

Search for Rare Charm Meson Decays at FNAL E791

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Abstract

We report the results of a *blind* search for flavor-changing neutral current (FCNC), lepton-flavor violating, and lepton-number violating decays of D^+ , D_s^+ , and D^0 mesons (and their antiparticles) into 2-, 3-, and 4-body states including a lepton pair. Such decays may involve Flavor-Changing Neutral Currents, Leptoquarks, Horizontal Gauge Bosons, or Majorana Neutrinos. No evidence for any of these decays is found. Therefore, we present 90% confidence level branching-fraction upper limits, typically at the 10^{-4} level. A total of 51 decay channels have been examined; 26 have not been previously reported and 18 are significant improvements over previous results.

Introduction

The E791 Collaboration has reported limits on rare and forbidden dilepton decays of charmed D mesons [1, 2, 3]. Such measurements probe the $SU(2)\times U(1)$ Standard Model of electroweak interactions in search of new mediators and couplings [4, 5] beyond the W^\pm and Z^0 discovered at CERN in 1983 [6]. Here we summarize the results of two related analyses. First [2] we examined the $\pi\ell\ell$ and $K\ell\ell$ decay modes of D^+ and D_s^+ and the $\ell^+\ell^-$ decay modes of D^0 . Then we extended the methodology to 27 dilepton decay modes of the D^0 meson [3] containing either resonant $V\ell^+\ell^-$ decays, where V is a ρ^0 , \bar{K}^{*0} , or ϕ , and non-resonant $h_1h_2\ell\ell$ decays, where h_i is either a π or a K . The leptons were either muons or electrons. Charge-conjugate modes are implied throughout this paper. The modes are lepton flavor-violating (e.g., $D^+ \rightarrow \pi^+\mu^+e^-$), or lepton number-violating (e.g., $D_s^+ \rightarrow \pi^-\mu^+\mu^+$), or flavor-changing neutral current decays (e.g., $D^0 \rightarrow \bar{K}^{*0}e^+e^-$). WW box diagrams can mimic FCNC decays, but only at the 10^{-10} to 10^{-9} level [5, 7]. Long range effects through resonant modes (e.g., $D^0 \rightarrow \bar{K}^{*0}\rho^0$, $\rho^0 \rightarrow e^+e^-$) can occur at the 10^{-6} level [7, 8]. Neither Lorentz nor gauge invariance [9] require lepton number conservation. A leptoquark [10] in an exchange diagram (e.g., $D^0 \rightarrow \mu^+e^-$) or a Horizontal Gauge Boson [11] in a spectator diagram (e.g., $D^+ \rightarrow \pi^+\mu^+e^-$) might mediate a change both in quark and lepton generation simultaneously. A Majorana Neutrino might lead to same sign dilepton decays [12]. Numerous experiments have studied rare decays of charge -1/3 strange quarks.

Charge 2/3 charm quarks are interesting because they might couple differently [13].

The data come from measurements made with the E791 spectrometer [14] at Fermilab's Tagged Photon Lab. The spectrometer has been upgraded for a series of charm experiments including E516 [15], E691 [16], E769 [17], and E791. E791 events were produced by a 500 GeV/c π^- beam interacting in a fixed target consisting of five thin disks, one platinum and four diamond. The discs were well separated to allow charmed hadrons to decay in air spaces where other interactions would be minimal. In addition to searching for rare decays, E791 has searched for $D^0 \bar{D}^0$ mixing [18], CP violation [19], and the pentaquark [20]. We have observed doubly cabibbo suppressed decays [21], discovered that the D_s^+ has a longer lifetime than the D^0 [22], tagged quarks as being c or \bar{c} using D - π production correlations [23], and measured the $\Sigma_c^0 - \Sigma_c^+$ mass splitting [24]. Leading effects (e.g. more forward $\pi^+(u\bar{d}) \rightarrow D^+(c\bar{d})$ than $\pi^+(u\bar{d}) \rightarrow D^-(\bar{c}d)$) have been observed in D^+ [25] and Λ_c^+ [26] production and not in D_s^+ production [27]. The total forward and differential cross section for D^0 production has been measured [28]. The differential cross section for D^{*+} hadroproduction has been measured [29]. The decays $\Lambda_c^+ \rightarrow pK^-\pi^+$ [30], $D^0 \rightarrow K^-K^+\pi^-\pi^+$ [31], $D^0 \rightarrow K^-K^-K^+\pi^+$ [32], $D^+ \rightarrow K^-\pi^+\pi^+$ [33], and $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ [34] have been studied. Evidence for the scalar meson $\sigma(500)$ in $D^+ \rightarrow \pi^-\pi^+\pi^+$ decays has been observed [35]. In non-charm physics, E791 has measured Λ^0 , Ξ^- , and Ω^- hyperon production asymmetries [36] and has used di-jet events to observe the pion valence quark distribution [37] and color transparency [38].

E791 recorded a total of 2×10^{10} events with a loose transverse energy requirement and data acquisition system writing at 10 MB/s to a great wall of 42 8mm Exabyte tape drives [39]. The resulting 50 Terabyte data set was totally unprecedented. It was nevertheless reconstructed at parallel computing farms built for this purpose at the University of Mississippi, Kansas State University, Fermilab, and CBPF-Rio de Janeiro [40] and yielded an unprecedented 200 000 fully reconstructed charmed hadron decays. Track and vertex information came from "hits" in 23 silicon microstrip planes and 45 wire chamber planes. This information and the bending provided by two dipole magnets were used for momentum analysis of charged particles. Kaon identification was carried out by two multi-cell Čerenkov counters [41] that provided π/K separation in the momentum range 6 – 60 GeV/c. We required that the momentum-dependent light yield in the Čerenkov counters be consistent for kaon-candidate tracks, except for those in $D^0 \rightarrow \phi\pi^+\pi^-$ decays with $\phi \rightarrow K^+K^-$, where the narrow mass window for the ϕ decay provided sufficient kaon identification (ID).

