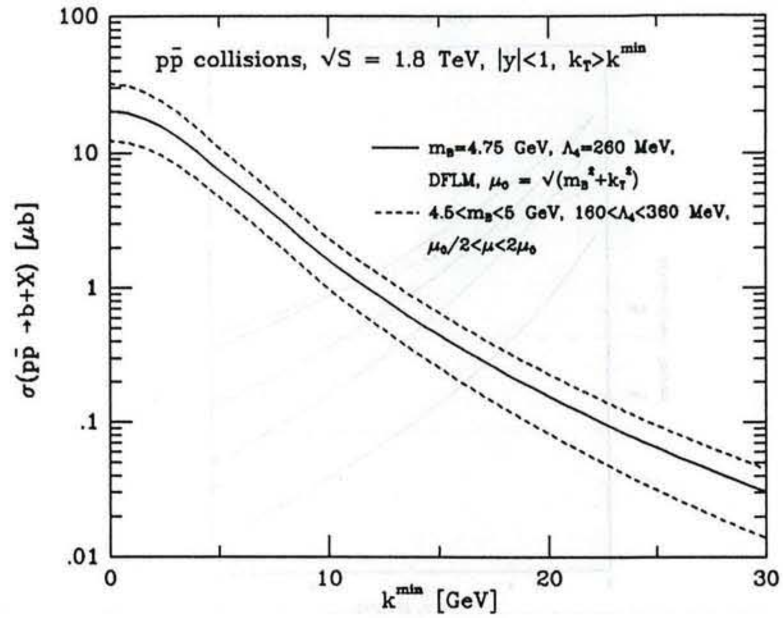
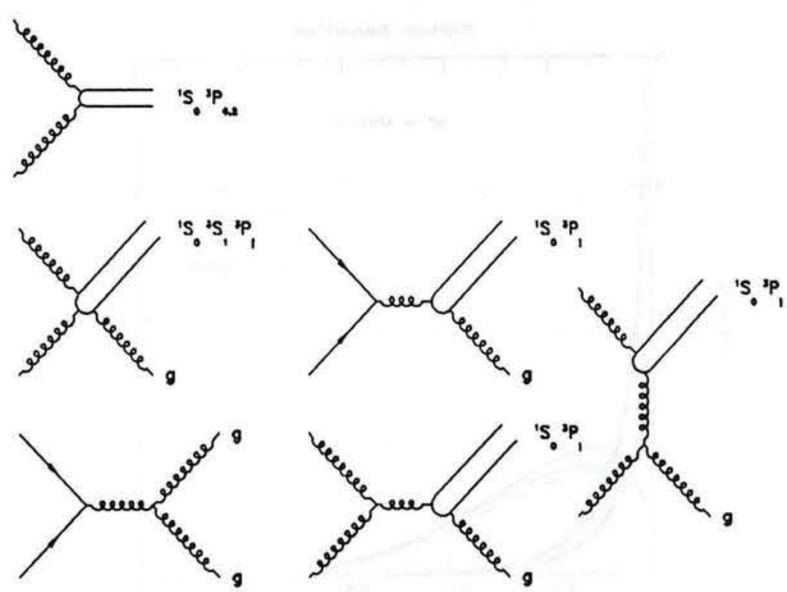


Figure 1: Predictions for $\sigma(p\bar{p} \to b + X,\ \mathrm{p_T} < \mathrm{p_T^{min}}\ , |y| < 1)$ by Nason, Dawson, and Ellis from a complete $\mathcal{O}(\alpha_s^3)$ calculation including one-loop corrections



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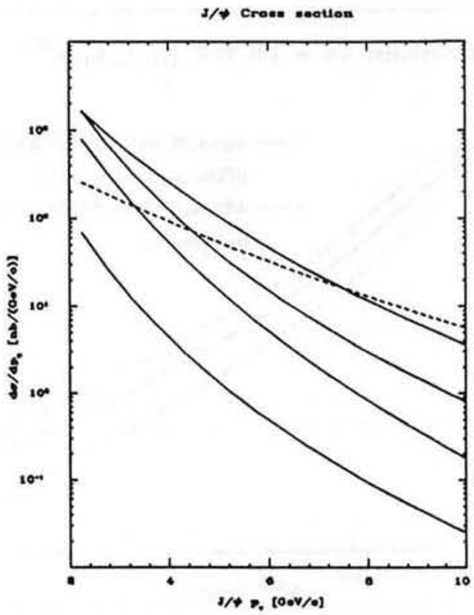

