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Fragmentation into b hadrons

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The fragmentation process of b quarks into b hadrons, produced in Z decays or $p\bar{p}$ collisions, cannot be fully described perturbatively but relies on phenomenological models. To test and tune the parameters of these models, precise experimental measurements have to be performed. Furthermore, properties of the b hadron production process affect many analyses dealing with decays of b hadrons. Thus, precise knowledge of the fragmentation properties allows more accurate measurements in this field. New results for the b fragmentation function and b hadron production fractions have been submitted to this conference and will be summarised in this article. Combined results for b hadron production rates will also be given.

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Abstract

The fragmentation process of b quarks into b hadrons, produced in Z decays or $p\bar{p}$ collisions, cannot be fully described perturbatively but relies on phenomenological models. To test and tune the parameters of these models, precise experimental measurements have to be performed. Furthermore, properties of the b hadron production process affect many analyses dealing with decays of b hadrons. Thus, precise knowledge of the fragmentation properties allows more accurate measurements in this field. New results for the b fragmentation function and b hadron production fractions have been submitted to this conference and will be summarised in this article. Combined results for b hadron production rates will also be given.

1. The b fragmentation function

Measuring the b fragmentation function provides essential tests of hadronisation models, both of the perturbative and non-perturbative part. Furthermore, a precise measurement of the b fragmentation function helps to reduce systematic errors in many heavy flavour physics measurements. The observable quantity used in measurements is the scaled energy of the b hadron, $x_B = 2E_B/\sqrt{s}$, with E_B being the energy of the b hadron and $\sqrt{s}$ the centre of mass energy.

The measurement performed by the SLD collaboration [1] overcomes the disadvantages of the 'traditional' methods which are either limited by systematics (e.g. analyses using inclusive leptons) or statistics (e.g. analyses using fully reconstructed D mesons in semileptonic decays). It is based on a very pure and efficient association of charged tracks to the secondary decay vertex of the b hadron.

The analysis exploits the capabilities of the high resolution CCD-pixel vertex detector which provides – together with the tiny beamspot of the SLC – an excellent impact parameter resolution. A topological vertex finder has been developed to assign charged tracks to the secondary B decay vertex. The efficiency and purity reached for this assignment are $\epsilon \approx 92\%$ and $p \approx 98\%$. A p_t-corrected vertex mass allows to select $b\bar{b}$ events with a purity of about 98%. The computation of the b hadron energy uses a constraint on the missing mass $0 \leq M_0^2 \leq M_{0,max}^2$ with $M_{0,max}^2 = M_B^2 + M_{ch}^2 - 2M_B\sqrt{M_{ch}^2 + p_t^2}$ ($M_B = 5.28$ GeV). For low values of $M_{0,max}$ a good resolution on x_B is expected. The cut on $M_{0,max}$ is chosen depending on the reconstructed b hadron energy to give an efficiency which is approximately flat over the entire range of x_B^{true} down to the kinematical limit. The overall efficiency (3.9%) and purity (99.5%) after all cuts allow a precise measurement of the b fragmentation function. Figure 1 shows the uncorrected B energy distribution together with the expectation from several fragmentation models [2]. The free parameter(s) of the models have been fitted by minimising a χ^2 function comparing the simulated with the background subtracted data distribution. The LUND, Bowler and Kartvelishvili (marginally) fragmentation

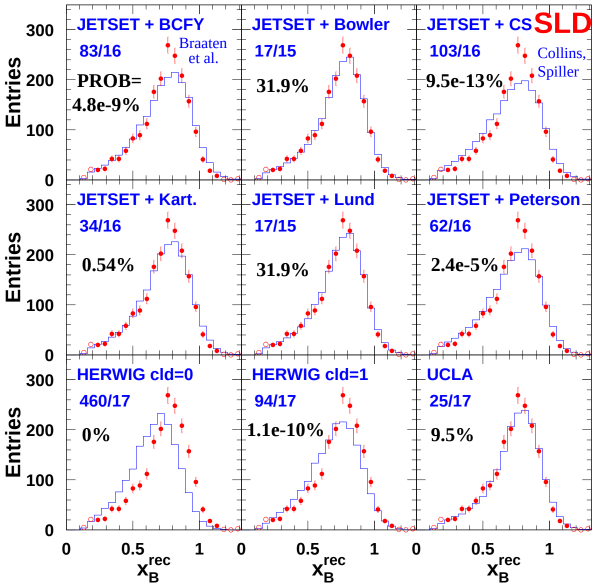

Figure 1. Comparison of SLD data with fragmentation models. For each model the χ^2/dof and the corresponding probability is shown.

