SEARCH FOR THE DECAY $D^0 \rightarrow \mu^+ \mu^-$

The BEATRICE Collaboration

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Abstract

We have searched for the decay $D^0 \rightarrow \mu^+ \mu^-$ among 1.25×10^5 $\mu^+ \mu^-$ pairs produced by 350 GeV/c π^- particles interacting in copper and tungsten targets. Using a high-resolution silicon-microstrip detector followed by a large-acceptance magnetic spectrometer and a muon filter we are able to discriminate between prompt and non-prompt muons and to measure dimuon masses. No candidate compatible with a $D^0 \rightarrow \mu^+ \mu^-$ decay has been found, allowing us to set an upper limit on the branching fraction $B(D^0 \rightarrow \mu^+ \mu^-)$ of 7.6×10^{-6} at 90 % confidence level.

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Flavour-changing neutral currents at the tree level are forbidden in the Standard Model [1]. The decay $D^0 \rightarrow \mu^+\mu^-$, mediated by charm-changing neutral currents, is therefore expected to acquire a non-vanishing branching fraction (B) only from higher-order diagrams. At the one-loop level $B(D^0 \rightarrow \mu^+\mu^-)$ has been evaluated to be $\sim 10^{-19}$ [2, 3]. Long-distance effects might increase this prediction to roughly 10^{-15} [3]. Such decay rates are too small to be measured. New physics beyond the Standard Model can modify the branching-fraction predictions by several orders of magnitude. For example, in the four-generation model, and for appropriate values of the mass and mixing of the fourth down-type quark, $B(D^0 \rightarrow \mu^+\mu^-)$ can be as high as 10^{-9} [4], a value which may be measured in future experiments. It is therefore interesting to explore the region beyond the current upper limit $B(D^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-5}$ [5].

In the present paper we give the results of a search for the decay $D^0 \rightarrow \mu^+\mu^-$, based on an analysis of events recorded during the 1992 data-taking period of the WA92 experiment, performed at the CERN Super Proton Synchrotron. Charmed particles were produced in the interactions of 350 GeV/c π^- particles in Cu and W targets. The apparatus, designed for study of the hadroproduction and decay of beauty particles, is described in detail elsewhere [6]. It consists (fig. 1) of a 2 mm thick target, preceded by a beam hodoscope and followed by a so-called in-target counter (IT), a Decay Detector, a Vertex Detector, a magnetic spectrometer, a pair of butterfly-shaped scintillator hodoscopes, an electromagnetic calorimeter and a muon filter. The beam hodoscope, consisting of 10 planes of 20 μm pitch silicon-microstrip detectors (SMD), allows measurement of the transverse coordinates of the interaction vertex. The IT counter, placed immediately downstream of the target, is a 300 μm thick SMD plane of 200 μm pitch. It provides a fast trigger signal if a charge equivalent to at least five minimum-ionizing particles is released in any strip, there then being a 96 % probability that an interaction has occurred in the target. A coincidence between the IT counter and scintillation counters placed upstream and downstream of the target defines the interaction trigger. The Decay Detector [7] consists of seventeen SMD planes with 10 μm pitch, for a total of 8704 analogue read-out channels. This device, which gives a high-resolution picture of the events, extends over the first 32 mm downstream of the target and contains most of the identified charm decays. The Vertex Detector is made of twelve SMD planes of 25 μm pitch and five SMD planes of 50 μm pitch. The Ω' spectrometer [8] is composed of a superconducting dipole magnet ($B_{\text{max}} = 1.8$ T; $\int B d\ell = 7.3$ Tm) filled with multiwire proportional chambers, containing a total of 50 planes with pitch of 1 or 2 mm. Two multiwire chambers, each having two planes of 4 mm pitch, and two large drift chambers, each having four planes giving a spatial resolution of 200 μm , are located just downstream of the magnet. The spectrometer allows measurement of charged-particle momenta to an accuracy of $\Delta p/p^2 = 1.6 \times 10^{-4}$ (GeV/c) $^{-1}$. The magnetic spectrometer is followed by two butterfly-shaped scintillator hodoscopes that only detect particles with $p_{\text{T}} \geq 0.6$ GeV/c, an electromagnetic calorimeter, not used in the present analysis, and a muon hodoscope. This hodoscope [9] is composed of two Resistive Plate Chamber (RPC) detectors [10], each covering an area of 12 m 2 . The first RPC detector is placed behind a 2 m thick iron absorber, which acts as a beam dump. The core of this dump is made of tungsten discs having diameters increasing from 58 mm to 208 mm. The second RPC detector, placed 16 m downstream of the target, is separated from the first by a 1.2 m thick iron absorber. Each RPC detector is divided into three planes, two measuring the vertical coordinate and one measuring the horizontal coordinate, all planes having 31 mm pitch read-out strips. A fast processor [11] reconstructs muon tracks in the non-

