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Semileptonic B meson decay to P-wave charm mesons

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Abstract

We have studied semileptonic B meson decays with a P-wave charm meson in the final state using 2.65 million $B\bar{B}$ events recorded by the CLEO II detector. We find upper limits for the exclusive semileptonic decays: $\mathcal{B}(B^- \to D_1^0 e^- \bar{\nu})\mathcal{B}(D_1^0 \to D^{*+}\pi^-) < 0.62\%$ and $\mathcal{B}(B^- \to D_2^{*0} e^- \bar{\nu})\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) < 0.44\%$. We also extract an upper limit on the inclusive semileptonic production of P-wave charm mesons in B decay with electron momentum in the laboratory frame between 0.8 GeV/c and 2.0 GeV/c: $\mathcal{B}(B \to D_1^0 X e^- \bar{\nu})\mathcal{B}(D_1^0 \to D^{*+}\pi^-) < 0.67\%$ and $\mathcal{B}(B \to D_2^{*0} X e^- \bar{\nu})\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) < 0.79\%$. All limits are at the 90% confidence level.

I. INTRODUCTION

The D_J mesons contain one charm quark and one light quark with relative angular momentum L=1. The quark spins can sum to S=0 or S=1, and consequently there are four spin-parity states given by $J^P = 1^+$ or $0^+, 1^+, 2^+$. Parity and angular momentum conservation restrict the decays available to the four states. The 2^+ state may decay to either $D\pi$ or $D^*\pi$ through D-wave decays and both 1^+ states may decay only to $D^*\pi$ through S- or D-wave decay, while the 0^+ state can decay only to $D\pi$ and must go through S-wave decay.

According to Heavy Quark Effective Theory (HQET), there exists an approximate spin-flavor symmetry for hadrons made of one heavy and one light quark [1]. In the limit of infinite heavy quark mass, such mesons are described by the quantum numbers $j = S_q + L$, (the total angular momentum of the light quark), S_Q (the spin of the heavy quark), and $J = j + S_Q$ (the total angular momentum of the meson). In HQET, the D_J mesons make up two doublets, j=1/2 and j=3/2. The members of the j=3/2 doublet are predicted to decay only in a D-wave and to be relatively narrow. The j=1/2 mesons are predicted to decay only in an S-wave and to be relatively broad. In this analysis we study the semileptonic decays of the B meson to final states containing the narrow (j=3/2) excited charm mesons: the ${}^jL_J = {}^{3/2}P_2$ and ${}^{3/2}P_1$, labeled by the Particle Data Group and referred to here as the D_2^* and D_1, respectively. The semileptonic B meson decays to excited charm mesons are of particular interest because the total B semileptonic branching ratio is not accounted for by the observed exclusive semileptonic decays to D and D^* [2–4] as illustrated in Table I. It is expected that the remaining semileptonic branching ratio is accounted for by $B \to D_J^0 \ell \bar{\nu}$ modes [5,6] or decays of the type $B \to D^{(*)}\pi\ell\bar{\nu}$ where the $D^{(*)}\pi$ are in a nonresonant state [7].

II. EXPERIMENTAL METHOD

The data used in this analysis were produced in e^+e^- collisions at the Cornell Electron-positron Storage Ring (CESR) and recorded with the CLEO II detector. The data sample consists of 2.65 million $B\bar{B}$ events collected at the $\Upsilon(4S)$ center-of-mass energy. A detailed description of the CLEO II detector is given elsewhere [8].

For this analysis we select hadronic events [9] that have at least one track identified as an electron with momentum between 0.8 and 2.0 GeV/c. Electron candidates are required to lie within the region $|\cos\theta_e| < 0.91$ where θ_e is the angle of the electron candidate with respect to the beam axis. Electrons are identified by matching energy deposition in the CsI calorimeter and momentum measured in the drift chamber, their energy loss in the drift chamber gas (dE/dx), and their time of flight in the detector. The lower limit on their momentum for this analysis is determined by our lepton identification capabilities and the upper limit is chosen to suppress backgrounds from $\bar{B}^0 \to D^{*+}e^-\bar{\nu}$ decays. We do not use muons for this analysis. The CLEO II detector is only efficient with low hadron misidentification rates for muons of momentum above 1.4 GeV/c, and the spectrum of leptons from semileptonic B decays to excited charm mesons peaks well below that. The use of electrons only allows us to quote results that are less dependent on the theoretical models of the lepton energy spectrum for these decays.

For each electron in these events we search for D_J^0 candidates in the decay chain $D_J^0 \to D^{*+}\pi^-$, $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$ [10]. All charged tracks in the decay chain must originate from the vicinity of the nominal e^+e^- interaction point and, with the exception of the slow pion from the decay of the D^{*+}, have measured ionization losses in the drift chamber within 2.5 standard deviations of those expected for the hypothesis under consideration. We also take advantage of the charge correlation with the lepton from the B semileptonic decay and the K^- in the $D^0 \to K^-\pi^+$ decay, and require the kaon candidate and the lepton candidate to have the same sign.

