RARE HEAVY FLAVOR DECAYS AT DØ

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DØ has searched for flavor changing neutral currents in the decay modes $D^+ \to \pi^+\mu^+\mu^-$, $B_s^0 \to \mu^+\mu^-$ and $B_S^0 \to \phi\mu^+\mu^-$. No significant signal is seen in any of these decay modes and upper limits are set.

Keywords: Heavy Quark; Rare Decays.

1. Introduction

In the Standard Model (SM), Flavor Changing Neutral Currents (FCNC) are forbidden at tree level, but can proceed via higher order box or penguin diagrams. Consequently, many extensions to the SM allow for alternate loop diagrams that can significantly alter the SM expectations. The DØ collaboration has looked for FCNC rare decay processes that may be enhanced by these SM extensions.

2. FCNC in the Charm Sector

Experiments have shown excellent agreement between the observed FCNC in the charm sector and SM predictions involving down-type quarks with charge -1/3.[1,2,3] However, certain models, such as SUSY R parity violation in a single coupling scheme,[3] or a little higgs model with a new up-type vector quark,[4] allow deviations from the SM only in the up sector. These types of scenarios motivate a search for the rare decay $c \to u\mu^+\mu^-$ via $D^+ \to \pi^+\mu^+\mu^-$.

The search for $D^+ \to \pi^+\mu^+\mu^-$ uses about 1 fb^{-1} of data. The strategy for this search is to first look for the resonant decays $D_s^+ \to \phi\pi+ \to \pi^+\mu^+\mu^-$ and $D^+ \to \phi\pi+ \to \pi^+\mu^+\mu^-$, then exclude the ϕ mass region and look for continuum decay of $D^+ \to \pi^+\mu^+\mu^-$. The D_S^+ is expected to decay 100% of the time through the resonant decay of a ϕ meson.

Backgrounds are reduced using five criteria: (1) the Isolation defined as $\mathcal{I}_D = p(D)/\sum p_{\text{cone}}$ where $p(D)$ is the momentum of the D meson and the sum is over all tracks in a cone of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 1$ centered on the D meson, (2) the transverse flight significance, S_D, defined as the transverse distance of the reconstructed D vertex from the primary vertex divided by the error of the two vertices, (3) the collinearity angle, Θ_D, defined as the angle between the D meson momentum and a line pointing from the primary vertex to the secondary vertex, (4) the pion impact parameter significance S_π, and (5) the variable $\mathcal{M} = \chi^2_{\text{vtx}} + \kappa_\pi^2 + \Delta R_\pi^2$ where χ^2_{vtx} is the χ^2 of the three track vertex and κ_π is the inverse of the transverse momentum of the pion in units of (GeV/c)$^{-1}$.

The optimized cuts are determined from the Monte Carlo for the D_s^+ sample to be $\mathcal{I}_D > 0.44$, $S_D < 3.4$, $\Theta_D < 32$ mrad, $S_\pi > 0.57$, and $\mathcal{M} < 6.1$. With these cuts, a di-muon invariant mass region is chosen in the ϕ mass window, $0.96 < m(\mu^+\mu^-) < 1.06$ GeV/c^2, and a fit to the data gives the number of D^+ and D_s^+ candidates as $n(D^+) = 26 \pm 9$ and $n(D_s) = 65 \pm 11$ as shown in Fig. 1.

The branching fraction $\mathcal{B}(D^+)$ for the resonant decay $D^+ \to \phi\pi^+ \to \pi^+\mu^+\mu^-$ is

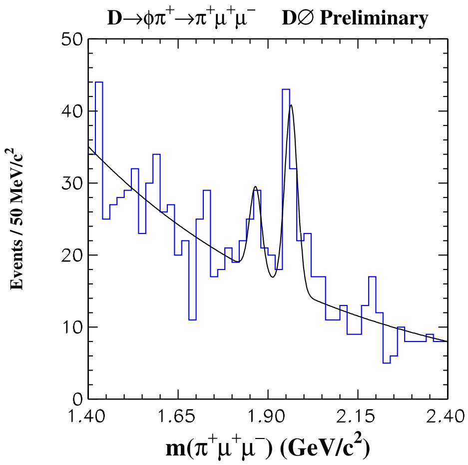

Fig. 1. The $\pi\mu^+\mu^-$ invariant mass with $0.96 < m(\mu^+\mu^-) < 1.06$ GeV/c^2.