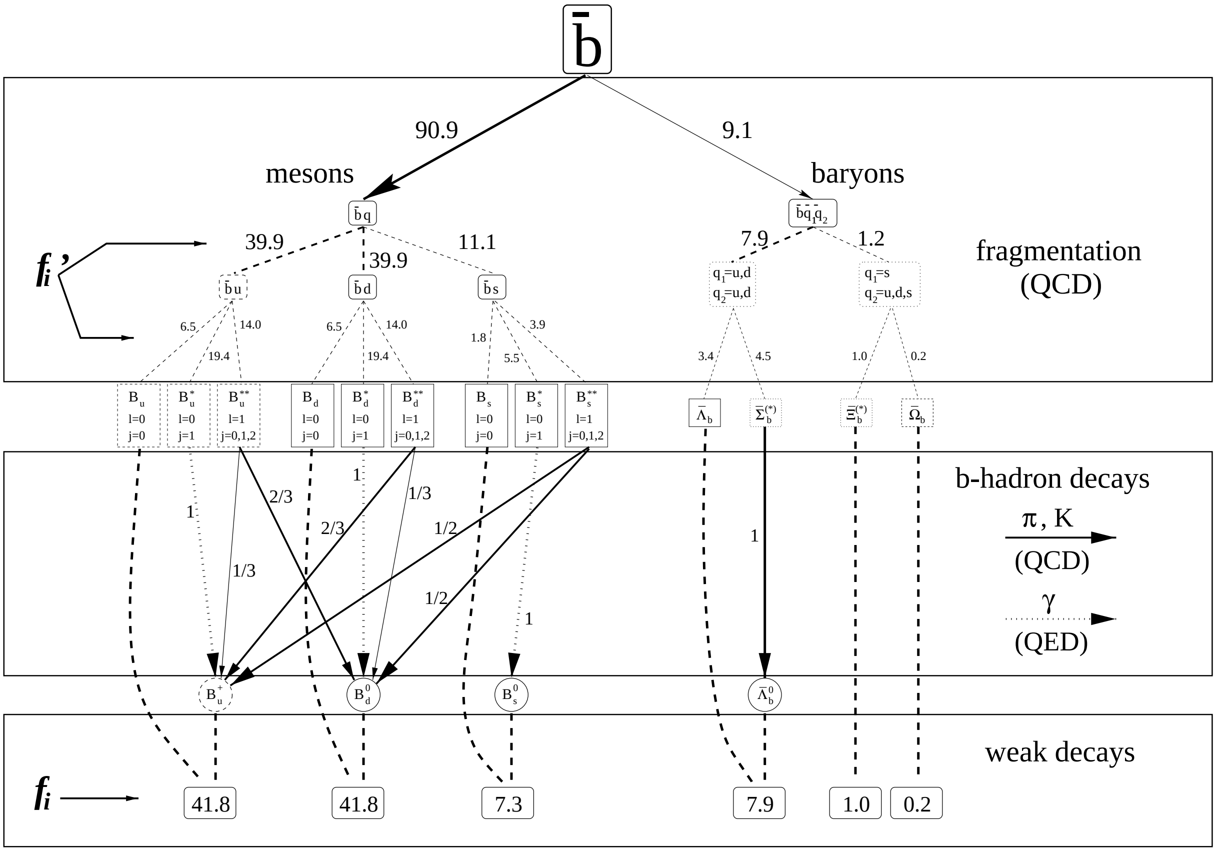

Figure 2. Scheme for the production process of b hadrons. The fractions of b hadrons produced in the fragmentation are denoted f_i'. Excited b hadrons may decay through strong or electromagnetic interaction. The ground state hadrons finally decay weakly. Their rates are denoted f_i. The numbers indicated are taken from simulation (JETSET 7.3 tuned according to DELPHI measurements [3]).

models together with the JETSET parton shower Monte Carlo show consistency with the data as well as the UCLA model based on perturbative calculations. The Peterson model, often used to describe fragmentation of heavy quarks, fails in reproducing the data. From the unfolded x_B distribution, the mean value of the b hadron energy has been extracted (150,000 events from the years 1996-1997 have been analysed):

$$\langle x_B \rangle = 0.714 \pm 0.005(\text{stat.}) \pm 0.007(\text{syst.}) \pm 0.002(\text{model}).$$