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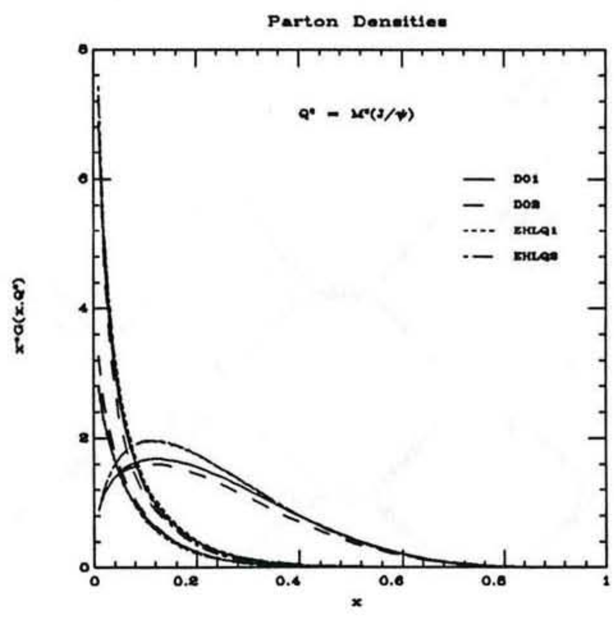

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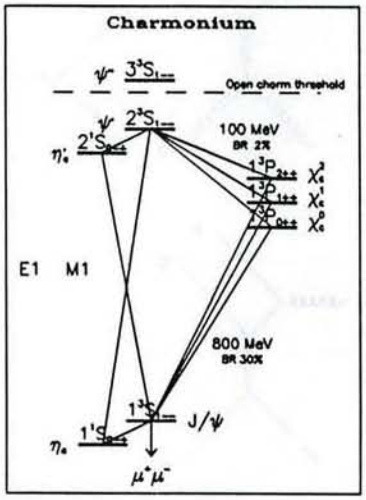

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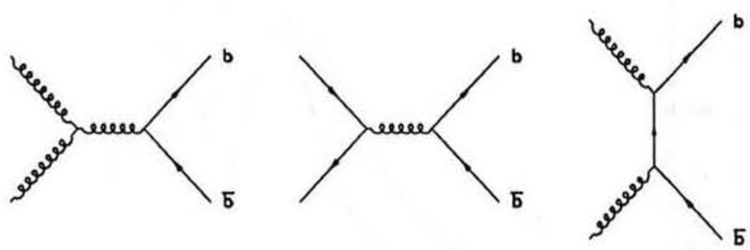

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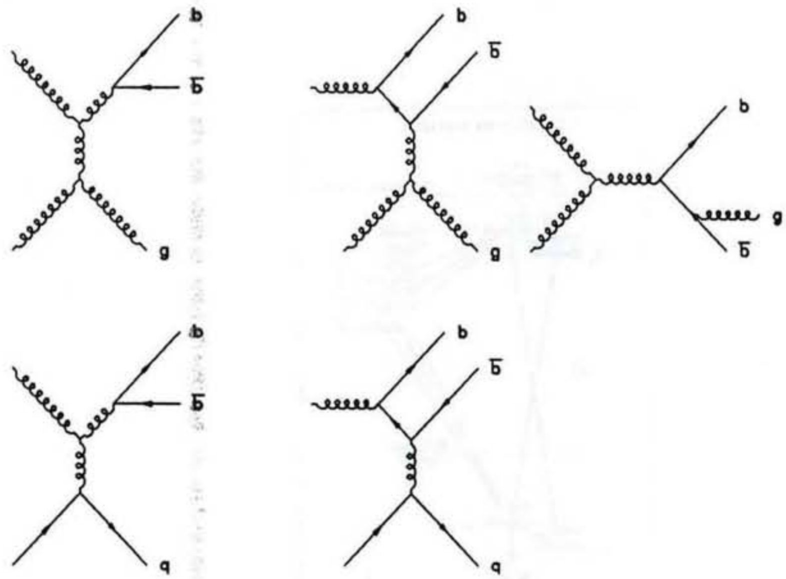

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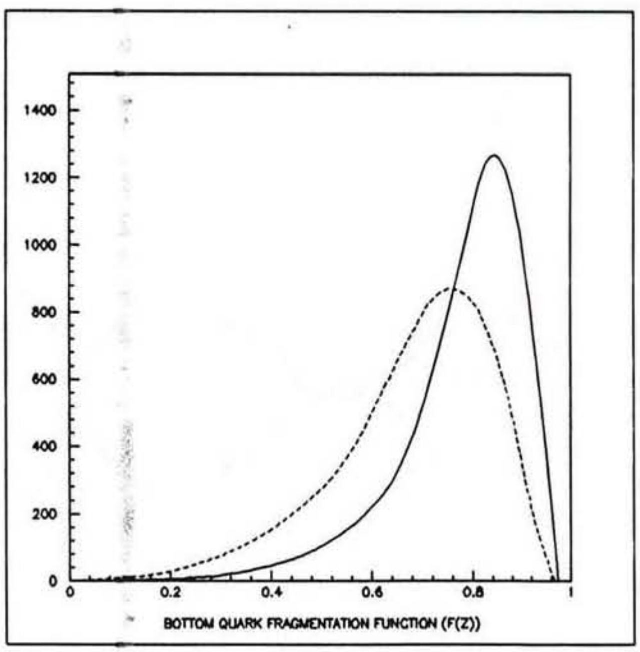