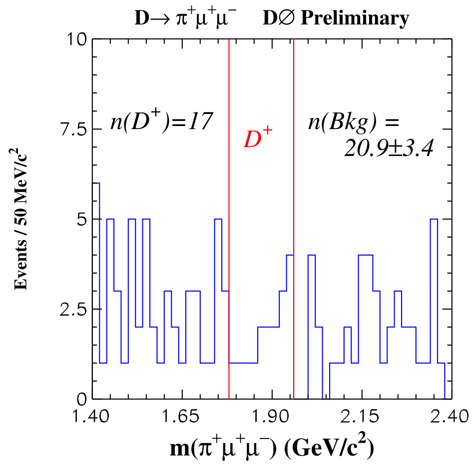

Fig. 2. The $\pi\mu^+\mu^-$ invariant mass with $0.2 < m(\mu^+\mu^-) < 0.96$ GeV/c^2 and $0.96 < m(\mu^+\mu^-) < 1.76$ GeV/c^2.

extracted using

$$\frac{n(D^+)}{n(D_s)} = \frac{f_c^+}{f_c^s} \cdot \frac{f_p^s}{f_p^+} \cdot \frac{\epsilon^+}{\epsilon^s} \cdot \frac{\mathcal{B}(D^+)}{\mathcal{B}(D_s) \times \mathcal{B}(\phi)} \quad (1)$$

where f_c^+ is the fraction of D^+ mesons produced in c quark fragmentation, f_c^s is the equivalent fraction for D_s^+ mesons, f_p^+ and f_p^s are the fraction of prompt D^+ and D_s^+ mesons, respectively, ϵ^+ and ϵ^s are the efficiency for reconstructing D^+ and D_s^+ mesons, respectively, $\mathcal{B}(D_s)$ is the branching fration for $D_s^+ \to \phi\pi^+$, and $\mathcal{B}(\phi)$ is the branching fraction for $\phi \to \mu^+\mu^-$.

Solving for the branching fraction ratio gives

$$\frac{\mathcal{B}(D^+)}{\mathcal{B}(D_s) \times \mathcal{B}(\phi)} = 0.17 \pm 0.07 \pm 0.05$$

where the first uncertainty is statistical and the second is systematic. Finally, using the PDG values for the two branching fractions in the denominator yields

$$\mathcal{B}(D^+) = (1.75 \pm 0.7 \pm 0.5) \times 10^{-6}.$$

The SM expectation for this branching fraction is 1.77×10^{-6}.

The search for the continuum decay of $D^+ \to \pi^+\mu^+\mu^-$ is conducted by limiting the $\mu^+\mu^-$ invariant mass to $0.2 < m(\mu^+\mu^-) < 0.96$ GeV/c^2 and $0.96 < m(\mu^+\mu^-) < 1.76$ GeV/c^2. The Monte Carlo is used to reoptimize the selection criteria to look for this decay, and chosen to be $\mathcal{I}_D > 0.71$, $S_D < 9.4$, $\Theta_D < 7$ mrad, $S_\pi > 1.8$, and $\mathcal{M} < 2.6$. With these cuts, 17 candidate events are found in the D^+ mass region, while 20.9 ± 3.4 background events are expected from the Monte Carlo, as shown in Fig. 2.

Using Eq. 1, but substituting the continuum decay $D^+ \to \pi^+\mu^+\mu^-$ for the resonant decay $D^+ \to \phi\pi^+ \to \pi^+\mu^+\mu^-$ gives

$$\frac{\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(D_s) \times \mathcal{B}(\phi)} < 0.46 \quad 90\% \text{ CL}.$$

Again, using the world average values for the branching fractions in the denominator yields

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 4.7 \times 10^{-6} \quad 90\% \text{ CL}$$

for the continuum ϕ decay.

3. FCNC in the Bottom Sector

3.1. *Search for $B_s^0 \to \mu^+\mu^-$*

Standard model predictions of the braching fraction for the decays $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ are $\mathcal{B}(B_s^0 \to \mu^+\mu^- = (3.42 \pm 0.54) \times 10^{-9}$ and $\mathcal{B}(B_d^0 \to \mu^+\mu^- =$

$(1.00 \pm 0.14) \times 10^{-10}$. Extensions to the SM, such as type-II two Higgs Doublet models,[5] minimum supersymmetric models,[6] minimal SO(10),[7,8] and minimal supergravity,[9] can greatly enhance the expected cross section.

About 300 pb^{-1} of data have been analyzed, and the sensitivity on the branching fraction limit has been determined for 700 pb^{-1}. The invariant mass side bands are used to determine the background, and a Monte Carlo simulation is used to determine the selection criteria without looking at the data in the signal region. That is, a blind analysis is done to avoid any possible bias in determining the selection criteria. The selection criteria used are that each muon candidate must have $p_T > 2.5$ GeV/c and $|\eta| < 2$, the χ^2 of the two track vertex must be less than 10, the B_s candidate must have $p_T > 5$ GeV/c, and the two dimensional decay length in the plane transverse to the beam line must have an uncertaintly less than 0.15 mm. Finally, the signal is further optimized by selecting on the collinearity angle, the significance of the decay length, and the isolation of the muon pair.

