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Abstract

Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, the branching ratios for semileptonic B meson decays to D^0, D^+, D^{*0} and D^{*+} have been determined by studying $D^{(*)}l$ combinations in 200,000 decays of the $\Upsilon(4S)$. Assuming equal production of B^0 and B^+ saturating the $\Upsilon(4S)$ decays and lepton universality, we obtain: $BR(B^- \to D^{*0}l^-\bar{\nu}) = (4.9 \pm 0.7 \pm 0.7)\%$, $BR(\bar{B}^0 \to D^{*+}l^-\bar{\nu}) = (5.2 \pm 0.8 \pm 0.8)\%$, $BR(B^- \to D^0 l^-\bar{\nu}) = (1.8 \pm 0.6 \pm 0.4)\%$ and $BR(\bar{B}^0 \to D^+ l^-\bar{\nu}) = (1.9 \pm 0.6 \pm 0.5)\%$. These results are in good agreement with previous measurements and constitute a valuable consistency check.

The study of the exclusive semileptonic B meson decays $B \to Dl\nu$ and $B \to D^*l\nu$ can provide important information on the Cabibbo-Kobayshi-Maskawa matrix element $|V_{cb}|$ and the ratio of lifetimes for charged and neutral B mesons. Theoretical predictions for the contribution of these channels to the total semileptonic width of the B meson are very sensitive to the model description of quark dynamics in the weak $b \to c$ transition. Existing models [1–3] assume that nearly 90% of the inclusive semileptonic width of the B meson is saturated by the D and D^* decay channels. On the other hand, the present experimental measurements show that the actual number is only about 70% [5–7]. Motivated by these considerations, we report here a new simultaneous measurement of the branching ratios for the four exclusive decay modes:[1]

$$B^- \to D^0 l^- \bar{\nu} \tag{1}$$
$$\bar{B}^0 \to D^+ l^- \bar{\nu} \tag{2}$$
$$B^- \to D^{*0} l^- \bar{\nu} \tag{3}$$
$$\bar{B}^0 \to D^{*+} l^- \bar{\nu} \tag{4}$$

The data used for this analysis were taken on the $\Upsilon(4S)$ resonance using the ARGUS detector at the e^+e^- storage ring DORIS II. The integrated luminosity is $235\ pb^{-1}$, corresponding to $200000 \pm 9500\ \Upsilon(4S)$ decays. The ARGUS detector, its trigger requirements and particle identification capabilities have been described in detail elsewhere [9].

For lepton identification, information from all detector components is used coherently by combining the measurements into an overall likelihood ratio. The available information consists of dE/dx and time-of-flight measurements, and the magnitude and topology of energy deposition in the shower counters. In addition, for muons, a

[1] References in this paper to a specific charged state are to be interpreted as implying the charged-conjugate state also.

hit in an outer muon chamber is required and information on the distance between the hit and the expected impact point is included in the likelihood. An electron or muon hypothesis is accepted if the appropriate likelihood ratio exceeds 70%.

Reactions (1-4) are measured by observing D^0, D^+ or D^{*+} mesons in combination with a lepton of the proper charge. D^0, D^+ and D^{*+} mesons are reconstructed in the decay channels $K^-\pi^+$, $K^-\pi^+\pi^+$, and $D^0\pi^+$, respectively.

D^0l^- combinations originate from B decay mode (1) and the cascade decays (3) and (4):

$$B^- \to D^0 l^- \bar{\nu}$$
$$B^- \to D^{*0} l^- \bar{\nu}, \quad D^{*0} \hookrightarrow D^0\pi^0 \text{ or } D^0\gamma$$
$$\bar{B}^0 \to D^{*+} l^- \bar{\nu}, \quad D^{*+} \hookrightarrow D^0\pi^+$$

D^+l^- combinations originate from B decay modes (2) and (4):

$$\bar{B}^0 \to D^+ l^- \bar{\nu}$$
$$\bar{B}^0 \to D^{*+} l^- \bar{\nu}, \quad D^{*+} \hookrightarrow D^+\pi^0 \text{ or } D^+\gamma$$

and $D^{*+}l^-$combinations only from (4). Contributions from $B \to D^{**}l\nu$ and possible decays to non-resonant hadronic final states are treated as background in the following.

