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D_s - Lepton Charge Correlations in B Meson Decays: A Study of the D_s Meson Production Mechanism

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Abstract

Using 2.4 fb^{-1} of data recorded at the Υ(4S) with the CLEO II detector at the Cornell Electron Storage Ring, we have studied D_s-lepton pairs in $\Upsilon(4S) \to \mathrm{B\bar{B}}$ decays. We have used the correlation between the charges of the D_s and the high momentum lepton to distinguish D_s mesons produced by W fragmentation from those produced by $b \to c$ transitions in combination with $s\bar{s}$ popping. We have measured f_l, the fraction of D_s's produced by the latter mechanism, and have found that $f_l = 0.172 \pm 0.079 \pm 0.026$. We have placed a limit on this quantity of $f_l < 0.31$ at the 90% confidence level.

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I. INTRODUCTION AND METHOD

A B meson can decay into a D_s meson in two ways [1]. In the first, the virtual W^- emitted by the b-quark hadronizes to produce a D_s^- (see figure 1(a)). In the second, the c-quark left after W^- emission combines with an $\bar{s}$-quark pulled from the vacuum to produce a D_s^+ (see figure 1(b)). The former means of production, known as upper vertex production, dominates; some 46% of D_s's are produced in two-body decays, such as $\bar{B} \to D_s^- D$, which necessarily involve this mechanism [2]. The latter, known as lower vertex production, has yet to be observed. We have searched for evidence of lower vertex production by studying charge correlations in D_s-lepton pairs.

Since the charge of the D_s differs for upper and lower vertex production, it serves as a tool for measuring the amounts of each, providing that we can determine the flavor of the B meson from which the D_s came. This we can do by insisting that the other B meson in the event decay semileptonically and using the charge of the lepton to tag the flavor of that meson and, hence, the flavor of the meson producing the D_s. If the D_s originates at the upper vertex, the D_s and the lepton will have opposite charges (see figure 2(a)); if the D_s originates at the lower vertex, they will have the same charge (see figure 2(b)). The presence of $B^0\bar{B}^0$ mixing complicates the matter, producing events that contain two B^0's or two $\bar{B}^0$'s instead of a $B^0\bar{B}^0$ pair and thereby reversing the correlations between the charges of the D_s and the lepton. However, it is easy to account for the effects of mixing and to extract the amount of D_s production that occurs at the lower vertex from the ratio of same-charge and opposite-charge yields.

Explicitly, the fraction of lower vertex production, f_l, is related to the fraction of B^0's that mix, χ_0, and to the same-charge and opposite-charge yields, n^{++} and n^{+-}, by the relationship

$$f_l = \left(\frac{\epsilon_u}{\epsilon_l}\right) \frac{R - R_0}{(1 - R_0)(1 + R)}, \tag{1}$$

where

$$R_0 = \frac{\chi_0}{2 - \chi_0}, \tag{2}$$

and

$$R = n^{++}/n^{+-}, \tag{3}$$

and ϵ_u and ϵ_l are the efficiencies for reconstructing D_s's from the upper vertex and from the lower vertex. Note that R_0 is precisely the ratio of same and opposite-charge yields we would observe were all D_s's produced at the upper vertex and all same charge pairs the result of $B^0\bar{B}^0$ mixing. Note also that as f_l depends only on the ratio $R = n^{++}/n^{+-}$ many of the systematic errors associated with lepton identification and tracking cancel out.

II. EXPERIMENTAL DETAILS

A. Event Selection

We selected hadronic events with five or more charged tracks and then required that the normalized second Fox-Wolfram moment for the event be less than 0.45. This requirement helped to suppress the background from the continuum beneath the $\Upsilon(4S)$ resonance by ensuring that each event was basically spherical in topology and thus more likely to be a $B\bar{B}$ event [3]. We did not make this cut particularly stringent because the dominant source of background was not the underlying continuum but rather combinatorics in the $B\bar{B}$ events themselves.

B. Lepton Identification

We identified a charged particle as an electron if it deposited an amount of energy in the CsI calorimeter that was consistent with its momentum as measured in the central drift chambers and if its energy loss was consistent with that expected of an electron. We identified a track as a muon if it penetrated the hadron absorber to a depth of five or more nuclear interaction lengths. We selected only those candidates passing through the most reliable portions of the detector, requiring $|\cos\theta| < 0.707$ for electrons and $|\cos\theta| < 0.610$ for muons, θ being the polar angle of the track.

Having identified our lepton candidates, we had to separate those produced in semileptonic B-decays from those produced in other ways, especially those produced in cascade decays, for instance $\bar{B} \rightarrow DX, D \rightarrow Xl^+\nu$. By accepting leptons with $p_{lep} > 1.5$ GeV/c we obtained a lepton sample containing only $2.0 \pm 0.6\%$ cascade leptons [4], while retaining 42% of the leptons from semileptonic B-decays. We further required that $p_{lep} < 2.4$ GeV/c, the kinematic limit for $b \rightarrow c$ decays, thus reducing the already small background from continuum. Leptons from other background sources (e.g. fakes and $J/\psi \rightarrow l^+l^-$ decays) contributed only weakly to our sample of tag leptons, and we accounted for them by making the appropriate corrections to the raw yields, as explained below. In summation, we accumulated a sample of leptons from semileptonic B decays that was in excess of 95% pure.

C. D_s Reconstruction

We were aware from the beginning that our largest challenge would be to obtain a clean signal, especially for the less numerous same-charge pairs. Consequently, we chose to reconstruct the D_s in the channel for which the product of the efficiency and the various branching fractions was the greatest, $D_s^+ \rightarrow \phi\pi^+, \phi \rightarrow K^+K^-$. The relevant branching fractions are $\mathcal{B}(D_s^+ \rightarrow \phi\pi^+) = 3.5 \pm 0.4\%$ and $\mathcal{B}(\phi \rightarrow K^+K^-) = 49.1 \pm 0.9\%$ [5].

We demanded that the tracks used to reconstruct a D_s point back to the event origin, to within 5 mm in the radial plane and to within 5 cm along the beam axis, and that the energy loss for each track fall within 2.5σ of the value expected for the appropriate particle type. We reconstructed the ϕ by accepting only those K^+K^- pairs whose invariant mass fell within 6 MeV of the nominal ϕ mass, 1.0194 GeV. We then employed four additional cuts, two to reduce the combinatoric background, one to suppress the continuum background, and one to eliminate correlated pairs, *i.e.* pairs coming from the same B meson.

