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Search For the Decay $B \to D_{s1}^+(2536)X$

CLEO Collaboration

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Abstract

We have searched for the decay $B \to D_{s1}^+(2536)X$ and measured an upper limit for the inclusive branching fraction of $\mathcal{B}(B \to D_{s1}^+X) < 0.95\%$ at the 90% confidence level. This limit is small compared with the total expected $B \to \bar{D}^{(*)}D^{(*)}KX$ rate. Assuming factorization, the D_{s1}^+ decay constant is constrained to be $f_{D_{s1}^+} < 114$ MeV at the 90% confidence level, at least 2.5 times smaller than that of D_s^+.

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I. INTRODUCTION

One of the outstanding issues in B meson physics is the semileptonic branching fraction puzzle. Experimentally $\mathcal{B}(B \to X\ell\nu)$ is measured to be $(10.43 \pm 0.24)\%$ [1], whereas theoretical calculations have difficulties accommodating a branching fraction below $\sim 12.5\%$ [2]. One way to reduce the theoretical expectations is through a two-fold enhancement in the assumed $\bar{b} \to \bar{c}c\bar{s}$ rate [3], which is estimated to be $\sim 15\%$ from the measured inclusive rates for $B \to D_s^+ X$ and $B \to \psi X$.

Recently, Buchalla *et al.* [4] and Blok *et al.* [5] have suggested that a significant fraction of the $\bar{b} \to \bar{c}c\bar{s}$ transition hadronizes into $B \to \bar{D}DKX$. This is supported by CLEO's [6] observation of "wrong-sign" D mesons from B decays, $\mathcal{B}(B \to DX) = (7.9 \pm 2.2)\%$, where the D comes from the virtual $W^+ \to c\bar{s}$. The ALEPH [7] and DELPHI [8] collaborations have also observed sizeable $B \to D^{(*)}\bar{D}^{(*)}X$ decay rates. Exclusive B decays involving wrong-sign D mesons can result from (1) resonant $B \to \bar{D}^{(*)}D_s^{**}$ decays, where the $W^+ \to c\bar{s}$ hadronizes to an excited D_s^+ meson that decays into DKX; and (2) non-resonant $B \to \bar{D}^{(*)}D^{(*)}K$ decays. This paper explores one possibility in the first case, namely, the decays $B \to D_{s1}^+(2536)X$ where D_{s1}^+ is the narrow P-wave D_s^+ meson with $J^P = 1^+$. The "upper-vertex" production of D_{s1}^+ from $W^+ \to c\bar{s}$ hadronization is shown in Figure 1(a). In addition, D_{s1}^+ mesons can be produced from "lower-vertex" decays $b \to c\bar{u}d$ with the creation of an $s\bar{s}$ quark pair, as shown in Figure 1(b). This produces right-sign D mesons; however, the decay rate is expected to be small. Throughout this paper charge conjugate states are implied.

Continuum D_{s1}^+ production has been thoroughly studied [1]. The D_{s1}^+ is just above the D^*K mass threshold and decays dominantly into $D^{*0}K^+$ and $D^{*+}K^0$. Other possible decay channels are negligible: $D_s^{(*)+}\pi^0$ due to isospin conservation, $D_s^{(*)+}(n\pi)$ due to OZI suppression [9], DK or $D_s^+\pi^0$ due to angular momentum and parity conservation, and $D_s^{(*)+}\gamma$ due to the small radiative decay rate.

II. DATA SAMPLE AND EVENT SELECTION

The data used in this analysis were selected from hadronic events collected by the CLEO II detector at the Cornell Electron Storage Ring (CESR). The CLEO II detector [10] is a large solenoidal detector with 67 tracking layers and a CsI electromagnetic calorimeter that provides efficient π^0 reconstruction. The data consist of an integrated luminosity of 3.11 fb^{-1} at the $\Upsilon(4S)$ resonance, corresponding to 3.3×10^6 $B\bar{B}$ events. To evaluate non-$B\bar{B}$ backgrounds we also collected 1.61 fb^{-1} of "continuum" data 60 MeV below the $\Upsilon(4S)$ resonance.

The inclusive $B \to D_{s1}^+X$ decay is studied by reconstructing the decay channels $D_{s1}^+ \to D^{*0}K^+$ and $D^{*+}K_S^0$ using the decay modes $D^{*0} \to D^0\pi^0$ and $D^{*+} \to D^0\pi^+$. The D^0 is reconstructed using the decay modes $D^0 \to K^-\pi^+$ and $K^-\pi^+\pi^0$. Hadronic events are required to satisfy the ratio of Fox-Wolfram moments [11] $R_2 = H_2/H_0 < 0.3$ to reduce the background from continuum events.

Charged tracks, except pions from K_S^0 decays, are required to be consistent with coming from the primary interaction point. Charged kaon and pion candidates are identified using specific ionization (dE/dx) and, when available, time-of-flight (TOF) information. For kaon identification, we consider the relative probability for a charged track to be a kaon, $\mathcal{R}_K = \mathcal{P}_K/(\mathcal{P}_\pi + \mathcal{P}_K + \mathcal{P}_p)$, where $\mathcal{P}$ is the χ^2 probability for a given particle hypothesis. The requirement on $\mathcal{R}_K$ depends on the decay mode of interest. Pion candidates are identified by requiring the dE/dx and, when available, TOF information to be within 3 standard deviations (σ) of that expected for pions. We select K^0_S candidates through the decay to $\pi^+\pi^-$ by requiring a decay vertex displaced from the primary interaction point and a K^0_S invariant mass within 10 MeV/c^2 of its nominal value. We reconstruct π^0 candidates through the decay to $\gamma\gamma$ by requiring candidates to have an invariant mass within 2.5 standard deviations ($\sigma \approx 5$ MeV/c^2) of the nominal π^0 mass.

