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Heavy Flavor Quark Production and Decay Using Prompt Leptons in the ALEPH detector. Global Lepton Analysis

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Abstract

In 434,000 hadronic Z decays, recorded in 1990 and 1991 with the ALEPH detector at LEP, the yields of electrons and muons were measured and analyzed over the entire range of lepton momenta.

Global Analysis

Basic Principles

In the global analysis quantities peculiar to the b–system such as $\Gamma(b\bar{b})/\Gamma(had)$, $\mathrm{Br}(b \to \ell\nu X)$, A^b_{FB}, and χ are determined from a simultaneous fit to the P and $P_\perp$ spectra of both single and dilepton events. This also allows a measurement of the fragmentation within the framework of a particular model and, as the fit covers the full range of transverse momentum, analogous quantities for the charm sector are obtained. A major advantage of this approach is that it also gives the correlations between the measured quantities.

Effectively three samples of events are considered for the fit.

- The Single Leptonic sample [SL] is composed of all electrons and muons with $P>$ 3 GeV/c.
- The Opposite Side Dilepton sample [OD] is composed of all lepton pairs with an angle between the two tracks greater than 90°.
- The Same Side Dilepton sample [SD] is composed of all lepton pairs with an angle smaller than 90°.

Dilepton events contribute twice to the [SL] sample as well as to either [OD] or [SD] whilst trilepton events contribute three time to [SL] and three times to the dilepton classes; the dilepton samples are also split into same charge [SC] and opposite charge [OC] samples.

Prompt electron and muon candidates result from the following physical processes:

- Primary semileptonic decays of B hadrons, denoted $b \to \ell$.
- Decays of a τ from a b decay, denoted $b \to \tau \to \ell$.
- Cascade decays from the charm daughter of a b parent, denoted $b \to c \to \ell$.
- Cascade decays of a charm state from the W in the b decay, denoted $b \to (\bar{c}s) \to \ell$.
- Semileptonic decays of charm states produced in $Z \to c\bar{c}$, denoted $c \to \ell$.
- Leptons from non–prompt sources or hadrons misidentified as leptons, denoted $fake$.

These six processes populate the variable space of the single and dilepton events in different ways. This enables them to be separated.

- Primary b–decays dominate the high (P,$P_\perp$) region for both the [SL] and [OD] samples. Such events effectively determine $\Gamma(b\bar{b})/\Gamma(had)$, Br($b \to \ell\nu X$), $< x_b >$ and A^b_{FB}whilst the [OD][SC] sample determine χ.

- Cascade b–decays have softer spectra for both P and $P_\perp$. The [SD][OC] sample is dominated by one of the leptons from a cascade decay and yields a measurement of Br($b \to c \to \ell\nu X$).

- Leptons from charm decay dominate the low $P_\perp$ region of the [SL] and [OD][OS] samples and enable measurements of $\Gamma(c\bar{c})/\Gamma(had)$, A^c_{FB}, and $< x_c >$. In principle Br($c \to \ell\nu X$) could also be determined from the low $P_\perp$ dileptons but the overlap with the cascade decays makes separation difficult with present statistics.

- The rates Br($b \to \tau \to \ell\nu X$), Br($b \to \bar{c}s \to \ell$), and Br($c \to \ell\nu X$) are taken from the best measurements available. The (P,$P_\perp$) distributions of the fake sample are taken from Monte Carlo simulation. The forms for the shape of the lepton spectra from each process is as the following:

