Search for Flavor-Changing-Neutral-Current $D$ Meson Decays

We study the flavor-changing-neutral-current process $c \rightarrow u \mu^+ \mu^-$ using 1.3 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the D0 detector operating at the Fermilab Tevatron Collider. We see clear indications of the charged-current mediated $D_s^-$ and $D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ final states with significance greater than 4 standard deviations above background for the $D^+$ state. We search for the continuum...
neutral-current decay of $D^+ \to \pi^+ \mu^+ \mu^-$ in the dimuon invariant mass spectrum away from the $\phi$ resonance. We see no evidence of signal above background and set a limit of $B(D^+ \to \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}$ at the 90% C.L. This limit places the most stringent constraint on new phenomena in the $c \to u \mu^+ \mu^-$ transition.

Many extensions of the standard model (SM) provide a mechanism for flavor-changing-neutral-current (FCNC) decays of beauty, charmed, and strange hadrons that could significantly alter the decay rate with respect to SM expectations. Since FCNC processes are forbidden at tree-level in the SM, new physics effects could become visible in FCNC processes if the new amplitudes are larger than the higher-order penguin and box diagrams that mediate FCNC decays in the SM. In $B$ meson decays, the experimental sensitivity has reached the SM expected rates for many FCNC processes. In contrast, Glashow-Higgs-Maiani mechanism suppression [1] in $D$ meson decays is significantly stronger and the SM branching fractions are expected to be as low as $10^{-9}$ [2,3]. This leaves a large window of opportunity still available to search for new physics in charm decays. There are several models of new phenomena such as SUSY $R$-parity violation in a single coupling scheme [2] that lead to a tree-level interaction mediated by new particles, or little Higgs models with a new uplike vector quark [4] that lead to direct FCNC FCNC processes if the new amplitudes are larger than the SM. In both scenarios deviations from the SM might only be seen in the up-type quark sector, motivating the extension of experimental studies of FCNC processes to the charm sector.

In this Letter we report on a study of FCNC charm decays including the first observation of the charged-current decay $D_{s(j)}^+ \to \phi \pi^+ \to \mu^+ \bar{\mu}^- \pi^+$ and the first evidence for the charged-current decay $D^+ \to \phi \pi^+ \to \mu^+ \bar{\mu}^- \pi^+$ by requiring a dimuon mass window around the nominal $\phi$ mass. The inclusion of charge conjugate modes is implied throughout the text. At the reported level of statistics, we expect no contributions from two body $D_{s(j)}^+$ decays due to the smaller $D_{s(j)}^+ \to \eta, \rho,$ and $\omega$ branching fractions and the smaller $\eta, \rho,$ and $\omega$ ${\mu^+ \mu^-}$ branching fractions [5]. The search for the neutral-current $c \to u \mu^+ \mu^-$ transition in the decay $D^+ \to \pi^+ \mu^+ \mu^-$ is performed in the continuum region of the dimuon invariant mass spectrum below and above the $\phi$ resonance. We focus on the $D^+$ continuum decay as opposed to similar $D_s^+$ or $\Lambda_c$ decays due to the longer lifetime and higher production fraction of the $D^+$ meson. The study uses a data sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV corresponding to an integrated luminosity of approximately 1.3 fb$^{-1}$ recorded by the D0 detector operating at the Fermilab Tevatron Collider. All analyzed events are collected using a suite of dimuon triggers. Similar studies have recently been published by the FOCUS [6] and CLEO-c [7] collaborations, and preliminary results have been presented by the BABAR [8] collaboration.

D0 is a general purpose detector described in detail in Ref. [9]. Charged particles are reconstructed using a silicon vertex tracker and a scintillating fiber tracker located inside a superconducting solenoidal coil that provides a magnetic field of approximately 2 T. The tracking volume is surrounded by a LAr-U calorimeter. Muons are reconstructed using a spectrometer consisting of magnetized iron toroids and three superlayers of proportional tubes and plastic trigger scintillators located outside the calorimeter.

The selection requirements are determined using PYTHIA [10] Monte Carlo (MC) events to model both $c\bar{c}$ and $b\bar{b}$ production and fragmentation. The EVTGEN [11] MC program is used to decay prompt $D$ mesons and secondary $D$ mesons from $B$ meson decay into the $\phi \pi^+$ and $\mu^+ \bar{\mu}^- \pi^+$ intermediate and final states. The detector response is modeled using a GEANT [12] based MC program. The dimuon trigger is modeled using a detailed simulation program incorporating all aspects of the trigger logic. Backgrounds are modeled using data in the mass sideband regions around the $D$ meson mass of $1.4 < m(\pi^+ \mu^+ \mu^-) < 1.6$ GeV/$c^2$ and $2.2 < m(\pi^+ \mu^+ \mu^-) < 2.4$ GeV/$c^2$.

