Study of the Decays $D^0 \to \pi^- e^+ \nu_e$, $D^0 \to K^- e^+ \nu_e$, $D^+ \to \pi^0 e^+ \nu_e$, and $D^+ \to \bar{K}^0 e^+ \nu_e$

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By using 1.8×10^6 $D\bar{D}$ pairs, we have measured $\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = 0.299(11)(9)\%$, $\mathcal{B}(D^+ \to \pi^0 e^+ \nu_e) = 0.373(22)(13)\%$, $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = 3.56(3)(9)\%$, and $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = 8.53(13) \times (23)\%$ and have studied the q^2 dependence of the form factors. By combining our results with recent lattice calculations, we obtain $|V_{cd}| = 0.217(9)(4)(23)$ and $|V_{cs}| = 1.015(10)(11)(106)$.

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Study of the semileptonic decays of D mesons plays an important role in determining the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. These decays both allow determination of $|V_{cs}|$ and $|V_{cd}|$ and provide rigorous tests [2] of lattice QCD (LQCD) calculations (e.g., [3]). The tests can be approached by comparing measured elements to those constrained by matrix unitarity [4] or by comparing the measured and calculated ratios of semileptonic and leptonic branching fractions, which are independent of the CKM matrix. Verification of LQCD calculations at the few percent level will provide validation for their application to the B system.

This Letter presents a study of the $D^0 \to K^- e^+ \nu_e$, $D^0 \to \pi^- e^+ \nu_e$, $D^+ \to \bar{K}^0 e^+ \nu_e$, and $D^+ \to \pi^0 e^+ \nu_e$ decay modes (charge conjugate modes implied). A companion article [5] provides a more detailed description. The results are based on 281 pb^{-1} of e^+e^- data at the $\psi(3770)$ resonance (1.8×10^6 $D\bar{D}$ pairs) collected with the CLEO-c detector at the Cornell Electron Storage Ring (CESR) [6]. The data are a superset of those used for the first CLEO-c semileptonic measurements [7]. For each mode, we measure the partial branching fractions in five $q^2 = m_{\ell\nu}^2$ ranges. Summing the rates yields the total branching fraction; fitting the rates constrains form factor (FF) shapes; comparing to LQCD calculations [3] determines the CKM elements $|V_{cd}|$ and $|V_{cs}|$.

The analysis technique rests upon association of the missing energy and momentum in an event with the neutrino four-momentum [8], enabled by the Hermeticity and excellent resolution of the CLEO-c detector. Charged particles are detected over 93% of the solid angle by two wire tracking chambers within a 1.0 T solenoid magnet. The momentum resolution is 0.6% at 800 MeV/c. Specific ionization and a ring imaging Čerenkov detector (RICH) provide charged particle identification; a CsI(Tl) electromagnetic calorimeter provides photon detection over 93% of 4π and a π^0 mass resolution of $\sim$6 MeV/c^2.

Electron candidates above 200 MeV/c are identified over 90% of the solid angle by combining specific ionization information with calorimetric, RICH, and tracking measurements. To reduce sensitivity to final state radiation (FSR), we add photons within 3.5° of the electron flight direction to the electron momentum. A π^0 candidate must have a $\gamma\gamma$ mass within 2.5 standard deviations (σ) of the π^0 mass. K_S^0 candidates are reconstructed by using a vertex fit to candidate $\pi^+\pi^-$ daughter tracks. The $\pi^+\pi^-$ mass must be within 4.5σ of the K_S^0 mass.

The missing four-momentum in an event is given by $p_{\mathrm{miss}} = (E_{\mathrm{miss}}, \vec{p}_{\mathrm{miss}}) = p_{\mathrm{total}} - \sum p_{\mathrm{charged}} - \sum p_{\mathrm{neutral}}$, where the event four-momentum p_{total} is known from the energy and crossing angle of the CESR beams. The charged and neutral particles included in the sums pass selection criteria designed to achieve the best possible $|\vec{p}_{\mathrm{miss}}|$ resolution by balancing the efficiency for detecting true particles against the rejection of false ones [5].

Association of p_{miss} with the neutrino is valid only if the event contains no more than one neutrino and all true particles are detected. We thus exclude events that have either more than one electron [9] or nonzero net charge. The core $|\vec{p}_{\mathrm{miss}}|$ resolution in our signal Monte Carlo (MC) events satisfying these criteria is $\sim$15 MeV/c.

