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# Distribution in $q^2$ of $\overline{B^0} \to D^{*+}\ell^-\overline{\nu}$ Via Partial Reconstruction

CLEO Collaboration

## Abstract

We have studied the form factors for the decay of $\overline{B^0} \to D^{*+}\ell^-\overline{\nu}$ through the method of partial reconstruction in 3.13 fb$^{-1}$ of data corresponding to 3.35 million $B^0$'s collected at the $\Upsilon$(4S) resonance by the CLEO II detector. Using an extended maximum likelihood fit, we have measured the slope of the form factor $\hat{\rho}^2$. We find $\hat{\rho}^2 = 0.54 \pm 0.05 \pm 0.10 \pm 0.02$ where the first error is statistical, the second error is due to systematics of our measurement, and the third error arises from correlated experimental errors on $R_1$ and $R_2$.

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There are currently two complementary approaches to the precise determination of $V_{cb}$ where theoretical and experimental progress is being made: inclusive measurements of the lepton spectrum in $b \to c\ell\nu$, and the measurement of the hadronic form factor $\overline{B^0} \to D^{*+}\ell\overline{\nu}$. Since some of the key inputs that are used to control the theoretical uncertainties remain to be verified experimentally, agreement between the two methods provides a powerful consistency check. Measurement of the $\overline{B^0} \to D^{*+}\ell\overline{\nu}$ form factor at the zero recoil point currently provides the determination of $V_{cb}$ with the least theoretical error. In general, the form factor cannot be calculated in a model independent way. However, within the framework of Heavy Quark Effective Theory (HQET), the form factor can be calculated at the zero recoil point with controllable theoretical uncertainties. In this paper we present a high statistics measurement of the slope of the hadronic form factor in $\overline{B^0} \to D^{*+}\ell\overline{\nu}$ using the partial reconstruction method. The method uses only the slow $\pi^+$ in the decay $D^{*+}\to D^0\pi^+$ to reconstruct the $D^{*+}$. This process has been analyzed previously at CLEO II using the identified leptons and $D^*$'s reconstructed through the channel $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ or $K^-\pi^+\pi^0$ [1,2].

The differential decay rate for $\overline{B^0} \to D^{*+}\ell^-\overline{\nu}$ in terms of the couplings and helicity amplitudes $H_\pm(q^2)$ and $H_0(q^2)$ is discussed in [1]. The helicity amplitudes can be written in terms of the two axial vector and one vector form factors $A_1(q^2)$, $A_2(q^2)$, and $V(q^2)$, which can all be expressed in the heavy quark symmetry limit in terms of the single (Isgur-Wise) function $\xi(w)$ where $w \equiv (M^2 + m^2 - q^2)/(2Mm)$. The form factors are usually parametrized to accommodate departures from the heavy quark limit in a transparent way through three functions, $h_{A_1}(w)$, $R_1(w)$, and $R_2(w)$, such that $h_{A_1}(w) \to \xi(w)$, $R_1(w) \to 1$, and $R_2(w) \to 1$ in the limit of heavy quark symmetry. The function $h_{A_1}(w)$ is considered to be sufficiently slowly varying over the allowed range of $w$ that it is often expressed in a linear form: $h_{A_1}(w) = h_{A_1}(1)[1-\rho^2_{A_1}(w-1)]$. $R_1$ and $R_2$ are usually assumed to be constant as a function of $w$. [3].

It is straightforward to obtain the differential decay rate with implicit dependences on $q^2$ (the momentum transfer to the lepton):

$$\begin{aligned}\frac{d\Gamma(\overline{B^0} \to D^{*+}\ell^-\overline{\nu})}{dw} &= \frac{G_F^2|V_{cb}|^2m^3M^2}{48\pi^3}h^2_{A_1}(1) \times \sqrt{w^2-1}(1-\rho^2_{A_1}(w-1))^2(w+1) \\ &\times\{2[(w+1)+(w-1)R_1^2](1+r^2-2rw)+(w+1)[1-r-(w-1)(R_2-1)]^2\} \qquad (1)\end{aligned}$$

where $M$ is the mass of the $\overline{B^0}$ meson, $m$ is the mass of the $D^{*+}$ meson, and $r \equiv m/M$. The ratios $R_1$ and $R_2$ are predicted by HQET as well as by various models, while $\rho^2_{A_1}$, which requires a specific wavefunction, is predicted by models but not by HQET.