The particle(s) X and the neutrino in $B \to D^{(*)}l\nu(X)$ decays are not observed. But since the kinematics of the $D^{(*)}l$ combinations depends on X, the contributions from sources with different X can be distinguished by studying the shape of suitable kinematical distributions.

The kinematical parameter measured in this study to detect $D^{(*)}l$ combinations from the decays

$$B \to l\nu D^{(*)}X$$

is the missing energy E_{miss} carried away by the unobserved particle(s) represented by X:

$$E_{miss} \approx E_X = E_B - E_D - E_l - E_\nu,$$

where E is the energy of the corresponding particle. The neutrino is also unobserved, but, since the momentum of X is small, due to the small Q value in the decay of the D^*, and neglecting the momentum of the B meson, the neutrino energy can be approximated by:

$$E_\nu = \left|\vec{P}_\nu\right| = \left|\vec{P}_B - \vec{P}_X - \vec{P}_D - \vec{P}_l\right| \approx \left|\vec{P}_D + \vec{P}_l\right|,$$

where P is the momentum of the corresponding particle. This allows E_{miss} to be obtained from measured quantities

$$E_{miss} = E_{beam} - E_D - E_l - \left|\vec{P}_D + \vec{P}_l\right|,$$

where the well known beam energy has been substituted for the energy of the B meson. In the case of a fully reconstructed D^{*+}, the energy and momentum of the D^{*+} meson are used in the calculation of E_{miss}.

The obtained E_{miss} spectra are superpositions of all possible contributions from reactions (1-4). Each individual contribution has a specific shape which has been determined by Monte Carlo simulation. The rates for processes (1-4) are extracted from the data by simultaneously fitting the three missing energy spectra of reconstructed D^0l^-, D^+l^- and $D^{*+}l^-$ pairs with a superposition of the contributions from (1-4) plus some background.

Events containing $K^-\pi^+(\pi^+)\ l^-$ combinations are accepted, if they satisfy the following conditions:

- Total multiplicity ($n_{charged} + n_\gamma/2$) larger than 5;
- second Fox-Wolfram moment less than 0.4;
- momentum of the l^- and the $K^-\pi^+(\pi^+)$ combination less than 2.5 GeV/c, which is the kinematic limit for particles produced in B meson decays at the $\Upsilon(4S)$ energy;
- lepton momentum larger than 1.1 GeV/c;
- opening angle between the momentum vectors of the D candidate and the lepton, θ_{Dl^-}, in the range of $-1 < \cos(\theta_{Dl^-}) < 0$. This requirement considerably reduces the uncorrelated background while retaining more than 95% of the decays (1-4).

In addition, the scalar sum of the D and l^- momenta is required[2] to be larger than 2.5 GeV/c. This restriction supresses the main sources of background, namely the contribution from $B \to D^{**}l\nu$ and possible decays to non-resonant hadronic final states, while retaining large acceptances for the decays $B \to Dl\nu$ (97%) and $B \to D^*l\nu$ (82%). The cut also strongly reduces combinatorial background. Finally, explicit contributions from $D^{*+} \to D^0\pi^+$ decays to the D^0l^- spectra are removed by requiring $K^-\pi^+\pi^+$ combinations to satisfy the following condition:

[2]In the case of the $D^{*+}l^-$ sample, the momentum of the daughter D^0 meson is used.

$$\left|M_{(K^-\pi^+)\pi^+} - M_{(K^-\pi^+)} - \Delta M\right| > 4 \cdot \sigma$$

where ΔM is the difference between the nominal masses of the D^{*+} and the D^0 meson, and σ is the experimental D^{*+} mass resolution ($\sigma \approx 1\ MeV/c^2$).

