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Heavy quark charge asymmetries with the CELLO detector

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Abstract. The production of b and c quarks in e^+e^- annihilation has been studied with the CELLO detector in the range from 35 GeV up to the highest PETRA energies. The heavy quarks have been tagged by their semileptonic decays. The charge asymmetries for b quarks at 35 and 43 GeV have been found to be $A^b = -(22.2 \pm 8.1)\%$ and $A^b = -(49.1 \pm 16.5)\%$, respectively, using a method incorporating jet variables and their correlations for the separation of the heavy quarks from the background of the lighter quarks. For c quarks we obtain $A^c = -(12.9 \pm 8.8)\%$ and $A^c = +(7.7 \pm 14.0)\%$, respectively. The axial vector coupling constants of the heavy quarks c and b are found to be $a_c = +(0.29 \pm 0.46)$ and $a_b = -(1.15 \pm 0.41)$ taking $B^0\bar{B}^0$ mixing into account. The results are in agreement with the expectations from the standard model.

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1 Introduction

In the standard model of electroweak interactions, e^+e^- annihilation into leptons or quarks is distinguished, in the limit of vanishing masses, by the electric charge and the third component of weak isospin of the elementary fermions involved. For leptons, which are observable particles, the predictions of the standard model, in particular the sign, magnitude and energy dependence of the charge asymmetry, have been impressively verified in experiments to date. With quarks, however, the measurement of the pair production cross section for a given flavour is complicated by the fact that free quarks do not exist but rather fragment into jets of hadrons. One therefore has to separate multihadronic final states arising from a given parent quark-antiquark pair from the competing background due to the other quark flavours. The identification of a given quark species is known as "flavour tagging".

Heavy quarks are customarily tagged either by requiring a semileptonic decay leading to a lepton with high transverse momentum p_T with respect to a suitably chosen event axis, or by explicitly reconstructing a meson carrying a definite quark flavour and charge. While meson tagging is very selective for charmed quarks, it suffers from low efficiency and is virtually impossible for b quarks at PETRA energies. Lepton tagging is more efficient but less selective and suffers from substantial background contributions. These facts have seriously limited the accuracy of the measurements of heavy quark production in e^+e^- annihilation.

In this letter we report on measurements of the charge asymmetries and the semileptonic branching ratios for c and b quarks employing, in addition to the lepton p_T, some specifically selected jet variables for improved separation of the heavy quark from the competing backgrounds. A likelihood method is used to determine the observables simultaneously by adjusting them to fit the experimental multi-dimensional distributions of the selected lepton and jet variables.

2 Experiment

The data were taken with the CELLO detector [1] at PETRA at a fixed centre of mass energy of $\sqrt{s}=35$ GeV ($\int \mathscr{L} dt = 87\,\mathrm{pb}^{-1}$) and at varying energies in the range 38 GeV and 46.78 GeV ($\langle\sqrt{s}\rangle = 43$ GeV, $\int \mathscr{L} dt = 42.7\,\mathrm{pb}^{-1}$). Charged particles are measured over 91% of the full solid angle in a cylindrical wire chamber assembly inside a 1.3 T magnetic field, with a transverse momentum resolution of $\sigma_p/p = 2\%\,p$ (p in GeV/c). The energy deposition of charged and neutral particles is measured in the barrel part of a fine-grain lead-liquid argon calorimeter, equipped with 19 planes of readout strips in three different orientations, covering 86% of 4π. The energy resolution of the calorimeter is $\sigma_E/E = 0.05 + 0.10/\sqrt{E}$ (E in GeV). The angular resolution, assuming the interaction point as origin, is 6 to 10 mrad. Muons are detected in 92% of 4π with planar drift chambers which are mounted behind the magnet yoke of 80 cm of iron. The spatial resolution of 0.6 cm obtained with these chambers is matched to the positional uncertainty due to multiple scattering of the muons passing the hadron absorber.

The analysis starts from a data sample of multihadronic events selected according to criteria described previously [2]. The total data sample consists of 24216 (8473) events at $\sqrt{s}=35\,(43)$ GeV, respectively. Background from cosmic rays, beam gas, $\tau^+\tau^-$, and other QED events was determined to be less than 3%.

Table 1. Identified lepton candidates in the data and expectations for signal and backgrounds from a full Monte Carlo simulation of the experiment. The input branching ratios for the Monte Carlo are $\mathrm{BR_{MC}}(c \to l) = 8.8\%$ and $\mathrm{BR_{MC}}(b \to l) = 12.2\%$

	Electron selection		Muon selection	
$\sqrt{s}$	35 GeV	43 GeV	35 GeV	43 GeV
Lepton candidates	940	374	806	453
Lepton ident. eff.	86.2%	85.4%	77.3%	63.6%
Hadron misident. prob.	2.49%	2.44%	2.54%	1.33%
MC expectation	967.5	368.1	828.1	393.2
$b \to l$	10.6%	10.4%	17.3%	13.6%
$b \to c \to l$	3.8%	3.9%	4.1%	5.3%
$c \to l$	17.4%	15.1%	29.9%	22.8%
$b \to$ hadrons	7.4%	7.9%	6.1%	8.2%
$c \to$ hadrons	24.1%	23.7%	20.0%	23.0%
uds hadrons	35.5%	37.7%	22.6%	27.1%
DIS/IC	1.2%	1.3%	0%	0%

