Fermi National Accelerator Laboratory

FNAL/C--96/364-E
~~FERMILAB-Conf-96/364-E~~

CONF-960812--DØ25

DØ Papers on B-Physics Submitted to DPF'96

D. Vititoe, A. Kozelov, and R. Jesik
For the DØ Collaboration
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

October 1996

Published Proceedings of *1996 Annual Divisional Meeting (DPF 96) of the Division of Particles and Fields of the American Physical Society*, Minneapolis, Minnesota, August 10-15, 1996.

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DØ PAPERS ON B-PHYSICS SUBMITTED TO DPF '96

D. Vititoe, A. Kozelov, and R. Jesik
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Contents

b-QUARK INCLUSIVE CROSS SECTIONS AND $b\bar{b}$ CORRELATIONS USING DIMUONS FROM THE DØ EXPERIMENT

D.L. VITITOE

Physics Department, University of Arizona,
Tucson, AZ 85721, USA
(for the DØ Collaboration)

Using dimuons collected with the DØ detector during the 1993-1995 Tevatron collider run, we have measured the b-quark cross section and $b\bar{b}$ correlations as given by the difference in azimuthal angle between the two muons. Both measurements agree with the NLO QCD predictions within experimental and theoretical errors.

1 Detector and Event Selection

The DØ detector and trigger system are described in detail elsewhere [1]. The data used in this analysis was taken during the 1993-1995 run of the Fermilab Tevatron collider and corresponds to a total integrated luminosity $\int \mathcal{L}dt = 46.2 \pm 2.3$ pb^{-1}. This analysis [2] requires two muons with $p_T^{\mu} > 4$ GeV/c, pseudorapidity $|\eta^{\mu}| < 0.8$, and each muon is required to have an associated jet ($E_T > 12$ GeV) within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$. The invariant mass of the dimuons is $6 < M^{\mu\mu} < 35$ GeV/c^2. A total of 1756 events pass all selection criteria [2].

2 Signal and Background Determination

In addition to $b\bar{b}$ production, dimuon events in the mass range 6-35 GeV/c^2 can also arise from other sources including semi-leptonic decays of $c\bar{c}$ pairs, and events in which one or both of the muons are produced by in-flight decays of π or K mesons. Muons from Drell-Yan and Υ decays are not expected to have jets associated with them. An additional source of dimuons originates from cosmic ray muons passing through the detector.

To extract the $b\bar{b}$ signal, we use a maximum likelihood fit with four different input distributions. These distributions are the transverse momentum of the muon with respect to the jet axis, p_T^{rel}, the fraction of longitudinal momentum of the jet carried by the leading muon, z, and the muon scintillator timing information.

3 Results and Discussion

The dimuon cross section originating from $b\bar{b}$ production is obtained from

$$\frac{d\sigma^{\mu\mu}_{b\bar{b}}}{dp_T^{\mu_1}} = \frac{1}{\Delta p_T^{\mu_1}} \frac{N_{b\bar{b}} f_p}{\epsilon \int \mathcal{L} dt} \quad \text{and} \quad \frac{d\sigma^{\mu\mu}_{b\bar{b}}}{d\Delta\phi^{\mu\mu}} = \frac{1}{\Delta\phi^{\mu\mu}} \frac{N_{b\bar{b}} f_p}{\epsilon \int \mathcal{L} dt}, \tag{1}$$

where μ_1 refers to the leading muon in the event, and f_p is an unfolding factor[3] that accounts for the smearing due to the muon momentum resolution. The total systematic error is found to be $p_T^{\mu_1}$ dependent, ranging from 30-43%.

To extract the integrated b-quark cross section from the dimuon data, we employ a method first used by UA1[4] and subsequently used by both CDF[5] and DØ[6]. We define p_T^{min} as that value of the b-quark p_T such that 90% of the accepted events have b-quark transverse momentum greater than p_T^{min}. The b-quark cross section can then be calculated as

$$\sigma_b(p_T^b > p_T^{min}) = \sigma^{\mu\mu}_{b\bar{b}}(p_T^{\mu_1}) \frac{\sigma_b^{MC}}{\sigma^{MC}_{b\bar{b}\to\mu\mu}}, \tag{2}$$

where $\sigma^{\mu\mu}_{b\bar{b}}(p_T^{\mu_1})$ is the measured integrated dimuon cross section of Eq. (1) integrated over different intervals of $p_T^{\mu_1}$. σ_b^{MC} is the total Monte Carlo b-quark cross section for $p_T^b > p_T^{min}$, and $\sigma^{MC}_{b\bar{b}\to\mu\mu}$ is the Monte Carlo cross section for dimuon production with cuts that match the data set. For each interval of $p_T^{\mu_1}$, p_T^{min} is calculated using ISAJET[7]. We obtain a total systematic uncertainty of 35-48% on the b-quark cross section.

