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

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We study the flavor-changing-neutral-current process $c \to u\mu^+\mu^-$ 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 $D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ 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 ϕ resonance. We see no evidence of signal above background and set a limit of $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$ at the 90% C.L. This limit places the most stringent constraint on new phenomena in the $c \to u\mu^+\mu^-$ transition.

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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-Iliopoulos-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 $Z \to cu$ couplings. 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 $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ and the first evidence for the charged-current decay $D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ by requiring a dimuon mass window around the nominal ϕ 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 $D_{(s)}^+$ decays due to the smaller $D_{(s)}^+ \to \eta$, ρ, and ω branching fractions and the smaller η, ρ, and $\omega \to \mu^+\mu^-$ 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 ϕ resonance. We focus on the D^+ continuum decay as opposed to similar D_s^+ or Λ_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 $\mu^+\mu^-\pi^+$ 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 ω and ϕ mesons are seen. The ρ is observed as a broad structure beneath the ω peak, and there is some indication of η production as well. For the initial search for resonance dimuon production we require the $\mu^+\mu^-$ mass be within ± 0.04 GeV$/c^2$ of the nominal ϕ mass and redetermine the muon momenta with a ϕ mass constraint imposed [5] which improves the $\mu^+\mu^-\pi^+$ invariant mass resolution by 33%.

Candidate $D_{(s)}^+$ 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 $\mathcal{S}_\pi$, defined as the point of closest approach of the track helix to the interaction

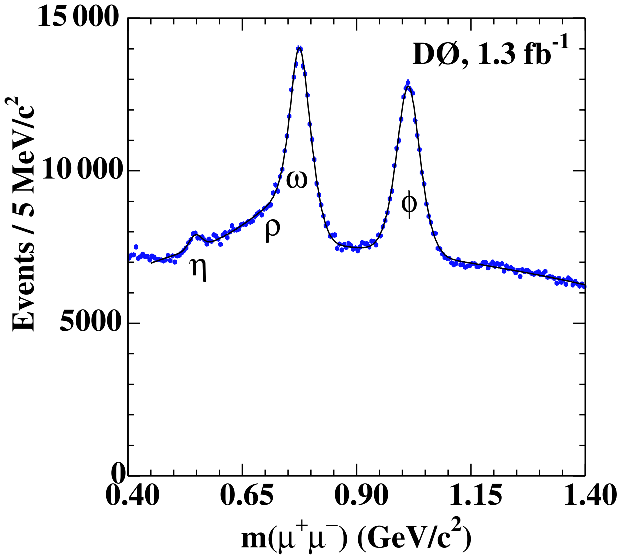

FIG. 1 (color online). The inclusive $m(\mu^+\mu^-)$ invariant mass spectrum. The fitting function includes components from the η, ρ, ω, and ϕ resonances.

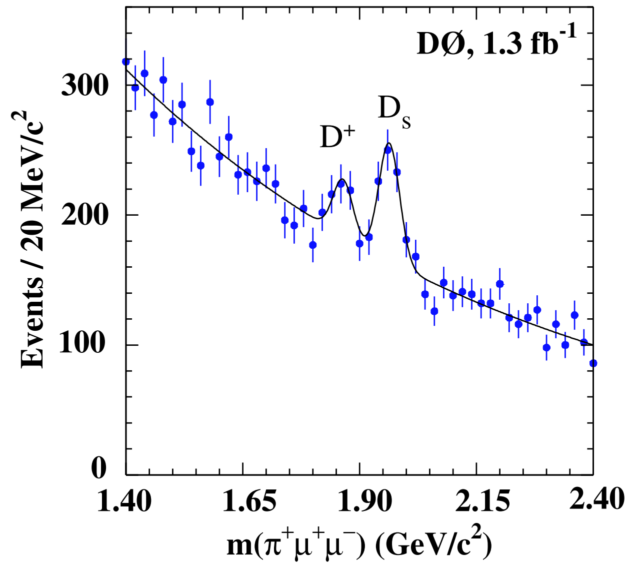

FIG. 2 (color online). The $m(\pi^+\mu^+\mu^-)$ mass spectrum in the $0.98 < m(\mu^+\mu^-) < 1.06$ GeV/c^2 ϕ mass window. The result of a binned likelihood fit to the distribution including contributions for D^+, D_s^+, and combinatoric background is overlaid on the histogram.

