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HADRONIC BRANCHING FRACTIONS OF THE Z^0 BOSON

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Hadronic Branching Fractions of the Z^0 Boson

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Abstract

The techniques used for classifying the decays of the Z^0 into different quark flavours are reviewed. From a sample of $\simeq 600,000$ hadronic decays of the Z^0 boson, the analyses of the groups at SLC and LEP lead to the following results for the hadronic branching fractions:

$$\begin{aligned} \Gamma_{u\bar{u}+d\bar{d}}/\Gamma_h &= 0.371 \pm 0.057 \\ \Gamma_{s\bar{s}}/\Gamma_h &= 0.233 \pm 0.053 \\ \Gamma_{c\bar{c}}/\Gamma_h &= 0.187 \pm 0.018 \\ \Gamma_{b\bar{b}}/\Gamma_h &= 0.209 \pm 0.009 , \end{aligned}$$

consistent with the predictions from the Standard Model.

Inside the Peterson fragmentation scheme, the values

$$\epsilon_b = 1.7^{+1.3}_{-1.0}\, 10^{-3} \, ; \, \epsilon_c = 25^{+15}_{-10}\, 10^{-3}$$

are derived for the fragmentation parameters of b and c quarks.

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1 Introduction

The Standard Model predicts that the probability that the Z^0 boson decays into a $q\bar{q}$ pair depends on the quark flavour in such a way that, in the first approximation, the ratio $\Gamma_{q\bar{q}}/\Gamma_h$ of the partial width into $q\bar{q}$ to the total hadronic width is $\simeq 0.217$ for quarks of charge Q=-1/3, $\simeq 0.175$ for quarks of charge Q=2/3. The situation is different from the process of exchange of a single photon, where the quarks share the hadronic width according to couplings proportional to Q^2. The determination of the hadronic branching fractions $\Gamma_{q\bar{q}}/\Gamma_h$ of the Z^0 is thus an important test of the Standard Model.

The classification of the hadronic decays is however difficult, because the hadronization hids the nature of the primary decay. Several techniques have thus been proposed to identify the originary quark flavour from the hadrons in the final state.

In this report, the different analyses related to the hadronic branching fractions of the Z^0 from SLC and LEP data are reviewed. These analyses are based on $\simeq 600,000$ hadronic decays of the Z^0 boson, collected before 1991.

2 Techniques for Flavour Classification

2.1 *High-p_T Leptons*

Due to the larger mass of b and c with respect to the other quarks, electrons and muons coming from b and c decay have in average larger transverse momentum with respect to the axis of their jets (Fig. 1). By fitting the high-p_T part of the lepton spectrum one can thus measure the hadronic branching fractions of the Z^0 into heavy quarks, times the probability that the hadrons produced by these quarks decay into a final state including a lepton. This measurement was performed at SLC and LEP [1], with the results summarized in Table 1.

The semileptonic branching fraction of heavy quarks is a function of the mixture of hadrons produced in the fragmentation, that depends on the energy in the center of mass. Keeping carefully into account this dependence is crucial especially in the case of the b quark, where most of the data come from measurements at the $\Upsilon(4S)$, close to the threshold for B production. A direct measurement at LEP energies has been performed by L3, based on dileptons ($Br(b \to \ell X) = 0.113 \pm 0.010 \pm 0.006$). We average it with the result from PEP/PETRA ($Br(b \to \ell X) = 0.1186 \pm 0.0064$) and we neglect the result at the $\Upsilon(4S)$ ($Br(b \to \ell X) = 0.1033 \pm 0.0023$), obtaining

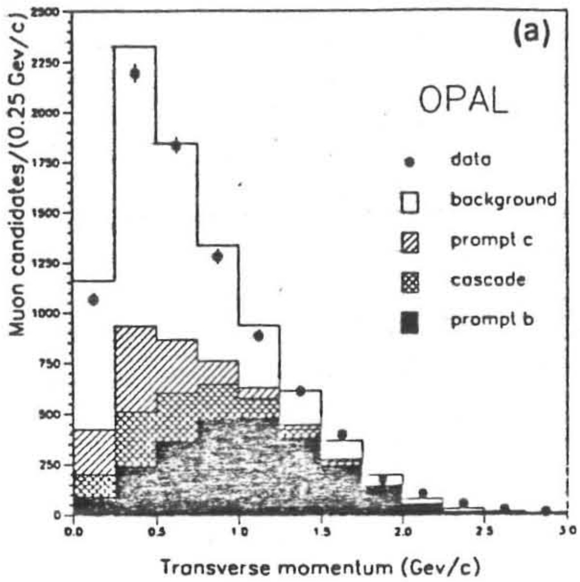
$$Br(b \to \ell X) = 0.1173 \pm 0.0056 \tag{1}$$