If one takes the values $R_1 = 1 = R_2$ predicted in the heavy quark symmetry limit and retains the linear form of $h_{A_1}(w)$, one has only one "slope" parameter, $\rho^2_{A_1} \to \hat{\rho}^2$, and one coefficient, $h_{A_1}(1) \to \mathcal{F}(1)$, so equation (1) becomes

$$\begin{aligned}\frac{d\Gamma(\overline{B^0} \to D^{*+}\ell^-\overline{\nu})}{dw} &= \frac{G_F^2|V_{cb}|^2m^3M^2}{48\pi^3}|\mathcal{F}(1)|^2 \times \sqrt{w^2-1}(1-\hat{\rho}^2(w-1))^2(w+1) \\ &\times\{4w(1+r^2-2rw)+(w+1)[1-r]^2\}. \qquad (2)\end{aligned}$$

Using the CLEO II dataset, we analyze the decay $\overline{B^0} \to D^{*+}\ell^-\overline{\nu}$ through the method of partial reconstruction. This approach yields a large sample of $\overline{B^0}\to D^{*+}\ell^-\overline{\nu}$ ($D^{*+} \to D^0\pi^+$)

candidates by exploiting the extremely low Q value of the $D^{*+}$ decay. Candidates are identified through detection of only two particles, the lepton and the $\pi^+$ produced in the $D^{*+}$ decay. The number of decays which are reconstructed via partial reconstruction exceeds by a factor of 20 the number obtained where the $D^*$ is fully reconstructed. In this analysis we measure the distribution in $q^2$.

The CLEO II detector [4] accumulated data from 1989 to 1995. The dataset consists of integrated luminosities of 3.13 fb$^{-1}$ on the $\Upsilon(4S)$ resonance and 1.61 fb$^{-1}$ taken at a center-of-mass energy which is lower by 60 MeV (continuum). This corresponds to 3.35 million $B\overline{B}$ events. The CLEO II detector accurately measures both charged and neutral particles over the majority of the $4\pi$ solid angle. Three concentric cylindrical wire chambers, in a 1.5 Tesla magnetic field, cover 94% of the solid angle and provide a total momentum resolution of $\frac{\Delta p}{p} \simeq 0.6\%$ for $p = 2.0$ GeV/$c$. A CsI electromagnetic calorimeter covers 98% of the solid angle and provides excellent resolution for the reconstruction of photons and $\pi^0$s. The calorimeter energy resolution is $\Delta E/E(\%) = 0.35/E^{3/4} + 1.9 - 0.1E$, where $E$ is in GeV, which corresponds to 4% at 0.1 GeV. To account for changes in the track reconstruction algorithm, in particular the change to the soft particle reconstruction efficiencies, we analyze earlier data (D1: $\simeq$1fb$^{-1}$), and later data (D2: $\simeq$2fb$^{-1}$) samples separately.

All events considered pass the standard CLEO hadronic criteria, which require at least 3 well-reconstructed charged tracks, a total visible energy of at least 0.15 times the CM energy and an event vertex consistent with the known interaction point. The requirement on the number of charged tracks is further restricted to be at least five in the present analysis. In order to remove $e^+e^- \to q\overline{q}$ continuum contributions, the ratio of the second to zeroth Fox-Wolfram moments [5] is required to be less than 0.25. In addition, we make two moderate event requirements designed to insure an adequate measurement of the missing neutrino momentum vector, $\mathbf{p}_{miss}$, using the missing momentum of the whole event by rejecting those events with obvious missing particle(s) other than the neutrino of interest. The requirements are: there is only one lepton in the event (an additional lepton implies the existence of another neutrino), and the absolute value of the net charge of the event must be less than or equal to one.

Electrons with momentum between 1.0 GeV/c and 2.4 GeV/c are identified by requiring that the ratio of the energy deposited in the CsI calorimeter and the momentum measured in the tracking system be close to unity and that the ionization energy loss measured by the tracking system be consistent with the electron hypothesis. The ratio of the log of the likelihood for the electron hypothesis to that for a hadron is required to be greater than or equal to 3. Electrons within the fiducial volume in this momentum range are identified with an efficiency of 94% while the probability that a charged hadron will be misidentified (fake rate) is $(0.20 \pm 0.06)\%$. Muons with momentum between 1.4 GeV/c and 2.4 GeV/c are identified by their ability to penetrate five nuclear interaction lengths of iron. Muons of this momentum are identified with an efficiency of 93%, while the fake rate is $(1.4 \pm 0.2)\%$ per charged hadron. We require the electrons and muons to be found in the well understood central region of the detector ($|\cos\theta| \leq 0.71$, where $\theta$ is the polar angle measured with respect to the beam axis) and they must also be consistent with coming from the primary vertex.