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 GeV/c^2 < $m(\pi^+\mu^+\mu^-) < 2.4$ 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 $\mathcal{S}_D$, 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 Θ_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 $\chi^2_{\rm vtx}$ of the three track vertex and the angular separation between the pion and the dimuon system in η-ϕ space, $(\Delta R_\pi)^2 = (\Delta\eta)^2 + (\Delta\phi)^2$, which is typically small for true candidates.

The resulting $\pi^+\mu^+\mu^-$ invariant mass distribution is shown in Fig. 2. The $D^+_{(s)} \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ 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 ± 36 D_s^+ candidates and 115 ± 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 $p\bar{p} \to c\bar{c} + X$ processes and D mesons from B meson decay and combined using the measured prompt fractions [14] $\epsilon^+ = f_p^+\epsilon^+_{\rm prompt} + (1 - f_p^+)\epsilon^+_{B\to D}$, where $\epsilon^+_{\rm prompt}$ is the efficiency for prompt D^+ mesons, $\epsilon^+_{B\to D}$ is the efficiency for D^+ mesons from B meson decay, and f_p^+ 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

$$\frac{n(D^+)}{n(D_s^+)} = \frac{f^+_{c\to D}}{f^s_{c\to D}}\frac{f^s_p}{f^+_p}\frac{\epsilon^+}{\epsilon^s}\frac{\mathcal{B}(D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)}{\mathcal{B}(D_s^+ \to \phi\pi^+)\mathcal{B}(\phi \to \mu^+\mu^-)},$$

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

Using the efficiency ratio, production fractions, and the $D_s^+ \to \phi\pi^+$ and $\phi \to \mu^+\mu^-$ branching fractions gives $\mathcal{B}(D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+) = (1.8 \pm 0.5(\text{stat}) \pm 0.6(\text{syst})) \times 10^{-6}$, which is consistent with the expected value of $(1.86 \pm 0.26) \times 10^{-6}$ given by the product of the $D^+ \to \phi\pi^+$ and $\phi \to \mu^+\mu^-$ branching fractions and other recent measurements [7,8]. The systematic uncertainty is overwhelmingly dominated by the uncertainty in the $D_s^+ \to \phi\pi^+$ branching fraction that enters both the normalization and $f^s_{c\to D}$.

We now turn to the search for the continuum decay of $D^+ \to \pi^+\mu^+\mu^-$ 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 $\mathcal{S}_D > 9.4$, $\mathcal{S}_\pi > 1.8$, $\Theta_D < 7$ mrad, $\chi^2_{\text{vtx}} < 2.6$ (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 ± 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%.

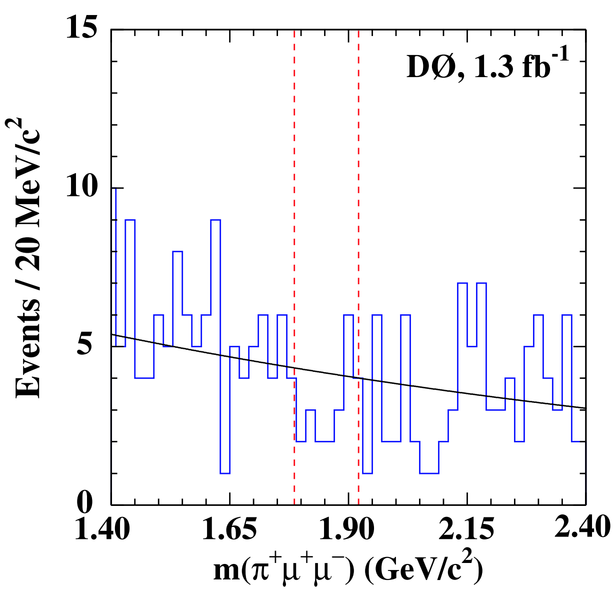

FIG. 3 (color online). Final $\pi^+\mu^+\mu^-$ invariant mass spectrum. The $\pm 2\sigma$ D^+ signal region, within the dashed lines, contains 19 events. The background level determined from the sidebands is 25.8 ± 4.6 events.