2. Production fractions of b hadrons

At e^+e^- and $p\bar{p}$ colliders with $\sqrt{s} \gg m_b$ all kinds of b hadrons can be produced, either in the ground or excited states (e.g. orbital excitation). Since the production of b hadrons takes place in the fragmentation process, the rates of individual types of b hadrons can not be calculated perturbatively. Nevertheless, fragmentation models with their set of (tuned) parameters allow to describe individual rates. Besides tests of these fragmentation models, precise values of b hadron production rates are essential input for many measurements in the heavy flavour sector. Figure 2 shows the process from an initial b quark to a weakly decaying b hadron.

Measurements of production fractions published so far used properties of the weak b hadron decay, thus being sensitive to the rates f_i. No published results for f_{B_u} or f_{B_d} exist. They have been derived from‡ $f_{B_u} = f_{B_d} = \frac{1}{2}(1 - f_{B_s} - f_{\Lambda_b})$.

2.1. DELPHI f'_{B_s}

DELPHI [4] performed a measurement of f'_{B_s} by exploiting the properties of the fragmentation kaon which is expected to accompany a primary $\bar{b}s$ system (figure 3). They get

‡ f_{Λ_b} will be used in this article for the rate of weakly decaying b baryons.

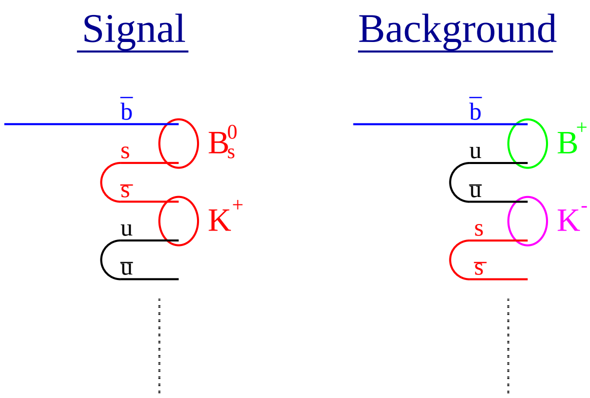

Figure 3. The principle of the f'_{B_s} measurement from DELPHI [4].

$$f'_{B_s} = (12.0 \pm 1.4(\text{stat.}) \pm 2.5(\text{syst.}))\%.$$

This measurement allows a determination of the parameter γ_s in the JETSET model which gives the suppression of s$\bar{\text{s}}$ pairs in the fragmentation with respect to u$\bar{\text{u}}$, d$\bar{\text{d}}$ pairs:

$$\gamma_s = 0.31 \pm 0.09(f'_{B_s}) \pm 0.01(f'_{b-Baryon}).$$

With a relative production rate for orbitally excited B_s^{**} mesons of 27 ± 8%, estimated from inclusive $\text{B}_{(s)}^{**}$ analyses at LEP [5], a value for the rate of weakly decaying B_s mesons can be extracted:

$$f_{B_s} = (8.8 \pm 1.0(\text{stat.}) \pm 1.8(\text{syst.}) \pm 1.0(\text{B}_s^{**} \text{ rate}))\%.$$

2.2. DELPHI f^+

DELPHI reconstructed the charge at the secondary decay vertex to measure the fractions of charged and neutral weakly decaying b hadrons [4]. Based on a neural network, a probability P_B is constructed for each track in the hemisphere to originate from the decay of a b hadron. The secondary vertex charge Q_B is then defined through $Q_B = \sum_{i=1}^{N_{hem}} Q_i \cdot P_{B,i}$.

The fraction of charged b hadrons has been extracted from a fit of the Q_B distribution to the shapes of charged and neutral b hadrons from simulation (figure 4). The result is:

$$f^+ = (42.48 \pm 1.06(\text{stat.}) \ \pm 1.03(\text{syst.}))\%.$$

Besides B_u mesons, only charged, strange b baryons (mainly Ξ_b^+) contribute to f^+. Subtracting this fraction (the relative rate of charged b baryons with respect to all b baryons has been taken from the JETSET model with 50% error assigned to it) gives:

$$f_{B_u} = (41.77 \pm 1.48(f^+) \pm 0.39(f^{(+)}_{b-baryon}))\%.$$

This result adds substantial input for the estimation of b hadron production fractions. With the assumption $f_{B_u} = f_{B_d}$, a complete set of measurements exist and the condition $\sum f_i = 1$ can be used to improve the accuracy of production rates (see section 2.3).

