Proceedings of the DIS'2004, Štrbské Pleso, Slovakia

SEARCH FOR THE FLAVOR-CHANGING NEUTRAL CURRENT DECAY $D^0 \to \mu^+\mu^-$ IN 920 GEV PROTON-NUCLEUS COLLISIONS

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We report on a search for the flavor-changing neutral current decay $\mathrm{D}^0 \to \mu^+\mu^-$ using 50×10^6 events recorded with a dimuon trigger in interactions of 920 GeV protons with nuclei by the HERA-B experiment. We find no evidence for such decays and set a 90% confidence level upper limit on the branching fraction $\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) < 2.0 \times 10^{-6}$ [1].

1 Introduction

The decay $\mathrm{D}^0 \to \mu^+\mu^-$ [a] is sensitive to flavor-changing neutral currents (FCNC), which are strongly suppressed in the Standard Model (SM). However, the $\mathrm{D}^0 \to \mu^+\mu^-$ decay mode can be exquisitely sensitive to the physics beyond the SM. According to one study [2], the highest branching fraction for the decay $\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) \leq 3.5 \times 10^{-7}$ is predicted in a minimal supersymmetric extension of the SM with R-parity violating couplings. The best published upper limit of $\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) \leq 2.5 \times 10^{-6}$ at the 90% C.L. was measured by the CDF group [3].

We report on a search for the $\mathrm{D}^0 \to \mu^+\mu^-$ decay using 50×10^6 events recorded with a dimuon trigger in interactions of 920 GeV protons with nuclei in the experiment HERA-B [4]. The data were recorded during the 2002-2003 HERA running period. The measurement relies on normalizing the number of events in the D^0 signal region to the number of reconstructed $\mathrm{J}/\psi \to \mu^+\mu^-$ events.

For proton interactions on a single target of atomic weight A, the branching fraction limit can be determined by:

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) \leq \left[\frac{n_{cl}}{N_{\mathrm{J}/\psi}}\right] \left[\frac{a_{\mathrm{J}/\psi}}{a_{\mathrm{D}^0}\epsilon_{\mathrm{D}^0}}\right] \left[\frac{\sigma^{pA}_{\mathrm{J}/\psi}}{\sigma^{pA}_{\mathrm{D}^0}}\right] \mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-) \tag{1}$$

where n_{cl} is the upper limit on the number of $\mathrm{D}^0 \to \mu^+\mu^-$ decays; $N_{\mathrm{J}/\psi}$ is the number of observed $\mathrm{J}/\psi \to \mu^+\mu^-$ events, a_{D^0} and $a_{\mathrm{J}/\psi}$ are the acceptances for $\mathrm{D}^0 \to \mu^+\mu^-$ and $\mathrm{J}/\psi \to \mu^+\mu^-$ after event quality and particle identification cuts are applied to both channels, ϵ_{D^0} is the efficiency of cuts designed to select $\mathrm{D}^0 \to \mu^+\mu^-$ by the possible detached secondary vertices, $\sigma^{pA}_{\mathrm{D}^0}$ and $\sigma^{pA}_{\mathrm{J}/\psi}$ are the

[a] In this paper, the symbol D^0 denotes both D^0 and $\overline{\mathrm{D}^0}$ mesons.

production cross sections per target nucleus for D^0 and J/ψ, $\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-) = (5.88 \pm 0.10)\%$ [5] is the branching fraction for $\mathrm{J}/\psi \to \mu^+\mu^-$.

The terms a_{D^0}, $a_{\mathrm{J}/\psi}$ and ϵ_{D^0} are evaluated with a complete Monte Carlo simulation. The systematic error is dominated by the large uncertainty on the available measurements of the $\sigma^{pA}_{\mathrm{D}^0}$.

2 The HERA-B Detector Systems and Data Analysis

The HERA-B is a forward spectrometer [4] which makes use of the HERA 920 GeV proton beam at DESY. The detector consists of a target (which has two stations of four wires of various materials including carbon, titanium and tungsten), a vertex detector, a tracking system with a fine grained inner tracker, a large area outer tracker, a ring imaging Cherenkov hodoscope (RICH), an electromagnetic calorimeter and muon identification system (MUON). The dedicated multilevel dilepton trigger was designed to effectively select beauty and charm decays out of the large hadronic background.

The search for $\mathrm{J}/\psi \to \mu^+\mu^-$ and D^0 candidates is performed by analyzing the mass spectrum for unlike-sign dimuon candidates. The mass spectrum for such candidates after minimal cuts is shown on Fig. 1. Peaks at the $\omega/\rho, \phi, \mathrm{J}/\psi$ and $\psi(2s)$ masses are clearly visible.