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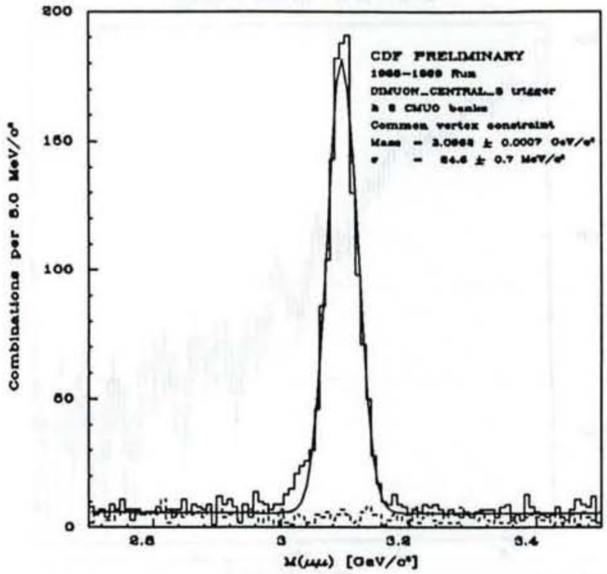

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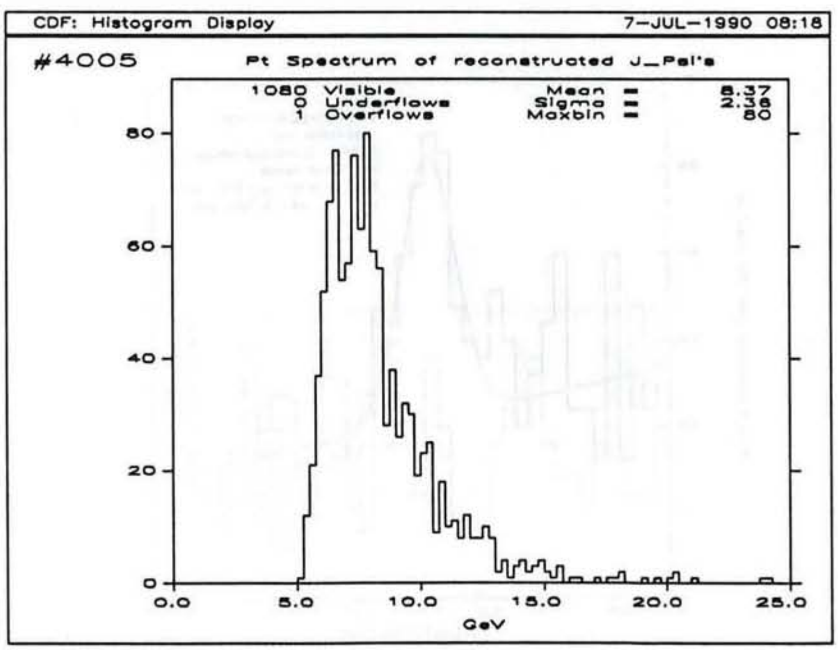

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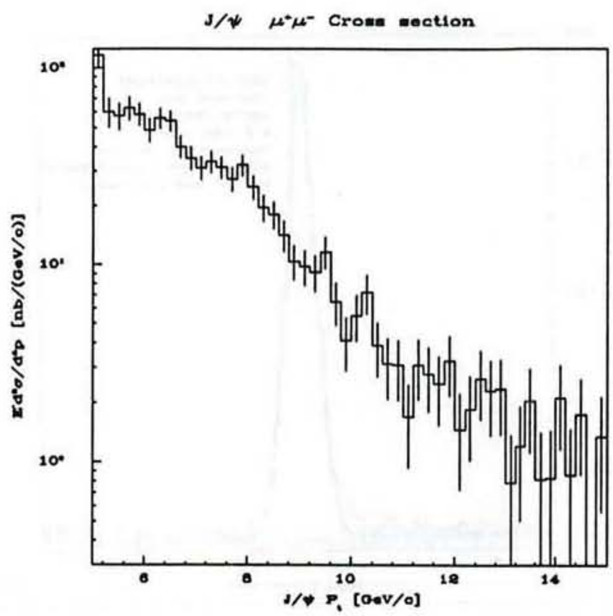

