Search for the Flavor Changing Neutral Current Decay $D^0 \to \mu^+\mu^-$ in 800 GeV Proton-Silicon Interactions

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We have searched for the flavor changing neutral current decay $D^0 \to \mu^+\mu^-$ in the dimuon data obtained by the E771 experiment conducted at Fermilab. No evidence is found. A 90% confidence level upper limit of 4.2×10^{-6} is obtained for the branching ratio. This new upper limit is about two times lower than the best published result. [S0031-9007(96)01183-0]

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One of the outstanding symmetries of the standard model (SM) is approximate flavor conservation in electroweak neutral current interactions. Historically, the charm quark was proposed to account for the highly suppressed decay rate of the strangeness nonconserving neutral current process $K_L \to \mu^+\mu^-$ [1]; the charm quark completes a two-generation quark model which forbids $K_L \to \mu^+\mu^-$ at the lowest (tree) level. The observed branching ratio (BR) of $(7.4 \pm 0.4) \times 10^{-9}$ [2] is consistent with higher order electroweak processes, involving insertion of loops to the tree-level diagrams [3]. Recently, the beauty changing neutral current process $B \to K^*\gamma$ has been observed at a rate expected from the three-generation SM [4].

The down-type quarks (d, s, and b) contribute to the loop diagrams in the charm changing neutral current process $D^0 \to \mu^+\mu^-$, resulting in a rate proportional to m_s^4, where m_s is the mass of the strange quark [3]. The expected BR at the quark level (short distance) for $D^0 \to \mu^+\mu^-$ is about 10^{-19} [5], about 14 orders of magnitude below the present experimental limit [2]. Nonperturbative quantum chromodynamics (long distance) effects may enhance the BR by several orders of magnitude [5], but still render the SM decay rate undetectable by current or future experiments. Consequently, this decay mode offers a clean search window for models with flavor changing neutral currents (FCNCs) at the tree level [6]. For such models, $D^0 \to \mu^+\mu^-$ is predicted to have a BR of 10^{-9}

to 10^{-8}. Therefore, it is of great interest to conduct a search for this decay mode of D^0 with a higher sensitivity.

Experiment E771 is a fixed-target experiment at Fermilab designed primarily for detection of beauty hadrons via their decay to a J/ψ which subsequently decays to two muons. Only the detector components relevant to this analysis are described here; details of the detector are given elsewhere [7]. The detector consists of a large acceptance open-geometry magnetic spectrometer, a silicon microstrip vertex detector (SMVD), an electromagnetic calorimeter, and a muon detector. The spectrometer is configured with 31 planes of wire chambers in front of a dipole bending magnet, followed by 21 planes of wire chambers, to measure the momenta of charged particles. The muon detector comprises three layers of resistive plate counters (RPCs) [8], interspersed in about 37 interaction lengths of hadron absorber. The central region of the absorber has a longer interaction length to reduce the hadronic punchthrough background, resulting in a minimum penetration energy which varies from 10 GeV in the central region to 6 GeV on the outside. The RPCs are read out by highly segmented pads which provide fast signals for muon triggering and tracking in the absorber. The SMVD is composed of 12 planes of 25–100 μm pitch silicon strip detectors [9], 5 for x, 5 for y, and 2 stereo planes at 45°. (The coordinate system is right-handed with the z axis pointing along the beam and the y axis pointing upward.) Six silicon planes of 25–250 μm pitch are installed in front of the target to track the beam protons. The target is a series of 12 silicon foils, each 2 mm thick separated by a 4 mm decay region.

The experiment was conducted in the High Intensity Lab with 800 GeV protons extracted from the Tevatron. The trigger for the experiment requires either two muons or one muon with high transverse momentum p_t in the muon detector. A muon trigger is defined as a threefold coincidence of pad signals in the three RPC layers, which lie within a road. Single high p_t muon triggers require a muon in coincidence with signals from a set of drift chambers with pad readouts [10] which defines the p_t of the muon. The data were taken during the 1991 fixed target run at Fermilab, with a typical interaction rate of $2 \times 10^6/s$. A total of 190×10^6 triggers was recorded during the one month long running period.