The events are first reconstructed with the standard HERA-B analysis package [6]. A general vertex-finding algorithm is applied and only events with at least one reconstructed primary vertex and at most one reconstructed primary vertex per target wire are retained. Muon candidate tracks are then selected by setting requirements on the muon probability derived from the MUON hit information ($\mathcal{P}_\mu$), the χ^2 per degree of freedom of the track fit ($\chi^2_{tr}/d.o.f.$), and the kaon identification likelihood probability derived from the RICH ($\mathcal{L}_K$). The two muon tracks are then combined into a dimuon secondary vertex and the primary and the dimuon vertices are fitted. In the following, we call the muon pair with a fitted secondary vertex a "dimuon pseudoparticle".

The further analysis deals with two regions of $\mu^+\mu^-$ invariant mass: $2.7 - 4.0\,\mathrm{GeV}/c^2$, which we refer to as the "J/ψ region", and $1.59 - 2.15\,\mathrm{GeV}/c^2$, which we refer to as the "D^0 region". The selection cuts are divided into two parts: the common (quality) cuts applied both for D^0 and J/ψ regions and the lifetime cuts which are applied only for the D^0 region.

The following common selection criteria are applied: a cut on total track multiplicity (N_{tr}), a cut on $\chi^2_{tr}/d.o.f.$ for each muon, a cut on $\mathcal{P}_\mu$, and a cut on the transverse momentum of each muon track p^μ_T.

To optimize the common cuts, we employ a blind analysis technique, maximizing the ratio of the number of J/ψ candidates over the expected background in the D^0 signal region ($1.815 - 1.915$ GeV/c^2), estimated from D^0 sidebands ($1.59 - 1.79\,\mathrm{GeV}/c^2$ and $1.94 - 2.14\,\mathrm{GeV}/c^2$). The resulting cut values are: $N_{tr} < 45$, $\chi^2_{tr}/d.o.f. < 7.5$, $\mathcal{P}_\mu > 0.7$, $p^\mu_T > 0.7\,\mathrm{GeV}/c$.

After applying the common cuts, there remain about 238000 events in the D^0 region and 46000 events in the J/ψ peak.

The lifetime cuts isolating the possible D^0 mesons are applied to three quantities:

the separation between primary and secondary vertices (Δz) [b], the proper decay length ($c\tau$), and the impact parameter of the dimuon pseudoparticle to the primary vertex (I_v).

Since these three quantities are correlated, a three-dimensional blind optimization is performed wherein the ratio of $\mathrm{D}^0 \to \mu^+\mu^-$ acceptance (determined from the Monte Carlo) over the "experimental sensitivity" [7] is maximized. This optimization procedure produces the following cuts: $\Delta z > 7.0$, $c\tau > 250\,\mu$m and $I_v < 110\,\mu$m. The optimized experimental sensitivity [7] is $S_{opt} = 5.53$ events.

3 Results

After all cuts, 31 events remain in the D^0 mass region as shown in Fig. 2. The signal region contains 3 events.

By performing a Monte Carlo study we have checked that the background shape would not be significantly changed by wrongly identified charm decays and estimated the expected number of background events in the signal region to be 6.0 ± 1.2 using the shape of the mass plot before D^0 selection cuts are applied.

From the published results on the D^0 production cross section at 800 GeV of $22^{+9}_{-7} \pm 5\,\mu$b/nucleon [8] and $38 \pm 3 \pm 13\,\mu$b/nucleon [9] we obtain the average of $\sigma^{pN}_{\mathrm{D}^0} = 27.3 \pm 7.7\,\mu$b/nucleon at 800 GeV.

Having adjusted the prompt J/ψ production cross sections measured at 800 GeV by E789 [10] and E771 [11] with the most recent value for the A-dependence parameter $\alpha_{\mathrm{J}/\psi} = 0.955 \pm 0.005$ [12], we take their average to obtain a prompt J/ψ production cross section of $\sigma^{pN}_{\mathrm{J}/\psi} = 333 \pm 6 \pm 26$ nb/nucleon at 800 GeV. We assume that the ratio of D^0 and J/ψ cross sections which appears in Eq. (1) does not noticeably change between $\sqrt{s} = 39$ GeV and 42 GeV.

The ratio of acceptances, excluding the cuts applied only for selecting $\mathrm{D}^0 \to \mu^+\mu^-$ (but taking into account triggering, target geometry, muon and kaon identification and Monte Carlo statistics), is $a_{\mathrm{D}^0}/a_{\mathrm{J}/\psi} = 0.287 \pm 0.028$. The efficiency of the additional secondary vertex cuts applied in the D^0 region is $\epsilon_{\mathrm{D}^0} = (6.83 \pm 1.08) \times 10^{-2}$.

