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Study of the decay $D_s^+ \to K^+K^-e^+\nu_e$

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Using 214 fb^{-1} of data recorded by the *BABAR* detector at the PEPII electron-positron collider, we study the decay $D_s^+ \to K^+K^-e^+\nu_e$. Except for a small S-wave contribution, the events with K^+K^- masses in the range 1.01–1.03 GeV/c^2 correspond to ϕ mesons. For $D_s^+ \to \phi e^+\nu_e$ decays, we measure the relative normalization of the Lorentz invariant form factors at $q^2 = 0$, $r_V = V(0)/A_1(0) = 1.849 \pm 0.060 \pm 0.095$, $r_2 = A_2(0)/A_1(0) = 0.763 \pm 0.071 \pm 0.065$ and the pole mass of the axial-vector form factors $m_A = (2.28^{+0.23}_{-0.18} \pm 0.18)$ GeV/c^2. Within the same K^+K^- mass range, we also measure the relative branching fraction $\mathcal{B}(D_s^+ \to K^+K^-e^+\nu_e)/\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = 0.558 \pm 0.007 \pm 0.016$, from which we obtain the total branching fraction $\mathcal{B}(D_s^+ \to \phi e^+\nu_e) = (2.61 \pm 0.03 \pm 0.08 \pm 0.15) \times 10^{-2}$. By comparing this value with the predicted decay rate, we extract $A_1(0) = 0.607 \pm 0.011 \pm 0.019 \pm 0.018$. The stated uncertainties are statistical, systematic, and from external inputs.

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Charm semileptonic decays can help to validate predictions from lattice QCD through precise measurements of hadronic form factors. Such measurements have been performed by *BABAR* for the $D^0 \to K^-e^+\nu_e$ decays [1]. The $D_s^+ \to \phi e^+\nu_e$ [2] channel is well suited to study form factors in semileptonic decays of charm mesons to a vector particle because the ϕ meson is a narrow resonance which can be well isolated experimentally. Because of the higher mass of the spectator s-quark, form factor determinations for this process by lattice QCD are expected to be more accurate than for nonstrange D mesons. However, measurements of this decay mode are impacted by the lower production rate for D_s^+ mesons and higher backgrounds. Form factors in $D_s^+ \to \phi e^+\nu_e$ have been previously studied by photoproduction experiments, at Fermilab [3–6], and by CLEOII at the CESR e^+e^- collider also operating at the $\Upsilon(4S)$ [7]. In charm meson semileptonic decays, a ϕ meson is expected to originate only from the D_s^+. A possible contribution from the Cabibbo suppressed $D^+ \to \phi e^+\nu_e$ decay, through the $d\bar{d}$ component of the ϕ meson [8] is neglected [9].

Using 214 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance by the *BABAR* detector, we measure the $D_s^+ \to K^+K^-e^+\nu_e$ channel decay characteristics, for events produced in the continuum $e^+e^- \to c\bar{c}$. The analysis focuses on the $\phi e^+\nu_e$ final state in the K^+K^- invariant mass range between 1.01 and 1.03 GeV/c^2. The ϕ resonance is dominant in this K^+K^- invariant mass region although a small S-wave component is observed, for the first time, through its interference with the ϕ.

The differential decay rate for $D_s^+ \to K^+K^-e^+\nu_e$ depends on five variables [10]: m_{KK}^2, the mass squared of the K^+K^- system; q^2, the mass squared of the $e^+\nu_e$ system; $\cos\theta_e$ ($\cos\theta_K$), where θ_e (θ_K) is the angle between the momentum of the e^+ (K^+) in the $e^+\nu_e$ (K^+K^-) rest frame and the momentum of the $e^+\nu_e$ (K^+K^-) system in the D_s^+ rest frame; and χ, the angle between the normals to the planes defined in the D_s^+ rest frame by the K^+K^- pair and the $e^+\nu_e$ pair. When analyzing a D_s^- candidate, the direction of the K^- is used in place of the K^+ and χ is changed to $-\chi$. The expression for the differential decay rate as a function of these variables is given in Ref. [11]. Neglecting contributions proportional to the square of the electron mass, it depends on three hadronic form factors which are related to the three possible helicity values of the hadronic current. Restricting to S- and P-wave contributions, these form factors can be written as

$$\mathcal{F}_1 = \mathcal{F}_{10} + \mathcal{F}_{11}\cos\theta_K, \quad \mathcal{F}_2 = \frac{1}{\sqrt{2}}\mathcal{F}_{21}, \quad \mathcal{F}_3 = \frac{1}{\sqrt{2}}\mathcal{F}_{31}. \tag{1}$$