  - **The $b \to l\nu X$ spectrum** Models of the b semileptonic decay differ primarily in their treatment of the higher mass D^{**} and $D^*\pi$ components. At the generator level 15% of D^{**} and $D^*\pi$ are introduced to give approximate agreement in $\Upsilon(4S)$ data in terms of the inclusive approach of the ACCMM model [1]. Models with explicit D^{**} states as GISW [2] yield softer lepton spectra and an increase in the proportion of higher D^{**} states to between 30 and 40%. Both methods have been used by the ARGUS and CLEO collaborations [3] to fit their lepton spectra. For these analyses the two approaches are taken as extremes and weights used for both models to reproduce the ARGUS and CLEO fits. The quoted results are the average of these two with an assigned modelling uncertainty of half the difference.
  - **The $c \to l\bar{\nu}X$ spectrum** The lepton energy spectrum in the c-hadron rest frame from charm decays contains large uncertainties. The main source of experimental information is from DELCO [4]. In this experiment ψ'' decays are the source of D^0 and D^+ with approximately the same production rate, except for a small phase space effect. The shape of the energy spectrum generated in JETSET [5] is softer that the DELCO results and is weighted to reproduce it. Half of the difference between the weighted and unweighted results is taken as the modelling uncertainty.
  - **The $b \to c \to l$ spectrum** This is a two step process and the experimental situation is less clear. For the analyses the energy spectrum

is taken directly from JETSET but the full difference between these results and those using the weights for the $c \to l\nu X$ is taken as the modelling uncertainty.

Choice of kinematical variables for the dilepton analysis

For each lepton pair there are essentially four kinematic quantities, P_i, $P_{\perp i}$ ($i = 1,2$) with P and $P_\perp$ being the longitudinal and transverse components of the lepton momentum with respect to the jet axis. Combinations of these were examined using an F–test method to maximize discrimination of the $(b \to \ell^-)(\bar{b} \to \ell^+)$ component from the others. The best variable was found to be $P_\otimes = p_{t_1}p_{\ell_2} + p_{t_2}p_{\ell_1}$, similar to the one originally proposed by MarkII [6]. A second variable $P_{\perp m} = Min\,(p_{t_1}, p_{t_2})$ is chosen because of its good discriminating power and its limited correlation with $P_\otimes$.

These variables are also effective for the [SD][OC] dilepton component where the signal events result from $(b \to \ell^-)(\bar{b} \to \ell^+)$. Dilepton decays of the J/ψ are a major contaminant but these two processes populate different areas of the ($P_\otimes$,$P_{\perp m}$) plane and so the analysis becomes very insensitive to uncertainties in the $B \to J/\psi X$ branching ratio.

Analysis Procedure

Single leptons are analysed in the (P,$P_\perp$,$-Q\cos\theta$) space while both sets of dileptons are analysed in the ($P_\otimes$,$P_{\perp m}$) plane. Results are obtained from a binned maximum likelihood fit to the weighted Monte Carlo data assuming Poissonian fluctuations. The likelihood is the sum of three components from the [SL], [OD] and [SD] samples. During the fitting iterations only the fragmentation parameters $< x_b >$ and $< x_c >$ distort the (P,$P_\perp$) spectra, all the others appear as simple multiplicative numbers for the various components.

For Heavy Quark fragmentation, the events are generated with both b and c fragmentation described by the PSSZ form [7] which is defined in terms of the variable z denoting the fraction of $(E+P_\parallel)$ and depends upon one parameter ϵ_Q for each quark. The effects of the alternative fragmentation scheme of Kartvelishvili *et al.* [8] are investigated by weighting the generated events in terms of their z value.

In general all lepton candidates with $P >$ 3 GeV/c are used for all measurements except as follows:

- As A^b_{FB} is energy dependent, the distribution in $-Q\cos\theta$ was only considered at the peak energy.

- The dilepton charge information was only used for the mixing measurement when both leptons had $P_\perp >$ 1.0 GeV/c. Use of the GISW $b \to \ell$ decay model rather than ACCMM starts to have a significant effect as the $P_\perp$ region is extended to lower values. This is because the softer spectrum reduces the $b \to c \to \ell$ component which is the principal background source. The cut at 1.0 GeV/c provides the most accurate value for χ from the global analysis when both statistical and systematic uncertainties are taken into account.

Results and systematic uncertainties

In table 1 the results of the fit for the two decay models, GISW and ACCMM are given.

