March 2008

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

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Abazov, V. M.; Snow, Gregory R.; Bloom, Kenneth A.; and Collaboration, D0, "Search for Flavor-Changing-Neutral-Current D Meson Decays" (2008). Kenneth Bloom Publications. 233.<br>https://digitalcommons.unl.edu/physicsbloom/233

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

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(Received 16 August 2007; published 14 March 2008)
We study the flavor-changing-neutral-current process $c \rightarrow u \mu^{+} \mu^{-}$using $1.3 \mathrm{fb}^{-1}$ of $p \bar{p}$ collisions at $\sqrt{s}=1.96 \mathrm{TeV}$ 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 $\phi$ resonance. We see no evidence of signal above background and set a limit of $\mathcal{B}\left(D^{+} \rightarrow \pi^{+} \mu^{+} \mu^{-}\right)<$ $3.9 \times 10^{-6}$ at the $90 \%$ C.L. This limit places the most stringent constraint on new phenomena in the $c \rightarrow u \mu^{+} \mu^{-}$transition.

DOI: 10.1103/PhysRevLett.100.101801
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-IliopoulosMaiani 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 $Z \rightarrow c u$ 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 chargedcurrent 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 $\phi$ 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 [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 $\phi$ 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 $\sqrt{s}=1.96 \mathrm{TeV}$ corresponding to an integrated luminosity of approximately $1.3 \mathrm{fb}^{-1}$ 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 $B A B A R[8]$ collaboration.

PACS numbers: $13.20 . \mathrm{Fc}, 11.30 . \mathrm{Fs}, 11.30 . \mathrm{Hv}, 12.15 . \mathrm{Mm}$

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 $1.4<$ $m\left(\pi^{+} \mu^{+} \mu^{-}\right)<1.6 \mathrm{GeV} / c^{2}$ and $2.2<m\left(\pi^{+} \mu^{+} \mu^{-}\right)<$ $2.4 \mathrm{GeV} / c^{2}$.

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 $2 \mathrm{GeV} / c$ and the total momentum $p$ is greater than $3 \mathrm{GeV} / c$. 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 $m\left(\mu^{+} \mu^{-}\right)$below $2 \mathrm{GeV} / c^{2}$. 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 be within $\pm 0.04 \mathrm{GeV} / c^{2}$ of the nominal $\phi$ mass and redetermine the muon momenta with a $\phi$ 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 $p_{T}>0.18 \mathrm{GeV} / c$. 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 $m\left(\mu^{+} \mu^{-}\right)$invariant mass spectrum. The fitting function includes components from the $\eta$, $\rho, \omega$, and $\phi$ 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 $1.4 \mathrm{GeV} / c^{2}<$ $m\left(\pi^{+} \mu^{+} \mu^{-}\right)<2.4 \mathrm{GeV} / c^{2}$. 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 $\Theta_{D}$, 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 $\chi_{\mathrm{vtx}}^{2}$ of the three track vertex and the angular separation between the pion and the dimuon system in $\eta-\phi$ space, $\left(\Delta R_{\pi}\right)^{2}=(\Delta \eta)^{2}+(\Delta \phi)^{2}$, 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 $m\left(\pi^{+} \mu^{+} \mu^{-}\right)$mass spectrum in the $0.98<m\left(\mu^{+} \mu^{-}\right)<1.06 \mathrm{GeV} / c^{2} \phi$ 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.
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] $\epsilon^{+}=f_{p}^{+} \epsilon_{\text {prompt }}^{+}+\left(1-f_{p}^{+}\right) \epsilon_{B \rightarrow D}^{+}$, 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
$\frac{n\left(D^{+}\right)}{n\left(D_{s}^{+}\right)}=\frac{f_{c \rightarrow D}^{+}}{f_{c \rightarrow D}^{s}} \frac{f_{p}^{s}}{f_{p}^{+}} \frac{\epsilon^{+}}{\epsilon^{s}} \frac{\mathcal{B}\left(D^{+} \rightarrow \phi \pi^{+} \rightarrow \mu^{+} \mu^{-} \pi^{+}\right)}{\mathcal{B}\left(D_{s}^{+} \rightarrow \phi \pi^{+}\right) \mathcal{B}\left(\phi \rightarrow \mu^{+} \mu^{-}\right)}$,
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 $D_{s}^{+} \quad(c \tau=147.0 \mu \mathrm{~m})$ and $D^{+}(c \tau=311.8 \mu \mathrm{~m})$ 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 $D_{s}^{+} \rightarrow \phi \pi^{+}$and $\phi \rightarrow \mu^{+} \mu^{-}$branching fractions gives $\mathcal{B}\left(D^{+} \rightarrow \phi \pi^{+} \rightarrow \mu^{+} \mu^{-} \pi^{+}\right)=(1.8 \pm 0.5($ stat $) \pm$ $0.6($ 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 $1.8 \mathrm{GeV} / c^{2}$, excluding $\quad 0.96<m\left(\mu^{+} \mu^{-}\right)<1.08 \mathrm{GeV} / c^{2}$. Backgrounds are further reduced by requiring $\mathcal{S}_{D}>9.4, \mathcal{S}_{\pi}>$ $1.8, \Theta_{D}<7 \mathrm{mrad}, \chi_{\mathrm{vtx}}^{2}<2.6$ (for 3 DOF ), and $\Delta R_{\pi}<$ 2.6. We also require the pion transverse momentum $p_{T}(\pi)$ be greater than $0.4 \mathrm{GeV} / c$ 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,


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 $25.8 \pm 4.6$ 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 $\chi_{\mathrm{vtx}}^{2}$ 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

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

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

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

This is approximately $30 \%$ below the limit one would expect to set given an expected background of $25.8 \pm 4.6$ 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 $\mathcal{B}\left(D^{+} \rightarrow \pi^{+} \mu^{+} \mu^{-}\right)<3.9 \times 10^{-6}$ at the $90 \%$ C.L. This is the most stringent limit to date in a decay

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

| $D^{+} \rightarrow \pi^{+} \mu^{+} \mu^{-}$yield | 19 events |
| :--- | :---: |
| Background expectation | $25.8 \pm 4.6$ events |
| $D^{+} \rightarrow \phi \pi^{+} \rightarrow \pi^{+} \mu^{+} \mu^{-}$Yield | $115 \pm 31$ events |
| Relative efficiency | $0.054 \pm 0.008$ |
| $\mathcal{B}\left(D^{+} \rightarrow \phi \pi^{+} \rightarrow \mu^{+} \mu^{-} \pi^{+}\right)$ | $1.86 \times 10^{-5}$ |
| $\mathcal{B}\left(D^{+} \rightarrow \pi^{+} \mu^{+} \mu^{-}\right) 90 \%(95 \%)$ 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 $\lambda_{22 k}^{\prime} \times \lambda_{21 k}^{\prime}$ [2]. However, it is still an order of magnitude above the expected level from little Higgs models [4].

We thank the staffs at Fermilab and collaborating institutions. We also thank Sandip Pakvasa for several useful discussions. We acknowledge support from the DOE and NSF (USA); CEA and No. CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); Science and Technology Facilities Council (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); Alexander von Humboldt Foundation; and the Marie Curie Program.
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