Search for the Decay $D^0 \to \mu^+\mu^-$

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Abstract

Using a silicon-microstrip detector array to identify secondary vertices occurring downstream of a short platinum target, we have searched for the decay $D^0 \to \mu^+\mu^-$. Normalized relative to the $J/\psi \to \mu^+\mu^-$ signal observed in the same data sample, for a 3.25-mm minimum decay distance our branching-ratio sensitivity is $(4.8 \pm 1.4) \times 10^{-6}$ per event, and after background subtraction we observe -4.1 ± 4.8 events. Using the statistical approach advocated by the Particle Data Group, we obtain a limit $BR\,(D^0 \to \mu^+\mu^-) < 3.1 \times 10^{-5}$ at 90% confidence, confirming with a different technique the limit previously obtained by Louis *et al.* The interpretation of the upper limit involves complex statistical issues; we present another approach which is more suitable for combining the results of different experiments.

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I. INTRODUCTION

The decay $D^0 \to \mu^+\mu^-$ is sensitive to flavor-changing neutral-currents (FCNC), which are forbidden at tree level in the Standard Model [1]; it is thus a potential window on new physics. Extensions of the Standard Model have been proposed in which FCNC could be substantially enhanced, including extended technicolor [2], composite models, supersymmetric models [3], and models with tree-level flavor-changing couplings [4]. While stringent limits have been set on FCNC in K decay [5], these do not necessarily apply to charm, since FCNC might couple differently to "up-type" (u, c, and t) and "down-type" (d, s, and b) quarks [6]. It is thus important to search for FCNC in charm decays.

II. APPARATUS AND DATA SAMPLE

We have carried out a search for $D^0 \to \mu^+\mu^-$ while commissioning an experiment (Fermilab E789) to search for rare decays of beauty. The Fermilab Meson-East spectrometer (see Figure 1) has been described elsewhere [7]. For this measurement, the six multiwire proportional chambers (MWPCs) following the SM12 analyzing magnet were replaced with a set of six small-cell drift chambers, and an array of eight silicon-microstrip detectors (SMDs) was added upstream of that magnet to reconstruct decay vertices of long-lived particles. SM12 was operated at a current of 1000 amperes, giving a transverse momentum kick of 1.77 GeV, suitable for the detection of two-prong charm decays.

A rectangular platinum target 0.2 mm high $\times$ 1.2 mm long $\times$ 5 cm wide was employed, with the 800-GeV primary proton beam incident on its narrow edge (Figure 2). The primary interaction vertex was thus localized in two dimensions, so that only the decay vertex needed to be reconstructed with the SMD array. Vacuum extended from upstream of the target to a 125-μm-thick titanium window located 28 cm downstream of the target, ensuring that interactions in windows or in air could not be confused with decay vertices.

The SMDs were $5\,\mathrm{cm} \times 5\,\mathrm{cm} \times 300\,\mu\mathrm{m}$ in size and featured 50-μm strip pitch. As shown in Figure 2, they were located from 37 to 78 cm downstream of the target and grouped into two arms of four detectors each, covering vertical-angle ranges (+20 to +60) mr and (-20 to -60) mr in the laboratory frame with respect to the beam direction. Within those angular ranges, 3,776 strips were instrumented with Fermilab-Penn preamplifiers [8] and Nevis Laboratories MWPC amplifier/discriminators and latches.

Following each arm was a thin scintillation counter used for triggering. The trigger required a pair of oppositely-charged muons originating in or near the target and traversing the spectrometer, with one track passing to the left and one to the right of the vertical centerline. The data sample corresponds to $\approx 5 \times 10^{11}$ interactions in the target, obtained at an average rate of $\approx 3 \times 10^6$ interactions/s using about $(1-2) \times 10^{10}$ protons per 20-second beam spill.

III. ANALYSIS AND EVENT SELECTION

In the off-line analysis, events are required to have hits consistent with each muon track in at least four of the five detector planes behind the hadron absorber, as well as energy deposit in the calorimeter consistent with the passage of a pair of minimum-ionizing particles. Figure 3 shows the distribution in mass of events satisfying these muon-identification criteria. The J/ψ resonance is clearly visible, with $N_{J/\psi} = 1088 \pm 36$ events in the rapidity interval $0.1 < y < 0.5$ within which our acceptance is concentrated. For this test data sample, the luminosity and efficiency are difficult to determine precisely, so we use the observed J/ψ yield to normalize our sensitivity to $D^0 \to \mu^+\mu^-$.