Pions must have momentum less than 0.2 GeV/c. The pion candidate must have specific ionization in the drift chamber consistent with the pion hypothesis, and satisfy good tracking requirements. These cuts place an effective minimum momentum cut of 0.05 GeV/c on the pion.

The momentum of the $D^*$ candidates of interest is typically 1.5-2 GeV/c. Due to the small Q value of the $D^*$ decay, their direction is very well represented by that of the daughter pion. The magnitude of the $D^*$ energy and momentum $(\widetilde{E}_{D^*}, \widetilde{\mathbf{p}}_{D^*})$ can be estimated by scaling the pion energy and momentum:

$$E_{D^*} \simeq \tfrac{E_\pi}{E_\pi^{CM}} M_{D^*} \equiv \widetilde{E}_{D^*}$$
$$\mathbf{p}_{D^*} \simeq \hat{\mathbf{p}}_\pi \times \sqrt{\widetilde{E}_{D^*}^2 - M_{D^*}^2} \equiv \widetilde{\mathbf{p}}_{D^*},$$

where $E_\pi$ is the $\pi^+$ energy, $E_\pi^{CM} = 145$ MeV is the energy of the $\pi^+$ in the $D^*$ rest frame, and $M_{D^*}$ is the mass of the $D^{*+}$.

This information is combined with the 4-momentum of the oppositely charged lepton candidate to obtain the squared missing mass recoiling against the $D^*\ell$ pair in a $B$ decay,

$$\widetilde{M}_{miss}^2 \equiv (E_{\text{beam}} - \widetilde{E}_{D^*} - E_\ell)^2 - (\widetilde{\mathbf{p}}_{D^*} + \mathbf{p}_\ell)^2,$$

where the energy of the $B$ is the beam energy and we approximate the momentum of the $B$ to be zero. We find a peak in the $\widetilde{M}_{miss}^2$ distribution near $\widetilde{M}_{miss}^2 = 0$ that is due to the decay $\overline{B^0} \to D^{*+}\ell^-\overline{\nu}$ as well as decays of the type $\overline{B^0} \to D^{*+}X\ell\overline{\nu}$, where $X$ is one or more pions. This can be seen in Figure 1.

For each candidate, we use the pion and lepton four momentum vectors to determine an estimate of $q^2$ which we label as $\widetilde{q^2}$. We consider a large number of $D^*$, $B$, and neutrino momenta which are kinematically consistent with the lepton and pion momenta. We arrive at a value, $\widetilde{q^2}$, by taking the phase space average of the $q^2$ values over the allowed combinations. In addition, we also calculate the mean value of the neutrino momentum, $\mathbf{p}_\nu$. This method is estimated to have an average resolution on $q^2$ of 1.4 GeV$^2$. Because the calculation requires that the candidate be consistent with $\overline{B^0} \to D^{*+}\ell^-\overline{\nu}$, those for which $\widetilde{q^2}$ is defined will necessarily have $\widetilde{M}_{miss}^2$ near the signal region.

In addition to calculating $\widetilde{q^2}$ and $\mathbf{p}_\nu$ for candidates which are consistent with $\overline{B^0} \to D^{*+}\ell^-\bar{\nu}$ ($\widetilde{M}_{miss}^2 \geq -2.0$ (GeV/c$^2$)$^2$), we also calculate

$$\Delta p_{\nu||} \equiv \frac{\hat{\mathbf{p}}_\nu \cdot (\mathbf{p}_\nu - \mathbf{p}_{miss})}{\delta p_\nu},$$

where $\delta p_\nu$ is the "resolution" on the numerator of this quantity. The quantity $\Delta p_{\nu||}$ is the projected difference between the neutrino momentum inferred from the lepton-pion pair and that obtained from missing momentum. Our final sample requires that the value of $\widetilde{q^2}$ be in the physical range (0-10.688 (GeV/$c^2$)$^2$) and that $\Delta p_{\nu||} < 0$. The $\Delta p_{\nu||} < 0$ cut is made as the background is concentrated at positive values as can be seen in Figure 2.