Background sources include hadrons misidentified as electrons (fake electrons), noncharm continuum production, and $D\bar{D}$ processes other than signal. Background suppression criteria were optimized with GEANT-based [10] MC samples independent of those used in fitting.

We require $M_{\mathrm{miss}}^2 \equiv E_{\mathrm{miss}}^2 - |\vec{p}_{\mathrm{miss}}|^2$ to be consistent with a massless neutrino: $|M_{\mathrm{miss}}^2/2|\vec{p}_{\mathrm{miss}}|| < 0.2\ \mathrm{GeV}/c^3$. Since the $|\vec{p}_{\mathrm{miss}}|$ resolution is roughly half that of E_{miss}, in subsequent calculations we take $p_\nu \equiv (|\vec{p}_{\mathrm{miss}}|, \vec{p}_{\mathrm{miss}})$.

Semileptonic decays $D \to h e \nu_e$, where $h = \pi$ or K, are identified by using four-momentum conservation. Specifically, energy conservation demands $\Delta E \equiv (E_h + E_e + E_\nu) - E_{\mathrm{beam}}$ to be close to zero within our 20 MeV resolution, and we require $-0.06 < \Delta E < 0.10$ GeV. Since the $|\vec{p}_\nu|$ resolution dominates ΔE resolution, we improve our p_ν measurement by scaling it by the factor ζ satisfying $\Delta E = (E_h + E_e + \zeta E_\nu) - E_{\mathrm{beam}} = 0$. The D momentum constraint is recast as the beam-constrained mass $M_{\mathrm{bc}} \equiv \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_h + \vec{p}_e + \zeta\vec{p}_\nu|^2}$, which peaks near the D mass for signal. Our M_{bc} ($q^2 \equiv [\zeta p_\nu + p_e]^2$) resolution is 4 MeV/$c^2$ (0.01 GeV^2/c^4), independent of q^2.

For the Cabibbo-favored modes, the background remaining after these requirements is only a few percent of the signal. For the Cabibbo-suppressed modes, significant background remains from signal-mode cross feed and from the related modes $D^+ \to K_L^0 e^+ \nu_e$ and $D^+ \to K_S^0(\pi^0\pi^0)e^+\nu_e$, where the $(\pi^0\pi^0)$ indicates the K_S^0 decay mode. Restricting the ΔE of the nonsignal side of the event reduces these backgrounds. To further reduce cross-feed backgrounds and simplify statistical interpretation, we limit multiple D^0 (D^+) candidates with $M_{\mathrm{bc}} > 1.794$ GeV/c^2 by choosing that with the smallest $|\Delta E|$. The $D^+ \to \pi^0 e^+ \nu_e$ requirements are stricter: Candidates must have the smallest $|\Delta E|$ of any final state candidate in the event, and the event must contain no $D^0 \to K^- e^+ \nu_e$ candidate. The multiple candidate requirements affect about 13% of π^0, 9% of $\pi^\pm$, 8% of K_S, and 3% of $K^\pm$ candidates. The average final background fraction (q^2 dependent) in the pion modes is about 20%.

To extract branching fractions, we perform a simultaneous binned maximum likelihood fit [11] to the M_{bc} distributions of the four signal modes in five q^2 ranges. The simultaneity guarantees self-consistent rates for misreconstruction of one signal process as another (cross feed) and for background from the related K^0 processes. We use 14 equal M_{bc} bins over the range 1.794–1.878 GeV/c^2.

We fit the data to the signal and five background components. The signal-mode MC components are based on EVTGEN [12] with modified pole-model [Becirevic and Kaidalov (BK) parametrization] FFs [13] and parameters from the most recent unquenched LQCD calculation [3]. Several corrections, relating to inclusive D decay and reconstruction (see Ref. [5]), are applied to our GEANT-based [10] MC samples. These lead to few percent (or less) changes in the measured yields and are determined precisely enough (by using a large $D\bar{D}$ sample with one fully reconstructed D meson per event) to yield subpercent systematic uncertainties. We are also sensitive to the signal efficiency and kinematic distortions due to FSR. Our signal MC simulation includes FSR distributed according to the leading-order kaon leading-order radiation [14] calculation applied to charm decay.

