

A MEASUREMENT OF THE ELECTROWEAK INDUCED CHARGE ASYMMETRY IN $e^+e^- \rightarrow b\bar{b}$

JADE Collaboration

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Received 24 July 1984

The forward-backward charge asymmetry for the process $e^+e^- \rightarrow b\bar{b} \rightarrow \mu^\pm + \text{hadrons}$ has been measured using the JADE detector at PETRA. An asymmetry of $(-22.8 \pm 6.0 \pm 2.5)\%$ was observed at an average center of mass energy of 34.6 GeV. For comparison, an asymmetry of -25.2% is expected on the basis of the standard Glashow-Salam-Weinberg model.

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⁷ Partially supported by Department of Energy, USA.

The existence of electroweak interference effects in e^+e^- collisions is now well established and the process can be used to measure the electroweak charges with an accuracy comparable to that obtained in neutrino reactions [1]. However, statistically significant asymmetry measurements to date have been restricted to purely leptonic final states for two main reasons: (a) Although the interference effects for quarks are expected to be large, the separation of the various flavours has formerly been a problem. (b) The determination of the primary quark charge is done with low efficiency. Previous experiments therefore [2], have not observed a statistically significant asymmetry. However, this paper describes a method for partially overcoming these problems to obtain a measurement for b quarks.

The question of flavour separation using kinematic quantities derived from the event shape has been investigated in detail [3,4] and we use the following three quantities to discriminate against the flavours:

- (1) $\langle M \rangle$, jet transverse mass = $\frac{2E_{\text{beam}}}{E_{\text{vis}}} \sum_N |p_T^{\text{out}}|$.
- (2) $p_T(\mu)$, the muon transverse momentum.
- (3) $p_T(\nu)$, the missing transverse momentum.

In all three cases, the momentum components are measured transverse to the major axis of the event sphericity ellipsoid which defines the jet axis. The p_T out component is measured along the minor axis of the ellipsoid.

The transverse mass is obtained by summing the transverse momentum components of all N charged and neutral particles (except the muon). This variable is related to the variable T (transverse thrust) used in our earlier paper [4] by a linear scale factor $2E_{\text{beam}}$ which allows data from different beam energies to be combined.

A Monte Carlo simulation showed that the quantity $\langle M \rangle$ has the average values 4.20 GeV, 4.69 GeV and 6.53 GeV for uds, c and b quark events respectively. It is hence a good indicator for heavy quarks.

The muon transverse momentum is also a good indicator for heavy quarks which decay semi-leptonically with a large Q value. The simulation indicated that the average values of $p_T(\mu)$ for uds, c and b quarks are 0.55 GeV/c, 0.61 GeV/c and 1.22 GeV/c respectively.

In addition, the muon was also used to identify the primary quark charge via the decay schemes:

$$b \text{ or } \bar{c} \rightarrow \mu^- \quad \left[\text{charge } -\frac{1}{3} \text{ or } -\frac{2}{3} \right],$$

$$\bar{b} \text{ or } c \rightarrow \mu^+ \quad \left[\text{charge } \frac{1}{3} \text{ or } \frac{2}{3} \right].$$

The overall missing momentum vector measured in the JADE apparatus contains contributions from many sources such as the finite resolution for measuring charged and electromagnetic particles, from undetected initial state radiation from the e^+e^- , from undetected non showering neutral particles (n, K_L^0 etc), from particles which enter a region of zero acceptance (beampipe) and most important for this application, from neutrinos. It turns out that the component of missing momentum transverse to the jet axis is dominated by the neutrino whenever a semi leptonic decay of a quark occurs. Other contributions to the missing momentum tend to have a small p_T with respect to this axis. The simulation clearly showed the contribution from neutrinos from heavy quarks; the average value of $p_T(\nu)$ for uds, c and b being 1.36 GeV/c, 1.48 GeV/c and 1.94 GeV/c respectively. Moreover, the simulation reproduced the detailed shape of the $p_T(\nu)$ spectrum, indicating that the variable is well understood. The JADE detector is therefore sufficiently hermetic to allow this variable to be used successfully.

