A Search for Rare B Meson Decays at the CERN Sp $\bar{p}$ S Collider*UA1 Collaboration, CERN, Geneva, Switzerland*

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ABSTRACT

We report on a search for the decays $B^0 \rightarrow \mu^+\mu^-$, $B \rightarrow \mu^+\mu^-X$ and $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$, which are expected to be rare if mediated by Flavor Changing Neutral Currents. Using data collected during the 1984–1989 CERN $p\bar{p}$ Collider runs, the UA1 search was carried out using $\mu^+\mu^-$ events with $3.9 \text{ GeV}/c^2 < M_{\mu\mu} < 5.5 \text{ GeV}/c^2$. We find 90% confidence level upper limits on the branching ratios for $B^0 \rightarrow \mu^+\mu^-$ of 8.3×10^{-6} , for $B \rightarrow \mu^+\mu^-X$ of 5.0×10^{-5} , and for $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$ of 2.3×10^{-5} . Implications for upper limits on the t -quark mass are discussed.

1. INTRODUCTION

Flavor changing neutral currents are forbidden at the tree level in the standard model of electroweak interactions. However, these transitions are expected at the one-loop level through the so-called penguin diagrams. Examples of B decays containing dimuons in the final state are shown in Fig. 1 [1,2]. The final state leptons provide an excellent signature for rare B decay searches at hadron colliders [3]. In this paper, we present results of a search for such decays to a final state containing a pair of unlike sign muons. We report on searches for the decays $B^0 \rightarrow \mu^+\mu^-$, $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$ as well as an inclusive search for $B \rightarrow \mu^+\mu^-X$, where X is any hadronic final state. The published 90% confidence level upper limits on these processes from e^+e^- experiments [4] are 5×10^{-5} for $B^0 \rightarrow \mu^+\mu^-$, 1.9×10^{-4} for $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$ and 2.4×10^{-3} for $B \rightarrow \mu^+\mu^-X$.

The organization of this paper is as follows: Section 2 covers the theoretical input relevant to the search, Section 3 describes the detector apparatus and the data samples used, Section 4 covers the methods and the results of the search, Section 5 contains a discussion of systematic errors and the method used to determine limits. Finally, in Section 6, implications of the results for an upper limit on the t -quark mass are presented.

2. THEORETICAL CONSIDERATIONS

The Minimal Standard Model diagrams contributing to the decay $B^0 \rightarrow \mu^+\mu^-$ are shown in Fig. 1. Fig. 1a consists of a neutral vector boson exchange generated by an induced bs or bd coupling, while Fig. 1b consists of a box diagram involving $W^\pm$ exchange [1]. Calculations of this branching ratio give results in the range from 10^{-9} to 10^{-8} for $100 \text{ GeV}/c^2 < M_{\text{top}} < 200 \text{ GeV}/c^2$ [5].

For the decay $B \rightarrow \mu^+\mu^-X$ and for the exclusive channel $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$, the contributing diagrams (Fig. 1c) are similar to those for $B^0 \rightarrow \mu^+\mu^-$. However, the situation is slightly more complicated: for $B \rightarrow \mu^+\mu^-X$, both charged and neutral B mesons contribute; the resulting dimuons are part of three or more body decays, thus complicating calculations of the dimuon invariant mass ($M_{\mu\mu}$) distribution; and there is an interference between the penguin-diagram decay and the resonance decay $B \rightarrow J/\psi$ or $\psi' + X$; J/ψ or $\psi' \rightarrow \mu^+\mu^-$. Fig. 2 shows the calculated differential branching ratios $d\text{BR}(b \rightarrow \mu^+\mu^-s)/dM_{\mu\mu}$ [6,8,10], for the combined decay (solid line) and for the penguin-diagram decays alone (dashed lines). The destructive interference above the J/ψ and ψ' is

clearly visible. However, beyond the ψ' , the differential branching ratio is dominated by the penguin–diagram decay. Theoretical calculations have also shown that this region has enhanced K^* production [7,10]. Furthermore, contributions from $b \rightarrow c\mu\nu \rightarrow s\mu\mu\nu$ chain decays are negligible. Therefore, we select the mass region above the ψ' for our search.