The $K^-\pi^+$ and $K^-\pi^+\pi^0$ combinations are required to have a kaon identification of $\mathcal{R}_K >$ 0.5 and 0.7, respectively, and an invariant mass within 15 and 25 MeV/c^2 ($\sim 2\sigma$) of the nominal D^0 mass, respectively. In addition, we select regions of the $D^0 \to K^-\pi^+\pi^0$ Dalitz plot to take advantage of the known resonant substructure [12]. For the $D^+_{s1} \to D^{*0}K^+$ mode, the Dalitz cut reduces the signal efficiency by 40% and the background by 80%. We relax the Dalitz cut for the $D^{*+}K^0_S$ mode since the combinatoric background is substantially lower.

The $D^{*+} \to D^0\pi^+$ candidates are required to have a mass difference $M(D^0\pi^+) - M(D^0)$ within 1.5 MeV/c^2 ($\sim 2\sigma$) of the nominal value of 145.4 MeV/c^2, where $M(X)$ is the reconstructed invariant mass of X. Similarly, the $D^{*0} \to D^0\pi^0$ candidates are required to have a mass difference $M(D^0\pi^0) - M(D^0)$ within 1.5 MeV/c^2 ($\sim 2\sigma$) of the nominal value of 142.1 MeV/c^2. To form D^+_{s1} candidates charged kaons are combined with D^{*0} candidates and K^0_S's are combined with D^{*+} candidates. Since the primary kaons from $D^+_{s1} \to D^{*0}K^+$ decays have low momentum, we can impose a stringent $\mathcal{R}_K > 0.9$ requirement on the K^+ with negligible loss of efficiency. The D^+_{s1} candidates are required to have a scaled momentum $x_p = p_{D^+_{s1}}/\sqrt{E^2_{beam} - M^2_{D^+_{s1}}} < 0.45$, which is the kinematic limit for $B \to D^+_{s1}X$ decays. (We ignore the negligible contributions from $b \to u$ decays.) Upper-vertex D^+_{s1} production results in a maximum x_p of 0.35, and this requirement is imposed when determining the D^+_{s1} decay constant. The D^+_{s1} decay channels with π^0's in the final state often have multiple D^+_{s1} candidates per event. We select the candidate with the highest χ^2 probability of being a D^+_{s1}, which is derived from the invariant masses of the reconstructed π^0, D^0 and D^* mesons.

III. RAW YIELDS

The D^+_{s1} signal is identified using the D^*K mass difference, $\Delta M_1 = M(D^{*0}K^+) - M(D^{*0}) - M_{K^+}$ and $\Delta M_2 = M(D^{*+}K^0_S) - M(D^{*+}) - M_{K^0_S}$, where M_{K^+} and $M_{K^0_S}$ are the known masses [1]. The D^*K mass difference signal has a resolution that is two to four times smaller than the corresponding signal in the reconstructed D^*K invariant mass distribution. The ΔM_1 and ΔM_2 distributions are shown in Figure 2, where the $D^0 \to K^-\pi^+$ and $K^-\pi^+\pi^0$ modes have been added together. The data is fit with a Gaussian signal and a threshold background function. The Gaussian width is fixed to that expected from a GEANT-based Monte Carlo simulation [13] ($\sigma = 2.4 - 3.6$ MeV/c^2, depending on the mode) and the mean is fixed to the measured D^+_{s1} mass difference from continuum data ($\Delta M_1 \approx 35$ MeV/c^2 and $\Delta M_2 \approx 27$ MeV/c^2.) We observe 42 ± 14 signal events in the $D^{*0}K^+$ mode and 9 ± 6 events in the $D^{*+}K^0_S$ mode.

However, when the $D^{*0}K^+$ candidates are further subdivided into the $D^0 \to K^-\pi^+$ and $K^-\pi^+\pi^0$ decay channels there is a discrepancy in the D_{s1}^+ yields. As shown in Figure 3, we observe 10 ± 8 signal events in the ΔM_1 distribution for the $D^0 \to K^-\pi^+$ channel and 33 ± 12 D_{s1}^+ signal events for the $D^0 \to K^-\pi^+\pi^0$ channel. After accounting for branching fractions and efficiencies, discussed below, this results in a 2.2σ discrepancy in the $D^{*0}K^+$ rates between the two D^0 modes. We cannot rule out the fact that background sources may be contributing a false D_{s1}^+ signal in the $D^0 \to K^-\pi^+\pi^0$ channel, but not in the $D^0 \to K^-\pi^+$ channel. However, no such mechanism has been uncovered. To be conservative, we choose to quote only an upper limit for the decay $B \to D_{s1}^+X$.

Since the D_{s1}^+ reconstruction efficiency increases rapidly with x_p and the D_{s1}^+ momentum distribution from B decays is not known, we compute the inclusive $B \to D_{s1}^+X$ branching fraction by dividing the data into four equal regions of x_p from 0.05 to 0.45 and summing the efficiency corrected yields. The $D_{s1}^+ \to D^{*0}K^+$ and $D^{*+}K^0$ branching fractions are equal according to isospin, and their ratio has been measured to be within 30% of unity [14]. We measure the branching fraction $B \to D_{s1}^+X$ to be $(0.77 \pm 0.22)\%$ from the $D^{*0}K^+$ mode and $(0.28 \pm 0.37)\%$ from the $D^{*+}K_S^0$ mode, where the error is statistical only. The two measurements are statistically consistent. The x_p distribution for our D_{s1}^+ candidates is shown in Figure 4.

