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Rare Decays at the Tevatron

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The confidence level limits of the CDF and DØ searches for the $B_s^0, B_d^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\phi$ rare decays are presented.

1. Introduction

In the quest to find new physics, two complementary methods are employed: direct searches, for example searches for supersymmetric particles, and indirect searches, for example tests for deviations from Standard Model predictions such as branching ratios. Through both of these methods, limits may be set on new physics model parameters. The searches for the $B_d^0, B_s^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\phi$ rare decays at the Tevatron are strong indirect tests of the Standard Model.

2. Search for $B_d^0, B_s^0 \to \mu^+\mu^-$

In the Standard Model, the flavour changing neutral current decays $B \to \mu^+\mu^-$ proceed through loop diagrams and are thus heavily suppressed. The predicted branching ratio of the $B_s^0 \to \mu^+\mu^-$ is $(3.4 \pm 0.5) \times 10^{-9}$ and the $B_d^0 \to \mu^+\mu^-$ is further CKM suppressed to $(1.00 \pm 0.14) \times 10^{-10}$ [1]. These branching ratios are both below the sensitivity of the Tevatron experiments, and so an observation of these decay modes would be clear evidence of new physics, independently of any model interpretation.

In new physics scenarios, the branching ratio of $B \to \mu^+\mu^-$ could be enhanced by orders of magnitude. For example, in the MSSM the branching ratio is proportional to $\tan^6\beta$. Alternatively, R-parity violating SUSY would give rise to a tree level diagram via a sneutrino which would increase the branching ratio sufficiently for an observation at low $\tan\beta$ values. In mSUGRA, the $B \to \mu^+\mu^-$ search complements direct trilepton SUSY searches [2].

The experimental challenge of a search for $B \to \mu^+\mu^-$ is the large combinatorial background present in a hadron collider. The key elements of the analysis are to determine the efficiencies for observing these decays, to select discriminating variables in order to reject background and to estimate the remaining background contribution.

The CDF and DØ collaborations have searched for $B \to \mu^+\mu^-$ in 360pb^{-1} and 300pb^{-1} of data respectively [3,4]. The CDF analysis searches for opposite sign μ pairs in the B_s^0 and B_d^0 mass windows, while DØ are limited by worse mass resolution and search for the B_s^0 decay only and assume Minimal Flavour Violation allowing B_d^0 decays to be neglected. Both analyses optimise the event selection without using events in the signal region in order to avoid introducing biases in the selection. The outcome of the search is designed to be a branching ratio measurement or limit depending on whether a significant signal is observed.

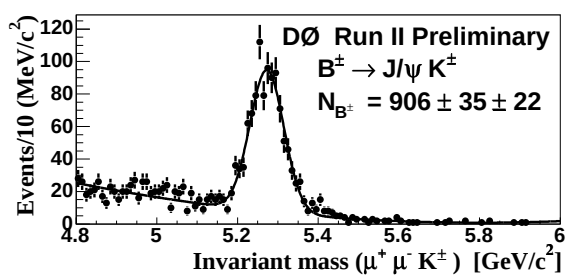

Figure 1. Invariant mass of control channel ($B^+ \to J/\Psi K^+$) candidates.

The analysis procedure is to reconstruct the

normalisation mode, $B^+ \to J/\Psi K^+$ with which a relative branching ratio for the $B \to \mu^+\mu^-$ can be obtained. The B^+ candidates are shown in figure 1. In the CDF analysis a discriminant is constructed to select the $B \to \mu^+\mu^-$ signal and suppress backgrounds whereas the DØ analysis uses cuts on individual variables to suppress the background. The remaining expected background is assessed from sideband regions, and the relative efficiency and acceptance for the $B \to \mu^+\mu^-$ and normalisation mode are obtained from Monte Carlo simulations and data. Then, the branching ratio is obtained relative to the control sample, $B^+ \to J/\Psi K^+$:

$$\begin{aligned} BR(B_s^0 \to \mu^+\mu^-) = & \frac{N_{B_s}}{N_{B^+}} \quad \frac{\alpha_{B^+}\epsilon_{B^+}^{total}}{\alpha_{B_s}\epsilon_{B_s}^{total}} \frac{f_u}{f_s} \\ & \times \quad BR(B^+ \to J/\Psi K^+) \\ & \times \quad BR(J/\Psi \to \mu^+\mu^-) \end{aligned} \tag{1}$$

Here, N_{B^+} is the yield of $B^+ \to J/\Psi K^+$ in the control sample, N_B is the yield of $B^0 \to \mu^+\mu^-$ decays, α_{B^+,B^0} are the acceptances and $\epsilon_{B^+,B^0}^{total}$ are the efficiencies for the decay modes. The yields, N_{B^+} and N_{B^0}, are corrected by the relative production fractions, f_u and f_s, and the branching ratios of the control sample are incorporated.

CDF and DØ both have dedicated rare B decay triggers which require two muons. CDF utilises muon chambers to a pseudorapidity of $|\eta| \leq 1.0$ whereas DØ has a greater muon chamber coverage of $|\eta| \leq 2.0$. This difference in the muon coverage is compensated for by CDF's tracking devices which give a finer mass precision. The CDF analysis is divided into two types of muon pair, central-central, where central corresponds to $|\eta| \leq 0.6$, and central-extension, where extension corresponds to $0.6 < |\eta| \leq 1.0$.

