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Search for the Flavour-Changing Neutral-Current Decay $D^0 \to \mu^+\mu^-$

The BEATRICE Collaboration

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Abstract

We have searched for the decay $D^0 \to \mu^+\mu^-$ among 2.0×10^5 $\mu^+\mu^-$ pairs produced, in the WA92 experiment, 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 measure the momentum of the muons, to visualize the event topology near their point of origin, and thus to discriminate between prompt and non-prompt muons. No $D^0 \to \mu^+\mu^-$ candidate has been found. This result allows us to set an upper limit on the branching fraction B($D^0 \to \mu^+\mu^-$) of 4.1×10^{-6} at 90 % confidence level.

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In the Standard Model of electroweak interactions, flavour-changing neutral currents are forbidden at lowest order [1]. In particular, the decay $D^0 \to \mu^+\mu^-$, mediated by charm-changing neutral currents, is expected to acquire a non-vanishing branching fraction (B) only from higher-order diagrams. At the one-loop level $\mathrm{B}(\mathrm{D}^0 \to \mu^+\mu^-)$ has been evaluated to be of the order of 10^{-19} [2, 3]. Long-distance effects might increase this branching fraction to $\sim 10^{-15}$ [3]. It is because these predictions are extremely small that the decay $D^0 \to \mu^+\mu^-$ is a good channel to search for possible contributions from new physics beyond the Standard Model. Alternative models [3, 4] predict a branching fraction $\mathrm{B}(\mathrm{D}^0 \to \mu^+\mu^-)$ as high as 10^{-9}, a value that could be reached in the next generation of experiments. At present the best published limit on $\mathrm{B}(\mathrm{D}^0 \to \mu^+\mu^-)$ is 4.2×10^{-6} at 90 % confidence level [5].

Results based on data recorded by the BEATRICE collaboration in 1992 have already been published [6]. In this paper we present the final result based on the full statistics collected by the WA92 experiment at the CERN Super Proton Synchrotron, during the 1992 and 1993 data-taking periods. A new limit for the branching fraction $\mathrm{B}(\mathrm{D}^0 \to \mu^+\mu^-)$ is obtained.

Charmed particles were produced in the interactions of 350 GeV/c π^- particles in a W target during 1992 (W92 runs) and in a Cu target during 1992 (Cu92 runs) and 1993 (Cu93 runs). The apparatus is described in detail elsewhere [7]. Briefly, it consists of a 2 mm thick target preceded by a beam hodoscope and followed by a so-called in-target (IT) counter, a high-resolution silicon-microstrip detector (SMD), a large-acceptance magnetic spectrometer and a muon hodoscope.

The IT counter, placed immediately downstream of the target, is a 300 μm thick silicon-microstrip 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 SMD consists of a Decay Detector (DkD) followed by a Vertex Detector (VxD). The DkD is composed of seventeen 10 μm pitch silicon-microstrip planes placed in the first 3.2 cm downstream of the target, the region where most of the charm decays occur. In the 1993 data taking its configuration was slightly modified with respect to that of 1992. In particular, one of the planes that measured the z-coordinates[1] was rotated by 90°, thus improving the track reconstruction in the x-y projection. The VxD, which consists of 17 silicon-microstrip planes, was also modified for the 1993 data taking. Its ability to reconstruct tracks in space has been improved by using an additional y-measuring plane and two planes at ± 45°.

The magnetic spectrometer [8] is composed of the Ω' superconducting dipole magnet ($B_{\mathrm{max}} = 1.8$ T; $\int B d\ell = 7.3$ Tm) equipped with multiwire and drift chambers. It allows measurement of charged-particle momenta to an accuracy of $\Delta p/p^2 = 1.6 \times 10^{-4}$ $(\mathrm{GeV}/c)^{-1}$.