Electron ID was based on transverse shower shape plus matching wire chamber tracks to shower positions and energies in an electromagnetic calorimeter [42]. The electron ID efficiency varied from 62% below 9 GeV/c to 45% above 20 GeV/c. The probability to misidentify a pion as an electron was $\sim 0.8\%$, independent of pion momentum.

Muon ID employs two planes of scintillation counters [43]. The first plane (5.5 m \times 3.0 m) of 15 counters measured the horizontal position while the second plane (3.0 m \times 2.2 m) of 16 counters measured the vertical position. There were about 15 interaction lengths of shielding upstream of the counters to filter out hadrons. Data from $D^+ \rightarrow \bar{K}^{*0}\mu^+\nu_\mu$ decays [44] were used to choose selection criteria for muon candidates. Timing information from the smaller set of muon scintillation counters was used to improve the horizontal position resolution. Counter efficiencies, measured using muons originating from the primary target, were found to be $(99 \pm 1)\%$ for the smaller counters and $(69 \pm 3)\%$ for the larger counters. The probability of misidentifying a pion as a muon decreased with increasing momentum, from about 6% at 8 GeV/c to 1.3% above 20 GeV/c.

Events with evidence of well-separated production (primary) and decay (secondary) vertices were selected to separate charm candidates from background. Secondary vertices were required to be

separated from the primary vertex by greater than $20\sigma_L$ for D^+ decays and greater than $12\sigma_L$ for D^0 and D_s^+ decays, where σ_L is the calculated resolution of the measured longitudinal separation. Also, the secondary vertex had to be separated from the closest material in the target foils by greater than $5\sigma'_L$, where σ'_L is the uncertainty in this separation. The vector sum of the momenta from secondary vertex tracks was required to pass within $40\ \mu\text{m}$ of the primary vertex in the plane perpendicular to the beam. The net momentum of the charm candidate transverse to the line connecting the production and decay vertices had to be less than $300\ \text{MeV}/c$ for D^0 candidates, less than $250\ \text{MeV}/c$ for D_s^+ candidates, and less than $200\ \text{MeV}/c$ for D^+ candidates. Finally, decay track candidates were required to pass approximately 10 times closer to the secondary vertex than to the primary vertex. These selection criteria and kaon identification requirements were the same for both the search mode and for its normalization signal (discussed below).

To determine our selection criteria, we used a *blind* analysis technique. Before the selection criteria were finalized, all events having masses within a window ΔM_S around the mass of the D^0 were “masked” so that the presence or absence of any potential signal candidates would not bias our choice of selection criteria. All criteria were then chosen by studying events generated by a Monte Carlo (MC) simulation program [45] and background events, outside the signal windows, from real data. The criteria were chosen to maximize the ratio $N_{MC}/\sqrt{N_B}$, where N_{MC} and N_B are the numbers of MC and background events, respectively, after all selection criteria were applied. The data within the signal windows were unmasked only after this optimization. We used asymmetric windows for the decay modes containing electrons to allow for the bremsstrahlung low-energy tail.

The upper limit for each branching fraction B_X was calculated using the following formula:

$$B_X = \frac{N_X}{N_{\text{Norm}}} \frac{\varepsilon_{\text{Norm}}}{\varepsilon_X} \times B_{\text{Norm}}; \text{ where } \frac{\varepsilon_{\text{Norm}}}{\varepsilon_X} = \frac{f_{\text{Norm}}^{\text{MC}}}{f_X^{\text{MC}}}. \quad (1)$$

N_X is the 90% confidence level (CL) upper limit on the number of decays for the rare or forbidden decay mode X and B_{Norm} is the normalization mode branching fraction obtained from the Particle Data Group [53]. $\varepsilon_{\text{Norm}}$ and ε_X are the detection efficiencies while $f_{\text{Norm}}^{\text{MC}}$ and f_X^{MC} are the fractions of Monte Carlo events that were reconstructed and passed the final selection criteria, for the normalization and decay modes, respectively.

The 90% CL upper limits N_X are calculated using the method of Feldman and Cousins [47] to account for background, and then corrected for systematic errors by the method of Cousins and Highland [48]. In these methods, the numbers of signal events are determined by simple counting, not by a fit. Upper limits are determined using the number of candidate events observed and expected number of background events within the signal region.

Systematic errors include: statistical errors from the fit to the normalization sample N_{Norm} ; statistical errors on the numbers of Monte Carlo events for both $N_{\text{Norm}}^{\text{MC}}$ and N_X^{MC} ; uncertainties in the calculation of mis-ID background; and uncertainties in the relative efficiency for each mode, including lepton and kaon tagging. These tagging efficiency uncertainties include: 1) the muon counter efficiencies from both Monte Carlo simulation and hardware performance; 2) kaon Čerenkov ID efficiency due to differences in kinematics and modeling between data and Monte Carlo simulated events; and 3) the fraction of signal events (based on simulations) that would remain outside the signal window due to bremsstrahlung tails. The large systematic errors for the D_s^+ modes are due to the uncertainty in the branching fraction for the D_s^+ normalization mode. The sums, taken in quadrature, of these systematic errors are listed in Table 2 and Table 4.