bending vertical plane and selects muon tracks that point to the target region. Only muons with a momentum $p_\mu \geq 7 \text{ GeV}/c$ reach the second RPC detector. The angular acceptance of the muon hodoscope ranges from 0 to $\pm 180 \text{ mrad}$ in the horizontal plane and from $\pm 8 \text{ mrad}$ to $\pm 70 \text{ mrad}$ in the vertical plane, requiring a minimum p_T of about $100 \text{ MeV}/c$.

Figure 1: Experimental set-up: Target (T), silicon-microstrip detectors (SMD), multiwire proportional chambers (MW), drift chambers (D), butterfly-shaped hodoscopes (BH), electromagnetic calorimeter (EC) and muon filter comprising beam dump (BD) and resistive-plate chambers (RPC). Enlarged views show the arrangement of the SMD planes as beam hodoscope, in-target counter (IT), decay detector (DkD) and vertex detector (VD).

The dimuon trigger requires two tracks in the muon hodoscope in coincidence with an interaction trigger. In the 1992 data-taking period we collected with Cu(W) target an integrated luminosity of $2.82 (1.53) \text{ nb}^{-1}$, which corresponds to $3.26 (7.6) \times 10^5$ dimuon triggers. The majority of these are due to decays in flight of π and K mesons, so that in only 20 % of cases are the tracks of the two triggering muons reconstructed back to the region of the SMD, giving with Cu(W) target 52488 (72666) opposite-sign and 37470 (50706) same-sign reconstructed dimuons. Reconstruction of the recorded events is performed using the computer program Trident [12], which identifies tracks and, where possible, assigns them to a primary or secondary vertex. The invariant-mass

distributions obtained are shown in fig. 2, for same-sign and opposite-sign dimuons, the ρ^0 - ω , ϕ and J/ψ peaks being clearly visible in the case of the latter. The peaks of the ρ^0 and ω resonances are not separated because the difference between the ρ^0 mass and the ω mass is small compared to the ρ^0 width. The low minimum p_T of the muons (~ 100 MeV/ c) is reflected in the high acceptance for low dimuon masses. Multiple scattering in the target substantially affects the experimental mass resolution for dimuons that originate in the target itself. This resolution changes from 21.6 ± 2.8 (32.0 ± 3.5) MeV/ c^2 (FWHM) at the ϕ mass to 64.3 ± 3.4 (66.9 ± 3.6) MeV/ c^2 at the J/ψ mass for the Cu (W) target. To determine the expected mass resolution for a decay $D^0 \rightarrow \mu^+\mu^-$, where most D^0 decays occur outside of the target, we have reconstructed the decay $D^0(\overline{D}^0) \rightarrow K^\mp\pi^\pm$ and found (fig. 3a) a mass resolution of 20.3 ± 0.3 MeV/ c^2 (FWHM), independent of target material. Using a Monte Carlo (MC) simulation we have scaled this value to the $D^0 \rightarrow \mu^+\mu^-$ case and here expect a mass resolution of 17.9 ± 0.3 MeV/ c^2 (FWHM).

Figure 2: Invariant-mass spectra for same-sign (shaded) and opposite-sign dimuons. The ρ^0 - ω , ϕ and the J/ψ regions are shown separately. Data obtained with the Cu and W targets have been summed.

The sensitivity of the search for the decay $D^0 \rightarrow \mu^+ \mu^-$ has been determined from a detailed MC simulation of the experimental situation. Events containing a pair of charmed quarks are generated, with Pythia 5.4 and Jetset 7.3 [13] used to describe the hard process and quark fragmentation and Fluka [14] determining the characteristics of all other interaction products, also taking into account the composition of the target nucleus. Tracking of particles through the experimental apparatus is performed using Geant 3.21 [15]. Detector inefficiencies and random noise are included and the trigger response is fully simulated. According to the MC simulation, an event in which a $D^0(\bar{D}^0)$ is produced in the target at $x_F \geq 0$ and decays into $\mu^+ \mu^-$ would be triggered and have the two muons reconstructed in 19 % of cases.