The form factors $\mathcal{F}_{ij}$ depend only on m_{KK}^2 and q^2; $\mathcal{F}_{10}$ characterizes the S-wave contribution, whereas the $\mathcal{F}_{i1}$ correspond to the ϕ meson:

$$\mathcal{F}_{i1} = \sqrt{3\pi}qH_i(q^2, m)\mathcal{A}_\phi(m), \tag{2}$$

where the ϕ meson decay amplitude $\mathcal{A}_\phi(m)$ is taken to be a relativistic Breit-Wigner distribution with a mass-dependent width including a Blatt-Weisskopf damping factor [12]. The form factors $H_{1,2,3}$ can be expressed in terms of the Lorentz invariant form factors V and $A_{1,2}$ [13], for which we assume a q^2 dependence dominated by a single pole:

$$V(q^2) = \frac{V(0)}{1 - q^2/m_V^2}; \qquad A_{1,2}(q^2) = \frac{A_{1,2}(0)}{1 - q^2/m_A^2}. \tag{3}$$

m_A and m_V are the pole masses, usually fixed to the values of corresponding resonance masses: $m_A = 2.5$ GeV/c^2 ($\simeq m_{D_{s1}}$) and $m_V = 2.1$ GeV/c^2 ($\simeq m_{D_s^*}$). At $q^2 = 0$, the ratios of the form factors V and A_2 relative to A_1 are denoted by r_V and r_2, respectively. The S-wave contribution is parameterized assuming f_0 production:

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$$\mathcal{F}_{10} = r_0 \frac{p_{KK} m_{D_s}}{1-(q^2/m_A^2)} \frac{m_{f_0} g_\pi}{m_{f_0}^2 - m^2 - i m_{f_0} \Gamma_{f_0}^0}, \quad (4)$$

where r_0 is a normalization factor and p_{KK} is the magnitude of the three-momentum of the K^+K^- system in the D_s^+ rest frame. The values of the f_0 parameters $(m_{f_0}, g_\pi, \Gamma_{f_0}^0)$ are taken from Ref. [14].

A detailed description of the detector and the algorithms used for charged and neutral particle reconstruction and identification is provided elsewhere [15]. Monte Carlo (MC) samples of $\Upsilon(4S)$ decays, charm and other light quarks pairs from continuum events are generated using a GEANT4 [16]. Quark fragmentation, in continuum events, is described using the JETSET package [17]. Signal MC events are generated with 7 times the equivalent statistics of the data, using a simple pole model for the form factors with $m_A = 2.5$ GeV$/c^2$ and $m_V = 2.1$ GeV$/c^2$. The simulation of the characteristics of D_s^+ production is corrected to account for measured differences compared to data. Radiative processes are simulated with PHOTOS [18].

We reconstruct $D_s^+ \to K^+K^-e^+\nu_e$ decays, for D_s^+ produced in $e^+e^- \to c\bar{c}$ events. The hadronization of the $c\bar{c}$ system leads to the formation of two jets, emitted back-to-back in the center-of-mass (c.m.) frame. The analysis method is similar to the one used for the decay $D^0 \to K^-e^+\nu_e$ [1]. The only differences are that the cascade from a D^* is not used to evaluate the signal, and the detector performance for the D_s^+ reconstruction is measured using $D_s^+ \to \phi\pi^+$ decays rather than the cascade decay $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$.