We select D^0 candidates from $K^-\pi^+$ combinations that have an invariant mass within 1.5 standard deviations (11 MeV/c^2) of the known D^0 mass. We require each D^0 candidate to have a momentum consistent with being a B meson decay product; the D^0 candidate must have $x_D < 0.5$, where x_D is the D^0 momentum divided by the momentum of a D^0 with the beam energy. We then combine D^0 candidates with π^+ candidates to form D^{*+} candidates. The slow pion used to form the D^{*+} must have a momentum of at least 65 MeV/c and the D^{*+} candidate must have $x_{D^*} < 0.5$ where x_{D^*} for the D^{*+} candidate is defined in the same manner as x_D for the D^0 candidate. For each D^{*+} candidate we calculate a mass difference, $\delta m \equiv m(D^0\pi^+) - m(D^0)$. D^{*+} candidates with a value of δm within 2 standard deviations (2 MeV/c^2) of the known $D^{*+} - D^0$ mass difference are then combined with an additional charged pion in the event to form a D_J^0 candidate.

There is significant background in this analysis from real D^*'s combined with pions not from D_J^0 mesons. To suppress this background we select $D_J^0 - e^-$ pairs that are consistent with $B^- \to D_J^0 e^- \bar{\nu}$ decays by taking advantage of our knowledge of the B meson momentum, p_B. For B mesons produced in e^+e^- annihilations at the $\Upsilon(4S)$ energy, the B meson energy must be equal to the beam energy which is precisely known; therefore, although the direction of p_B cannot be measured, p_B can be determined from the beam energy and the known B mass [11]. We construct a four-vector, (E_W, p_W), out of the sum of (E_e, p_e) and (E_{D_J}, p_{D_J}), the four-momenta of the electron and D_J^0 candidates respectively. We define the quantity $\cos\theta_{BW}$ as the cosine of the angle between p_B, and p_W, the three-momentum of the $D_J^0 - e^-$

system, given by the following expression:

$$\cos\theta_{BW} = \frac{p_W^2 + p_B^2 - p_\nu^2}{2 p_B p_W}$$

where $p_\nu = E_B - E_W$. For true $B^- \to D_J^0 e^- \bar{\nu}$ decays, $\cos\theta_{BW}$ will have physical values, i.e., it will fall between -1 and 1. For decays in which either particles from the B decay chain are missing ($B \to D_J^0 X e^- \bar{\nu}$ where X is one or more unreconstructed particles), or for combinatoric background events when an extra random pion has been added to a true semileptonic B decay ($\bar{B}^0 \to D^{*+} e^- \bar{\nu}$ + an extra pion), $\cos\theta_{BW}$ need not have physical values. For the former background source, $\cos\theta_{BW}$ is shifted toward negative values, and it is shifted towards positive values for the latter. Figure 1 shows $\cos\theta_{BW}$ plotted for $B^- \to D_J^0 e^- \bar{\nu}$, for $B \to D_J^0 X e^- \bar{\nu}$ and for generic $B\bar{B}$ background events in Monte Carlo. We require $D_J^0 - e$ pairs to have $\cos\theta_{BW}$ values in the physical range between -1 and 1. This cut effectively suppresses the dominant background to this analysis which comes from true $\bar{B}^0 \to D^{*+} e^- \bar{\nu}$ decays, where the D^{*+} is combined with a random pion in the event to make a D_J^0 candidate, but does not introduce significant dependence on our model of the $B^- \to D_J^0 e^- \bar{\nu}$ decay.

After applying all the above cuts, a plot of the mass difference $\delta m_J \equiv m(D^{*+}\pi^-) - m(D^{*+})$ is made containing one entry for each candidate $D_J - e^-$ pair, potentially with multiple entries per event. The data are shown in Figure 2. While there appears to be a statistically significant enhancement in the region of the narrow D_J^0 resonance at $\delta m_J = 0.411$ GeV/c^2, there is not compelling evidence for a signal, based on a study of other relevant kinematic variables such as the distribution of $\cos\theta_{BW}$.

This plot can then be fit to Breit-Wigner resonance functions corresponding to the line-shapes of the two narrow D_J^0 resonances [12] that have each been convoluted with a Gaussian to describe the detector resolution. The resonance parameters used in the fit are given in Table II. The width of the Gaussian is measured in Monte Carlo to be 4 MeV/c^2. The background is described by a polynomial in δm_J consisting of half-integer powers with a root at the pion mass, as constrained by kinematics. The solid line in Figure 2 illustrates the results of the fit. The yields obtained from the fit are 32 ± 12 events and 7 ± 11 events for the D_1^0 and the D_2^{*0} respectively.