Due to the dominant contribution of the virtual t -quark in the penguin diagram, these decay modes are sensitive to the t -quark mass. In this analysis, for the inclusive decay $B \rightarrow \mu^+\mu^-X$, we use the $M_{\mu\mu}$ distribution of Grinstein et al. [8] and the total branching ratio calculations of Grigjanis et al. [9]. For the exclusive decay $B_d \rightarrow \mu^+\mu^-K^{0*}$, we use the calculations of Jaus et al. [10] for the $M_{\mu\mu}$ distribution and the total branching ratio. We assume that the $M_{\mu\mu}$ and M_{ee} distributions have the same shape where the calculations are made with electrons in the final state.

3. DETECTOR AND DATA SELECTION

A detailed description of the UA1 detector can be found elsewhere [11]. In brief, as particles leave the interaction vertex, they first encounter a large volume drift chamber, the central detector. Here, momenta of charged particles are measured in a 0.7 T dipole magnetic field, with a typical accuracy on $\Delta p/p$ of $0.01 * p$ (GeV/c) for a 1m long track. These particles then pass through an air gap of 0.5 – 1.0 m in thickness. This gap is the result of removing the electromagnetic calorimeters (Gondolas and Bouchons) in preparation for the envisaged installation of a new uranium–TMP calorimeter. The particles next encounter the hadronic calorimeter and at least 60 cm of additional iron shielding (about 1.5 m in the forward region). Together, the hadronic calorimeter and the shielding wall consist of at least 8 nuclear interaction lengths of material, which almost completely absorbs strongly interacting particles. The iron shielding wall is partially instrumented with planes of limited streamer tubes. These tubes measure the position of muons, as they leave the hadronic calorimeter, with a resolution of 1 to 2 mm. Finally, muons are detected in the muon chambers, which surround the experimental apparatus and cover approximately 75% of the solid angle. These muon chambers allow the detection of muons in a pseudorapidity range $|\eta| < 2.3$. Muon trigger processors require tracks in the muon chambers which point back to the interaction region. These processors permit triggering with $|\eta| < 1.5$ for single high p_T muons, and with $|\eta| < 2.3$ for muon pairs.

The analysis presented here is based on data collected with the UA1 detector during runs at the CERN $p\bar{p}$ Collider from 1984 to 1989, and corresponds to a total integrated luminosity of about 5.3 pb^{-1} . We combine data taken with the old and new detector configurations. Muons are identified as high p_T tracks in the central detector, which when extrapolated through the iron shielding have corresponding tracks in the muon chambers. Dimuon events are selected by requiring two muons of opposite charge originating from the primary interaction vertex. For the $B^0 \rightarrow \mu^+\mu^-$ and $B \rightarrow \mu^+\mu^-X$ searches, we require both muons to have $p_T > 3 \text{ GeV}/c$. For the $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$ search, where the added requirement of a K^{0*} in the event reduces the background, we require the first muon to

have $p_T > 3 \text{ GeV}/c$ and the second muon to have $p_T > 2 \text{ GeV}/c$.