Parameter	GISW Spectrum	ACCMM Spectrum	Statistical Uncertainty
$R(b)$	0.216	0.221	0.0062
$R(c)$	0.167	0.162	0.0055
$< x_b >$	0.704	0.724	0.004
$< x_c >$	0.486	0.484	0.008
$BR(b \to l)$	0.112	0.116	0.0033
$BR(b \to c \to l)$	0.088	0.076	0.0025
χ	0.109	0.118	0.014
A^c_{FB}	0.091	0.106	0.021
A^b_{FB}	0.086	0.088	0.014

Table 1: Effect of the semileptonic primary b decay modelling

It can be seen that the softer GISW spectrum leads to a 2% increase in the value of $\Gamma(b\bar{b})/\Gamma(had)$ and a harder fragmentation function. The procedures adopted to estimate the $b \to \ell$, $b \to c \to \ell$, and $c \to \ell$ modelling uncertainties have been previously described.

Other systematic uncertainties arise from experimental uncertainties associated with the lepton identification and input branching ratios not obtained from the fit. Their effect on the measured parameters are given in tables 2, 3 and 4.

The final results are given in table 5 and the correlation matrix from the fit in table 6.

It should be noted that:

- As many parameters are fitted, errors which in the high $P_\perp$ analyses feature as systematic, are included here as statistical. This is particularly true for the contribution from the mixing uncertainty for A^b_{FB}; it gives a much more realistic indication of the benefits which future statistics can bring and shows

Par.	e-eff.	μ-eff	γ	e-mis.	μ-dec.	μ-p.t.	$A_{charge}^{back.}$
$R(b)$	0.02	0.02	0.06	0.02	0.16	0.28	
$R(c)$	0.47	0.40	0.62	0.24	0.57	1.03	
$b \to l$	0.18	0.15	0.13	0.08	0.04	0.16	
$b \to c \to l$	0.15	0.18	0.06	0.01	0.15	0.28	
$< x_b >$	0.001	0.001	0.000	0.000	0.000	0.001	
$< x_c >$	0.023	0.009	0.009	0.003	0.005	0.005	
χ	0.002	0.04	0.03	0.005	0.12	0.21	0.05
$A_b^{cor.}$	0.05	0.02	0.030	0.001	0.076	0.003	
A_c	0.16	0.07	0.312	0.114	0.368	0.42	

Table 2: Global analysis: experimental systematical errors

Par.	$c \to l$	$B \to \tau$	$b \to W \to c$	$b \to$ J/ψ	$b \to u$	$A_{FB}^{back.}$	Total
$R(b)$	0.098	0.03	0.06	0.03	0.22		0.41
$R(c)$	0.93	0.06	0.5	0.06	0.06		1.83
$BR(b \to l)$	0.048	0.03	0.03	0.02	0.038		0.33
$BRb \to c \to \ell$	0.015	0.09	0.2	0.06	0.41		0.62
$< x_b >$	0.000	0.001	0.001	0.002	0.004		0.005
$< x_c >$	0.001	0.006	0.027	0.001	0.027		0.056
χ	0.004	0.07	0.20	0.04	0.16		0.35
$A_b^{obs.}$	0.001	0.007	0.04	0.023	0.024	0.07	0.11
$A_b^{cor.}$	0.001	0.026	0.091	0.023	0.004	0.07	0.15
A_c	0.035	0.107	0.475	0.019	0.15	1.38	1.62

Table 3: Global analysis: systematical errors from Branching ratios

Par.	$c \to l$	$b \to c \to l$	Total c model	Total
$R(b)$	0.09	0.04	0.10	0.42
$R(c)$	0.40	0.54	0.67	1.87
$BR(b \to l)$	0.09	0.14	0.17	0.37
$BRb \to c \to \ell$	0.03	0.79	0.79	1.00
$< x_b >$	0.001	0.001	0.001	0.005
$< x_c >$	0.005	0.004	0.005	0.006
χ	0.04	0.58	0.58	0.68
$A_b^{cor.}$	0.026	0.024	0.035	0.16
A_c	0.112	0.142	0.180	1.63

