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A measurement of the charge asymmetry of hadronic events in electron positron annihilation

JADE Collaboration

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Abstract. The quark charge asymmetry, summed over flavours, has been measured at centre of mass energies of 35 GeV and 44 GeV using the JADE detector sited on the electron-positron storage ring PETRA. The asymmetry is found to be consistent with the expectations of the standard model at both energies and enables a measurement of the product of the axial-vector coupling constant of the electron with the axial-vector coupling constants of the quarks, assuming the moduli of these latter to be flavour independent. This gives, with reasonable assumptions concerning the effects of $B^0\overline{B^0}$ mixing, $a_e a_q = -1.09 \pm 0.18 \pm 0.23$ where the first error is statistical and the second systematic.

Introduction

The existence of the asymmetry predicted by the standard model in the polar angle distribution of μ and τ pairs produced in electron-positron annihilation is now well established [1]. Measurements of the asymmetries of the heavy quarks, using various techniques to identify the quarks in question, have also been made [2]. This paper describes a measurement of the charge asymmetry arising from the production of all five quark flavours at two centre of mass energies, 35 GeV and 44 GeV, performed at the PETRA storage ring by the JADE collaboration.

The standard model predicts that the cross-section for quark production in electron positron annihilation be [3]

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(a(1+\cos^2\theta) + b\cos\theta)$$

where

$$a = e_q^2 - 2e_q v_e v_q \mathcal{R}(\chi) + (v_e^2 + a_e^2)(v_q^2 + a_q^2)|\chi|^2,$$
$$b = -4e_q a_e a_q \mathcal{R}(\chi) + 8v_e v_q a_e a_q |\chi|^2$$

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and

$$\chi=\frac{G_F M_Z^2}{8\pi\alpha\sqrt{2}}\,\frac{s}{(s-M_Z^2+iM_Z\Gamma_Z)}.$$

In the above expressions θ is the angle between the electron and quark directions, e_q the quark charge, v_e and v_q are the vector and a_e and a_q the axial coupling constants of the electron and quark respectively. The forward backward asymmetry is defined as

$$A=\frac{1}{\sigma}\left(\int_0^{+1}\frac{d\sigma}{d(\cos\theta)}\,d(\cos\theta)-\int_{-1}^{0}\frac{d\sigma}{d(\cos\theta)}\,d(\cos\theta)\right).$$

This gives

$$A=\frac{3}{8}\frac{b}{a}\approx-\frac{3}{2}\frac{a_e a_q}{e_q}\,\mathcal{R}(\chi).$$

If the quark flavours are produced in the proportions f_d, f_u, f_s, f_c and f_b with asymmetries A_d, A_u etc. and defining θ to be the angle between the positively charged quark or anti-quark direction and that of the positron, the hadronic asymmetry is then

$$A_h=f_d A_d-f_u A_u+f_s A_s-f_c A_c+f_b A_b,$$

the negative signs arising because of the quark charges. At a centre of mass energy of 35 GeV and using $M_Z=91.9$ GeV the expressions above give $A_h \approx 0.030$, while at 44 GeV $A_h \approx 0.061$.

The measurement of the asymmetry

The measurement described here was made using data collected by the JADE experiment in the years 1980 to 1986, during which time PETRA was operated at centre of mass energies ranging from 32.0 to 46.7 GeV. In total 160 pb^{-1} were collected at energies around 35 GeV and 30 pb^{-1} at energies around 44 GeV.

The components of the JADE detector which are of interest in the following are the jet chamber, which is situated in a 0.48 T magnetic field and enables the measurement of the charges and the momenta of charged particles, and the array of lead glass blocks which surrounds the jet chamber and serves as an electromagnetic calorimeter. This latter is divided into a cylindrical barrel section and two end caps. A more detailed description of the detector is given in [4] and the trigger conditions are described in [5]. Multihadronic events were selected by requiring that:

a) The energy deposited in the lead glass exceed 3 GeV in the barrel part or 0.4 GeV in each of the endcaps.

b) At least four charged tracks originating from the interaction region be present, the topology three tracks opposite one track being excluded in order to reduce the tau pair contamination.

c) The visible energy $E_{\mathrm{vis}}=\Sigma p_i$, where the p_i, are the particle momenta and the sum runs over all charged and neutral particles, be greater than the beam energy.

d) The absolute value of the momentum balance $p_{\mathrm{bal}}=\Sigma p_i^z/E_{\mathrm{vis}}$ be less than 0.4, the p_i^z being the components of the charged and neutral track momenta along the beam direction.

