

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

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We study the flavor-changing-neutral-current process $c \rightarrow u\mu^+\mu^-$ using 1.3 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ 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 $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ in the dimuon invariant mass spectrum away from the ϕ resonance. We see no evidence of signal above background and set a limit of $\mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}$ at the 90% C.L. This limit places the most stringent constraint on new phenomena in the $c \rightarrow u \mu^+ \mu^-$ 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 $Z \rightarrow cu$ 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 $D_s^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ and the first evidence for the charged-current decay $D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ 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 $D_{(s)}^+ \rightarrow \eta, \rho,$ and ω branching fractions and the smaller $\eta, \rho,$ and $\omega \rightarrow \mu^+ \mu^-$ branching fractions [5]. The search for the neutral-current $c \rightarrow u \mu^+ \mu^-$ transition in the decay $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ 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 $1.4 < m(\pi^+ \mu^+ \mu^-) < 1.6 \text{ GeV}/c^2$ and $2.2 < m(\pi^+ \mu^+ \mu^-) < 2.4 \text{ GeV}/c^2$.

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 $2 \text{ GeV}/c$ and the total momentum p is greater than $3 \text{ GeV}/c$. 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 $2 \text{ GeV}/c^2$. 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 $\pm 0.04 \text{ GeV}/c^2$ 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 $p_T > 0.18 \text{ GeV}/c$. The pion impact parameter significance \mathcal{S}_π , defined as the point of closest approach of the track helix to the interaction

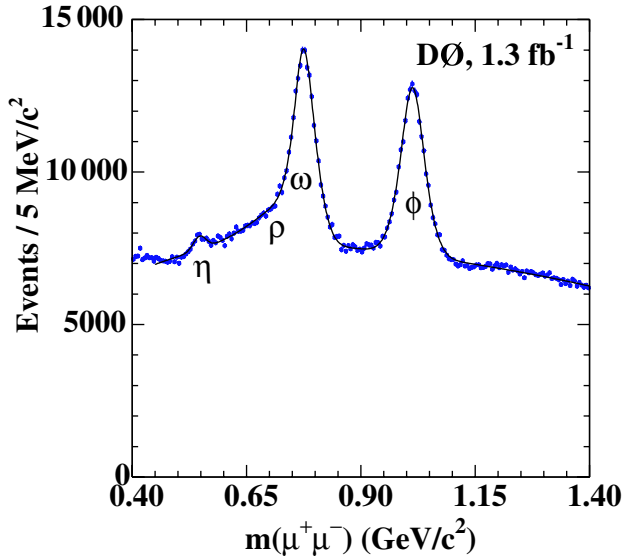


FIG. 1 (color online). The inclusive $m(\mu^+\mu^-)$ invariant mass spectrum. The fitting function includes components from the η , ρ , ω , and ϕ resonances.

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 \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 $\chi^2_{\text{ vtx}}$ 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 $D_{(s)}^+ \rightarrow \phi\pi^+ \rightarrow \mu^+\mu^-\pi^+$ 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

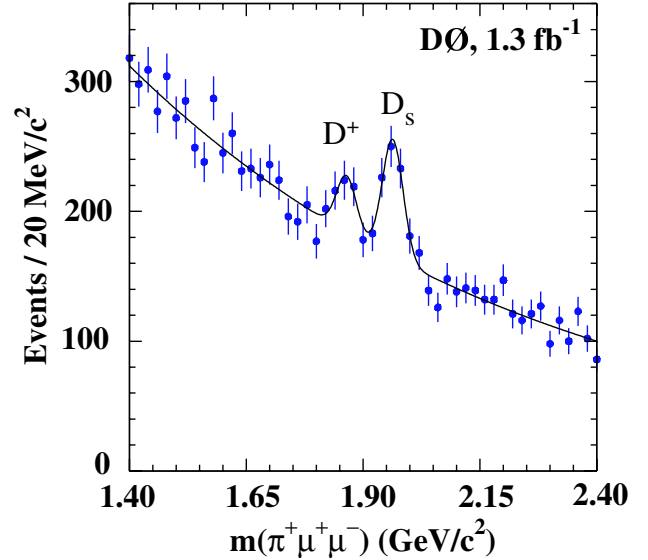


FIG. 2 (color online). The $m(\pi^+\mu^+\mu^-)$ mass spectrum in the $0.98 < m(\mu^+\mu^-) < 1.06 \text{ GeV}/c^2$ ϕ mass window. The result of a binned likelihood fit to the distribution including contributions for D^+ , D_s^+ , and combinatoric background is overlaid on the histogram.