The background in Figure 2 is predicted by Monte Carlo to be dominated by combinatoric background in which a real electron and a real D^{*+} combine with a random pion in the event to pass all selection criteria. According to Monte Carlo, such combinatoric background accounts for 89% of the background to our signal, the remainder being misreconstructed D^{*+}'s. The combinatoric background is well modeled, both in Monte Carlo and in data, by a sample of events that pass all the same selection criteria as our signal except that in forming the D_J^0 candidate, a D^{*+} and a wrong sign pion (a pion with the same sign as the D^{*+}) are used. This wrong sign sample is shown as the dashed histogram in Figure 2. Figure 3 shows the difference between the right sign signal sample and the wrong sign background sample. In order to extract yields in this method, we take events between 0.371 GeV/c^2 and 0.431 GeV/c^2 (-2Γ and $+\Gamma$) of the nominal values of δm_J for the D_1^0 resonance. For the D_2^{*0} resonance we take δm_J between 0.427 GeV/c^2 and 0.511 GeV/c^2 ($-\Gamma$ and $+2\Gamma$). In both cases we have taken into account the incomplete acceptance of this cut on a Breit-Wigner lineshape. We find $n(D_1^0) = 44 \pm 14$ and $n(D_2^{*0}) = 23 \pm 15$. Because of the poor quality of the fits to the data as described above, we use the yields extracted by subtracting the wrong sign sample to form our upper limits.

We also perform the same analysis with the $\cos\theta_{BW}$ cut removed in order to put an upper limit on decays of the type $B \to D_J^0 X e^- \bar{\nu}$, where X can be extra particles in the decay chain that are undetected. The δm_J plot without the $\cos\theta_{BW}$ cut is shown in Figure 4. The δm_J spectrum is fit to Breit-Wigner resonance functions convoluted with Gaussians to describe the detector resolution plus a function to describe the background as described above. The yields from the fit are 35 ± 16 and 9 ± 17 for the D_1 and the D_2^{*0} resonances respectively.

In Monte Carlo studies, events with a real D^* and a real lepton make up 87% of the background to the signal in the analysis without the $\cos\theta_{BW}$ cut, and so the wrong sign sample is still an accurate model of the background. The data in this mode with the wrong sign sample subtracted are shown in Figure 5. We extract yields using the procedure outlined above for the exclusive decays and find $n(D_1^0 X) = 40 \pm 23$ and $n(D_2^{*0} X) = 42 \pm 24$. We use the yields from the wrong sign subtraction to form our upper limits on the branching ratio.

III. EFFICIENCY

Our event selection efficiency was obtained using Monte Carlo data generated as $B^- \to D_1^0 e^- \bar{\nu}$ and $B^- \to D_2^{*0} e^- \bar{\nu}$ and containing one signal decay per event. The Monte Carlo was generated according to the ISGW model [5]. The entire procedure applied to the data was carried out on this Monte Carlo sample and the final signal yield divided by the number of events generated was interpreted as the efficiency. The δm_J distributions for signal Monte Carlo events are shown in Figure 6, where the fits shown are made following the same procedure as the fits to the data. The efficiencies are $\varepsilon_1 \equiv \varepsilon(B^- \to D_1^0 e^- \bar{\nu}) = (15.0 \pm 0.4)\%$ and $\varepsilon_2 \equiv \varepsilon(B^- \to D_2^{*0} e^- \bar{\nu}) = (15.2 \pm 0.5)\%$, where the quoted error is statistical only.

For the $B \to D_J^0 X e^- \bar{\nu}$ analysis, we also generate $B^- \to D_J^0 \pi^0 e^- \bar{\nu}$ events and pass them through our signal analysis where the $\cos\theta_{BW}$ cut has been released. The lepton spectrum for these decays is unknown, so we calculate our efficiency only for events with an electron within our cut on the lepton momentum in the lab: $0.8 < p_e < 2.0$ GeV/c. We find $\varepsilon_{1X} \equiv \varepsilon(B \to D_1^0 X e^- \bar{\nu}) = (16.0 \pm 0.9)\%$ and $\varepsilon_{2X} \equiv \varepsilon(B \to D_2^{*0} X e^- \bar{\nu}) = (14.4 \pm 0.9)\%$.

IV. EXTRACTION OF BRANCHING RATIO UPPER LIMITS

Upper limits on the product branching fractions, $\mathcal{B}(B^- \to D_1^0 e^- \bar{\nu})\mathcal{B}(D_1^0 \to D^{*+}\pi^-)$ and $\mathcal{B}(B^- \to D_2^{*0} e^- \bar{\nu})\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-)$ are extracted by correcting the observed yields by the signal reconstruction efficiency and dividing by the total number of $\Upsilon(4S)$ decays, $N_{\Upsilon(4S)}$, in our sample. We have assumed that the $\Upsilon(4S)$ decays 50% of the time to a pair of charged B's and 50% of the time to a pair of neutral B's. Because we choose to quote an upper limit, we make no attempt to subtract backgrounds due either to misreconstruction of the events (such as events where a hadron has been misidentified as a lepton) or due to physics (such as contributions to our yield from higher mass states: $B \to D_J^0 X e^- \bar{\nu}$). From our yields we compute the product branching ratios:

$$\mathcal{B}(B^- \to D_J^0 e^- \bar{\nu})\mathcal{B}(D_J^0 \to D^{*+}\pi^-) = \frac{n(D_J)/\varepsilon_J}{N_{\Upsilon(4S)} \times \mathcal{B}(D^{*+} \to D^0\pi^+) \times \mathcal{B}(D^0 \to K^-\pi^+)}$$

