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 $1.3 \text{ fb}^{-1}$ 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 $D_{s}^{+}$ and $D^{+} \rightarrow \phi \pi^{+} \rightarrow \mu^{+}\mu^{-}\pi^{+}$ final states with significance greater than four standard deviations above background for the $D^{+}$ state. We search for the continuum decay of $D^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$ in the dimuon invariant mass spectrum away from the $\phi$ resonance. We see no evidence of signal above background and set a limit of $B(D^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}) < 3.9 \times 10^{-6}$ 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, GIM suppression in $D$ meson decays is significantly stronger and the SM branching fractions are expected to be as low as $10^{-5}$ \cite{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 \cite{4} that lead to a tree level interaction mediated by new particles, or little Higgs models with a new up-like vector quark \cite{5} 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 decay $D_{s}^{+} \rightarrow \phi \pi^{+} \rightarrow \mu^{+}\mu^{-}\pi^{+}$ and the first evidence for the decay $D^{+} \rightarrow \phi \pi^{+} \rightarrow \mu^{+}\mu^{-}\pi^{+}$ 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 $D_{s}^{+}$ decays due to the smaller $D_{s}^{+} \rightarrow \eta, \rho$, and $\omega$ branching fractions and the smaller $\eta, \rho$, and $\omega \rightarrow \mu^{+}\mu^{-}$ branching fractions \cite{6}. The search for the $c \rightarrow u\mu^{+}\mu^{-}$ 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 $\phi$ 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. Similar studies have recently been published by the FOCUS \cite{2} and CLEO-c \cite{3} collaborations, and preliminary results have been presented by the BaBar \cite{2} collaboration.

D0 is a general purpose detector described in detail in Ref. \cite{10,11}. 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. Photons and electrons are reconstructed using the inner region of a liquid argon calorimeter optimized for electromagnetic shower detection. Jet reconstruction and electron identification are further augmented with the outer region of the calorimeter optimized for hadronic shower detection. Muons are reconstructed using a spectrometer consisting of magnetized iron toroids and three super-layers of proportional tubes and plastic trigger scintillators located outside the calorimeter.

The analysis is based on data collected with dimuon triggers. The D0 trigger is based on a three-tier system. The level 1 and 2 dimuon triggers rely on hits in the muon spectrometer and fast reconstruction of muon tracks. The level 3 trigger performs fast reconstruction of the entire event allowing for further muon identification algorithms, matching of muon candidates to tracks reconstructed in the central tracking system, and requirements on the $z$ position of the $p\bar{p}$ interaction.

The selection requirements are determined using PYTHIA \cite{12} Monte Carlo (MC) events to model both $c\bar{c}$ and $b\bar{b}$ production and fragmentation. The EVTGEN \cite{12} MC 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 \cite{14} based MC. 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 super-layers and to be associated with a track reconstructed with hits in both the silicon and fiber trackers. We require that the muon transverse momentum $p_{T}$ be greater than 2 GeV/$c$ and the total momentum $p$ to be above 3 GeV/$c$. The dimuon system is formed by combining two oppositely charged muon candidates that are associated with the same track jet \cite{15}, form a well reconstructed vertex, and have an invariant mass $m(\mu^{+}\mu^{-})$
below 2 GeV/c². 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 resonances are seen. The ρ is observed as a broad
structure beneath the ω peak, and there is some indica-
tion of η production as well. For the initial search for
resonance dimuon production we require the μ⁺μ⁻ mass
be within ±0.04 GeV/c² of the nominal φ mass and re-
determine the muon momenta with a φ mass constraint
imposed [6] which improves the μ⁺μ⁻ invariant mass reso-
lation by 33%.

Candidate D(±) 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 pT > 0.18 GeV/c. The
pion impact parameter significance Sπ, defined as
the point of closest approach of the track helix to the
interaction 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/c² < m(π⁺π⁻μ⁻) < 2.4 GeV/c². The three par-
ticles must form a well-reconstructed D meson candidate
vertex displaced from the primary vertex. The transverse
flight length significance SD, 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 ΘD, 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 p̅p collisions, the longitudi-
dinal track impact parameters are used to reject muons
and tracks produced in the secondary p̅p interactions. In
events with multiple D candidates, the best candidate is
chosen based on the χ² of the three track vertex and
the angular separation between the pion and the dimuon
system in η-φ space, (∆Rχ²)² = (∆η)² + (∆φ)², which is
typically small for true candidates.

The resulting π⁺μ⁺μ⁻ invariant mass distribution is
shown in Fig. [2]. The D(±) → φπ⁻ → μ⁺μ⁻π⁺ signal
is extracted from a binned likelihood fit to the data assum-
possible contributions from D⁺ and D(±) inv.
as signal and from combinatoric background. The D(±)
component is modeled as 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(±) Gau-
sian functions is constrained by the known mass differ-
ence and the ratio of the standard deviations is con-
strained to the ratio of masses [6]. The background is mod-
eled as an exponential function with floating parameters.
The normalization of all functions are free parameters.
The fit yields 254 ± 36 D(±) candidates and 115 ± 31 D(±)
candidates. The statistical significance of the combined
D(±) and D(±) signal is 8 standard deviations above back-
ground. The significance of the D(±) yield, treating both
the combinatorial and D(±) candidates as background, is
4.1 standard deviations.