First, we cut on the helicity angle of the ϕ, the angle between the trajectory of the D_s and the trajectory of the K^+ in the rest frame of the ϕ. For $D_s^+ \rightarrow \phi\pi^+, \phi \rightarrow K^+K^-$ decays, the spin one ϕ is produced in a helicity zero state, and consequently the helicity angle follows a $\cos^2\theta_H$ distribution. For the combinatoric background, the helicity angle distribution is flat in $\cos\theta_H$. We chose to cut at $|\cos\theta_H| > 0.40$, thus eliminating 40% of the background and retaining 94% of our signal.

Secondly, we cut on the decay angle of the D_s, the angle between the D_s trajectory and the trajectory of the ϕ in the rest frame of the D_s, which we denote θ_D. Since the D_s has spin zero, the ϕ emerges isotropically in the D_s rest frame, and the distribution of $\cos\theta_D$ is flat. On the other hand, the combinatoric background peaks at $\cos\theta_D = 1.0$, since the abundance of pions increases at lower momentum. We chose to cut at $\cos\theta_D < 0.70$, thus retaining 85% of our signal while rejecting more than 40% of the background.

Thirdly, we employed a cut to suppress continuum background. We cut on the scaled momentum of the D_s, $x = p_{D_s}/\sqrt{E_{beam}^2 - m_{D_s}^2}$. We required $x < 0.5$, thus eliminating D_s candidates that could not come from a B decay.

Finally, we employed a single cut to eliminate correlated D_s-lepton pairs. Such pairs can be produced in either upper or lower vertex decays, and they are always oppositely charged. To get rid of them, we cut on the angle inscribed by the trajectories of the D_s and the lepton in the lab frame, θ_{D_s-l}. For correlated pairs the D_s and the lepton emerge predominately back-to-back, and the distribution of $\cos\theta_{D_s-l}$ peaks at -1.0 (see figure 3). For pairs in which the D_s and the lepton come from opposite B mesons, the trajectories of the two particles are independent, and the distribution of $\cos\theta_{D_s-l}$ is flat. We employed a cut, for opposite-charge pairs only, of $\cos\theta_{D_s-l} > -0.5$. The combination of this cut and the lepton momentum cut rendered the correlated background negligible. It also reduced our efficiency for opposite-charge pairs by $25.0 \pm 0.5\%$, and when extracting our yields we compensated for this loss by multiplying the raw opposite-charge yield by a factor of 1.33. Note that, unlike the systematic errors associated with all the cuts mentioned above, the systematic error associated with this cut does not cancel when measuring the ratio $R = n^{++}/n^{+-}$.

As a check we plotted the distribution of $\cos\theta_{D_s-l}$ in data. We found that it was flat in the region $\cos\theta_{D_s-l} > -0.5$. However, we noted some peaking at $\cos\theta_{D_s-l}$=-1.0, which suggested that our sample contained some correlated pairs. (See figure 4.)

III. RESULTS

A. Raw Yields

We extracted the yields, n^{++} and n^{+-}, by fitting the $\phi\pi$ mass peaks in the data subsets containing a lepton and a D_s candidate of the same and of the opposite charge respectively. We used a first order polynomial to model the background under the peak and a simple gaussian to model the peak itself. We fixed the mean and the width of the gaussian to values determined from a fit to the inclusive $\phi\pi$ mass distribution, setting these to $m_{D_s} =$ 1968.4 MeV and $\sigma_{m_{D_s}} = 5.9$ MeV. We used only on-resonance data in extracting the raw yields. We searched 1.1 fb^{-1} of off-resonance data for D_s-lepton pairs and found that our off-resonance yields for both charge combinations were consistent with zero. The various $\phi\pi$ mass distributions and the fits to on-resonance peaks appear in figures 5.

We obtained raw yields of

$$n_{raw}^{++} = 34.3 \pm 9.1 \tag{4}$$

and

$$n_{raw}^{+-} = 1.33 \times (87.2 \pm 11.1) \tag{5}$$

$$= 116.3 \pm 14.8, \tag{6}$$

The fits to the inclusive $\phi\pi$ mass distributions gave us an inclusive yield for D_s mesons from B mesons of

$$n_{D_s} = 2497 \pm 109. \tag{7}$$

We used the inclusive yield in correcting the raw yields for leptons from $J/\psi \to l^+l^-$, as explained below.

B. Corrections

Before converting our yields into an estimate of f_l, we had to make several small corrections to the raw yields. All of the corrections involved our lepton tags. Our sample of leptons was susceptible to contamination from three different sources:

- hadrons faking leptons,
- leptons from $J/\psi \to l^+l^-$ decays,
- leptons from charm decays (*i.e.* uncorrelated cascade leptons that survived our lepton momentum cut).

1. Lepton Fakes

Fakes were hadrons that we misidentified as leptons. Their presence inflated both the same and opposite-charged yields, although not to the same degree. We estimated the contributions of fakes to n_{raw}^{++} and n_{raw}^{+-} by skimming our dataset for same and opposite charged $D_s - h$ pairs, h being a hadronic track that satisfied our momentum and polar angle cuts for leptons, and multiplying these yields by previously determined fake rates. Following this procedure, we found

$$n_{fake}^{++} = 2.2 \pm 0.7 \tag{8}$$

and

$$n_{fake}^{+-} = 3.9 \pm 1.2. \tag{9}$$

The uncertainties in these numbers reflect the uncertainties in the fake rates themselves. We subtracted n_{fake}^{++} and n_{fake}^{+-} from n_{raw}^{++} and n_{raw}^{+-} respectively.

2. Leptons from $J/\psi \to l^+l^-$ Decays

We estimated how many leptons from $J/\psi \to l^+l^-$ we should expect per B meson by generating one million $B\bar{B}$ Monte Carlo events and simply counting the number of such leptons that satisfied our lepton acceptance cuts. We found that, per B meson, we should expect $(6.3 \pm 0.4) \times 10^{-4}$ leptons of either sign for each B. We multiplied this figure by our inclusive D_s yield to obtain the number of D_s-lepton pairs of either sign combination that involve a lepton from a J/ψ decay,

$$n^{++}_{J/\psi} = n^{+-}_{J/\psi} = 1.5 \pm 0.1. \tag{10}$$

The uncertainty in this number reflects the uncertainties in the $B \to J/\psi X$ branching ratio [6]. We subtracted this amount from both the same and opposite-charge yields.

