A MEASUREMENT OF *b* QUARK FRAGMENTATION FRACTIONS BY CDF*

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A new technique to measure the b quark fragmentation fractions in $p\overline{p}$ collisions is described. Using a 70 pb^{-1} sample of low-mass dimuon trigger data recorded with the Collider Detector at Fermilab, we identify B mesons by observing double semileptonic decays $b \to c\mu X$ with $c \to s\mu X$. By counting the numbers of $K^*(892)^0$, $K^*(892)^+$ and $\phi(1020)$ mesons produced in association with these muon pairs, we measure the ratio of strange to non-strange B meson production to be $f_s/(f_u + f_d) = (21.0 \pm 3.6(\mathrm{stat.})^{+3.8}_{-3.0}(\mathrm{syst.}))\%$. This measurement and the complementary measurement done at CDF are the most precise available from hadron collisions to date. The combined CDF result on the absolute fragmentation fraction for B^0_s mesons is $f_s = (16.0 \pm 2.5)\%$.

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1. Introduction

The production of b quarks in hadronic collisions is described by perturbative quantum chromodynamics. The ensuing production of hadrons containing b quarks is described by phenomenological models where a free quark combines with an anti-quark to form a colourless meson [1, 2]. In these fragmentation models the flavour of the anti-quark is not predicted a priori and must be taken from experiment. The knowledge of the b quark fragmentation fractions is important for the measurement of other B meson properties such as $B\bar{B}$ oscillations and B hadron lifetimes. A precise determination of f_s will impact numerous other measurements.

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The LEP experiments have determined the fragmentation fractions for b quarks produced in the $e^+e^- \to Z^0 \to b\bar{b}$ process. The probabilities f_u and f_d, to produce B^+ or B^0 mesons respectively, are assumed to be equal since the two spectator quarks have nearly equal masses. The combined LEP result is $f_u \equiv f_d = (39.7\ ^{+1.8}_{-2.2})\%$ [3]. The most precise estimate of f_s, the fragmentation fraction into B^0_s mesons, is currently derived from $B\bar{B}$ oscillations using measurements of the flavour averaged mixing parameter $\bar{\chi} = f_s\chi_s + f_d\chi_d$ together with measurements of $\chi_d = x_d^2/[2(1+x_d^2)]$ where $x_d = \Delta m_d \tau_{B^0}$. The result of this determination combined with measurements of f_s from the product branching fraction $f_s \times \mathcal{B}(B^0_s \to D^-_s l^+ \nu X)$ from the LEP experiments [4] gives $f_s = (10.5\ ^{+1.8}_{-1.7})\%$ [3].

In this paper, we briefly describe a measurement of $f_s/(f_u + f_d)$ done by the CDF collaboration at the Tevatron $p\bar{p}$ collider. The result was first reported in [5], where a description of the detector and a more detailed description of the method can be found. The measurement is based on the observation of double semileptonic B meson decays produced in $p\bar{p}$ collisions at a center of mass energy of 1.8 TeV. We select decays where first the B meson decays to a muon, neutrino and charm meson. We further require the resulting charm meson decay to a muon that is opposite in charge to the muon resulting from the B meson decay. The decays used in this analysis are:

$$\begin{array}{llll} B^0_s \to \mu^+\nu_\mu & D^-_s X & & \\ & \hookrightarrow \mu^-\overline{\nu}_\mu & \phi(1020) & \\ & & \hookrightarrow K^+K^-; & \end{array}$$

$$\begin{array}{llll} B^0, B^+ \to \mu^+\nu_\mu & D^- X & & \\ & \hookrightarrow \mu^-\overline{\nu}_\mu & K^*(892)^0 & \\ & & \hookrightarrow K^+\pi^-; & \end{array}$$

$$\begin{array}{llll} B^0, B^+ \to \mu^+\nu_\mu & \overline{D}^0 X & & \\ & \hookrightarrow \mu^-\overline{\nu}_\mu & K^*(892)^+ & \\ & & \hookrightarrow K^0_{\mathrm{S}}\pi^+ & \\ & & & \hookrightarrow \pi^+\pi^-. \end{array}$$

In this paper all references to a specific charge state imply the charge conjugate state as well. We use our data to measure the relative fragmentation fractions for strange, B^0_s, and light, B^0 or B^+, meson production by identifying $\phi(1020)$, $K^*(892)^0$ and $K^*(892)^+$ mesons in the final state. In the course of extracting these measurements we also set limits on the relative branching fraction for charm mesons to decay into the heavier strange mesons, $K_1(1270)$, $K_1^*(1410)$ and $K_2^*(1430)$.