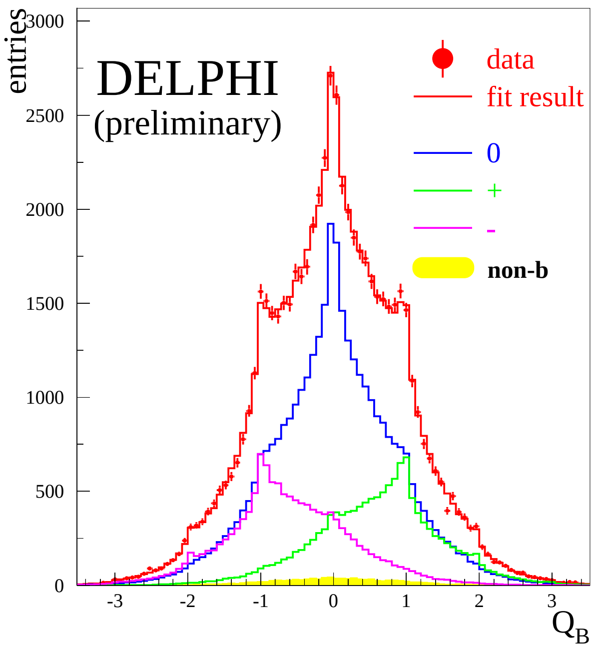

Figure 4. The secondary vertex charge used for the measurement of f^+ from DELPHI [4].

2.3. Average of b hadron fractions in Z decays

The averaging of b hadron production rates is performed by the 'B Oscillations Working Group'. The procedure can be divided in three steps. In the first step, the rates are estimated based on measurements not using any information from mixing analyses ($\text{D}_s/\Lambda_c/\Xi$-lepton correlations, proton production in B decays, secondary vertex charge [6]). f_{B_u} $=f_{B_d}$ is assumed and the constraint $\sum f_i = 1$ is imposed. These rates are used as Gaussian constraints in the second step, the Δm_d fit. A value for f_{B_s} from mixing measurements can be computed from $\bar{\chi}$, χ_d, f_{B_d} (from step 1) and lifetime ratios of b hadrons ($\chi_s = 0.5$ is assumed). In the final step, f_{B_s} from mixing is averaged with f_{B_s} from the first step and the constraint $\sum f_i = 1$ is imposed again. Correlations between the measurements are taken into account throughout the procedure. The result for the b hadron fractions, using measurements performed at LEP in Z decays, is:

$$\begin{aligned} f_{B_s} &= (9.6 \pm 1.3)\% \\ f_{\Lambda_b} &= (9.5 \pm 1.9)\% \\ f_{B_u} = f_{B_d} &= (40.5 \pm 1.1)\% \end{aligned}$$

with correlation coefficients $\rho(f_{B_s}, f_{\Lambda_b}) = 0.003$, $\rho(f_{B_s}, f_{B_u}) = -0.58$ and $\rho(f_{B_u}, f_{\Lambda_b}) = -0.82$.

2.4. b hadron production rates at the TEVATRON

It might be possible that the fragmentation process at p$\bar{\text{p}}$ colliders, where the environment in which the b quarks are produced is different from Z decays, leads to different production fractions. Thus, precise measurements of these fractions at e^+e^- and $p\bar{p}$ colliders are essential to study differences in the fragmentation process. The CDF collaboration measured b hadron fractions in $p\bar{p}$ collisions at the TEVATRON using two different techniques.

2.4.1. CDF double semileptonic decays

In the first analysis [7], they observe the double semileptonic decay chain $b\to c\mu X$ with $c\to s\mu X$ in association with the production of ϕ and K^* mesons. The decays used for the analysis are thus (see also figure 5): $B_s^0 \to D_s^-\mu^+\nu X$, followed by $D_s^- \to \phi\mu^-\bar{\nu}Y$ and $B_d^0/B_u^+ \to D^-(\bar{D}^0)\mu^+\nu X$, followed by $D^-(\bar{D}^0) \to K^{*0(+)}\mu^-\bar{\nu}Y$. The vector mesons are reconstructed in the channels $\phi \to K^+K^-$, $K^{*0} \to K^+\pi^-$ and $K^{*+} \to K_s^0\pi^+$. The result is

$$\frac{f_{B_s}}{f_{B_u}+f_{B_d}} = (21.0 \pm 3.6(\mathrm{stat.})^{+3.8}_{-3.0}(\mathrm{syst.}))\%.$$

This is the most precise single measurement at $p\bar{p}$ colliders.