We have verified that using acceptances given by the MC simulation we measure a rate for $J/\psi \rightarrow \mu^+ \mu^-$ that is consistent with results obtained in other experiments. The J/ψ production has been simulated in accordance with experimentally determined p_T and x_F distributions [16], including both the hard and diffractive components of the production mechanism. According to the MC calculation 25 % of the J/ψ produced in the target at $x_F \geq 0$ and decaying into $\mu^+ \mu^-$ are reconstructed. Parameterizing the cross-section for J/ψ production as $\sigma(x_F \geq 0) = \sigma_0 \times A^\alpha$ with $\alpha = 0.9$ [17] and assuming that the branching fraction for $J/\psi \rightarrow \mu^+ \mu^-$ is 0.06 [18], the 675 ± 29 $J/\psi \rightarrow \mu^+ \mu^-$ events found experimentally with the Cu and W targets give $\sigma_0 = 159 \pm 8$ nb, which is in very good agreement with the value of 169 ± 4 nb predicted by a global fit [17] to other experimental results obtained at different energies and with a variety of target materials. This agreement gives us confidence in our MC predictions and in particular

Figure 3: *a)* Invariant-mass distribution for secondary vertices formed by two charged tracks, in the hypothesis that one track is a kaon and the other is a pion. The peak from the $D^0(\bar{D}^0) \rightarrow K^\mp \pi^\pm$ decay is superimposed on the physical and combinatorial background. *b)* Comparison of the inclusive $D^0(\bar{D}^0)$ cross-section measured in the present experiment from the $D^0(\bar{D}^0) \rightarrow K^\mp \pi^\pm$ signal, with that obtained by other experiments [20] at different π^- beam energies and with different target materials. In all of the cross-section calculations it has been assumed that there is a linear A-dependence and the PDG 1994 [18] branching fractions have been used. The line represents the total $c\bar{c}$ cross-section as given by perturbative QCD [21], normalized to the experimental points.

in the simulation of the two-muon trigger.

As a further check the inclusive cross-section for production of D^0 or $\overline{D}^0$ has been deduced from the observed $D^0(\overline{D}^0) \rightarrow K^\mp \pi^\pm$ events and compared with existing measurements. The decay considered is detected in events selected when an interaction trigger coincides with there being at least two secondary tracks flagged by an online processor [19] and at least one (two) high- p_T particle(s) in the butterfly-shaped hodoscopes for the Cu (W) data. The overall acceptance for $D^0(\overline{D}^0) \rightarrow K^\mp \pi^\pm$ events ($x_F \geq 0$) is 1.3 % for the Cu target and 0.63 % for the W target. Parameterizing the cross-section for production of D^0 or $\overline{D}^0$ as $\sigma(x_F \geq 0) = \sigma_0 \times A^\alpha$, then taking $\alpha = 1$ and $B(D^0 \rightarrow K^- \pi^+) = 0.04$ [18], the 1406 ± 67 $D^0(\overline{D}^0) \rightarrow K^\mp \pi^\pm$ events recorded with the Cu and W targets (fig. 3a) yield $\sigma_0 = 8.4 \pm 0.7 \mu\text{b}$, which is in good agreement (fig. 3b) with the values obtained in other experiments [20]. The MC reproduces well not only the measured trigger rates for $J/\psi \rightarrow \mu^+ \mu^-$ and $D^0(\overline{D}^0) \rightarrow K^\mp \pi^\pm$ but also the observed charged-particle multiplicities and kinematics.

In the off-line analysis, MC simulated events and experimental data are treated in the same way. Muons are classified as primary (P), secondary (S), or extra (E) when associated respectively to the primary vertex, to a secondary vertex or to no vertex at all. The 1088 opposite-sign dimuon events (439 from Cu target and 649 from W target) comprised in the mass interval $1.8 - 1.92$ GeV/c^2 are then divided into 7 categories, according to the classification of the two muons. Events where the two muons are associated to a single secondary vertex (S=S category) are distinguished from events where the two muons are associated to different secondary vertices (S $\neq$ S category). In Table 1 we report the sharing between the 7 categories of these events and of the MC simulated $D^0 \rightarrow \mu^+ \mu^-$ events accepted by the trigger. The $D^0 \rightarrow \mu^+ \mu^-$