Table 4: Global analysis: systematical errors from charm models

Parameter	e+μ	Statistical Uncertainty	Systematic Uncertainty	Model Uncertainty
$R(b)(\%)$	21.9	0.62	0.42	0.23
$R(c)(\%)$	16.5	0.54	1.87	0.25
$< x_b >$	0.714	0.004	0.005	0.010
$< x_c >$	0.485	0.008	0.006	0.001
$BR(b \to l)$ (%)	11.4	0.33	0.37	0.20
$BR(b \to c \to l)(\%)$	8.2	0.25	1.00	0.60
$\chi(\%)$	11.4	1.40	0.68	0.44
$A_{FB}^c(\%)$	9.9	2.04	1.63	0.74
$A_{FB}^b(\%)$	8.7	1.4	0.16	0.13

Table 5: Global analysis: Final results

ρ	Γ_c	$< X_b >$	$< X_c >$	$b \to \ell$	$b \to c \to \ell$	χ	A^b_{FB}	A^c_{FB}
Γ_b	-0.478	0.229	-0.048	-0.942	-0.378	-0.070	-0.004	0.050
Γ_c		0.057	0.494	0.471	-0.311	0.087	-0.009	-0.070
$< X_b >$			0.120	-0.352	-0.270	-0.007	-0.003	0.000
$< X_c >$				0.149	-0.295	0.048	-0.039	-0.002
$b \to \ell$					0.246	0.090	0.001	-0.036
$b \to c \to \ell$						-0.074	0.002	-0.013
χ							0.214	-0.003
A^b_{FB}								0.213

Table 6: Global analysis: statistical correlation matrix

that systematics will not prevent the accuracy of the asymmetry reaching levels sensitive to the one loop radiative corrections.

- The ratios $\Gamma(b\bar{b})/\Gamma(had)$ and $\text{Br}(b \to \ell\nu X)$ have a high negative correlation; this is because the product is measured to better than 1% statistically from the single lepton sample. Systematic uncertainties from lepton identification only significantly affect the branching ratio measurement.

- Modelling uncertainties affect mainly the b–fragmentation parameter, the $\text{Br}(b \to c \to \ell\nu X)$, and the charm asymmetry.

- The charm fragmentation parameter agrees very well with the ALEPH measurement based on D^* production [9].

The results of the fit are displayed on the data distributions in figure 1. The predicted components are shown.

Consistency Check

To check for consistency between the electron and muon samples the fit is repeated on each sample independently, fitting for $\text{Br}(b \to \ell\nu X)$, $\text{Br}(b \to c \to \ell\nu X)$, $\text{Br}(c \to \ell\nu X)$, $< x_b >$ and $< x_c >$ with the values of $\Gamma(b\bar{b})/\Gamma(had)$ and $\Gamma(c\bar{c})/\Gamma(had)$ taken from the Standard Model. The results are given in table 7 with statistical errors only. Agreement between the electron and muon results is very good suggesting the backgrounds in the two cases are well estimated. The value obtained for $\text{Br}(c \to \ell\nu X)$ is also very consistent with the world average value used in the full analysis.