The $D^+ \rightarrow h\ell\ell$, $D_s^+ \rightarrow h\ell\ell$, and $D^0 \rightarrow \ell^+\ell^-$ Analysis

We normalized the sensitivity of our search to the topologically similar Cabibbo-favored decays shown in Table 1 and Figure 1. For the D^+ decays we used $D^+ \rightarrow K^-\pi^+\pi^+$; for D_s^+ decays we used $D_s^+ \rightarrow \phi\pi^+$; and for D^0 decays we used $D^0 \rightarrow K^-\pi^+$ events. The efficiencies for the normalization modes varied from about 0.5% to 2%.

Table 1: Normalization modes used for $D^+ \rightarrow h\ell\ell$, $D_s^+ \rightarrow h\ell\ell$, and $D^0 \rightarrow \ell^+\ell^-$.

Rare D Decay	D Norm.	Events	MC Efficiency	PDG98 [46] Branching Ratio
$D^+ \rightarrow \pi\ell\ell$	$D^+ \rightarrow K^-\pi^+\pi^+$	24010 ± 166	1.06%	$(9.0 \pm 0.6)\%$
$D^+ \rightarrow K\ell\ell$	$D^+ \rightarrow K^-\pi^+\pi^+$	17730 ± 141	0.82%	$(9.0 \pm 0.6)\%$
$D_s^+ \rightarrow \pi\ell\ell$	$D_s^+ \rightarrow \phi\pi^+$	952 ± 34	0.60%	$(3.6 \pm 0.9)\%$
$D_s^+ \rightarrow K^+\ell^+\ell^-$	$D_s^+ \rightarrow \phi\pi^+$	782 ± 30	0.46%	$(3.6 \pm 0.9)\%$
$D_s^+ \rightarrow K^-\ell^+\ell^+$	$D_s^+ \rightarrow \phi\pi^+$	679 ± 27	0.49%	$(3.6 \pm 0.9)\%$
$D^0 \rightarrow \ell^+\ell^-$	$D^0 \rightarrow K^-\pi^+$	25210 ± 179	1.81%	$(3.85 \pm 0.09)\%$

The widths of our normalization modes were $10.5 \text{ MeV}/c^2$ for D^+ , $9.5 \text{ MeV}/c^2$ for D_s^+ , and $12 \text{ MeV}/c^2$ for D^0 . The signal windows used are:

$$\begin{array}{ll}
 1.84 < M(D^+) < 1.90 \text{ for } D^+ \rightarrow h\mu\mu & 1.78 < M(D^+) < 1.90 \text{ GeV}/c^2 \text{ for } D^+ \rightarrow hee \text{ and } h\mu e \\
 1.95 < M(D_s^+) < 1.99 \text{ for } D_s^+ \rightarrow h\mu\mu & 1.91 < M(D_s^+) < 1.99 \text{ GeV}/c^2 \text{ for } D_s^+ \rightarrow hee \text{ and } h\mu e \\
 1.83 < M(D^0) < 1.90 \text{ for } D^0 \rightarrow \mu\mu & 1.76 < M(D^0) < 1.90 \text{ GeV}/c^2 \text{ for } D^0 \rightarrow ee \text{ and } \mu e
 \end{array}$$

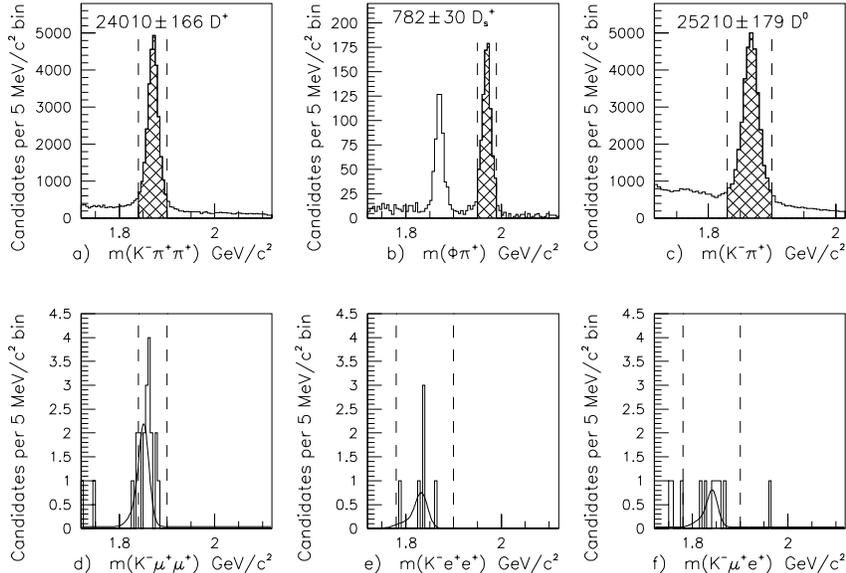


Figure 1: Top row: typical normalization charm signals. The signal region is shaded. Bottom row: invariant mass plots of D^+ candidate decays to $K^-\mu^+\mu^+$, $K^-e^+e^+$, and $K^-\mu^+e^+$, showing reflections mostly from misidentified $D^+ \rightarrow K^-\pi^+\pi^+$ decays. These modes are used to set mis-ID rate rather than upper limits. The solid curves are normalized Monte Carlo fits. The dashed lines show the signal window.