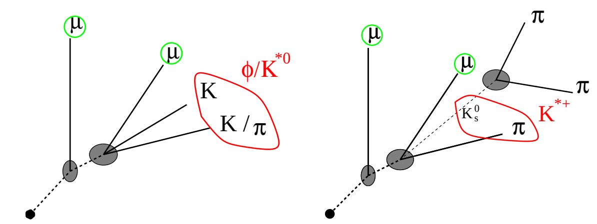

Figure 5. The topologies used in [7]. Shown is the secondary b decay vertex followed by the c decay vertex for the channels involving ϕ or K^{*0} mesons (left) and K^{*+} mesons with an additional K_s^0 vertex (right).

2.4.2. CDF semileptonic decays

In the second analysis [8], semileptonic decays of b hadrons involving electrons and charmed hadrons have been used: $B^+ \to e^+\nu_e\bar{D}^0X$, $B^0 \to e^+\nu_e D^{(*)-}X$, $B_s^0 \to e^+\nu_e D_s^- X$, $\bar{\Lambda}_b^0 \to e^+\nu_e\Lambda_c^- X$, with the charmed hadrons decaying according to $\bar{D}^0 \to K^+\pi^-$, $D^{*-} \to \bar{D}^0\pi^-$, $D^- \to K^+\pi^-\pi^-$, $D_s^- \to \phi\pi^-$ ($\phi \to K^+K^-$), $\Lambda_c^- \to \bar{p}K^+\pi^-$. The five event yields have been fitted to ratios of fragmentation fractions taking into account cross contaminations (see figure 6). These cross contaminations come from intermediate D^* and D^{**} states, mixing the charges of the weakly decaying charmed hadrons, and D_s^{**} states decaying according to $D_s^{**} \to DK$ and thus changing the strangeness content of the final state. Fixing $f_{B_u} = f_{B_d}$ gives:

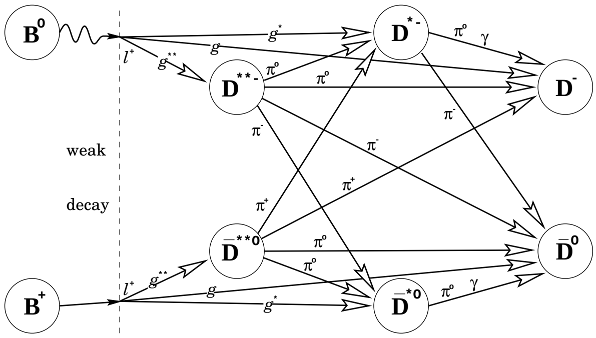

Figure 6. Cross contaminations for B^0 and B^+ decays. g, g^*, g^{**} are the relative semileptonic branching ratios of B mesons to D, D^* and D^{**} mesons (individually for B^0 and B^+). Spectator model predictions have been used to estimate g_s, g_s^*, g_s^{**}, the corresponding quantities for B_s^0 decays.

$$\frac{f_{B_s}}{f_{B_u}+f_{B_d}} = (21.3 \pm 6.8)\%$$
$$\frac{f_{\Lambda_b}}{f_{B_u}+f_{B_d}} = (11.8 \pm 4.2)\%$$

(leaving f_{B_u} and f_{B_d} free gives $\frac{f_{B_d}}{f_{B_u}} = 0.84\pm0.16$). An average with the result of [7] has also been performed. Assuming $\sum f_i = 1$ allows to derive the individual combined rates:

$$f_{B_s} = (16.0 \pm 2.5)\%$$
$$f_{\Lambda_b} = (9.0 \pm 2.8)\%$$
$$f_{B_u} = f_{B_d} = (37.5 \pm 1.5)\%.$$

This combined value of f_{B_s} is about two standard deviations above the combined result in Z decays (assuming no correlations between the two sets of numbers). From the current available experimental results, no final conclusion can be drawn, if differences in the fragmentation process leading to different b hadron production rates in Z decays and $p\bar{p}$ collisions exist. More precise measurements are needed to answer this question with more accuracy.

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