Background sources in this analysis include: continuum ($e^+e^- \to q\overline{q}$), "fake" leptons, "correlated" events, and "uncorrelated" events. The continuum contribution is estimated using data collected at an energy below the resonance, corrected for the difference in the luminosity of the on and off resonance samples, and the energy dependence of the cross section. The background contribution where the lepton is a misidentified hadron ("fake") is evaluated by reanalyzing the data using tracks which pass all requirements except the lepton

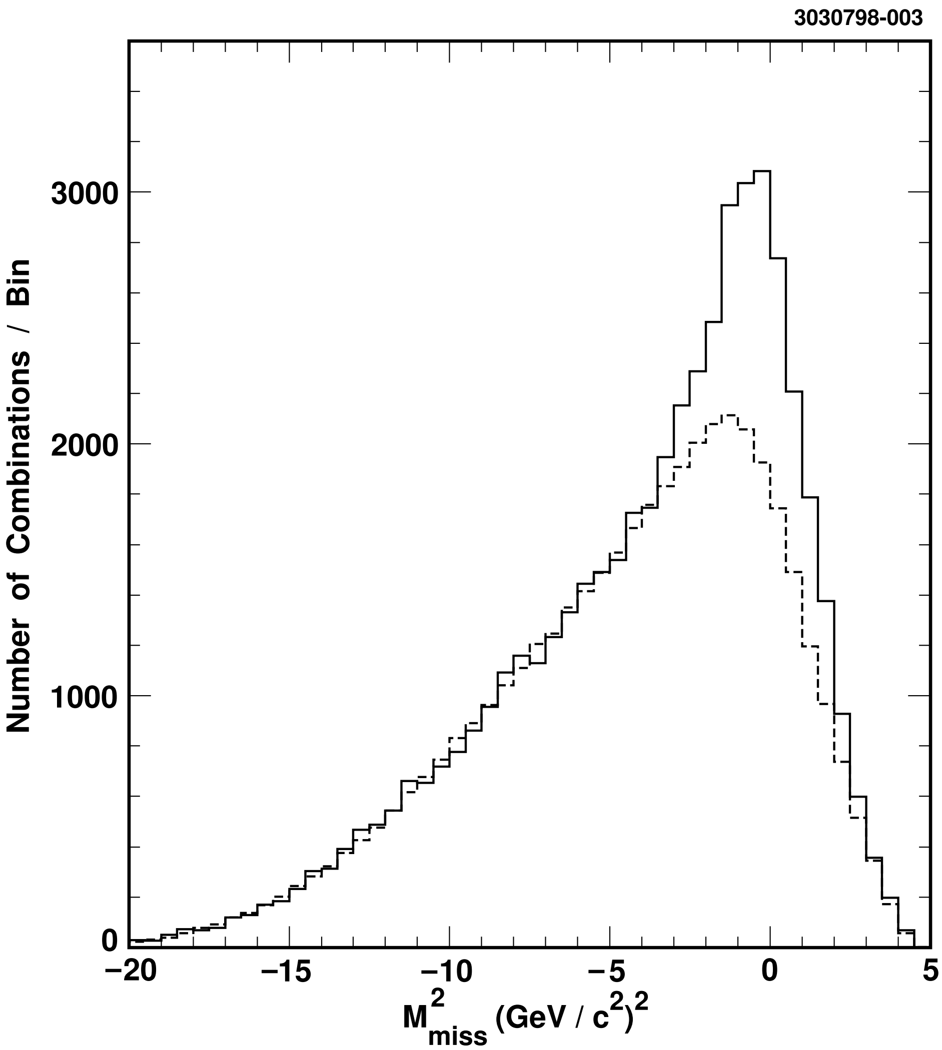


FIG. 1. Continuum- and fake-subtracted $\widetilde{M}^2_{miss}$ distributions in data for opposite-sign pion-lepton candidates (solid histogram). The dashed histogram shows the uncorrelated background estimated via Monte Carlo simulation.