3 Lepton identification

In the multihadronic event sample, electrons were identified as charged particles with momentum greater than 1 GeV/c, with an energy deposit in the calorimeter matching the momentum measurement, and a longitudinal and lateral energy distribution compatible with that from an electromagnetic shower. Details of the likelihood ratio technique used to tag the electron are given elsewhere [3]. The average efficiency for identifying electrons was determined by Monte Carlo calculations to 86%, with a hadron misidentification probability of 2.5%. Deep-inelastic electron photon scattering and inelastic Compton scattering backgrounds were further reduced by requiring the sum of the positive longitudinal components of all particle momenta in the electron direction, projected into the $r\phi$ plane, to exceed 1 GeV/c. The number of electron candidates and the respective fractions from the various sources, as determined by a detailed Monte Carlo simulation of the experiment, are shown in Table 1. This simulation takes into account the time-dependent performance of the detector and the contributions from the various center-of-mass energies, using event samples proportional to the accumulated luminosities at each energy point. For the calculations the inclusive semileptonic branching ratios $\mathrm{BR}(b \to l) = 12.2\%$ and $\mathrm{BR}(c \to l) = 8.8\%$ have been assumed [4].

The identification of muons is based on their range, using the space points reconstructed in the muon chambers. Two variables are employed to evaluate a track-hit association: the distance d between a reconstructed hit and the track extrapolated from the central detector and the quality Q, defined as the ratio of the distance d over the uncertainty in the extrapolation. All muon candidates had to exceed a minimum momentum of 1.6 GeV/c in order to penetrate the iron absorber. As for the electron case, the observed number of muon candidates and the expected backgrounds are shown in Table 1. Additional cuts on the sphericity (>0.025) and the polar angle for the thrust axis ($|\cos\theta|<0.65$) were applied for both lepton samples in order to reduce background not well described by the Monte Carlo simulation. In this way possible correlations between the discriminating variables and the polar scattering angle, which tend to increase close to the acceptance limit, are minimised.

4 Flavour separation

Semileptonic decays of the heavy quarks b (c) can be enhanced over the competing background from light quark decays using cuts in the transverse momentum p_T of the decay lepton with respect to the event axis, defined by thrust or sphericity [5, 6–9]. As was shown previously [7, 10], the separation of b quarks from the light-quark background can be substantially improved using additional event shape variables reflecting the mass difference between these quarks. JADE [7], e.g., have chosen the transverse jet mass and the missing transverse momentum partly due to the presence of high energy neutrinos in the semileptonic decays.

We have investigated many such variables (details of this analysis are described elsewhere [3]) and have found that, in addition to the transverse momentum p_T of the lepton with respect to the thrust axis, the sum of the momenta $\sum p_T^{\text{out}}$ of all particles perpendicular to the event plane (similar to the "transverse" mass used by JADE [7, 11]) and a variable E_{corr}, first introduced by the PLUTO collaboration [8], provide optimal separation. The dimensionless variable E_{corr} is the total energy of all particles inside a given cone around the direction of the lepton candidate, divided by the total energy of all particles in the event. For our experimental conditions, the optimum half angle of the cone was found to be 10 degrees. In contrast to JADE and PLUTO, the lepton momenta are included in the definition of both variables. The separating power of these variables was studied on the basis of Monte Carlo calculations, using the $O(\alpha_s^2)$LUND 5.2 generator [12], both at the four-vector level and for the full detector simulation. The distributions of the three most powerful discriminating variables are shown in Fig. 1 at the four-vector level and in Fig. 2 for the full detector simulation, using the muon channel at a centre of mass energy of 35 GeV. While the distributions for b quarks show good separation, one notices that the c quarks strongly overlap with the background from the light quarks.