This technique of identifying B meson decays with two neutrinos in the final state has recently been used by the CDF collaboration [6]. In general, CDF has identified B mesons using either fully-reconstructed decays containing a charmonium meson (*e.g.* $B^+ \to J/\psi K^+$ or $B^0 \to J/\psi K^0_{\rm S}$) or lepton-charm correlations to reconstruct semileptonic B meson decays. In the latter case the charm decays were fully reconstructed such that there was only one missing neutrino in the reconstructed B meson final state.

This analysis expands the territory of B physics at CDF by identifying double semileptonic B decays in which neither the parent B meson nor its daughter charm meson are fully reconstructed. CDF can trigger efficiently on dimuon events that constitute the dataset used in this study.

We assume equal fragmentation fractions to both light B mesons, *i.e.* $f_u = f_d$. We measure the ratio of $f_s/(f_u+f_d)$ in order to avoid the systematic uncertainties coming from the uncertainty in the b quark production cross-section. In addition, the detector and trigger inefficiencies that are common to the three signal channels cancel in the ratio. The measurement of the ratio of fragmentation fractions will therefore be more precise than a measurement of f_s alone.

Another measurement of the fragmentation fractions, using $B \to De\nu X$ decays with fully reconstructed charm decays, was also done at CDF [7,8]. The results of the second measurement, as well as the results of the combined CDF fit, are given in Section 6.

2. Data selection

Some description of the CDF detector can be found in [5] and a more detailed one can be found in [9]. The data used in this study correspond to an integrated luminosity of 70 pb^{-1} and were collected between November 1994 and July 1995. The data was collected using a dedicated trigger channel sensitive to dimuons with invariant mass was between 1.0 and 2.8 GeV/c^2. The $p_{\rm T}$ of both muon candidates needed to be greater than 2.1 GeV/c for the trigger to select the event.

The selection following the trigger is described in more detail in [5]. The final event sample is subdivided into classes by identifying ϕ mesons, K^{*0} mesons and K^{*+} mesons associated with dimuons in the final state. We fit the invariant mass distributions of the strange meson daughters to extract our candidate yields. In this section we present fits to distributions associated with Opposite-Sign (OS) dimuons, where we expect to see the signals from B meson decay.

We denote ϕ, K^{*0} and K^{*+} mesons as "K". We label two muons in each event as μ_B and μ_D in such a way that the relationship $M(\text{“}K\text{”}\mu_B) > M(\text{“}K\text{”}\mu_D)$ is satisfied. In 98% of signal events μ_D defined in such a way is the muon from the c quark decay and not from the b quark decay. Being able to distinguish the two muons helps to resolve the charge combinations in case of K^{*0} and K^{*+} signals. It also helps to fit B and D decays vertices separately with the correct track assignment.

Figure 1 shows the ϕ meson signal observed in the K^+K^- mass distribution. The crosses represent the data distribution while the solid line shows the fit described by a Breit–Wigner lineshape smeared by our reconstruction resolution. The dashed line shows the extrapolation of the polynomial background under the signal peak. From this sample we measure a yield of $N(\phi) = 103 \pm 16$ events.

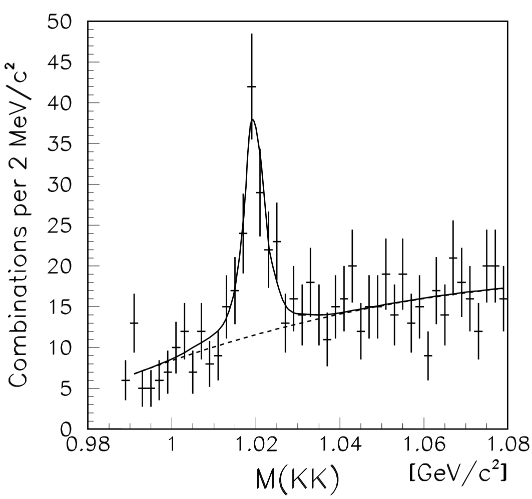

Fig. 1. The observed K^+K^- invariant mass distribution showing the ϕ meson signal in opposite sign dimuon events. The data are represented by crosses. The fit of the signal and background is shown with the solid line and the background component under the signal peak is indicated by the dashed line.

A K^{*0} signal is visible in the $K^+\pi^-$ invariant mass distribution shown in Fig. 2. The charge of the charm muon (μ_D) designates the track with a charge opposite that of μ_D to be the kaon and the remaining track is then a pion. Those combinations form the Right-Sign distribution (RS). Swapping the K π particle assignments results in a Wrong-Sign (WS) distribution. A simultaneous fit of both distributions gives us additional constraints on the combinatorial background.