3. Leptons from Charm

Despite our cut of $p_{lep} > 1.5$ GeV/c, some leptons from charm survived to contaminate our sample of tag leptons, and we had to compensate for their presence. Leptons from charm inflated the same and opposite-charge yields, but more importantly, they reversed the charge correlations and thus mimicked the effect of $B^0\bar{B}^0$ mixing. We accounted for their presence by modifying our expression for f_l, replacing the parameter R_0 in equation (1), with the parameter

$$\tilde{R}_0 = \frac{\chi_0 + 2\Delta - 2\Delta\chi_0}{2 - \chi_0 - 2\Delta + 2\Delta\chi_0} \tag{11}$$

where Δ is the fraction of our tag sample comprising leptons from charm decays. We took the values of χ_0 and Δ from reference [4]:

$$\Delta = 2.0 \pm 0.6\% \tag{12}$$

and,

$$\chi_0 = 0.157 \pm 0.016. \tag{13}$$

In using the CLEO measurement of χ_0, we needed to consider only the quoted statistical error. This was because the systematic error was dominated by the uncertainty in Δ, which we were treating explicitly, and the uncertainty in f_{00}, the fraction of $\Upsilon(4S)$'s that decay to $B^0\bar{B}^0$ pairs, which affected this analysis in precisely the same way it affected the dilepton analysis used to measure χ_0 [4]. Using these values of Δ and χ_0, we found that

$$\tilde{R}_0 = 0.115 \pm 0.015. \tag{14}$$

C. The Ratio of Efficiencies ϵ_u/ϵ_l

In order to extract the fraction of lower vertex production, we also required an estimate of the ratio of efficiencies for finding D_s's produced at the upper and lower vertices. This ratio may be written as

$$\left(\frac{\epsilon_u}{\epsilon_l}\right) = \frac{\int_{0.0}^{0.5} \epsilon(x)\rho_u(x)dx}{\int_{0.0}^{0.5} \epsilon(x)\rho_l(x)dx}, \tag{15}$$

where $\epsilon(x)$ is the efficiency for reconstructing a D_s of scaled momentum x and $\rho_u(x)$ and $\rho_l(x)$ are the spectra for upper and lower vertex D_s's, normalized to equal areas. This ratio deviates from unity because $\epsilon(x)$ is not a constant and the spectrum for upper vertex production, which often involve two body decays, differs from the spectrum for lower vertex production, which necessarily involve decays into at least three bodies.

We determined $\epsilon(x)$ in $B\bar{B}$ Monte Carlo by plotting the ratio of the number of D_s's reconstructed to the number generated in each of 9 equally sized bins in the region $0.0 < x < 0.45$ and fitting the resulting distribution to a first order polynomial. (See figure 6.) We simulated the spectrum for lower vertex by using Monte Carlo to generate spectra for events in which a D_s^+, a K^-, and n pions ($n = 0, 1, 2$) were produced at the lower vertex and an $l^-\bar{\nu}$ pair, a $\bar{c}s$ pair, or a $\bar{u}d$ pair was produced at the upper vertex. We assumed that the $\bar{c}s$ pair always hadronized into a D_s^- or a D_s^{*-} and that the $\bar{u}d$ pair hadronized into either a π^-, a ρ^-, an a_1^- or a higher multiplicity state. We took a weighted average of these spectra to arrive at our best estimate for the inclusive spectrum for D_s's produced at the lower vertex. (See figure 7(a).) We modeled upper vertex spectrum by taking the spectrum obtained in the study of inclusive D_s production [2] and subtracting from it the spectrum for lower vertex production, appropriately scaled. We assumed that roughly one sixth of all D_s's were produced at the lower vertex. The subtraction of the lower vertex contribution did not drastically effect the shape of the resultant spectrum for upper vertex D_s's. (See figure 7(b).)

Performing the integration numerically, we obtained the result,

$$\left(\frac{\epsilon_u}{\epsilon_l}\right) = 1.15 \pm 0.15. \tag{16}$$

To estimate the uncertainty in the entire procedure, we varied the invariant mass of the $D_s^+K^-n\pi$ system and the relative branching fractions for the various number of pions produced at the lower vertex. We found that the lower vertex spectrum is rather insensitive to the details of the modeling.

D. Corrected Yields and the Value of f_l

Correcting for fakes and leptons from $J/\psi \to l^+l^-$ decays, we obtained the following yields for the same and opposite-charge pairs:

$$n^{++} = 30.6 \pm 9.1, \tag{17}$$

and

$$n^{+-} = 110.9 \pm 14.8. \tag{18}$$

The errors are just the statistical errors from the fits to the $\phi\pi$ mass peaks.

Note that a sizable portion of the same-charge yield must be attributed to upper vertex production. If we assume that there is no lower vertex production and that all same-charge pairs are the result of either $B^0\bar{B}^0$ mixing or the contamination of our lepton tag sample with leptons from charm, then the same and opposite-charge yields should obey the relationship,

$$n^{++} = n^{+-} \times \tilde{R}_0. \tag{19}$$

Using our opposite-charge yield as input to this equation, we find that upper vertex production is responsible for 11.7 ± 1.6 of our 30.6 ± 9.1 same-charge pairs. This implies that the number of same-charge pairs remaining to be accounted for by lower vertex production is

$$n_l = 18.9 \pm 9.2. \tag{20}$$

With this statistical significance, we do not claim to have observed a signal for such production.

Using the corrected yields and our values for the parameter $\tilde{R}_0$ and the ratio of efficiencies ϵ_u/ϵ_l, we extracted a value for the fraction of D_s production occurring at the lower vertex of,

$$f_l = 0.172 \pm 0.079 \pm 0.026. \tag{21}$$

The first error is statistical, and the second is systematic.

IV. SYSTEMATIC ERRORS

Our systematics errors, all of which are summarized in table 1, were of four types:

- errors involving corrections to the yields,
- errors involving the parameter $\tilde{R}_0$ (*i.e.* errors involving the mixing parameter χ_0 and the fraction of tag leptons coming from charm Δ),
- errors in the estimations of the continuum yields,
- errors involving ϵ_u/ϵ_l, the ratio of efficiencies for finding upper and lower vertex D_s's.

Errors of the first type increased the uncertainties in n^{++} and n^{+-} (for instance, the correction for fakes increases the uncertainty in n^{++} by ± 0.5 events). To determine how much each contributed to the systematic error in f_l we propagated it through our expression for f_l. (Refer to equations (3), (4), and (5)). Note that we have included in this category the error due to our cut of $\cos\theta_{D_s-l} > -0.5$ for opposite-charge pairs.

Errors of the second type could also be dealt with by propagating them through our algebra. We have chosen to list separately the systematic errors deriving from the uncertainties in χ_0 and in Δ. In doing so, we demonstrate that the uncertainty in χ_0 is the more important of the two.