The missing energy spectra for $D^0 l^-$, $D^+ l^-$ and $D^{*+} l^-$ combinations are shown in Figure 1. The number of D^0, D^+, and D^{*+} mesons in each E_{miss} bin is determined by a fit to the $K^-\pi^+$, $K^-\pi^+\pi^+$, and $D^0\pi^+$ invariant mass distributions, respectively. For the D^{*+} analysis, the $K^-\pi^+$ combination forming a D^0 candidate are kinematically constrained to the known D^0 mass, thereby improving the mass resolution for the D^{*+}. The parametrizations of the signal and background shapes used to describe the invariant mass spectra, as well as the technique employed to account for double misidentification of $\pi^- K^+$ combinations from $\bar{D}^0$ decays as $K^-\pi^+$, are described in detail in [4,5].

Possible background contributions to the observed $D^{(*)}l$ spectra originate from the following sources:

(a) Non-resonant e^+e^- annihilation (continuum)

(b) $D^{(*)}$ and l^- from different B mesons

(c) $D^{(*)}$ and hadron misidentified as lepton

(d) $D^{(*)}$ and l^- from possible cascade or non-resonant semileptonic decays: $B \to D^{**} l \nu$ or $B \to D^{(*)}(n\pi) l \nu$.

The shape of the E_{miss} distribution of the background from sources (a) and (b) has been determined by Monte Carlo studies. For the background (a) the absolute normalization is fixed using continuum data taken at centre-of-mass energies below the $\Upsilon(4S)$, while background (b) is normalized by the Monte Carlo studies. The background due to fake leptons, (c), is measured directly from the data using the E_{miss} spectra of $D^{(*)}$-hadron combinations and known misidentification probabilities [6]. The contributions from background sources (a), (b) and (c) are broken down in detail in the Table 1 and their sum is shown in Figure 1, while (d) is treated separately below.

For the next step we use additional information about the kinematics of the decays studied. Due to the V-A structure, semileptonic $B \to D l \nu$ decays are characterized by a fast D and a relatively slow lepton, while the opposite, i.e. a fast lepton and slow D^*, is true for $B \to D^* l \nu$ decays. This statement is illustrated by Figure 2. On this basis, the $D^{(*)}l$ data are divided into two independent samples:[3]

[3] In the case of the $D^{*+}l^-$ sample, the momentum of the daughter D^0 meson is used.

$$(I)\quad \left|\vec{P}_D\right| > \left|\vec{P}_l\right| \quad \text{(enriched with } B \to D l \nu \text{ decays)}$$
$$(II)\quad \left|\vec{P}_D\right| < \left|\vec{P}_l\right| \quad \text{(enriched with } B \to D^* l \nu \text{ decays)}$$

Monte Carlo studies indicate that the fraction of D mesons produced in the direct decay $B \to D l \nu$ in sample (I), $f_D^I \equiv N_D(P_D > P_l)/N_D$, is $(69 \pm 3)\%$, while the same fraction for D mesons coming from the cascade decay $B \to D^* l \nu$, $f_{D^*}^I$, is $(32 \pm 5)\%$.

Figure 3 shows the observed E_{miss} spectra for $D^0 l^-$, $D^+ l^-$ and $D^{*+} l^-$ combinations in both samples after subtraction of the backgrounds arising from sources (a), (b) and (c). A simultaneous fit to these spectra is performed by using contributions from the decays (1-4) and background from source (d). The shape of each individual contribution is taken from Monte Carlo simulations. For the semileptonic decays (1-4) generators based on the models of BSW [2], GISW [1] and KS [3] are used. The E_{miss} spectra exhibit no significant model dependence and can be reasonably well described by Gaussian distributions. For background (d) the shape of the E_{miss} spectrum depends mainly on the mass of the final hadronic state and the distribution of the opening angles between the lepton and D momentum vectors. In order to investigate this dependence, the GISW model was used to describe $B \to D^{**} l \nu$ decays, and non-resonant semileptonic decays were generated according to phase space. The uncertainties in the fit result brought about by changes in a range of assumptions concerning the background are included in the systematic error of the final fit result. The main contribution to the systematic error is due to the uncertainty in the D^{**} peak position and width, and amounts to 12% of the branching ratios.