In Fig. 2 the crosses show the data distribution and the solid line shows the combined fit. The RS distribution has three components: a Breit–Wigner K^{*0} signal (dashed line), a “satellite” structure peaking near threshold (dotted line) and a combinatorial background (dashed-dotted line). The “satellite” is produced by combinations of charged kaons, primarily from $\bar{D}^0 \to K^+\mu^-\bar{\nu}$ decays, with pions of low transverse momentum, mostly from $D^{*-} \to \bar{D}^0\pi^-$ decays. The wrong-sign distribution has three components: a reflection of the K^{*0} signal produced by mistaken $K - \pi$ mass assignments (dashed line), a reflection of the “satellite” peak (dotted line) and a combinatorial background (dashed-dotted line). The combinatorial background does not contain kaons correlated in charge with μ_D. Thus, by construction, it has the same shape in the RS and WS distributions. We perform a simultaneous fit to the RS and WS distributions with the combi-

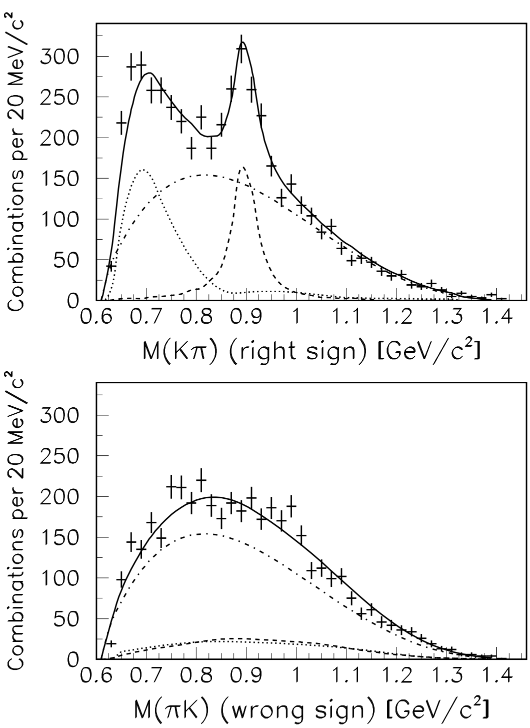

Fig. 2. The observed $K^+\pi^-$ invariant mass distributions showing the fit of the K^{*0} meson signal observed in opposite sign dimuon events. The top plot shows right-sign $K\pi$ combinations with respect to the muon from charm decay and the bottom plot shows the wrong sign distribution. Crosses represent the data and the solid line shows the fit result. Details of the fit components, shown with non-solid lines, are described in the text.

natorial background constrained to be the same in both distributions. The templates for the mass shape of the signal, the "satellite" and their reflections were produced by a Monte Carlo calculation. The fit returns a yield of $N(K^{*0}) = 683 \pm 55$ events.

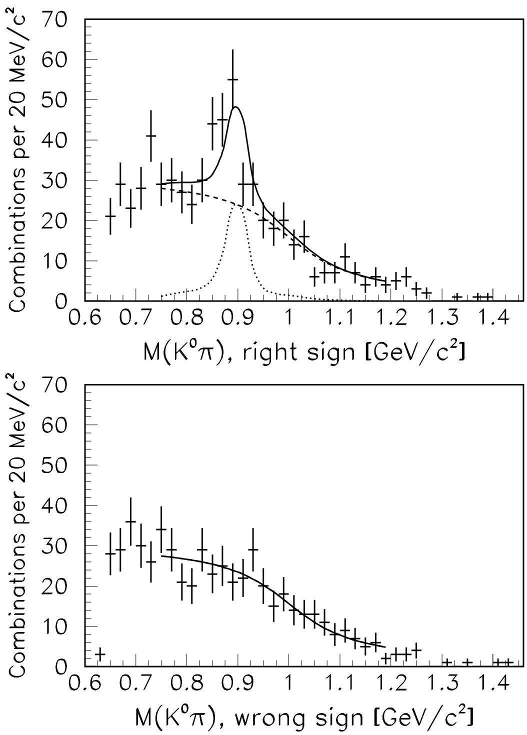

Fig. 3. Observed $K^0_S\pi^+$ invariant mass distributions showing the K^{*+} meson signal observed in opposite sign dimuon events. The top plot shows right-sign $K^0_S\pi^+$ combinations with respect to the muon from charm decay and the bottom plot shows the wrong sign distribution. Crosses represent the data. The solid line represents the fit result, the dotted line shows the K^{*+} signal and the dashed line shows the extrapolation of the combinatorial background under the signal peak.

