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Abstract

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 branching ratio of $(-1.0\ ^{+1.7}_{-0.8} \pm 0.2) \times 10^{-6}$ is obtained, corresponding to a 90% confidence level upper limit of 3.3×10^{-6}. This new upper limit is about three times more sensitive than the best published limit.

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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]. Non-perturbative QCD (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 current 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 wires in front of a dipole bending magnet, followed by 21 planes of wires, 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 minimum penetration energy varies from 10 GeV in the central region to 6 GeV on the outside. The RPCs are readout 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 three-fold 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 2×10^6 per second. A total of 190 million triggers was recorded during the one month long running period.

The search for $D^0 \to \mu^+\mu^-$ was conducted 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, 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 decay. 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. The mass resolution at the J/ψ peak is 47 MeV, obtained by fitting the peak to two Gaussians superposed on the continuum which is well described by an exponential function. The J/ψ yield from the fit is 11333 $\pm$ 181, consistent with our estimate.

There is no obvious peak in the unlike-sign dimuon spectrum at the D^0 mass (1864.6 $\pm$ 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], which is comparable to the best published limit of 1.1×10^{-5} [11]. Both results are limited by the π/K decay background.

Muons from D^0 decay are expected to come from a secondary vertex downstream of the primary interaction vertex (PIV). The lifetime of the D^0 has been measured to be $(4.15 \pm 0.04) \times 10^{-13}$ s [2]. Our monte carlo simulation based on PYTHIA [13] shows that about 50% of the D^0 mesons decay at more than 3 mm downstream of the PIV, resulting in a typical impact parameter over 100 μm. The resolution of the SMVD has been determined to be about 500 μm along the beam, and 20 to 50 μm for the impact parameter depending on the location of the interaction (or decay) point [14].

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 re-fitted with the silicon hits together with hits from the front spectrometer chambers. The spectrometer tracking information was used because the SMVD alone cannot provide 3-D information for most muon tracks due to the lack of complete coverage by the stereo silicon planes. Using the tracking parameters of the global fit, a preliminary selection of D^0 candidates was made based on the impact parameter of the muons; events with at least one muon within 50 μm in both x and y projections from the PIV were removed. The PIV was determined by the silicon tracks alone.

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, which is a very loose criterion since most of the J/ψ dimuons have a χ^2 under 10. A total of 8514 unlike-sign dimuons was found to have a common vertex. The efficiency for finding a D^0 decay vertex was determined by using the J/ψ dimuons as a control sample. Identical selection criteria, except the impact parameter cut, were applied to the J/ψ sample. Out of the 11333 J/ψ dimuons found in the spectrometer without requiring silicon tracking, 2188 $\pm$ 62 events were found to have a silicon vertex, corresponding to an overall efficiency of 19.3%. The main loss is due to the inefficiency of the SMVD, as a result of radiation damage near the beam [15].

The distance between the PIV and the muon pair vertex along the beam (Δz) for the 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 Δz distribution was fitted to two Gaussians, one fixed at a σ of 600 μm to simulate the 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 efficiency of the vertex isolation cut alone was determined by our monte carlo simulation to be 56.9%. The additional loss of the D^0 signal due to the impact parameter cut is 13%. The loss due to the fiducial cuts is negligible, but is taken into account in the control sample.

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 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 interpolating the observed resolutions at J/ψ and ϕ in our data. The events in the side-bands allow us to determine the background in the final search region of $\pm 2\sigma_D$ (1804-1926 MeV) centered at the D^0 mass.

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 assume that the scanning efficiency is 100%.

The mass distribution for the 7 remaining unlike-sign events is shown in Fig. 3. No event is seen in the final D^0 search region, between the dotted lines in Fig. 3. One event is seen in the like-sign sample in the same search region.