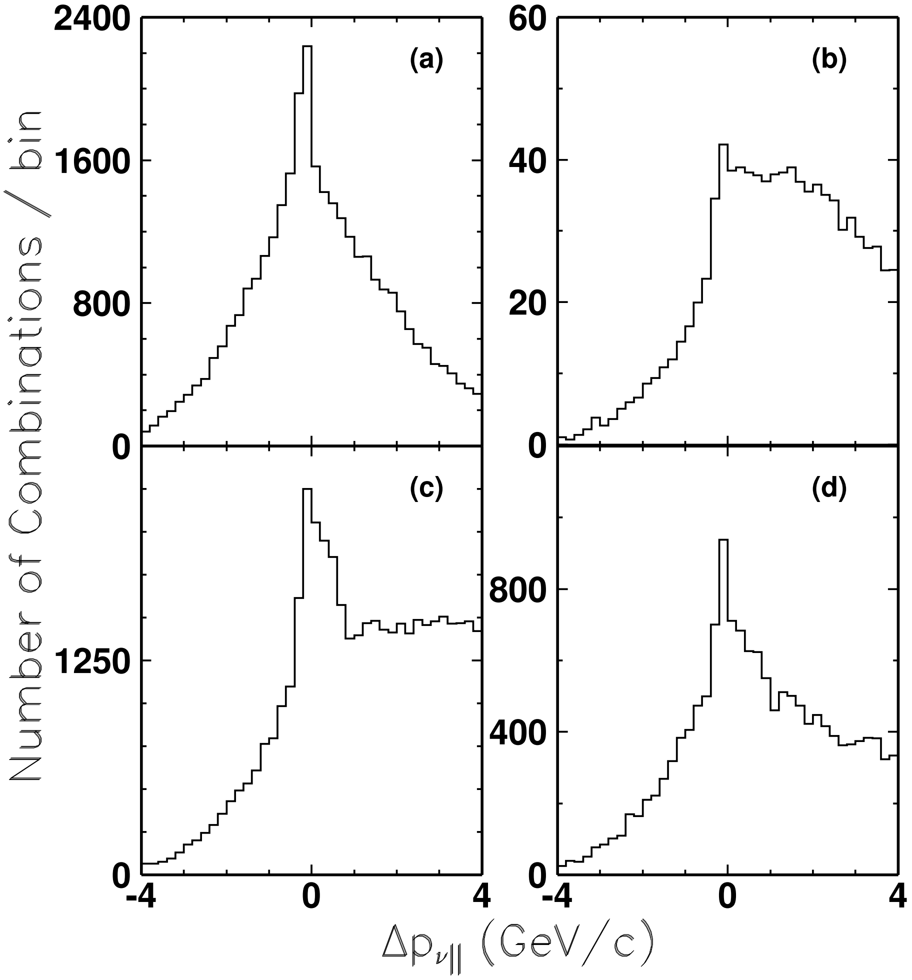


FIG. 2. Distributions in the variable $\Delta p_{\nu||}$ after all other cuts for a) $D^{*}e\nu$ Monte Carlo, b) $D^{**}e\nu$ Monte Carlo, c) uncorrelated background from miscellaneous $B\overline{B}$ events, and d) data.

TABLE I. Evaluation of reconstructed decays for candidates passing all requirements. Data sets D1 and D2 are tabulated separately. The values of $\hat{\rho}^2$ are found from the fits to the data.

| Source | D1 $e$ | D2 $e$ | D1 $\mu$ | D2 $\mu$ |
|---|---|---|---|---|
| 4S | $5366 \pm 73$ | $9176 \pm 96$ | $3124 \pm 56$ | $5756 \pm 76$ |
| continuum | $279 \pm 25$ | $478 \pm 29$ | $82 \pm 14$ | $129 \pm 15$ |
| fake lepton | $9 \pm 2$ | $14 \pm 8$ | $11 \pm 4$ | $18 \pm 6$ |
| correlated BG | $226 \pm 79$ | $392 \pm 136$ | $100 \pm 34$ | $183 \pm 67$ |
| uncorrelated BG | $1975 \pm 23$ | $3328 \pm 32$ | $1200 \pm 24$ | $2043 \pm 24$ |
| net $D^*\ell\nu$ | $2877 \pm 113$ | $4964 \pm 172$ | $1731 \pm 71$ | $3383 \pm 105$ |
| $\hat{\rho}^2$ | $0.57 \pm 0.10$ | $0.56 \pm 0.08$ | $0.30 \pm 0.16$ | $0.58 \pm 0.10$ |

identification criteria combined with the hadron misidentification probability. "Correlated" background is defined to be decays of the type $\overline{B^0} \to D^{*+}X\ell\overline{\nu}$. The "correlated" background is dominated by "$D^{**}$"$\ell^-\overline{\nu}$ decays and is estimated via Monte Carlo simulation. The "uncorrelated" background is composed of events with a real lepton and a random pion. If the pion and lepton are from the same $B$ decay, it is still called "uncorrelated" as long as the pion is not from a $D^*$ decay. The "uncorrelated" background is estimated via Monte Carlo simulation, using the "control region" ($-20.0 < \widetilde{M}^2_{miss} < -4.0$ GeV$^2$) to evaluate the appropriate scaling factor. We obtain the scaling factors as a function of slow pion momentum as it is related to $q^2$. Table I gives the event yields and background contributions for each data sample.

