Search for the Decay $D^+ \to \mu^+ \nu_\mu$ and an Upper Limit on the Pseudoscalar Decay Constant

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We report the results of a search for the leptonic decay $D^+ \to \mu^+ \nu_\mu$ using the Mark III detector at the SLAC e^+e^- storage ring SPEAR. A data sample of 9.3 pb^{-1} collected at the $\psi(3770)$ resonance yields no signal events, corresponding to a 90%-confidence-level upper limit of 7.2×10^{-4} on the branching ratio $B(D^+ \to \mu^+ \nu_\mu)$. This represents an upper limit on the pseudoscalar decay constant f_D of 290 MeV/c^2.

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The decay constant f_D characterizes the magnitude of the charged weak axial-vector current matrix element in D^+ decay,[1] and is a direct measure of the overlap of the wave functions of the heavy and light quarks in the meson. It thus plays a fundamental role in the understanding of extensions to the light-quark spectator model, such as W-exchange and W-annihilation processes,[2,3] and enters in the evaluation of second-order weak diagrams leading to $D^0\bar{D}^0$ mixing.[4] In many models[5] a measurement of f_D provides a phenomenological bound on f_B which, when combined with the observed rate for $B_d\bar{B}_d$ and $B_s\bar{B}_s$ mixing,[6,7] may yield a lower bound on the mass of the top quark.[8]

A measurement of the leptonic decay of the D^+ provides an unambiguous determination[9] of f_D:

$$B(D^+ \to \mu^+ \nu) = \frac{\Gamma(D^+ \to \mu^+ \nu)}{\Gamma(D^+ \to \text{all})} = \frac{G_F^2}{8\pi} f_D^2 \tau_D m_D m_\mu^2 |V_{cd}|^2 \left(1 - \frac{m_\mu^2}{m_D^2}\right)^2, \quad (1)$$

where m_D is the meson mass, m_μ the muon mass, V_{cd} the Kobayashi-Maskawa matrix element, G_F the Fermi constant, and τ_D the lifetime of the D^+.

This Letter reports the results of a search for the decay[10] $D^+ \to \mu^+ \nu_\mu$ using the Mark III detector[11] at the SLAC e^+e^- storage ring SPEAR. The data were obtained at an average energy of $\sqrt{s} = 3.768$ GeV, near the peak of the $\psi(3770)$. The integrated luminosity of 9.3 pb^{-1} corresponds to $\simeq 2 \times 10^4$ produced D^+D^- pairs.[12] Events are selected in which one D^- hadronic decay candidate is found. The recoil system is examined for evidence of $D^+ \to \mu^+ \nu_\mu$, thus providing a direct measurement of the absolute branching ratio $B(D^+ \to \mu^+ \nu_\mu)$. The D^- candidates (tags) are selected as follows: Charged particles are identified by time of flight or by energy loss (dE/dx) in the drift chamber. Seven final states are reconstructed: $K^+\pi^-\pi^-$, $K^0\pi^-$, $K^0\pi^-\pi^-\pi^+$, $K^0\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^0$, K^0K^-, and $K^+K^-\pi^-$. The total energy of the candidate is constrained to the beam energy; if the final state contains a π^0, the π^0 mass is imposed as an additional constraint. A D^--tag candidate must have a mass between 1.862 and 1.875 GeV/c^2. This procedure[13] results in 2490 $\pm 42 \pm 42$ identified D^- tags (Fig. 1).

The isolation of $\mu^+\nu_\mu$ candidates proceeds as follows. The recoil to a tag is required to contain exactly one track with the expected charge. The data are then separated into two classes depending on whether the recoil track is within the acceptance of the muon detection system ($|\cos\theta| \leq 0.65$, where θ is the polar angle from the beam axis), or is detected only in the central