IV. CROSS-CHECKS

Several cross-checks, shown in Figure 5, were performed to corroborate the validity of the D_{s1}^+ signal. The scaled continuum background from data after satisfying all selection cuts is negligible, and there is no excess in the ΔM_1 signal region (3 ± 5 events). The uncertainty in the continuum D_{s1}^+ contribution is included in the systematic error. There is also no evidence of peaking in the ΔM_1 signal region for wrong-sign $D^{*0}K^-$ combinations (0 ± 9 events), D^0 mass sidebands (5 ± 5 events), and D^{*0} mass sidebands (-4 ± 6 events).

We have also searched for the D^0 signal from $D_{s1}^+ \to D^{*0}K^+$ candidates in the ΔM_1 signal region, $|\Delta M_1 - 35\,\mathrm{MeV/c^2}| < 10\,\mathrm{MeV/c^2}$, by relaxing the D^0 mass cut and histogramming the invariant mass of all $K^-\pi^+$ and $K^-\pi^+\pi^0$ combinations that satisfy the remaining selection criteria. In events with multiple candidates per D^0 decay mode we select the candidate with the highest χ^2 probability, which is derived from the reconstructed π^0 and D_{s1}^+ masses. We observe 100 ± 15 D^0 events. However, there are also real D^0's in the random $D^{*0}K^+$ combinations under the D_{s1}^+ peak; after a ΔM_1 sideband subtraction the D^0 invariant mass spectrum yields 44 ± 18 events (see Figure 6(a)). This is consistent with our $D_{s1}^+ \to D^{*0}K^+$ yield in Figure 2.

Similarly, we have studied the D^{*0} signal from $D_{s1}^+ \to D^{*0}K^+$ candidates in the ΔM_1 signal region. We observe 59 ± 15 D^0 events. As in the D^0 case there are also real D^{*0}'s in the random $D^{*0}K^+$ combinations under the D_{s1}^+ peak. After a ΔM_1 sideband subtraction the D^{*0} mass difference spectrum yields 25 ± 18 events (See Figure 6(b)), consistent with our $D_{s1}^+ \to D^{*0}K^+$ yield.

Finally, we have studied the D_{s1}^+ production from continuum $e^+e^- \to c\bar{c}$ events. The selection criteria is similar to that used to find D_{s1}^+ from B decays, but since continuum charm production has a hard fragmentation, we require $x_p > 0.5$. In addition, we remove the $R_2 < 0.3$ cut, relax the charged kaon identification to $\mathcal{R}_K > 0.1$, and remove the Dalitz cut for $D^0 \to K^-\pi^+\pi^0$. The mass difference distribution for $D^{*0}K^+$ and $D^{*+}K^0_S$ combinations are shown in Figure 7, where the $D^0 \to K^-\pi^+$ and $K^-\pi^+\pi^0$ modes have been added together. We extract the D^+_{s1} signal by fitting the data with a Gaussian signal and a threshold background function. The Gaussian width is fixed to the value predicted by Monte Carlo (2.1 MeV/c^2), and the mean is allowed to float. We observe 222 ± 19 events in the $D^+_{s1} \to D^{*0}K^+$ mode with a mass difference of 35.0 ± 0.2 MeV/c^2 (statistical error only), and 101 ± 11 events in the $D^+_{s1} \to D^{*+}K^0_S$ mode with a mass difference of 27.5 ± 0.3 MeV/c^2. The results are consistent with the previous CLEO analysis [14].

V. SYSTEMATIC ERRORS AND FINAL RESULTS

There are several sources of systematic error. We assign a systematic error of 16% to account for the 2.2σ discrepancy between the $D^{*0}K^+$ rates for the $D^0 \to K^-\pi^+$ and $K^-\pi^+\pi^0$ modes. This accomodates different methods of computing the weighted average of the $B \to D^+_{s1}X$ branching fraction from the four separate decay chains. Uncertainties due to reconstruction efficiencies include 1.5% per charged track, 5% per π^0, 5% for slow pions from D^*, and 5% for K^0_S. We also include systematic errors of 7% for Monte Carlo statistics, 5% for kaon identification and the Dalitz decay cut efficiency, 4% for uncertainties in the yield for $x_p < 0.05$, and 8% for uncertainties in the continuum D^+_{s1} contribution that passes our selection criteria. The total systematic error is 24%.

Averaging the $D^{*0}K^+$ and $D^{*+}K^0_S$ modes together, we obtain $\mathcal{B}(B \to D^+_{s1}X) = (0.64 \pm 0.19 \pm 0.15)\%$. Since the D^+_{s1} signal is observed largely in only one decay mode $D^+_{s1} \to D^{*0}K^+$ with $D^0 \to K^-\pi^+\pi^0$, and since there is a discrepancy between this mode and the corresponding mode involving $D^0 \to K^-\pi^+$, we instead prefer to quote an upper limit on the branching fraction to be $\mathcal{B} < 0.95\%$ at the 90% C.L. [15] This decay rate limit is small relative to the total rate expected for $B \to \bar{D}^{(*)}D^{(*)}KX$ of about $(7.9 \pm 2.2)\%$ from the wrong-sign D meson yield in B decays [6]. This is not surprising considering the $c\bar{s}$ system has appreciable phase space beyond the D^+_{s1} mass [4]. Also, CLEO's [16] recent observation of exclusive $B \to \bar{D}^{(*)}D^{(*)}K$ decays shows that the $D^{(*)}K$ invariant mass distribution lies mostly above the D^+_{s1} mass.