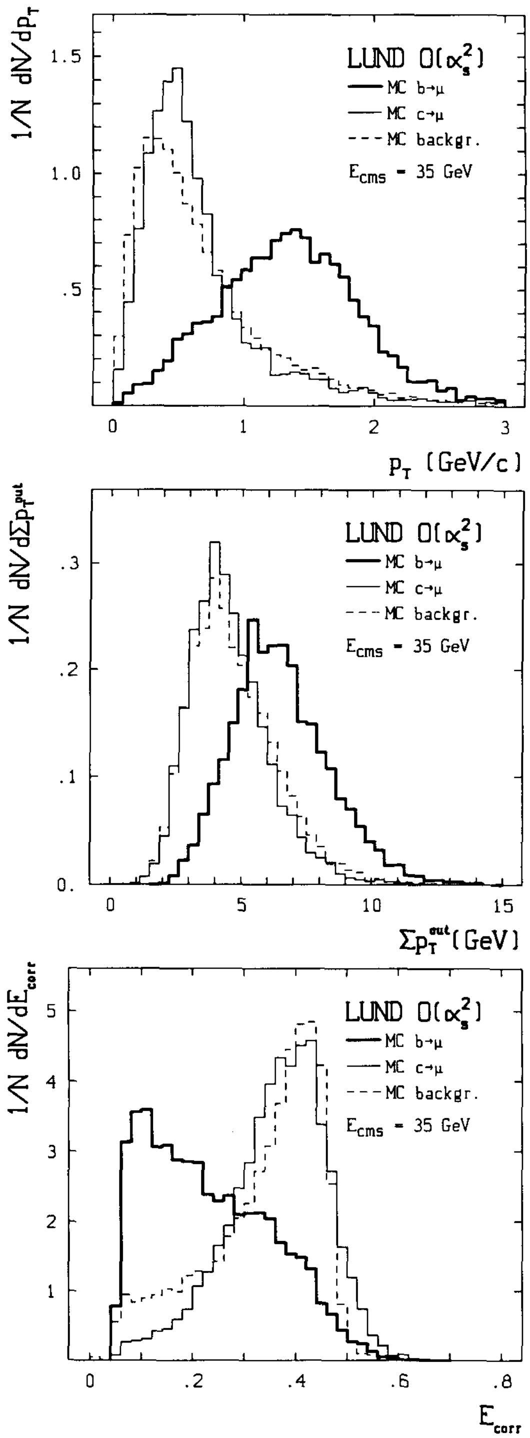

Fig. 1. Monte Carlo expectations for the three discriminating variables at the four-vector level ("ideal" detector). The individual contributions are normalized to the same area. a) lepton transverse momentum p_T with respect to the event thrust axis, b) sum of momenta $\sum p_T^{\text{out}}$ of all particles perpendicular to the event plane, including the lepton, c) total energy E_{corr} of all particles inside a cone of 10 degrees half angle around the direction of the lepton, normalized to the total energy in the event

5 Analysis method

To eliminate the systematic uncertainty from the imperfect knowledge of the semileptonic branching ratios of the heavy quarks we have performed a simultaneous determination of these ratios and of the charge asymmetries for b and c quarks in a maximum likelihood fit to the observed distributions of the discriminating variables p_T, $\sum p_T^{\text{out}}$ and E_{corr}. The likelihood function is given by

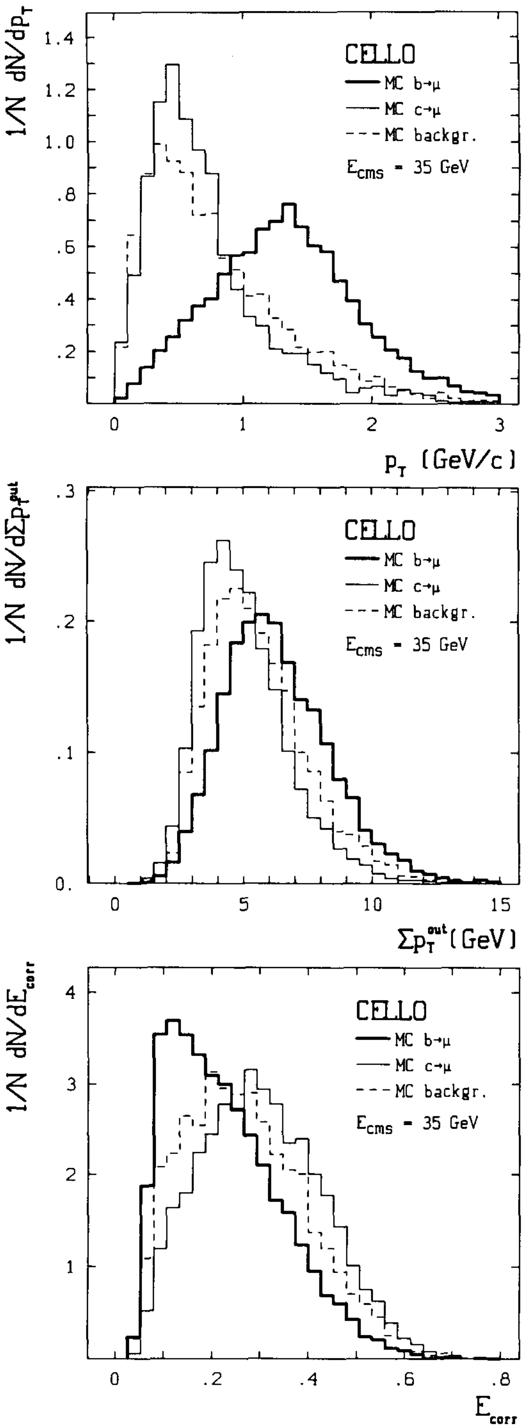

Fig. 2. Monte Carlo expectations for the three discriminating variables including a full simulation of the detector. The individual contributions are normalized to the same area. a) lepton transverse momentum p_T with respect to the event thrust axis, b) sum of momenta $\sum p_T^{out}$ of all particles perpendicular to the event plane, including the lepton, c) total energy E_{corr} of all particles inside a cone of 10 degrees half angle around the direction of the lepton, normalized to the total energy in the event

$$\mathscr{L}=\prod_{i=1}^{N}\{f^b\rho^b(p_T,\sum p_T^{out},E_{corr})[\tfrac{3}{8}(1+x_i^2)+A^b x_i] +f^c\rho^c(p_T,\sum p_T^{out},E_{corr})[\tfrac{3}{8}(1+x_i^2)+A^c x_i] +f^{bg}\rho^{bg}(p_T,\sum p_T^{out},E_{corr})[\tfrac{3}{8}(1+x_i^2)+A^{bg} x_i]\},$$

where the dependence on $x=\cos\theta_{jet}$ is the standard model expectation with asymmetries A^k for the contributions from the heavy quarks ($k=b, c$) and the background ($k=$bg). The sign of A^c in (5.1) accounts for the fact that c quarks decay into leptons with the opposite charge sign in comparison to b quarks. The functions $\rho^k(p_T, \sum p_T^{out}, E_{corr})$ are three-dimensional probability densities for events with identified leptons arising from heavy quark decays or background, with all experimental detection conditions folded in. For the fractions of $b\to l$ decays (f^b), $c\to l$ decays (f^c) and background events (f^{bg}) in the number N of identified leptons the normalisation

$$f^b+f^c+f^{bg}=1 \tag{5.2}$$

is used with

$$f^{bg}=f^{had}+f^{bc},$$

where f^{had} and f^{bc} are the fractions of background events with misidentified hadrons and cascade decays ($b\to c\to l$), respectively. Note that f^{bc} is only 4% of the total background f^{bg} (see Table 1), so the assumption (5.2) of a background independent of f^b will not introduce any noticible bias for f^b.