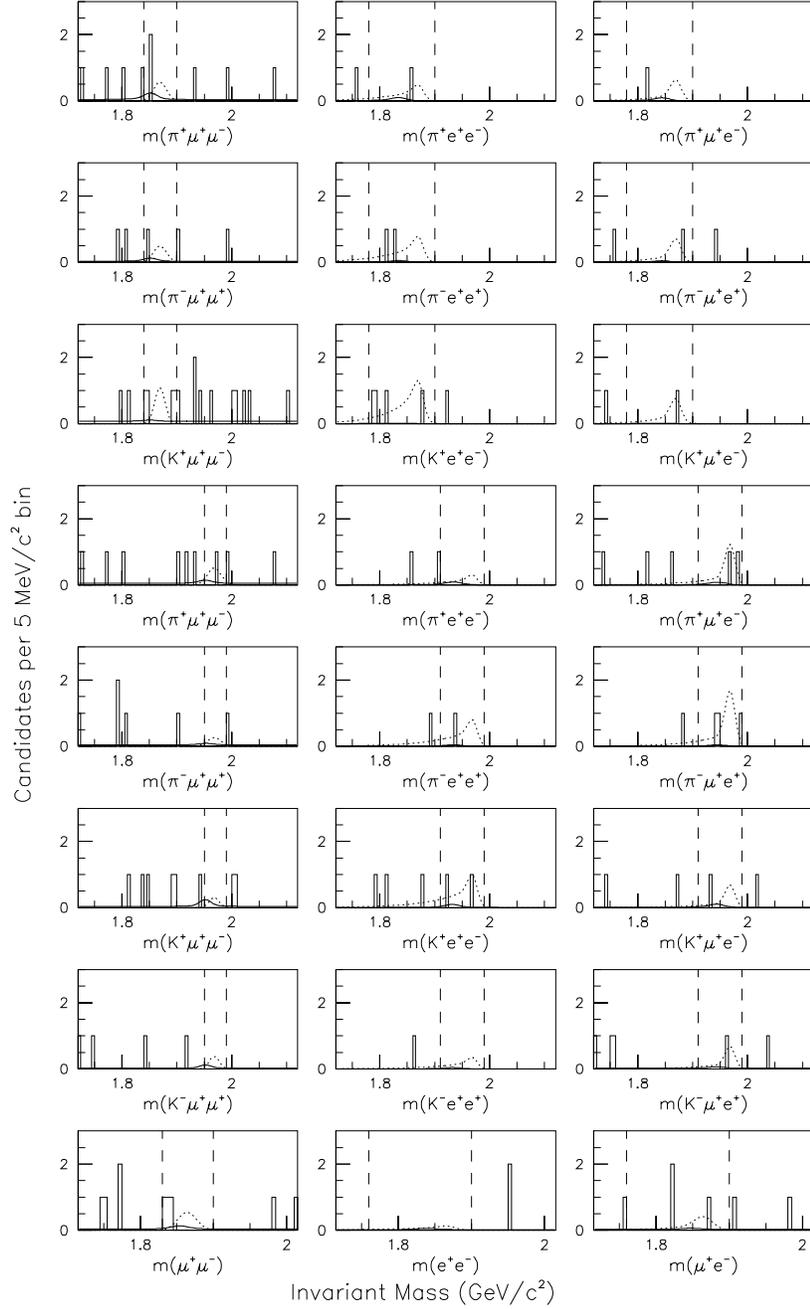


Figure 2: Final event samples for the D^+ (rows 1–3), D_s^+ (rows 4–7), and D^0 (row 8) decays. The solid curves represent estimated background; the dotted curves represent signal shape for a number of events equal to the 90% CL upper limit. The dashed vertical lines are ΔM_S boundaries.

Background that is not removed by cuts include decays in which hadrons (from real, fully-hadronic decay vertices) are misidentified as leptons. In the case where kaons are misidentified as leptons, candidates have effective masses which lie outside the signal windows. Most of these originate from Cabibbo-favored modes $D^+ \rightarrow K^- \pi^+ \pi^+$, $D_s^+ \rightarrow K^- K^+ \pi^+$, and $D^0 \rightarrow K^- \pi^+$. These Cabibbo-favored reflections were explicitly removed prior to cut optimization. There remain two sources of

background in our data: hadronic decays with pions misidentified as leptons (N_{MisID}) and “combinatoric” background (N_{Cmb}) arising primarily from false vertices and partially reconstructed charm decays. After cuts were applied and the signal windows opened, the number of events within the window is $N_{\text{Obs}} = N_{\text{Sig}} + N_{\text{MisID}} + N_{\text{Cmb}}$.

Table 2: E791 90% confidence level (CL) branching fractions (BF) compared to previous experiments. The background and candidate events correspond to the signal region only. The Monte Carlo (MC) yield is from 250 000 generated events in each of the 24 cases.