Remaining cosmic ray, purely leptonic QED events and most of the tau pair background were removed in a visual scan. The events used in this analysis were required to satisfy the following further criteria:

e) Two jet topologies were selected by requiring that the sphericity of the event, calculated using charged tracks only, be less than 0.1. This reduces the problems associated with identifying the direction of flight of the quark and anti-quark and also reduces the influence of QCD on the asymmetry.

f) The two jets of each event were separated using a plane passing through the interaction point and perpendicular to the sphericity axis, one jet was required to contain at least four charged particles of momentum greater than 0.2 GeV/c and originating from the interaction point and the other at least three charged particles satisfying the same criteria. The tau pair contamination in the event sample was thus reduced to a negligible level.

g) To ensure that the jets were well defined it was required that the summed charged momentum in each jet exceed one fifth of the beam momentum, only charged particles with momenta greater than 0.2 GeV/c being used to form the sums.

The resulting data samples contained 15615 and 3224 events at energies around 35 GeV and 44 GeV respectively.

In outline the analysis was performed as follows. The charges of the partons which gave rise to the jets, defined as above, were deduced from the charges and momenta of the hadrons in the jets and the direction of the positively charged parton was determined. The angular distribution of this direction for the events studied was then used to determine the asymmetry. As identifying the positive direction, that of the positive parton, on an event by event basis proved to be impossible, the weight technique discussed in

[6] and used in a previous JADE analysis [7] was used to make the identification on a statistical basis.

Three variables were studied to determine which of them enabled the clearest identification of the positive direction. These were:

(a) The "jet charges" as originally proposed by Field and Feynman [8] and recently used by the MAC collaboration in a similar study [9], namely the sums $\Sigma q_i \eta_i^\gamma$ over all particles in each jet, where q_i is the charge of the i^{th} particle in the jet, η its rapidity and γ an index chosen to maximise the effectiveness of this variable. The γ value which maximised the probability of correct jet charge identification was determined using Monte Carlo studies and was about 0.4 with the event selection criteria listed above.

(b) The products of the charges and rapidities of the three particles in each jet with the largest $|p_l|$, where p_l is the momentum component along the sphericity axis.

(c) The z values of the particles used in (b), where z is defined as

$$z=\frac{qp_l}{E_b},$$

q being the particles charge and E_b the beam energy. For the selected events (b) and (c) proved to be approximately equally efficient identifiers of the positive direction, while (a), at least at PETRA energies, was not quite as effective. In the following the last named of the above variables was used, the z values in each jet being ordered such that $|z_1|>|z_2|>|z_3|$.

The necessary distributions of the quantities mentioned above were obtained using a Monte Carlo program which included QED effects to order α^3 [10], perturbative QCD to order α_s^2 and simulated the fragmentation process according to the Lund 5.2 scheme [11] using the Peterson fragmentation function [12] for the heavy quarks. All the events produced using this Monte Carlo were tracked through the JADE detector by a further simulation program and then underwent the same selection procedures as applied to the data. That this results in accurate simulation of the data may be seen in Fig. 1 in which, for the lower energy, the marginal distributions of z_1, z_2 and z_3 from the data and Monte Carlo are compared. Similar agreement was obtained at the higher energy.