The event thrust axis is determined from all charged and neutral particles in the c.m. system and its direction is required to be in the range $|\cos(\theta_{\text{thrust}})| < 0.6$ to minimize the loss of particles in regions close to the beam axis. A plane perpendicular to the thrust axis is used to define two hemispheres, equivalent to the two jets produced by quark fragmentation. In each hemisphere, we search for the decay products of the D_s^+, namely, a positron, of momentum greater than 0.5 GeV$/c$, and two oppositely charged kaons. Since the ν_e momentum is unmeasured, a kinematic fit is performed, constraining the invariant mass of the candidate $K^+K^-e^+\nu_e$ system to the D_s^+ mass. In this fit, the D_s^+ direction and the neutrino energy are estimated from the other, charged and neutral, particles measured in the event. The D_s^+ direction is taken as the direction opposite to the sum of the momenta of all reconstructed particles, except for the kaons and the positron associated with the signal candidate. The neutrino energy is estimated as the difference between the total energy of the jet containing the candidate and the sum of the energies of all reconstructed particles in that hemisphere. The D_s^+ candidate is retained if the χ^2 probability of the kinematic fit exceeds 10^{-2}.

Sizable backgrounds arise from $\Upsilon(4S) \to B\bar{B}$ decays and two-jet events from $e^+e^- \to q\bar{q}$, $q = u, d, s, c$. Backgrounds are predominantly rejected by using two Fisher discriminant variables that exploit differences in the production characteristics of hadrons in signal and background. The first variable is used to separate signal in jetlike $c\bar{c}$ events from $B\bar{B}$ with a more spherical topology. The chosen cut retains 71% of the signal and rejects 86% of the $B\bar{B}$ background. The second Fisher discriminant uses variables related to the different production characteristics of particles from D_s decays and c-quark fragmentation. The selected cut retains 71% of the signal decays, and rejects 72% of the background.

The overall signal efficiency is approximately 4.5%. Figure 1(a) shows the K^+K^- invariant mass distribution for the selected decays compared to the simulation. There are 31 839 events in the signal region, with an estimated background of 20.3%. About 70% of the total background is peaking, corresponding to a ϕ decay combined with an electron from another source. The interference between S- and P-waves generates an asymmetry in the $\cos\theta_K$ distribution which is revealed in Fig. 1(b), where events have been weighted by $\cos\theta_K$.

To extract N_S (the number of reconstructed signal events), r_V, r_2, m_A, and r_0, we perform a binned maximum likelihood fit to the four-dimensional decay distribution in

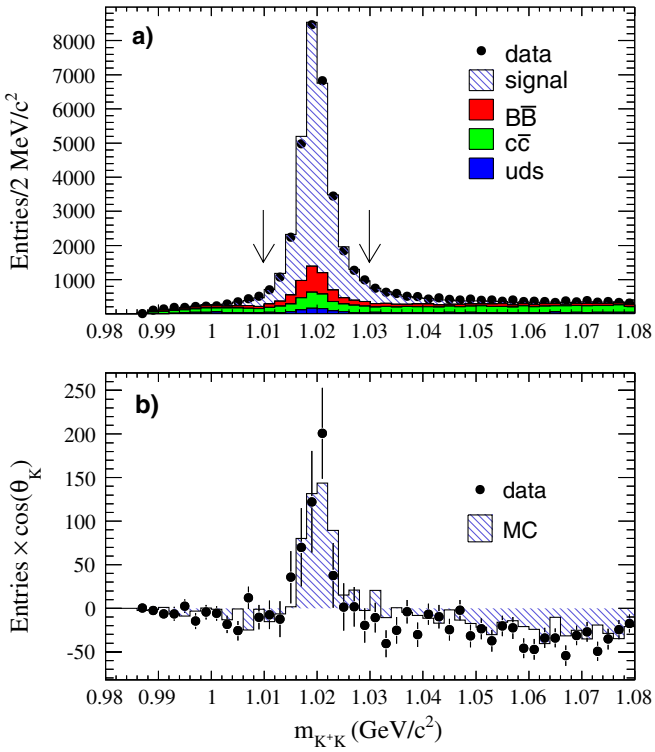

FIG. 1 (color online). (a) K^+K^- invariant mass distribution from data and simulated events. MC events have been normalized to the data luminosity according to the different cross sections. The arrows indicate the selected K^+K^- mass interval. In (b), each event is weighted by the measured value of $\cos\theta_K$. Negative entries are produced by the $c\bar{c}$ background asymmetry in $\cos\theta_K$.

the variables q^2, $\cos\theta_e$, $\cos\theta_K$, and χ. The sensitivity to m_V is weak and we fix this parameter to 2.1 GeV/c^2. The data are divided into 625 bins, with five equal-sized bins per variable, and

$$\mathcal{L} = -\sum_{i=1}^{625} \ln \mathcal{P}(n_i^{\rm data}|n_i^{\rm MC}). \quad (5)$$