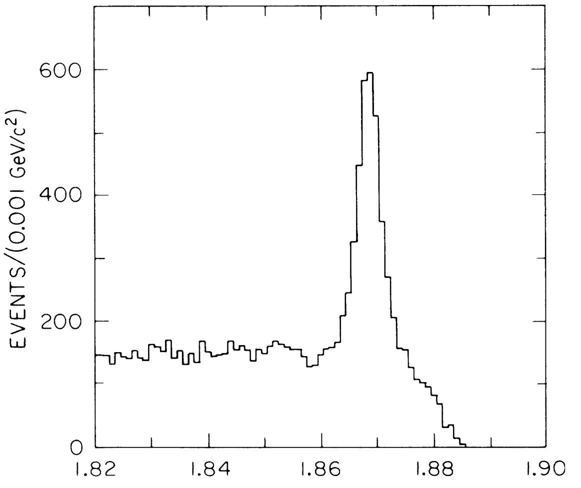

FIG. 1. Combined mass plot for the seven D^- tags used in this analysis: $K^+\pi^-\pi^-$, $K^0\pi^-$, $K^0\pi^-\pi^-\pi^+$, $K^0\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^0$, K^0K^-, and $K^+K^-\pi^-$.

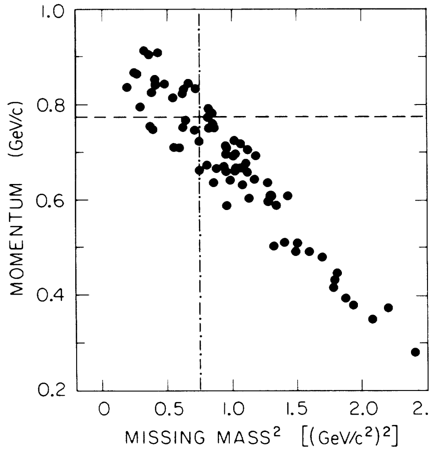

FIG. 2. Scatter plot of p_μ vs $M^2_{\rm miss}$ for the data. The dashed line indicates the cut on momentum (p_μ). Only events in the upper left box defined by the dashed and dot-dashed lines are included in the fit.

tracking chamber and the calorimeter ($0.65 \leq |\cos\theta| \leq 0.92$).

Recoil tracks within the acceptance of the muon system are subjected to one further requirement to reject hadrons: Two (one) layers are required to be hit for track momenta $p_\mu \geq 1$ GeV/c ($p_\mu < 1$ GeV/c). As the 95% (90%) rejection of π (K) mesons provided by the muon system is sufficient for this analysis, no further event topology cuts are applied to this sample.[14]

For recoil tracks outside the acceptance of the muon system, the barrel and end-cap calorimeters (0.4 absorption length) provide some hadron rejection. The reduction of π and K backgrounds is achieved by the requirement that the candidate recoil muon deposit less than 300 MeV in the calorimeter.[15] Those tracks within the acceptance of the time-of-flight or dE/dx systems must have identification consistent with a μ hypothesis.

Events with a recoil track lying outside the muon system are subjected to further cuts to suppress backgrounds. The principal sources of background to the $\mu^+\nu_\mu$ signal are the hadronic decays $D^+ \rightarrow \pi^+\pi^0$, $\bar{K}^0\pi^+$, $\bar{K}^0K^+$, and $\bar{K}^0\rho^+$, and the semileptonic decays $D^+ \rightarrow \bar{K}^0\mu^+\nu_\mu$, $\bar{K}^{*0}\mu^+\nu_\mu$, and $\pi^0\mu^+\nu_\mu$. Those background events containing direct π^0's or daughter π^0's from $K^0_S \rightarrow \pi^0\pi^0$ are rejected by the requirement of the absence of any isolated photons in an event.[16] This cut also rejects those K^0_L which interact in the shower counter. The fraction of interacting K^0_L is modeled by use of the decays $J/\psi \rightarrow K^0_S K^0_L$, $K^0_S \rightarrow \pi^+\pi^-$ and $J/\psi \rightarrow \phi\eta$, $\phi \rightarrow K^0_S K^0_L$, $K^0_S \rightarrow \pi^+\pi^-$ from a separate data set.[17]