4. METHOD AND RESULTS

4.1 Search for the decay $B^0 \rightarrow \mu^+\mu^-$

For the decay $B^0 \rightarrow \mu^+\mu^-$, we search for candidate events with a dimuon invariant mass near the mass of the B_d^0 or the B_s^0 meson. We use $M(B_d^0) = 5.28 \text{ GeV}/c^2$ [12] and $M(B_s^0) = 5.38 \text{ GeV}/c^2$. The mass resolution of the UA1 detector for dimuon masses near $5.3 \text{ GeV}/c^2$ is about $200 \text{ MeV}/c^2$; it is determined from a study of the mass resolution of dimuons coming from J/ψ decay [13]. Fig. 3 shows a scatter plot of $p_T(\mu\mu)$ versus $M_{\mu\mu}$, where $p_T(\mu\mu)$ is the p_T of the dimuon system. For $p_T(\mu\mu) > 6 \text{ GeV}/c$, the detection efficiency is nearly independent of the dimuon mass. However, the greatest sensitivity to a possible signal is obtained with a cut of $p_T(\mu\mu) > 7 \text{ GeV}/c$. We therefore define our search region for the decay $B^0 \rightarrow \mu^+\mu^-$ as:

$$5.1 \text{ GeV}/c^2 < M_{\mu\mu} < 5.5 \text{ GeV}/c^2, \text{ and} \\ p_T(\mu\mu) > 7 \text{ GeV}/c.$$

A plot of dimuon masses in the region of interest and with $p_T(\mu\mu) > 7 \text{ GeV}/c$ is shown in Fig. 4. We see no evidence for an excess of events in the region of the B^0 mesons.

To place an upper limit on this decay mode, we must determine the production cross-section, the overall detection efficiency and the background to this decay mode. We have used the b -quark cross-section measured by UA1 [14], which is in good agreement with recent QCD predictions [15] which take account of higher order corrections.

We use the ISAJET program [16] to generate decays of the B_d^0 and the B_s^0 mesons into muon pairs. Assuming that a b -quark picks up a light quark in the same way as a u -quark, the measured K/π ratio for leading particles suggests a corresponding $B_s^0:B_d^0$ ratio of 1:2 [17]. We also assume a $B^+:B_d^0$ ratio of 1:1, and a 10% baryon fraction. The generated events are then passed through a detailed simulation of the UA1 detector and trigger. We apply the same selection and physics cuts as used for the data. We find an overall efficiency of $(4.0 \pm 0.8)\%$ (see Table 1) for dimuons coming from a parent b or $\bar{b}$ quark with $p_T > 6 \text{ GeV}/c$ and $|y| < 1.5$.

Finally, the background to this decay mode is determined using a fit to the data. The solid line in Fig. 4 is a phenomenological fit to the data, excluding events in the two search regions for $B^0 \rightarrow \mu^+\mu^-$ and $B \rightarrow \mu^+\mu^-X$. We use a sum of three terms: a Gaussian distribution centered at the J/ψ mass, a second Gaussian distribution centered at the ψ' mass, and a term linear in $M_{\mu\mu}$. We estimate the background in the $B^0 \rightarrow \mu^+\mu^-$ search region to be 5.0 ± 1.0 events while we see 6 events. After folding in the various systematic uncertainties (see Section 5) and the uncertainty from the background subtraction, we obtain the following 90% confidence level limit on the branching ratio for

the B^0 decays into two muons: $BR(B^0 \rightarrow \mu^+\mu^-) < 8.3 \times 10^{-6}$ (B^0_d and B^0_s not separated).

$$BR(B^0 \rightarrow \mu^+\mu^-) < 8.3 \times 10^{-6} \quad (B^0_d \text{ and } B^0_s \text{ not separated}).$$

Assuming that 36% (18%) of $\bar{b}$ -quarks give rise to B^0_d (B^0_s) mesons as described earlier, we obtain $BR(B^0_d \rightarrow \mu^+\mu^-) < 1.2 \times 10^{-5}$ and $BR(B^0_s \rightarrow \mu^+\mu^-) < 2.5 \times 10^{-5}$ at 90% confidence level.

4.2 Search for the decay $B \rightarrow \mu^+\mu^-X$

The search region for the $B \rightarrow \mu^+\mu^-X$ decay is chosen to be $3.9 \text{ GeV}/c^2 < M_{\mu\mu} < 4.4 \text{ GeV}/c^2$, which is above the destructive interference between the penguin-diagram and the ψ' decays (see Fig. 2). We find that a cut of $p_T(\mu\mu) > 7 \text{ GeV}/c$ again provides the greatest sensitivity to a possible signal.