Source (X)	$X \pm \delta X$	$\delta f_l/f_l$ (in %)
n^{++}_{fake}	2.2 ± 0.7	3.2
n^{+-}_{fake}	3.9 ± 1.2	1.5
$n^{++}_{J/\psi} = n^{+-}_{J/\psi}$	1.5 ± 0.1	0.5
$\cos\theta_{D_s-l}$ cut	-	2.8
Δ	0.02 ± 0.006	2.7
χ_0	0.157 ± 0.016	4.0
$n^{++}_{continuum}$	0.0	0.0
$n^{+-}_{continuum}$	$0.0\pm$ 3.2	4.0
ϵ_u/ϵ_l	1.15 ± 0.15	13.0
Total	-	15.1

TABLE I. The various systematic errors associated with our measurement of f_l.

We assigned no systematic error to our estimate of the same-charge continuum yield because the only production mechanism for same same-charge pairs in continuum was lepton fakes, for which we were already correcting. However, opposite-charge pairs could be produced in the continuum by charm semileptonic decays. We counted events within 2.5σ of the D_s mass and found one event. We then used Poisson statistics to estimate the 90% confidence level limit for the number of signal events in the region. We scaled this number to compensate for the difference in the sizes of the on and off-resonance datasets and too to arrive at our systematic error in the opposite-charge yield in continuum.

Finally, we took the uncertainty of ± 0.15 in the ratio ϵ_u/ϵ_l and estimated the uncertainty in f_l caused by it. In doing so, we considered only the uncertainties associated with our modeling of the spectra $\rho_u(x)$ and $\rho_l(x)$ in equation 15. We did not consider systematic errors associated with absolute D_s reconstruction efficiency, $\epsilon(x)$, because these canceled in the ratio. We found that the uncertainty in our modeling of the spectra constituted the single largest systematic error in our study.

Adding the various individual errors in quadrature, we arrived at an estimate of our total systematic error of 15.1% of our value for f_l, or $\delta_{f_l} = 0.026$.

V. CONCLUSIONS

Given our estimate of the systematic error in our measurement, we proceeded to set an upper limit on the fraction of D_s production occurring at the lower vertex. In doing so, we took a conservative approach. First, we estimated the 90% confidence level upper limit using only the statistical error in f_l. Next, we summed in quadrature all of the systematic errors except for the uncertainty due to the estimation of the opposite-charge continuum yield; we added the resultant quantity to our limit. Finally, we calculated the 90% confidence level limit on the number of opposite-charge pairs in continuum (i.e. we doubled the error on $n^{++}_{continuum}$), propagated this figure through our algebra, and added the resultant change in f_l to our limit. We achieved a limit at the 90% confidence level of

$$f_l < 0.31. \tag{22}$$

We note that the dominant error in this measurement is the 30% statistical error in the raw same-charged yield, n^{++}_{raw}. This study would certainly benefit from more data. Moreover, we might do better to study correlated D_s-lepton pairs or to search for exclusive modes that necessitate such production (*e.g.* $B^- \to D_s^+ K^- l^- \bar{\nu}$ or $B^- \to D_s^+ K^- \pi^-$). We intend to explore these avenues as we continue our investigation of the production mechanisms of D_s mesons in B meson decays.

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REFERENCES

[1] In this paper, D_s denotes either a D_s^- or a D_s^+. Reference to a specific state or decay always implies that the charge conjugate state or decay has been included.

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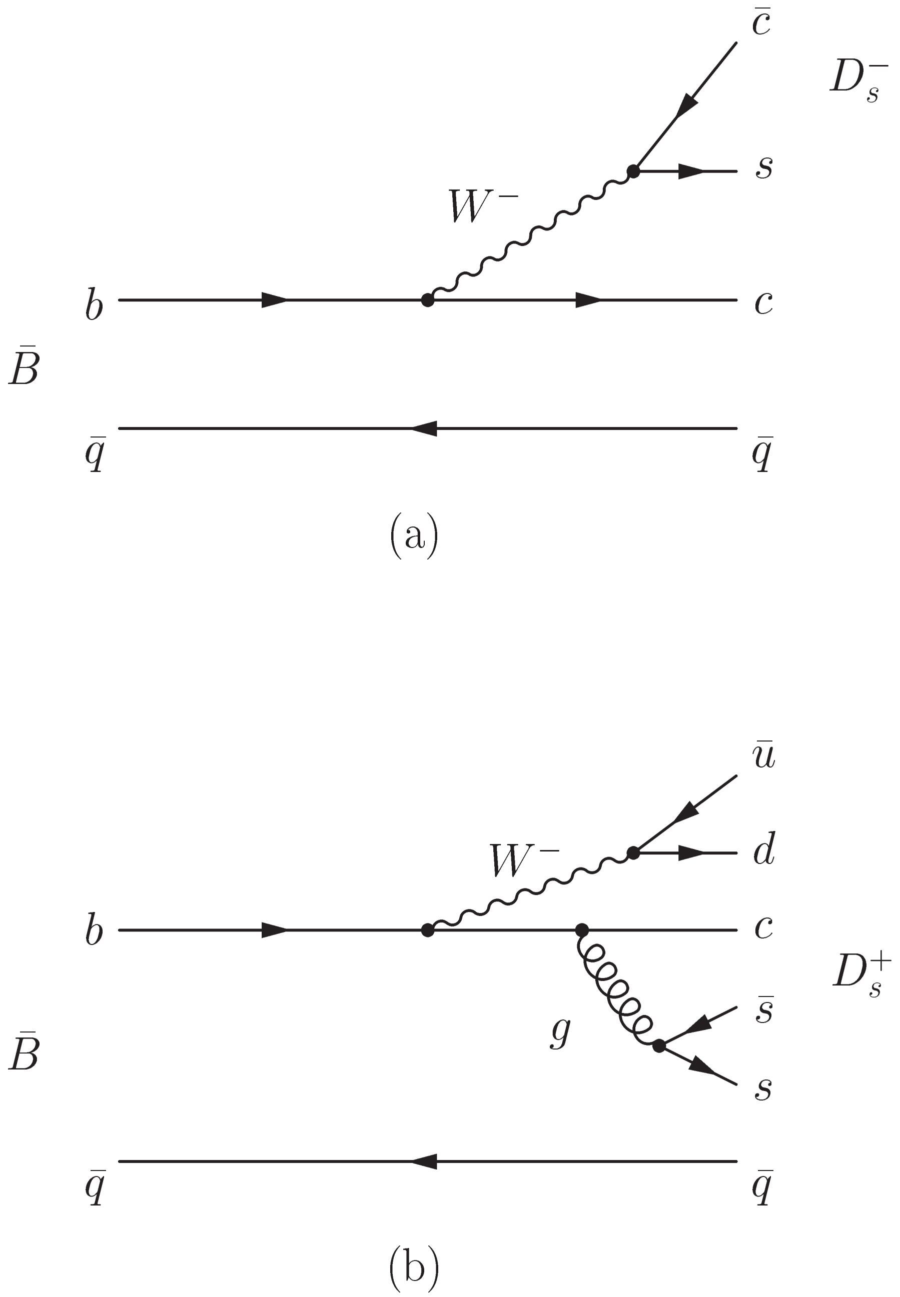

FIG. 1. The simplest Feynman diagrams for *upper vertex production* (a) and *lower vertex production* (b) of D_s mesons.