Kinematic variables are used to separate remaining $\mu^+\nu_\mu$ candidate events from background. Figure 2 shows a scatter plot of p_μ versus the square of the missing mass ($M^2_{\rm miss}$) in each event. The p_μ distribution from Monte Carlo simulation for two-body $\mu^+\nu_\mu$ events is limited to the region indicated by dashes in Fig. 3. Figure 3 also shows the p_μ projection of the scatter plot of observed events. Our requiring $0.775 < p_\mu < 1.125$ GeV/c loses 2% of an expected signal while retaining 18 events in the data. The final separation of a $\mu^+\nu_\mu$ signal from background is obtained from the $M^2_{\rm miss}$ distribution, whose projection after the cut on p_μ is shown in Fig. 4. A Gaussian peak near $M^2_{\rm miss} = 0$ is expected for $D^+ \rightarrow \mu^+\nu_\mu$, while a peak near $m^2_{\pi^0}$ or $m^2_{K^0}$ is expected for the two-body backgrounds. The distribution peaks at higher $M^2_{\rm miss}$ in the case of three-body backgrounds with or without missing neutrinos. No event appears near $M^2_{\rm miss} = 0$.

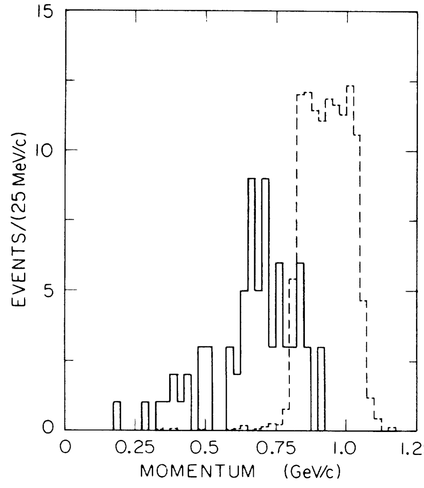

FIG. 3. Momentum of recoil muons, p_μ, for tagged D^- candidates (solid line) and for Monte Carlo-generated events (dashed line).

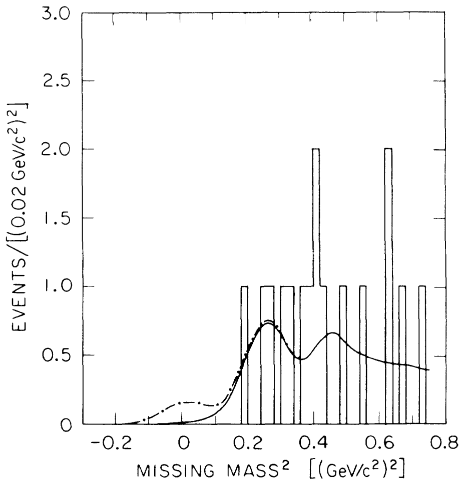

FIG. 4. The $M^2_{\rm miss}$ distribution. The best fit (containing no $\mu^+\nu_\mu$ events) is shown as a solid line; the dashed line corresponds to the 90% C.L. limit of 1.5 produced events.

A maximum-likelihood fit to the $M^2_{\rm miss}$ distribution, incorporating shape information on the background both in and above the signal region, provides an upper limit on the number of $\mu^+\nu_\mu$ events.[18] The acceptance for $D^+ \to \mu^+\nu_\mu$ varies by less than 3% for the seven different tagging modes; the weighted average acceptance is 0.74 ± 0.01. An upper limit on the branching fraction $B(D^+ \to \mu^+\nu_\mu)$ is obtained by performance of a likelihood-ratio test.[19] This procedure gives $B(D^+ \to \mu^+\nu_\mu) \leq 6.1 \times 10^{-4}$ at the 90% confidence level (C.L.), corresponding to 1.5 produced events. Inclusion of systematic errors[20] increases this to 7.2×10^{-4}.[21] Use of a D^+ lifetime of $(10.9 \pm 0.3 \pm 0.25) \times 10^{-13}$ s,[22] and $|V_{cd}|^2 = 0.0493$,[23] gives $f_D \leq 290$ MeV/c^2.[24]

For comparison, a Bayesian application[25] of Poisson statistics, with zero observed events, yields an upper limit of $B(D^+ \to \mu^+\nu_\mu) < 13.6 \times 10^{-4}$ at the 90% C.L., corresponding to 2.3 signal events. The limit on f_D would be 390 MeV/c^2.