The muon hodoscope [9] consists of two Resistive Plate Chamber (RPC) [10] detectors. The first is placed 14 m downstream of the target, behind a 2 m thick iron absorber with a tungsten core, which acts as a beam dump. The second is placed 16 m downstream of the target and is separated from the first by a 1.2 m thick iron absorber. The muon hodoscope accepts muons with momentum $p_\mu \geq 7$ GeV/c pointing in the

[1] The right-handed coordinate system is defined so that the beam runs along the x axis and the magnetic field points upwards, parallel to the z axis.

angular interval from 0 to $\pm$ 180 mrad in the horizontal plane and from $\pm$ 8 mrad to $\pm$ 70 mrad in the vertical plane. This corresponds to a minimum p_T of about 100 MeV/c and a minimum dimuon mass of $\sim$ 200 MeV/c^2. Muons are identified, their momentum is measured and their tracks are reconstructed with high accuracy back to the charm decay region, so that $D^0 \to \mu^+\mu^-$ decays, if any, can be identified.

Dimuon events are selected by a dimuon trigger, which requires two muons in the muon hodoscope, in coincidence with an interaction trigger. Most of the decays $D^0(\overline{D}^0) \to K^\mp\pi^\pm$, which will be used for normalization, are detected, in the Cu (W) runs, by a secondary-vertex trigger [7], which uses the VxD information, in coincidence with at least one (two) high-p_T particle(s), and with an interaction trigger. Triggering events where the primary interaction is in the target or in the IT counter are accepted for the analysis.

The event-reconstruction program, Trident [7], has also been improved for the 1993 data analysis, so that the number of tracks incorrectly reconstructed or not assigned to a vertex is reduced compared to 1992.

As a consequence of the hardware and software improvements and of a better magnetic field stability, the tracks are reconstructed with a higher accuracy, so that the particle momenta and masses are determined with better precision for the 1993 data than for the 1992 data. In Fig. 1 and Table 1 we compare the invariant-mass distributions and the mass resolutions measured in the decays $\phi \to \mu^+\mu^-$, $D^0(\overline{D}^0) \to K^\mp\pi^\pm$, and $J/\psi \to \mu^+\mu^-$, and expected for the decay $D^0 \to \mu^+\mu^-$, for the Cu target, in the 1992 and 1993 set-ups. The improved track identification in 1993 is reflected also in a higher signal-to-background ratio, as shown in Fig. 1.