that gives, with the results of Table 1,

$$\Gamma_{b\bar{b}}/\Gamma_h = 0.204 \pm 0.011 . \tag{2}$$

For the partial width into c quark pairs, assuming the semileptonic branching fraction to be 0.093 ± 0.006 from the average of the results of the experiments in the continuum e^+e^- [2], we obtain

$$\Gamma_{c\bar{c}}/\Gamma_h = 0.189 \pm 0.019 . \tag{3}$$



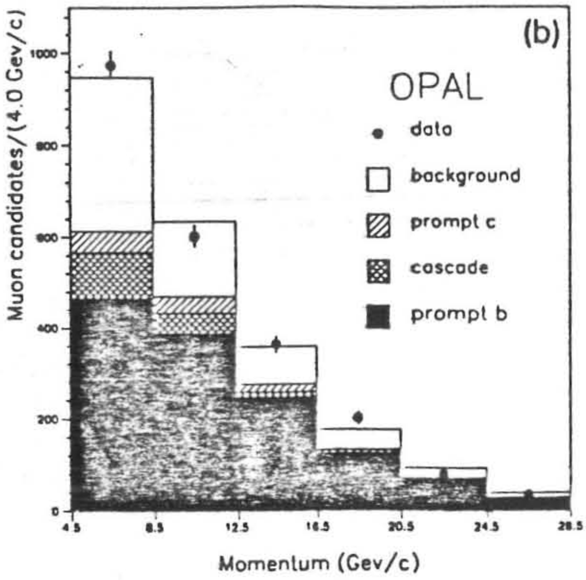


Figure 1: p_T *(a) and* p *(b) distributions for inclusive muon candidates from OPAL, showing Monte Carlo predictions for the various contributions.*

	$\Gamma_{b\bar{b}}/\Gamma_h \times Br(b \to \ell X)$	$\Gamma_{c\bar{c}}/\Gamma_h \times Br(c \to \ell X)$
MARK II	$0.0253^{+0.0119}_{-0.0097}$	
ALEPH	0.0224 ± 0.0012	0.0158 ± 0.0019
DELPHI	0.0221 ± 0.0014	0.0193 ± 0.0018
L3	0.0259 ± 0.0009	
OPAL	0.0226 ± 0.0015	0.0176 ± 0.0049
AVERAGE	0.0239 ± 0.0006	0.0176 ± 0.0013

Table 1: *Results on* $\Gamma_{b\bar{b}}/\Gamma_h \times Br(b \to \ell X)$ *and* $\Gamma_{c\bar{c}}/\Gamma_h \times Br(c \to \ell X)$ *from the experiments at SLC and LEP.*

	$< x_B >$	$< x_C >$
ALEPH	0.719 ± 0.022	0.469 ± 0.039
DELPHI	0.703 ± 0.032	
L3	0.686 ± 0.017	-
OPAL	0.726 ± 0.023	0.56 ± 0.04
AVERAGE	0.705 ± 0.011	0.513 ± 0.028

Table 2: *Results on $< x_B >$ and $< x_C >$ from the experiments at LEP.*

Most of the experiments perform the fit of the lepton spectrum both in p and in p_T. This allows to determine the average energy fraction of hadrons containing b and c, that can be useful in the determination of the fragmentation parameters for heavy flavours. The results are summarized in Table 2 [3].

2.2 *Boosted Sphericity Product*

The Boosted Sphericity Product is a shape variable defined for two-jet events. Each of the two jets (1 and 2) is boosted along the sphericity axis towards its hypothetical B hadron rest frame by a boost β, and the sphericities S_1 and S_2 are calculated. Due to the large rest mass of the B hadrons, $b\bar{b}$ events appear to have larger values for S_1 and S_2. The boost β is tuned via Monte Carlo in order to optimize the rejection of non-b events. The Boosted Sphericity Product is defined as the product of S_1 and S_2.