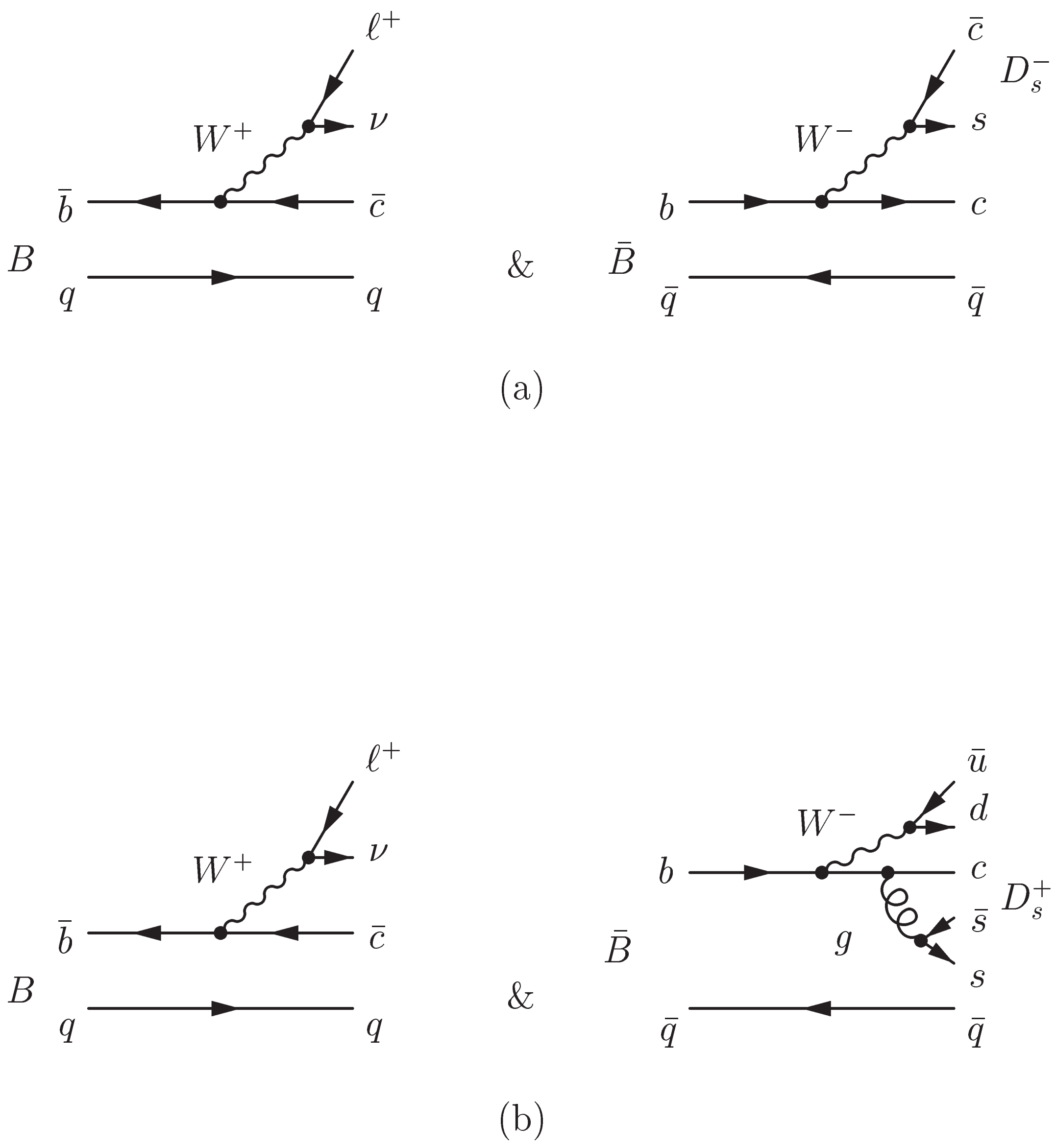

FIG. 2. Feynman diagrams illustrating the correlation between the charges of the D_s and the lepton in Υ(4S) events in which the $\bar{B}$ decays to the D_s and the B decays semileptonically. (a) In the absence of mixing, the D_s and the lepton have opposite charges if the D_s is produced at the upper vertex. (b) They have similar charges if the D_s is produced at the lower vertex. Mixing reverses the charge correlations.