The search for $D^0 \to \mu^+\mu^-$ was performed with events obtained by the dimuon trigger. Muon candidates were required to have a reconstructed track in the spectrometer which points to a muon track in the RPC. To reduce background due to π/K decay in flight, at least one muon was required to have a p_t greater than 1 GeV, in conjunction with a second muon with $p_t > 0.4$ GeV. A crude vertex requirement was imposed to remove spurious muons originating outside the target region.

The mass spectrum for the unlike-sign dimuons, with no silicon tracking requirement, is shown in Fig. 1 as a solid histogram, where peaks at the J/ψ, ϕ, and ω/ρ are clearly visible. Also shown in Fig. 1 is the like-sign dimuon spectrum (dotted histogram) which represents the continuum background. The near equality of the like- and unlike-sign spectra suggests that most of the events are from π/K decays in flight. The decrease of the dimuon yield below 1.5 GeV is a result of the p_t cut on the muons. The excess in the unlike-sign spectrum below 1 GeV is expected from hadronic decays.

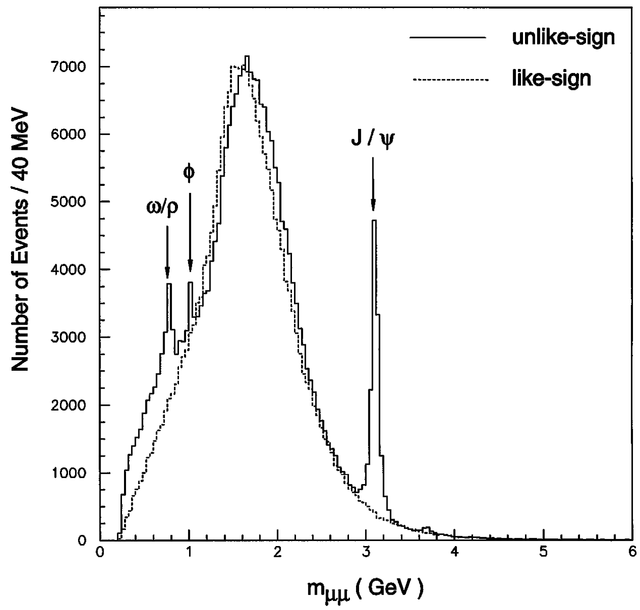

FIG. 1. Mass spectra for like-sign (dotted histogram) and unlike-sign (solid histogram) muon pairs.

There is no obvious peak in the unlike-sign dimuon spectrum at the D^0 mass (1864.6 ± 0.5 MeV) [2]. A search for a D^0 signal in about 50% of the data following the procedure described in Ref. [11] resulted in a limit for the BR of 1.3×10^{-5} at 90% confidence level (CL) [12].

To carry out a more sensitive search, we have used the tracking information from the SMVD. The spectrometer muon tracks were matched to silicon tracks found in the SMVD. Each matched track was refitted with the silicon hits, together with hits from the front spectrometer chambers. The primary interaction vertex (PIV) for each event was determined by reconstructing a common vertex for the silicon tracks and the beam tracks. The decay background is first suppressed by removing events with at least one muon with an impact parameter less than 50 μm in both x and y projections.

The vertex positions of all muon pairs whose distance of closest approach is less than 500 μm were reconstructed by a vertex-constrained fit. The χ^2 of the fit has to be less than 50 per degree of freedom, which is a very loose criterion since most of the J/ψ dimuons have a χ^2 less than 10 per degree of freedom. A total of 8514 unlike-sign dimuons was found to have a common vertex.

The distance between the PIV and the muon pair vertex along the beam (Δz) for the 8514 D^0 candidates is shown in Fig. 2, where a peak at Δz near zero due to double π/K decays is clearly seen. The solid curve is a fit consisting of two Gaussians, one fixed at a σ of 600 μm to simulate the Δz resolution for the prompt muon pairs, superposed on a polynomial for the continuum. We applied a vertex isolation cut of $\Delta z > 3$ mm to remove the prompt muon pairs. We have also applied a fiducial cut of $\Delta r < 3$ mm and $\Delta z < 3$ cm to remove poorly reconstructed muon pairs; Δr is the radial distance of the muon vertex from the beam line.