As can be seen in Fig. 4, no evidence for an excess of events in our search region is observed. To determine our efficiency to this decay mode, we use the ISAJET program to simulate this process. We force the $M_{\mu\mu}$ distribution of dimuons coming from the b -quark decay to be that of Ref. 8. We find an overall efficiency of $(1.1 \pm 0.3)\%$ (see Table 1) for dimuons coming from a parent b or $\bar{b}$ quark of $p_T > 6 \text{ GeV}/c$ and $|y| < 1.5$. Using the fitted curve of Fig. 4, we estimate the background to this decay mode to be 8.7 ± 1.7 events compared with 9 events seen. After folding in the systematic uncertainties and the uncertainty from the background subtraction, and using the UA1 b -quark cross-section, we obtain a 90% confidence level upper limit of:

$$BR(B \rightarrow \mu^+\mu^-X) < 5.0 \times 10^{-5} \quad (B^0_d, B^\pm \text{ and } B^0_s \text{ not separated}).$$

4.3 Search for the decay $B^0_d \rightarrow \mu^+\mu^-K^{0*}$

Finally, we have conducted a search for the exclusive decay $B^0_d \rightarrow \mu^+\mu^-K^{0*}$. Since we are only concerned with dimuon events which contain an associated K^{0*} candidate, we can relax our muon selection criteria, namely:

$$p_T(\mu_1) > 3 \text{ GeV}/c,$$

$$p_T(\mu_2) > 2 \text{ GeV}/c, \text{ and}$$

$$p_T(\mu\mu) > 4 \text{ GeV}/c.$$

These cuts increase the sensitivity to a possible signal by a factor of 4. Requiring the same cut on $M_{\mu\mu}$ as in the $B \rightarrow \mu^+\mu^-X$ search, we look for charged tracks in the central detector arising from the decay $K^{0*}(\bar{K}^{0*}) \rightarrow K^{+(-)}\pi^{-(+)}$. We accept all charged tracks associated to the dimuon vertex which have $p_T > 100 \text{ MeV}/c$ and which are separated from the direction of the dimuon system by $\Delta R < 1.0$ ($\Delta R = (\Delta\phi^2 + \Delta\eta^2)^{1/2}$, where ϕ is

the azimuthal angle around the beam direction and η is the pseudorapidity). The energy of each track is computed successively assuming it to be a kaon and a pion. All possible $K^{+(-)}\pi^{-(+)}$ combinations are taken if:

$$p_T(K\pi) > 2 \text{ GeV}/c, \text{ and} \\ p(K) > 0.5 * p(\pi).$$

The latter cut exploits the effect of Lorentz boost on decay products of unequal masses. A plot of the obtained $K\pi$ masses is shown in Fig. 5a. By comparison with Monte Carlo, $K\pi$ combinations are accepted as K^{0*} candidates if $M(K\pi)$ is within 40 MeV/c^2 of the K^{0*} mass.

The background is estimated by loosening the cuts on the $K\pi$ system. For the background sample, we take $K\pi$ combinations with $p_T(K\pi) > 1 \text{ GeV}/c$ and without any cut on the K to π momentum ratio. The background is plotted as the dashed curve in Fig. 5a., normalised to the number of events outside the K^{0*} candidate region. No significant excess of K^{0*} candidates is seen in the data. The mass of the $\mu\mu K^{0*}$ (candidate) system is plotted in Fig. 5b; note that multiple entries per dimuon event are allowed. We define a $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$ candidate as a dimuon event which has at least one associated K^{0*} candidate with a $\mu\mu K^{0*}$ mass within 200 MeV/c^2 of the B_d^0 mass. Here, we do not allow for multiple entries per dimuon as this could lead to an over-estimation of the background. We find two B_d^0 candidates in the data and a background of 1.0 ± 0.6 events, which is estimated by looking in the K^{0*} candidate mass region in the background sample as described above.