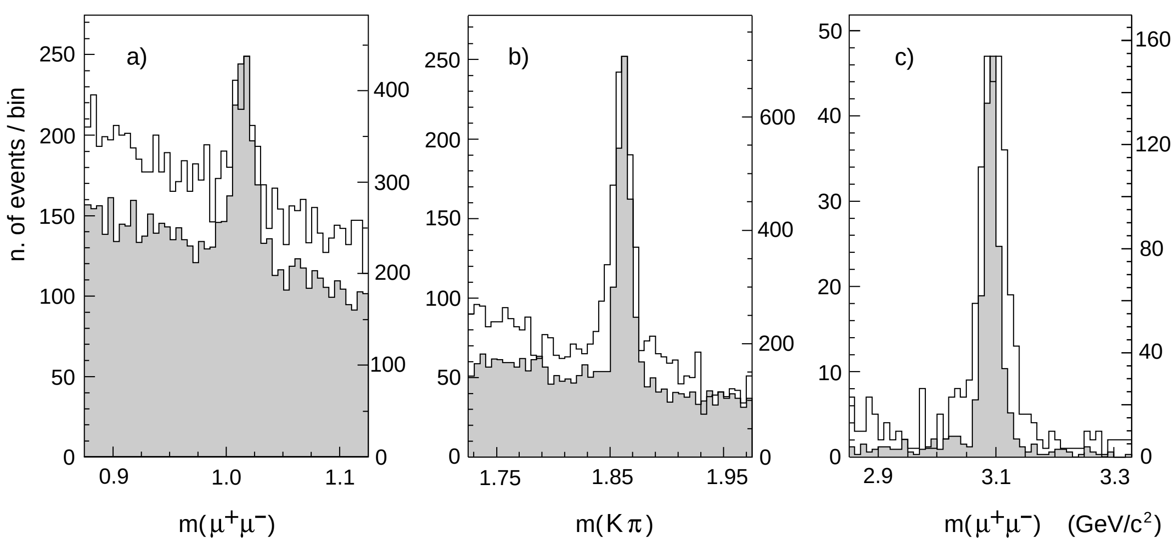

Figure 1: Invariant-mass distribution a): in bins of 5 MeV/c^2 for the decay $\phi \to \mu^+\mu^-$; b): in bins of 5 MeV/c^2 for the decay $D^0(\overline{D}^0) \to K^\mp\pi^\pm$ and c): in bins of 10 MeV/c^2 for the decay $J/\psi \to \mu^+\mu^-$, as measured with a Cu target in the data-taking periods of 1992 (non-shaded histograms and left scales) and 1993 (shaded-histograms and right scales).

The observed mass resolutions for the decays $\phi \to \mu^+\mu^-$ and $J/\psi \to \mu^+\mu^-$ are in part due to multiple scattering of the muons in the target. To determine the expected mass resolution for decays of the type $D^0 \to \mu^+\mu^-$, which would mostly occur outside the target, we have used the Monte Carlo (MC) simulation described below to scale

Table 1: Comparison between the FWHM mass resolution (Γ) observed for the decays $\phi \to \mu^+\mu^-$, $D^0(\overline{D}^0) \to K^\mp\pi^\pm$, $J/\psi \to \mu^+\mu^-$, and expected for the decay $D^0 \to \mu^+\mu^-$, with the 1992 and 1993 set-ups. All data refer to Cu target.

		decay channel			
		$\phi \to \mu^+\mu^-$	$D^0(\overline{D}^0) \to K^\mp\pi^\pm$	$J/\psi \to \mu^+\mu^-$	$D^0 \to \mu^+\mu^-$
Γ (MeV/c^2)	1992	21.6 ± 2.8	20.3 ± 0.3	64.3 ± 3.4	22.7 ± 0.4
	1993	20.9 ± 1.6	14.3 ± 0.2	47.2 ± 2.9	17.2 ± 0.3

the value of Γ observed for the $D^0(\overline{D}^0) \to K^\mp\pi^\pm$ decay to the $D^0 \to \mu^+\mu^-$ case. The results of this calculation are reported in the last column of Table 1 for the 1992[2] and 1993 set-ups.

Acceptances with the 1992 and 1993 set-ups have been determined from a detailed MC simulation. For the 1992 set-up the MC used for the previous analysis [6] has been revised. In particular, for the Cu92 runs, we have corrected for a partial inefficiency of a multiwire chamber, while, for the W92 runs, we have taken into account the fact that the trigger condition that accepts most of the $D^0(\overline{D}^0) \to K^\mp\pi^\pm$ events was, for ~ 10 % of the data taking period, looser than that simulated in the MC. We have also performed a more precise evaluation of the detection efficiency of the RPC planes. All these corrections are of the order of a few percent. Taking into account the updated value [11] of the branching fraction $\mathrm{B}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+) = 0.0383$, these corrections leave the limit on $\mathrm{B}(\mathrm{D}^0 \to \mu^+\mu^-)$ for the 1992 data practically unchanged relative to the value already published [6]. For the 1993 analysis the MC simulates the modified set-up described above.

During the Cu92, W92 and Cu93 data taking the effective integrated luminosities were respectively 2.65 nb^{-1}, 1.26 nb^{-1}, and 5.00 nb^{-1} for interactions in the target; 0.23 nb^{-1}, 0.15 nb^{-1}, and 0.44 nb^{-1} for interactions in the IT counter. The data correspond to a total of 3.0×10^6 dimuon triggers. Most of the muons come from pion and kaon decays in flight, so that the tracks of muon pairs are unambiguously reconstructed back to the SMD in only ~ 11 % of the cases, yielding 2.0×10^5 (1.4×10^5) opposite-sign (same-sign) dimuons. In order to check our muon acceptance we have measured [12] the $J/\psi \to \mu^+\mu^-$ rate, and found it in agreement with the J/ψ production cross-section obtained in other experiments.