For each bin i, $\mathcal{P}(n_i^{\rm data}|n_i^{\rm MC})$ is the Poisson probability to observe $n_i^{\rm data}$ events when $n_i^{\rm MC}$ events are expected,

$$n_i^{\rm MC}(\vec{\lambda}) = N_S \frac{\sum_{j=1}^{n_i^{\rm SMC}} w_j(\vec{\lambda})}{W_{\rm tot}(\vec{\lambda})} + n_i^{\rm BMC}. \quad (6)$$

Here $n_i^{\rm SMC}$ is the number of signal MC events with reconstructed values of the four variables corresponding to bin i and $n_i^{\rm BMC}$ is the number of estimated background events. They are obtained from MC simulation, corrected for measured differences between data and simulation. Weights, w_j, are evaluated for each event, using the generated values of the kinematic variables, thus accounting for resolution effects. $W_{\rm tot}(\vec{\lambda}) = \sum_{j=1}^{N^{\rm SMC}} w_j(\vec{\lambda})$ is the sum of the weights for all simulated signal events ($N^{\rm SMC}$) and $\vec{\lambda}$ corresponds to the parameters to be fitted. The data and results of the fit are shown in Fig. 2 and listed in Table I. From the fit we extract a contribution due to S-P wave interference. The value obtained for r_0 corresponds to a S-wave fraction of $(0.22^{+0.12}_{-0.08})\%$ of the decay rate.

In the fitting procedure, two sources of statistical fluctuations are not included. They originate from the finite sample of simulated signal events and the estimate of the average number of background events in each bin. These effects are evaluated with parameterized simulations and included in the systematic uncertainties. Other systematic effects have been assessed to account for the uncertainties in the c-quark hadronization, the background contributions, and the remaining uncertainties in the simulation of the detector response. They are summarized in Table I.

Corrections to the simulation of the c-quark fragmentation were performed iteratively, comparing variables used in the event selection for samples of $D_s^+ \to \phi\pi^+$ decays and applying a weight which depends on the values of these variables. We adopt the observed changes in the fit parameters for the last step in this iterative process as an estimate of the systematic uncertainty. Furthermore we assume a 30% uncertainty in the simulation of radiative effects.

The peaking and combinatorial background components from $e^+e^- \to c\bar{c}$ events have been studied separately. The peaking background contributions are studied by measuring inclusive ϕ production in events with a fully reconstructed D^{*+} or D_s^+ decay. The combinatorial background