Mode	(Est. N_{Cmb})	BG N_{MisID}	Cand. Obs.	Syst. Err.	90% CL Num.	MC Yield	E791 BF Limit	Previous BF Limit	Experiment
$D^+ \rightarrow \pi^+ \mu^+ \mu^-$	1.20	1.47	2	10%	3.35	2706	1.5×10^{-5}	1.8×10^{-5}	E791 [1]
$D^+ \rightarrow \pi^+ e^+ e^-$	0.00	0.90	1	12%	3.53	816	5.2×10^{-5}	6.6×10^{-5}	E791 [1]
$D^+ \rightarrow \pi^+ \mu^\pm e^\mp$	0.00	0.78	1	11%	3.64	1272	3.4×10^{-5}	1.2×10^{-4}	E687 [49]
$D^+ \rightarrow \pi^- \mu^+ \mu^+$	0.80	0.73	1	9%	2.92	2088	1.7×10^{-5}	8.7×10^{-5}	E687 [49]
$D^+ \rightarrow \pi^- e^+ e^+$	0.00	0.45	2	12%	5.60	701	9.6×10^{-5}	1.1×10^{-4}	E687 [49]
$D^+ \rightarrow \pi^- \mu^+ e^+$	0.00	0.39	1	11%	4.05	976	5.0×10^{-5}	1.1×10^{-4}	E687 [49]
$D^+ \rightarrow K^+ \mu^+ \mu^-$	2.20	0.20	3	8%	5.07	1206	4.4×10^{-5}	9.7×10^{-5}	E687 [49]
$D^+ \rightarrow K^+ e^+ e^-$	0.00	0.09	4	11%	8.72	453	2.0×10^{-4}	2.0×10^{-4}	E687 [49]
$D^+ \rightarrow K^+ \mu^\pm e^\mp$	0.00	0.08	1	9%	4.34	664	6.8×10^{-5}	1.3×10^{-4}	E687 [49]
$D_s^+ \rightarrow K^+ \mu^+ \mu^-$	0.67	1.33	0	27%	1.32	647	1.4×10^{-4}	5.9×10^{-4}	E653 [50]
$D_s^+ \rightarrow K^+ e^+ e^-$	0.00	0.85	2	29%	5.77	244	1.6×10^{-3}		
$D_s^+ \rightarrow K^+ \mu^\pm e^\mp$	0.40	0.70	1	27%	3.57	388	6.3×10^{-4}		
$D_s^+ \rightarrow K^- \mu^+ \mu^+$	0.40	0.64	0	26%	1.68	686	1.8×10^{-4}	5.9×10^{-4}	E653 [50]
$D_s^+ \rightarrow K^- e^+ e^+$	0.00	0.39	0	28%	2.22	257	6.3×10^{-4}		
$D_s^+ \rightarrow K^- \mu^+ e^+$	0.80	0.35	1	27%	3.53	381	6.8×10^{-4}		
$D_s^+ \rightarrow \pi^+ \mu^+ \mu^-$	0.93	0.72	1	27%	3.02	1725	1.4×10^{-4}	4.3×10^{-4}	E653 [50]
$D_s^+ \rightarrow \pi^+ e^+ e^-$	0.00	0.83	0	29%	1.85	565	2.7×10^{-4}		
$D_s^+ \rightarrow \pi^+ \mu^\pm e^\mp$	0.00	0.72	2	30%	6.01	809	6.1×10^{-4}		
$D_s^+ \rightarrow \pi^- \mu^+ \mu^+$	0.80	0.36	0	27%	1.60	1588	8.2×10^{-5}	4.3×10^{-4}	E653 [50]
$D_s^+ \rightarrow \pi^- e^+ e^+$	0.00	0.42	1	29%	4.44	528	6.9×10^{-4}		
$D_s^+ \rightarrow \pi^- \mu^+ e^+$	0.00	0.36	3	28%	8.21	911	7.3×10^{-4}		
$D^0 \rightarrow \mu^+ \mu^-$	1.83	0.63	2	6%	3.51	5297	5.2×10^{-6}	4.1×10^{-6}	WA92 [51]
$D^0 \rightarrow e^+ e^-$	1.75	0.29	0	9%	1.26	1577	6.2×10^{-6}	8.2×10^{-6}	E789 [52]
$D^0 \rightarrow \mu^\pm e^\mp$	2.63	0.25	2	7%	3.09	2983	8.1×10^{-6}	1.7×10^{-5}	E789 [52]

The background N_{MisID} arises mainly from singly-Cabibbo-suppressed (SCS) modes. These misidentified leptons can come from hadronic shower punchthrough, decays-in-flight, and random overlaps of tracks. We do not attempt to establish a limit for $D^+ \rightarrow K^- \ell^+ \ell^+$ modes, as they have relatively large feedthrough signals from copious Cabibbo-favored $K^- \pi^+ \pi^+$ decays. Instead, we use the observed signals in $K^- \ell^+ \ell^+$ channels to measure three dilepton mis-ID rates under the assumption that the observed signals (shown in Figs. 1d-f) arise entirely from lepton mis-ID. The curve shapes are from Monte Carlo. The following mis-ID rates were obtained: $r_{\mu\mu} = (7.3 \pm 2.0) \times 10^{-4}$, $r_{\mu e} = (2.9 \pm 1.3) \times 10^{-4}$,

and $r_{ee} = (3.4 \pm 1.4) \times 10^{-4}$. Using these rates we estimate the numbers of misidentified candidates, $N_{\text{MisID}}^{h\ell\ell}$ (for D^+ and D_s^+) and $N_{\text{MisID}}^{\ell\ell}$ (for D^0), in the signal windows as follows: $N_{\text{MisID}}^{h\ell\ell} = r_{\ell\ell} \cdot N_{\text{SCS}}^{h\pi\pi}$ and $N_{\text{MisID}}^{\ell\ell} = r_{\ell\ell} \cdot N_{\text{SCS}}^{\pi\pi}$, where $N_{\text{SCS}}^{h\pi\pi}$ and $N_{\text{SCS}}^{\pi\pi}$ are the numbers of SCS hadronic decay candidates within the signal windows. For modes in which two possible pion combinations can contribute, e.g., $D^+ \rightarrow h^+ \mu^\pm \mu^\mp$, we double the rate.

To estimate the combinatoric background N_{Cmb} within a signal window ΔM_S , we count events having masses within an adjacent background mass window ΔM_B , and scale this number ($N_{\Delta M_B}$) by the relative sizes of these windows: $N_{\text{Cmb}} = (\Delta M_S / \Delta M_B) \cdot N_{\Delta M_B}$. To be conservative in calculating our 90% confidence level upper limits, we take combinatoric backgrounds to be zero when no events are located above the mass windows.

In Table 2 we present the numbers of combinatoric background, mis-ID background, and observed events for all 24 modes. The efficiencies for the search modes varied from about 0.1% to 2%. Data are shown in Figure 2 and limits are compared with previous results in Figure 4.