Muon candidates are required to have segments reconstructed in at least two out of the three muon system superlayers and to be associated with a track reconstructed with hits in both the silicon and fiber trackers. We require that the muon transverse momentum $p_T$ is greater than 2 GeV/c and the total momentum $p$ is greater than 3 GeV/c. The dimuon system is formed by combining two oppositely charged muon candidates that are associated with the same track jet [13], form a well-reconstructed vertex, and have an invariant mass $m(\mu^+ \mu^-)$ below 2 GeV/$c^2$. The dimuon mass distribution in the region of the light quark-antiquark resonances is shown in Fig. 1. Maxima corresponding to the production of $\omega$ and $\phi$ mesons are seen. The $\rho$ is observed as a broad structure beneath the $\omega$ peak, and there is some indication of $\eta$ production as well. For the initial search for resonance dimuon production we require the $\mu^+ \mu^-$ mass to be within $\pm 0.04$ GeV/$c^2$ of the nominal $\phi$ mass and reenumerate the muon momenta with a $\phi$ mass constraint imposed [5] which improves the $\mu^+ \mu^- \pi^+$ invariant mass resolution by 33%.

Candidate $D_{s(j)}^+$ mesons are formed by combining the dimuon system with a track that is associated with the same track jet as the dimuon system, has hits in both the silicon and fiber trackers, and has $p_T > 0.18$ GeV/c. The pion impact parameter significance $S_{\pi}$, defined as the point of closest approach of the track helix to the interaction

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point in the transverse plane relative to its error, is required to be greater than 0.5. The invariant mass of the three body system must be in the range $1.4 \text{ GeV}/c^2 < m(\pi^+ \mu^+ \mu^-) < 2.4 \text{ GeV}/c^2$. The three particles must form a well-reconstructed $D$ meson candidate vertex displaced from the primary vertex. The transverse flight length significance $S_D$, defined as the transverse distance of the reconstructed $D$ vertex from the primary vertex normalized to the error in the reconstructed flight length, is required to be greater than 5. The collinearity angle $\Theta_D$, defined as the angle between the $D$ momentum vector and the position vector pointing from the primary to the secondary vertex, is required to be less than 500 mrad. In events with multiple $p\bar{p}$ collisions, the longitudinal track impact parameters are used to reject muons and tracks produced in the secondary $p\bar{p}$ interactions. In events with multiple $D$ candidates, the best candidate is chosen based on the $\chi^2_{3\mu}$ of the three track vertex and the angular separation between the pion and the dimuon system in $\eta$-$\phi$ space, $(\Delta R_\eta)^2 = (\Delta \eta)^2 + (\Delta \phi)^2$, which is typically small for true candidates.

The resulting $\pi^+ \mu^+ \mu^-$ invariant mass distribution is shown in Fig. 2. The $D_{(s)}^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ signal is extracted from a binned likelihood fit to the data assuming possible contributions from $D^+$ and $D_s^+$ initial states as signal and from combinatoric background. The $D_s^+$ component is modeled by a Gaussian function with the mean and standard deviation as free parameters. The $D^+$ component is modeled as a Gaussian function. The difference in means between the $D^+$ and $D_s^+$ Gaussian functions is constrained by the known mass difference and the ratio of the standard deviations is constrained to the ratio of masses $[5]$. The background is modeled as an exponential function with floating parameters. The normalization of all functions are free parameters. The fit yields $254 \pm 36 D_s^+$ candidates and $115 \pm 31 D^+$ candidates. The statistical significance of the combined $D_s^+$ and $D^+$ signal is 8 standard deviations above background. The significance of the $D^+$ yield, treating both the combinatorial and $D_s^+$ candidates as background, is 4.1 standard deviations.