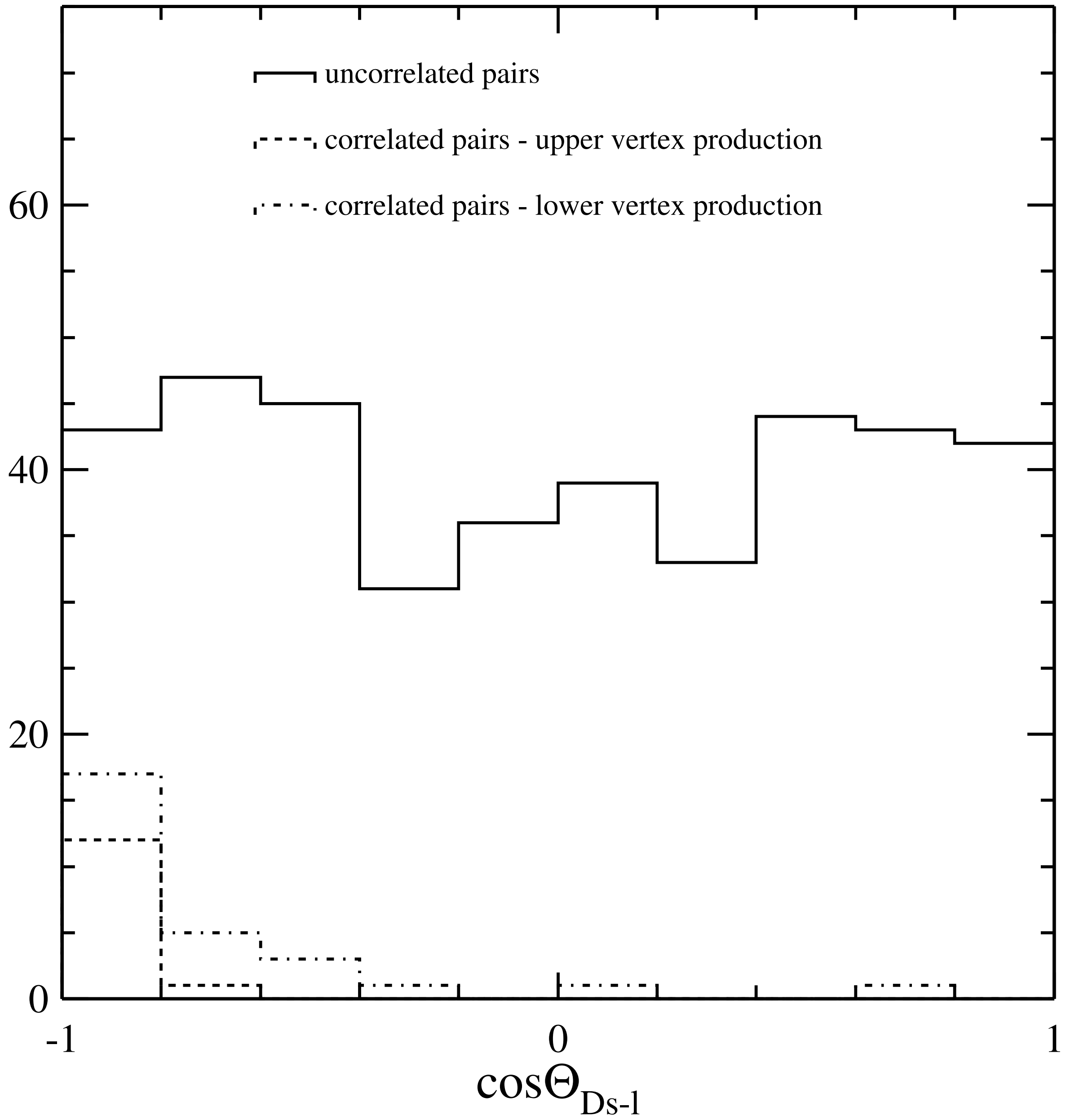

FIG. 3. Plots of the distribution of $\cos\theta_{D_s-l}$ for uncorrelated D_s-lepton pairs, correlated pairs comprising an upper vertex D_s, and correlated pairs comprising a lower vertex D_s in Monte Carlo. The normalizations of the uncorrelated distribution and correlated upper vertex distribution are in the correct proportion. The correlated lower vertex distribution was generated using dedicated $B^- \to D_s^+ K^- l^- \bar{\nu}$ Monte Carlo. The normalization of this distribution corresponds to a branching fraction to this mode of 1%.

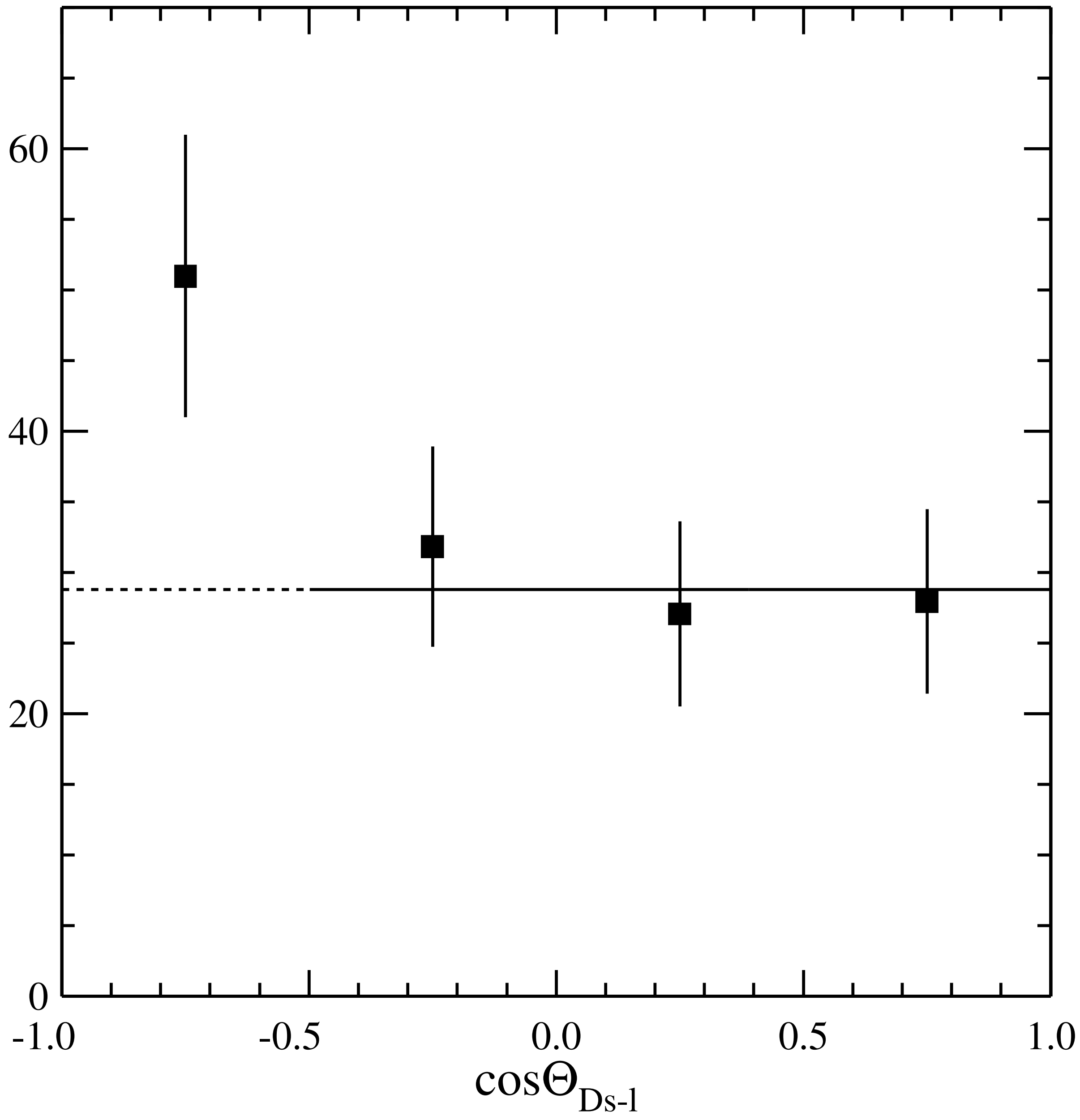

FIG. 4. Plots of the distribution of $\cos\theta_{D_s-l}$ for opposite-charge D_s-lepton pairs in data. The fit is to a constant in the region $\cos\theta_{D_s-l} > -0.5$ only. The slight peaking at $\cos\theta_{D_s-l}$=-1.0 suggests that some of these pairs were correlated.