VI. D^+_{S1} DECAY CONSTANT

Measurement of the $B \to D^+_{s1}X$ decay rate also provides an estimate of the D^+_{s1} decay constant, $f_{D^+_{s1}}$, assuming that the D^+_{s1} comes dominantly from upper-vertex decays. The inclusive decay rate for B mesons into ground state or excited D^+_s mesons can be calculated assuming factorization [17],

$$\Gamma(B \to D_sX) = \frac{G_F^2|V_{cb}V_{cs}|^2}{16\pi} M_b^3 a_1^2 f_{D_s}^2 I(x,y)$$

where a_1 is the BSW [18] parameter for the effective charged current, and $I(x,y)$ is a kinematic factor with $x = M^2_{D_s}/M^2_b$ and $y = M^2_c/M^2_b$. For scalar or pseudoscalar D_s mesons,

$I(x,y) = \sqrt{(1-x-y)^2 - 4xy}(1-x-2y-xy+y^2)$, and for vector or axial-vector D_s mesons, $I(x,y) = \sqrt{(1-x-y)^2 - 4xy}(1+x-2x^2-2y+xy+y^2)$.

We have tightened the x_p requirement to $x_p < 0.35$ since this is the kinematic limit for upper-vertex $B \to D_{s1}^+ \bar{D} X$ decays. The production of ground state and excited D_s^+ mesons from lower-vertex decays such as $\bar{B} \to D_{s1}^+ \bar{K} X$ is expected to be suppressed. This is certainly true for $B \to D_s^+ X$ decays where the fraction of D_s^+ produced at the lower-vertex is measured to be $0.172 \pm 0.079 \pm 0.026$ [19]. Moreover, there is no evidence of D_{s1}^+ production in the region $x_p = 0.35-0.45$ where lower-vertex production is likely to occur (see Figure 4.)

With the assumption $f_{D_s^+} = f_{D_s^{*+}}$ we can extract $f_{D_{s1}^+}$ from the ratio of inclusive rates,

$$\frac{\mathcal{B}(B \to D_{s1}^+ X)}{\mathcal{B}(B \to D_s^+ X)} = \frac{\Gamma(B \to D_{s1}^+ X)}{\Gamma(B \to D_s^+ X) + \Gamma(B \to D_s^{*+} X)} \approx 0.49 \left(\frac{f_{D_{s1}^+}}{f_{D_s^+}}\right)^2$$

Many systematic errors cancel in the ratio. When computing the D_{s1}^+ decay constant from the above equation, we use $(75 \pm 25)\%$ of the measured $B \to D_{s1}^+ X$ branching fraction to account for uncertainties in the upper and lower vertex contributions to D_{s1}^+. This accomodates the excess of $B \to D_{s1}^+ X$ candidates observed at low $x_p < 0.15$ as seen in Figure 4. From our upper limit on $B \to D_{s1}^+ X$ and CLEO's [20] measurement of $\mathcal{B}(B \to D_s^+ X) = (12.11 \pm 0.39 \pm 0.88 \pm 1.38)\%$, we derive $f_{D_{s1}^+}/f_{D_s^+} < 0.40$ at the 90% C.L. The central value is $f_{D_{s1}^+}/f_{D_s^+} = 0.29 \pm 0.06 \pm 0.06$, where the first error is due to the total error in the inclusive $B \to D_s^+ X$ and $B \to D_{s1}^+ X$ branching fractions, and the second is the uncertainty in the non-factorizable and lower-vertex contributions to the $B \to D_{s1}^+ X$ decay rate. Using the measured value of $f_{D_s^+} = 280 \pm 40$ MeV [20] gives $f_{D_{s1}^+} = 81 \pm 26$ MeV which corresponds to an upper limit of $f_{D_{s1}^+} < 114$ MeV. This limit accomodates the prediction of $f_{D_{s1}^+} = 87 \pm 19$ MeV by Veseli and Dunietz [21].

VII. CONCLUSIONS

In summary, we have searched for B mesons decaying into the P-wave $D_{s1}^+(2536)$ meson. The upper limit of $\mathcal{B}(B \to D_{s1}^+ X) < 0.95\%$ at the 90% C.L. accounts for at most only a fraction of the total wrong-sign $B \to DX$ rate. Assuming factorization, the decay constant $f_{D_{s1}^+}$ is at least a factor of 2.5 times smaller than the decay constant for the pseudoscalar D_s^+.