The resolution in mass for the J/ψ is dominated by multiple scattering of the muons in the target material. To determine the expected mass resolution for two-body D decays occurring outside the target, we use data from a subsequent run of our experiment [9], also carried out at 1000-ampere SM12 current. In that sample we reconstruct the decays $D^0/\overline{D}^0 \to K^\mp\pi^\pm$ at an observed mass 1868.5 ± 0.5 MeV with 8.4 ± 0.5 MeV RMS resolution. Any $D^0 \to \mu^+\mu^-$ events should thus be observed at that mass and with that resolution. (The small difference between our observed D^0 mass and the world-average value [10] reflects the calibration accuracy of our spectrometer [11].)

Figure 4a shows the mass distribution of dimuon events near the D mass satisfying the requirements $b_1 < 0\,\mu$m, $b_2 > 0\,\mu$m, $|y_v| < 250\,\mu$m, and $2 < z_v < 18$ mm, and Figure 4b shows the two-dimensional distribution of these events in mass and z_v. No $D^0 \to \mu^+\mu^-$ signal is evident, and a deficit of events is observed at the D^0 mass at the few-mm decay distances which (as indicated in Figure 4c) in our experiment are characteristic of the D^0 lifetime. In the region of Figure 4a the continuum is well fit by a first-order polynomial in mass times a sum of two exponentials in z_v (Figure 5). While the first, more-steeply falling exponential approximates the Gaussian tail of the vertex resolution, the more-slowly falling exponential background at large z_v is most likely due to real physics processes such as semileptonic decay of strange and charmed particles and the non-Gaussian plural- and single-scattering tails of measurement-error distributions, which will continue to be important even for searches with better vertex resolution than the $\approx$ 1-mm RMS provided by our SMD array (though vertex reconstruction in three dimensions might allow further suppression of this background). To suppress the more-steeply falling exponential background component, we require $z_v > 3.25$ mm. (Tighter requirements than this have no significant effect on the net number of signal events, but they reduce our sensitivity due to the exponential falloff of D decays.) We subtract the continuum fit from the data to obtain the net number of signal events; the subtracted spectrum is shown in Figure 6. Within the signal bin $1852 < m < 1885$ MeV we observe -4.1 ± 4.8 events.

IV. BRANCHING RATIO

To relate the observed event deficit to the branching ratio for $D^0 \to \mu^+\mu^-$, we normalize to the observed J/ψ signal, since triggering and reconstruction efficiencies, as well as absolute-normalization uncertainties, are thereby largely cancelled. The result thus depends on the assumed cross section and production and decay models for the J/ψ as well as those for the D.

Three experiments [12] have studied D production in 800-GeV p-N collisions; they find a good fit to the form $d^2\sigma/dx_F dp_t^2 \propto (1-|x_F|)^n \exp(-bp_t^2)$. We have averaged their results to obtain $n = 7.7 \pm 1.4$, $b = 0.86 \pm 0.07\,\text{GeV}^{-2}$, and we use these values to estimate the acceptance times efficiency $\eta_D = (1.74 \pm 0.24) \times 10^{-4}$ for detection of $D^0 \to \mu^+\mu^-$. Due to the vertex requirements, the D^0 acceptance also depends on the mean D^0 lifetime, which we take as $(4.20 \pm 0.08) \times 10^{-13}$ s [10]. Averaging the cross-section measurements [12] for charged and neutral D mesons, we obtain $\sigma\,(pN \to D^0\,X) + \sigma\,(pN \to \overline{D}^0\,X) = (20.9 \pm 3.5)\,\mu$b/nucleon.

The J/ψ cross section at 800 GeV has not yet been published, but measurements of the cross section differential in rapidity ($d\sigma/dy$) are available from the CERN ISR at values of $\sqrt{s}$ above and below ours. Using an exponential fit to the differential cross section vs. $\sqrt{\tau}$ ($\equiv m/\sqrt{s}$) measured by Clark *et al.* [13], we interpolate to $\sqrt{\tau} = 0.08$ to obtain $BR\,(J/\psi \to \mu^+\mu^-) \times d\sigma_{J/\psi}/dy|_{y=0} = 9.4 \pm 0.9 \pm 0.5$ nb/nucleon. (Our results from a subsequent data sample [14] confirm this value.) To estimate the J/ψ acceptance we assume that $d\sigma_{J/\psi}/dy$ is independent of the center-of-mass rapidity y over $0 < y < 0.5$, and that the tranvserse-momentum distribution is proportional to $p_t \exp\,(-bp_t)$, with $b = 1.27 \pm 0.06\,\text{GeV}^{-1}$ [13]; we find the acceptance times efficiency $\eta_{J/\psi} = (8.42 \pm 0.45) \times 10^{-3}$ averaged over $0.1 < y < 0.5$.