The determination of the $\cos\theta$ distribution of the positive direction in the data was performed as follows. The sphericity axes of the Monte Carlo events were assigned a sense such that $\cos\theta>0$, that is they point in the forward direction. The distributions of z_1, z_2, z_3 in jet one, that in the forward direction and z_1, z_2, z_3 in jet two, that in the backward direction, were determined for events in which the positive parton travelled in the forward direction and for events in which it travelled in the backward direction. The first of these distributions was termed f_+ and the second f_-. The projections of the f_+ distribution at 35 GeV onto the z_1, z_2 and z_3 axes are shown in Fig. 2. These distributions were used to form the weight function

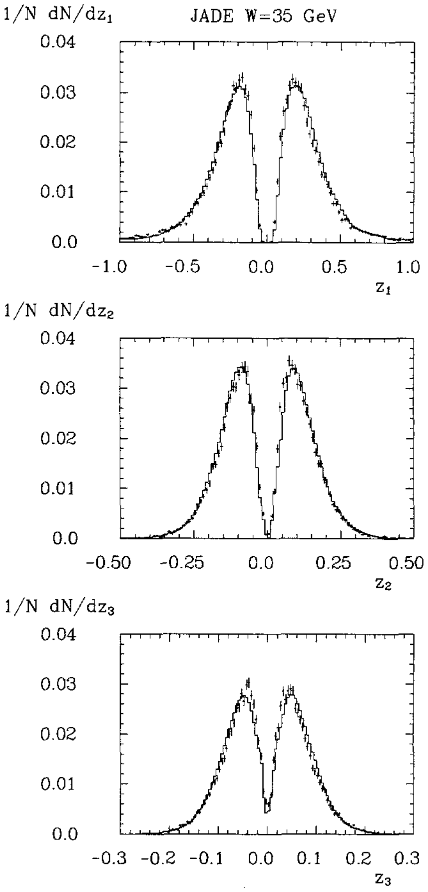

Fig. 1. A comparison on Monte Carlo (histogram) and data (points with error bars) marginal z_1, z_2 and z_3 distributions at a centre of mass energy of 35 GeV

$$W((z_1,z_2,z_3)_1,(z_1,z_2,z_3)_2)=\frac{f_+((z_1,z_2,z_3)_1,(z_1,z_2,z_3)_2)}{f_+((z_1,z_2,z_3)_1,(z_1,z_2,z_3)_2)+f_-((z_1,z_2,z_3)_1),(z_1,z_2,z_3)_2)}.$$

In the data events the sphericity axes were assigned a sense and the z values in jets one and two determined as above. The weight function then represents the probability that, in a data event with discriminator variable values $(z_1,z_2,z_3)_1$ in jet one and $(z_1,z_2,z_3)_2$ in jet two, the positive parton travelled in the forward direction. In a sample of N events, an estimate of the number of events in which the positive parton travelled in the forward direction is

$$N_+ = \sum_{i=1}^{N} \frac{W_i - \overline{W_-}}{\overline{W_+} - \overline{W_-}},$$

where W_i is the value of the weight function for event i and the quantities

$$\overline{W_+} = \int_{-1}^{+1} \dots \int_{-1}^{+1} W f_+ (dz_1, dz_2, dz_3)_1, (dz_1, dz_2, dz_3)_2$$

and

$$\overline{W_-} = \int_{-1}^{+1} \dots \int_{-1}^{+1} W f_- (dz_1, dz_2, dz_3)_1, (dz_1, dz_2, dz_3)_2$$

must be calculated from the appropriate Monte Carlo distributions. The remaining $N_- = N - N_+$ events are those in which the positive parton travelled in the backward direction. At both 35 GeV and 44 GeV the data were analysed in $|\cos\theta|$ bins of width 0.2, the values of N_+ and N_- were determined and plotted at the relevant $\cos\theta$. These plots, corrected for acceptance effects and normalised, are shown in Fig. 3. The errors are approximately a factor 1.7 larger than those that would be obtained if the charges of the quarks were directly measurable, this factor being slightly dependent on $|\cos\theta|$. This is in agreement with calculations of the expected error which were performed using the $\overline{W_+}$ and $\overline{W_-}$ values and the variances of the f_+ and f_- distributions.