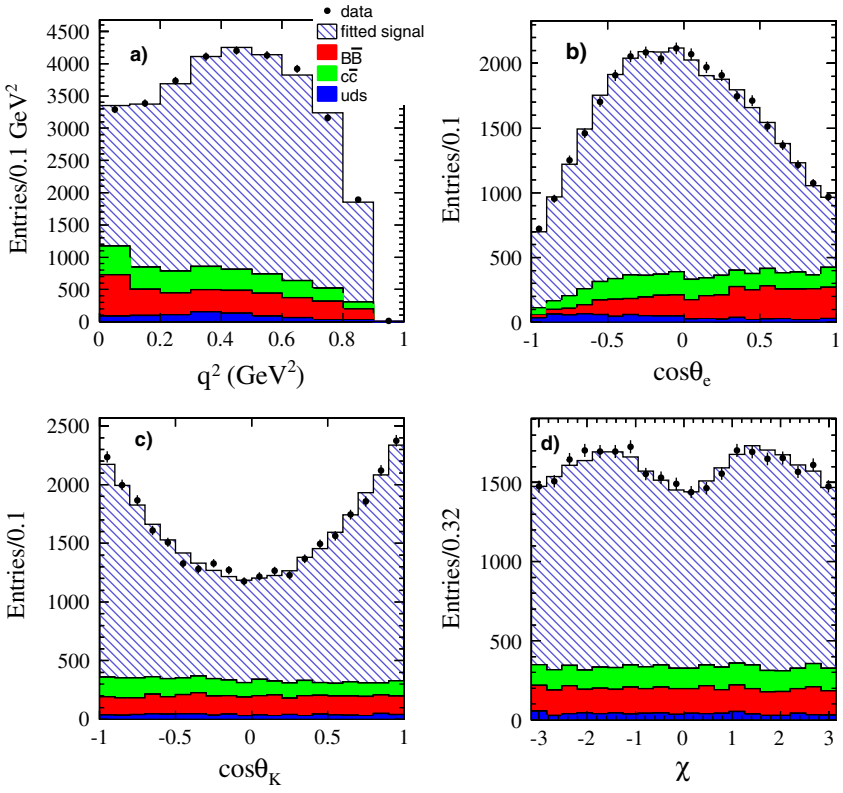

FIG. 2 (color online). Projected distributions of the reconstructed values of the four kinematic variables. The data (points with statistical uncertainties) are compared to the sum of four histograms, the fitted signal (light hatched) and the estimated background contributions (dark shaded).

TABLE I. Measured values of the parameters N_S, r_V, r_2, m_A (GeV/c^2), r_0 (GeV^{-1}), their statistical and systematic uncertainties.

	N_S	r_V	r_2	m_A	r_0
Fitted value	25 341	1.849	0.763	2.28	15.1
Statistical uncertainty	178	0.060	0.071	$+0.23-0.18$	2.6
MC statistics	81	0.029	0.034	0.09	0.0
$c\bar{c}$ fragmentation	5	0.031	0.014	0.07	0.4
Background subtraction	480	0.081	0.049	0.14	0.6
Detector effects	12	0.021	0.021	0.07	0.6
Total syst. uncertainties	488	0.095	0.065	0.18	1.0

consists mainly of events with a charged lepton, one kaon from a D decay and a second kaon from fragmentation. We have measured the rate, momentum and angular distributions of $K^{\pm}$ accompanying a D^0, D^{*+}, or D_s^+ meson in data and corrected the corresponding simulation.

After these corrections, the K^+K^- distribution for selected signal events in MC and data agree to within 10% above 1.03 GeV/c^2, and this remaining difference is adopted as the uncertainty in the normalization of the combinatorial background. The $B\bar{B}$ background is obtained from the difference of the data recorded at the $\Upsilon(4S)$ resonance and the data recorded 40 MeV/c below. The related systematic uncertainties are obtained from the statistical accuracy of these measurements and from the uncertainty (0.25%) between the relative normalization of the two data samples. Systematic uncertainties also originate from the simulation of the detector response. There are small differences in the efficiencies for charged particle reconstruction and electron and kaon identification. They lead to data-MC differences in the reconstruction of the D_s^+ direction and the neutrino energy. They are estimated using $D_s^+ \to \phi\pi^+$ decays.

We measure the $D_s^+ \to K^+K^-e^+\nu_e$ branching fraction relative to the decay, $D_s^+ \to K^+K^-\pi^+$ for which we adopt the K^+K^- mass interval, 1.0095–1.0295 GeV/c^2, to match the range used by CLEO-c for the $D_s^+ \to K^+K^-\pi^+$ branching fraction measurement [19]. Specifically, we compare the ratio of rates for the two channels in data and simulated events so that most systematic uncertainties cancel [1]. In the considered mass intervals, we obtain $R_{Ds} = \frac{\mathcal{B}(D_s^+ \to K^+K^-e^+\nu_e)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} = 0.558 \pm 0.007 \pm 0.016$.

TABLE II. Summary of the relative systematic uncertainties on R_{Ds}.

Source	Relative variation
Fisher variable against $c\bar{c}$ events	$\pm 1.77\%$
Fisher variable against $b\bar{b}$ events	$\pm 0.58\%$
Fitted signal (N_S)	$\pm 1.92\%$
PID corrections	$\pm 0.74\%$
D_s^+ production	$\pm 0.20\%$
Mass constrained fit	$\pm 0.61\%$
Total systematic uncertainty	$\pm 2.85\%$

Systematic uncertainties are summarized in Table II. They originate mainly from selection criteria that are not common for the two channels. Differences in the impact of the two Fisher discriminants have been estimated by varying the selection cuts and differences in particle identification for electrons and pions are accounted for. The uncertainty on N_S is taken from the previous fit; it is dominated by uncertainties in the background evaluation.