Assuming isospin symmetry, the following constraints are applied during the fitting procedure:

- The ratio of semileptonic widths for final states with a pseudoscalar versus a vector D meson are equal for charged and neutral B decays:
$$\frac{\Gamma(B^- \to D^0 l^- \bar{\nu})}{\Gamma(B^- \to D^{*0} l^- \bar{\nu})} = \frac{\Gamma(\bar{B}^0 \to D^+ l^- \bar{\nu})}{\Gamma(\bar{B}^0 \to D^{*+} l^- \bar{\nu})} \equiv r$$
- The fraction of D mesons produced in the direct decays $B \to D l \nu$ in sample (I) (f_D^I) is the same for D^0 and D^+.
- The fraction of D mesons produced in the cascade decays $B \to D^* l \nu$ in sample (I) $(f_{D^*}^I)$ is the same for D^0 and D^+.

No constraint is made for the background contribution from source (d), i.e. the background amplitudes in all six spectra are independent and free. Likewise the ratio r and the fraction $f_{D^*}^I$ are free parameters in the fit. However, the fraction f_D^I is fixed from Monte Carlo studies, since it is reliably predicted by theory.

The decays (1,3) and (2) contribute only to the D^0l^- and D^+l^- spectra, respectively, while channel (4) populates all three E_{miss} distributions for $D^{*+}l^-$, D^0l^- and D^+l^-. It is worthwhile to note that, since the fraction of cascade decays (3,4) is extracted by observing either the number of fully reconstructed D^{*+} mesons or daughter D mesons, our results are independent of the individual branching ratios for $D^* \to D\,X$ transitions.

The contributions from channels (1-4) to the E_{miss} spectra are parametrized in the fit by the following independent variables:

- $N_{D^0}(D^{*+} \to D^0\pi^+)$, the number of reconstructed D^0 mesons originating from the decay $D^{*+} \to D^0\pi^+$, as obtained from the D^0l^- and $D^{*+}l^-$ spectra.
- $N_{D^+}(D^{*+} \to D^+\pi^0(\gamma))$, the number of reconstructed D^+ mesons originating from the decay $D^{*+} \to D^+\pi^0(\gamma)$, as obtained from the D^+l^- spectrum.
- $N'_{D^0}(D^{*0} \to D^0\pi^0(\gamma))$, the number of reconstructed D^0 mesons originating from the decay $D^{*0} \to D^0\pi^0(\gamma)$, as obtained from the D^0l^- spectrum.

The fit was performed using the MINUIT package. The obtained values are

$$\begin{aligned} N'_{D^0}(D^{*0} \to D^0\pi^0(\gamma)) &= 181 \pm 26 \pm 23, \\ N_{D^0}(D^{*+} \to D^0\pi^+) &= 112 \pm 17 \pm 13, \\ N_{D^+}(D^{*+} \to D^+\pi^0(\gamma)) &= 122 \pm 40 \pm 28 \quad \text{and} \\ r = 0.34 \pm 0.10 \pm 0.05, & \end{aligned}$$

where the first error is statistical and the second one systematic, arising from the uncertainties in the shapes of fitted E_{miss} functions discussed above. The fitted sum of all contributions is indicated in Figure 3, along with a separate display of the individual contributions.

The fit results were stable, second minima were not observed. The correlation coefficients were less than 0.72. The stability of the fit was also checked using Monte Carlo data with different input branching ratios and spectrum shapes for the decays (1-4). The fit results well reproduced the input parameters.