The relative efficiency of the $D^+$ and $D_s^+$ channels is determined separately for prompt $D$ mesons produced in direct $p\bar{p} \rightarrow c\bar{c} + X$ processes and $D$ mesons from $B$ meson decay and combined using the measured prompt fractions $[14]$ $\epsilon^D = f^p_\text{prompt} + (1 - f^p_\text{prompt}) \epsilon^0_{B \rightarrow D}$, where $\epsilon^D_{\text{prompt}}$ is the efficiency for prompt $D^+$ mesons, $\epsilon^0_{B \rightarrow D}$ is the efficiency for $D^+$ mesons from $B$ meson decay, and $f^p_\text{prompt}$ is the fraction of prompt $D^+$ mesons; we use equivalent expressions for $D_s^+$ mesons. The yield ratio is related to the ratio of branching fractions by

$$n(D^+) = f^+_{c \rightarrow D} f^p_\text{prompt} \epsilon^D B(D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+)$$

$$n(D_s^+) = f^+_{c \rightarrow D} f^p_\text{prompt} \epsilon^D B(D_s^+ \rightarrow \phi \pi^+) B(\phi \rightarrow \mu^+ \mu^-),$$

where $f^+_{c \rightarrow D}$ is the fraction of $D^+$ mesons produced in $c$ quark fragmentation, and $f^+_{c \rightarrow D}$ is the equivalent fraction for $D_s^+$ mesons $[15]$. We use $f^p_\text{prompt} = 0.891 \pm 0.004 [14]$, $f^p_\text{prompt} = 0.773 \pm 0.038 [14]$, and $f^p_{c \rightarrow D} / f^+_{c \rightarrow D} = 0.40 \pm 0.09 [15]$. The efficiency ratio is determined from MC calculations to be $\epsilon^D / \epsilon^0 = 0.70 \pm 0.06$ (stat + syst). The difference from unity is caused by the lifetime difference between $D^+_s$ ($\tau = 147.0 \mu\text{m}$) and $D^+$ ($\tau = 311.8 \mu\text{m}$) mesons, and the systematic uncertainty is dominated by uncertainties in the resolution modeling of $S_D$ and $S_\pi$. 

![FIG. 1 (color online). The inclusive $m(\mu^+ \mu^-)$ invariant mass spectrum. The fitting function includes components from the $\eta$, $\rho$, $\omega$, and $\phi$ resonances.](image1)

![FIG. 2 (color online). The $m(\pi^+ \mu^+ \mu^-)$ mass spectrum in the 0.98 < $m(\mu^+ \mu^-) < 1.06 \text{ GeV}/c^2$ $\phi$ mass window. The result of a binned likelihood fit to the distribution including contributions for $D^+$, $D_s^+$, and combinatoric background is overlaid on the histogram.](image2)
Using the efficiency ratio, production fractions, and the $D_s^+ \rightarrow \phi \pi^+$ and $\phi \rightarrow \mu^+ \mu^-$ branching fractions gives $B(D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+) = (1.8 \pm 0.5 \text{(stat)} \pm 0.6 \text{(syst)}) \times 10^{-6}$, which is consistent with the expected value of $(1.86 \pm 0.26) \times 10^{-6}$ given by the product of the $D^+ \rightarrow \phi \pi^+$ and $\phi \rightarrow \mu^+ \mu^-$ branching fractions and other recent measurements [7,8]. The systematic uncertainty is overwhelmingly dominated by the uncertainty in the $\nu$ ground estimation from variation in the background shape [4].

We now turn to the search for the continuum decay of $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ mediated by FCNC interactions. We study the dimuon invariant mass region below 1.8 GeV/$c^2$, excluding $0.96 < m(\mu^+ \mu^-) < 1.08$ GeV/$c^2$. Backgrounds are further reduced by requiring $S_D > 9.4$, $S_p > 1.8$, $\Theta_D < 7 \text{ mrad}$, $\chi_{\text{vis}}^{2} < 2.6$ (for 3 DOF), and $\Delta R_{\pi} < 2.6$. We also require the pion transverse momentum $p_T(\pi)$ be greater than 0.4 GeV/c and the isolation, defined as $I_D = p(D) / \sum p_{\text{cone}}$ where the sum is over tracks in a cone centered on the $D$ meson of radius $\Delta R = 1$ be greater than 0.7. The final requirements are chosen using a random grid search [16] optimized using the Punzi [17] criteria to give the optimal 90\% C.L. upper limit.

The final $\pi^+ \mu^+ \mu^-$ invariant mass distribution in data is shown in Fig. 3. The $D^+$ signal region contains 19 events. The combinatorial background in the signal region is estimated by performing sideband extrapolations to be $25.8 \pm 4.6$ events. The uncertainty reflects the range in the background estimation from variation in the background shape across the $\pi^+ \mu^+ \mu^-$ mass spectrum. The probability of the background fluctuating to fewer events than observed, including the systematic uncertainty on the background prediction, is 14\%.