To reduce our sensitivity to FFs, we extract an independent rate for each of the five q^2 intervals in each reconstructed mode (a total of 20 yields).

We use MC samples to describe the $D\bar{D}$ background and continuum contributions. We normalize the continuum components by using their cross sections at the $\psi(3770)$ and the measured data luminosity. The nonsignal $D\bar{D}$ sample was generated by using EVTGEN, with decay parameters updated to reflect our best knowledge of D meson decays. This component floats separately for each reconstructed mode but is fixed over the five q^2 regions within that mode, reducing our sensitivity to inaccuracies in the D decay model. Finally, we input explicit MC components for $D^+ \to K_L^0 e^+ \nu_e$ and $D^+ \to K_S^0(\pi^0\pi^0)e^+\nu_e$. Their normalization in each q^2 range in the fit is scaled by the appropriate amplitude or branching fraction factor to the corresponding $D^+ \to K_S^0(\pi^+\pi^-)e^+\nu_e$ parameter.

The contributions of events with fake electrons are evaluated by weighting hadron-momentum spectra in candidate events with misidentification probabilities measured in other CLEO-c data. This component is included with a fixed normalization in the fit.

We allow the fit to adjust the $M_{\rm bc}$ resolution in the $D^0 \to \pi^- e^+ \nu_e$, $D^0 \to K^- e^+ \nu_e$, and $D^+ \to \pi^0 e^+ \nu_e$ modes by smearing the distributions with a Gaussian. The signal MC $M_{\rm bc}$ resolution of $\sim 3.5\ \mathrm{MeV}/c^2$ thereby increases to match the data resolution of $\sim 4\ \mathrm{MeV}/c^2$.

Figure 1 shows the $M_{\rm bc}$ distributions summed over the five q^2 ranges, with the fit results overlaid. The two highest bins are not fit. Our $-2\ln\mathcal{L}$ behavior should be approximately χ^2-like, and our fit yields $-2\ln\mathcal{L} = 275.5$ for $280 - 27 = 253$ degrees of freedom.

We obtain branching fractions (see Table I) for each q^2 region by combining the efficiency-corrected yields from the fit with the number of $D^0\bar{D}^0$ ($N_{D^0\bar{D}^0}$) and D^+D^- ($N_{D^+D^-}$) pairs for our sample. An independent study of hadronic D decays [15] finds $N_{D^0\bar{D}^0} = 1.031(16) \times 10^6$ and $N_{D^+D^-} = 0.819(13) \times 10^6$. We find ratios of branching fractions $R_0 = \mathcal{B}(D^0 \to \pi^- e^+ \nu_e)/\mathcal{B}(D^0 \to K^- e^+ \nu_e) = 8.41(32)(13)\%$ and $R_+ = \mathcal{B}(D^+ \to \pi^0 e^+ \nu_e)/\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = 4.37(27)(12)\%$ and partial-width ratios $I_\pi = \Gamma(D^0 \to \pi^- e^+ \nu_e)/\Gamma(D^+ \to \pi^0 e^+ \nu_e) = 2.03(14)(8)$ and $I_K = \Gamma(D^0 \to K^- e^+ \nu_e)/\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e) = 1.06(2)(3)$ by using lifetimes from Ref. [4]. Isospin symmetry predicts $I_\pi = 2$ and $I_K = 1$.

The systematic uncertainty (see Ref. [5]) is dominated by the uncertainty in the number of $D\bar{D}$ pairs and in neutrino reconstruction simulation. The latter includes inaccuracies in the detector simulation and in the decay model of the nonsignal D, which were evaluated mainly by using events with a reconstructed hadronic decay. We evaluate q^2-dependent systematic biases for the efficiency of finding and identifying signal hadrons, identifying signal electrons and fake electron rates, as well as for uncertainties that affect the cross-feed rates, such as those associated with nonsignal π^0 and π^- production spectra, and K^- faking π^-. We correct statistically significant biases and propagate the uncertainty of each study into our measurement uncertainty. The remaining systematic uncertainties include $M_{\rm bc}$ resolution, the effect of the single-electron requirement, MC FSR modeling, dependence on FFs, and the $N_{D\bar{D}}$ determinations.