The fractions $f^{b,c}$ are related to the semileptonic branching ratios $BR_{b,c}$ via the branching ratios $BR_{b,c}(MC)$ input to the Monte Carlo simulation and the expected signal $N_{MC}^{b,c}$:

$$BR_{b,c}=\frac{Nf^{b,c}}{N_{MC}^{b,c}}\,BR_{b,c}(MC).$$

The asymmetry of the background due to $b\to c\to l$ decays (f^{bc})

$$A^{bg}=-\frac{f^{bc}}{f^{bg}}A^b_{GSW}$$

has been determined from Monte Carlo and is found to be $<3\%$.

In the likelihood fit the fraction f^b and the charge asymmetries A^b and A^c were treated as free parameters. The density functions $\rho(p_T, \sum p_T^{out}, E_{corr})$ and the background contribution f^{bg} were taken from Monte Carlo. The fraction f^c is calculated from the normalisation condition in (5.2). Note that the density function ρ is a 3-dimensional distribution (with projections shown in Figs. 1, 2) and thus takes advantage of the full correlation of the separating variables. We used binned distributions, unbiased by smoothing algorithms, with typically 30 bins in each dimension.

The central aim of the Monte Carlo investigations was to study the effects of the additional jet variables on the semileptonic branching ratios, charge asymmetries and their errors. The Monte Carlo calculations were carried out at the four-vector level and at the full detector simulation level to study potential biases of the methods. These investigations also serve to determine the asymptotic (ideal detector, large statistics) and the expected (real detector, experimental statistics) results for the four

Table 2. Results of the Monte Carlo study for the charge asymmetry and the signal fraction of b quarks at 35 GeV, tagged by muons, as functions of an increasing number of discriminating variables (see text). The numbers given are based on 40000 events for the four-vector (generator) study and on 4000 events with full detector simulation, selected from a sample of 100000 generated multihadronic events

	LUND generator		Detector simulation	
	A^b [%]	f^b [%]	A^b [%]	f^b [%]
p_T	$-(22.0 \pm 2.0)$	22.3 ± 0.39	$-(24.2 \pm 8.7)$	19.8 ± 1.5
$p_T \otimes \sum p_T^{out}$	$-(18.7 \pm 1.8)$	22.2 ± 0.34	$-(26.0 \pm 6.2)$	19.9 ± 1.0
$p_T \otimes \sum p_T^{out} \otimes E_{corr}$	$-(18.4 \pm 1.5)$	22.3 ± 0.29	$-(27.0 \pm 4.2)$	19.8 ± 0.7
MC input	$-(22.7 \pm 1.3)$	22.3	$-(29.0 \pm 4.0)$	19.9

Table 3. Statistical errors on the b quark charge asymmetry at 35 GeV in the data and for the expectation from a full detector simulation and a four-vector Monte Carlo, as functions of an increasing number of discriminating variables (see text). The b quarks have been tagged by muons. The statistics in the Monte Carlo are chosen to match the number of muon candidates in the data (806 events)

ΔA^b_{stat}	Data	Detector simulation	LUND generator
p_T	21%	20%	14%
$p_T \otimes \sum p_T^{out}$	15%	15%	11%
$p_T \otimes \sum p_T^{out} \otimes E_{corr}$	10%	10%	10%

physical observables. Initially only p_T was used as discriminating variable; subsequently the further variables $\sum p_T^{out}$ and E_{corr} were added, thus increasing the separation power, and fits for the charge asymmetries and semileptonic branching ratios were performed at each stage. The results of this investigation for the charge asymmetry of the b quark A^b and the fractions f^b are shown in Table 2. While the central value of A^b is stable on varying the number of discriminators, it is seen that the inclusion of the additional jet variables and their correlations improves the error considerably. The resulting values for the experimental statistics are shown in Table 3 as functions of increasing number of discriminating variables. The expectations from the full Monte Carlo are in good agreement with the actual errors in the data. One can see that the errors are smallest for 3 variables, as observed consistently in the high statistics Monte Carlo studies and in the data. Furthermore, when all three discriminating variables are used the smearing due to the imperfect particle detection does not reduce the statistical precision of the asymmetry measurement.

It was also found that stable results for the charge asymmetry could only be obtained taking into account the full correlation of variables in the density functions ρ: If instead the likelihood is taken as a product of the individual projections, we obtain systematic shifts of A^b towards lower absolute values with an increasing number of event shape variables. This result is verified both on the four-vector and the detector simulation level. The multi-dimensional correlation functions ρ give a consistent reproduction of the charge asymmetries and event fractions input to our simulations (see Table 2). This is due to the superior separating ability when the full correlation is taken into account.

As examples of these correlations we show in Fig. 3 the projections onto the planes p_T vs. $\sum p_T^{out}$ and p_T vs. E_{corr} for the muon channel at 35 GeV, separately for b quarks, c quarks and the background from the other quarks. The distributions have been obtained from a full Monte Carlo simulation of the experiment.

6 Results

With the method optimised as described, the semileptonic branching fractions and the charge asymmetries were simultaneously determined for the b and c quarks in each of the two leptonic channels at 35 and 43 GeV. The results of the fits to the p_T, $\sum p_T^{out}$ and E_{corr} distributions are shown in Fig. 4 together with the experimental data. Good agreement of the model calculations with the data is observed. The numerical results for the semileptonic branching fractions and charge asymmetries are shown in Table 4 and 5, respectively, the errors quoted are statistical and systematic. We find good agreement of the semileptonic branching ratios with previous experiments [13, 4].