The limit on f_D provides a constraint on nonspectator contributions to weak hadronic charmed-meson decay. It rules out the large value of f_D required by perturbative calculations[2] to explain the ratio $\tau(D^+)/\tau(D^0) \approx 2.4$. It does not, however, exclude nonperturbative mechanisms[3] proposed to enhance W-exchange contributions to the D^0 width.

Most models[5,26] conclude that the pseudoscalar decay constants for mesons containing different species of heavy quarks are ordered in magnitude $f_D \gtrsim f_B \gtrsim f_T$. This limit on f_D may thus be interpreted as a phenomenological bound on f_B. Specific calculations[5] lie in the range $0.6 < f_B/f_D < 0.95$. Estimates[8] of lower limits on the top-quark mass based on the recent observation of $B^0\bar{B}^0$ mixing[6,7] have employed theoretical values of f_B significantly below this bound. If the limit obtained herein were used, these calculations would result in less stringent bounds[27] on the top-quark mass.

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[15] The distribution of energy deposited by minimum-ionizing particles peaks at about 180 MeV. The overlap region $0.78 \leq |\cos\theta| \leq 0.84$ between the barrel and end-cap calorimeters was removed from the analysis, as no μ-π separation is possible there.

[16] Isolated photons are defined as those showers with energy greater than 100 MeV which are not used in the formation of a π^0 in the tag, and which make an angle $\alpha \gtrsim 23°$ with respect to each charged track.

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[18] The likelihood function contains contributions from all noted D backgrounds. The branching ratios are constrained within errors by existing measurements, or by theoretical expectations for unmeasured Cabibbo-suppressed modes. The leptonic decay $D^+ \rightarrow \tau^+ \nu_\tau$ is coupled in the fit to the $\mu^+ \nu_\mu$ fraction by Eq. (1). A contribution of 1.9 ± 0.8 events from erroneously tagged D mesons is also propagated.

[19] The C.L. is defined as the probability that a given hypothesis, here $B(D^+ \rightarrow \mu^+ \nu_\mu)$ and a set of background branching fractions, will give an observed likelihood ratio $\lambda = L_{\rm true}/L_{\rm max}$ that is greater than that measured by this experiment [cf. A. G. Fodesen *et al.*, *Probability and Statistics in Particle Physics* (Universitettsforlaget, Bergen, Norway, 1979), pp. 388–395]. Here, $L_{\rm true}$ denotes the likelihood of the true hypothesis, while the maximum likelihood is $L_{\rm max}$. The 90% C.L. is found by generation and analysis of Monte Carlo experiments with different values of $B(D^+ \rightarrow \mu^+ \nu_\mu)$, and then determination of that value of λ which rejects 10% of the Monte Carlo experiments for each branching ratio.

[20] Systematic errors are propagated linearly. The uncertainties in the modeling of K_L^0 interactions contributes 6%. The remaining 8.6% arises from uncertainty in the counting of D tags, the Monte Carlo simulation of the muon system, drift-chamber track reconstruction, and of the isolated photon cuts.

[21] J. J. Aubert *et al.*, Nucl. Phys. **B213**, 31 (1983) obtained $B(D^+ \rightarrow \mu^+ \nu_\mu) < 0.02$ at 90% C.L.

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[24] Dividing $B(D^+ \rightarrow \mu^+ \nu_\mu)$ by the central value of τ_D, we obtain $f_D < 280$ MeV/c^2. The final result (290 MeV/c^2) includes the error on τ_D, and is obtained by division of $B(D^+ \rightarrow \mu^+ \nu_\mu)$ by $\tau_D - \delta\tau_D^{\rm stat} - \delta\tau_D^{\rm syst}$.

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[27] The bag constant remains a parameter in these calculations; the presence of either a fourth generation of fermions or exotic extensions of the standard model is not considered.