The results of the b-quark production cross section as a function of p_T^{min}, for $|y^b| < 1.0$, are shown in Fig. 1. Also included are previous measurements of the b-quark cross section from DØ[6,8,9]. The curve represents the NLO QCD predictions[10] using $m_b = 4.75$ GeV/c^2 and the MRSD0[11] structure functions with $\Lambda^4_{\overline{MS}} = 140$ MeV.

The differential $b\bar{b}$ cross section from Eq. (1), $d\sigma^{\mu\mu}_{b\bar{b}}/d\Delta\phi^{\mu\mu}$, gives further information on the underlying QCD production mechanisms by studying the topological correlations between the two b-quarks. The difference between the azimuthal angle between the b and $\bar{b}$-quarks (or equivalently, between the daughter muons), allows us to differentiate between the contributing QCD production mechanisms. These contributions include the leading order term, flavor creation, and the two next-to-leading order terms, gluon splitting and flavor excitation. There are also contributions from interference terms.

The cross section $d\sigma^{\mu\mu}_{b\bar{b}}/d\Delta\phi^{\mu\mu}$ is shown in Fig. 2. Also shown is the NLO QCD prediction that we have determined using the HVQJET[12] Monte Carlo. HVQJET is a direct implementation of the NLO MNR[13] calculation which uses a modified version of ISAJET for hadronization, particle decays, and modeling of the underlying event.

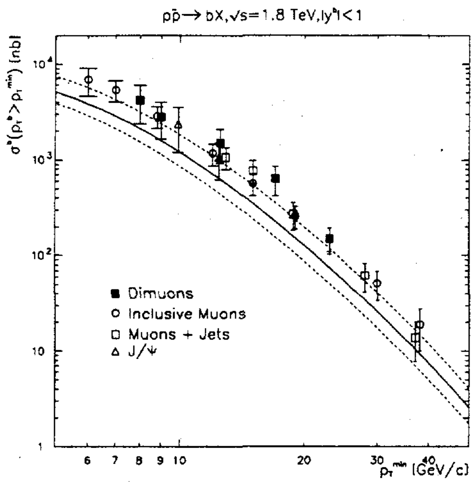

Figure 1: The b-quark production cross section compared with previous DØ results and the NLO QCD predictions.

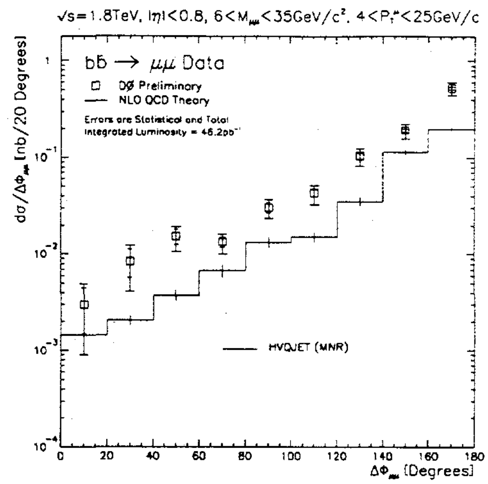

Figure 2: The $\Delta\phi^{\mu\mu}$ spectrum for $b\bar{b}$ production compared to the HVQJET prediction (see text).

4 Conclusions

We have measured both the b-quark production cross section and the azimuthal correlations between the two b-quarks using dimuons to tag the presence of b-quarks. Both measurements are found to agree reasonably well with the NLO QCD calculation of heavy flavor production but lie above the central values of the theory.