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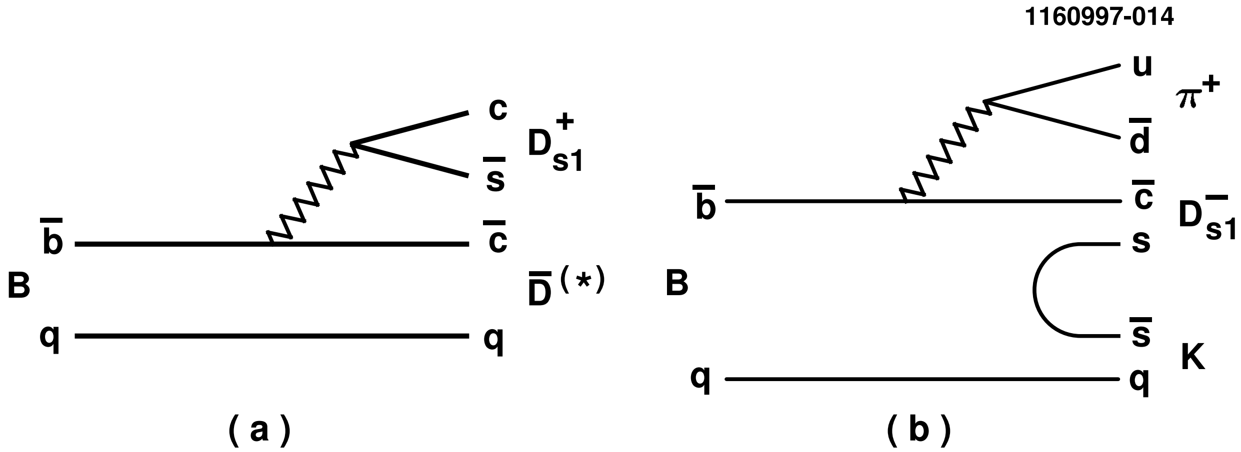

FIG. 1. Feynman diagrams for (a) $B \to D_{s1}^{+}X$ decays producing D_{s1}^{+} at the upper-vertex and (b) $B \to D_{s1}^{-}X$ decays producing D_{s1}^{-} at the lower-vertex.

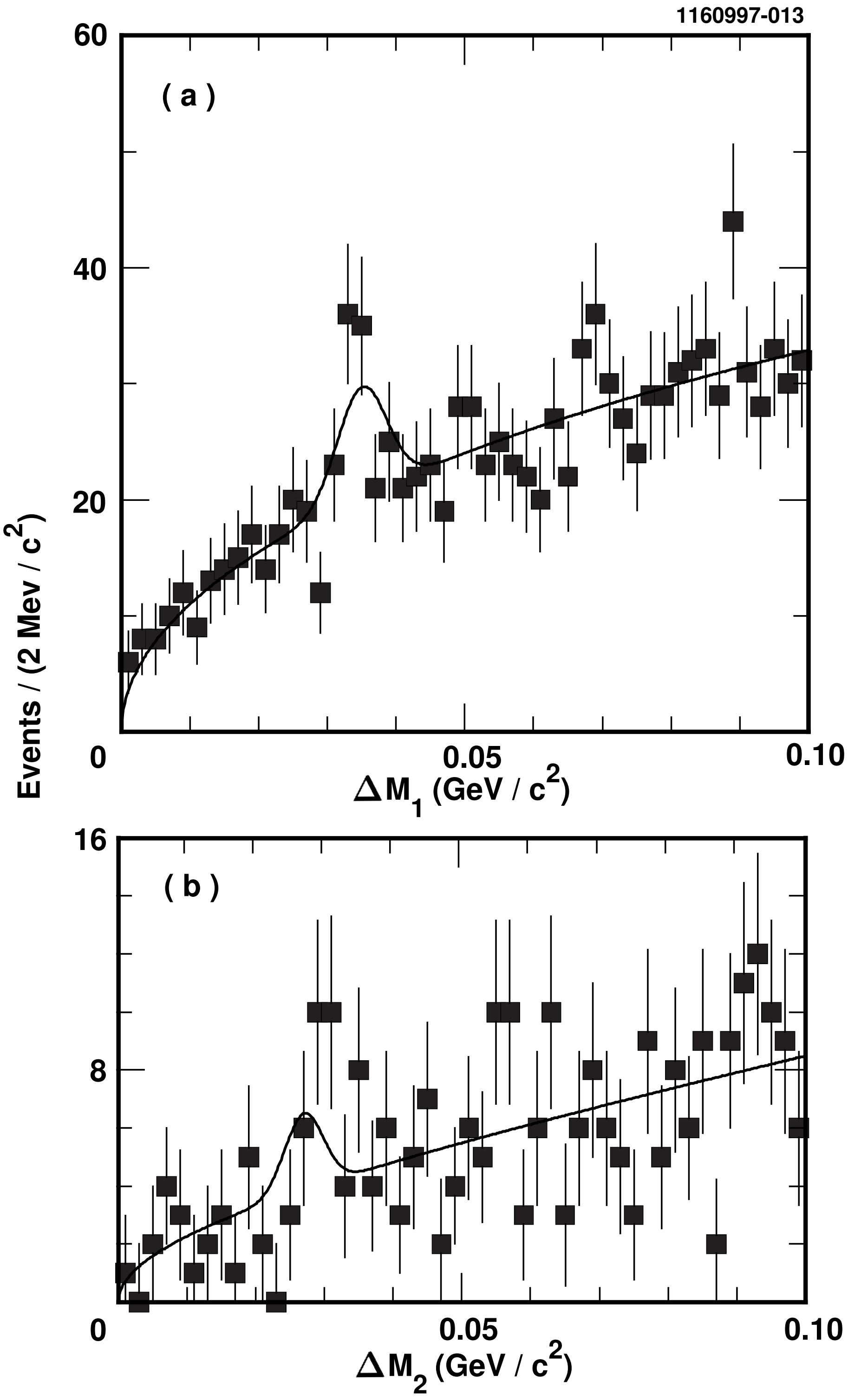

FIG. 2. The mass difference distribution for (a) $D^{*0}K^{+}$ and (b) $D^{*+}K^{0}_{S}$ candidates from B meson decays.