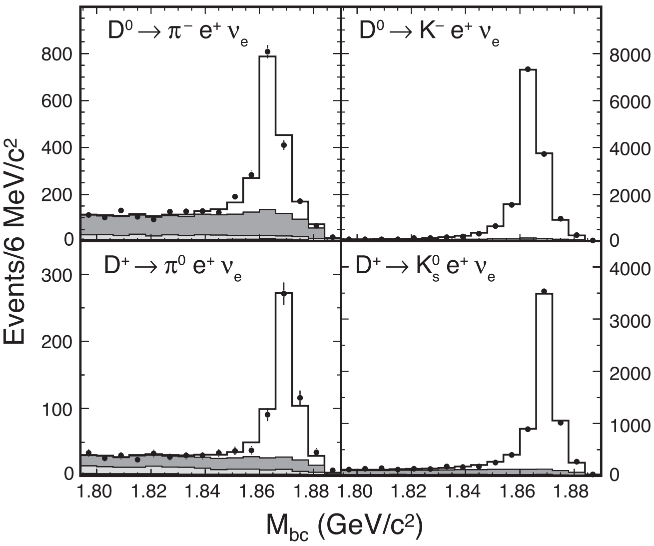

FIG. 1. The $M_{\rm bc}$ distributions, integrated over q^2, for data (points), the signal MC (clear), and cross-feed and nonsignal $D\bar{D}$ MC (gray) and continuum MC (light gray) fit components. The e^+ fake component is negligible on this scale.

Our primary FF shape analysis utilizes a series expansion that has been widely advocated as a physical description of heavy meson FFs [16–19]:

$$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} \sum_{k=0}^{\infty} a_k(t_0)[z(q^2, t_0)]^k. \qquad (1)$$

The expansion results from an analytic continuation of the FF into the complex $t = q^2$ plane, with a branch cut on the real axis for $t > (M_D + M_{K,\pi})^2$ that is mapped by $z(t, t_0) = (\sqrt{t_+ - t} - \sqrt{t_+ - t_0})/(\sqrt{t_+ - t} + \sqrt{t_+ - t_0})$ onto the unit circle. The constants $t_\pm \equiv (M_D \pm m_{K,\pi})^2$, and t_0 is the (arbitrary) q^2 value that maps to $z = 0$. The physical region is restricted to $|z| < 1$, so good convergence is expected. $P(q^2)$ accommodates subthreshold resonances: $P(q^2) = 1$ for $D \to \pi$ and $P(q^2) = z(q^2, M_{D_s^*}^2)$ for $D \to K$. The function $\phi(q^2, t_0)$ can be any analytic function. We report a_k parameters for $t_0 = 0$ and the "standard" choice for ϕ (see, e.g., Ref. [19]) that arises in studies of unitarity bounds on $\sum a_k^2$.

TABLE I. Branching fractions (top) and FF fits for the series (middle) and simple pole (bottom left) and modified pole (bottom right) parametrizations. The $\pi^0 e^+ \nu$ FF results are isospin-corrected. Errors are (stat)(syst)[(theor)]. The correlation coefficients (ρ or ρ_{ij}) are for the combined stat + syst uncertainties. The a_i normalization uses $|V_{cs}| = 0.976$ and $|V_{cd}| = 0.224$.