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Single Muon Production in the Forward Region at $\sqrt{s} = 1.8$ TeV

Alexander Kozelov
Institute for High Energy Physics, Protvino, 142284, Russia

For the DØ Collaboration

We present preliminary results on the single muon cross section in the forward rapidity region $2.4 < |\eta^\mu| < 3.2$ using data collected with the DØ detector at the Fermilab collider. We have estimated the fraction of the inclusive μ cross section in this region due to b-quark production and decay.

DØ Small Angle Muon System

The DØ small angle muon spectrometer consists of two iron toroids and six modules of 3.0 cm diameter drift tubes with each module having six planes in a horizontal, vertical and stereo configuration [1]. The $|\eta^\mu|$ coverage of the system is $2.2 < |\eta^\mu| < 3.3$.

A multi-level trigger system selected events with muon candidates. Since the small angle muon spectrometer faced a large combinatoric background due to the large flux of particles near the beam axis, offline muon identification cuts were necessary. To reduce the beam halo, only events with single $p\bar{p}$ interaction per crossing were accepted, leaving an effective integrated luminosity of (59.8 ± 4.8) nb^{-1}. A good muon was required to have at least 16 hits in 18 planes, and the energy deposited in the calorimeter along the muon track had to exceed 1.5 GeV. To ensure good momentum resolution the integral of magnetic field traversed by a muon had to be greater 1.5 T·m. And, finally, muons passing through regions with a trigger and reconstruction efficiency less than 5% were rejected.

The total number of events with muons satisfying the above criteria in the forward rapidity region ($2.4 < |\eta| < 3.2$) is 3224. The combinatoric background after offline cuts was estimated to be less than 2% for muons with $10 < p^\mu < 50$ GeV/c and it increases from 2 to 10 % in the $50 < p^\mu < 200$ GeV/c region.

Inclusive Muon Cross Section

The inclusive muon cross section was determined as follows:

$$\frac{d\sigma^\mu}{dp_T^\mu} = \frac{1}{L\Delta\eta}\frac{N^\mu f_p}{\epsilon}, \qquad (1)$$

where L is the integrated luminosity, N^μ is the number of events in the rapidity region $\Delta\eta$, f_p is a momentum smearing correction factor and ϵ is the

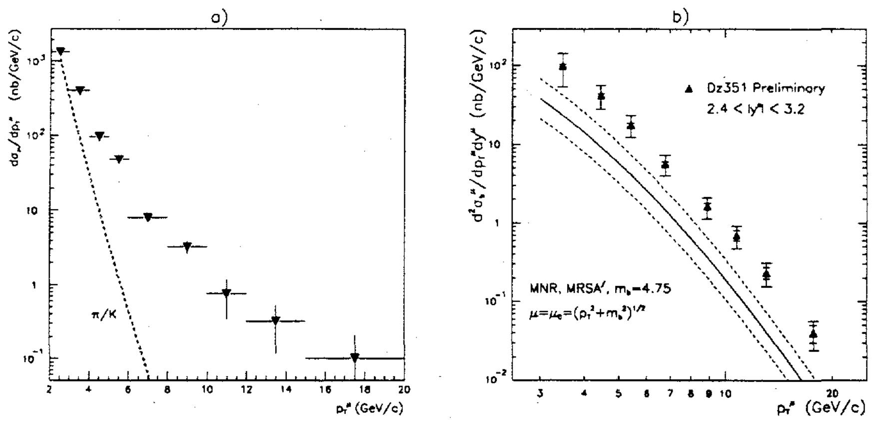

Figure 1: (a) The inclusive muon cross section, per unit of rapidity, in the forward region as a function of p_T^{μ} (errors are statistical only). The dashed line shows the expected contribution from π/K decays. (b) The measured differential muon cross section from b production and decay as a function of p_T^{μ}(per unit of rapidity).

acceptance, trigger and reconstruction efficiency.

Efficiency and smearing correction factors were determined from full detector simulation. The Monte-Carlo events were weighted in an iterative procedure to match the p_T and η spectra of the data.

The inclusive muon cross section (μ^+ and μ^- added) is shown in Fig. 1(a). The contributions to this cross section from cosmic rays and hadronic punchthrough are estimated to be negligible (both less than 1%). The W and Z decay contribution is also negligible. The pion and kaon decay spectrum (also shown in Fig.1(a)) was obtained using ISAJET[3], which was found to be in agreement with the charged particle spectrum measured by the CDF collaboration [4] in the central region. The excess of the cross section above the π/K contribution is attributed to b- and c-quark decay.