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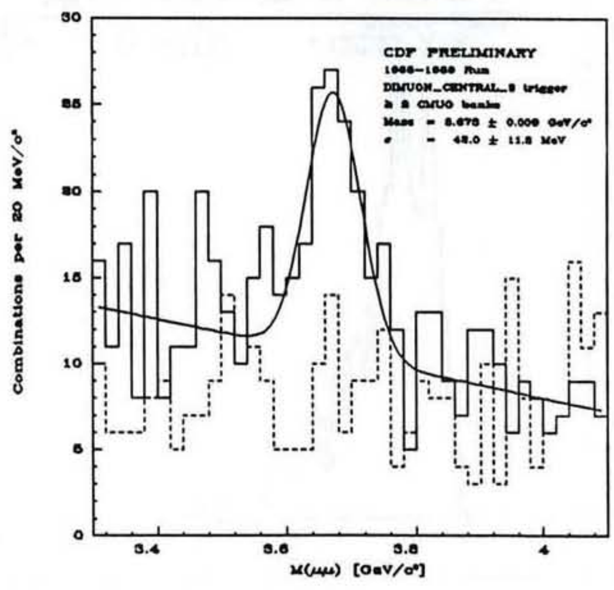

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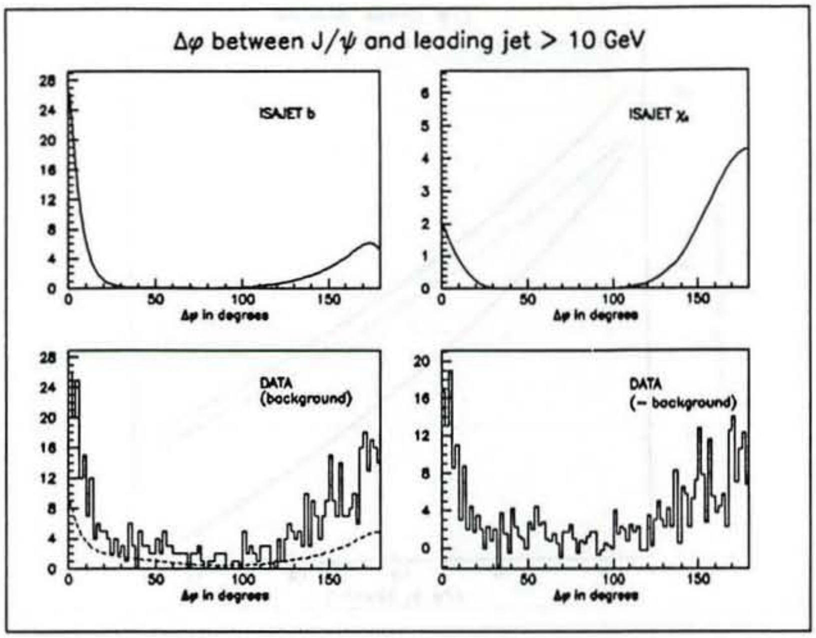

Figure 13:

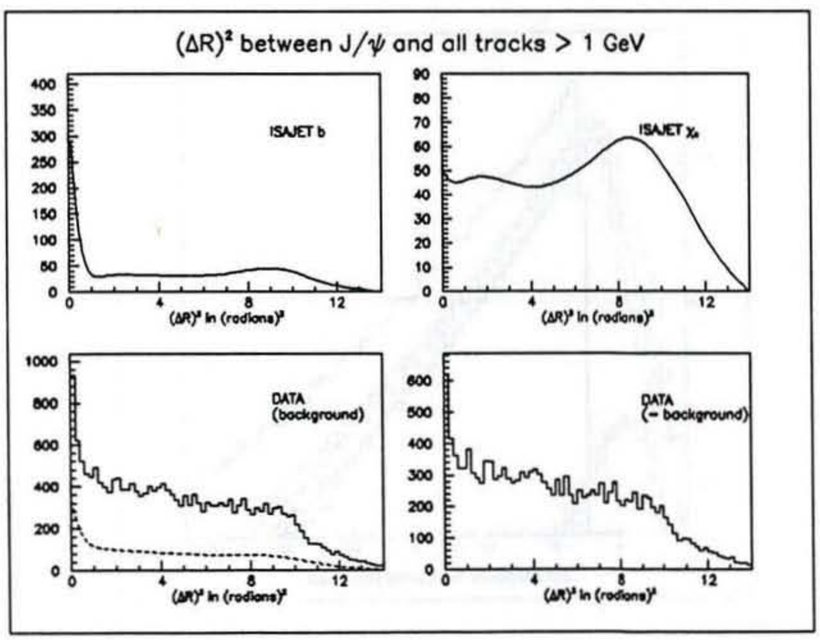

Figure 14:

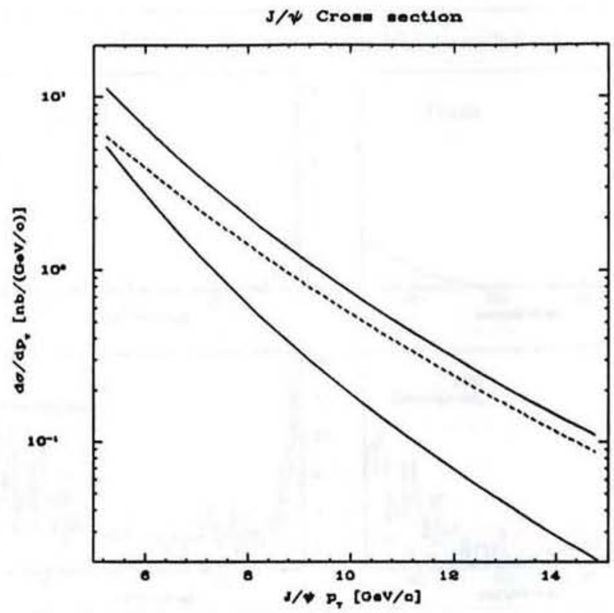

Figure 15: Monte Carlo prediction of the p_T spectra for J/ψ produced from χ_c , from B and from the sum of both processes, for J/ψ $|\eta| < 0.5$.

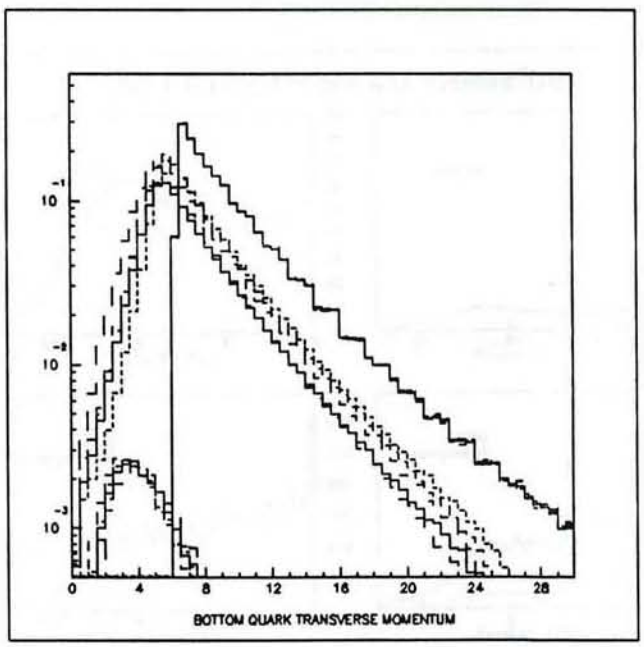

Figure 16: Relationship between the b-quark , B meson, and J/ψ p_T spectra using the Nason *et al.* parametrization or the b-quark p_T and the EURODEC Monte Carlo for the fragmentation and decays.

CDF/ANAL/HEAVY_FLAVOR/GROUP/1232
VERSION 1.0

A limit on $B^0 \rightarrow \mu^+\mu^-$

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July 16, 1990

Abstract

A search for neutral B mesons decaying into muon pairs has been made using the CDF detector at the Fermilab Tevatron. An upper limit is set on the on the branching ratio, $\mathrm{Br}(B^0 \rightarrow \mu^+\mu^-) < 6 \times 10^{-6}$ at the 90% confidence level.

1 Introduction

$B^0 \rightarrow \mu^+\mu^-$ is a flavor-changing neutral current decay allowed by the Standard Model. The Feynman diagrams describing this decay are shown in Figure 1. The calculation of the partial width for this decay poses a challenge to theory because it involves complicated box diagrams and three-boson interactions. These diagrams are sensitive to the (unknown) top quark mass in the calculation of the loop contributions.

2 Theory

This decay is completely analogous to the known decay of $K_L^0 \rightarrow \mu^+\mu^-$. The predicted branching ratio for $B^0 \rightarrow \mu^+\mu^-$ is on the order of 10^{-8} [1]. The current best upper limits have been established in e^+e^- collisions at CESR and DESY [2,3]; these limits are for B_d^0 only. UA1 has published a combined limit for B_d^0 and B_s^0 [4], their published limits for B_d^0 and B_s^0 separately are considerably higher.

The purpose of this analysis is to determine how well CDF can do. It is motivated by our superb mass resolution and our spectacular signals for J/ψ , ψ' , $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and Z^0 in the dimuon channel, as well as our demonstration of our understanding of exclusive decays of B mesons [5,6].