The data samples obtained with the various targets can be combined into a single data set assuming the production cross sections per nucleon depend on atomic weight (A) as $\sigma^{pA}_{\mathrm{D}^0(\mathrm{J}/\psi)} = \sigma^{pN}_{\mathrm{D}^0(\mathrm{J}/\psi)} \cdot A^{\alpha_{\mathrm{D}^0(\mathrm{J}/\psi)}}$, with $\alpha_{\mathrm{D}^0} = 1.02 \pm 0.03 \pm 0.02$ [13].

Introducing the detector sensitivity, F^{sens}, the Eq. (1) can be rewritten as:

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) \le n_{cl}/F^{sens} \tag{2}$$

with

$$F^{sens} \equiv \sum_i \left(N^i_{\mathrm{J}/\psi} A_i^{\alpha_{\mathrm{D}^0} - \alpha_{\mathrm{J}/\psi}} \right) \left[\frac{a_{\mathrm{D}^0}}{a_{\mathrm{J}/\psi}} \epsilon_{\mathrm{D}^0} \right] \left[\frac{\sigma^{pN}_{\mathrm{D}^0}}{\sigma^{pN}_{\mathrm{J}/\psi}\ \mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-)} \right] \tag{3}$$

where the sum runs over the target materials.

[b] Δz compares the distance in z-coordinate (along the beam direction) between the secondary and the associated primary vertices with its uncertainty, $\Delta z = (z_{sec} - z_{pr})/\sqrt{\sigma^2_{z_{sec}} + \sigma^2_{z_{pr}}}$.

The numbers of decays observed in the normalization channel are $N^{C}_{J/\psi} = 31010 \pm 200(stat)$, $N^{W}_{J/\psi} = 12660 \pm 140(stat)$, $N^{Ti}_{J/\psi} = 2430 \pm 60(stat)$. After combining statistical and systematic errors quadratically the total relative error on F^{sens} from all contributing terms in equation (3) is 38% ($F^{sens} = (1.57 \pm 0.58) \times 10^6$).

To incorporate systematic uncertainties into the upper limit, we assume that the errors related to F^{sens} and to the background estimates have Gaussian distributions and used the method of Cousins and Highland [14], as implemented by Conrad et al. [15] using the unified Feldman-Cousins likelihood ratio test [7], and improved by a more appropriate choice of the likelihood ratio test by Hill [16].

Using equation (2) and taking systematic errors and background fluctuations into account with the Hill prescription [16], the upper limit at 90% confidence level on $\mathcal{B}(D^0 \to \mu^+\mu^-)$ is 2.0×10^{-6} [1].

4 Conclusions

We have investigated the dimuon mass spectrum with HERA-B detector in a search for the FCNC decay $D^0 \to \mu^+\mu^-$. No evidence was found. Using the D^0 and J/ψ production cross sections published in the literature we have set an upper limit of

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.0 \times 10^{-6} \text{ at } 90\% \text{ C.L. [1]}$$

This new measurement of the upper limit on the $D^0 \to \mu^+\mu^-$ branching fraction is the best to date.

Acknowledgments

The authors are thankful to W. Hofmann and A. Schwartz for many fruitful and stimulating discussions during the analysis. We specially thank R. D. Cousins, G. Zech and G. C. Hill for help and discussions on procedures for setting confidence limits.

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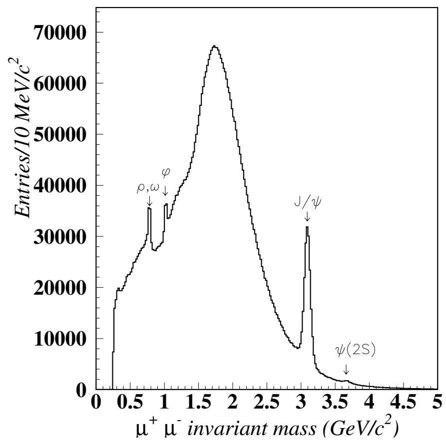

Figure 1. Invariant mass of unlike-sign dimuon candidates after minimal cuts.

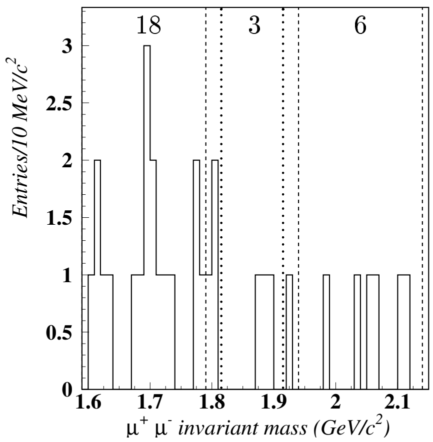

Figure 2. Unlike-sign dimuon mass spectrum in the D^0 region after all cuts have been applied. The sidebands are indicated by dashed lines and the signal region is indicated by dotted lines. The numbers of events in each of the regions are given.