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A Measurement of the $e^+e^- \to b\bar{b}$ Forward-Backward Charge Asymmetry at $\sqrt{s} = 29\,\mathrm{GeV}$*

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Abstract

High $p_\perp$ inclusive muon events produced in e^+e^- annihilations at $\sqrt{s} = 29\,\mathrm{GeV}$ have been analyzed to obtain a measurement of the $b\bar{b}$ forward-backward charge asymmetry. The result $A_b = 0.034 \pm 0.070 \pm 0.035$ differs from the theoretical expectation (-0.16) unless substantial B^0-$\bar{B}^0$ mixing is assumed.

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The standard model predicts a forward-backward asymmetry in the production of $b\bar{b}$ events in electron-positron annihilations as a result of interference between the electromagnetic and weak production processes [1]. This asymmetry may be measured using the charge of a decay muon to discriminate between the b quark and $\bar{b}$ antiquark. In the presence of B^0-$\bar{B}^0$ mixing the asymmetry observed by this technique is reduced [2–3], thus a measurement of the asymmetry provides an indirect measure of mixing.

A measurement of the forward-backward asymmetry has been performed with inclusive muon multihadron data recorded by the MAC detector from $310\,\mathrm{pb}^{-1}$ accumulated luminosity. Events were produced in electron-positron annihilations at 29 GeV in the PEP storage ring at the Stanford Linear Accelerator Center. The MAC detector is described in detail elsewhere [4]. A brief description of the components most important for this measurement is given here. The central detector is a ten-layer drift chamber in a reversible axial magnetic field of 5.7 kG with six layers at angles of $\pm 3°$ to the beam axis and with the first and last layers at radii of 12 and 45 cm respectively. The vertex chamber inside the central detector has six layers of thin-walled axial drift tubes. Calorimeters covering 98% of the solid angle surround the central detector. The barrel calorimeter has an electromagnetic shower detector of lead interspersed with proportional wire chambers, comprising a total of 14 radiation lengths. The hadronic barrel and end-cap calorimeters are constructed of alternating layers of steel and proportional wire chambers. Penetrating particles traverse an average of ~6.5 nuclear interaction lengths in the calorimeters. The small inner diameter of the calorimeters reduces the path length available for decays of pions and kaons into muons. The steel of the hadronic calorimeter is toroidally magnetized to 17 kG; the toroid field is also reversible. The entire calorimetric detector is surrounded by an outer drift chamber system consisting of four to six layers that measures the exit polar angles of muons traversing the steel and consequently muon momenta to ~25%.

Muons are identified [5] over 95% of the solid angle by requiring: (1) consistent measurements of the muon momentum vector from independent reconstruction in the inner and outer drift chambers; (2) energy deposition in the hadron calorimeter consistent with the passage of a minimum ionizing particle; (3) $2 < p < 10$ GeV/c, where p is the weighted average of the two independent momentum measurements; and (4) $p_{\perp}/p > 0.1$, where $p_{\perp}$ is the transverse momentum relative to the thrust axis. The last requirement removes the 'fake' muon background in the core of the jet and reduces background from charm decays. The thrust axis [6] is determined from energy deposition in the calorimeters with muon-associated calorimeter energy augmented to correspond to the measured muon momentum. To have greater assurance of the reliability of the thrust axis reconstruction, events are rejected if the thrust is less than 0.72 or if the thrust axis is within 30° of the beam axis.

The angular distribution of initial $\bar{b}$ antiquarks is predicted by the standard model to be

$$\frac{d\sigma(e^+e^- \to b\bar{b})}{d(\cos\theta)} = \frac{\pi\alpha^2}{2s} R_b \left(1 + \cos^2\theta + \frac{8}{3} A_b \cos\theta\right) \tag{1}$$

where θ is the angle between the $\bar{b}$ and the incident e^+ direction, A_b is the b-quark forward-backward asymmetry for full acceptance, s is the square of the center-of-mass energy, and $R_b = \sigma\left(e^+e^- \to b\bar{b}\right)/\sigma\left(e^+e^- \to \mu^+\mu^-\right)$. The forward-backward asymmetry is defined as

$$A_b = \frac{N_F - N_B}{N_F + N_B}$$

where N_F and N_B are the numbers of initial $\bar{b}$ antiquarks produced in the *forward* ($\theta < 90°$) and *backward* ($\theta > 90°$) hemispheres. Higher order QED corrections to Eq. 1 are negligible in this analysis because angles close to the beam axis are excluded and because of the large b quark mass [1].