To measure the K^{*+} signal we reconstruct $K^0_S \to \pi^+\pi^-$ decays. We fit the K^0_S decay vertex using opposite-charge track pairs. We require the K^0_S transverse decay length to be greater than 2 cm and less than 100 cm. We also require $|M(\pi^+\pi^-) - M(K^0_S)| < 20$ MeV. The reconstructed trajectory of the K^0_S meson is used with the trajectories of the μ_D and $\pi^\pm$ candidates, to fit the charm decay vertex ($\bar{D}^0 \to K^{*+}\mu^-\bar{\nu}, K^{*+} \to K^0_S\pi^+$). The subsequent fit of the B meson decay vertex is the same as in the other two signal channels.

The $K^0_S\pi^+$ mass distributions are shown in Fig. 3 together with the results of the fits to the RS and WS distributions. The right sign combinations are those for which the charge of the reconstructed K^{*+} is opposite to that of μ_D. Unlike the K^{*0} fit, there is no ambiguity in the $K-\pi$ mass assignment, hence no reflection of the signal into the WS distribution exists. However the background can have components correlated in charge to μ_D. In the simultaneous fit of the RS and WS distributions, we use the same background shape but allow the relative normalisation to vary. The fit returns a yield of $N(K^{*+}) = 94 \pm 21$ events.

3. Backgrounds

The final state B meson decays studied here involve two missing neutrinos. Therefore many of the usual constraints on potential backgrounds are weaker than in cases where the final state is more fully reconstructed. We quantify potential sources of background in [5]. In this section we can only briefly list the backgrounds that were quantified.

In the semileptonic decay of charm mesons there is a difference between the sum of measured branching fractions to particular channels and the measured total semileptonic branching fraction [3]. This deficit is large enough to accommodate a significant branching fraction for the decays $D \to K_x\mu\nu$, where K_x could represent $K_1(1270)$, $K_1^*(1410)$ or $K_2^*(1430)$. The semileptonic charm decay to K_x could be followed by a strong decay $K_x \to K^*X$, where K^* represents K^{*0} or K^{*+}, contributing to the signals we are studying and providing a potential background to the measurement. An upper limit was set on this background by searching for evidence of other decays of the heavy kaons K_x in the data sample.

Several other potential backgrounds can be caused by other decays of the type $b \to \mu^+\mu^-X$:

- $B \to D_sDX \to \phi\mu^+\mu^-X$,
- $B_s \to D_s^{**}\mu\nu \to K^*\mu^+\mu^-X$,
- $\Lambda_b \to pD^0\mu^-\nu$ *etc.*

Other backgrounds that were quantified included cases where:

- one or both muon candidates were hadrons that have traversed the calorimeters (punch-through),
- one or both muons were from the other b than "K"
- "K" and/or muon candidates were from the underlying $p\bar{p}$ event,
- a $c\bar{c}$ event was producing all the signatures expected of the signals.

The estimates of the backgrounds were obtained with Monte Carlo techniques calibrated with CDF data. A detailed description is available in [5].

The backgrounds listed above tend to produce dimuon candidates where the muon charge signs are opposite. As an additional check against unforeseen backgrounds a fit of data distributions associated with like-sign dimuons was done. The $M(K^+K^-)$, $M(K^+\pi^-)$ and $M(K^0_\mathrm{S}\pi^+)$ distributions were examined for evidence of "K" production. We find that the ϕ, K^{*0} and K^{*+} signals seen in association with like-sign dimuon candidates are consistent with zero.

4. Acceptance and efficiency corrections

The observed event yields for the three final states, corrected for the backgrounds described above, need to be further corrected for the acceptance of the detector, the efficiencies of the various reconstruction stages and selection requirements, and for the trigger efficiency. To study the kinematic and geometric acceptances we used a Monte Carlo calculation of b quark production and B meson decay followed by a simulation of the detector response. We used both Monte Carlo calculations and measurements from our data to estimate the remaining efficiencies.

A significant advantage of measuring a ratio of fragmentation fractions using similar decays is that many of the acceptances and efficiencies cancel. For example the overall b quark production cross-section leading to B^0, B^+ and B^0_s meson final states will be the same. Different signal decays also have very similar triggering probabilities. We have studied the effect of the different phase-space available for double semileptonic muon decays due to the different B meson masses and find this to be a negligible correction to our result. Furthermore, the track finding efficiencies for the "K" decay products almost cancel in the ratio. In two of the three cases, we reconstruct the final "K" from two charged particles ($\phi \to K^+K^-$ and $K^{*0} \to K^+\pi^-$). In the third channel we reconstruct three final state charged particles ($K^{*+} \to K^0_\mathrm{S}\pi^+; K^0_\mathrm{S} \to \pi^+\pi^-$). In order to properly include the effect of this difference on our result we have studied the relative reconstruction efficiency for single charged tracks compared to $K^0_\mathrm{S} \to \pi^+\pi^-$ decays using inclusive rates measured in data.