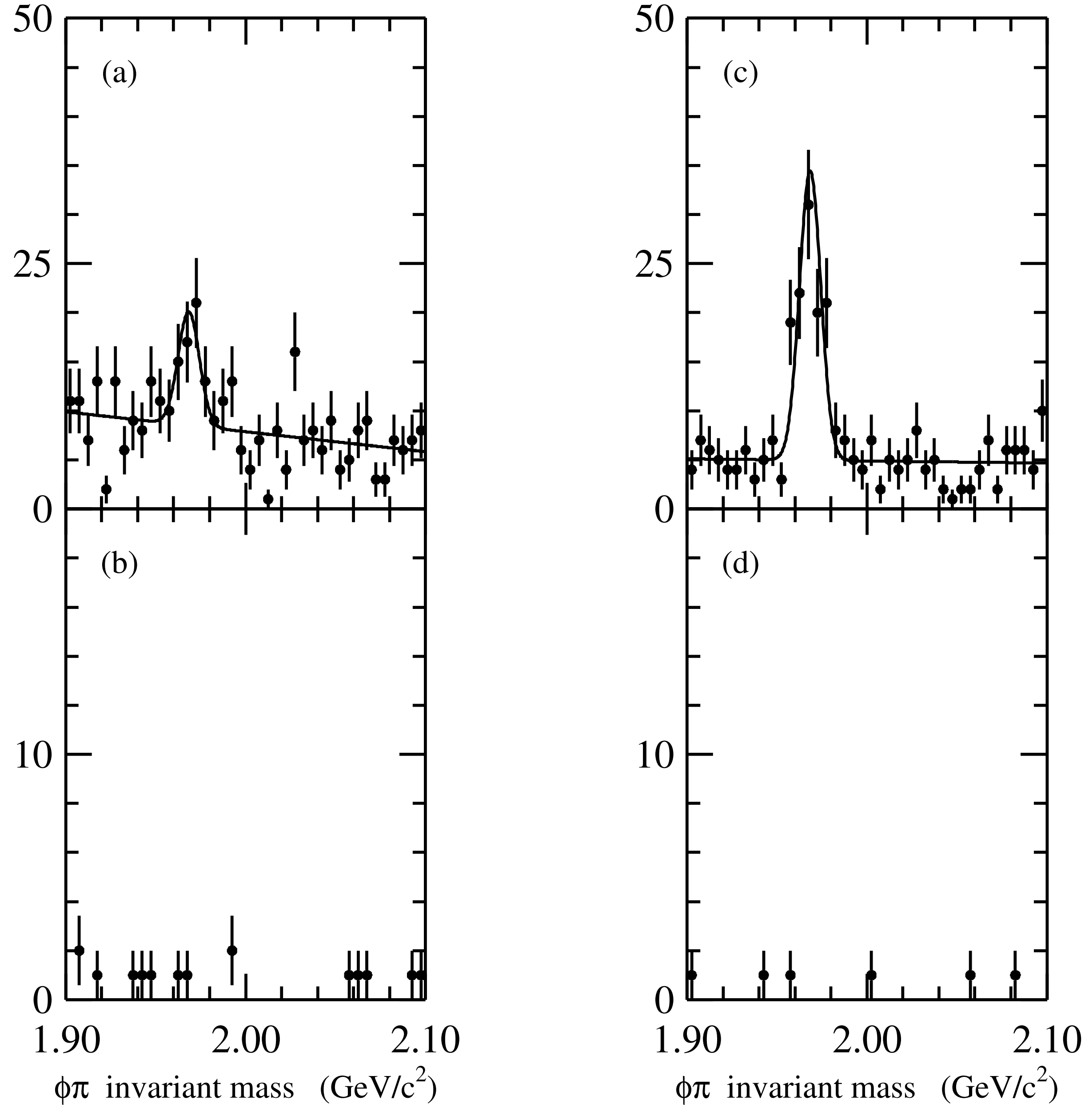

FIG. 5. The various $\phi\pi$ mass distributions: (a) same-charge on-resonance, (b) same-charge off-resonance, (c) opposite-charge on-resonance, and (d) opposite-charge off-resonance.