Muon Cross Section from b decays

The fraction of muons from b decays to those from both b and c decays was determined in a Monte Carlo simulation. ISAJET events were used for b/c production, fragmentation, and decay, with cross sections normalized to NLO QCD calculations[6]. Subtracting the π/K contribution from the inclusive muon cross section, and multiplying the resulting spectrum by the b fraction as a function of p_T^μ gives the differential muon cross section from b production and decay Fig. 1(b).

The main sources of the 31% systematic uncertainty in this cross section are due to the detection efficiency correction (20%), the π/K subtraction (14%), and the b fraction (10%). The normalization of the muon cross section from π/K decay affects mainly the first p_T bin. Comparing with the data in this bin, we determine that the ISAJET normalization is correct to a factor of ≈ 1.3. This normalization factor was used to determine the uncertainty due to the π/K subtraction. The uncertainty due to the b-fraction correction was estimated by using fractions determined using ISAJET cross sections and a data measurement in the central region [5].

The cross section for muons from b production and decay is shown in Fig. 1(b), along with a NLO QCD theoretical prediction[6] using MRSA′ parton distribution functions [7], $\mu = \mu_0 = \sqrt{m_b^2 + p_T^2}$, and $m_b = 4.75$ GeV/c^2. The theoretical uncertainty was determined by using MRSD0 pdf's, and by varying the parameters m_b and μ from 4.5 to 5.0 GeV/c^2 and $\mu_0/2$ to $2\mu_0$, respectively. The corresponding muon spectrum was obtained using the weighted ISAJET technique described previously. The theoretical predictions match the shape of the cross section, but are approximately a factor of four lower than the data.

Conclusions

We have measured the inclusive muon cross section in the forward rapidity region ($2.4 < |\eta| < 3.2$) at $\sqrt{s} = 1.8$ TeV. We have estimated the b contribution to this cross section, and have extracted differential cross sections for muons from b decay as a function of p_T.

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Rapidity Dependence of the Inclusive J/ψ Production in the Forward Region at $\sqrt{s} = 1.8$ TeV

Alexander Kozelov

Institute for High Energy Physics, Protvino, 142284, Russia

For the DØ Collaboration

We have studied the J/ψ production in $p\bar{p}$ collisions in the forward rapidity region ($2.5 < |\eta^{J/\psi}| < 3.7$) at $\sqrt{s}$ =1.8 TeV with the DØ detector using $\mu^+\mu^-$ events collected during the 1994-95 running period. The cross section measurement $d\sigma/dp_T^{J/\psi}$ covers the $p_T^{J/\psi}$ range from 1 to 16 GeV/c. We combine the measurements in several rapidity regions to present $d\sigma/d\eta^{J/\psi}$ for $p_T^{J/\psi} > 8$ GeV/c.

Small Angle Muon System Data Selection

The DØ small angle muon spectrometer consists of two iron toroids and six modules of 3.0 cm diameter drift tubes with each module having six planes in a horizontal, vertical and stereo configuration [1]. The $|\eta^\mu|$ coverage of the system is $2.2 <|\eta^\mu|< 3.3$. The combined calorimeter plus the toroid thickness is about 19 interaction lengths in this region reducing the hadron punchthrough to a negligible level.

The dimuon event selection used a multi-level trigger system [2]. The first level corresponds to a scintillator hodoscope that requires an inelastic collision within 1 m of the center of the detector. Then a hardware trigger searches for coarse triplets and finds roads corresponding to these triplets. To improve background rejection it also includes hit multiplicity cuts. The search roads are narrowed at the next level. The final level is a software filter that reconstructs tracks without using drift times and requires energy deposited in calorimeter consistent with a minimum ionizing particle.

Offline cuts were applied to select two high quality muons. A good muon was required to have at least 5 hits in six planes of the first module and at least 16 hits in 18 planes in total. The energy deposited in the calorimeter along the muon trajectory had to exceed 1.5 GeV and the integral of the magnetic field traversed by a muon had to be greater than 1.2 T·m. A kinematic cut on a muon momentum of $p^\mu < 150$ GeV/c was imposed to ensure a reliable muon charge determination.