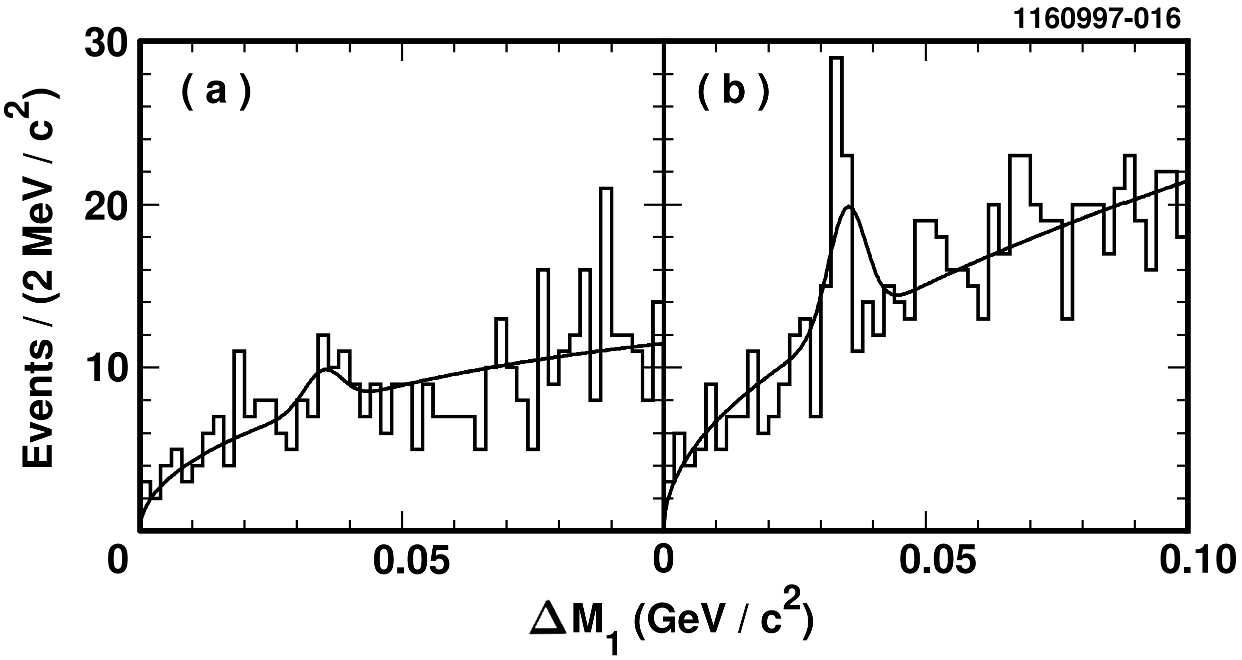

FIG. 3. The ΔM_1 mass difference distribution for $D^{*0}K^+$ candidates from the (a) $D^0 \to K^-\pi^+$ and (b) $D^0 \to K^-\pi^+\pi^0$ decay channels.

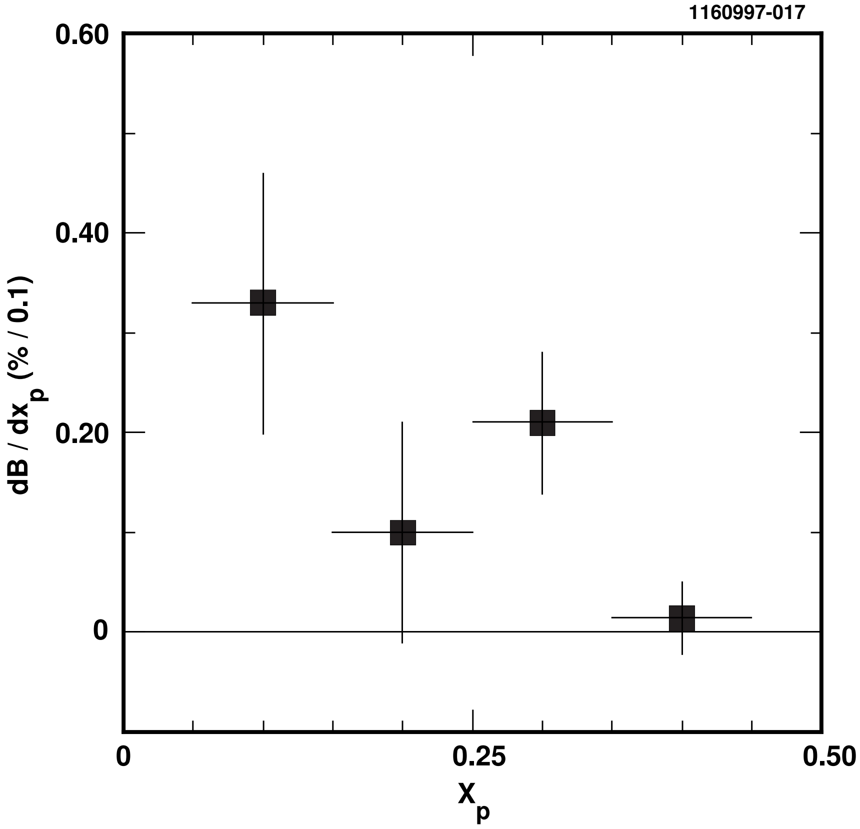

FIG. 4. The efficiency corrected yield for our $B \to D_{s1}^{+} X$ candidates as a function of the D_{s1}^{+} scaled momentum x_p. The kinematic limit from upper-vertex and lower-vertex $B \to D_{s1}^{+} X$ decays is $x_p < 0.35$ and $x_p < 0.45$, respectively.