CLEO	$\mathrm{Br}(B_d^0 \to \mu^+\mu^-)$	$<$	0.5×10^{-4}
ARGUS	$\mathrm{Br}(B_d^0 \to \mu^+\mu^-)$	$<$	0.5×10^{-4}
UA1	$\mathrm{Br}(B_{d,s}^0 \to \mu^+\mu^-)$	$<$	0.9×10^{-4}
	$\mathrm{Br}(B_d^0 \to \mu^+\mu^-)$	$<$	1.4×10^{-4}
	$\mathrm{Br}(B_s^0 \to \mu^+\mu^-)$	$<$	3.0×10^{-4}

Table 1: Current limits (90% Confidence Level)

3 Method

Rather than trying to calculate the branching ratio limit directly, which involves knowing the B^0 cross section and dealing with the large uncertainties in this cross section, we compare the (lack of) signal in this channel to a known signal in another channel. In this manner, we are measuring a ratio of branching ratios in which many systematic effects cancel. In particular, the luminosity uncertainty, the production properties of the B mesons (p_T , η spectra), and the trigger efficiency cancels in this ratio. Explicitly, we measure:

$$\frac{\mathrm{Br}(B^0 \to \mu^+\mu^-)}{\mathrm{Br}(B^0 \to \psi' X \to \mu^+\mu^- X)}$$

Why use the ψ' signal? Because virtually all of the ψ' come from B decay [7,8], whereas many of the J/ψ come from other processes. To get a feel for what sort of product branching ratios we are sensitive to for B decays, we present the following "back of the envelope" calculation:

$$\begin{aligned}
\mathrm{Br}(B \to \psi' X) &= (3.3 \pm 1.4) \times 10^{-3} \\
\mathrm{Br}(\psi' \to \mu^+\mu^-) &= (7.7 \pm 1.7) \times 10^{-3} \\
\mathrm{Br}(B \to \psi' X \to \mu^+\mu^- X) &= (2.5 \pm 1.2) \times 10^{-5}
\end{aligned}$$

$$\begin{aligned}
\mathrm{Br}(B \to J/\psi\, K) &= (0.8 \pm 0.3) \times 10^{-3} \\
\mathrm{Br}(J/\psi \to \mu^+\mu^-) &= (6.9 \pm 0.9) \times 10^{-2} \\
\mathrm{Br}(B \to J/\psi\, K \to \mu^+\mu^- K) &= (5.5 \pm 2.2) \times 10^{-6}
\end{aligned}$$

This shows that we are able to detect B decays with product branching ratios in the "interesting" range of one part in 10^{-5}, so we should be able to set a limit on $B^0 \to \mu^+\mu^-$ in this range. As can be seen in Table 1, this is competitive with the current limits.

4 Inclusive Dimuon sample

The analysis presented here uses the dimuon data sample described in a separate note [7]. Briefly, events were selected from the MUO04 production output stream by requiring that they pass the DIMUON_CENTRAL_3 trigger and contain two or more CMUO banks. No cuts were made on the CMUO objects in order to define good muons. The total integrated luminosity in our data sample after correction for event builder losses is about 3.03 pb^{-1} . A plot of the dimuon inviariant mass for events in this sample is shown in Figure 2. The regions about the ψ' mass and the B^0 mass are shown enlarged in Figure 3 and Figure 4 respectively.

5 Acceptance

The limit derived in this analysis depends only on the ratio of the acceptance for $B^0 \to \mu^+\mu^-$ to the acceptance for $B^0 \to \psi'\ X$ and not on the absolute value of either acceptance. The acceptance of the CDF detector for signal events was calculated using a simple detector model which incorporates parameters measured from data, like the ϕ and η coverage of the muon chambers, the trigger turn-on curves [9] (which account for the multiple scattering of the muons in the calorimeter), the event z-vertex smearing, and the effects of the level 2 trigger clustering. The magnitude of the central solenoidal magnetic field was set to 14.116 for this entire analysis [10]. We measure the acceptance as a function of p_T for dimuons J/ψ with $\eta < 0.5$ (chosen because this is where the acceptance as a function of η falls by a factor of ≈ 2 from its peak value at $\eta = 0.0$), and as a function of η for dimuons $p_T > 5$ GeV/c . Our acceptance calculations do not depend on the p_T or η distributions generated by the Monte Carlo as long as those generated distributions are not rapidly changing (in which case we have to worry about feed-down) because we are taking the ratio of the number of found dimuons in the above region to the number of generated dimuons in the same region. Likewise, structure functions have no effect on the acceptance calculation.