The branching ratios for the decays $B^- \to D^{*0}l^-\bar{\nu}$ and $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ are calculated using $BR(D^0 \to K^-\pi^+) = (3.71 \pm 0.25)\%$, $BR(D^+ \to K^-\pi^+\pi^+) = (7.7 \pm 1.0)\%$ [12] and efficiencies obtained from Monte Carlo studies. Assuming electron-muon universality and $BR(\Upsilon(4S) \to B^0\bar{B}^0) = BR(\Upsilon(4S) \to B^+B^-) = 50\%$, the following results are obtained:

$$BR(B^- \to D^{*0}l^-\bar{\nu}) = (4.9 \pm 0.7 \pm 0.7)\%$$
$$BR(\bar{B}^0 \to D^{*+}l^-\bar{\nu}) = (5.2 \pm 0.8 \pm 0.8)\%$$

$$BR(B^- \to D^0l^-\bar{\nu}) = (1.8 \pm 0.6 \pm 0.4)\%$$
$$BR(\bar{B}^0 \to D^+l^-\bar{\nu}) = (1.9 \pm 0.6 \pm 0.5)\%$$

where the first error is statistical and the second one systematic. The systematic errors arise mainly from uncertainties in the number of $\Upsilon(4S)$ decays, $BR(D^0 \to K^-\pi^+)$, $BR(D^+ \to K^-\pi^+\pi^+)$, the reconstruction efficiencies and systematic errors originating from the fit procedure, primarily due to possible D^{**} contributions. The branching ratios for the decays $B^- \to D^0l^-\bar{\nu}$ and $\bar{B}^0 \to D^+l^-\bar{\nu}$ are calculated from those for $B^- \to D^{*0}l^-\bar{\nu}$ and $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ using the obtained value of r and the ratio of lepton acceptances for the decays $B \to Dl\nu$ and $B \to D^*l\nu$.

The sum of the processes (1-4) is found to account for only $(60 \pm 10)\%$ of the total semileptonic decay width of the B meson [12]. This value is in good agreement with the result obtained by CLEO $(64 \pm 10)\%$ [8] and lower than the value of 87 % predicted by the GISW model [1].

Using the results of the combined fit we obtain a lifetime ratio for neutral and charged B mesons of

$$\tau(B^+)/\tau(B^0) = 0.95 \pm 0.15 \pm 0.19$$

in good agreement with the theoretical expectation. This value is consistent with our previously published indirect measurements [10,11] and the result obtained by CLEO [8].

It is well known that the most reliable way to estimate $|V_{cb}|$ is to measure the decay width for the channel $B \to Dl\nu$. Using our measurement of the rates for decays (1) and (2), and the present average for the lifetime of charged and neutral b hadrons $\tau_B = (1.18 \pm 0.11)ps$ [12], one finds

$$|V_{cb}| = 0.044 \pm 0.007$$

based on the model of BSW [2]. For comparison the value for $|V_{cb}|$ determined from other theoretical models is summarized in Table 2. Note that the result for $|V_{cb}|$ is nearly independent of the fraction of charged and neutral B mesons produced at the $\Upsilon(4S)$.

In summary, the missing energy spectra for D^0l^-, D^+l^- and $D^{*+}l^-$ combinations produced in B meson decays have been studied. From a combined fit to these distributions, the branching ratios for the decays $B^- \to D^0l^-\bar{\nu}$, $\bar{B}^0 \to D^+l^-\bar{\nu}$, $B^- \to D^{*0}l^-\bar{\nu}$ and $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ and the lifetime ratio for charged and neutral

B mesons have been obtained.

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Table 1. Event and background summary for the $D^0 l^-$, $D^+ l^-$ and $D^{*+} l^-$ combinations.

	$D^0 l^-$	$D^+ l^-$	$D^{*+} l^-$
Total number of events	367 ± 26	312 ± 42	97 ± 10
Background:			
Continuum	7.4 ± 3.7	8.9 ± 4.5	3.4 ± 3.0
Mixed events	8.2 ± 2.7	8.6 ± 2.7	2.5 ± 0.8
Secondary leptons	3.8 ± 0.9	4.1 ± 1.0	1.0 ± 0.3
Fake leptons	15.3 ± 3.1	18.2 ± 3.5	2.7 ± 0.6
$B \to l\nu DX$	332 ± 26	272 ± 42	87 ± 10

Table 2. Determination of $|V_{cb}|$ from $B \to Dl\nu$ decay using the result of this analysis $\Gamma(B \to Dl\nu) = (0.016 \pm 0.005) ps^{-1}$.