We normalize the results to the $D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ signal instead of the larger $D_s^+$ signal to avoid the uncertainties associated with the $D^+$ and $D_s^+$ production fractions. We use the product of the known $D^+ \rightarrow \phi \pi^+$ and $\phi \rightarrow \mu^+ \mu^-$ branching fractions [5]. The signal efficiency ratio between the $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ channel in the final sample and the $D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ channel in the preselection samples is determined from MC calculations to be $(5.4 \pm 0.8)\%$. The inputs to the limit calculation are summarized in Table I. The systematic uncertainty is dominated by the modeling of the vertex resolution particularly in the $\chi_{\text{vis}}^{2}$ requirement. The systematic uncertainty from the vertex resolution is determined by varying the resolution in MC calculations by $\pm 20\%$ and recomputing the efficiency ratio. The range is taken from studies of the resolution in several $b$ hadron lifetime and mixing parameter measurements [18]. Using this, we find

$$\frac{B(D^+ \rightarrow \pi^+ \mu^+ \mu^-)}{B(D^+ \rightarrow \phi \pi^+) \times B(\phi \rightarrow \mu^+ \mu^-)} < 2.09, 90\% \text{C.L.}$$

The limit is determined using a Bayesian technique [19]. Using the central value of $D^+ \rightarrow \phi \pi^+$ and $\phi \rightarrow \mu^+ \mu^-$ branching fractions gives

$$B(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}, 90\% \text{C.L.}$$

This is approximately 30\% below the limit one would expect to set given an expected background of $25.8 \pm 4.6$ events. The single event sensitivity, given by the branching fraction one would derive based on one observed signal candidate, is $3.0 \times 10^{-7}$.

In conclusion, we have performed a detailed study of $D^+$ and $D_s^+$ decays to the $\pi^+ \mu^+ \mu^-$ final state. We clearly observe the $D_s^+ \rightarrow \phi \pi^+$ intermediate state and see evidence for the $D^+ \rightarrow \phi \pi^+$ intermediate state. The branching fraction for the $D^+ \rightarrow \phi \pi^+ \rightarrow \pi^+ \mu^+ \mu^-$ final state is consistent with the product of $D^+ \rightarrow \phi \pi^+$ and $\phi \rightarrow \mu^+ \mu^-$ branching fractions. We have performed a search for the continuum decay of $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ by excluding the region of the dimuon invariant mass spectrum around the $\phi$. We see no evidence of signal above background and set a limit of $B(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}$ at the 90\% C.L. This is the most stringent limit to date in a decay

![FIG. 3 (color online). Final $\pi^+ \mu^+ \mu^-$ invariant mass spectrum. The ±2σ $D^+$ signal region, within the dashed lines, contains 19 events. The background level determined from the sidebands is $25.8 \pm 4.6$ events.](image-url)

<table>
<thead>
<tr>
<th>TABLE I.</th>
<th>Inputs to the $B(D^+ \rightarrow \pi^+ \mu^+ \mu^-)$ upper limit calculation and resulting upper limit at the 90% and 95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow \pi^+ \mu^+ \mu^-$ yield</td>
<td>19 events</td>
</tr>
<tr>
<td>Background expectation</td>
<td>$25.8 \pm 4.6$ events</td>
</tr>
<tr>
<td>$D^+ \rightarrow \phi \pi^+ \rightarrow \pi^+ \mu^+ \mu^-$ Yield</td>
<td>$115 \pm 51$ events</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>$0.054 \pm 0.008$</td>
</tr>
<tr>
<td>$B(D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+)$</td>
<td>$1.86 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B(D^+ \rightarrow \pi^+ \mu^+ \mu^-)$ 90% (95%) C.L.</td>
<td>$&lt;3.9(6.1) \times 10^{-6}$</td>
</tr>
</tbody>
</table>
mediated by a $c \rightarrow u \mu^+ \mu^-$ transition. Although this is approximately 500 times above the SM expected rate, it already reduces the allowed parameter space of the product of SUSY R-parity violating couplings $\lambda_{221}^r \times \lambda_{211}^r$ [2]. However, it is still an order of magnitude above the expected level from little Higgs models [4].

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[15] S. Chekanov et al. (ZEUS Collaboration), Eur. Phys. J. C 44, 351 (2005). We rescale the values to be consistent with the $D^+ \rightarrow K^+ \pi^+ \pi^-$ and $D_s^+ \rightarrow \phi \pi^+$ branching fractions in Ref. [5].