The radiative corrections that influence A_h were studied using Monte Carlo data. The net effect of the corrections is a reduction in the individual quark asymmetries, but when these are added to form A_h the radiative corrections cancel to a large extent, leaving A_h almost unaffected. QCD effects are stongly suppressed as a result of the two jet nature of the events selected [13].

The pronounced two jet structure of the events also ensures that the sphericity axis accurately represents the direction of flight of the quarks. As a result of this the effect on A_h of approximating the quark direction using the sphericity axis is negligible as was checked using Monte Carlo studies.

The asymmetries were determined by fitting the positive direction distributions, obtained as described above, to their expected Standard Model form with the asymmetry as a free parameter. The results were $A_h = 0.060 \pm 0.013$ at a mean centre of mass energy

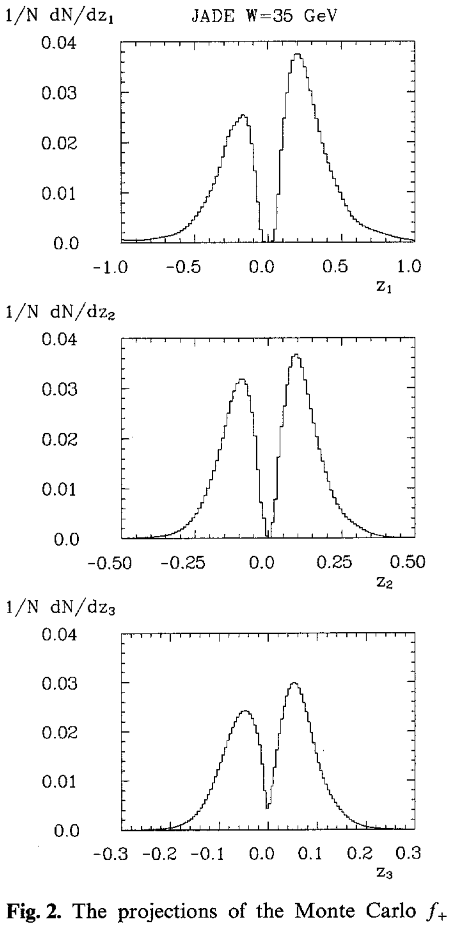

Fig. 2. The projections of the Monte Carlo f_+ distribution at a centre of mass energy of 35 GeV on the z_1, z_2 and z_3 axes

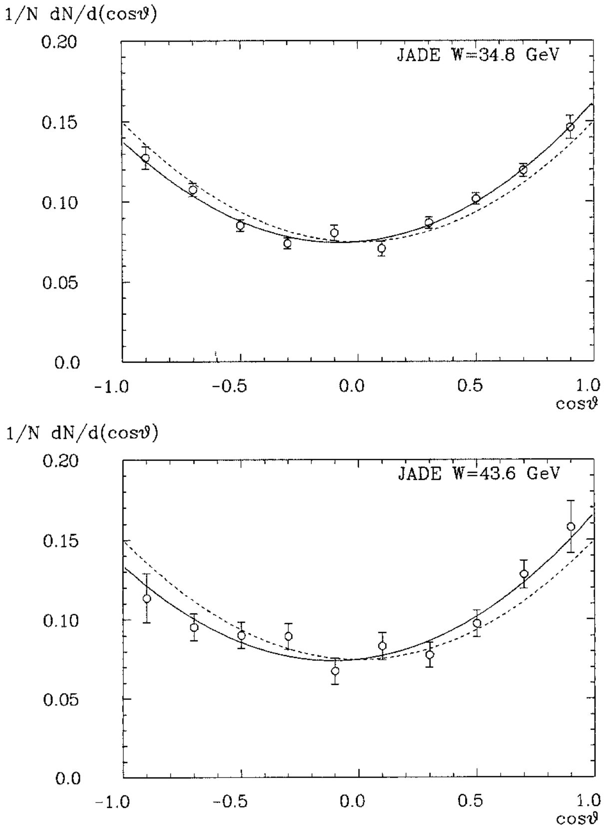

Fig. 3. The acceptance corrected $\cos\theta$ distribution of the direction of the positive parton, at 34.8 GeV (upper figure) and at 43.6 GeV (lower figure). The solid lines are fits to the data with asymmetries of 0.060 and 0.082 respectively and the dotted lines are fits with the asymmetry set to zero