	$\Gamma(B \to Dl\nu)[10^{12} s^{-1}]$	$\lvert V_{cb}\rvert$
Models:		
BSW [2]	$8.1 \cdot \lvert V_{cb}\rvert^2$	0.044 ± 0.007
SP [15]	$7.2 \cdot \lvert V_{cb}\rvert^2$	0.047 ± 0.007
KS [3]	$8.3 \cdot \lvert V_{cb}\rvert^2$	0.044 ± 0.007
GISW[1]	$11.1 \cdot \lvert V_{cb}\rvert^2$	0.038 ± 0.006
CPK [13]	$9.0 \cdot \lvert V_{cb}\rvert^2$	0.042 ± 0.007
OS [14]	$9.4 \cdot \lvert V_{cb}\rvert^2$	0.041 ± 0.007

Figure Captions

Figure 1: Spectrum of E_{miss} for (a) $D^0 l^-$, (b) $D^+ l^-$ and (c) $D^{*+} l^-$ combinations. The sum of background contributions arising from continuum events, uncorrelated D mesons and leptons produced in different B meson decays and missidentified leptons is shown in the histogram.

Figure 2: Spectrum of D (D^*) meson momentum versus lepton momentum (a) in semileptonic $B \to D^* l\nu$ decays, (b) in semileptonic $B \to Dl\nu$ decays (Monte Carlo data).

Figure 3: Spectrum of E_{miss} after background subtraction. The curves show the fit result for the contributions from the decay channels (1-4) and background from semileptonic B decays into heavier charmed hadronic states. The spectra are given for:

- $D^0 l^-$ combinations with (a) $|\vec{P_D}| > |\vec{P_l}|$ and (b) $|\vec{P_D}| < |\vec{P_l}|$, overlayed by the fitted results for contribution from $B^- \to D^0 l^- \bar{\nu}$ (long dashed), $B^- \to D^{*0} l^- \bar{\nu}$ (short dashed), $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ (dash-dotted) and backgrounds (dotted).
- $D^+ l^-$ combinations with (c) $|\vec{P_D}| > |\vec{P_l}|$ and (d) $|\vec{P_D}| < |\vec{P_l}|$, overlayed by the fitted contribution from $\bar{B}^0 \to D^+ l^- \bar{\nu}$ (long dashed), $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ (short dashed) and backgrounds (dotted).
- $D^{*+} l^-$ combinations with (e) $|\vec{P_D}| > |\vec{P_l}|$ and (f) $|\vec{P_D}| < |\vec{P_l}|$, overlayed by the fitted contribution from $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ decay (short dashed) and backgrounds (dotted).

The sum of the contributions is shown by the solid curves.