We have determined the $D^0 \to \mu^+\mu^-$ BR by normalizing to the J/ψ yield, according to the following formula.

$$BR(D^0 \to \mu^+\mu^-) = BR(J/\psi \to \mu^+\mu^-)\frac{\sigma_{J/\psi}}{\sigma_D}A^{-\beta}\frac{\eta_{J/\psi}}{\eta_D}\frac{1}{\epsilon_s}\frac{N_D}{N_{J/\psi}}. \quad (1)$$

$N_D = -0.7\,^{+1.2}_{-0.6} \pm 0.1$ is the number of background-subtracted D^0 events in the search region. We have estimated the background in the search region from the side-bands to be 1.3 ± 0.3 (stat) $\pm\ 0.1$ (syst) events. The product $BR(J/\psi \to \mu^+\mu^-)\sigma_{J/\psi}$ has been measured by this experiment to be 21.8 ± 0.26 (stat) $\pm\ 1.44$ (syst) nb/nucleon [16], assuming an atomic-mass (A) dependence of $A^{0.92}$ [17]. The D^0 production cross section σ_{D^0} has been measured by several experiments in 800 GeV proton-nucleus collisions [18, 19, 20]. Due to the large spread in the results, we have averaged the charged [18, 19] and neutral [18, 19, 20] D cross sections, yielding $\sigma_{D^0} = 20.9 \pm 3.5$ μb/nucleon. We assumed a linear A dependence for the D^0 cross section [20]. The difference in A dependence of the J/ψ and D^0 production cross sections was taken into account by $A^{-\beta}$ where $\beta = 0.08$ is the difference of the exponents for the two processes. $N_{J/\psi} = 2188 \pm 62$ is the number of J/ψs which meet the same vertex requirements as those of the D^0 mesons. The relative acceptance times efficiency for J/ψ and D^0 muon pairs $\eta_{J/\psi}/\eta_D$ without vertex requirement was determined by a monte carlo simulation to be 1.7 ± 0.2. The overall efficiency for additional cuts to extract the D^0 signal, mainly the vertex isolation and angle cuts, is $\epsilon_s = 0.44$.

The BR was determined to be $(-1.0\,^{+1.7}_{-0.8} \pm 0.2) \times 10^{-6}$, consistent with a null signal. We therefore quote the result as an upper limit on the BR according to the procedure described in Ref. [21]. Since the number of observed events in the search region is zero, the 90% CL upper limit for the number of signal events is 2.3, independent of the expected background. Using Eqn. 1, the 90% CL upper limit for the BR was determined to be 3.3×10^{-6}. The systematic error of the upper limit is 21%, dominated by the uncertainty in the D^0 cross section and the $D^0 \to \mu^+\mu^-$ detection efficiency. It is noted that this new upper limit is about three times more sensitive than the best published limit [11], and is about ten times better than the limit recently published by E789 [22].