Using the CLEO values for the D^{*+} [13] and D^0 [14] branching ratios,

$$\mathcal{B}(D^{*+} \to D^0\pi^+) = (68.1 \pm 1.6)\%$$

and

$$\mathcal{B}(D^0 \to K^-\pi^+) = (3.91 \pm 0.19)\%$$

we find

$$\mathcal{B}(B^- \to D_1^0 e^- \bar{\nu})\mathcal{B}(D_1^0 \to D^{*+}\pi^-) < 0.62\%$$

and

$$\mathcal{B}(B^- \to D_2^{*0} e^- \bar{\nu})\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) < 0.44\%,$$

where both limits are at the 90% confidence level. In order to assess the contribution of these decays to the total semileptonic B meson branching fraction, we need to make some assumptions about the branching fractions of the D_J^0 mesons. If we assume, based on isospin conservation and recent CLEO measurements of the decays of the D_J^0 mesons [12], that $\mathcal{B}(D_1^0 \to D^{*+}\pi^-) = 67\%$ and $\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) = 20\%$, we find $\mathcal{B}(B^- \to D_1^0 e^- \bar{\nu}) < 0.93\%$ and $\mathcal{B}(B^- \to D_2^{*0} e^- \bar{\nu}) < 2.2\%$.

From our analysis without the $\cos\theta_{BW}$ cut we find, for $0.8 < p_e < 2.0$,

$$\mathcal{B}(B \to D_1^0 X e^- \bar{\nu})\mathcal{B}(D_1^0 \to D^{*+}\pi^-) < 0.67\%$$

and

$$\mathcal{B}(B \to D_2^{*0} X e^- \bar{\nu})\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) < 0.79\%.$$

Both limits are at the 90% confidence level.

In Table III and Table IV these results are compared with recent results from other experiments and from a theoretical model. A clear picture has not yet emerged of the exclusive modes which make up the 30 - 40% of the B semileptonic decays that are not $Dl\nu$ and $D^{*}l\nu$. However, it appears that no more than 25% of the excess can be accounted for by exclusive semileptonic decays to D_1^0.

V. CONCLUSIONS

In summary, we have searched for semileptonic decays of B mesons to P-wave charm mesons. We find upper limits on the branching ratios for the exclusive and inclusive semileptonic decays to P-wave charm mesons. The results indicate that a substantial part of the inclusive semileptonic rate is from modes other than $Dl\nu$, $D^{*}l\nu$, and $D_1l\nu$.

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TABLES

TABLE I. The measured exclusive semileptonic branching ratios and the measured inclusive semileptonic branching ratio of the B meson from CLEO. Note that all results use the same value for the $D^0 \to K^-\pi^+$ branching ratio. Over 30% of the inclusive semileptonic branching ratio is not accounted for by decays to the lowest pseudoscalar and vector charm mesons.

Decay Mode	Branching Fraction	Reference
$B^- \to D^0 e^- \bar{\nu}$	$(1.95 \pm 0.55)\%$	[4]
$B^- \to D^{*0} e^- \bar{\nu}$	$(5.13 \pm 0.84)\%$	[2]
$\mathcal{B}(B \to X e^- \bar{\nu})$	$(10.49 \pm 0.46)\%$	[3]
Inclusive - Exclusive	$(3.4 \pm 1.1)\%$	

TABLE II. The parameters of the Breit-Wigner resonance functions that are used in the fits to describe the D_1 and D_2^* resonances. The resonance function is convoluted in the fit with a Gaussian of width 4 MeV/c^2 to describe the detector resolution.

Resonance	δm_J (GeV/c^2)	Γ (GeV/c^2)	Reference
D_1^0	0.411	0.020	[12]
D_2^{*0}	0.455	0.028	[12]

TABLE III. A summary of the exclusive results of this analysis. The theoretical values given for comparison are based on the partial rates given in the ISGW2 model, where we have used $|V_{cb}| = 0.04$, a B lifetime of $\tau_B = 1.5$ ps, and D_J^0 branching fractions of $\mathcal{B}(D_1^0 \to D^{*+}\pi^-) = 67\%$ and $\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) = 20\%$, to convert the theoretical rates to product branching fractions.