The total number of dimuons in the forward ($2.5<|\eta^{J/\psi}| <3.7$) region satisfying the above criteria is 1544 (opposite charge dimuons) and 269 (same charge dimuons). The corresponding integrated luminosity is 9.3 ± 0.5 pb^{-1}.

Dimuon mass spectra

It was demonstrated that the dominant contribution to the continuum in the central rapidity region is due to processes involving heavy quarks [3]. Other mechanisms that yield opposite sign dimuons are the Drell-Yan process and decays of light mesons. Similar processes, however with different relative rates, are expected to contribute over the entire rapidity range.

The trigger efficiency and detector resolution were determined by a complete Monte Carlo simulation (about 20000 events were generated). Monte Carlo events were mixed with real minimum bias single interaction events for better simulation of background conditions. The shape of the J/ψ peak for Monte-Carlo events was fitted by Gaussian-like function:
$f(M) = A \cdot exp\{-(M - M^{J/\psi})^2/\sigma(M)^2\}$, where $\sigma(M) = a + b \cdot M + c \cdot M^2$.

A fit of data to a sum of this Gaussian-like function and a background yields a total number of 115±11±6, 255±16±13, 159±13±10 and 71±8±5 J/ψ events for $2.5<|\eta^{J/\psi}|<2.8$, $2.8<|\eta^{J/\psi}|<3.1$, $3.1<|\eta^{J/\psi}|<3.4$ and $3.4<|\eta^{J/\psi}|<3.7$, respectively (the first error is statistical, the second is the uncertainty of the background estimation).

Differential Cross Sections $d\sigma/dp_T^{J/\psi}$

The J/ψ transverse momentum distribution was corrected for a finite detector momentum resolution [4], acceptance and efficiency.

The inclusive differential J/ψ production cross section as a function of $p_T^{J/\psi}$ in the forward region is shown in Fig. 1a. The data are compared with the expected contribution from the b quark decay [5]. This prediction, is based on the use of MRSDO structure functions with $\Lambda^5_{\overline{MS}} = 140$ MeV, the factorization-renormalization scale μ=μ_0, where $\mu_0 = \sqrt{m_b^2 + \langle p_T^b \rangle^2}$, and $m_b = 4.75$ GeV/c^2.

Differential Cross Sections $d\sigma/d\eta^{J/\psi}$

The $d\sigma/d\eta^{J/\psi}$ plot, Fig. 1b, combines data from the central [3] and forward dimuon analyses for $p_T^{J/\psi} > 8$ GeV/c. There are three entries for $|\eta^{J/\psi}| < 0.6$, consistent with no η dependence in that region. On the other hand, the cross section for $|\eta^{J/\psi}| \sim 2.9$ is lower by a factor ~ 5. The predicted b quark contribution to the J/ψ production, calculated with the MRSD0 structure functions, exhibits a similar $|\eta^{J/\psi}|$ dependence.

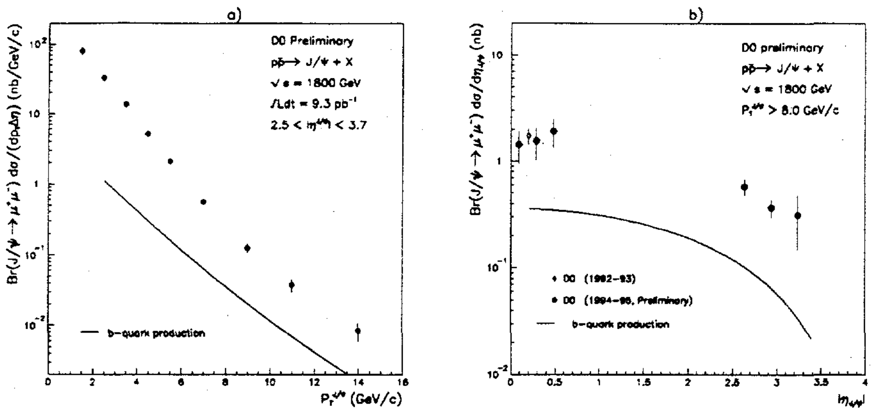

Figure 1: a) The p_T dependence of the inclusive J/ψ production cross section. The error bars are statistical only. The solid line shows expected contribution from b quark decays [5]. b) The rapidity dependence of the inclusive J/ψ production cross section. The error bars are statistical and systematic added in quadrature.