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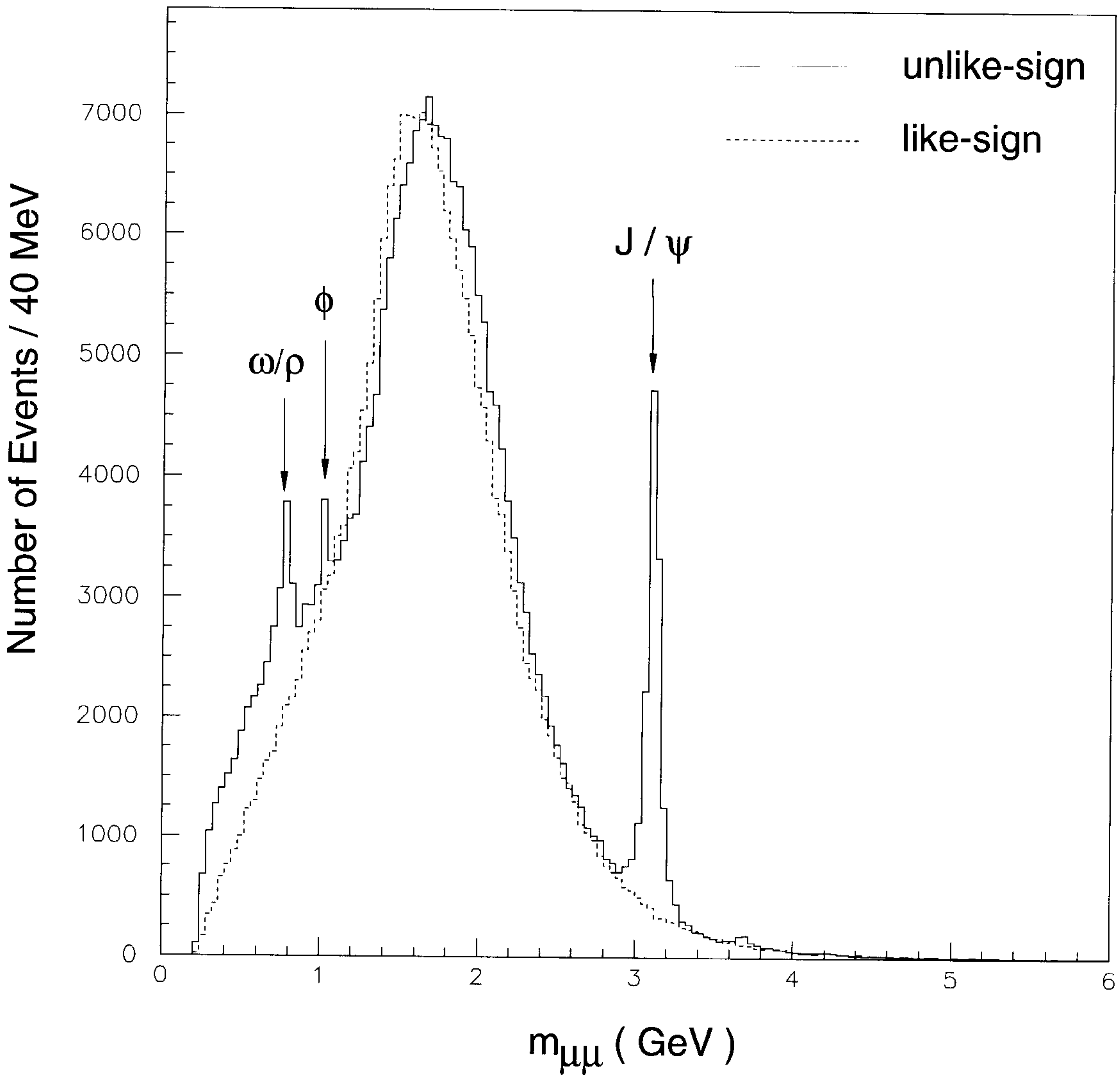

Figure 1: Mass spectra for like-sign (dotted histogram) and unlike-sign (solid histogram) muon pairs.