The momentum of the D^0 candidate $\vec{p}_D$ can be calculated from the momenta of the two muons. For D^0 decays, $\vec{p}_D$ is parallel to the direction of flight of the D^0 ($\hat{n}_D$) which can be determined by the position of the secondary vertex of the two muons. The angle between $\vec{p}_D$ and $\hat{n}_D$ ($\Delta\theta$) is expected to be small. Our Monte Carlo simulation, using realistic secondary vertex resolution and momentum measurement error for the muons, shows that the resolution of $\Delta\theta$ is about 0.4°. We have therefore imposed a cut of $\Delta\theta < 0.9°$. There are 14 unlike-sign and 18 like-sign dimuon events remaining in the mass region 1560–2170 MeV which corresponds to $\pm 10\sigma_D$ centered at the D^0 mass; σ_D is the mass resolution at D^0, determined to be 30.5 MeV by a linear interpolation of the observed resolutions at J/ψ and ϕ in our data [7].

We have inspected these 32 events visually, and attributed 7 events in the unlike-sign category and 8 events in the like-sign category to secondary interactions. The criterion for secondary interaction requires at least one additional silicon track emerging from the dimuon vertex. We have determined the efficiency for retaining D^0 events in the scanning to be $97^{+3}_{-15}\%$ by two independent scannings.

The mass distribution for the 7 remaining unlike-sign events is shown in Fig. 3. The final search region, indicated by the double-headed arrow in Fig. 3, was chosen to be $\pm 2\sigma_D$ centered at the D^0 mass (1804–1926 MeV). No event is seen in the final D^0 search region for the unlike-sign events. Of the 10 like-sign events left after scanning, one event falls in the final search region.

Since no excess events are observed in the search region, we report our result as an upper limit on the BR of $D^0 \to \mu^+\mu^-$, computed according to the following formula:

$$\mathrm{BR}(D^0 \to \mu^+\mu^-) < \frac{N_D}{\mathcal{L}\,\sigma(D)\eta_D A}\,. \qquad (1)$$

$N_D = 2.3$ is the upper limit on the number of D^0 events at 90% CL [2,13]. $\mathcal{L}$ is the integrated luminosity, determined to be (1.6 ± 0.1) pb^{-1}. η_D is the overall acceptance times efficiency for D^0 dimuon events, and $\sigma(D)$ is the total production cross section per nucleon for D^0 and $\overline{D}^0$. We assumed a linear dependence for the D^0 cross section on the atomic mass A [14].

We have determined η_D by a Monte Carlo simulation. The D^0 events are generated with PYTHIA [15] with x_F

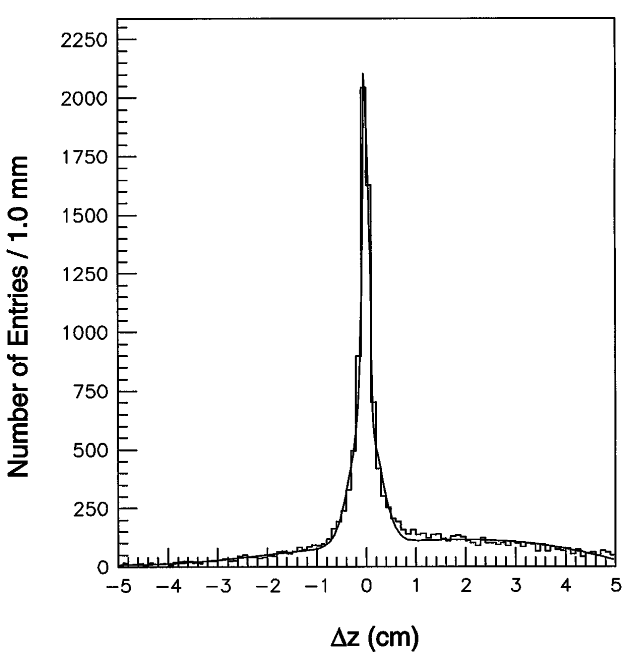

FIG. 2. Distribution of Δz for dimuon events. The solid line is a fit described in the text.