The fitting procedure compares the measured distributions of $\widetilde{q^2}$ with distributions for simulated data generated with known parameters. We use an unbinned extended maximum likelihood technique [1,6] implemented with a numerical method pioneered by Schmidt *et al.* [7]. In order to determine the efficiency as a function of $\widetilde{q^2}$ the likelihood fit integrates over the nonuniform acceptance of the decay angles. For this acceptance integral we assume nominal values of $R_1$ and $R_2$ even though the $q^2$ distribution is parameterized using Equation (2) which assumes $R_1 = 1 = R_2$.

We report as the principal result the values found where we set $R_1$ and $R_2$ in the acceptance integral to the central values found from the previous CLEO form factor analysis. [1] They found $R_1 = 1.18 \pm 0.30 \pm 0.12$ and $R_2 = 0.71 \pm 0.22 \pm 0.07$, where the first error is statistical and the second error is systematic. To find the central value, we take the statistically weighted average over electron and muon candidates for datasets D1 and D2 to obtain

$$\hat{\rho}^2 = 0.54 \pm 0.05 \pm 0.10 \pm 0.02.$$

Here the first error is statistical, the second is the systematic error as discussed below, and the third error is due to the experimental uncertainties in $R_1$ and $R_2$. Table I gives the fit results for each of the four datasets. The distributions of $\widetilde{q^2}/q^2_{max}$ for the background subtracted data together with the results of the fit are shown in Figure 3.

To explore the uncertainties in the values of $R_1$ and $R_2$ as used when integrating over decay angles, we repeated the analysis after changing the values of $R_1$ and $R_2$ within the errors quoted in [1] including the correlation between them. To determine the resulting systematic errors, we use the maximum excursion found in the result (0.02) as $R_1$ and $R_2$