DELPHI [4] used the data sample collected during 1990 to compute $\Gamma_{b\bar{b}}/\Gamma_h$. Fig. 2 displays the distribution of the Boosted Sphericity Product ($\beta = 0.96$) for the data, and for the Monte Carlo in the two extreme hypotheses that all the events are $b\bar{b}$ and that none of the events is. The best fit gives

$$\Gamma_{b\bar{b}}/\Gamma_h = 0.213 \pm 0.014\,(stat) \pm 0.016\,(sys)\,, \tag{4}$$

where the systematic error comes mainly from the uncertainty on the fragmentation of the b quark.

2.3 *Impact Parameters*

The relatively long b lifetime causes many of the hadrons produced in the final states of $b\bar{b}$ events to have measurable impact parameters with respect to the primary vertex. The distribution of the impact parameters in the sample of the hadronic decays can thus be used to measure the average lifetime of B hadrons. On the other hand, the lifetime obtained in such a way depends strongly on $\Gamma_{b\bar{b}}$; therefore the partial width into $b\bar{b}$ pairs can be constrained by the b lifetime measured with different techniques.

In Fig. 3 the dependence of τ_B on the partial hadronic width into $b\bar{b}$. Assuming $\tau_B = 1.24 \pm 0.07$ ps, DELPHI [6] obtains

$$\Gamma_{b\bar{b}}/\Gamma_h = 0.222^{+0.033}_{-0.031} \pm 0.017\,, \tag{5}$$

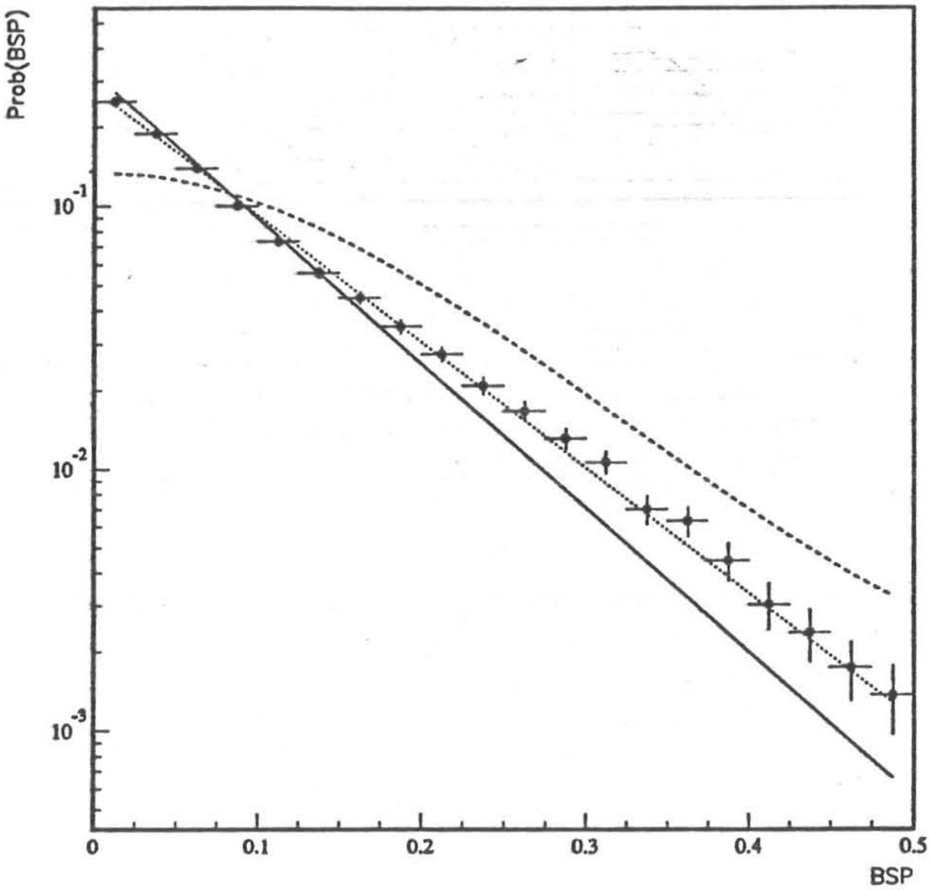


Figure 2: *Distribution of the Boosted Sphericity Product in DELPHI. The lines superimposed are predictions of JETSET PS for* $\Gamma_{b\bar{b}}/\Gamma_h$ *=0 (solid), =1 (dashed), =0.217 (dotted).*