The charge asymmetries in Table 5 have been corrected for electroweak radiative effects up to the one-loop level [14, 15]. Furthermore, $O(\alpha_s)$ QCD corrections and mass effects [16] have been taken into account. The total corrections to the b (c) quark asymmetry at 35 and 43 GeV amount to $+2.8\%$ and $+3.3\%$ (-1.9% and -1.4%), respectively [3]. Our measurements include the first determinations of the heavy quark charge asymmetries at 43 GeV. At both energies the charge asymmetries for b and c quarks are in good agreement with the expectation of the standard model. The value for A^b at 35 GeV is also in good agreement with the only other measurement significantly different from zero, done by JADE [7] at the same centre-of-mass energy.

The systematic errors have been estimated by varying the main parameters entering the fitting procedure. The most important contribution comes from the fragmentation parameters of the Peterson function [17] for the heavy quarks which we varied between conservatively wide limits, from the world averages $\varepsilon_b = 0.012$, $\varepsilon_c = 0.09$ [18] used in the standard Monte Carlo to the "hard" values $\varepsilon_b = 0.0035$, $\varepsilon_c = 0.025$. We also varied the criteria for lepton identification, resulting in efficiences between 70% and 88%. The number of bins for the density functions was varied between 20 and 30, limited on the lower side by the loss of separating power of the variable and on the high side by the available Monte Carlo statistics. The background contribution f^{bg} (including the contribution $b \to c \to l$, determined from Monte Carlo) was varied by $\pm 10\%$ and turned out to be insensitive to the results. Finally, we studied the influence of the cut for

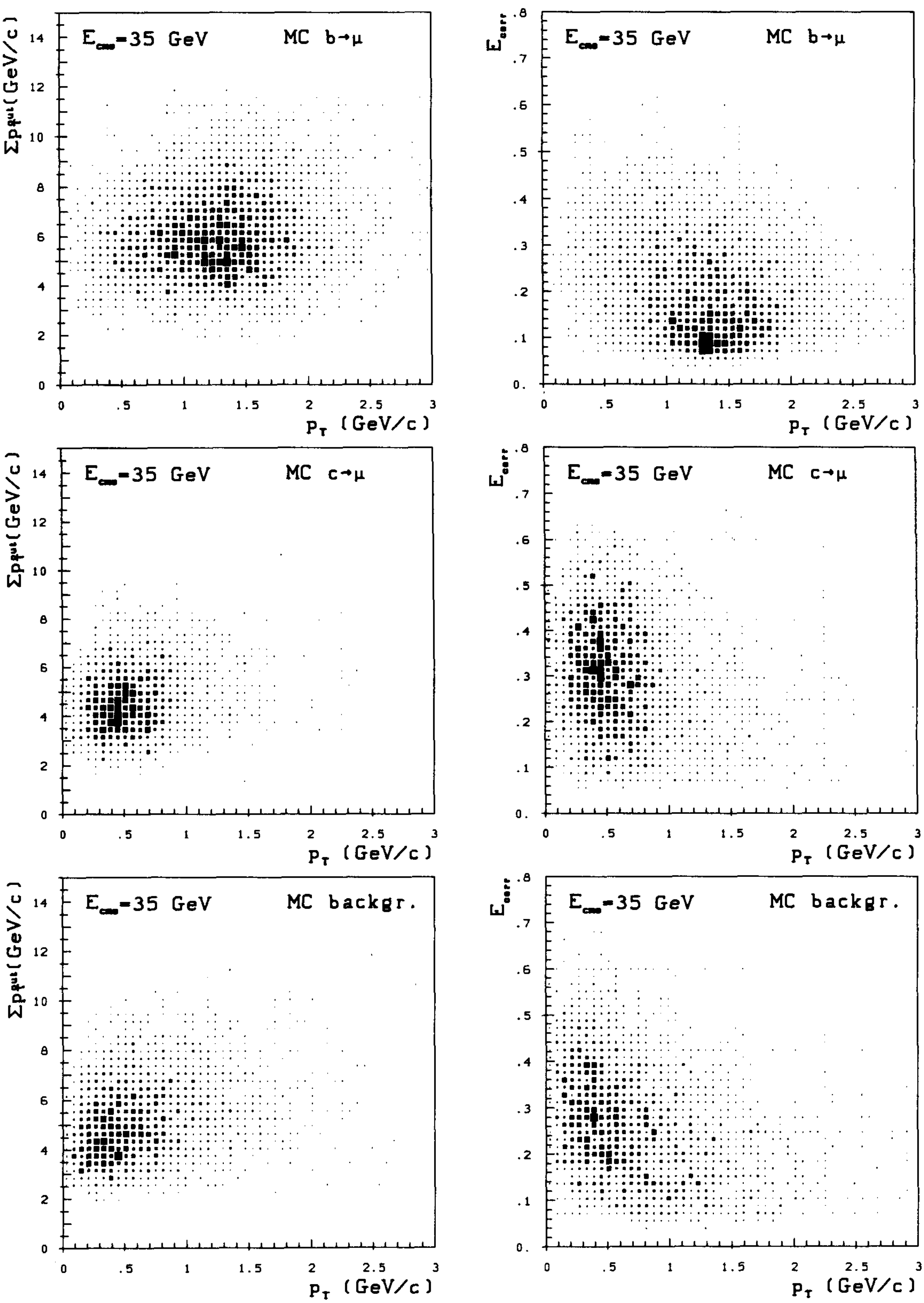

Fig. 3. The correlations of the variables p_T^{lept} and $\sum p_T^{\text{out}}$ and of p_T^{lept} with E_{corr} for b-, c-, and background events with muon candidates at $\sqrt{s}=35$ GeV after the full detector simulation