Decay Mode	CLEO 90% c.l.	ISGW2 [6]
$\mathcal{B}(B^- \to D_1^0 e^- \bar{\nu})\mathcal{B}(D_1^0 \to D^{*+}\pi^-)$	$< 0.62\%$	0.29 %
$\mathcal{B}(B^- \to D_2^{*0} e^- \bar{\nu})\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-)$	$< 0.44\%$	0.04 %

TABLE IV. A summary of the results of this analysis for $B \to D_J^0 X e^- \bar{\nu}$ decays, and a comparison with other recent measurements. The results of the LEP experiments have all been expressed as B branching fractions under the assumption that $\mathcal{B}(b \to B^-) = \mathcal{B}(b \to \bar{B}^0) = 0.4$. The OPAL numbers for $\mathcal{B}(B \to D_1^0 X e^- \bar{\nu})\mathcal{B}(D_1^0 \to D^{*+}\pi^-)$ and $\mathcal{B}(B \to D_2^{*0} X e^- \bar{\nu})\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-)$ are based on numbers quoted in their paper, and are extracted from their measured yields with the assumptions that their observed D_J^0 signals are due to D_1^0 and D_2^{*0} and assuming $\mathcal{B}(D_1^0 \to D^{*+}\pi^-) = 67\%$ and $\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) = 20\%$.

Decay Mode	CLEO $0.8 < p_e < 2.0$ GeV/c	ALEPH [15]	OPAL [16]
$\mathcal{B}(B \to D_1^0 X e^- \bar{\nu})$ $\times\mathcal{B}(D_1^0 \to D^{*+}\pi^-)$	$< 0.67\%$ (90% c. l.)	$(0.51 \pm 0.17)\%$	$(1.36 \pm 0.46)\%$
$\mathcal{B}(B \to D_2^{*0} X e^- \bar{\nu})$ $\times\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-)$	$< 0.79\%$ (90% c. l.)	$< 0.20\%$ (95 % c. l.)	$(0.18 \pm 0.08)\%$
$\mathcal{B}(B \to D_J^0 X e^- \bar{\nu})$ $\times\mathcal{B}(D_J^0 \to D^{*+}\pi^-)$	$< 1.47\%$ (90% c. l.)		$(1.53 \pm 0.46)\%$

FIGURES

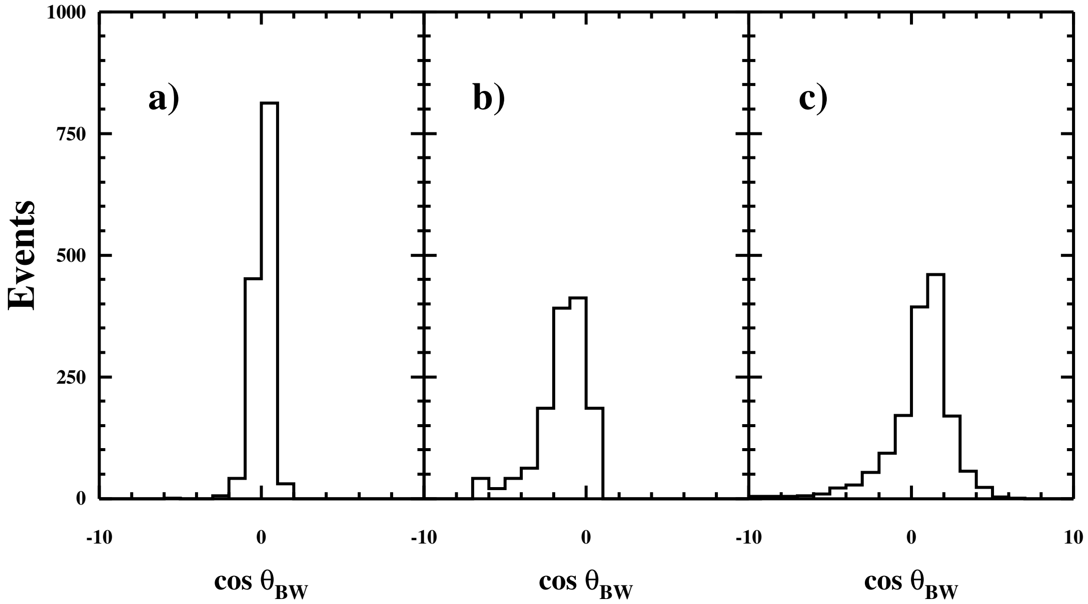

FIG. 1. The distribution of $\cos\theta_{BW}$ from Monte Carlo for (a) $B^- \to D_1^0 e^- \bar{\nu}$ decays (b) $B \to D_1^0 X e^- \bar{\nu}$ decays and (c) generic $B\bar{B}$ events that have passed all other cuts in the analysis. In the analysis we require $|\cos\theta_{BW}| < 1.0$.