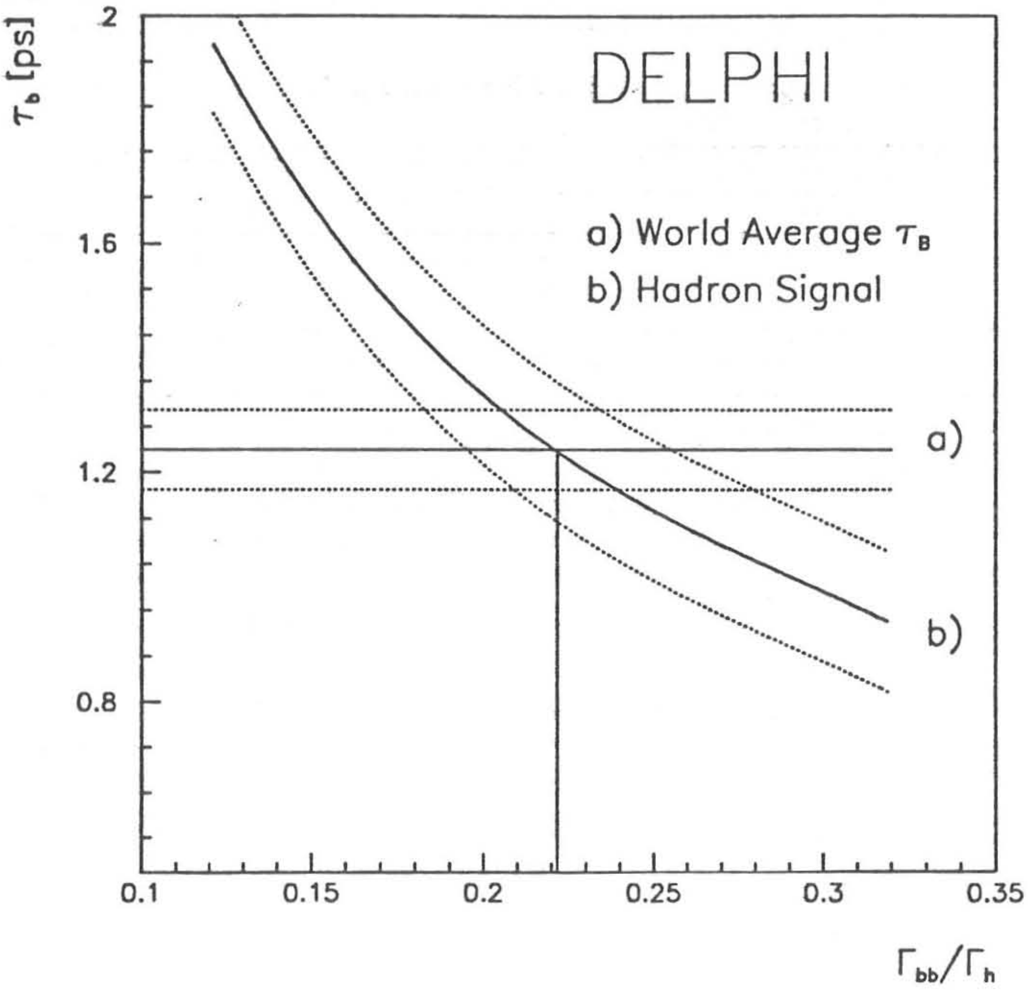


Figure 3: *Variation of the b lifetime measured from the hadron sample versus the partial width into $b\bar{b}$ pairs.*

where the second error expresses the systematics from the b lifetime. Using a similar technique, MARK II [7] obtains

$$\Gamma_{b\bar{b}}/\Gamma_h = 0.251 \pm 0.049\,(stat) \pm 0.030\,(sys)\,. \tag{6}$$

Averaging the two measurements (and keeping into account the common error on the b lifetime), the result from the impact parameters technique is

$$\Gamma_{b\bar{b}}/\Gamma_h = 0.229 \pm 0.032\,. \tag{7}$$

2.4 $D^{*\pm}$

The production rate of $c\bar{c}$ events can be derived from the inclusive analysis of charged pions coming from the decay of the charmed meson $D^{*+} \to D^0\pi^+$ (and charge conjugate), where the charged pion is constrained by kinematics to have a low p_T with respect to the direction of flight of the vector meson. This is reflected into an excess of pions with low transverse momentum with respect to the jet axis in $c\bar{c}$ events. From this excess, DELPHI [5] measures

$$\Gamma_{c\bar{c}}/\Gamma_h = 0.175 \pm 0.022\,(stat) \pm 0.043\,(sys)\,. \tag{8}$$