the jet axis, which was varied between $0.50 < |\cos\theta_{\text{jet}}(\text{cut})| < 0.80$. Fits were repeated for each of the above variations and the standard deviations of the distributions for the resulting asymmetries and branching ratios, weighted with their statistical errors, were determined. These standard deviations were taken as the systematic errors and are shown in Tables 4 and 5. To convince ourselves that statistical fluctuations in the Monte

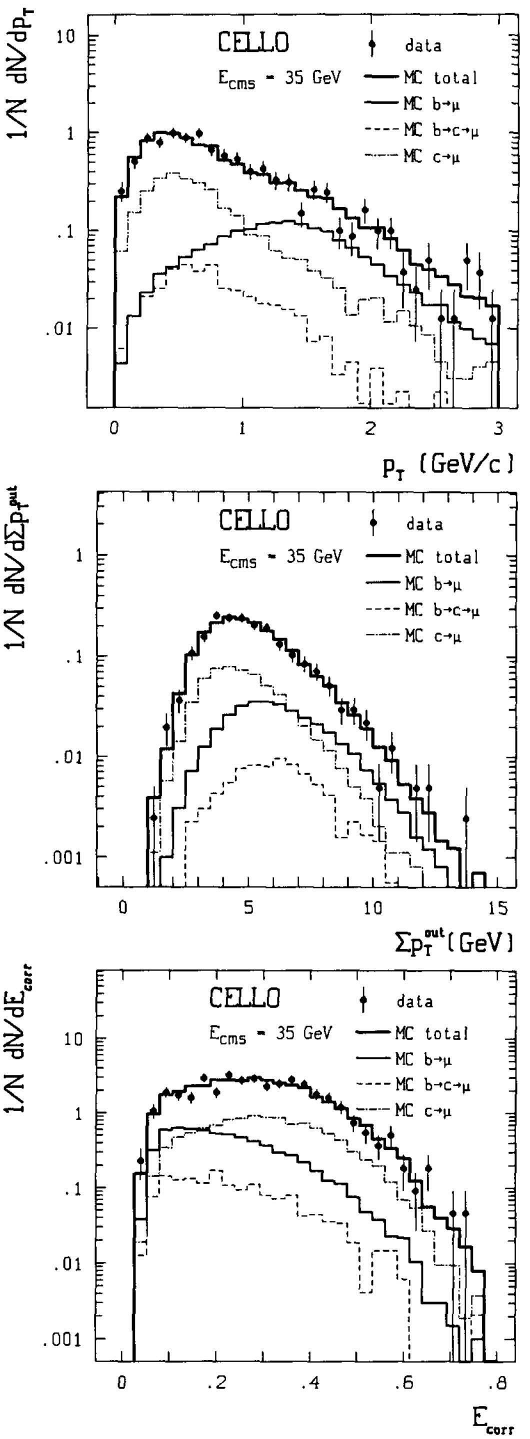

Fig. 4. Distributions for the three discriminating variables for the μ candidate sample (data points). The histograms show the result of the fit and the expectations for the b and c quarks and the contribution of the cascade decay background. The Monte Carlo distributions are based on a total of 25000 fully simulated muon candidate events. a) lepton transverse momentum p_T with respect to the event thrust axis, b) sum of momenta $\sum p_T^{out}$ of all particles perpendicular to the event plane, including the lepton, c) total energy E_{corr} of all particles inside a cone of 10 degrees half angle around the direction of the lepton, normalized to the total energy in the event

Table 4. Measurements of the semileptonic branching ratios of c and b quarks for the electron and muon channel and at both centre-of-mass energies. For the individual measurements, the first errors given are statistical and the second ones systematic. The averages (weighted by statistical and systematic errors) over both lepton channels and energies have been calculated taking into account the correlations of the systematic errors. The systematic error of an average over lepton channels is taken to be the arithmetic mean of the individual contributions. The combined errors for these averages are given in square brackets

$\sqrt{s}$	Channel	Branching ratio [%] charm	Branching ratio [%] bottom
43 GeV	$q\to e$	$9.2\pm1.4\pm2.0$	$11.1\pm2.8\pm2.6$
43 GeV	$q\to\mu$	$11.4\pm1.0\pm1.3$	$10.4\pm2.3\pm1.6$
43 GeV	$q\to l$	$10.4\pm0.8\pm1.7$ [1.4]	$10.7\pm1.8\pm2.1$ [2.3]
35 GeV	$q\to e$	$6.9\pm0.5\pm1.1$	$15.0\pm1.1\pm2.2$
35 GeV	$q\to\mu$	$7.2\pm0.4\pm0.6$	$14.8\pm1.0\pm1.6$
35 GeV	$q\to l$	$7.1\pm0.3\pm0.9$ [0.7]	$14.9\pm0.7\pm1.9$ [1.5]
$\langle\ \rangle$	$q\to l$	7.7 ± 0.6	13.6 ± 1.3

Carlo models of the true ρ functions do not influence our results, we varied the contents of the binned three-dimensional distributions randomly within one standard deviation and repeated the fits many times. The resulting values for the observables agreed well within their statistical errors and the statistical uncertainties themselves were found to be insensitive to the changes in the ρ functions.