The ISAJET program is used to calculate the overall efficiency for this decay mode, forcing the $M_{\mu\mu}$ distribution of dimuons coming from the b -quark decay to be that of Ref. 10. We find an overall efficiency of $(1.1 \pm 0.3)\%$ (see Table 1) for a $\mu\mu K^{0*}$ coming from a parent b or $\bar{b}$ quark of $p_T > 6 \text{ GeV}/c$ and $|y| < 1.5$. After folding in the systematic uncertainties and the uncertainty from the background subtraction, and using the UA1 b -quark cross-section, we obtain, assuming 36% of $\bar{b}$ -quarks give B_d^0 mesons, a 90% confidence level upper limit of:

$$\text{BR} (B_d^0 \rightarrow \mu^+\mu^-K^{0*}) < 2.3 \times 10^{-5}.$$

5. SYSTEMATIC ERRORS AND CALCULATION OF LIMITS

The systematic errors affecting this analysis fall into three categories:

- the uncertainty on the measured b -quark cross-section, which is 34% (see Ref. 14);
- the uncertainty from the acceptance of the cuts used, which is 21%, and from the Monte Carlo statistics (1–2%);
- the uncertainty on the calculations of $M_{\mu\mu}$ distributions for the decays $B \rightarrow \mu^+\mu^-X$ and $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$, which is estimated to be 20%.

Including the uncertainty on the b-quark cross-section, the total systematic error on the $\mu^+\mu^-$ production from the decay $B^0 \rightarrow \mu^+\mu^-$ is 40%, while from the decays $B \rightarrow \mu^+\mu^-X$ and $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$ is 45%.

To obtain upper limits, we convolute the Poisson nature of a low statistics experiment with normal distributions describing the systematic errors and uniform distributions describing unknown parameters. A numerical integration over all variables is then performed, from which the limits are extracted. Details can be found in Ref. 18.

6. IMPLICATIONS FOR THE t-QUARK MASS

Because of the virtual t-quark exchange in the penguin-diagram loops, each of the decays $B^0 \rightarrow \mu^+\mu^-$, $B \rightarrow \mu^+\mu^-X$ and $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$ is sensitive to the t-quark mass. Standard Model calculations of $BR(B^0 \rightarrow \mu^+\mu^-)$ give values of about 10^{-9} to 10^{-8} for $100 \text{ GeV}/c^2 < M_{\text{top}} < 200 \text{ GeV}/c^2$ [5]. Our experimental limit in this case is still 3 to 4 orders of magnitude above these values; however, the $BR(B \rightarrow \mu^+\mu^-X)$ limit can be used to place constraints on the t-quark mass. Grigjanis et al. have calculated the total branching ratio for $B \rightarrow \mu^+\mu^-X$ versus the t-quark mass [9]. Their results are shown in Fig. 6. Using our upper limit on the $BR(B \rightarrow \mu^+\mu^-X)$ of 5.0×10^{-5} , we find an upper limit on the t-quark mass of $400 \text{ GeV}/c^2$ at 90% confidence level. We have not placed an upper limit on the t-quark mass using the limit on $BR(B_d^0 \rightarrow \mu^+\mu^-K^{0*})$ because calculations of this branching ratio as a function of the t-quark mass for large masses are not yet available.