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 meson from B meson decay and combined using the measured prompt fractions [14] $\epsilon^+ = f_p^+ \epsilon_{\text{prompt}}^+ + (1 - f_p^+) \epsilon_{B \rightarrow D}^+$, where $\epsilon_{\text{prompt}}^+$ is the efficiency for prompt D^+ mesons, $\epsilon_{B \rightarrow D}^+$ 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

$$\frac{n(D^+)}{n(D_s^+)} = \frac{f_{c \rightarrow D}^+}{f_{c \rightarrow D}^s} \frac{f_p^s}{f_p^+} \frac{\epsilon^+}{\epsilon^s} \frac{\mathcal{B}(D^+ \rightarrow \phi\pi^+ \rightarrow \mu^+\mu^-\pi^+)}{\mathcal{B}(D_s^+ \rightarrow \phi\pi^+) \mathcal{B}(\phi \rightarrow \mu^+\mu^-)},$$

where $f_{c \rightarrow D}^+$ is the fraction of D^+ mesons produced in c quark fragmentation, and $f_{c \rightarrow D}^s$ 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 $f_{c \rightarrow D}^s/f_{c \rightarrow D}^+ = 0.40 \pm 0.09$ [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^+ ($c\tau = 147.0 \mu\text{m}$) and D^+ ($c\tau = 311.8 \mu\text{m}$) mesons, and the systematic uncertainty is dominated by uncertainties in the resolution modeling of \mathcal{S}_D and \mathcal{S}_π .

Using the efficiency ratio, production fractions, and the $D_s^+ \rightarrow \phi\pi^+$ and $\phi \rightarrow \mu^+\mu^-$ branching fractions gives $\mathcal{B}(D^+ \rightarrow \phi\pi^+ \rightarrow \mu^+\mu^-\pi^+) = (1.8 \pm 0.5(\text{stat}) \pm 0.6(\text{syst})) \times 10^{-6}$, 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 $D_s^+ \rightarrow \phi\pi^+$ branching fraction that enters both the normalization and $f_{c \rightarrow D}^s$.

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 $1.8 \text{ GeV}/c^2$, excluding $0.96 < m(\mu^+\mu^-) < 1.08 \text{ GeV}/c^2$. Backgrounds are further reduced by requiring $\mathcal{S}_D > 9.4$, $\mathcal{S}_\pi > 1.8$, $\Theta_D < 7 \text{ mrad}$, $\chi_{\text{vtx}}^2 < 2.6$ (for 3 DOF), and $\Delta R_\pi < 2.6$. We also require the pion transverse momentum $p_T(\pi)$ be greater than $0.4 \text{ GeV}/c$ 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,

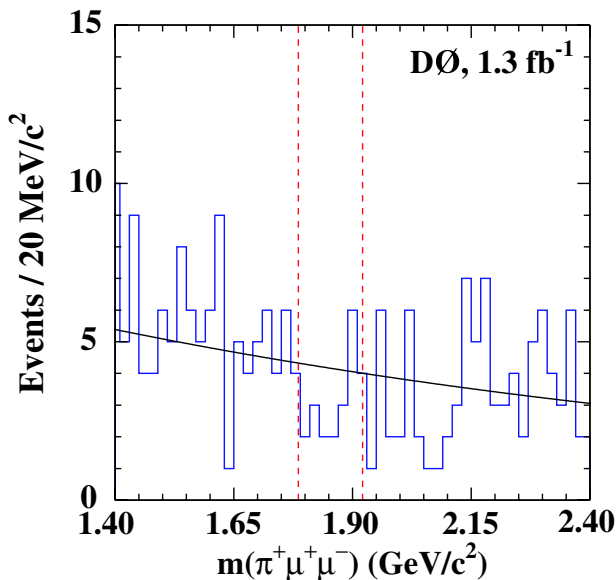


FIG. 3 (color online). Final $\pi^+\mu^+\mu^-$ invariant mass spectrum. The $\pm 2\sigma$ D^+ signal region, within the dashed lines, contains 19 events. The background level determined from the sidebands is 25.8 ± 4.6 events.

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 χ_{vtx}^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

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

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

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

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 $D_s^+ \rightarrow \phi\pi^+$ 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 ϕ . We see no evidence of signal above background and set a limit of $\mathcal{B}(D^+ \rightarrow \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$ at the 90% C.L. This is the most stringent limit to date in a decay

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

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

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 $\lambda'_{22k} \times \lambda'_{21k}$ [2]. However, it is still an order of magnitude above the expected level from little Higgs models [4].

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