The kinematic quantities $\langle M \rangle$, $p_T(\mu)$ and $p_T(\nu)$ were used to separate the flavours using the methods described in ref. [3]. The probability functions $\rho_i(\langle M \rangle, p_T(\mu), p_T(\nu))$ were calculated using the simulating programme for uds ($i=1$), c ($i=2$) and b ($i=3$) quarks. These distributions are quite different for each flavour and the projections onto the three axes, $\langle M \rangle$, $p_T(\mu)$ and $p_T(\nu)$, are shown in fig. 1.

Different models^{#1} were used to establish the sensitivity to assumptions about QCD and the fragmentation process, although these transverse quantities were specially selected due to their insensitivity to fragmentation distributions. From this point of view, variables like sphericity, thrust or jet invariant mass were found to be too sensitive to QCD and fragmentation and were discarded.

The electroweak induced charge asymmetry A , for

^{#1} We used the Lund model including 2nd order QCD process and compared the effects of soft, flat and hard fragmentation functions for the heavy quarks [5].

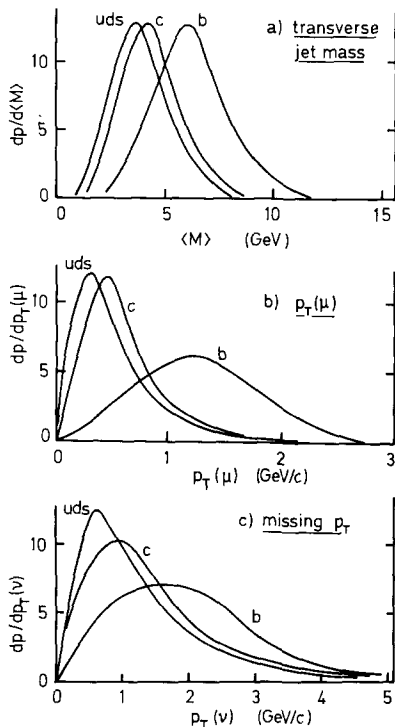


Fig. 1. The probability distribution functions for the three flavour classes uds, c and b. The distributions are plotted as a function of (a) transverse jet mass (b) $p_T(\mu)$ and (c) $p_T(\nu)$. All curves are normalised to the same area.

a fermion-antifermion pair $f\bar{f}$ is defined in terms of the number of fermions produced in the electron direction N_f^F (forward) and the number produced in the positron direction N_f^B (backward) thus $A = (N_f^F - N_f^B) / (N_f^F + N_f^B)$. It is proportional to the ratio of weak axial to electric charge, viz a_f/Q_f , and this quantity is positive for all fermions in the standard model. Thus all fermion asymmetries are negative due to the negative sign of the Z propagator amplitude.

However, a μ^- flags either a b or a \bar{c} and these have opposite asymmetries which tend to cancel if no attempt is made to separate the b and \bar{c} contributions. The aim of the analysis is to discriminate against the two contributions and to identify the b component.

The measurement was made using the JADE detector, a solenoidal spectrometer at PETRA. The apparatus has been described elsewhere [6] and only a summary of its features is given here.

A cylindrical jetchamber, situated in a magnetic field of 4.8 kG was used to measure the vector mo-

menta and charges of the charged final state particles.

An array of lead glass blocks, in the form of a cylinder with planar end caps detected photons and electrons, which together with the charged particle detection, allowed a good reconstruction of the jets and their axes. The accuracy with which the parton direction can be reconstructed is about 5° and this is the major source of error in $p_T(\mu)$. One of the advantages of $\langle M \rangle$ however, is that it is insensitive to the error on the parton axis.