ALEPH, DELPHI and OPAL [3] measure also the average energy fraction carried by the D^*. The three measurements are compatible [3], and their average gives

$$< x^E_{D^{*\pm}} >= 0.509 \pm 0.015\,. \tag{9}$$

2.5 *Linear Multidimensional Analysis and Neural Networks*

The problem of flavour separation can be simplified by mapping a set of variables calculated from the topology of the event onto a feature space in which the different species are well separated. This procedure allows to reduce drastically the statistical errors in the determination of the fractions, although delicate problems due to the evaluation of systematics can arise.

The simplest case of multidimensional separation is the linear case, explored by ALEPH [12] and DELPHI [13] on simulation. ALEPH provides also an estimate of branching fractions on data, although the study of systematics is not yet completed.

A more powerful probe can be given by nonlinear separators, and in particular feed-forward neural networks [8]. The possibility to use a feed-forward neural network for this purpose was explored in [9], for the problem of the classification of decays into $b\bar{b}$ pairs. The result of this study was that, in the case of a perfect detector, a separation could be achieved with a higher efficiency with respect to traditional separation variables [10]. Further studies [11] demonstrated that, also in the presence of detector effects, feed-forward neural networks could be a useful tool for the classification of $b\bar{b}$ events.

Properties related to the structure of multiparticle production, can be used by a feed-forward neural network to classify not only $b\bar{b}$ events, but also $s\bar{s}$, $c\bar{c}$ and $(u\bar{u}+d\bar{d})$ unresolved. The robustness of the separation against a wide range of systematics related to model-dependence of the classification has been investigated. As a result, it has been possible to measure, from the data collected by the DELPHI detector at LEP during 1990, the rates of the hadronic decays into the four classes listed above [14]

$$\Gamma_{u\bar{u}+d\bar{d}}/\Gamma_h = 0.417 \pm 0.015\,(stat) \pm 0.058\,(sys) \quad (10)$$

$$\Gamma_{s\bar{s}}/\Gamma_h = 0.233 \pm 0.016\,(stat) \pm 0.051\,(sys) \quad (11)$$

$$\Gamma_{c\bar{c}}/\Gamma_h = 0.139 \pm 0.010\,(stat) \pm 0.058\,(sys) \quad (12)$$

$$\Gamma_{b\bar{b}}/\Gamma_h = 0.211 \pm 0.006\,(stat) \pm 0.020\,(sys) \quad (13)$$

avoiding the use of leptons and impact parameters, not to introduce heavy correlations to the other techniques described. The neural network used by ALEPH [12] converges to separation of the c and b classes with slightly higher efficiencies, but the study of the systematics has not yet been completed.

3 Summary and Conclusions

To average the various determinations, we used:

- For $\Gamma_{b\bar{b}}/\Gamma_h$, the expressions (2), (4) and (7). The statistical independence of these determinations was checked by generating 100,000 events by the JETSET PS Monte Carlo, and studying the correlation coefficients between the determinations from the different techniques in subsamples of events.
- For the determination of $\Gamma_{c\bar{c}}/\Gamma_h$, the expressions (3) and (8).
- For the determination of $\Gamma_{s\bar{s}}/\Gamma_h$, expression (11).

We then imposed the sum of the four probabilities to be equal to one, obtaining the final results (plotted in Fig.4):

$$\Gamma_{u\bar{u}+d\bar{d}}/\Gamma_h = 0.371 \pm 0.057 \quad (14)$$

$$\Gamma_{s\bar{s}}/\Gamma_h = 0.233 \pm 0.053 \quad (15)$$

$$\Gamma_{c\bar{c}}/\Gamma_h = 0.187 \pm 0.018 \quad (16)$$

$$\Gamma_{b\bar{b}}/\Gamma_h = 0.209 \pm 0.009\,. \quad (17)$$

Results are consistent with the predictions from the Standard Model; the accuracy on the determination of $\Gamma_{b\bar{b}}/\Gamma_h$ is not yet enough to allow predictions on the mass of the top quark[1].