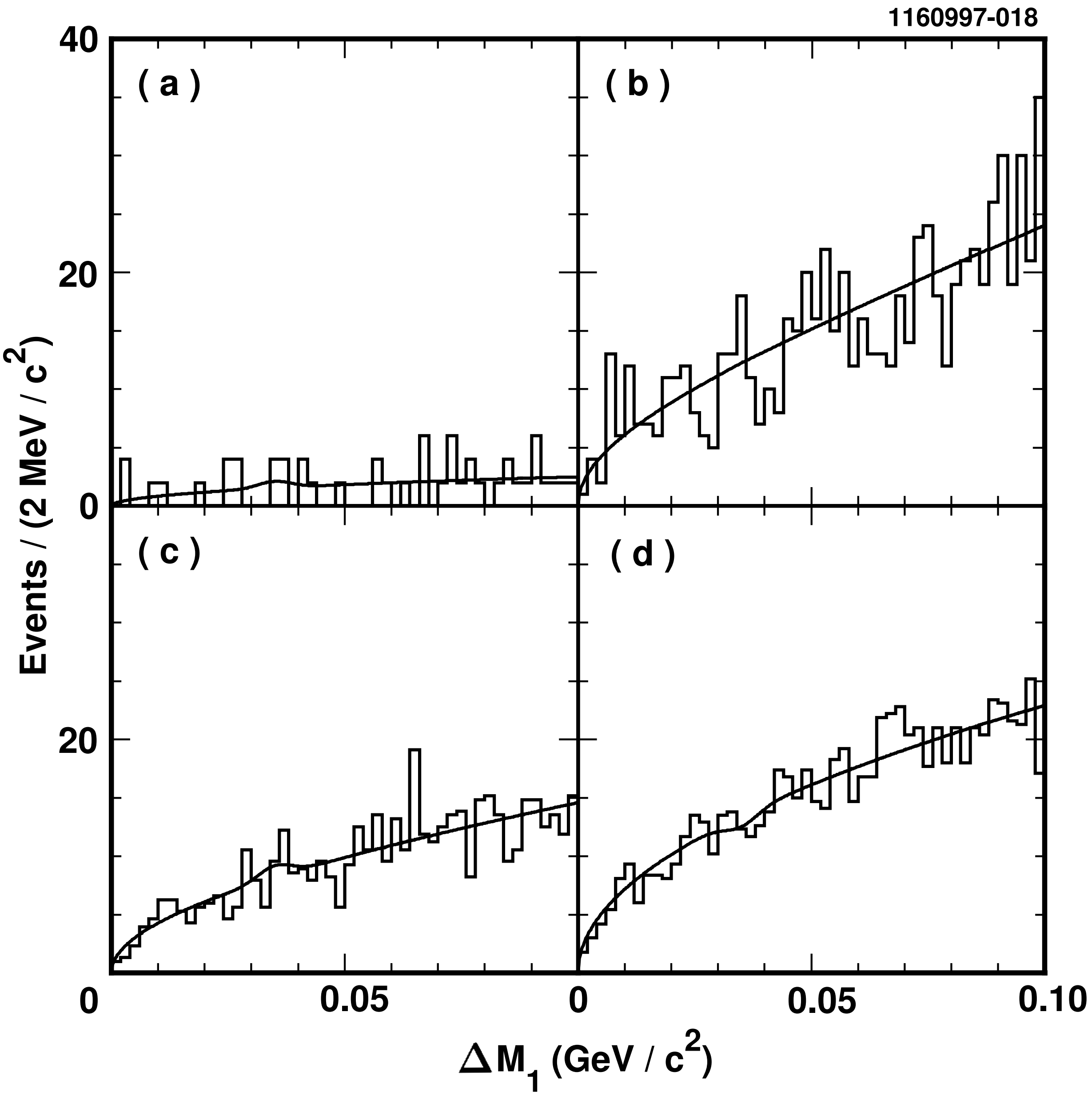

FIG. 5. The normalized $D^{*0}K^+$ mass difference distributions from (a) continuum events, (b) $D^{*0}K^-$ "wrong-sign" combinations, (c) D^0 mass sidebands, and (d) D^{*0} mass sidebands.