Conclusions

We have measured the inclusive J/ψ production cross section as a function of J/ψ transverse momentum $p_T^{J/\psi}$ in the forward rapidity region. The measured cross section $d\sigma/dp_T^{J/\psi}$ for $2.5 < |\eta^{J/\psi}| < 3.7$ covers the $p_T^{J/\psi}$ range from 1 to 16 GeV/c. The rapidity dependence of the inclusive J/ψ production was extracted for $p_T^{J/\psi} > 8$ GeV/c. Theoretical predictions for the b quark contribution exhibit a similar rapidity dependence.

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A SEARCH FOR $b \to X\mu^+\mu^-$ AND $B^\circ \to \mu^+\mu^-$ DECAYS IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ =1.8 TeV

RICHARD JESIK
Indiana University, Bloomington, IN 47405

for the DØ Collaboration

We have searched for the flavor-changing neutral current decays $b \to X\mu^+\mu^-$ and $B^\circ \to \mu^+\mu^-$ in $p\bar{p}$ collisions at $\sqrt{s}$ =1.8 TeV with the DØ detector at Fermilab. Using our observed $\mu^+\mu^-$ mass spectrum and the measured b-quark production cross section, we determine a 90% confidence limit of $BR(b \to X\mu^+\mu^-) < 3.6 \times 10^{-5}$. For the exclusive, purely leptonic decay $B^\circ \to \mu^+\mu^-$ we obtain an upper limit of $BR(B^\circ \to \mu^+\mu^-) < 8.0 \times 10^{-6}$, at 90% confidence.

1 Introduction

In the Standard Model, the decay processes $b \to X\mu^+\mu^-$ and $B^\circ \to \mu^+\mu^-$ are forbidden at the tree level and are only possible through loop diagrams. The expected branching fractions are 6×10^{-6} and 1.4×10^{-9} for $b \to X\mu^+\mu^-$ and $B^\circ \to \mu^+\mu^-$ decays, respectively[1]. Extensions of the Standard Model can have new particles in the loop, providing additional sources of FCNC. Precision measurements of these rare b-decays can therefore point to new physics.

2 Data Selection

The data set used in this analysis corresponds to a total integrated luminosity of 45.7 pb^{-1}. Opposite sign two muon events were subject to standard quality cuts and the following kinematic selection: (i) $p_T^\mu > 3$ GeV/c, (ii) $|\eta_\mu| < 1.0$, (iii) $p_T^{\mu\mu} > 5$ GeV/c, and (iv) $M_{\mu\mu} < 7$ GeV/c^2. The dimuon mass spectrum for the 1349 events satisfying this selection is shown in Fig. 1a. The spectrum above 2 GeV/c^2 is well described by the J/ψ and ψ' resonances, and a background shape simulating the sum of the known physics processes: Drell-Yan and semileptonic b and c decays.

3 Search for the Decay $b \to X\mu^+\mu^-$

The simulated dimuon mass spectrum for $b \to X\mu^+\mu^-$ decays[2] is shown in Fig. 1b. We define a search window of $3.9 < M_{\mu\mu} < 4.6$ GeV/c^2. The combined effects of the geometric and kinematic acceptances, and trigger and reconstruction efficiencies for a muon pair from $b \to X\mu^+\mu^-$ decay to fall in this