Besides the improvement on the accuracy of these determinations that will come from the analysis of the 1991 data, a further constraint to the hadronic branching fractions can be given by a more careful study of the partial width into $s\bar{s}$ pairs. Important information [16] on the production of strange particles (Fig. 5), already available, is not yet used for the determination of $\Gamma_{s\bar{s}}/\Gamma_h$. This last quantity offers the additional advantage of a large and QCD-independent sensitivity of the ratio $\Gamma_{s\bar{s}}/\Gamma_{b\bar{b}}$ on the mass of the top quark [15].

For the sake of completeness, the LEP measurements of the rate of final state radiation from $q\bar{q}$ pairs have been used to compute the relative probabilities of decay into $u\bar{u}$ and

[1] As the t mass varies between 50 and 250 GeV/c^2, $\Gamma_{b\bar{b}}/\Gamma_h$ is expected to vary between 0.219 and 0.212 for a Higgs mass of 100 GeV/c^2.

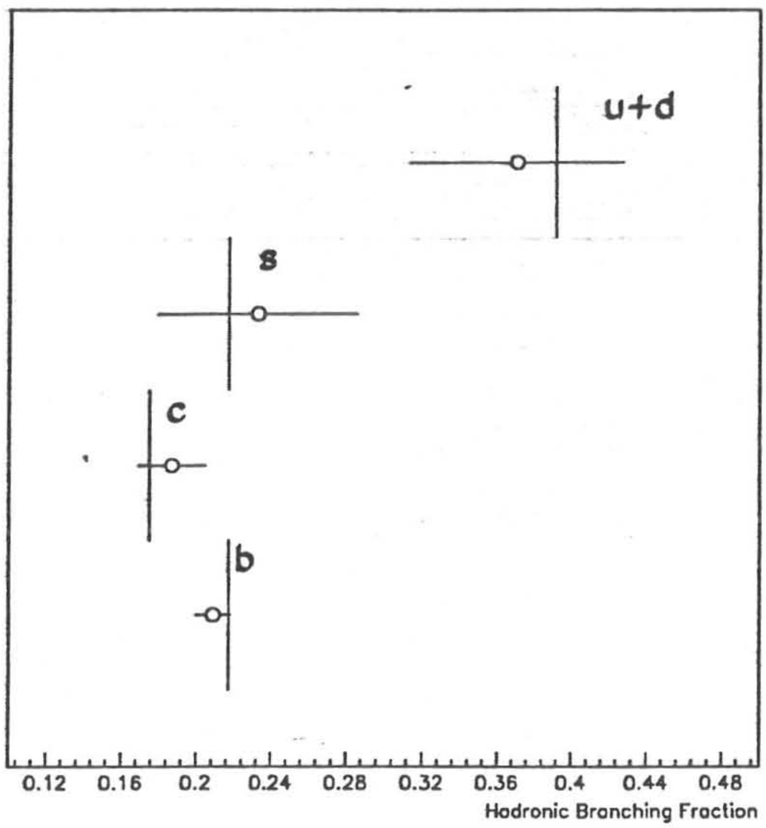


Figure 4: *Average values of the partial hadronic widths of the Z^0 from SLC and LEP, compared with the predictions from the Standard Model (vertical lines).*