q^2 (GeV$^2/c^4$)	<0.4	0.4–0.8	0.8–1.2		1.2–1.6		≥ 1.6	Total	$\lvert V_{cq}\rvert$	
$\mathcal{B}(\pi^- e^+ \nu_e)$(%)	0.070(5)(3)	0.059(5)(2)	0.060(5)(2)		0.044(4)(2)		0.066(5)(2)	0.299(11)(9)	0.218(11)(5)(23)	
$\mathcal{B}(\pi^0 e^+ \nu_e)$(%)	0.084(10)(4)	0.097(11)(4)	0.062(9)(3)		0.063(10)(2)		0.067(11)(3)	0.373(22)(13)	0.216(17)(6)(23)	
$\mathcal{B}(K^- e^+ \nu_e)$(%)	1.441(21)(35)	1.048(18)(28)	0.681(15)(18)		0.340(11)(10)		0.048(5)(12)	3.557(33)(90)	1.023(13)(13)(107)	
$\mathcal{B}(\bar{K}^0 e^+ \nu_e)$(%)	3.436(82)(93)	2.544(73)(69)	1.589(58)(44)		0.821(42)(24)		0.139(18)(5)	8.53(13)(23)	1.004(20)(15)(105)	
Decay	a_0	a_1	a_2	ρ_{01}	ρ_{02}	ρ_{12}	$\lvert V_{cq}\rvert f_+(0)$	$1 + 1/\beta - \delta$	ρ	$P(\chi^2)$
$\pi^- e^+ \nu_e$	0.044(2)(1)	−0.18(7)(2)	−0.03(35)(12)	0.81	0.71	0.96	0.140(7)(3)	1.30(37)(12)	−0.85	0.38
$\pi^0 e^+ \nu_e$	0.044(3)(1)	−0.23(11)(2)	−0.60(57)(15)	0.80	0.67	0.95	0.138(11)(4)	1.58(60)(13)	−0.86	0.24
$K^- e^+ \nu_e$	0.0234(3)(3)	−0.009(21)(7)	0.52(28)(6)	0.62	0.56	0.96	0.747(9)(9)	0.62(13)(4)	−0.62	0.89
$\bar{K}^0 e^+ \nu_e$	0.0224(4)(3)	0.009(32)(7)	0.76(42)(8)	0.72	0.64	0.96	0.733(14)(11)	0.51(20)(4)	−0.72	0.44
Decay	$\lvert V_{cq}\rvert f_+(0)$	$m_{\rm pole}$ (GeV$/c^2$)	ρ	$P(\chi^2)$			$\lvert V_{cq}\rvert f_+(0)$	$\alpha_{\rm BK}$	ρ	$P(\chi^2)$
$\pi^- e^+ \nu_e$	0.146(4)(2)	1.87(3)(1)	0.63	0.21			0.142(4)(2)	0.37(8)(3)	−0.75	0.37
$\pi^0 e^+ \nu_e$	0.149(6)(3)	1.97(7)(2)	0.65	0.11			0.147(7)(4)	0.14(16)(4)	−0.75	0.13
$K^- e^+ \nu_e$	0.735(5)(9)	1.97(3)(1)	0.36	0.26			0.732(6)(9)	0.21(5)(3)	−0.42	0.12
$\bar{K}^0 e^+ \nu_e$	0.710(8)(10)	1.96(4)(2)	0.53	0.13			0.708(9)(10)	0.22(8)(3)	−0.59	0.07

For comparison purposes, we provide results based on the simple and modified pole models [13]. The latter introduces the shape parameter $\alpha_{\rm BK}$ to give $f_+(q^2) = f_+(0)/[(1 - q'^2)(1 - \alpha_{\rm BK} q'^2)]$, with $q'^2 \equiv q^2/m_{\rm pole}^2$. These parametrizations can typically accommodate the FF shapes observed in previous measurements but only with parameters that deviate from the underlying physical motivation [20]. Note that differing experimental sensitivities across phase space can result in differing parameter values for a nonphysical parametrization.

Each parametrization is fit to our measured rates for the five q^2 regions; each parameter systematic uncertainty is obtained from a fit to the rates for that systematic variation. Table I summarizes the results; Fig. 2 compares the three fits in our most precise mode $D^0 \to K^- e^+ \nu_e$. For the series expansion, we also express our results as physical observables: the intercept $|V_{cq}| f_+(0)$ and $1 + 1/\beta - \delta \propto (df_+/dq^2)/f_+|_{q^2=0}$ [19], which represents the effects of gluon hard-scattering (δ) and scaling violations (β). D^0 and D^+ results agree well.

For the series expansion, our kaon data prefer a nonzero quadratic z term. The probability of χ^2 [$P(\chi^2)$] improves from 29% (22%) to 89% (44%) with that additional term for the K^- ($\bar{K}^0$) fit. The pion measurements lack the sensitivity to probe this term, and two and three parameter fits yield similar results for the first two parameters. Since a quadratic term appears preferred for the kaons, however, we include that term in our series fits to the pion data to improve the probability that our shape uncertainties bracket the true FF shape. While three of the central values for a_2 are an order of magnitude larger than the other terms, regions of parameter space with a_2 of similar magnitude to a_0 and a_1 fall well within the 90% hypercontour for the fit, so no conclusion can be drawn about the size of a_2 or (potential lack of) convergence of the series from these data.