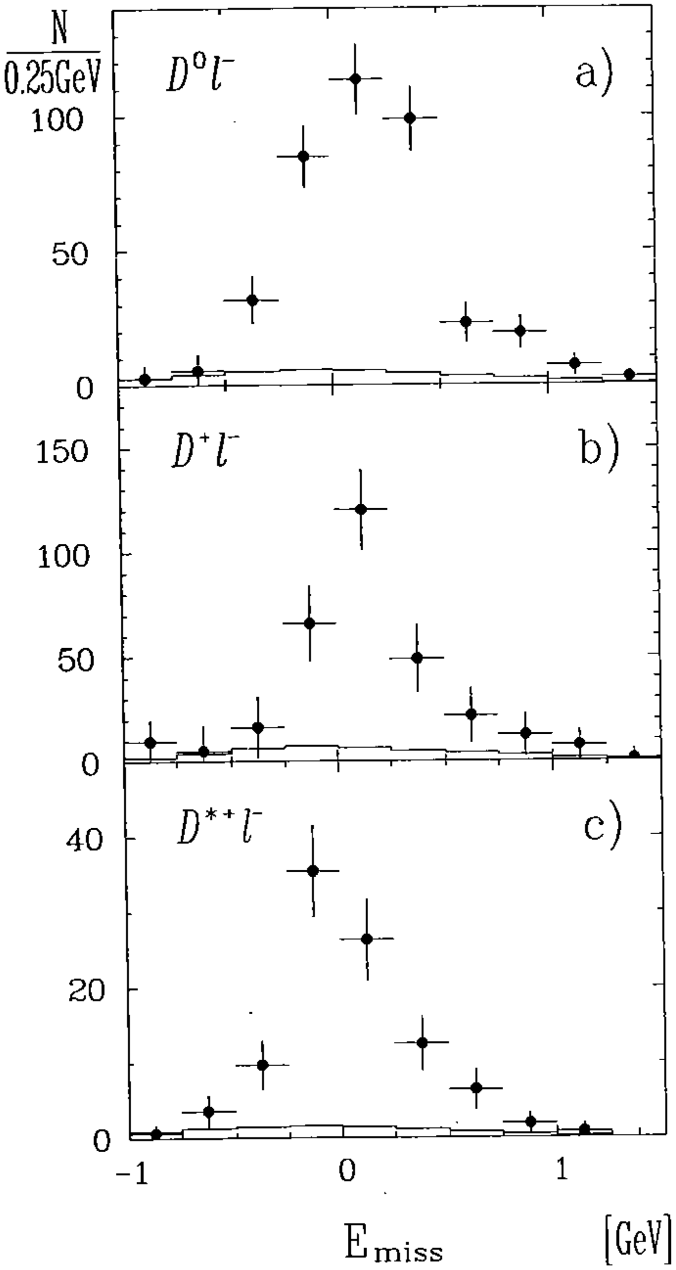

Figure 1.