The search for the decay $D^0 \to \mu^+\mu^-$ has been performed among 1633 opposite-sign dimuon events (439 from Cu92, 649 from W92 and 545 from Cu93) comprised in the mass interval 1.80$-$1.92 GeV/c^2. Muon tracks are classified as primary (P), secondary (S), or extra (E) when associated by the reconstruction program to the primary vertex, to a secondary vertex or to no vertex at all respectively . The events are then divided into 7 categories, according to the classification of the two muons. Events where the two muons are associated to a single secondary vertex (S=S category) are distinguished from events where the two muons are associated to different secondary vertices (S$\neq$S category). In the MC simulation, events containing a pair of charmed particles are generated using Pythia 5.4 and Jetset 7.3 [13] to describe the hard process and quark

[2] In Ref. [6] the expected width for the decay $D^0 \to \mu^+\mu^-$ was erroneously reported to be 17.9 Mev/c^2 instead of 22.7 MeV/c^2.

fragmentation and Fluka [14] to determine the characteristics of all other interaction products. The composition of the target nucleus is also taken into account. Dimuons coming from the MC simulated $D^0 \to \mu^+\mu^-$ decays are treated in the same way as the experimental data. In Table 2 we compare the sharing between the 7 categories for data and for MC simulated $D^0 \to \mu^+\mu^-$ events accepted by the trigger. The improvements introduced in the 1993 set-up are reflected in the smaller number of events with one muon not associated to a vertex (PE, SE and EE categories). The fact that, in about half of the MC events, the two muons are not assigned to the same vertex reflects the imperfect track and vertex reconstruction of Trident.

Table 2: Sharing between the seven categories defined in the text of the opposite-sign dimuons recorded experimentally with a mass $1.80 \leq \mathrm{m}(\mu^+\mu^-) \leq 1.92$ GeV/c^2, and of the Monte Carlo simulated $D^0 \to \mu^+\mu^-$ events. Results of the 1992 and 1993 analyses are quoted separately for comparison.

		category						
		PP	PS	PE	S=S	S≠S	SE	EE
Data	1992	27.1 %	7.7 %	39.1 %	0.7 %	0.3 %	8.2 %	16.9 %
	1993	56.7 %	11.4 %	21.5 %	2.2 %	0.7 %	2.9 %	4.6 %
MC	1992	16.2 %	9.8 %	13.8 %	28.1 %	5.1 %	15.9 %	11.1 %
	1993	17.5 %	10.0 %	10.1 %	38.5 %	5.6 %	13.6 %	4.7 %

Following this event classification we have carried out two different analysis procedures. In the first analysis procedure we consider only the events belonging to the S=S category, which is the most favourable for finding $D^0 \to \mu^+\mu^-$ candidates. We then request that the distance in space between the dimuon line-of-flight and the primary vertex is less than 40 μm. This value has been deduced from the MC simulation and from the observed distribution of the distance in space between the $K\pi$ line-of-flight and the primary vertex, in the $D^0(\overline{D}^0) \to K^\mp\pi^\pm$ events [6]. Four events (one in the 1992 and three in the 1993 data) survive these selection criteria and have a dimuon mass in the interval 1.80−1.92 GeV/c^2 (Fig. 2). One of these has a dimuon mass in the interval 1.84−1.89 GeV/c^2, which contains ~ 94 % of the $D^0 \to \mu^+\mu^-$ decays. The presence of this $D^0 \to \mu^+\mu^-$ candidate, together with the relatively low acceptance of this analysis procedure, would lead to an upper limit on $\mathrm{B}(\mathrm{D}^0 \to \mu^+\mu^-)$ of $\sim 9.4 \times 10^{-6}$ at 90 % confidence level.