The relative efficiency of the D(±) and D(±) chan-
nels is determined separately for prompt D mesons produced
in direct p̅p → c+c+X processes and D mesons from B
meson decay and combined using the measured prompt frac-
tions [16] e⁺ = fB⁺εB⁺ + (1 − fB⁺)εD→D, where
εB⁺ is the efficiency for prompt D⁺ mesons, εD→D is
the efficiency for D⁺ mesons from B meson decay, and fB⁺
is the fraction of prompt D⁺ mesons; we use equivalent
expressions for D(±) mesons. The yield ratio is related to
We study the dimuon invariant mass region below 1 GeV. The normalization and uncertainty is overwhelmingly dominated by the uncertainty in the systematic uncertainty is dominated by uncertainties excluding 0.25 ground shape across the T Table I. The efficiency ratio is determined from MC to be $e^\pm/e^\mp = 0.70 \pm 0.06$ (stat + sys). The difference from unity is caused by the lifetime difference between $D^+$ ($\tau = 147.0$ $\mu$m) and $D^*$ ($\tau = 311.8$ $\mu$m) mesons, and the systematic uncertainty is dominated by uncertainties in the resolution modeling of $S_D$ and $S_s$.

Using the efficiency ratio, production fractions, and the $D^+ \to \phi \pi^+$ and $\phi \to \mu^+ \mu^-$ branching fractions gives $B(D^+ \to \phi \pi^+ \to \mu^+ \mu^- \pi^+) = (1.8 \pm 0.5$ (stat.) $\pm 0.6$ (sys.)) $\times$ 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 [3,9]. The systematic uncertainty is overwhelmingly dominated by the uncertainty in the $D_s^+ \to \phi \pi^+$ branching fraction that enters both the normalization and $f^{\pm}_{c-D}$.

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 < $m(\mu^+ \mu^-)$ < 1.06 GeV/$c^2$. Backgrounds are further reduced by requirements on the $S_D, S_s, \Theta_D, \chi^2_{011x}$, and $\Delta R_s$ variables defined above. The pion transverse momentum $\rho_T(\pi)$ and the isolation defined as $I_D = p(D)/\sum \rho_{cone}$ where the sum is over tracks in a cone centered on the $D$ meson of radius $\Delta R = 1$ are also used. The final requirements are chosen using a random grid search [18] optimized using the Punzi [19] criteria to give the optimal 90% C.L. upper limit. The final requirements along with the number of candidates surviving each requirement are listed in Table IV.

The $\pi^+ \mu^+ \mu^-$ invariant mass distribution in data for the dimuon invariant mass region below 1.8 GeV/$c^2$ excluding 0.96 < $m(\mu^+ \mu^-)$ < 1.06 GeV/$c^2$ 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 the measured event yield or fewer events is 14%.

We normalize the results to the $D^+ \to \phi \pi^+$ and $\phi \to \mu^+ \mu^-$ branching fractions. We use the product of the known $D^+ \to \phi \pi^+$ and $\phi \to \mu^+ \mu^-$ branching fractions [6]. The signal efficiency ratio between the $D^*$ signal instead of the larger $D_s^*$ channel in the preselection sample is determined from MC to be (5.4 $\pm$ 0.8)%. The inputs to the limit calculation are summarized in Table III. The systematic uncertainty is dominated by the modeling of the vertex resolution particularly in the $\chi^2_{011x}$ requirement. Using this, we find

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

The limit is determined using a Bayesian technique [20].
TABLE III: Inputs to the $\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-)$ upper limit calculation and resulting upper limit at the 90% and 95% C.L.

| $D^+ \to \pi^+ \mu^+ \mu^-$ candidate yield | 19 events |
|---------------------------------------------|-----------|
| Background expectation                      | 25.8 ± 4.6 events |
| $D^+ \to \phi \pi^+ \to \pi^+ \mu^+ \mu^-$ candidate yield | 115 ± 31 events |
| Relative efficiency                         | 0.054 ± 0.008 |
| $\mathcal{B}(D^+ \to \phi \pi^+)$           | $6.5 \times 10^{-3}$ |
| $\mathcal{B}(\phi \to \mu^+ \mu^-)$         | $2.86 \times 10^{-4}$ |
| Single event sensitivity                    | $3.0 \times 10^{-7}$ |
| $\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-)$ 95% C.L. | $< 6.1 \times 10^{-6}$ |
| $\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-)$ 90% C.L. | $< 3.9 \times 10^{-6}$ |

branching fractions gives

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

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 $D_s^+ \to \phi \pi^+$ 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 $\phi$. 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 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 [3].

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