The JADE muon filter, which is a segmented system with five layers of absorber and drift chambers, covers a solid angle of 92% of 4π . The lead glass, the magnet return yoke and the muon filter absorber present a total of at least six absorption lengths, depending on angle, to particles emanating from the interaction point. The selection of muon tracks has been described in earlier publications [4,7,8]. For this analysis, the muon candidate was required to have a momentum of at least 1.8 GeV/c. This cut substantially reduces the background from π and K decay and punch through but has little effect on muons coming from the weak decay of high momentum particles with a mass of about 5 GeV (i.e. B mesons).

The data used for this analysis were collected up to the summer of 1983 and correspond to an integrated luminosity of 76 pb^{-1} . From the sample of multihadronic events with the PETRA beam energy above 15 GeV, 1780 events were selected containing a muon candidate together with hadrons which satisfied the standard JADE visible energy and longitudinal momentum balance criteria [9]. The average CM energy of this sample was 34.6 GeV.

Further selections were made on the events to purify the sample. Events were rejected if the event contained six or fewer particles. This cut removed 16 events with poorly measured $\langle M \rangle$ due to the low multiplicity.

When a π or K meson decays into a muon within the JADE detector, this sometimes manifests itself as a kinked track which does not extrapolate to the vertex and can be rejected. If, however, the kink is of the same order as the curvature, then the reconstructed momentum can be abnormally high and so any muon candidate with a momentum above 10 GeV/c was rejected. This selection removed a further 35 events.

Monte Carlo studies showed that this cut is four times more likely to remove a background muon from a uds

event than a genuine muon from a c or b event. Moreover, π or K decay muons from b decays were also removed preferentially. The sample now contained 1729 events. The fraction of $b\bar{b}$ events in this sample was estimated from Monte Carlo studies to be 19% which can be compared with about 9% $b\bar{b}$ in a random sample of hadronic events.

The polar angle θ of the final state $q\bar{q}$ system was estimated using the sphericity axis. If the event had a μ^- in the direction of the e^- beam or a μ^+ in the direction of the e^+ beam, then $\cos \theta$ was defined to be positive. Conversely, if the event had a μ^+ in the e^- direction or a μ^- in the e^+ direction, then $\cos \theta$ was defined to be negative.

The three main processes are described by the probability distributions ρ_1, ρ_2 and ρ_3 as follows:

ρ_1 : $uds \rightarrow$ background “ μ ”

(punch through and decays),

ρ_2 : $c \rightarrow$ direct μ + hadrons,

ρ_3 : $b \rightarrow$ direct μ + hadrons.

In addition, there are three more combinations corresponding to further sources of muons in the sample:

ρ_{32} : $b \rightarrow c \rightarrow \mu$ cascade decays ,

ρ_{31} : $b \rightarrow$ hadrons \rightarrow background “ μ ” ,

ρ_{21} : $c \rightarrow$ hadrons \rightarrow background “ μ ” .

In each case, the $\langle M \rangle$ distribution is determined by the appropriate parent quark whereas the $p_T(\mu)$ distributions depend on the particular source of muon. The data were split into forward ($\cos \theta > 0$) and backward ($\cos \theta < 0$) samples which were simultaneously fitted using maximum likelihood in $\langle M \rangle$ and $p_T(\mu$ and $\nu)$ space to the following functions:

$$d^2N^F/d\langle M \rangle dp_T = N_1\rho_1 + N_c^F\rho_2 + N_b^F\rho_3 + (\epsilon_1 N_c^{F+B}\rho_{21} + \epsilon_2 N_b^B\rho_{32} + \epsilon_3 N_b^{F+B}\rho_{31}), \quad (1a)$$

$$d^2N^B/d\langle M \rangle dp_T = N_1\rho_1 + N_c^B\rho_2 + N_b^B\rho_3 + (\epsilon_1 N_c^{F+B}\rho_{21} + \epsilon_2 N_b^F\rho_{32} + \epsilon_3 N_b^{F+B}\rho_{31}). \quad (1b)$$