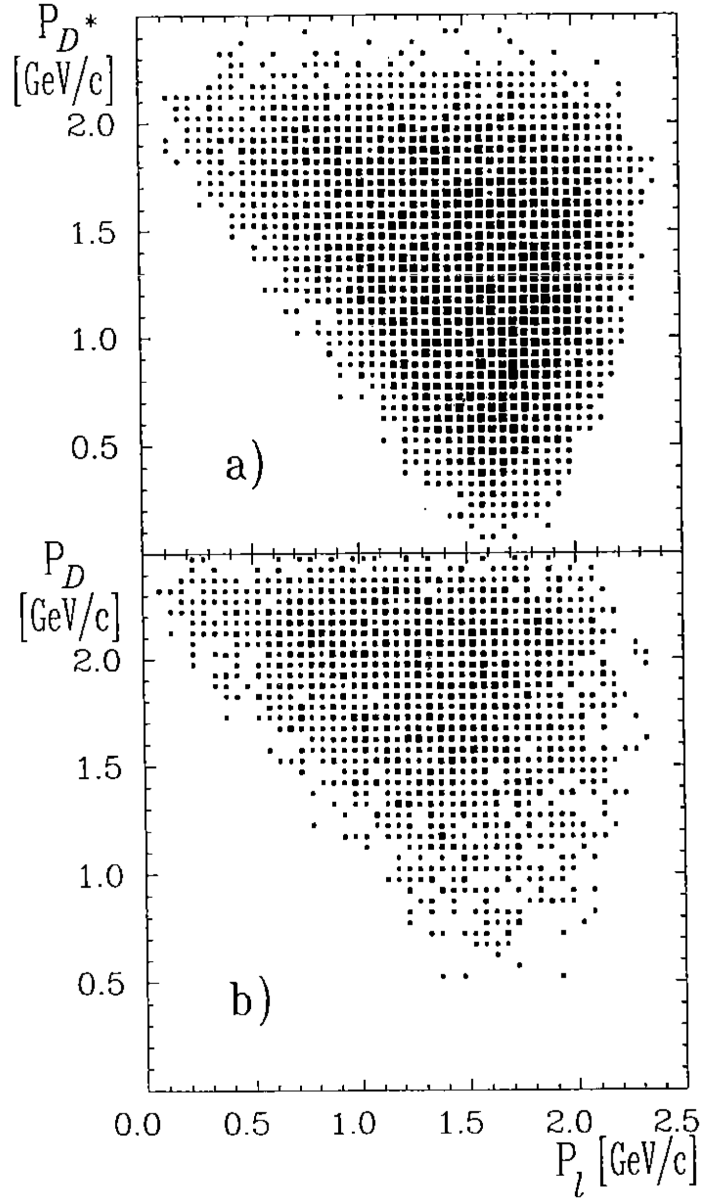

Figure 2.

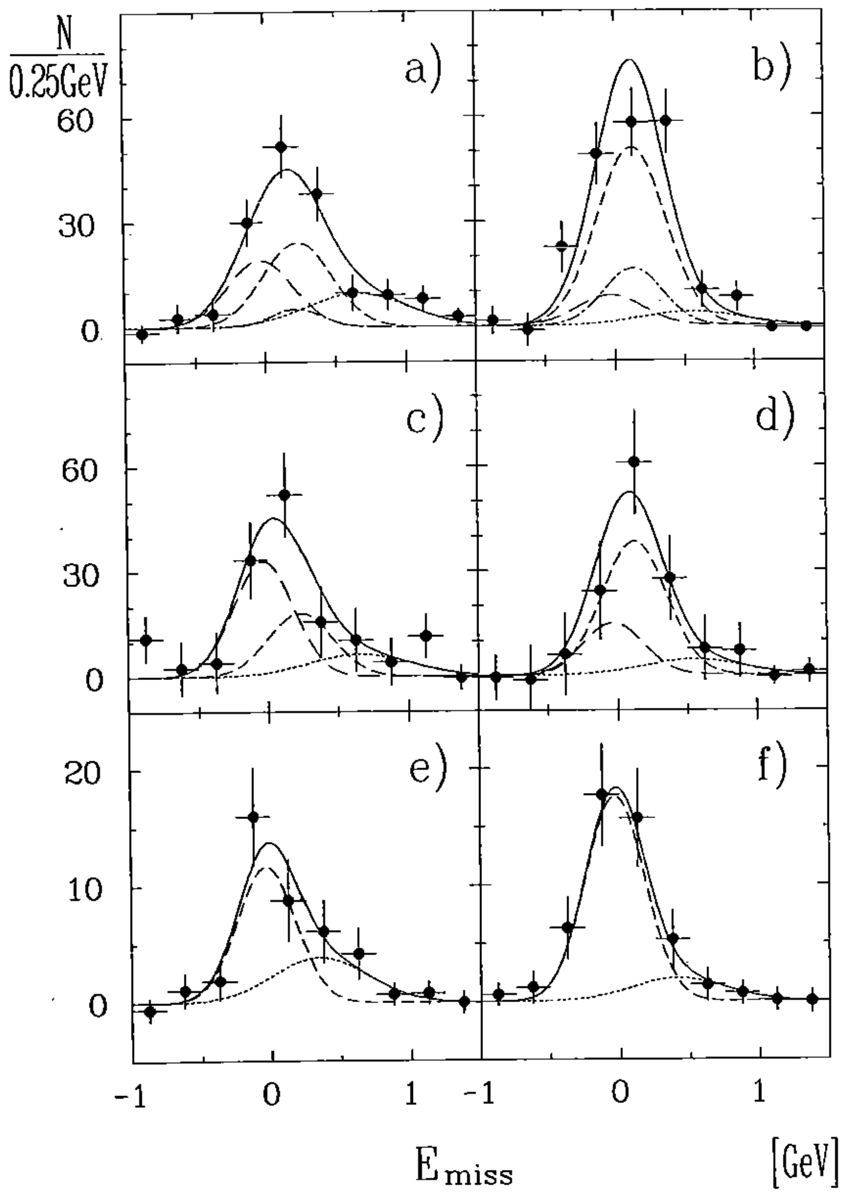

Figure 3.