5.1 Ratio of Acceptances

The absolute acceptance is irrelevant; the only thing that matters for this analysis is the ratio of the acceptances for $B \to \psi'$ vs. $B \to \mu^+\mu^-$. In the process $B \to \psi' + X$ there is an intermediate stage between the B and the $\mu^+\mu^-$ where some momentum is lost to the X , so the p_T spectrum of the B meson and the kinematics of the $B \to \psi'$ X decay enter into this ratio. However, if we do not account for the decay kinematics, i.e. if we assume the p_T of the B is the same as the p_T of the ψ' , we over-estimate the acceptance for $B \to \psi'$ X which is erring on the conservative side (the acceptance for the artificially higher p_T ψ' will always be higher than for a ψ' with the correct momentum). By ignoring the decay kinematics in this fashon the p_T spectrum of the B cancels out in the ratio of the acceptances. The shape of the acceptance curves is very similar; the magnitudes are in the ratio of 1/4. The increased acceptance for the higher mass dimuons can be understood by realizing that a dimuon pair with invariant mass near the ψ' mass needs to have substantial transverse momentum in order to boost the muons enough so they have sufficient energy to traverse the calorimeter. A higher mass dimuon has more energy, so the p_T needed for the muons is less. Also, at any given dimuon p_T , the higher mass object has to have a larger opening angle, hence less acceptance due to the limited geometrical coverage of the central muon chambers.

6 Results

We use a binned χ^2 fit to determined the number of ψ' in our sample. The signal was modeled by a Gaussian, constrained to the measured width of the J/ψ . The background was assumed to be linear over the region 3.3 – 4.9 GeV/c^2 . The fit yields 72 ± 17 events in the peak. Note that the background has been fit too high on the low mass side; increasing the mass range fit decreases the background and slightly increases the number of ψ' fit. This underestimation of the number of ψ' actually makes our result more conservative. We assume half of the ψ' come from B^0 decays, and half from $B^\pm$ decays.

To determine a limit on the number of $B^0 \to \mu^+\mu^-$ events, we use an unbinned maximum likelihood fit to a Gaussian (with a width equal to our assumed mass resolution, 40 GeV/c^2 for this decay) over a linear background. The fit gives us an upper limit of 12 events at the 90% confidence level. The B_s^0 is thought to have a mass of roughly 5.4 GeV/c^2 – this is sufficiently more massive than the B_d that we do not have to worry about possible overlap between a $B_s^0 \to \mu^+\mu^-$ signal and a $B_d^0 \to \mu^+\mu^-$ signal. To determine the limit, we simply make the following computation:

$$\begin{aligned}\frac{\mathrm{Br}(B^0\to \mu^+\mu^-)}{\mathrm{Br}(B^0\to \psi' X)} &= \frac{\#(B^0\to \mu^+\mu^-)}{\#(\psi' \to \mu^+\mu^-)\cdot\frac{1}{2}} \cdot \frac{\mathrm{A}(B^0\to \psi' \to \mu^+\mu^- X)}{\mathrm{A}(B^0\to \mu^+\mu^-)} \\ &= \frac{12}{(72\pm17)\times\frac{1}{2}} \times \frac{1}{4} \\ &< \frac{1}{5} \text{ at the 90\% confidence level}\end{aligned}$$

Where the 90% confidence level is determined by moving each of the uncertainties by 1.64σ in the most unfavorable direction. Using this calculation and the previously quoted product branching ratio for $B^0 \to \psi' X \to \mu^+\mu^- X$ we find

$$\boxed{\mathrm{Br}(B^0\to \mu^+\mu^-) < 6.0 \times 10^{-6}}$$

This is a conservative limit, and is still almost an order of magnitude better than the published limits [11].

7 Conclusions

We have presented a limit on the decay of neutral B mesons into muon pairs. While this limit is still several orders of magnitude larger than theoretical expectations of the decay rate, it is significantly better than the current limits from CLEO, ARGUS, and UA1. With a better treatment of the systematic uncertainties in this analysis, in particular the uncertainties associated with the ratio of the acceptances, it is likely that this limit can be improved by a factor of two or more. With five times more data in the 1991 Collider run, we should be able to extend this limit by at least an additional order of magnitude, perhaps far enough to test the Standard Model prediction.

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[11] UA1 has a new, preliminary number of $\mathrm{Br}(B^0 \to \mu^+\mu^-) < 1.0 \times 10^{-5}$ which was announced at the Duke Physics in Collision conference.