of 34.8 GeV and $A_h = 0.082 \pm 0.029$ at 43.6 GeV. These are to be compared with the standard model expectations of 0.048 and 0.079 respectively, where the influence of $B^0 \overline{B^0}$ mixing has been neglected. The standard model expectations are somewhat larger than those quoted in the introduction as the applied event selection criteria, particularly the requirement that the sphericity be less than 0.1, alter the relative proportions of the quark flavours. The proportion of b events is strongly reduced as the large Q value of the b decay tends to give these events a spherical topology.

The statement concerning the assumptions made on $B^0 \overline{B^0}$ mixing is not superfluous as, coupled with the fact that practically all the particles used in the positive direction determination in b events come from the decay of the hadron containing the primary quark, such mixing would tend to reduce the magnitude of the measured asymmetry, A_b', as compared to the standard model expectation, A_b. The reduction factor is given by

$$A_b' = (1 - 2(R_d^0\, \chi_d + R_s^0\, \chi_s))\, A_b$$

where the R's are the proportions of B_d^0 and B_s^0 mesons and their conjugate partners produced in the fragmentation of b quarks, χ_d is the mixing parameter

$$\chi_d = \frac{\Gamma(B_d^0 \to \overline{B_d^0})}{\Gamma(B_d^0 \to B_d^0) + \Gamma(B_d^0 \to \overline{B_d^0})}$$

and χ_s is given by the equivalent expression for B_s^0 mesons. In the above it has also been assumed that the z_1, z_2, z_3 distributions arising from the decay of $b\bar{d}, b\bar{s}$ and $b\bar{u}$ mesons are similar. Monte Carlo studies showed this to be a reasonable first approximation. A measurement by the ARGUS group [14] gives $\chi_d = 0.17$ and it is likely that mixing in the $B_s^0 \overline{B_s^0}$ system is maximal. This is certainly compatible with a recent UA1 measurement [15]. Using the ARGUS result, assuming full mixing in the B_s^0 system, that is $\chi_s = 0.5$, and taking R_d^0 and R_s^0 from the Lund Monte Carlo gives a reduction factor of $A_b' \approx 0.75\, A_b$. A further correction must be made as the occurrence of b events containing two B^0's or $\overline{B^0}$'s was not allowed for in calculating $\overline{W}_+$ and $\overline{W}_-$, this however only changes the result by less than 1% of A_h. Inserting the above in the calculation of the standard model expectations for A_h gives $A_h = 0.050$ at 34.8 GeV and $A_h = 0.085$ at 43.6 GeV. Comparison of these numbers with the expectations without mixing shows that the effect is unfortunately too small to be measureable with the data available.

It would be possible to increase the statistical significance of the measurements of A_h described above by performing the analysis in eight dimensions, that is by obtaining the asymmetries directly from a fit involving the discriminator variables used above, $\cos\theta$ and the sphericity. This was considered unnecessary as the statistical error on the axial-couping constant measurement is already smaller than the systematic error arising from the sources discussed below.

In order to check the above analysis several independent measurements of A_h were made using a subset of the 35 GeV data. The methods used were quite different to those described above. The most accurate of these determinations of A_h is described below. The events used in the measurement were required to fulfil the following conditions:

a) They had to contain at least five charged particles and at least three photons, none of which was allowed to have an energy greater than half the beam energy.

b) The sphericity of the events, calculated using all charged and neutral tracks, was required to be between 0.01 and 0.25 and the sphericity axis to lie in the angular region $|\cos\theta| < 0.8$.

c) Each jet, defined using a plane perpendicular to the sphericity axis and passing through the interaction point, was required to contain at least 4 particles of which at least one had to be charged, one to have a momentum greater than 1.2 GeV/c and one to have a rapidity of modulus at least 1.5.

d) The summed energy of the particles in each jet was required to exceed three tenths of the beam energy and the sum of the moduli of the momenta of the charged particles to exceed 1.4 GeV/c.

e) The sum of the charges of the particles in a jet with a rapidity of modulus at least 0.75 was termed the jet charge and was required to be less than six. The modulus of the difference of the two jet charges was required to be at least two.