Table 1: Sharing between the seven categories defined in the text of the Monte Carlo simulated $D^0 \rightarrow \mu^+ \mu^-$ events and of the opposite-sign dimuons recorded in the experiment with a mass $1.8 \leq m(\mu^+ \mu^-) \leq 1.92$ GeV/c^2 . The percentages are similar for the Cu and W targets. Comparison of MC and experimental data allows determination of the categories where the signal-to-noise ratios are more favourable.

	category						
	PP	PS	PE	S=S	S $\neq$ S	SE	EE
MC	16.2%	9.8%	13.8 %	28.1%	5.1%	15.9 %	11.1%
Data	27.1%	7.7%	39.1 %	0.7%	0.3%	8.2 %	16.9%

simulated events do not only populate the S=S category. In particular, events where the $D^0(\overline{D}^0)$ has a short decay length are often assigned to the PP or PE category, and for an event where the $D^0(\overline{D}^0)$ decay length is large a reconstruction error may result in a wrong category assignment. Following the event classification we have carried out two different analysis procedures.

In the first analysis procedure we consider only events belonging to the S=S category, where conditions for finding $D^0 \rightarrow \mu^+ \mu^-$ candidates are most favourable. We then request that the dimuon momentum points towards the primary vertex by selecting those events where the distance in space ($d_{\mu\mu}$) between the dimuon line-of-flight and the primary vertex is less than $40 \mu\text{m}$. This selection criterion has been deduced from the MC simulation and from the corresponding $d_{K\pi}$ distribution (fig. 4a) obtained from

Figure 4: a) Distribution of the distance in space ($d_{K\pi}$) between the line-of-flight of the $K^\mp\pi^\pm$ system and the primary vertex, for the $D^0(\bar{D}^0) \rightarrow K^\mp\pi^\pm$ events (fig. 3a) after background subtraction. b) and c) Correlation between mass and $d_{\mu\mu}$ for S=S events from experiment and MC simulation respectively. The dashed line delimits the zone considered in the first analysis procedure.

the observed $D^0(\bar{D}^0) \rightarrow K^\mp\pi^\pm$ events. In fig. 4b we show the dimuon mass as a function of $d_{\mu\mu}$ for all the S=S events within the mass interval 1.8–1.92 GeV/c^2 . No event is found in the region defined by $1.84 \leq m(\mu^+\mu^-) \leq 1.88 \text{ GeV}/c^2$ and $d_{\mu\mu} \leq 40 \mu\text{m}$, which would contain (fig. 4c) 90 % of the $D^0 \rightarrow \mu^+\mu^-$ decays belonging to the S=S category. The overall acceptance of this first analysis procedure for $D^0 \rightarrow \mu^+\mu^-$ events generated in the target at $x_F \geq 0$ is 4.8 %.

In the second analysis procedure we exploit the imaging capabilities of the Decay Detector and perform an interactive scanning of $D^0 \rightarrow \mu^+\mu^-$ candidates. This allows the use of less stringent selection criteria, so that the acceptance for $D^0 \rightarrow \mu^+\mu^-$ is increased. In this procedure, we first reject events belonging to the PP and PE categories, where there is highest background contamination. Subsequently, an event is accepted for analysis if the distance of closest approach in space of the two muon tracks is less than 0.5 mm. This loose requirement reduces the number of events to be scanned by a factor ~ 3 , whereas only 9 % of the $D^0 \rightarrow \mu^+\mu^-$ MC events are lost. In fig. 5a, we show the invariant-mass distribution of the 118 dimuons – 42 from Cu target and 76 from W target – that survive the selection stage and have a mass in the region 1.8–1.92 GeV/c^2 , which would contain 90 % of the $D^0 \rightarrow \mu^+\mu^-$ decays belonging to the categories considered. These events are scanned using an interactive graphical analysis program. Only two events (fig. 5a) are found where the two muons come from the same secondary vertex and no other reconstructed tracks emerge from this vertex. At this level the background is essentially due to secondary interactions occurring in the Decay Detector and giving rise to just two charged particles that decay in flight before reaching the muon filter. Such secondary interactions are characterized by a large energy release in the SMD planes, close to the interaction point and, as shown in the example of fig. 5b, may easily be identified on the basis of the analogue information of the Decay Detector. After discarding events where the two muons emerge from a secondary interaction, no event compatible with a $\mu^+\mu^-$ decay has been found in the mass interval 1.8–1.92 GeV/c^2 , for either Cu or W target. To determine the efficiency