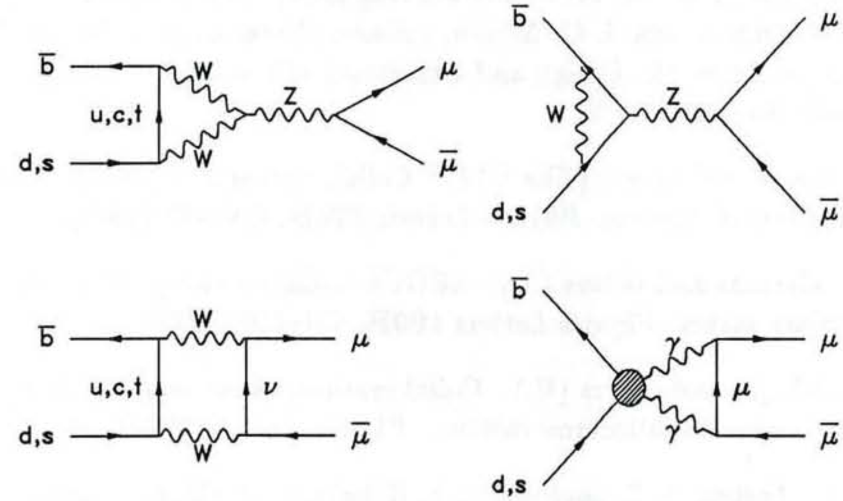

Figure 1: Feynman diagrams for the decay $B^0 \to \mu^+\mu^-$.

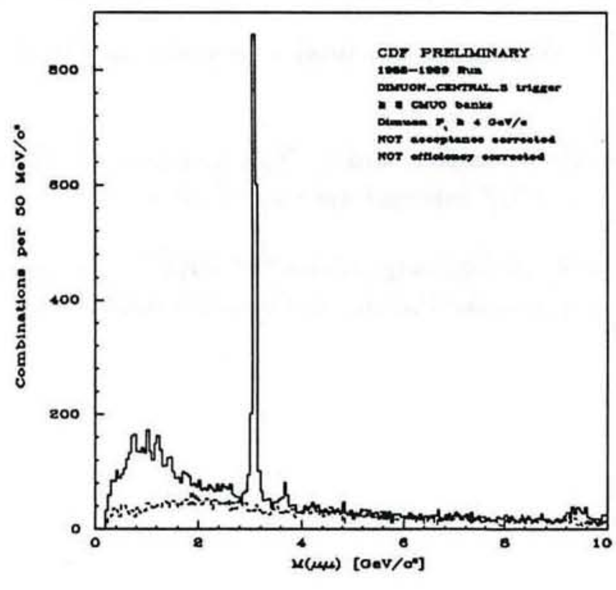

Figure 2: Dimuon invariant mass for the mass range 0 – 10 GeV/c^2 . The J/ψ and ψ' peaks are clearly visible. The $\Upsilon(1S)$ is also visible, but on this scale appears only as a broad, low hump. There is no apparent signal in the B^0 mass region.

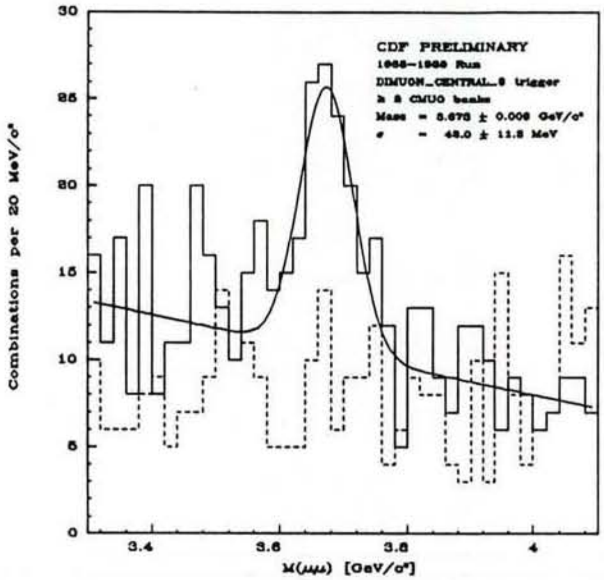

Figure 3: Dimuon invariant mass showing the fit to the ψ' .

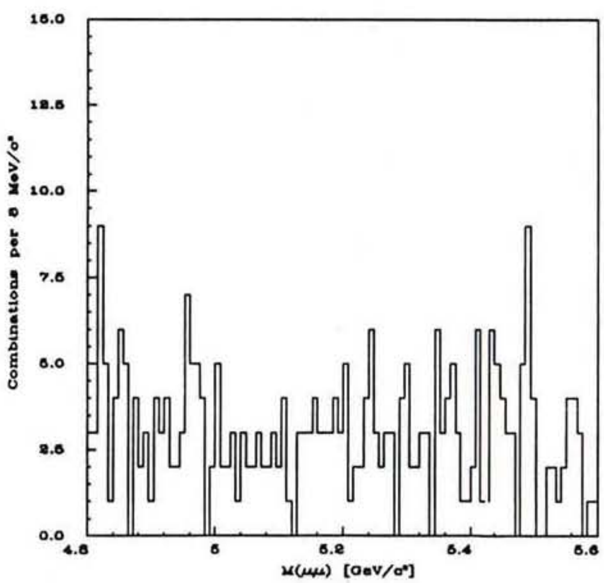

Figure 4: Dimuon invariant mass in the B^0 region