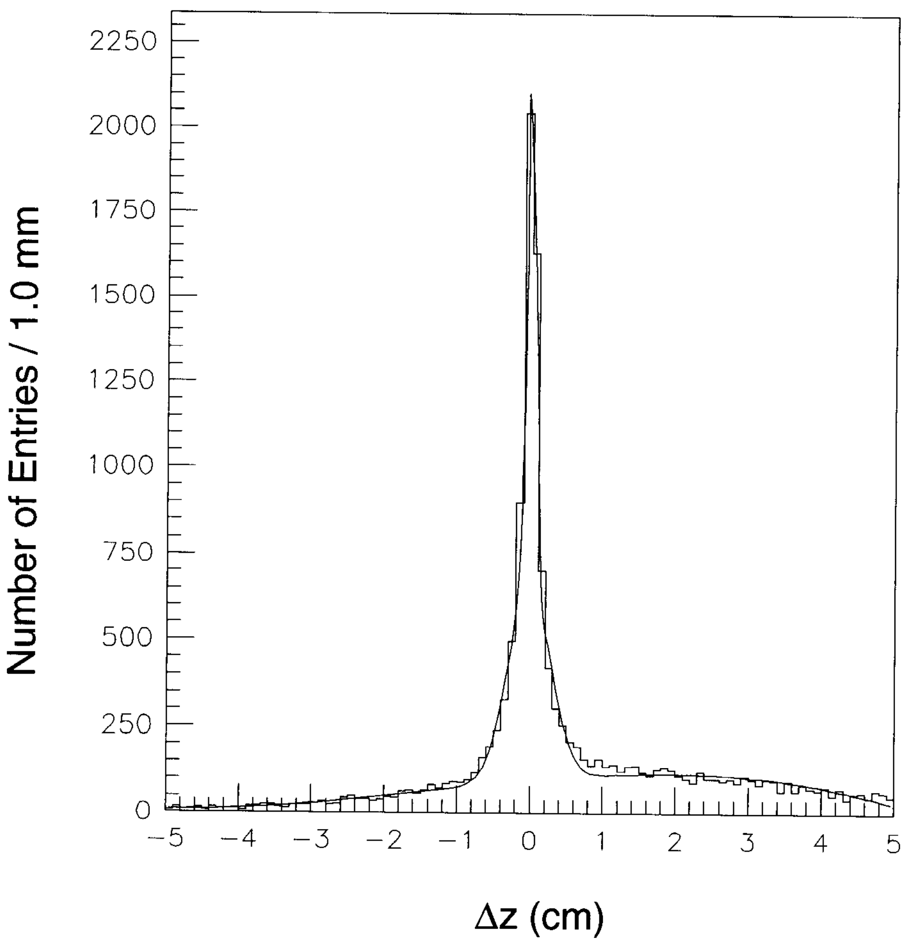

Figure 2: Distribution of Δz for dimuon events. The solid line is a fit described in the text.

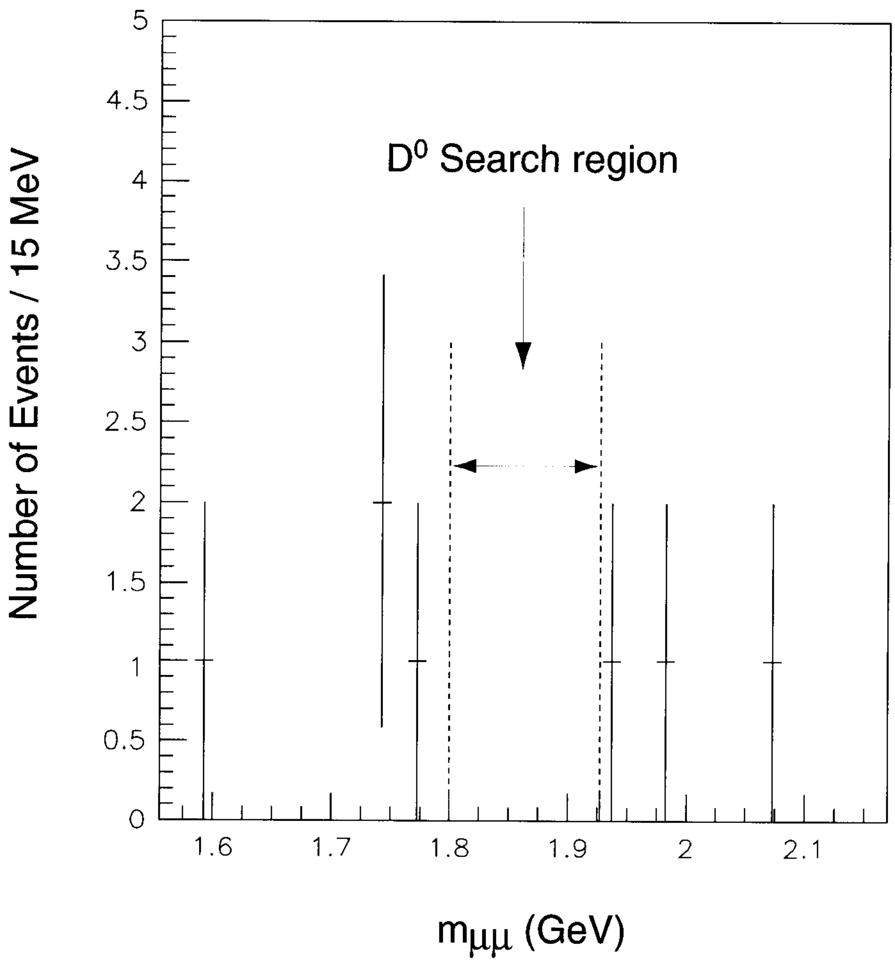

Figure 3: Mass distribution for the unlike-sign D^0 dimuon candidates. The final search region for a D^0 signal is indicated by the double arrow.