In order to increase our sensitivity, we have developed [6] a second analysis procedure, in which we exploit the imaging capabilities of the Decay Detector and perform an interactive scanning of dimuon events, allowing us to detect and rectify errors made by Trident in track reconstruction and vertex association. In this second procedure less stringent initial selection criteria are applied, resulting in an increased acceptance for the $D^0 \to \mu^+\mu^-$ decay. The criteria are slightly different for the 1992 and 1993 data. In the analysis of the 1992 data [6] we reject events where the distance of closest approach in space of the two muon tracks is greater than 0.5 mm, and events belonging to the PP and PE categories, where there is the highest background contamination. In the analysis of the 1993 data sample, we take advantage of the better track reconstruction and reject only the events belonging to the PP category. The acceptance

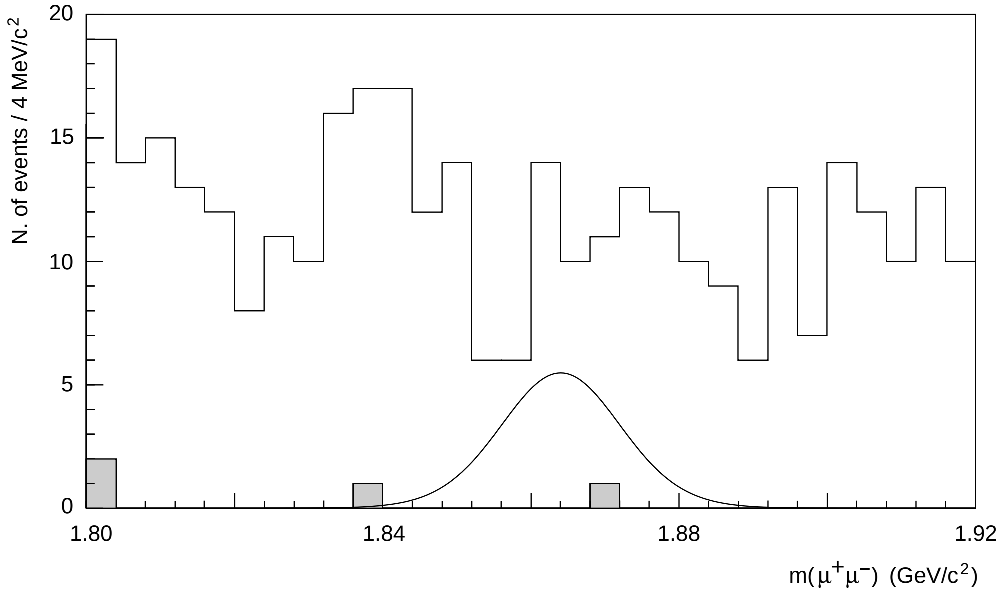

Figure 2: Invariant-mass distribution of the 4 opposite-sign dimuon events selected in the first analysis procedure (shaded events), and of the 354 events selected for the visual scanning in the second analysis procedure. The curve, which is normalized to $\mathrm{B}(\mathrm{D}^0 \rightarrow \mu^+\mu^-) = 5\times10^{-5}$, gives the expected position and shape of $D^0 \rightarrow \mu^+\mu^-$ decays, as expected with the second analysis procedure applied to the full 1992 and 1993 data sample.

for the 1993 analysis is then even higher than for the 1992 analysis. We have selected and scanned 354 events (118 from 1992 and 236 from 1993) having a dimuon mass in the region 1.80−1.92 GeV/c^2. This region is larger than the mass resolution expected for the $D^0 \rightarrow \mu^+\mu^-$ decay, allowing a background estimate. In Fig. 2 we show the invariant mass distribution of the selected events. During the scanning we search for events where the two muons come from the same secondary vertex, with no other tracks emerging from this vertex or connecting this vertex to the primary interaction, and where the dimuon momentum points to within 40 μm of the primary vertex. Secondary interactions in the silicon planes, which could simulate a $D^0 \rightarrow \mu^+\mu^-$ decay, are characterized by a large energy release close to the interaction point [7] and so may be easily rejected on the basis of the analogue information of the DkD. Among the 354 events scanned, none is found that satisfies all requirements.