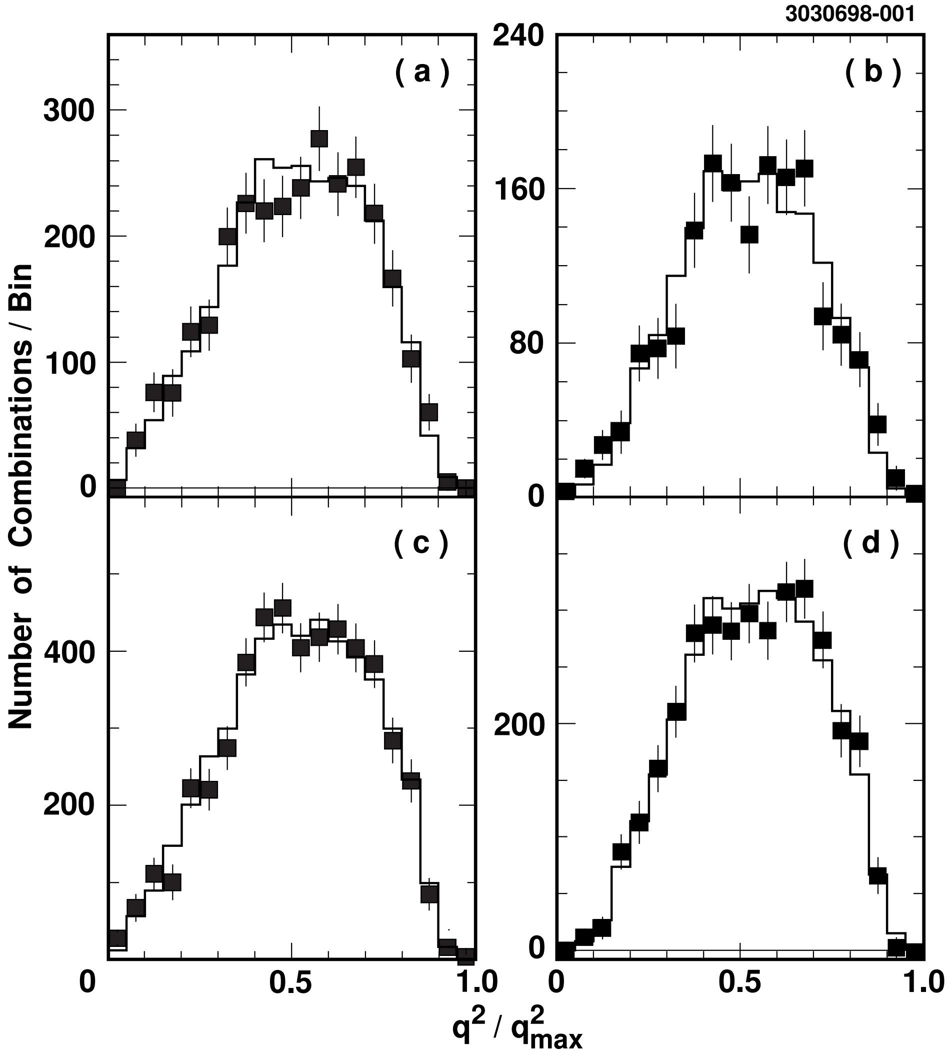


FIG. 3. The background subtracted $\widetilde{q^2}/q^2_{max}$ distributions of data (points with error bars) and the fitter result (solid line) for a) dataset D1 electrons, b) dataset D1 muons, c) dataset D2 electrons, and d) dataset D2 muons.

TABLE II. Systematic errors on $\hat{\rho}^2$.

| ERROR TYPE | SIZE |
|---|---|
| Background | 0.09 |
| Acceptance | 0.04 |
| Miscellaneous | 0.01 |
| TOTAL ERROR | 0.10 |

are varied along this error ellipse. If one constrains $R_1 = 1 = R_2$ as other experiments have done, we find $\hat{\rho}^2 = 0.58$.

The identified sources of systematic variation and their effects on $\hat{\rho}^2$ are summarized in Table II. To evaluate the uncertainty in each case the relevant contributions are modified and the fit is run again. The shift in the fitted value is taken to be the uncertainty. The errors can be broken down into three types: background, acceptance, and miscellaneous. The total systematic error, which is obtained by adding the individual errors in quadrature, is 0.10 which is dominated by two error sources. The first is from the uncorrelated background and the second is from the lack of knowledge on the decays of the type $D^* X \ell \nu$, *i.e.* the correlated background.

To obtain the background systematic error the errors of each of the four background sources discussed below are added in quadrature. The continuum and fake lepton background contributions are found by varying the amounts of each by their statistical error. For the error on correlated background, we combine the error from the determination of $D^{**}$ branching ratios [8,9] with an error that accounts for the differing $q^2$ distributions between the resonant and non-resonant components. Error sources in the uncorrelated background estimates include: statistics of MC and control region data, possible $q^2$ shape inaccuracy of Monte Carlo due to mismodelling, and possible acceptance effects of the Monte Carlo. The determination of the size of this error is based on the comparison of wrong sign (same sign pion-lepton pairs) data and Monte Carlo.

The most significant acceptance systematic errors result from the ability of the Monte Carlo to simulate reliably highly curved tracks, and from the measurement errors on missing energy-momentum and their effect on the $\Delta p_{\nu||}$ cut. An embedding technique is used to determine the uncertainty in the single track efficiency, and the efficiency is varied accordingly in the MC to estimate the systematic error. The distribution in $\Delta p_{\nu||}$ may be affected by the proportion of undetected neutral hadrons in events as well as uncertanties in tracking efficiency. To obtain this systematic error contribution, we account for the following possible effects: the rate of $K_L$ production, variation of tracking efficiency, the fraction of secondary leptons among candidates, and the fraction of event energy carried by the $K_L$. Errors found from modelling the lepton and its momentum cut are found to have a negligible effect on the acceptance.

Other miscellaneous systematic errors given in Table II come from the limited statistics of the MC sample and the fitting technique we use.

In conclusion, we have measured the the slope $\hat{\rho}^2$ in the $q^2$ distribution of the decay $\overline{B^0} \to D^{*+} \ell^- \overline{\nu}$ at the $\Upsilon(4S)$ resonance using a partial reconstruction method. Setting $R_1 = 1.18$

TABLE III. Previously published results.

| Experiment | $\hat{\rho^2}$ |
|---|---|
| This result | $0.54 \pm 0.05 \pm 0.10$ |
| CLEO II [2] | $0.84 \pm 0.12 \pm 0.08$ |
| OPAL [10] | $0.55 \pm 0.24 \pm 0.05$ |
| ALEPH [11] | $0.31 \pm 0.17 \pm 0.08$ |
| DELPHI [12] | $0.81 \pm 0.16 \pm 0.10$ |
| ARGUS [13] | $1.08 \pm 0.11 \pm 0.03$ |

and $R_2 = 0.71$ for the acceptance integral,

$$\hat{\rho^2} = 0.54 \pm 0.05 \pm 0.10 \pm 0.02,$$

where the first error is statistical, the second systematic, and the third due to uncertainties in the values of $R_1$ and $R_2$.