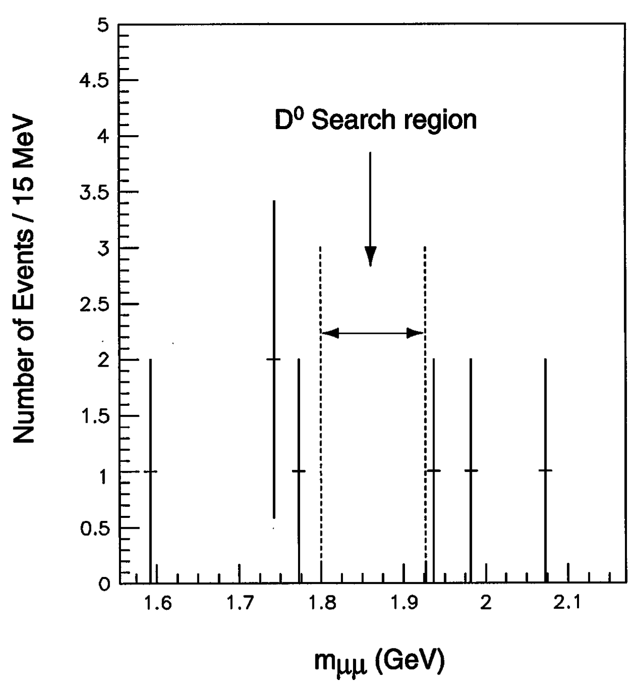

FIG. 3. Mass distribution for the unlike-sign D^0 dimuon candidates. The final search region for a D^0 signal is indicated by the double arrow.

and p_t distributed according to the following model:

$$\frac{d\sigma}{dx_F dp_t^2} \propto (1 - |x_F|)^n \exp(-a p_t^2) .$$

The parameters n and a have been measured by three different experiments [14,16,17] in 800 GeV proton-nucleus interactions. The average values for n and a are 7.7 ± 1.4 and 0.86 ± 0.07 GeV^{-2}, respectively. The $D^0 \rightarrow \mu^+\mu^-$ events were simulated by a GEANT-based detector Monte Carlo program, and were superimposed on data events. η_D was determined by applying the same cuts to the overlaid Monte Carlo events to be $(6.2 \pm 1.5) \times 10^{-4}$. The error in η_D includes detector systematic uncertainty (23%), and uncertainty in the D^0 production model (7%), combined in quadrature. It is worth pointing out that η_D is fairly insensitive to the D^0 production model; η_D changes by 7% when the parameters n and a are varied by one standard deviation.

The D^0 production cross section has been measured by several experiments in 800 GeV proton-nucleus collisions [14,16,17]. Because of the large spread in the results, we have averaged the charged [16,17] and neutral [14,16,17] D production cross sections, yielding $\sigma(D) = 20.9 \pm 3.5\ \mu\text{b}/\text{nucleon}$.

Using Eq. (1), the 90% CL upper limit for the BR was determined to be 4.2×10^{-6}. The limit includes a systematic error of 33%, according to the prescription of [18], which increased the statistical limit by about 6%. The systematic error was computed as a sum in quadrature of the contributing terms in Eq. (1), dominated by the uncertainty in the $D^0 \rightarrow \mu^+\mu^-$ detection efficiency (24%), the D^0 cross section (17%), and the A dependence of the D^0 cross section (14%). It is noted that this new upper limit is 2–10 times more stringent than previous limits [19–21].

We have performed a sensitive search for the FCNC decay $D^0 \rightarrow \mu^+\mu^-$ with the use of a vertex detector in a high-rate fixed-target experiment. The present search is limited by $\mathcal{L}\,\eta_D$. Beauty-physics experiments planned at HERA (HERA-B) [22] and the LHC (LHC-B) [23] are expected to have 10^4–10^5 times higher $\mathcal{L}\,\eta_D\sigma(D)$. The sensitivity for $D^0 \rightarrow \mu^+\mu^-$ is expected to reach the level of one event per 10^{-10} to 10^{-8} in BR. This will eventually allow us to discover or severely constrain many extensions of the SM [6].

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