To determine the efficiency of the visual scanning, MC events have been selected and scanned in the same way as the experimental data; 75 ± 5 (79 ± 5) % of the $D^0 \rightarrow \mu^+\mu^-$ decays simulated in the 1992 (1993) set-up were unambiguously recognized.

To illustrate the power of the visual scanning, we show two events in Fig. 3a and 3b. The first event is the one with a dimuon mass of ~ 1.87 GeV/c^2 selected in the first analysis procedure (Fig. 2). In this event the primary interaction takes place in the first plane of the DkD. The position of the primary vertex has been wrongly reconstructed by Trident ~ 400 μm downstream of the true interaction point, so that the dimuon vertex, which is on the first DkD plane, has been considered by the reconstruction program to be distinct from the primary vertex. The visual scanning allows this event to be assigned to the PP category, which is rejected in our analysis because there the $D^0 \rightarrow \mu^+\mu^-$ events cannot be disentangled from the background. In the second event shown in Fig. 3b the track of the negative muon has, near the ninth plane of the DkD,

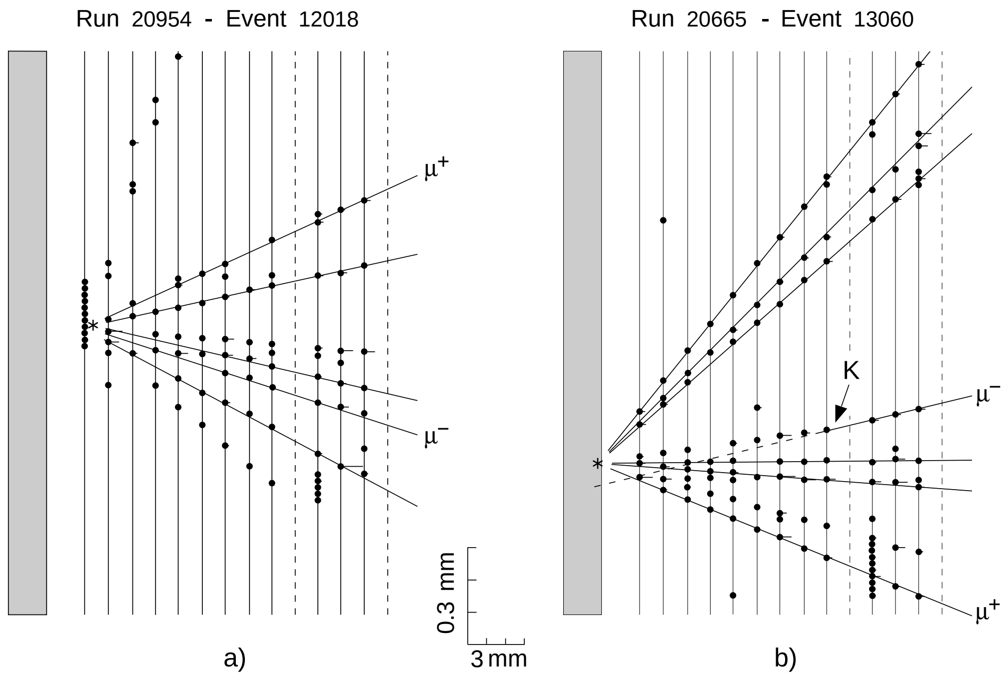

Figure 3: Display of two events, to show the power of the visual scanning. Hits on the first 12 z-planes of the DkD and tracks reconstructed in the magnetic spectrometer are shown. The length of the segment displayed for each fired microstrip is proportional to the energy released in that strip. The primary vertex reconstructed by Trident is marked by a $*$. a) The event with a dimuon mass of ~ 1.87 GeV$/c^2$ selected in the first analysis procedure (see text). b) An event wrongly classified in the PE category by the reconstruction program. The kink (K) near the ninth plane of the DkD is most probably due to the leptonic decay of a kaon produced in the primary interaction.

a kink not considered by Trident. This muon probably comes from the leptonic decay of a primary-interaction kaon, whose hits are clearly visible in seven of the first eight planes of the DkD. These examples show how the visual scanning can resolve some topological situations that Trident cannot disentangle.