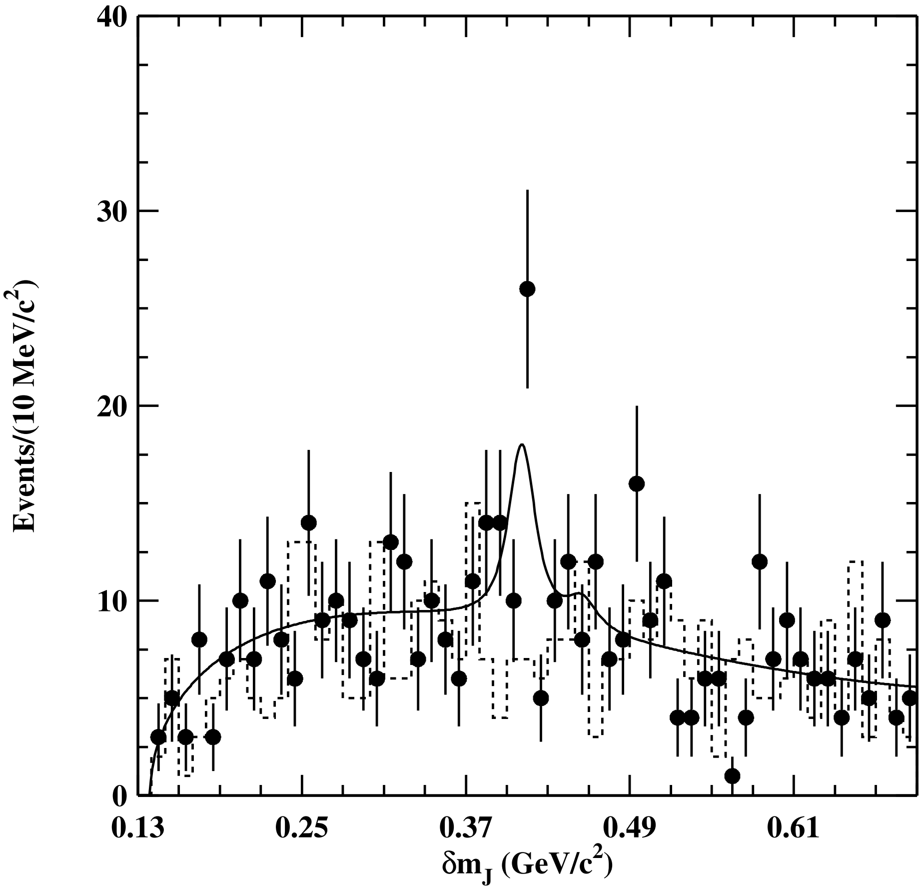

FIG. 2. The points are the δm_J distribution for $D^{*\pm}\pi^{\mp}$ events in data passing all analysis cuts. The solid line is the result of the fit as described in the text. The dashed histogram is the δm_J distribution for the wrong sign ($D^{*\pm}\pi^{\pm}$) sample in the data.

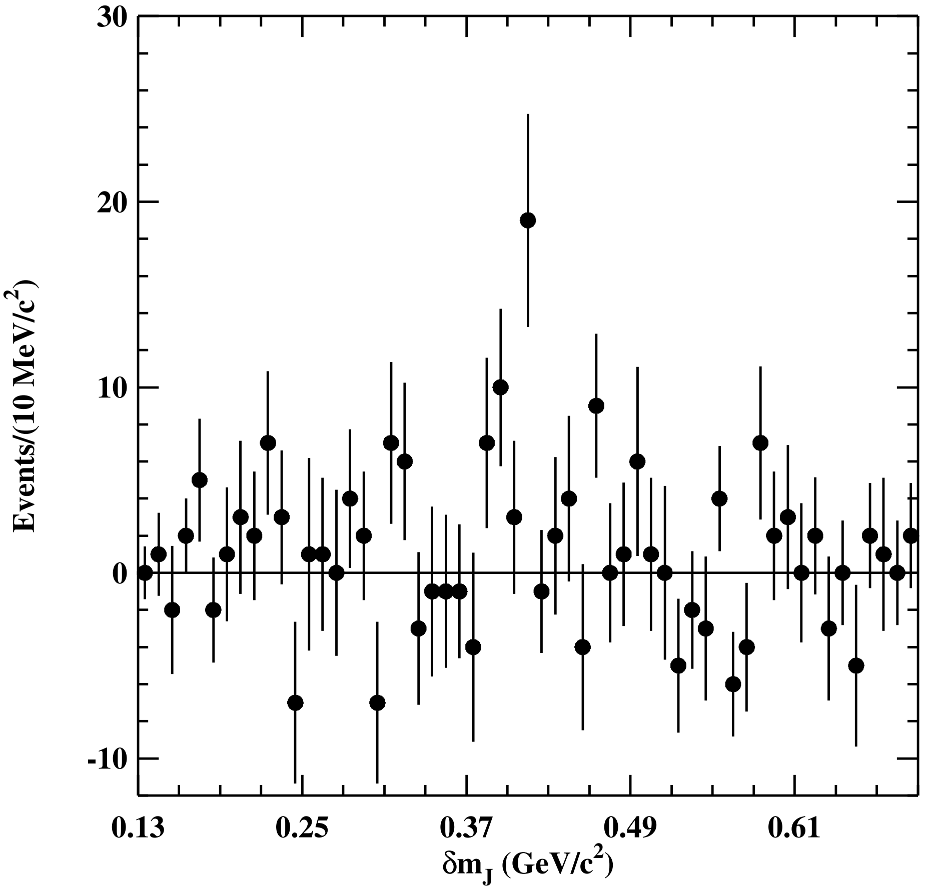

FIG. 3. The δm_J distribution of events in data passing all analysis cuts, where the δm_J distribution of the wrong sign sample (the dashed histogram in Figure 2) has been subtracted. The signal regions for extracting our yields are 0.371 GeV/c^2 $< \delta m_J(D_1^0) <$ 0.431 GeV/c^2 and 0.427 GeV/c^2 $< \delta m_J(D_2^{*0}) <$ 0.511 GeV/c^2.