In the simple pole model, we fit for the intercept and the pole mass $m_{\rm pole}$. In the modified pole model, we fix $m_{\rm pole}$ at its physical value and fit for the intercept and $\alpha_{\rm BK}$, which determines the effective higher pole contribution. We obtain reasonable χ^2 values, but the pole masses deviate from $M_{D_s^*}$ (M_{D^*}) in the kaon (pion) modes by over 3σ for the most precise fits. The $1 + 1/\beta - \delta$ value for the series expansion fit to the $K^- e^+ \nu_e$ data is over 3σ from the value of ~2 necessary for physical validity of the BK parametrization, while our values for the BK $\alpha_{\rm BK}$ parameters from the kaon modes imply $1 + 1/\beta - \delta$ values tens of σ away. Overall, $P(\chi^2)$ improves noticeably for our preferred z expansion fit relative to these pole fits.

We extract (Table I) $|V_{cd}|$ and $|V_{cs}|$ from the $|V_{cq}| f_+(0)$ of our series expansion fits using $f_+^{(D\to\pi)}(0) = 0.64(3)(6)$ and $f_+^{(D\to K)}(0) = 0.73(3)(7)$ from unquenched LQCD [3].

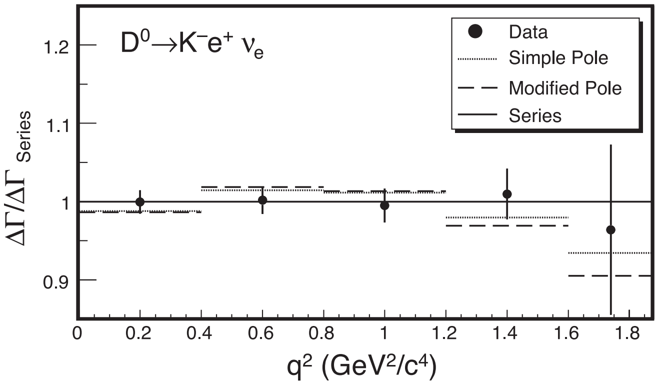

FIG. 2. The $D^0 \to K^- e^+ \nu_e$ form factor fits, normalized to the series expansion result.

The D^0 and D^+ averages (heeding correlations) are $|V_{cd}| = 0.217(9)(4)(23)$ and $|V_{cs}| = 1.015(10)(11)(106)$. Discretization uncertainty in the charm quark action dominates the f_+ uncertainty, listed last.

We also extract the ratio $|V_{cd}|/|V_{cs}|$ from the ratio of our measured FFs. Averaging over D^0 and D^+ modes, with correlations accounted for, gives $|V_{cd}|f^{(D\to\pi)}(0)/|V_{cs}|f^{(D\to K)}(0) = 0.188(8)(2)$. A recent light cone sum rules calculation [21] gives $f^{(D\to\pi)}(0)/f^{(D\to K)}(0) = 0.84(4)$, giving $|V_{cd}|/|V_{cs}| = 0.223(10)(3)(11)$.

In summary, we have measured branching fractions and their ratios for four semileptonic D decay modes in five q^2 bins. The branching fraction results are the most precise ever measured and agree well with world averages. Our modified pole $\alpha_{\rm BK}$ parameter results agree within 1.3σ with previous determinations by CLEO III [22], FOCUS [23], and $Ke\nu$ results from Belle [24] but show over 3σ disagreement with Belle $K\mu\nu$ results and LQCD fits. The $\alpha_{\rm BK}$ parameters obtained with our individual $Ke\nu$ results are separated from the recent *BABAR* result [25] by about 2.5σ. Our z expansion results agree with *BABAR*'s at about the 2σ level, depending on the total level of correlation between the *BABAR* r_1 and r_2 parameters. We have made the most precise CKM determinations from D semileptonic decays to date, and the results agree well with neutrino-based determinations of $|V_{cd}|$ and charm-tagged W decay measurements of $|V_{cs}|$ [4]. Overall, these measurements represent a marked improvement in our knowledge of D semileptonic decay.

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