The $D^0 \rightarrow V\ell^+\ell^-$ and $D^0 \rightarrow hh\ell\ell$ Analysis

There were a few minor differences between this analysis and our previous analysis as discussed above. First, we examined resonant modes, where the mass ranges used were: $|m_{\pi^+\pi^-} - m_{\rho^0}| < 150$ MeV/ c^2 , $|m_{K^-\pi^+} - m_{\bar{K}^{*0}}| < 55$ MeV/ c^2 , and $|m_{K^+K^-} - m_\phi| < 10$ MeV/ c^2 . We normalized the sensitivity of each search to similar hadronic 3-body (resonant) or 4-body (non-resonant) decays. One exception is the case of $D^0 \rightarrow \rho^0 \ell^\pm \ell^\mp$ where we normalize to nonresonant $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ because no published branching fraction exists for $D^0 \rightarrow \rho^0 \pi^+ \pi^-$. Table 3 lists the normalization mode used for each signal mode and the fitted numbers of normalization data events (N_{Norm}). The efficiencies for the normalization modes varied from 0.2% to 1%, and the efficiencies for the search modes varied from 0.05% to 0.34%. The signal windows are: $1.83 < M(D^0) < 1.90$ GeV/ c^2 for $\mu\mu$ and $1.76 < M(D^0) < 1.90$ GeV/ c^2 for ee and μe modes.

Table 3: Normalization modes used for $D^0 \rightarrow V\ell^+\ell^-$ and $D^0 \rightarrow hh\ell\ell$.

Rare D^0 Decay	D^0 Norm.	Events	MC Efficiency	PDG2000 [53] Branching Ratio
$\rho^0 \ell^\pm \ell^\mp$	$\pi^+ \pi^- \pi^+ \pi^-$	2049±53	0.95%	$(7.3 \pm 0.5) \times 10^{-3}$
$\bar{K}^{*0} \ell^\pm \ell^\mp$	$\bar{K}^{*0} \pi^+ \pi^-$	5451±72	0.28%	$(1.4 \pm 0.4)\%$
$\phi \ell^\pm \ell^\mp$	$\phi \pi^+ \pi^-$	113±19	0.21%	$(1.07 \pm 0.28) \times 10^{-3}$
$\pi\pi\ell\ell$	$\pi^+ \pi^- \pi^+ \pi^-$	2049±53	0.95%	$(7.3 \pm 0.5) \times 10^{-3}$
$K\pi\ell\ell$	$K^- \pi^+ \pi^- \pi^+$	11550±113	0.41%	$(7.49 \pm 0.31)\%$
$KK\ell\ell$	$K^+ K^- \pi^+ \pi^-$	406±41	0.26%	$(2.5 \pm 0.23) \times 10^{-3}$

Background sources that are not removed by the selection criteria discussed earlier include decays in which hadrons (from real, fully-hadronic decay vertices) are misidentified as leptons. These misidentified leptons can come from hadronic showers reaching muon counters, decays-in-flight, and random overlaps of tracks from otherwise separate decays (“accidental” sources). In the case where kaons are misidentified as pions or leptons, candidate masses shift below signal windows. However, we remove these events to prevent them from influencing our background estimate, which is partially obtained from the mass sidebands (see discussion of N_{Cmb} below). To remove these events prior to the selection-criteria optimization, we reconstruct all candidates as each of the non-resonant normalization

modes and test whether the masses are consistent with m_{D^0} . If so, we remove the events, but only if the number of kaons in the final state differs from that of the search mode. We do not remove events having the same number of kaons, as the loss in acceptance for true signal events would be excessive.

There remain two sources of background: hadronic decays where pions are misidentified as leptons (N_{MisID}) and “combinatoric” background (N_{Cmb}) arising primarily from false vertices and partially reconstructed charm decays. The background N_{MisID} arises from the normalization modes. To estimate the rate for misidentifying $\pi\pi$ as $\ell\ell$, for all but the $D^0 \rightarrow K^-\pi^+\ell^+\ell^-$ modes, we assume all $D^0 \rightarrow K^-\pi^+\ell^+\ell^-$ candidates observed (after subtracting combinatoric background estimated from mass