7. CONCLUSIONS

We have searched for several rare decay modes of B mesons involving muon pairs and flavor changing neutral currents. We find no evidence for these decays in our data sample and place 90% confidence level upper limits on their branching ratios of:

$$BR(B^0 \rightarrow \mu^+\mu^-) < 8.3 \times 10^{-6} \text{ for an unseparated mixture of } B_d^0 \text{ and } B_s^0 \text{ mesons,}$$

$$BR(B \rightarrow \mu^+\mu^-X) < 5.0 \times 10^{-5} \text{ for an unseparated mixture of B mesons, and}$$

$$BR(B_d^0 \rightarrow \mu^+\mu^-K^{0*}) < 2.3 \times 10^{-5}.$$

We have assumed that B^+ , B_d^0 , B_s^0 and B-baryons are produced in the ratio 36:36:18:10. Using our limit on $BR(B \rightarrow \mu^+\mu^-X)$, we find an upper mass limit for the t-quark of $400 \text{ GeV}/c^2$ at 90% confidence level, assuming the Minimal Standard Model calculation of Grigjanis et al. [9].

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FIGURES

- Fig. 1 Examples of diagrams contributing to B meson decays containing dimuons:
for $B^0 \rightarrow \mu^+\mu^-$, a) neutral vector boson exchange generated by an induced bs or bd coupling, and b) box diagram involving $W^\pm$ exchange; for $B \rightarrow \mu^+\mu^-X$ and $B_d^0 \rightarrow \mu^+\mu^-K^{0*}$, c) neutral vector boson exchange generated by an induced bs or bd coupling and box diagram involving $W^\pm$ exchange.
- Fig. 2 The calculated differential branching ratio $dBR(b \rightarrow \mu^+\mu^-s)/dM_{\mu\mu}$ for a 200 GeV/c² t-quark mass. The solid line corresponds to the differential branching ratio calculation for the combined resonance and penguin-diagram decays, the dashed lines represent the penguin-diagram decays alone. These plots are obtained from References 6, 8 and 10 assuming $M_b = 5.0$ GeV/c² and $M_B = 5.28$ GeV/c².
- Fig. 3 A scatter plot of $p_T(\mu\mu)$ versus $M_{\mu\mu}$ for the data sample. The dashed line corresponds to the $p_T(\mu\mu)$ cut of 7 GeV/c.
- Fig. 4 The mass distribution for dimuons with $p_T(\mu\mu) > 7$ GeV/c: a) the region over which the phenomenological fit was performed; b) an expanded view showing the $B^0 \rightarrow \mu^+\mu^-$ and $B \rightarrow \mu^+\mu^-X$ search regions. The solid line represents the results of the phenomenological fit to the data.
- Fig. 5 a) The $K\pi$ mass distribution for oppositely charged tracks associated to a dimuon with $3.9 \text{ GeV}/c^2 < M_{\mu\mu} < 4.4 \text{ GeV}/c^2$. The dashed curve is an estimation of the combinatorial background. b) The $K\pi\mu\mu$ mass distribution for K^{0*} candidates.
- Fig. 6 The calculated $BR(b \rightarrow sl^+l^-)$ versus top quark mass. The solid curve is the calculation for $BR(b \rightarrow se^+e^-)$, the dashed curve the corresponding calculation for $BR(b \rightarrow s\mu^+\mu^-)$. The horizontal dotted line shows the 90% confidence level limit from this analysis. The arrows indicate the 90% confidence level upper limit on M_{top} from this analysis and the CDF 95% confidence level lower limit on M_{top} [19].

Description of Cuts Applied	Number of Events		
	$B^0 \rightarrow \mu^+\mu^-$	$B \rightarrow \mu^+\mu^-X$	$B^0_d \rightarrow \mu^+\mu^-K^{0*}$
$p_T(\mu_1), p_T(\mu_2)$ Cuts $p_T(\mu\mu)$ Cut Matching Cuts	11,465	14,713	23,989
$M_{\mu\mu}$ Cut	8,025	2,207	14,393
K^{0*} Cuts			2,218
Overall Efficiency	4.0%	1.1%	1.1%

Table 1: Overall efficiencies for rare B meson decays. For each process, 200,000 ISAJET events were generated with mesons produced from b quarks with $p_T(b) > 6$ GeV/c and $|\eta(b)| < 1.5$.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6