In the absence of an apparent signal, a limit on the branching fraction $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ can be computed by normalizing the upper limit on the number events in the B_s^0 region to the number of reconstructed $B^\pm \to J/\psi K^\pm$ events using

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq \frac{N_{\rm ul}}{N_{B^\pm}} \cdot \frac{\epsilon^{B^\pm}_{\mu\mu K}}{\epsilon^{B_s^0}_{\mu\mu}} \cdot \frac{\mathcal{B}(B^\pm)}{\mathcal{A}}$$

where $N_{\rm ul}$ is the upper limit on the number of signal decays, $N_{B^\pm}$ is the observed number of $B^\pm$ events decaying to $J/\psi K^\pm$, $\epsilon^{B^\pm}_{\mu\mu K}$ and $\epsilon^{B_s^0}_{\mu\mu}$ are the efficiencies of the signal and normalization channels, respectively, $\mathcal{B}(B^\pm)$ is the branching fraction for the decay $B^\pm \to J/\psi K^\pm$ when the J/ψ decays to a pair of muons, and

$$\mathcal{A} = \frac{f_{b\to B_s}}{f_{b\to B_{u,d}}} + R \cdot \frac{\epsilon^{B_d^0}_{\mu\mu}}{\epsilon^{B_s^0}_{\mu\mu}}$$

where $f_{b\to B_s}/f_{b\to B_{u,d}}$ is the ratio of mesons produced in the fragmentation, $R = \mathcal{B}(B_d)/\mathcal{B}(B_s)$ which is approximately equal to zero due to the small value of $|V_{td}|/|V_{ts}|$, and $\epsilon^{B_d^0}_{\mu\mu}/\epsilon^{B_s^0}_{\mu\mu}$ is the ratio of the detection efficiencies for the two mesons.

In the initial 300 pb^{-1} of data, four events were observed in the signal region with 4.3 ± 1.2 expected from the Monte Carlo. Using the Feldman-Cousins scheme,[10] this gives a branching fraction limit of

$$\mathcal{B}(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-7} \quad 95\%\text{CL}.$$

The expected 95% confidence limit sensitivity for the total data set of 700 pb^{-1} is 1.9×10^{-7}.

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

The SM predictions of the braching fraction for the decay $B_s^0 \to \phi J/\psi$ neglecting the interference effects with the much stronger $B_s^0 \to \phi\mu^+\mu^-$ and $B_s^0 \to \phi\psi(2S)$ resonance decays, is predicted to be of the order of 1.6×10^{-6}.[11] Observation of this decay, or an experimental upper limit, can yield important information on the dynamics of FCNC.

This analysis uses about 450 pb^{-1} of data. The selection criteria are similar to thos used in the $B_s^0 \to \mu^+\mu^-$ analysis. In addition, a 5σ mass region, $0.5 < m(\mu\mu) < 4.4$ GeV/c^2, around the J/ψ and $\psi(2S)$ is excluded from the analysis. The ϕ meson is required to decay to a K^+K^- pair with each K meson having $p_T > 0.7$ GeV/c and a ϕ invariant mass of $1.008 < m(K^+K^-) < 1.032$ GeV/c^2. In order to avoid biasing the result, all selection criteria are determined before the signal region in the data is examined.

In the absence of an apparent signal, a limit on the branching fraction $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$ can be computed by normalizing the upper limit on the number events in the B_s^0 region to the number of reconstructed $B_s \to J/\psi\phi$, shown in Fig. 3, using the latter as a reference mode.

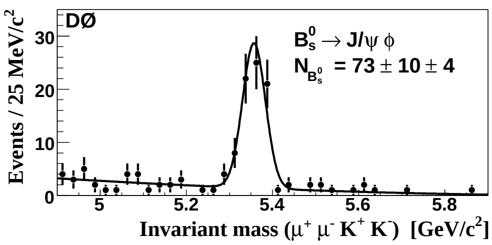

Fig. 3. Reconstructed mass for the decay $B_s \to J/\psi\phi$.

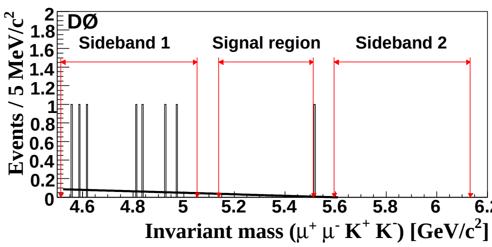

Fig. 4. The invariant mass distribution for $B_s \to \phi\mu^+\mu^-$ after all selection criteria.

Figure 4 shows the signal region in the data. There are no events in the signal region with an expected background of 1.6±0.4 events.

An upper limit is extracted using the ratio

$$\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = \frac{N_{\rm ul}}{N_{B_s^0}} \cdot \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu\mu}} \cdot \mathcal{B}(J/\psi)$$

where $\mathcal{B}(J/\psi)$ is the branching fraction for the decay $J/\psi \to \mu^+\mu^-$. The 95% CL result is

$$\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} < 4.4 \times 10^{-3}$$

Using the world average for $\mathcal{B}(B_s^0 \to J/\psi\phi)$, we determine that at the 95% CL

$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) < 4.1 \times 10^{-6}$$

which is within a factor of 3 from the SM expectation.

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