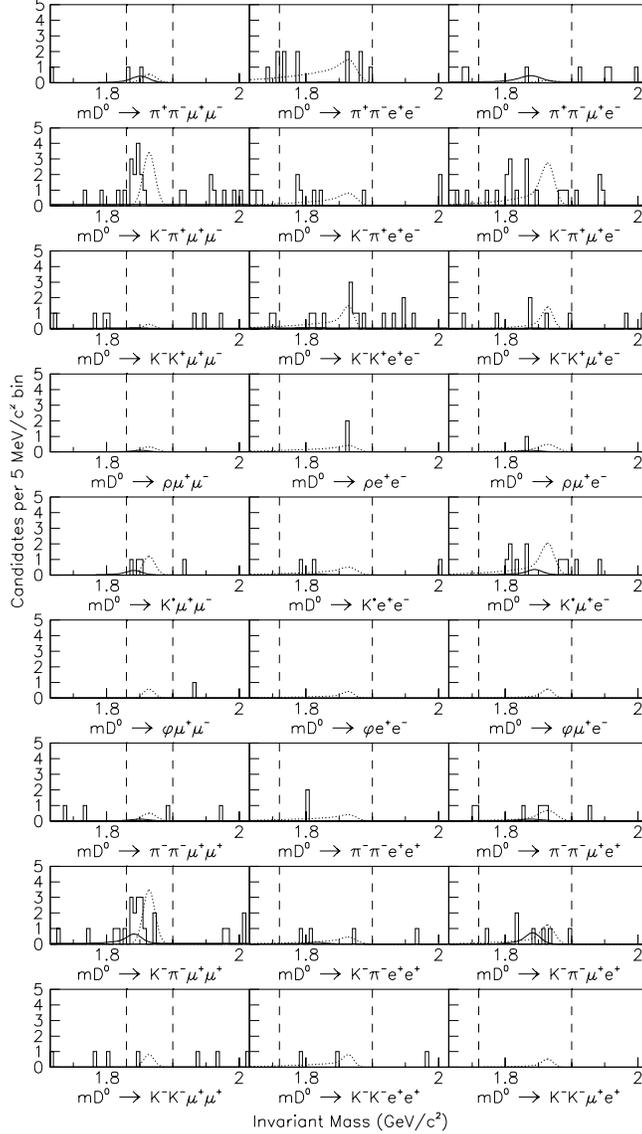


Figure 3: Final event samples for the opposite signed dilepton (rows 1–3), resonant (rows 4–6), and same signed dilepton modes (rows 7–9) of D^0 decays. The solid curves display total estimated background; the dotted curves display signal shape for a number of events equal to the 90% CL upper limit. The dashed vertical lines are the ΔM_S boundaries.

sidebands) result from misidentification of $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays and count the number of $D^0 \rightarrow K^- \pi^+ \ell^+ \ell^-$ decays passing the final selection criteria. We then divide by twice the number of $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ normalization events with $K^- \pi^+ \ell^+ \ell^-$ mass within ΔM_S boundaries (twice because there are two possible π^+ misidentifications).

Table 4 shows numbers of combinatoric background, misidentification background, and observed events for all 27 modes. Data are shown in Figure 3 and compared with previous results in Figure 5.

From this procedure, the following misidentification rates were obtained: $r_{\mu\mu} = (3.4 \pm 2.4) \times 10^{-4}$, $r_{\mu e} = (4.2 \pm 1.4) \times 10^{-4}$, and $r_{ee} = (9.0 \pm 6.2) \times 10^{-5}$. For modes in which two possible pion combinations can contribute, e.g., $D^0 \rightarrow K^- \pi^+ \mu^\pm \mu^\mp$, we use twice the above rate; and for $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$, where

Table 4: E791 90% confidence level (CL) upper limits on the number of events and branching fraction limits ($\times 10^{-5}$). The Monte Carlo (MC) yield is from 250 000 generated events in each of the 27 cases. Previously published limits are listed for comparison [53, 54, 50].

Mode $D^0 \rightarrow$	(Est. BG)		N_{Obs}	Sys.		MC E791	PDG	Limit	Limit
	N_{Cmb}	N_{MisID}		Err.	N_X				
$\pi^+ \pi^- \mu^+ \mu^-$	0.00	3.16	2	11%	2.96	840	3.0		
$\pi^+ \pi^- e^+ e^-$	0.00	0.73	9	12%	15.2	345	37.3		
$\pi^+ \pi^- \mu^\pm e^\mp$	5.25	3.46	1	15%	1.06	620	1.5		
$K^- \pi^+ \mu^+ \mu^-$	3.65	0.00	12	11%	15.4	286	35.9		
$K^- \pi^+ e^+ e^-$	3.50	0.00	6	15%	7.53	135	38.5		
$K^- \pi^+ \mu^\pm e^\mp$	5.25	0.00	15	12%	17.3	217	55.3		
$K^+ K^- \mu^+ \mu^-$	2.13	0.17	0	17%	1.22	145	3.3		
$K^+ K^- e^+ e^-$	6.13	0.04	9	18%	9.61	120	31.5		
$K^+ K^- \mu^\pm e^\mp$	3.50	0.17	5	17%	6.61	149	18		
$\rho^0 \mu^+ \mu^-$	0.00	0.75	0	10%	1.80	694	2.2	23	
$\rho^0 e^+ e^-$	0.00	0.18	1	12%	4.28	294	12.4	10	
$\rho^0 \mu^\pm e^\mp$	0.00	0.82	1	11%	3.60	466	6.6	4.9	
$\bar{K}^{*0} \mu^+ \mu^-$	0.30	1.87	3	24%	5.40	275	2.4	118	
$\bar{K}^{*0} e^+ e^-$	0.88	0.49	2	25%	4.68	121	4.7	14	
$\bar{K}^{*0} \mu^\pm e^\mp$	1.75	2.30	9	24%	12.8	185	8.3	10	
$\phi \mu^+ \mu^-$	0.30	0.04	0	33%	2.33	187	3.1	41	
$\phi e^+ e^-$	0.00	0.01	0	33%	2.75	117	5.9	5.2	
$\phi \mu^\pm e^\mp$	0.00	0.05	0	33%	2.71	146	4.7	3.4	
$\pi^- \pi^- \mu^+ \mu^+$	0.91	0.79	1	9%	2.78	821	2.9		
$\pi^- \pi^- e^+ e^+$	0.00	0.18	1	11%	4.26	322	11.2		
$\pi^- \pi^- \mu^+ e^+$	2.63	0.86	4	10%	5.18	559	7.9		
$K^- \pi^- \mu^+ \mu^+$	2.74	3.96	14	9%	15.7	268	39.0		
$K^- \pi^- e^+ e^+$	0.88	1.04	2	16%	4.14	134	20.6		
$K^- \pi^- \mu^+ e^+$	0.00	4.88	7	11%	7.81	238	21.8		
$K^- K^- \mu^+ \mu^+$	1.22	0.00	1	17%	3.27	137	9.4		
$K^- K^- e^+ e^+$	0.88	0.00	2	17%	5.28	137	15.2		
$K^- K^- \mu^+ e^+$	0.00	0.00	0	17%	2.52	175	5.7		