Both analyses employ three variables, two of which are the same: the pointing angle, α, defined as the difference in ϕ angle between the B momentum direction and the B direction as given by the vertexing procedure (defined in 3d (2d) for the CDF (DØ) analysis); and the isolation of the B meson defined by

$$Iso = \frac{p_t(B)}{pt(B) + \sum_i p_t^i(\Delta R < 1.0)} \tag{2}$$

where the sum is over all tracks within a cone of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ of 1.0. The CDF analysis uses the proper decay length

$$\lambda = \frac{cLM(B)}{p(B)} \tag{3}$$

where L is the 3d decay length. The DØ analysis uses the (2d) variable $L_{xy}/\sigma(L_{xy})$ instead.

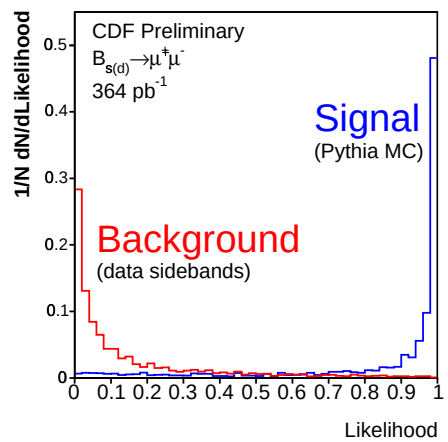

Figure 2. Likelihood discriminant for signal and background regions.

The DØ analysis optimises cuts on its three variables using Pythia Monte Carlo samples for the signal and data sidebands for the background. A random grid search is performed, optimising the cuts to achieve the best 95% confidence level limit. The optimal cuts are Iso>0.56, α >0.2rad, and $L_{xy}/\sigma(L_{xy})$ >18.5. The CDF analysis combines its variables into a likelihood discriminant:

$$\mathcal{L} = \frac{\Pi_i P_{sig}(x_i)}{\Pi_i P_{sig}(x_i) + \Pi_i P_{bkg}(x_i)} \tag{4}$$

where i is an index over all discriminating variables and $P_{sig/bkg}(x_i)$ is the probability for an event to be signal or background for a given measured x_i. The $P_{sig/bkg}(x_i)$ are given by probability density functions of the discriminating variables determined using data sidebands for the

background distribution and Pythia Monte Carlo samples for the signal distribution. The likelihood distributions are shown in figure 2. An optimisation of the likelihood and the $p_t(B)$ is then performed to achieve the best 90% confidence level limit. A Bayesian approach is used for this optimisation which takes into account statistical and systematic errors and assumes 1fb^{-1} of integrated luminosity. The resulting optimal cuts are $p_t(B) > 4GeV/c$ and $\mathcal{L} > 0.99$.

After applying the cuts, the expected background in the B signal region is obtained by extrapolating the number of sideband events into the signal region. The CDF analysis scales the number of sideband events by the expected rejection from the likelihood ratio cut. The expected background is 0.81 ± 0.12 events for the central-central dimuons and 0.66 ± 0.13 for the central-extended dimuons. The background estimate compares well with the number of events found in several control regions. The DØ analysis does not require the number of events to be scaled, and obtains an expected background of 4.3 ± 1.2 events.

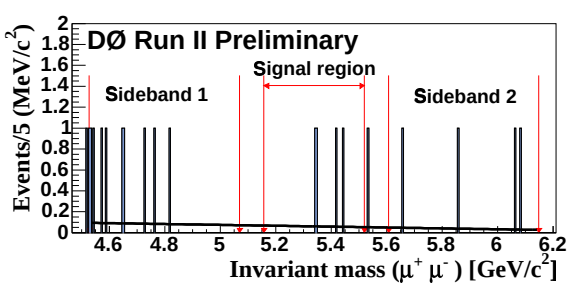

Figure 3. Invariant mass of $B \to \mu^+\mu^-$ candidates in DØ analysis.

The unblinded invariant mass of the dimuon candidates found by the DØ analysis is shown in figure 3. Four events are observed in the signal region, consistent with the expected background, and the resulting branching ratio limits are

$BR(B_s^0 \to \mu^+\mu^-) < 3.0 \times 10^{-7}$ at 90% C.L.

$BR(B_s^0 \to \mu^+\mu^-) < 3.7 \times 10^{-7}$ at 95% C.L.

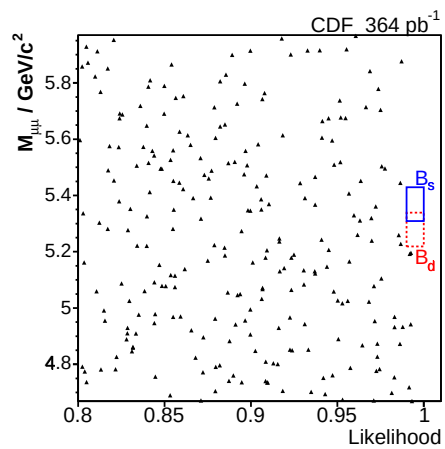

Figure 4. Invariant mass of $B \to \mu^+\mu^-$ candidates in CDF analysis.