Since we use a platinum target, our branching-ratio sensitivity depends on the target atomic-weight (A) dependences of J/ψ and D production. We assume $\sigma_{J/\psi} \propto A^{0.90 \pm 0.01}$ [15] and $\sigma_D \propto A^{1.00 \pm 0.03}$ [16,9].

The branching ratio is then given by

$$BR\,(D^0 \to \mu^+\mu^-) = A^{-0.10} \times \frac{\Delta y\; BR\,(J/\psi \to \mu^+\mu^-)\; d\sigma_{J/\psi}/dy|_{y=0}}{\sigma(D^0) + \sigma(\overline{D}^0)}\, \frac{\eta_{J/\psi}}{\eta_D}\, \frac{N_D}{N_{J/\psi}}\,.$$

The single-event sensitivity is $(4.8 \pm 1.4) \times 10^{-6}$. Using the method of Helene [17] advocated by the Particle Data Group, we obtain an upper limit of 6.4 events and branching ratio $< 3.1 \times 10^{-5}$ at 90% confidence, confirming (with worse sensitivity) the 1.1×10^{-5} obtained by Louis *et al.* [18] using a π^- beam and no vertex detection.

V. BAYESIAN VS. CLASSICAL UPPER LIMITS

Due to statistical fluctuations of the background, an event deficit such as we observe is a not-unlikely occurrence; indeed, if the signal-to-background ratio is sufficiently small, 50% of experiments will observe a negative background-subtracted signal. Opinions differ on how to derive an upper limit from such an observation, and considerable literature exists on the statistical issues of setting an upper limit [17,19–23]. Avignone *et al.* [20] and James and Roos [21] have emphasized that an upper limit is an *interpretation* of data and can be derived in various ways, which might be based on the "classical" or the "Bayesian" approach to statistics. The Particle Data Group (PDG) advocate a Bayesian approach [17,10] in which the number of events observed in the region of interest is compared to the number outside that region. James and Roos point out, however, that Bayesian approaches lead to a biased estimator in the neighborhood of an unphysical region [24] (as in the present case, in which the observed signal size is negative), and they emphasize that the primary duty of experimentalists is to provide *unbiased* results which can be combined with other measurements. We therefore advocate interpreting our observed event deficit as a (negative) branching ratio, as follows.

We observe -4.1 ± 4.8 events, implying a branching ratio of $(-1.9 \pm 2.2) \times 10^{-5}$ and a classical upper limit of 9×10^{-6} at 90% confidence. We infer from Figure 1 of Louis *et al.* [18] that their observed branching ratio was $(-0.4 \pm 1.2) \times 10^{-5}$. Averaging this result and ours, we obtain $BR\,(D^0 \rightarrow \mu^+\mu^-) = (-0.7 \pm 1.1) \times 10^{-5}$, implying the "world-average" classical upper limit $BR\,(D^0 \rightarrow \mu^+\mu^-) < 6 \times 10^{-6}$ at 90% confidence [25].

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is that not just the number of events observed in the signal region but also their distributions affect the likelihood that a signal is present. Cousins [23] has recently proposed a method to take into account the known signal shape if little background is observed, but a generalization to the case of significant background has not been presented.

[25] According to Cousins and Highland [22], the limits should be increased somewhat due to the systematic normalization uncertainty, but as it is unclear how to do this and the effect is probably small, we follow Louis *et al.* in neglecting this effect.

FIGURES

FIG. 1. Plan view of E789 spectrometer.

FIG. 2. Vertex SMD array; only the instrumented portion of each detector is shown.

FIG. 3. Dimuon mass distribution. The plot contains a total of 16,160 dimuon events, of which sideband subtraction gives 1551 ± 45 J/ψ events.

FIG. 4. a) Dimuon mass distribution after requirements described in text; b) two-dimensional distribution in mass and z_v of events from a portion of Figure 4a, with dashed lines delimiting the signal mass bin; c) two-dimensional distribution in mass and z_v of Monte-Carlo $D^0 \to \mu^+\mu^-$ events; comparison of Figures 4b and c shows the deficit of observed events in the range of mass and z_v expected for $D^0 \to \mu^+\mu^-$.

FIG. 5. Distribution in z_v of events in Figure 4a; the curve is the fit $1430e^{-2.0z_v} + 62e^{-0.33z_v}$. (Monte-Carlo simulation shows that $D^0 \to \mu^+\mu^-$ events would fall as $e^{-0.26z_v}$.)

FIG. 6. Net events after background subtraction; the errors include a contribution due to the statistical uncertainty of the background fit. The dashed lines delimit the signal bin.