The resulting data sample contained 5165 events. The sphericity axis was assigned the sense of the positive jet and A_h determined from a fit to the $\cos\theta$ distribution of the direction of the sphericity axes. The result was $A_h = 0.038 \pm 0.015$. This should not be compared directly with the result of the first analysis at 34.8 GeV as it has not been corrected for the positive direction mis-identification probability. In addition the flavour proportions present in the two data samples are different. It may however be compared with the result obtained by applying the above procedure to Monte Carlo events generated including the effects of electroweak interference, namely $A_h = 0.036 \pm 0.009$.

The agreement of the expectations of the standard model with the measurements, regardless of the details of the analyses, was considered to support the contention that the measured asymmetry is indeed a result of an asymmetry at the patron level and is not an artefact of the analysis. Further, that the nonzero A_h value be due to asymmetries in the apparatus can be ruled out as such asymmetries have been searched for using muons in both multihadronic [16] and dimuon [17] events. No asymmetries could be found.

Using the first asymmetry measurements and assuming that

$$a_u = -a_d = a_c = -a_s = -a_b \equiv a$$

the value of the product $a_e a$ was obtained at both energies by comparison with the standard model expression for the asymmetry. Ignoring the effects of $B^0\overline{B^0}$ mixing, at a mean centre of mass energy of 34.6 GeV $a_e a = -1.22 \pm 0.24$, while at a mean centre of mass energy of 43.6 GeV $a_e a = -1.03 \pm 0.30$. If the previously described assumptions concerning $B^0\overline{B^0}$ mixing are made, these results become $a_e a = -1.16 \pm 0.24$ and $a_e a = -0.97 \pm 0.30$ respectively.

Systematic effects were investigated by repeating the analysis after varying various fragmentation parameters in the Monte Carlo simulation. The parameter found to have the most influence on the above results was the proportion of s quarks relative to u and d quarks produced from the vacuum in the fragmentation process. This is understandable as this ratio influences, among other things, the probability of producing neutral as opposed to charged mesons, which has a direct effect on the positive direction determination. Parameters affecting the momentum distribution of the final state particles, for example the values of ε_c and ε_b used in the Peterson fragmentation function, also slightly affected the positive direction determination and thus give a contribution to the systematic error. Combining the above and including in the systematic error a reasonable estimate of the effects of the uncertainties in the $B^0\overline{B^0}$ system gives

$$a_e a = -1.09 \pm 0.18 \pm 0.23$$

where a correction for mixing effects has been applied using the assumptions listed above.

Summary

A study of the charge asymmetry of hadronic events in electron-positron annihilation enabled the determination of the product of the axial-vector coupling constant of the electron with that of the quarks at centre of mass energies of 34.8 GeV and 43.6 GeV. The asymmetries determined were $A_h = 0.060 \pm 0.013$ at the lower energy and $A_h = 0.082 \pm 0.029$ at the higher energy, which are to be compared with the standard model expectations, including reasonable assumptions concerning the mixing in the $B^0\overline{B^0}$ system, of $A_h = 0.050$ and $A_h = 0.085$ respectively. The resulting values of the product of the axial-vector coupling constants are in agreement with the standard model value of $a_e a = -1$ at both energies and with a previous measurement made by the MAC collaboration [9], the result of which was $a_e a = -1.36 \pm 0.24 \pm 0.20$. Combining the JADE measurements gives

$$a_e a = -1.09 \pm 0.18 \pm 0.23$$

where the above mentioned assumptions concerning the effects of $B^0\overline{B^0}$ mixing have been made.

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