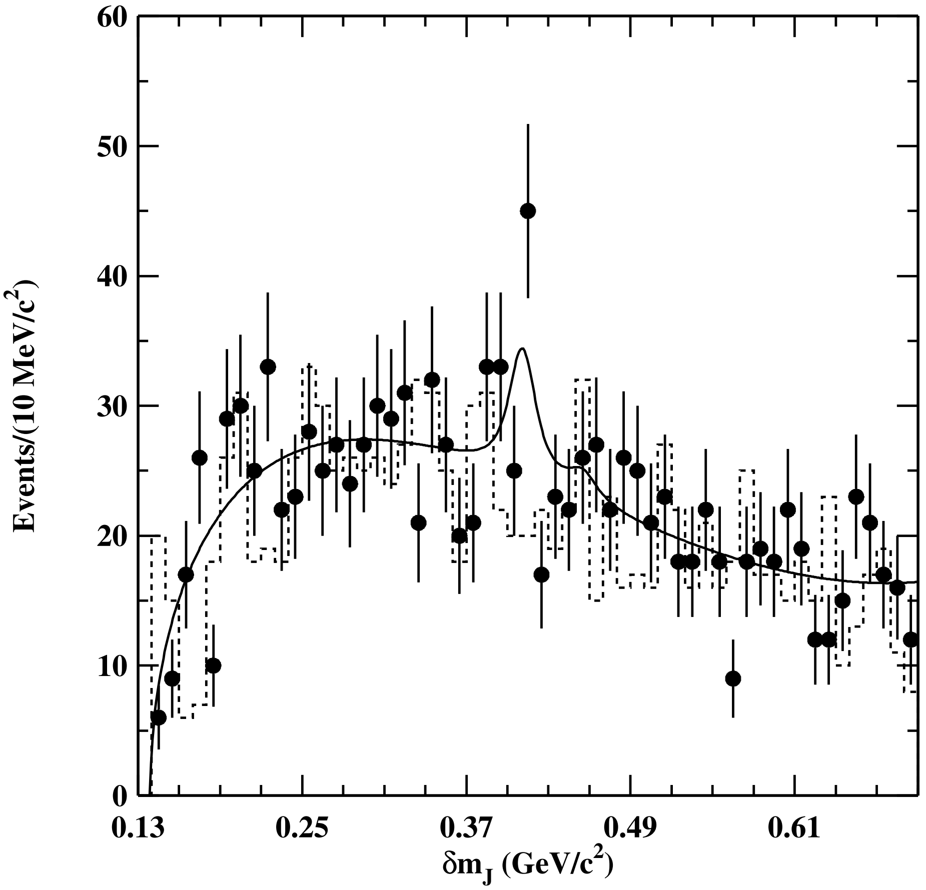

FIG. 4. The points are the δm_J distribution for $D^{*\pm}\pi^{\mp}$ events in data passing all analysis cuts except the $\cos\theta_{BW}$ cut. The solid line is the result of the fit as described in the text. The dashed histogram is the δm_J distribution for the wrong sign ($D^{*\pm}\pi^{\pm}$) sample in the data.