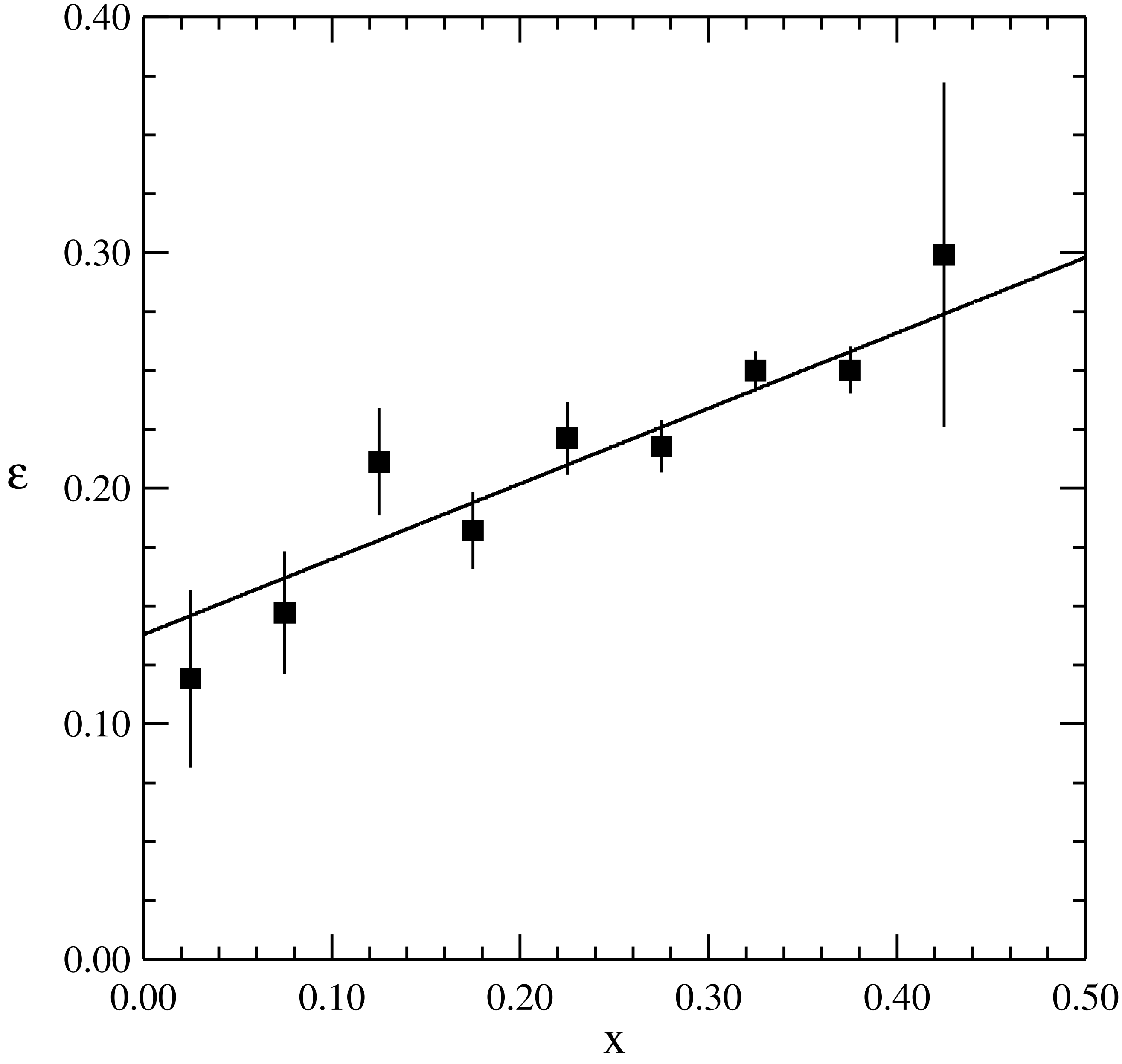

FIG. 6. The efficiency for reconstructing D_s's in the mode $D_s^+ \rightarrow \phi\pi^+, \phi \rightarrow K^+K^-$ as a function of the scaled momentum of the D_s. We have fit the distribution to a straight line.

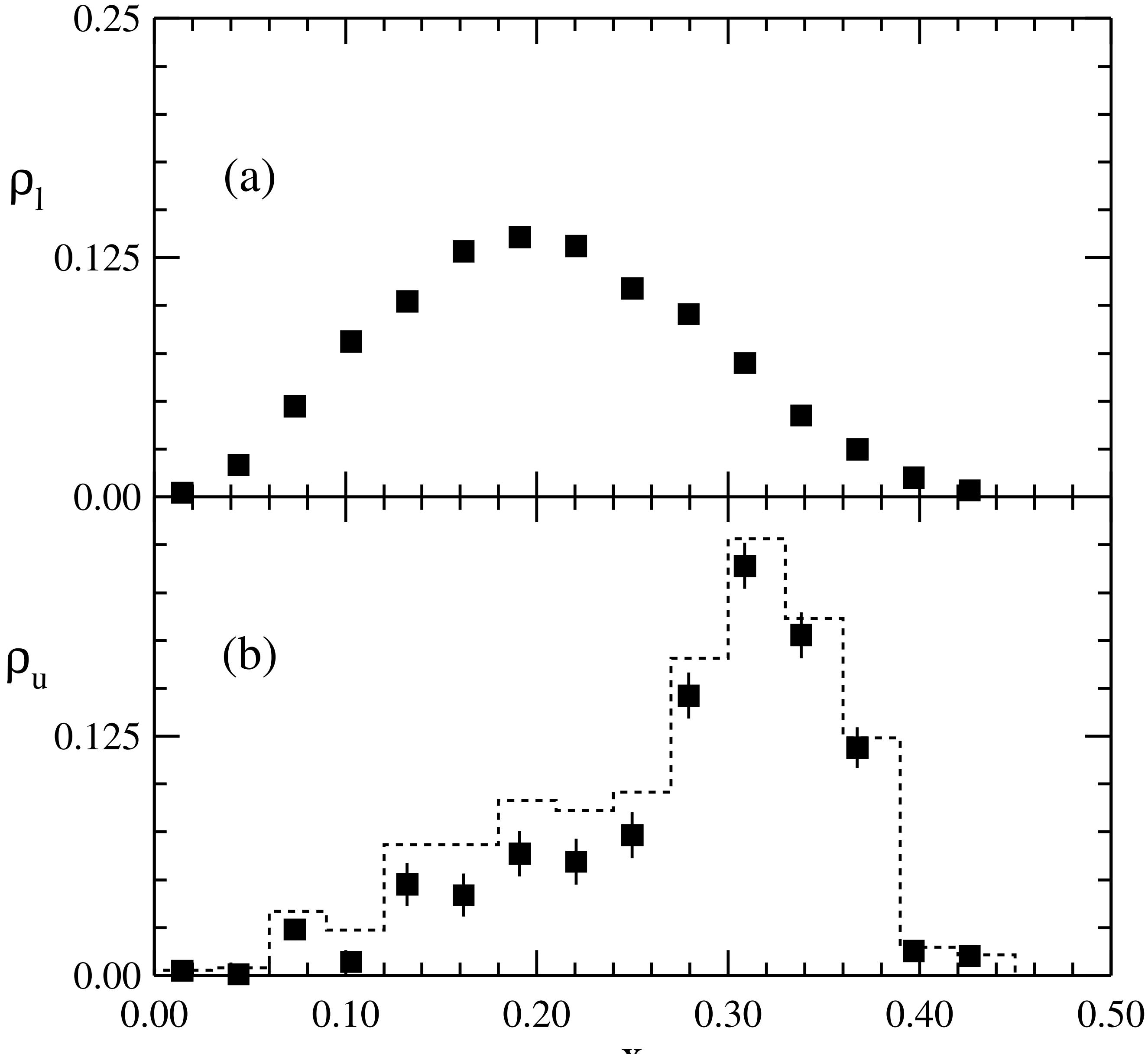

FIG. 7. The spectra for lower vertex (a) and upper vertex (b) D_s's used in calculating the ratio ϵ_u/ϵ_l. The spectra have been normalized to equal areas. The dashed histogram overlaid on the upper vertex spectrum is the inclusive D_s spectrum from [2].