The terms in the brackets represent corrections to the

three main contributions. The ρ functions and the quantities $N_1, \epsilon_1, \epsilon_2$ and ϵ_3 were all determined from the Monte Carlo simulation of inclusive muon events. The final results for N_b^F and N_b^B are insensitive to changes in N_1 because the $\langle M \rangle$ and p_T distributions for uds are so different from those for b. The results for N_c^F and N_c^B are however highly correlated with the amount of uds background N_1 due to the similarity in the $\langle M \rangle$ and p_T distributions. For this reason, a statistically significant result is only obtained for the b quark whereas the error on the c quark asymmetry, taking correlations into account, is over 25%.

The combined forward and backward yields for the direct b quark signal was found to be 305.9 ± 20.5 . The same percentage error would be obtained from 223 events without background and so the presence of background has reduced the effective statistics.

The results of the fit, plotted as a function of $\langle M \rangle$, $p_T(\mu)$ and $p_T(\nu)$ are shown in fig. 2. The good agreement between data and fitted functions in the detailed shape of the spectra gives confidence that the data are well understood in terms of these variables.

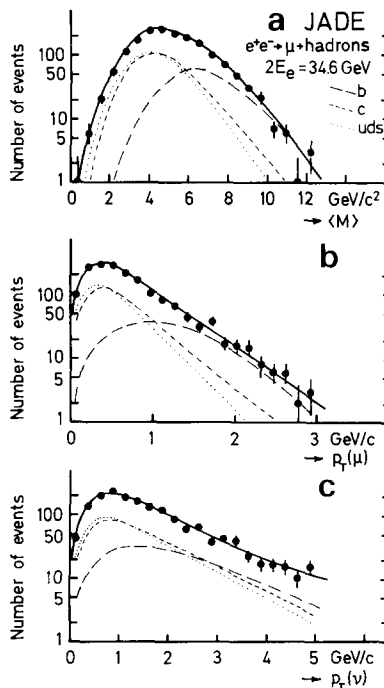


Fig. 2. The data plotted as a function of (a) transverse jet mass (b) $p_T(\mu)$ and (c) $p_T(\nu)$. The curves are the result of the fit described in the text.

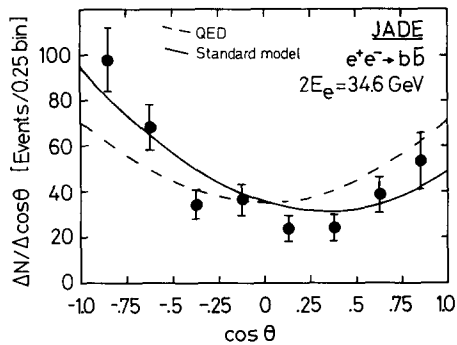


Fig. 3. The extracted angular distribution for $b\bar{b}$ events. The dashed curve is proportional to $1 + \cos^2\theta$ (no asymmetry) and the solid curve is the prediction of the standard model at 34.6 GeV, namely $N[\frac{3}{8}(1 + \cos^2\theta) + 0.252 \cos\theta]$. The data points at the two extreme values of $\cos\theta$ have been corrected for acceptance.

The numbers for forward and backward b events were found to be

$$N_b^F = 114.6 \pm 12.5, \quad N_b^B = 191.3 \pm 16.2,$$

yielding an asymmetry uncorrected for acceptance, of $(-25.0 \pm 6.5)\%$. Fits were also carried out in smaller angular intervals than the forward and backward hemispheres to obtain the overall $b\bar{b}$ angular distribution and to check that the asymmetry did not arise from a small region of the detector. The result is shown in fig. 3.