Figure 5: a) Invariant-mass distribution of the opposite-sign dimuons selected, in the second analysis procedure, for the interactive graphical analysis. The curve that represents the expected position and width of a $D^0 \rightarrow \mu^+\mu^-$ decay, is normalized to the previous limit $B(D^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-5}$. The two shaded events survive the visual scanning but are discarded on the basis of energy deposition in the Decay Detector. b) Display of the event that survives the visual scanning and has a dimuon mass of ~ 1.86 GeV/c^2 . The shaded area corresponds to the target. Hits on the first 13 planes of the Decay Detector and tracks reconstructed in the magnetic spectrometer are shown: solid line for muons, dashed lines for other particles. The length of the segment displayed for each fired microstrip is proportional to the energy released in that strip. The large energy released around the secondary vertex is typical of a hadronic interaction. This and the large value of $d_{\mu\mu} \simeq 144$ μm allow us to discount the possibility that there is a $D^0 \rightarrow \mu^+\mu^-$ decay.

of the graphical analysis, MC events have been scanned in exactly the same way as the experimental data, and 75 ± 5 % of the $D^0 \rightarrow \mu^+\mu^-$ decay were recognized. To estimate the error on this efficiency, the scanning was repeated by different observers. The overall acceptance of the second analysis procedure for $D^0 \rightarrow \mu^+\mu^-$ events generated in the target at $x_F \geq 0$ is 8.1 %, including the scanning efficiency. Therefore, to determine the upper limit on $B(D^0 \rightarrow \mu^+\mu^-)$ we use the results of this second procedure, which yields no $D^0(\bar{D}^0) \rightarrow \mu^+\mu^-$ candidate, the same as the first procedure, and has the larger acceptance.

In order to deduce an upper limit for the branching fraction $B(D^0 \rightarrow \mu^+\mu^-)$ independently of the total cross-section for $D^0(\bar{D}^0)$ production, we normalize our result obtained with Cu and W targets to the observed $D^0(\bar{D}^0) \rightarrow K^\mp\pi^\pm$ decay rate, so that:

$$B(D^0 \rightarrow \mu^+\mu^-) = B(D^0 \rightarrow K^-\pi^+) \times \frac{N_{\mu\mu}}{\varepsilon_{\mu\mu}} \times \left(\frac{N_{K\pi}^{\text{Cu}}}{\varepsilon_{K\pi}^{\text{Cu}}} + \frac{N_{K\pi}^{\text{W}}}{\varepsilon_{K\pi}^{\text{W}}} \right)^{-1}$$

where $N_{\mu\mu} = 2.3$ is, at 90 % confidence level, the upper limit on the number of $D^0(\bar{D}^0) \rightarrow \mu^+\mu^-$ events; $\varepsilon_{\mu\mu} = 8.1$ % is the acceptance for $D^0(\bar{D}^0) \rightarrow \mu^+\mu^-$ events ($x_F \geq 0$); $N_{K\pi}^{\text{Cu}} = 873 \pm 52$ and $N_{K\pi}^{\text{W}} = 533 \pm 43$ are the numbers of $D^0(\bar{D}^0) \rightarrow K^\mp\pi^\pm$ events observed with the Cu and W targets respectively and $\varepsilon_{K\pi}^{\text{Cu}} = 1.3$ % and $\varepsilon_{K\pi}^{\text{W}} = 0.63$ % are the corresponding overall acceptances ($x_F \geq 0$). Assuming that the branching fraction for $D^0 \rightarrow K^-\pi^+$ is 0.04 [18], we set an upper limit on the branching

fraction $B(D^0 \rightarrow \mu^+ \mu^-)$ of 7.6×10^{-6} at 90 % confidence level. Statistical errors on MC calculations and systematic errors on the whole analysis procedure can affect this value by ~ 10 %. The value we obtain may be compared with the previous published limit at 90 % confidence level of 1.1×10^{-5} [5] and with two new measurements performed at Fermilab, where the E789 Collaboration and the E771 Collaboration have determined upper limits of 3.1×10^{-5} [22] and 1.7×10^{-5} [23] respectively.

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