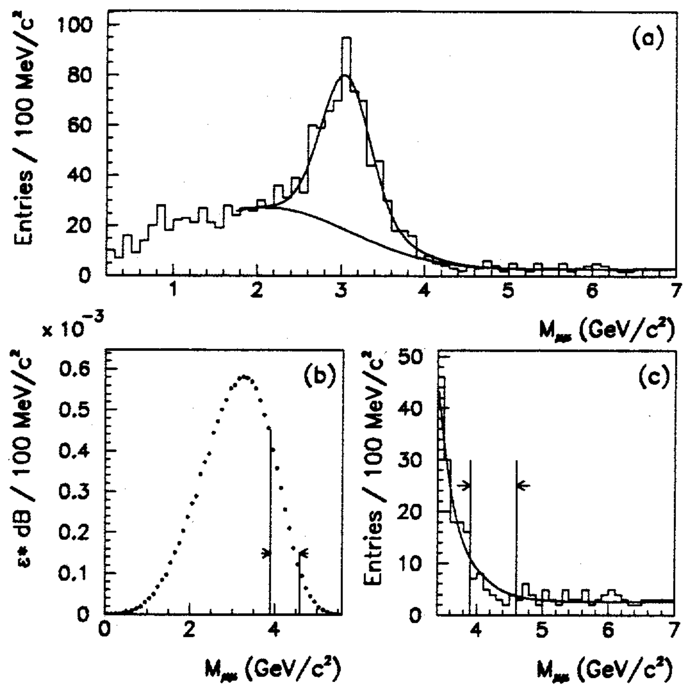

Figure 1: (a) The invariant mass distribution for dimuons with $p_T^{\mu\mu} > 5$ GeV/c. (b) The simulated invariant mass distribution for dimuons from the decay $b \rightarrow X\mu^+\mu^-$ in the DØ detector. (c) Expanded view of (a). The arrows indicate the search window.

search window gives an overall detection efficiency of $\epsilon = (3.1 \pm 0.6) \times 10^{-4}$. As shown in Fig. 1c, we find no evidence for an excess of data events in the search window: we observe 33 events, with an expected background of 44 $\pm$ 4 events. To derive an upper limit, we have applied the Bayesian approach in which the observed number of events is compared to the number of background events in the region of interest. We assume Poisson statistics for the signal and the background, and account for uncertainties in the background, cross section, and detection efficiency. Using an inclusive b-quark production cross section for $p_T(b) > 6$ GeV/c and $|y(b)| < 1$ of 7.2 $\pm$ 1.5 μb, based on a compilation of DØ measurements [3], we obtain a 90% confidence level upper limit of $BR(b \rightarrow X\mu^+\mu^-) < 3.6 \times 10^{-5}$.

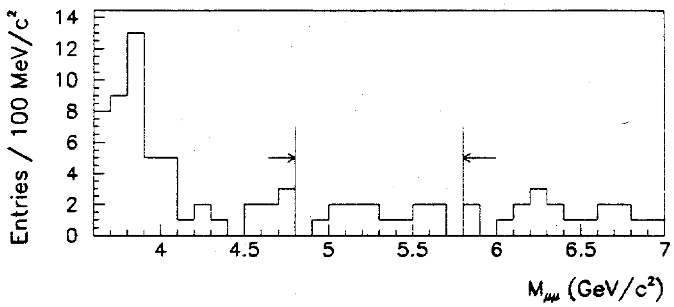

Figure 2: The invariant mass distribution for isolated dimuons with $p_T^{\mu\mu} > 5$ GeV/c. The arrows indicate the search window for the decay $B^\circ \rightarrow \mu^+\mu^-$.

4 Search for the Decay $B^\circ \rightarrow \mu^+\mu^-$

For the exclusive decay $B^\circ \rightarrow \mu^+\mu^-$ (an unseparated mixture of B_d and B_s decays) we define the search window as $4.8 < M_{\mu\mu} < 5.8$ GeV/c^2. In this process, the two muons are expected to carry a large fraction of the energy in a cone around the direction of the parent b-quark. To reduce background, we require that the energy deposition in the calorimeter in a cone $\Delta R< 0.6$ around each muon is less than 8 GeV. The overall detection efficiency for $B^\circ \rightarrow \mu^+\mu^-$ decays with these cuts is $\epsilon = (4.1 \pm 0.6) \times 10^{-3}$. The dimuon mass spectrum for isolated dimuons is shown in Fig. 2. We find 13 events in the search region. The background in this region, estimated from the side bands of the mass distribution, is 14.5 ± 2.7 events. Using a B° production cross section at $p_T(B) > 6$ GeV and $|y(B)| < 1$ of 2.39 ± 0.54 μb[4], we obtain an upper limit of $BR(B^o \rightarrow \mu^+\mu^-) < 8.0 \times 10^{-6}$ at 90% confidence level.

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