The normalized angular distribution (probability distribution) for flavour f , including electroweak terms is $\rho_f(\cos\theta) = \frac{3}{8}(1 + \cos^2\theta) + A_f \cos\theta$, where A_f is the asymmetry for flavour f . Having established the existence of a statistically significant asymmetry, a likelihood fit was carried out to the whole data sample including the appropriate angular function as follows.

$$\mathcal{L} = \prod_{j=1}^{N \text{ events}} \frac{1}{N} [N_1 \rho_1 \rho_{uds}(\cos\theta_j) + N_c \rho_2 \rho_c(\cos\theta_j) + N_b \rho_3 \rho_b(\cos\theta_j) + O(\epsilon)].$$

The result for the b quark (which now does not depend on acceptance [10]) was

$$A_b = (-22.8 \pm 6.0)\%.$$

According to the fit, the b asymmetry is based on 252 direct events and 54 cascade events and in the absence of any background, the statistical error on the asym-

metry A [10]^{‡2} would be given by $\sigma^2 = \frac{1}{306}(\frac{7}{8} - \frac{4}{3}A^2)$. This gives an error of 5.1%, which has increased to 6.0% as a result of fitting in the presence of a background.

Two sources of systematic error have been considered. (a) The different models^{‡1} for the fragmentation process were tried and the results propagated through to the final asymmetry where changes of 2–3% were observed. (b) The coefficients $\epsilon_{1,2,3}$ introduce a slight dependence on the absolute value of the branching ratio for $B \rightarrow \mu X$. Taking the world average [11] of $11.6 \pm 0.5\%$ for this quantity and propagating the error leads to an additional error of less than 1% on the asymmetry. The overall systematic error is thus about 2.5%.

Further checks were made on the muon sample to ensure that the asymmetry does not arise from detector biases. The total number of forward muons of both charges was compared with the total number of backward muons and a computed asymmetry of $A_{FB} = (1.0 \pm 2.4)\%$ was found. Charge conservation says that the total number of μ^+ and μ^- should be equal and a measured asymmetry of $(3.9 \pm 2.4)\%$ was observed. Both of these measurements are consistent with the expectation of zero and give confidence that neither the acceptance nor the detection of muons is biased.

The standard model prediction for the b asymmetry with $a_b = -1$, $Q_b = -\frac{1}{3}$ and $\sin^2\theta_w = 0.23$ is -25.2% . This number is only 2.8 times the $\mu^+\mu^-$ asymmetry (and not 3 as expected from the ratio of charges) due to the significant mass of the b quark. Our result is in good agreement with this prediction. The existence of rapid $B^0\bar{B}^0$ mixing would reduce this number further to about -12% and so our measurement rules out such mixing at the 90% confidence level. Rapid mixing means that the product of the interaction rate and the B^0 lifetime is much greater than one. A similar result has been obtained by the CLEO collaboration [12].

Our measured value can be used to determine a value for the ratio of the b weak axial to electric charge a_b/Q_b . Assuming $a_e = -1$ we find

$$a_b/Q_b = -2.71 \pm 0.71 \text{ (stat)} \pm 0.30 \text{ (syst)}.$$

Assuming $a_b = a_e = -1$, the result determines the b

^{‡2} This formula for the error is a good approximation for $|A| < 0.7$.

electric charge as follows:

$$Q_b = -0.37_{-0.07}^{+0.13} (\text{stat}) \pm 0.03 (\text{syst}),$$

which is consistent with charge $-\frac{1}{3}$ for the b quark.

Finally, assuming $Q_b = -\frac{1}{3}$, the value for the b weak axial charge is

$$a_b = -0.90 \pm 0.24 \pm 0.10.$$

We acknowledge the efforts of the PETRA machine group who provided us with the opportunity of doing this experiment, and also the efforts of the technical support groups of participating institutes in the construction and maintenance of our apparatus. The experiment was supported by the Bundesministerium für Forschung und Technologie, by the Education Ministry of Japan, and by the UK Science and Engineering Research Council through the Rutherford Appleton Laboratory. The visiting groups at DESY wish to thank the DESY directorate for their hospitality.

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