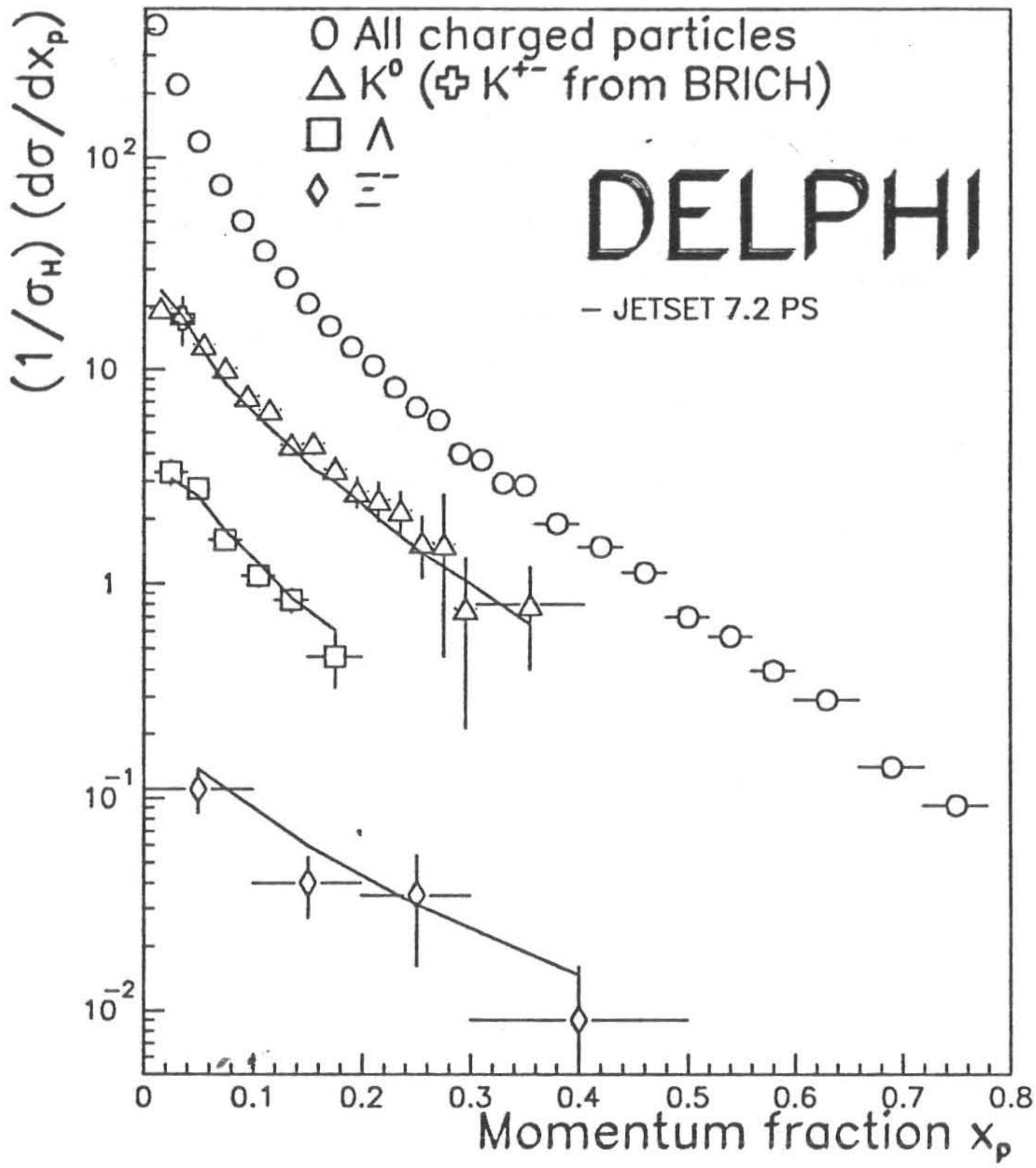


Figure 5: *Differential production cross sections of strange particles from DELPHI.*

$d\bar{d}$ pairs. This last separation is based on the assumption that the absolute value of the charge of the u quark is double with respect to the absolute value of the charge of the d quark, and thus, the probability for the photon bremsstrahlung process is four times larger. From the average of [17], one obtains

$$\Gamma_{u\bar{u}}/\Gamma_h + \Gamma_{c\bar{c}}/\Gamma_h = 0.44 \pm 0.08 \tag{18}$$

that, together with the determinations of the hadronic branching fractions of the four classes separated in (14..17), gives

$$\Gamma_{u\bar{u}}/\Gamma_h = 0.25 \pm 0.08\,;\, \Gamma_{d\bar{d}}/\Gamma_h = 0.12 \pm 0.10\,. \tag{19}$$

Finally, the results in Table 2. and Eq. (9) were used to constrain the fragmentation parameters ϵ_b and ϵ_c in the Peterson scheme for fragmentation. From the best tuning of the JETSET 7.2 Monte Carlo [18] based on Parton Shower (PS), allowing the free variation of both ϵ_b and ϵ_c, the values

$$\epsilon_b = 1.7^{+1.3}_{-1.0}\,10^{-3}\,;\, \epsilon_c = 25^{+15}_{-10}\,10^{-3} \tag{20}$$

were obtained, consistent with results at PEP/PETRA energies [19].

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