We compare our results for $\hat{\rho^2}$ to previously published ones in Table III. We believe all the results listed in this table have assumed that $R_1 = 1.0$ and $R_2 = 1.0$. If we fix $R_1$ and $R_2$ to these values in our fit, the value of $\hat{\rho^2}$ changes to 0.58. Although the measured values of $\hat{\rho^2}$ span a large range, we are consistent with the average. This measurement is essentially statistically independent of the two previous measurements from CLEO II which used the $D^*$ full-reconstruction method. The CLEO II measurement of $\hat{\rho^2}$ reported in Table III was determined from examining only the $q^2$ distribution [2] and differs from this result by $2\sigma$. The CLEO II full form factor analysis [1] performed a fit which simultaneously determined $R_1 = 1.18 \pm 0.30 \pm 0.12$, $R_2 = 0.71 \pm 0.22 \pm 0.07$, and $\rho^2_{A1} = 0.91 \pm 0.15 \pm 0.06$, where the measured value of $R_2$ is marginally consistent with 1.0. In order to compare to the slope $\rho^2_{A1}$, we perform fits using the parameterization of Equation (1). We map out a surface for the central value of $\rho^2_{A1}$ in the $R_1$-$R_2$ parameter space. This is shown in Figure 4. . For the particular values $R_1 = 1.18$ and $R_2 = 0.71$, we find $\rho^2_{A1} = 0.77 \pm 0.04 \pm 0.09$ which is consistent with the CLEO II full form factor result.

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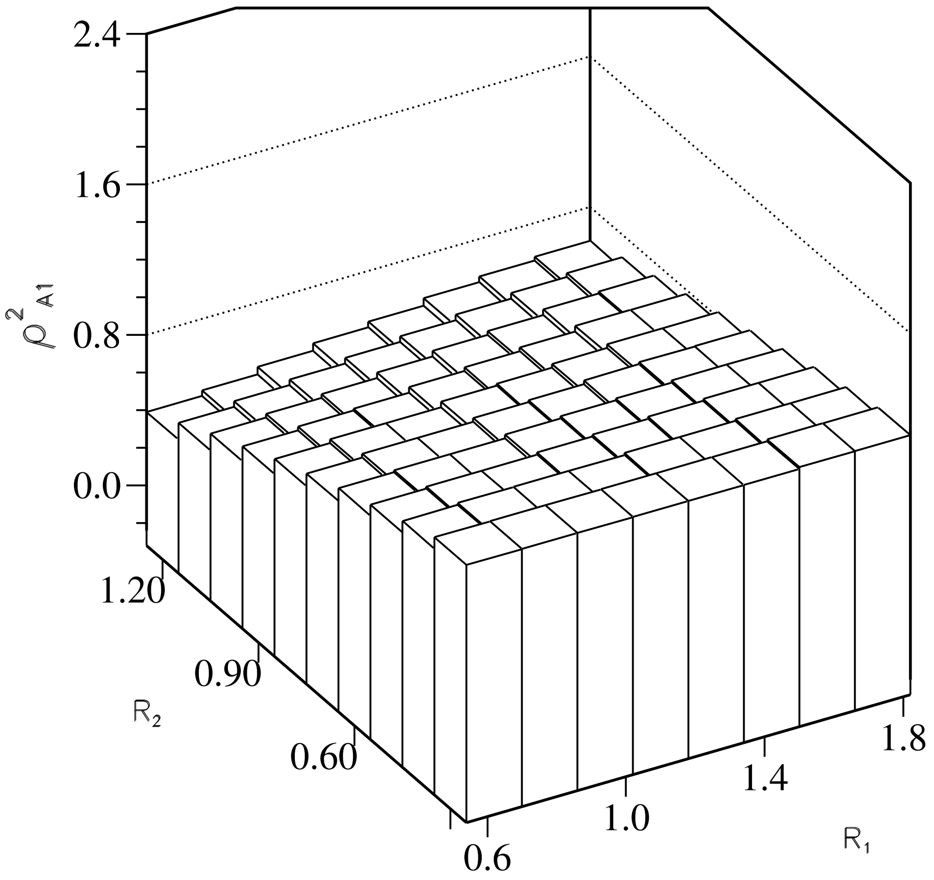


FIG. 4. The central values found for $\rho^2_{A1}$ as a function of the values of $R_1$ and $R_2$ fixed in the fit.

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