7 Determination of the axial-vector charges

At the Born level of the standard theory, the charge asymmetry for a massless quark q (note that we have corrected the experimental charge asymmetries for mass effects) is given by

$$A^q=\frac{3}{4}\frac{C_2}{C_1}$$

with

$$C_1=Q_e^2Q_q^2+Q_eQ_qv_ev_q\,\mathrm{Re}\,g(s)+\tfrac{1}{4}(v_e^2+a_e^2)(v_q^2+a_q^2)|g(s)|^2$$
$$C_2=Q_eQ_qa_ea_q\,\mathrm{Re}\,g(s)+v_ev_qa_ea_q|g(s)|^2$$
$$g(s)=\frac{1}{8\sin^2\theta_W\cos^2\theta_W}\frac{s}{s-M_Z^2+iM_Z\Gamma_Z}. \quad (7.1)$$

This expression can be used to determine the axial-vector charges a_q of the b and c quarks ($q=b, c$), once the electric charges Q_q are inserted, the standard model predictions for the vector charges v_q are assumed, and the mass of the Z^0 and the value of the Weinberg angle are chosen ($M_Z=91.17$ GeV [19] and $\sin^2\theta_W=0.2307$). Table 6 shows the results for the axial-vector charges separately and combined for the two lepton channels and centre of mass energies. The values for a_c are directly obtained from (7.1) and the measurements in Table 5.

Table 5. Measurements of the charge asymmetries A^q ($q=c, b$) for c and b quarks, separately and combined for the two lepton channels. The weighted averages and their errors have been determined as described in the caption of Table 4. The combined errors of the averages over lepton channels are given in square brackets. The charge asymmetries are radiatively corrected to the Born level (see text). $B^0\overline{B}^0$ mixing has not been taken into account. The Born prediction $A_{\text{GSW}}^{\text{Born}}$ the standard model for $M_Z=91.17$ GeV and $\sin^2\theta_W=0.2307$ is also given

$\sqrt{s}$	Channel	Lepton cand. (signal)	A^q [%]	$A_{\text{GSW}}^{\text{Born}}$ [%]
43 GeV	$c \to e$	374 (58)	$-(22.2 \pm 26.7 \pm 5.0)$	
43 GeV	$c \to \mu$	453 (116)	$+(18.5 \pm 15.5 \pm 5.0)$	
43 GeV	$c \to l$	827 (174)	$+(7.7 \pm 13.4 \pm 5.0)$ [14.0]	−22.1
43 GeV	$b \to e$	374 (35)	$-(44.6 \pm 27.6 \pm 6.0)$	
43 GeV	$b \to \mu$	453 (45)	$-(51.3 \pm 19.7 \pm 4.0)$	
43 GeV	$b \to l$	827 (80)	$-(49.1 \pm 16.0 \pm 5.0)$ [16.5]	−39.7
35 GeV	$c \to e$	940 (132)	$-(14.1 \pm 13.0 \pm 6.0)$	
35 GeV	$c \to \mu$	806 (203)	$-(12.2 \pm 9.7 \pm 5.0)$	
35 GeV	$c \to l$	1746 (335)	$-(12.9 \pm 7.8 \pm 5.5)$ [8.8]	−13.6
35 GeV	$b \to e$	940 (126)	$-(21.0 \pm 11.8 \pm 4.0)$	
35 GeV	$b \to \mu$	806 (173)	$-(23.0 \pm 10.2 \pm 3.0)$	
35 GeV	$b \to l$	1746 (299)	$-(22.2 \pm 7.7 \pm 3.5)$ [8.1]	−26.0

Table 6. Determinations of the axial-vector charges a_b (a_c) of b (c) quarks from the two lepton channels and centre-of-mass energies for $M_Z=91.17$ GeV and $\sin^2\theta_W=0.2307$. a_b is given with and without $B^0\overline{B}^0$ mixing (see text). The errors are statistical (first) and systematic (second). Averages over all lepton channels and energies have also been calculated taking into account correlations of the systematic errors in the charge asymmetries. The uncertainties of the averages are obtained by adding the statistical and systematic errors in quadrature

$\sqrt{s}$	channel	a_c	a_b without mixing	a_b with mixing
43 GeV	$q \to e$	$+(1.01 \pm 1.27 \pm 0.24)$	$-(1.15 \pm 0.91 \pm 0.20)$	$-(1.60 \pm 1.65)$
43 GeV	$q \to \mu$	$-(0.83 \pm 0.72 \pm 0.23)$	$-(1.39 \pm 0.76 \pm 0.16)$	$-(2.08 \pm 1.93)$
43 GeV	$q \to l$	$-(0.36 \pm 0.65)$	$-(1.29 \pm 0.60)$	$-(1.80 \pm 1.25)$
35 GeV	$q \to e$	$+(1.04 \pm 0.98 \pm 0.45)$	$-(0.80 \pm 0.47 \pm 0.16)$	$-(1.02 \pm 0.66)$
35 GeV	$q \to \mu$	$+(0.90 \pm 0.72 \pm 0.37)$	$-(0.88 \pm 0.41 \pm 0.12)$	$-(1.12 \pm 0.58)$
35 GeV	$q \to l$	$+(0.95 \pm 0.66)$	$-(0.84 \pm 0.32)$	$-(1.08 \pm 0.43)$
$\langle\ \rangle$	$q \to l$	$+(0.29 \pm 0.46)$	$-(0.94 \pm 0.29)$	$-(1.15 \pm 0.41)$