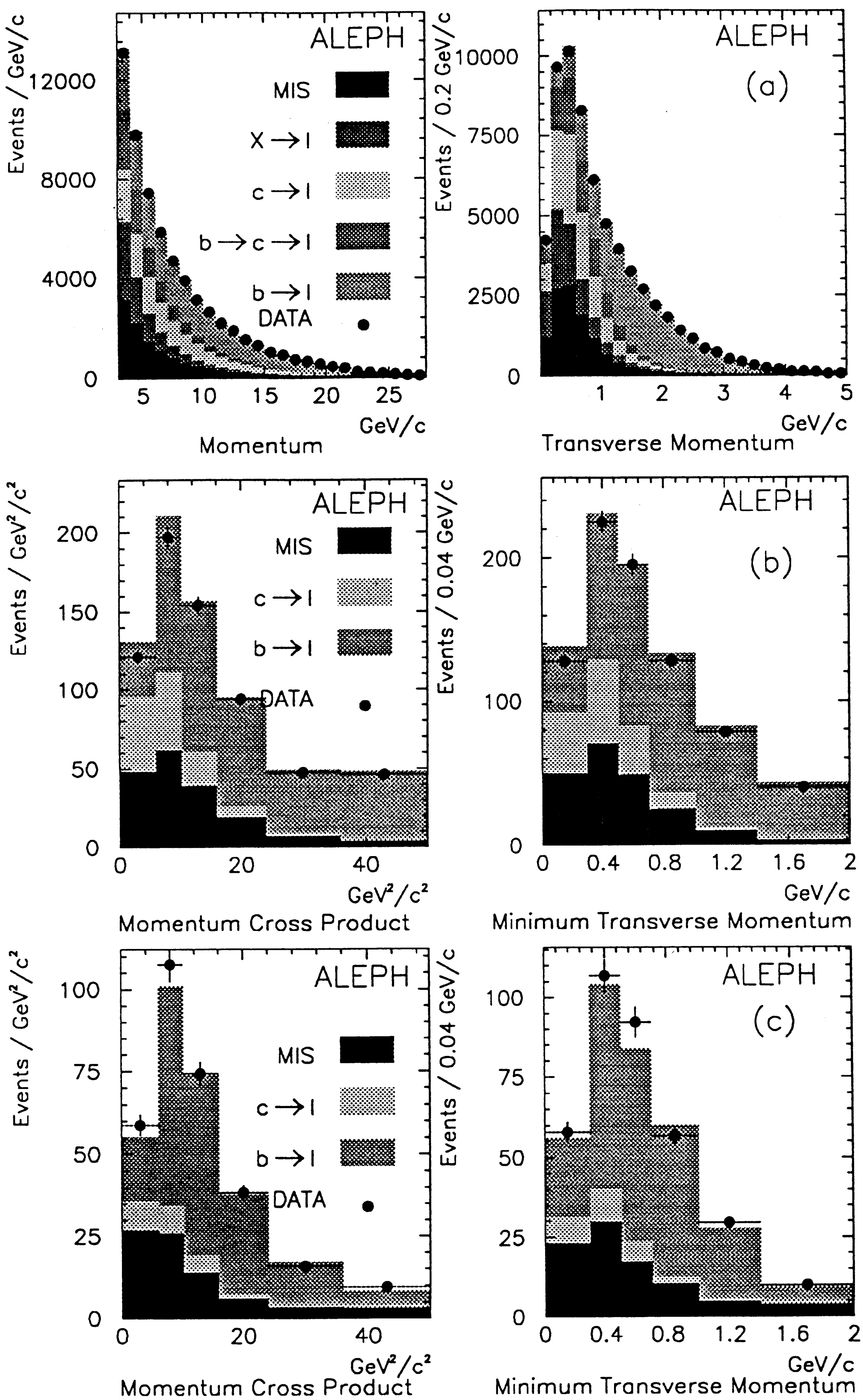

Figure 1: (a) P and $P_\perp$ distributions for single leptons (l=e and μ), and $P_\otimes$ and $P_{\perp m}$ distributions for (b) opposite direction dileptons and (c) same direction dileptons.

Parameter	e (Stat. error)	μ (Stat. error)	e+μ (Stat. error)
$BR(b \to l)(\%)$	11.1±0.2	11.3±0.2	11.3±0.1
$BR(b \to c \to l)(\%)$	8.9±0.5	8.8±0.4	8.8±0.2
$BR(c \to l)(\%)$	10.4±0.4	9.2±0.4	9.7±0.2
$< x_b >$	0.713±0.007	0.696±0.007	0.702± 0.003
$< x_c >$	$0.54^{+0.012}_{-0.013}$	$0.503^{+0.012}_{-0.010}$	0.514±0.009

Table 7: Comparison of e and μ results

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