We normalize the results to the $D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ 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 $D^+ \to \phi\pi^+$ and $\phi \to \mu^+\mu^-$ branching fractions [5]. The signal efficiency ratio between the $D^+ \to \pi^+\mu^+\mu^-$ channel in the final sample and the $D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ 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 χ^2_{vtx} 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

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

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

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

This is approximately 30% below the limit one would expect to set given an expected background of 25.8 ± 4.6 events. The single event sensitivity, given by the branching fraction one would derive based on one observed signal candidate, is 3.0×10^{-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 $D_s^+ \to \phi\pi^+$ intermediate state and see evidence for the $D^+ \to \phi\pi^+$ intermediate state. The branching fraction for the $D^+ \to \phi\pi^+ \to \pi^+\mu^+\mu^-$ final state is consistent with the product of $D^+ \to \phi\pi^+$ and $\phi \to \mu^+\mu^-$ branching fractions. We have performed a search for the continuum decay of $D^+ \to \pi^+\mu^+\mu^-$ by excluding the region of the dimuon invariant mass spectrum around the ϕ. We see no evidence of signal above background and set a limit of $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$ at the 90% C.L. This is the most stringent limit to date in a decay

TABLE I. Inputs to the $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$ upper limit calculation and resulting upper limit at the 90% and 95% C.L.

$D^+ \to \pi^+\mu^+\mu^-$ yield	19 events
Background expectation	25.8 ± 4.6 events
$D^+ \to \phi\pi^+ \to \pi^+\mu^+\mu^-$ Yield	115 ± 31 events
Relative efficiency	0.054 ± 0.008
$\mathcal{B}(D^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)$	1.86×10^{-5}
$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$ 90% (95%) C.L.	$<3.9(6.1) \times 10^{-6}$

mediated by a $c \to u\mu^+\mu^-$ 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 $\lambda'_{22k} \times \lambda'_{21k}$ [2]. However, it is still an order of magnitude above the expected level from little Higgs models [4].

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¶Deceased.

[1] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970).
[2] G. Burdman, E. Golowich, J. A. Hewett, and S. Pakvasa, Phys. Rev. D **66**, 014009 (2002).
[3] S. Fajfer, S. Prelovsek, and P. Singer, Phys. Rev. D **64**, 114009 (2001).
[4] S. Fajfer and S. Prelovsek, Phys. Rev. D **73**, 054026 (2006).
[5] W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
[6] J. M. Link *et al.* (FOCUS Collaboration), Phys. Lett. B **572**, 21 (2003).
[7] Q. He *et al.* (CLEO Collaboration), Phys. Rev. Lett. **95**, 221802 (2005).
[8] B. Aubert *et al.* (*BABAR* Collaboration), hep-ex/0607051, submitted to the Proceedings of ICHEP2006.
[9] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods A **565**, 463 (2006).
[10] T. Sjostrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).
[11] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).
[12] R. Brun, F. Bruyant, M. Maire, A. C. McPherson, and P. Zanarini, CERN Report No. CERN DD/EE/84-1, 1987.
[13] All charged particles in the event are clustered into jets using the DURHAM clustering algorithm with the p_T cutoff parameter of 15 GeV/c. S. Catani *et al.*, Phys. Lett. B **269**, 432 (1991).
[14] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **91**, 241804 (2003).
[15] S. Chekanov *et al.* (ZEUS Collaboration), Eur. Phys. J. C **44**, 351 (2005). We rescale the values to be consistent with the $D^+ \to K^+\pi^+\pi^-$ and $D_s^+ \to \phi\pi^+$ branching fractions in Ref. [5].
[16] N. Amos *et al.*, in *Proceedings of Computing in High Energy Physics (CHEP'95)*, edited by R. Shellard and T. Nguyen (World Scientific, River Edge, NJ, 1996), p. 215.
[17] G. Punzi, in *Proceedings of the Conference on Statistical Problems in Particle Physics, Astrophysics and Cosmology (Phystat 2003)*, edited by L. Lyons *et al.* (SLAC, Menlo Park, CA, 2003), p. 79.
[18] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **97**, 021802 (2006); V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **98**, 121801 (2007).
[19] I. Bertram *et al.*, FERMILAB Report No. FERMILAB-TM-2104, 2000.