The unblinded invariant mass versus the likelihood of the dimuon candidate in the CDF analysis is shown in figure 4. No events were found in either the B_s^0 or B_d^0 search windows. The resulting branching ratio limits are

$BR(B_s^0 \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ at 90% C.L.
$BR(B_s^0 \to \mu^+\mu^-) < 2.0 \times 10^{-7}$ at 95% C.L.
$BR(B_d^0 \to \mu^+\mu^-) < 3.9 \times 10^{-8}$ at 90% C.L.
$BR(B_d^0 \to \mu^+\mu^-) < 5.1 \times 10^{-8}$ at 95% C.L.

The CDF results are currently the world's best limits. Combined results of the CDF and DØ limits are now available [5].

3. Search for $B_s^0 \to \mu^+\mu^-\phi$

The rare decays $B^+ \to \mu^+\mu^-K^+$ and $B_d^0 \to \mu^+\mu^-K^{*0}$ have been observed at Babar and Belle. However the analogous decays $B_s^0 \to \mu^+\mu^-\phi$ and $\Lambda_b \to \mu^+\mu^-\Lambda$ have not been observed. This type of rare decay proceeds through penguin or box processes in the Standard Model and branching

ratios measured by Babar and Belle are $\mathcal{O}(10^{-7})$. Such rare decays allow tests of the SM predictions for the branching ratio and, given sufficient statistics, the kinematic distributions. The parameters of these decays are described in terms of the Wilson coefficients [6]. The decay amplitude is sensitive to the 9th Wilson coefficient, C_9; the dilepton mass distribution is sensitive to both C_7 and C_9 and the forward-backward asymmetry of the leptons is sensitive to C_{10}. These coefficients have been predicted in many new physics scenarios, including SUSY and technicolor, and the kinematic distributions of the rare decays can thus be used to rule out or verify the various models.

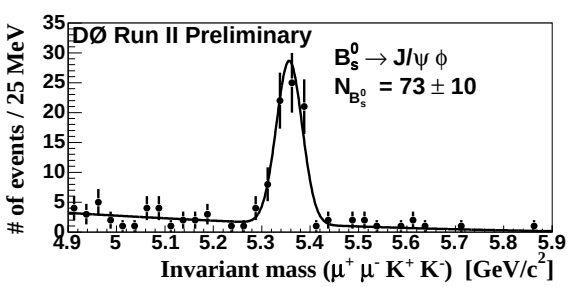

Figure 5. Invariant mass of control channel ($B_s^0 \to J/\Psi\phi$) candidates.

The aim of the CDF and DØ analyses is to either make first observations of the B_s^0 and Λ_b decays or to set strong branching ratio limits. here a limit on the branching ratio of $B_s^0 \to \mu^+\mu^-\phi$ by DØ is reported. The branching ratio is measured relative to the control channel $B_s^0 \to J/\Psi\phi$. This control channel has exactly the same final state (with $J/\Psi \to \mu^+\mu^-$) as the rare decays and so many systematic errors and effects are expected to cancel. The distribution of the invariant mass of the B_s^0 candidates in the control sample, $B_s^0 \to J/\Psi\phi$, is shown in figure 5. The DØ analysis is similar to the $B_s^0 \to \mu^+\mu^-$ analysis described in section 2. The same discriminating variables are used in the optimisation procedure. An additional complication in this analysis is the removal of the candidates with dimuon masses in the range of the J/Ψ, Ψ' and ϕ since the contribution from rare decays is not well understood theoretically under the resonances. The candidates are shown in figure 6. At the time of Beauty 05, the DØ collaboration had performed a sensitivity analysis which has now been unblinded to yield a branching ratio limit of $< 4.1 \times 10^{-6}$ at 95% confidence level [7].

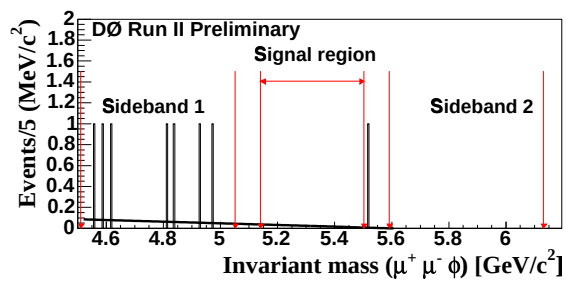

Figure 6. Invariant mass of $B_s^0 \to \mu^+\mu^-\phi$ candidates.

4. Conclusions

The $B_d^0, B_s^0 \to \mu^+\mu^-$ rare decays are a powerful probe of new physics and the Tevatron is currently yielding the world's best limits on their branching ratios with which new SO(10) and mSUGRA sapce can be excluded. The DØ collaboration have set the world's best limit on the $B_s^0 \to \mu^+\mu^-\phi$ rare decay which should be seen at the Tevatron if the Standard Model expectation is correct and has the potential to provide knowledge of the Wilson coefficients.

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