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

$$\mathrm{B}(\mathrm{D}^0 \to \mu^+\mu^-) \;=\; \frac{\mathrm{B}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+) \times \mathrm{N}_{\mu\mu}}{(\mathrm{N}_{\mathrm{K}\pi}^{\mathrm{Cu92}} \times \mathrm{R}^{\mathrm{Cu92}}) + (\mathrm{N}_{\mathrm{K}\pi}^{\mathrm{W92}} \times \mathrm{R}^{\mathrm{W92}}) + (\mathrm{N}_{\mathrm{K}\pi}^{\mathrm{Cu93}} \times \mathrm{R}^{\mathrm{Cu93}})}$$

where $\mathrm{B}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+) = 0.0383 \pm 0.0012$ [11] is the branching fraction of the decay $D^0 \to K^-\pi^+$, $\mathrm{N}_{\mu\mu} = 2.30$ is the upper limit, at 90 % confidence level, on the total number of $D^0(\overline{D}^0) \to \mu^+\mu^-$ events observed in the 1992 and 1993 data taking, $\mathrm{N}_{\mathrm{K}\pi}^{\mathrm{Cu92}} = 873 \pm 52$, $\mathrm{N}_{\mathrm{K}\pi}^{\mathrm{W92}} = 533 \pm 43$ and $\mathrm{N}_{\mathrm{K}\pi}^{\mathrm{Cu93}} = 1695 \pm 76$ are the numbers of observed $D^0(\overline{D}^0) \to K^\mp\pi^\pm$ events, and where $\mathrm{R}^{\mathrm{Cu92}} = 6.47$, $\mathrm{R}^{\mathrm{W92}} = 10.9$, and $\mathrm{R}^{\mathrm{Cu93}} = 5.86$ are the ratios between the acceptance for the $D^0 \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ decays, obtained from the MC simulations relative to the Cu92, W92 and Cu93 data taking periods respectively.

With the values reported above, we set a final upper limit on the branching fraction

$B(D^0 \to \mu^+\mu^-)$ of 4.1×10^{-6} at 90 % confidence level. Systematic errors on the whole analysis procedure do not significantly alter this value. From the systematic uncertainties evaluated for our dimuon and $D^0 \to K^-\pi^+$ acceptances [12, 15], we estimate the systematic error on R^{Cu92}, R^{W92} and R^{Cu93} to be ≤ 5 %. Taking into account this and the quoted uncertainties on $B(D^0 \to K^-\pi^+)$, $N_{K\pi}^{Cu92}$, $N_{K\pi}^{W92}$, $N_{K\pi}^{Cu93}$, the sensitivity factor [16] of the experiment, defined by:

$$S = \frac{N_{\mu\mu}}{B(D^0 \to \mu^+\mu^-)} = \frac{(N_{K\pi}^{Cu92} \times R^{Cu92}) + (N_{K\pi}^{W92} \times R^{W92}) + (N_{K\pi}^{Cu93} \times R^{Cu93})}{B(D^0 \to K^-\pi^+)}$$

would be affected by a relative error ≤ 5.5 %. Incorporating this error in the upper limit on $B(D^0 \to \mu^+\mu^-)$ would increase this limit by less than 0.35 % [16].

The value of 4.1×10^{-6} we obtain reinforces the best published limit, at 90 % confidence level, of 4.2×10^{-6} [5].

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