For the case of the b quark, however, a further correction to the charge asymmetry is necessary due to $B^0\overline{B}^0$ mixing, which reduces the observed charge asymmetry. With the measured value for the mixing parameter $\chi_l=0.10 \pm 0.03$ [20] (with the same assumptions as in [6]) the b quark charge asymmetries at the Born level A_{GSW}^b are determined from the measurements A_{obs}^b by

$$A^b = \frac{1}{1-2_{\chi_l}} A_{\text{obs}}^b. \tag{7.2}$$

Inserting this expression into (7.1) yields the values for a_b in Table 6 with mixing. It should be noted that neglecting the purely weak terms in (7.1), as is usually done for lepton pair production and also in many previous determinations of the axial-vector couplings of the heavy quarks, may lead to inaccurate results for these couplings and to an underestimation of their errors, especially at high energies and for large charge asymmetries.

Our determinations of the axial-vector coupling constants, $a_b=-(1.15 \pm 0.41)$ (with mixing) and $a_c=+(0.29 \pm 0.46)$, are in agreement with the expectation of the standard model ($a_b=-1$, $a_c=+1$) and with other experiments. A compilation of the world data on a_b and a_c is shown in Figs. 5 and 6, where the values for a_b, a_c have been recalculated from the measured asymmetries [5, 6–8]* using the full expression (7.1). It is interesting to note that the inclusion of $B^0\overline{B}^0$ mixing improves the agreement with the standard model: with the inclusion of the present data, the new world average without mixing is $a_b=-(0.70 \pm 0.14)$, whereas the value including

* After completing this analysis we learnt of a new measurement of A^b from AMY [21] and JADE [22]

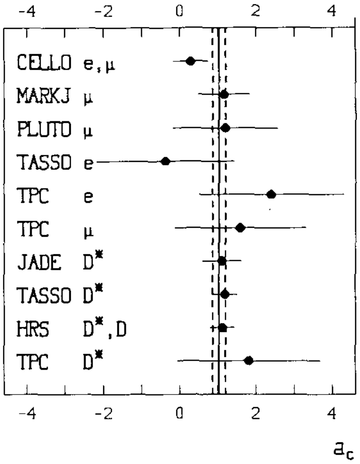

Fig. 5. Compilation of measurements for the axial-vector coupling of the c quark. The solid line with dashed error margins corresponds to the new world average of $a_c = +(1.03 \pm 0.17)$

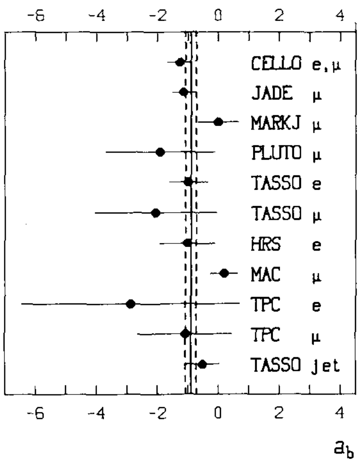

Fig. 6. Compilation of measurements for the axial-vector coupling of the b quark. With the exception of the MAC experiment (see text), the charge asymmetries A^b from which the individual results for the couplings are derived have been corrected for $B^0\bar{B}^0$ mixing. The solid line with dashed error margins corresponds to the new world average of $a_b = -(0.81 \pm 0.19)$

mixing is $a_b = -(0.81 \pm 0.19)$. The MAC measurement [9] of A^b, due to its positive value, cannot be corrected consistently for $B^0\bar{B}^0$ mixing: The correction due to mixing is multiplicative, so the corrected value would result in a larger positive asymmetry, even further away from the negative expectation by the standard model. In view of the other experimental results, which are all consistent with the standard model demanding a negative charge asymmetry, we consider a positive charge asymmetry as the result of a statistical fluctuation in the data which should not be enhanced even further by the mixing correction. Therefore, in the compilation of Fig. 6, the uncorrected MAC result for a_b is displayed. However, for the calculation of the mean value of a_b with mixing, the MAC measurement was taken into account by averaging it with the b asymmetry measurements of the other PEP experiments at $\sqrt{s} = 29$ GeV before the mixing correction. For charmed quarks, the new world average is $a_c = +(1.03 \pm 0.17)$.

The b asymmetry measurement can also be used to set a limit on the mixing parameter χ_l, assuming an expected asymmetry according to the standard model (see Table 5). From the results of this experiment at $\sqrt{s} = 35$ GeV alone one obtains $\chi_l < 0.28$ (90% C.L.). Using all PETRA data at 35 GeV the limit is $\chi_l < 0.20$ (90% C.L.).

8 Conclusions

In conclusion, we have used the semileptonic decays of b and c quarks into electrons and muons to determine the charge asymmetries and the semileptonic branching ratios of these quarks. For the separation of the heavy quarks from the competing background of the light quarks we used, in addition to the transverse momentum of the lepton, suitably chosen jet variables. With Monte Carlo calculations we verified that, incorporating these additional jet variables and retaining their full correlation, stable results are produced and that the uncertainties of the measured quantities (branching ratios and charge asymmetries) are substantially reduced. While the observed charge asymmetry for c quarks is not significant statistically, the charge asymmetry for b quarks, A^b, is found to be $A^b = -(22.2 \pm 8.1)\%$ at 35 GeV, and $A^b = -(49.1 \pm 16.5)\%$ at 43 GeV. From our measurements we deduce the axial-vector coupling constant a_b and a_c, which are in good agreement with the standard model expectation.

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