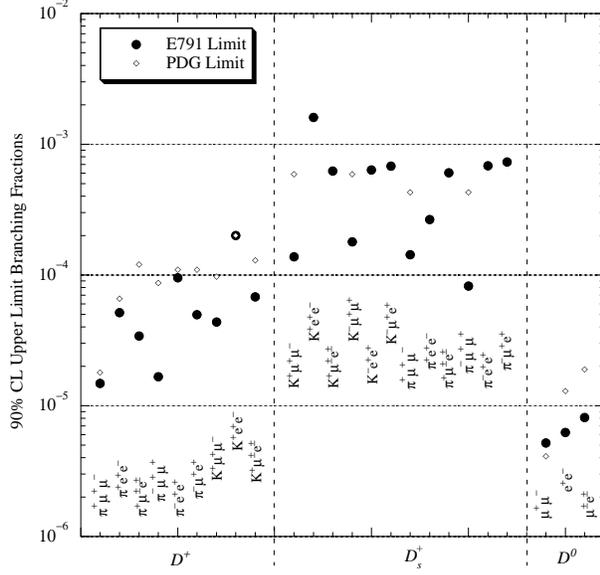


Figure 4: Comparison of the 90% CL upper-limit branching fractions from E791 data (dark circles) with existing limits (open diamonds) from the 1998 PDG [44]. The modes are D^+ or $D_s^+ \rightarrow \pi\ell$ or $K\ell\ell$ and $D^0 \rightarrow \ell^+\ell^-$.

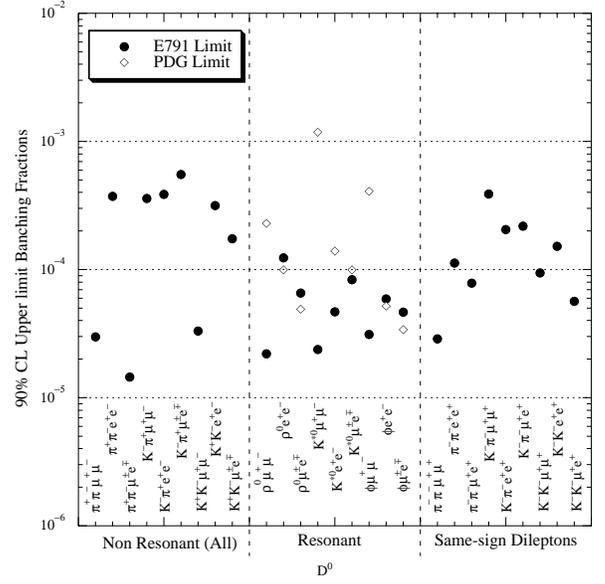


Figure 5: Comparison of the 90% CL upper-limit $D^0 \rightarrow V\ell^+\ell^-$ and $hh\ell\ell$ branching fractions from E791 data (dark circles) with existing limits (open diamonds) from the 2000 PDG [51].

there are 4 possible combinations, we use 4 times this rate in calculating $D^0 \rightarrow \pi^+\pi^-\ell^+\ell^-$. Using these rates, we estimate the numbers of misidentified candidates, $N_{\text{MisID}}^{V\ell\ell}$ and $N_{\text{MisID}}^{hh\ell\ell}$, in the signal windows as follows:

$$N_{\text{MisID}}^{hh\ell\ell} = r_{\ell\ell} \times N_{\text{Norm}}^{hh\pi\pi} \text{ and } N_{\text{MisID}}^{V\ell\ell} = r_{\ell\ell} \times N_{\text{Norm}}^{V\pi\pi}, \quad (2)$$

where $N_{\text{Norm}}^{hh\pi\pi}$ and $N_{\text{Norm}}^{V\pi\pi}$ are the numbers of normalization hadronic decay candidates in the signal windows.

To calculate the upper limits for the $D^0 \rightarrow K^-\pi^+\ell^+\ell^-$ modes, we set N_{MisID} to zero as we do not have an independent estimate of the misidentification rates. This results in conservative upper limits. If we had used the misidentification rates from our previous, 3-body decay study [2], then our limits for the three $D^0 \rightarrow K^-\pi^+\ell^+\ell^-$ modes would be lower by about a factor of two.

To estimate the combinatoric background N_{Cmb} within a signal window ΔM_S , we count events having masses within an adjacent background mass window ΔM_B , and scale this number ($N_{\Delta M_B}$) by the relative sizes of these windows: $N_{\text{Cmb}} = (\Delta M_S/\Delta M_B) \times N_{\Delta M_B}$. To be conservative in calculating our 90% confidence level upper limits, we take combinatoric backgrounds to be zero when no events are located above the mass windows.

Conclusion

We used a *blind* analysis of data from Fermilab experiment E791 to obtain upper limits on the dilepton branching fractions for 51 flavor-changing neutral current, lepton-number violating, and lepton-family violating decays of D^+ , D_s^+ , and D^0 mesons. No evidence for any of these 2, 3 and 4-body decays was found. Therefore, we presented upper limits on the branching fractions at the 90% con-

fidence level. Eighteen limits represented significant improvements over previously published results. Twenty-six of the remaining modes had no previously reported limits. Work is currently underway at the Fermilab FOCUS [55] experiment and others to further improve the limits presented here or to observe signals.

Acknowledgments

Many thanks to Eric Aitala [56], Jeff Appel [57], Steve Bracker [58], Lucien Cremaldi [59], Ai Nguyen [60], Milind Purohit [61], David Sanders [62], Alan Schwartz [5], Jean Slaughter [63], Noel Stanton [64], Nick Witchey [65], and all the members of the Fermilab E791 collaboration. Also many thanks to the staffs of Fermilab and participating institutions. This research was supported by the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico, CONACyT (Mexico), the Israeli Academy of Sciences and Humanities, the U.S.-Israel Binational Science Foundation, and the U.S. National Science Foundation and Department of Energy. The Universities Research Association operates Fermilab for the U.S. Department of Energy.

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