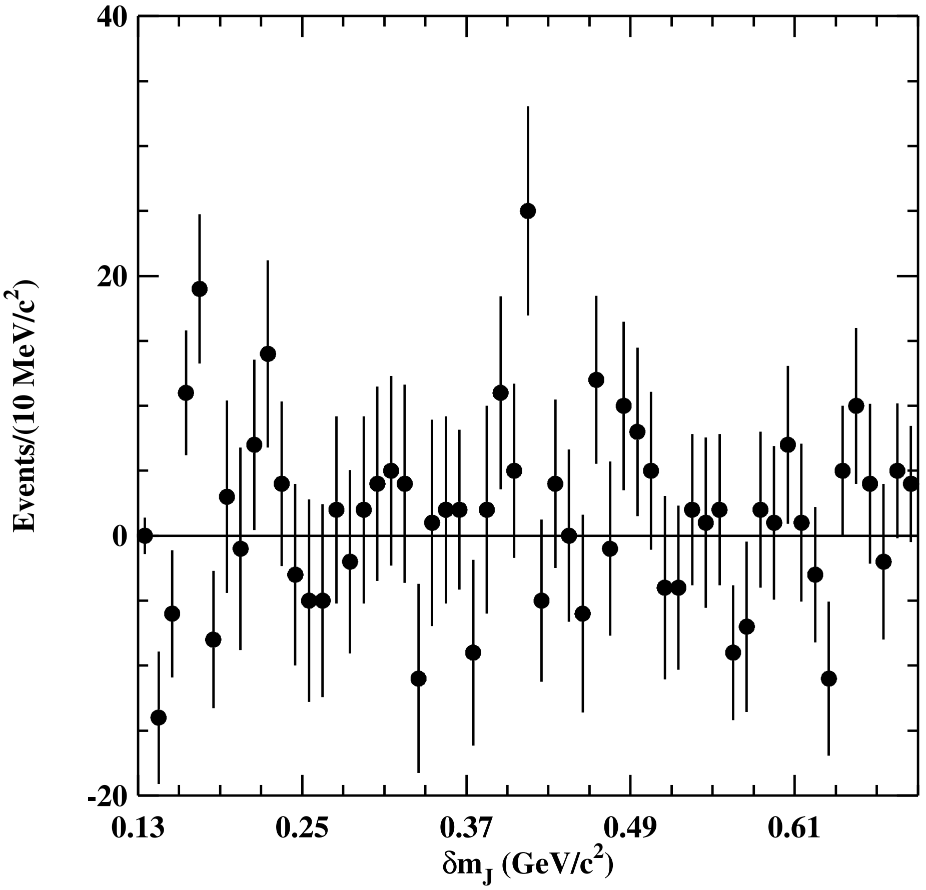

FIG. 5. The δm_J distribution of events in data passing all cuts except the $\cos\theta_{BW}$ cut, where the δm_J distribution for the wrong sign sample (the dashed histogram in Figure 4) has been subtracted. The signal regions for extracting our yields are 0.371 GeV/c^2 $< \delta m_J(D_1^0) <$ 0.431 GeV/c^2 and 0.427 GeV/c^2 $< \delta m_J(D_2^{*0}) <$ 0.511 GeV/c^2.

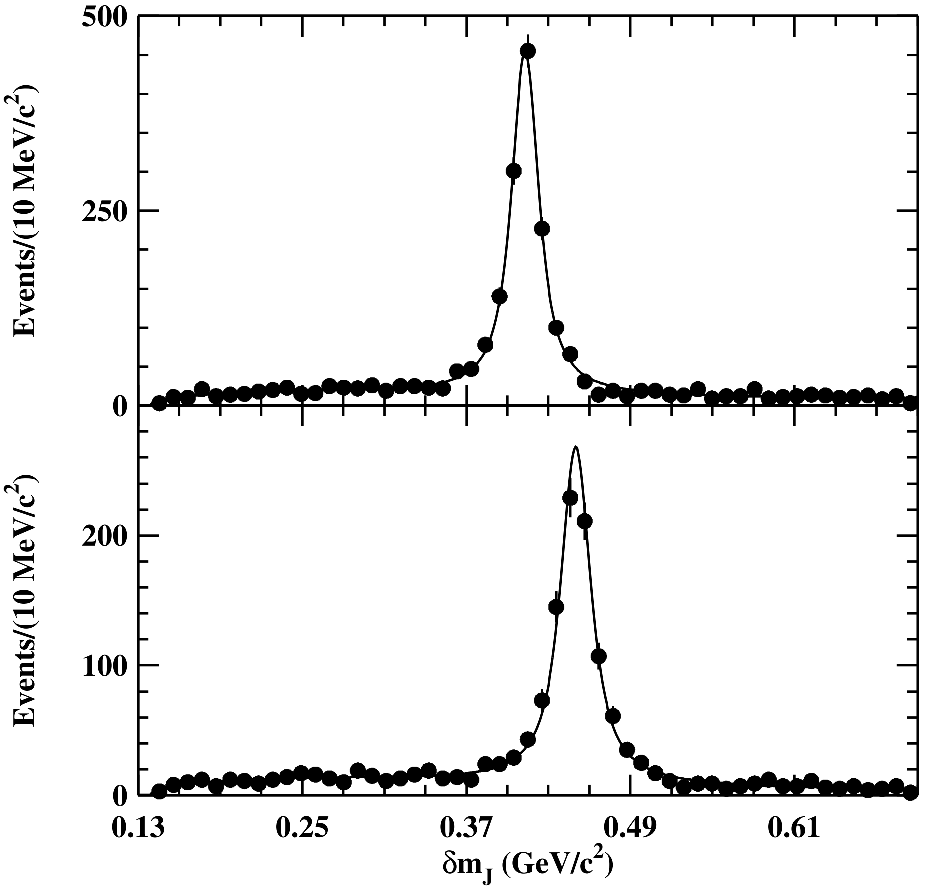

FIG. 6. The signal shapes for the D_1^0 and the D_2^{*0} resonance from $B^- \to D_J^0 e^- \bar{\nu}$ decays in Monte Carlo. The fits are the same as those described in the text for fitting the signal. The yields extracted from these fits are used to determine our efficiency for signal events.

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