We translate the ratio R_{Ds} to a branching fraction, using $\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = (1.99 \pm 0.10 \pm 0.05)\%$ [19], correcting for the finite mass range used to select signal events $(86.37 \pm 1.22)\%$, subtracting the S-wave contribution, and taking $\mathcal{B}(\phi \to K^+K^-) = (49.2 \pm 0.6)\%$ [8]. We find

$$\mathcal{B}(D_s^+ \to \phi e^+\nu_e) = (2.61 \pm 0.03 \pm 0.08 \pm 0.15) \times 10^{-2},$$

where the last quoted uncertainty corresponds to external inputs.

In conclusion, we have studied the decay $D_s^+ \to K^+K^-e^+\nu_e$ with a sample of approximately 25 000 signal events, which greatly exceeds any previous measurement. This decay is dominated by the ϕ vector meson; we measure a small S-wave contribution, possibly associated with $f_0 \to K^+K^-$, corresponding to $(0.22^{+0.12}_{-0.08} \pm 0.03)\%$ of the $K^+K^-e^+\nu_e$ decay rate. We have extracted form factor parameters from a fit to the four-dimensional decay distribution, assuming single pole dominance and obtain: $r_V = V(0)/A_1(0) = 1.849 \pm 0.060 \pm 0.095$, $r_2 = A_2(0)/A_1(0) = 0.763 \pm 0.071 \pm 0.065$ and the pole mass of the axial-vector form factors $m_A = (2.28^{+0.23}_{-0.18} \pm 0.18)$ GeV/c^2. For comparison with previous measurements we also perform the fit to the data with fixed pole masses $m_A = 2.5$ GeV/c^2 and $m_V = 2.1$ GeV/c^2, ignoring also the small S-wave contribution.

The results on r_2 and r_V represent a large improvement in statistical and systematic precision compared to earlier measurements [3–7] (see Table III).

We also measure the relative branching fraction $\mathcal{B}(D_s^+ \to K^+K^-e^+\nu_e)/\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = 0.558 \pm 0.007 \pm 0.016$, from which we obtain the total branching

TABLE III. Results from previous experiments and present measurements.

Experiment	r_V	r_2
E653 [3]	$2.3^{+1.1}_{-0.9} \pm 0.4$	$2.1^{+0.6}_{-0.5} \pm 0.2$
E687 [4]	$1.8 \pm 0.9 \pm 0.2$	$1.1 \pm 0.8 \pm 0.1$
E791 [5]	$2.27 \pm 0.35 \pm 0.22$	$1.57 \pm 0.25 \pm 0.19$
FOCUS [6]	$1.549 \pm 0.250 \pm 0.145$	$0.713 \pm 0.202 \pm 0.266$
CLEOII [7]	$0.9 \pm 0.6 \pm 0.3$	$1.4 \pm 0.5 \pm 0.3$
BABAR	$1.807 \pm 0.046 \pm 0.065$	$0.816 \pm 0.036 \pm 0.030$

fraction $\mathcal{B}(D_s^+ \to \phi e^+ \nu_e) = (2.61 \pm 0.03 \pm 0.08 \pm 0.15) \times 10^{-2}$. By comparing this quantity with the predicted decay rate, using the fitted parameters for the form factor pole ansatz we extract $A_1(0) = 0.607 \pm 0.011 \pm 0.019 \pm 0.018$. Here the third uncertainty refers to the combined value from external inputs, namely, the branching fractions of the D_s^+ into $K^+K^-\pi^+$ and of the ϕ into K^+K^-, the D_s^+ lifetime $[(500 \pm 7) \times 10^{-15}$ s$]$ and $V_{cs} = 0.9729 \pm 0.0003$. Predictions for this decay channel of lattice QCD calculations, in the quenched approximation [20], give: $r_V = 1.35^{+0.08}_{-0.06}$, $r_2 = 0.98 \pm 0.09$, $m_A = 2.42^{+0.22}_{-0.16}$ GeV/c^2, and $A_1(0) = 0.63 \pm 0.02$. They agree with our determination of $A_1(0)$, r_2, and m_A, but are lower than the measured value of r_V. The measured form factor's ratio r_2 is in agreement with the value obtained for the same parametrization for the vector decay $D \to \bar{K}^* e^+ \nu_e$, whereas r_V is 2 standard deviations higher [8]. The branching fraction presented here agrees well with the value $(2.68 \pm 0.13)\%$, consistent with the assumption of equal semileptonic decay widths for the different charm mesons.

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