5. Results

The final result is computed from the measured event yields and calculated acceptances. We measure

$$\frac{f_s}{f_u + f_d} = (21.0 \pm 3.6(\mathrm{stat.})\ {}^{+3.8}_{-3.0}(\mathrm{syst.}))\%, \tag{1}$$

where the first uncertainty is statistical and the second is systematic. Table I lists all sources of uncertainty and their contributions to the final result expressed as a fraction of the measured $f_s/(f_u + f_d)$ value. We combine these in quadrature to determine the total uncertainty.

TABLE I

Statistical and systematic uncertainties as a fraction of the measured value, expressed in percent, on the measurement of $f_s/(f_u + f_d)$. Unless otherwise indicated the uncertainties are symmetric.

Source of uncertainty	Contribution [%] of $f_s/(f_u + f_d)$
Statistical uncertainty on $N(\phi)$	15.5
Statistical uncertainty on $N(K^{*+})$	7.1
Statistical uncertainty on $N(K^{*0})$	2.7
Total statistical uncertainty	17.3
Potential K^* from heavy strange mesons	+10.7
Potential K^* from Λ_b	+2.0
Other K^{*0} background	7.0
Other K^{*+} background	1.0
ϕ background	9.0
Total background uncertainty	$^{+15.6}_{-11.2}$
f,f^*,f^{**} composition	5.9
$\tau(B_s)/\tau(B)$	5.2
$\tau(D_s)$	3.6
$\mathcal{B}(\phi \to K^+K^-)$	1.6
Tracking efficiency for K^0_S daughters	1.4
$\tau(D^+)$	1.3
Trigger acceptance	1.2
$\tau(D^0)$	0.1
$\mathcal{B}(K^0_S \to \pi^+\pi^-)$	0.1
Total systematic uncertainty	$^{+18.1}_{-14.4}$

Our largest uncertainty is the statistical precision on the ϕ meson signal. The largest systematic uncertainties result from our background estimates. Our limits on the heavier strange meson backgrounds result in an asymmetric systematic uncertainty. Uncertainties on the background corrections to the ϕ, K^{*+} and K^{*0} signals are partially correlated because they all rely on the same muon misidentification probability. The combined systematic uncertainty associated with the "total background" takes this correlation into account.

The next largest systematic uncertainty is related to the composition of semileptonic B meson decays. The uncertainties on f, f^* and f^{**} affect the precision with which we can calculate the acceptance. Uncertainties on the B and D meson lifetimes also affect the acceptance because we use branching fractions derived from the spectator model. The reconstruction efficiency for $K^0_{\rm S}$ mesons also introduces an uncertainty, as mentioned in Section 4. The remaining systematic uncertainties come from the branching fractions of $K^0_{\rm S} \to \pi^+\pi^-$ and $\phi \to K^+K^-$ decays, although these are relatively small.

6. Combined CDF result

Another measurement of fragmentation fractions was done by CDF using $b \to ceX$ decays selected by a trigger sensitive to single electrons [7, 8]. Charm decays were fully reconstructed and the appearances of B^+, B^0, B^0_s as well as of Λ_b were counted. Assuming $f_u = f_d$, the analysis yields $f_s/(f_u + f_d) = (21.3 \pm 6.8)\%$.

The combined result of both CDF measurement of the fragmentation fractions was calculated assuming that the hadron species listed above saturate the b-quark production rate, in other words $f_u + f_d + f_s + f_{\rm baryon} \equiv 1$. This assumption allows to calculate the absolute fragmentation fractions. The combined CDF result is $f_u \equiv f_d = (37.5 \pm 1.5)\%$, $f_s = (16.0 \pm 2.5)\%$ and $f_{\rm baryon} = (9.0 \pm 2.8)\%$.

The $p\bar{p}$ result of $f_s = (16.0 \pm 2.5)\%$ is 1.8 standard deviations higher than the LEP result quoted in Section 1. It is worth pointing out in this context that the average transverse momentum of b hadrons reconstructed by both CDF analyses is $\sim$ 20 GeV/c, significantly lower than at LEP. It is not excluded that this difference causes a difference in the hadronisation process producing different fragmentation fractions.

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