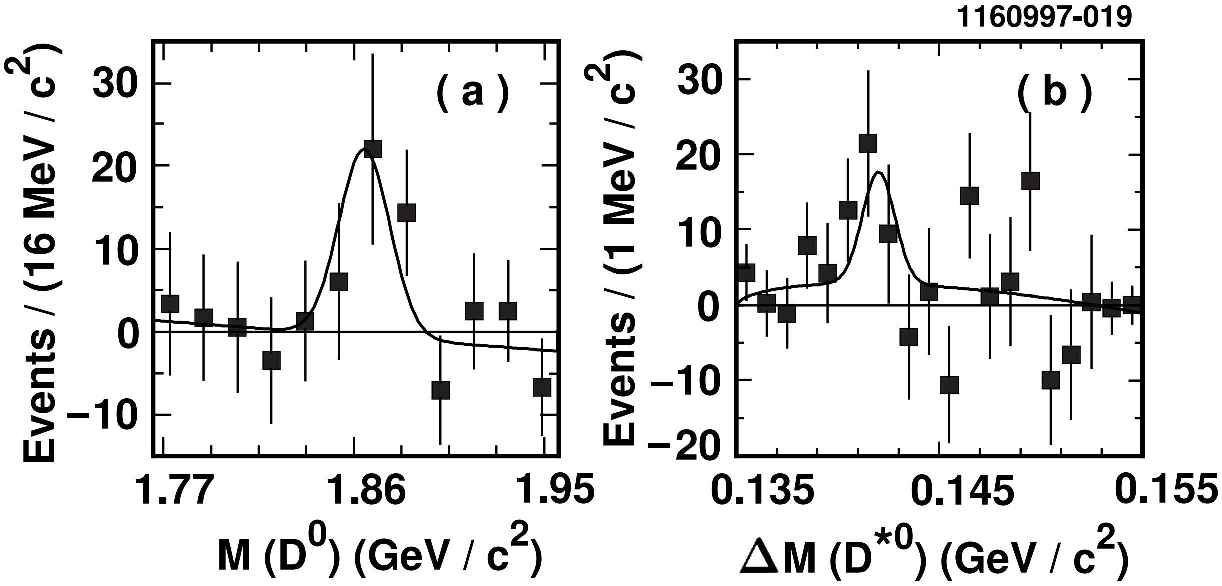

FIG. 6. (a) The invariant mass distribution for $K^-\pi^+$ and $K^-\pi^+\pi^0$ combinations from $D^{*0}K^+$ candidates in the ΔM_1 signal region, after sideband subtraction. (b) The D^{*0} mass difference distribution from $D^{*0}K^+$ candidates in the ΔM_1 signal region, after sideband subtraction.

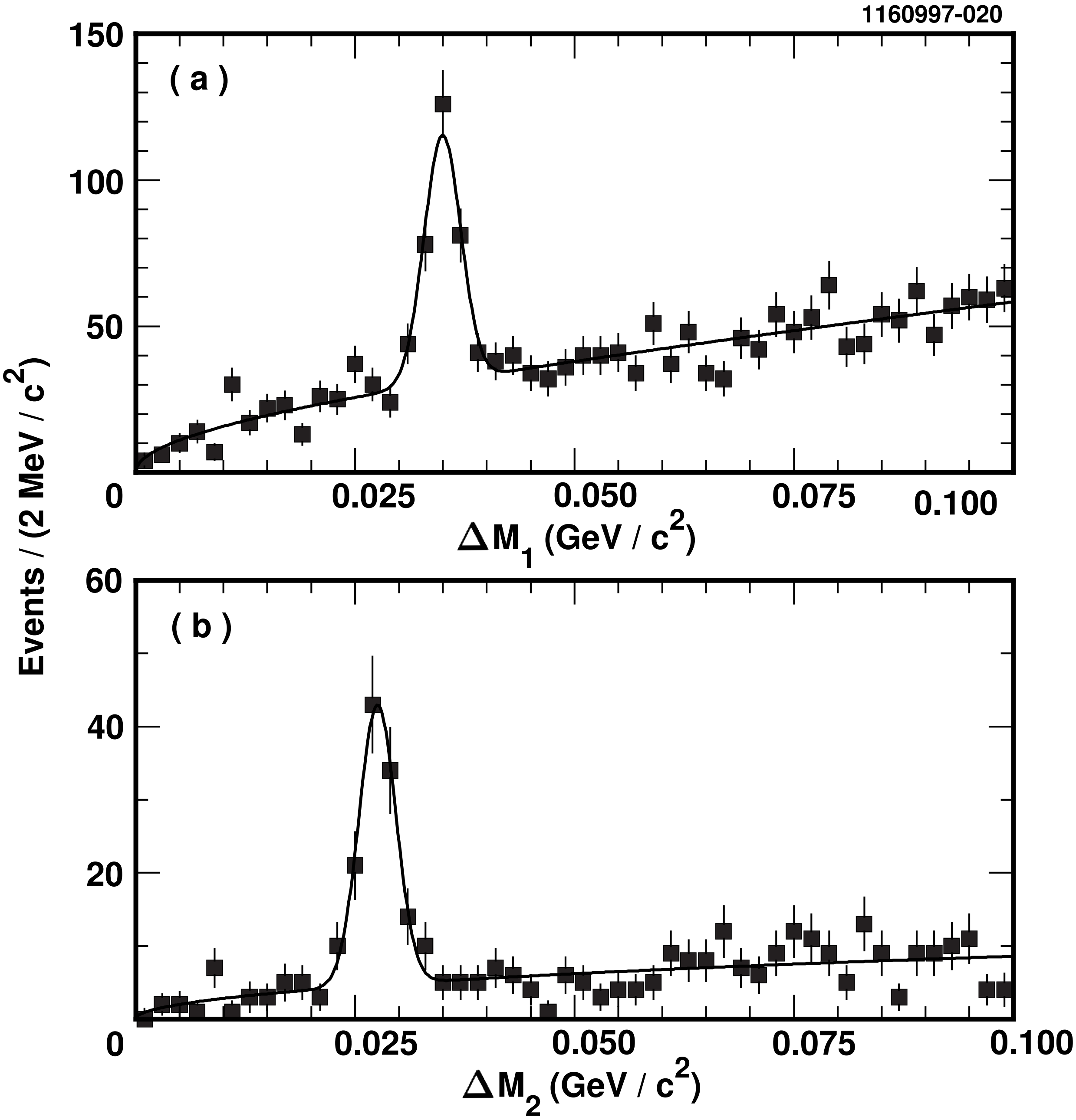

FIG. 7. The mass difference distribution for (a) $D^{*0}K^{+}$ and (b) $D^{*+}K_S^0$ candidates from continuum $e^+e^- \to c\bar{c}$ events.