The charge of a muon which is produced by semileptonic decay of the heavy hadron is used to infer the charge of the heavy quark and therefore discriminate $\bar{b}$ from b. The thrust axis approximates the common line of flight of the $\bar{b}$ and b quarks and the direction of the initial $\bar{b}$ antiquark is discerned from the direction and charge of the observed muon. In the presence of B^0-$\bar{B}^0$ mixing a μ^- sometimes is produced from an initial $\bar{b}$ decay instead of a μ^+ thus confusing the quark identification. Therefore the numbers of observed forward and backward events are

$$N_F^{\text{obs}} = N_F - \chi N_F + \chi N_B$$
$$N_B^{\text{obs}} = N_B - \chi N_B + \chi N_F$$

where χ is the mixing parameter defined by

$$\chi = \frac{\Gamma(B \to \mu^- X)}{\Gamma(B \to \mu^\pm X)}.$$

In this definition of χ, B represents an average over all the various beauty hadrons in the data sample. As a result of mixing the observed asymmetry is reduced to

$$A_b^{\text{obs}} = \frac{N_F^{\text{obs}} - N_B^{\text{obs}}}{N_F^{\text{obs}} + N_B^{\text{obs}}} = (1 - 2\chi)A_b. \tag{2}$$

The asymmetry of $b\bar{b}$ events contributes to the asymmetry of the total sample of events

$$A_{\text{tot}} = (\eta_b - \eta_{cb})A_b^{\text{obs}} + \eta_c A_c \tag{3}$$

where η_b, η_{cb}, and η_c are the fractions of $b \to \mu$, $b \to c \to \mu$, and $c \to \mu$ in the sample and A_c is the asymmetry of $c\bar{c}$ events. We assume that the asymmetry of the punch-through and K/π decay background is zero.

The data sample used in the measurement consists of 681 events which pass a b-flavor enrichment cut of $p_\perp > 1.2\,\text{GeV}$. This cut was chosen *a priori* from Monte Carlo studies to maximize the statistical sensitivity of the measurement. The composition of the data sample was predicted from a combination of empirical measurements and Monte Carlo calculations performed with the Lund Monte Carlo [7]. First, the $p_\perp$ spectra were predicted for muons arising from $b \to \mu$, $b \to c \to \mu$, and $c \to \mu$ decays and for 'fake' muons arising from hadron punch-through and K/π decay. These predictions were made from a Monte Carlo sample with a natural mixture of flavors and decay modes and with detailed detector simulation performed with EGS and HETC [8]. Next, the absolute fraction of $b \to \mu$ events was determined by fitting the data $p_\perp$ spectrum with the predicted component spectra. This technique gives a reliable estimate of the fraction of $b \to \mu$ because the shape of that spectrum is quite different from that of the other components and it is largely determined by kinematics; QCD uncertainties are unimportant. Then, the relative proportions of $b \to \mu$, $b \to c \to \mu$, and $c \to \mu$ events in the data sample were predicted from a Monte Carlo sample equivalent to approximately 10 times data luminosity. This Monte Carlo calculation considered only heavy flavor events which decay semileptonically and measurement errors for variables were simulated by empirically determined detector resolutions. Finally, the absolute fractions of $b \to c \to \mu$ and $c \to \mu$ in the data were found by multiplying these relative proportions by the absolute $b \to \mu$ fraction determined above. The predicted fractions of semimuonic decay events in the data are $\eta_b = 0.59 \pm 0.03$, $\eta_{cb} = 0.02 \pm 0.01$, and $\eta_c = 0.16 \pm 0.03$; the remainder is punch-through and K/π decay background. The errors on η_b, η_{cb}, and η_c include contributions from limited Monte Carlo statistics and from uncertainties in branching ratios and fragmentation parameters used in the Monte Carlo. Reference [9] describes some of the checks performed to test the reliability of the Monte Carlo as an accurate model of the data.

The forward-backward asymmetry of the data is found from the maximum of the log likelihood function [10]

$$\ln \mathcal{L}(A_{\text{tot}}) = \sum_{\text{events}} \ln \left[\left(1 + \cos^2 \theta_i\right) + \frac{8}{3} A_{\text{tot}} \cos \theta_i \right]$$

to be

$$A_{\text{tot}} = +0.034 \pm 0.040 \text{ (statistical error only)}.$$

The log likelihood is plotted in Fig. 1. The angular distribution of the data, corrected for acceptance, is plotted in Fig. 2 along with the curve $(1 + \cos^2 \theta + \frac{8}{3} A_{\text{tot}} \cos \theta)$ for the experimental value of A_{tot}. If we use the Monte Carlo predictions for η_b, η_{cb}, and η_c and the standard model values of $A_c = +0.09$[♯1] and $A_b = -0.16$, we expect $A_{\rm tot} = -0.077 \pm 0.006$. The experimental result differs from the theoretical expectation by 2.8σ. Including the effects of B^0-$\bar{B}^0$ mixing with $\chi = 0.21$ (the value measured in a previous MAC analysis [9]) reduces the standard model value of A_b to -0.09 and the expected asymmetry of the data sample is then $A_{\rm tot} = -0.037 \pm 0.004$ (uncertainty in χ ignored) which is 1.8σ from the experimental value.

A check of the analysis procedure was performed with Monte Carlo events generated with the standard model values of electroweak asymmetries but without B^0-$\bar{B}^0$ mixing. The input asymmetries were reproduced within statistical errors. As a further check of our procedure we determined the asymmetry of the sample of events with muon $p_\perp < 1.0$ GeV/c which is expected to be dominated by $e^+e^- \to c\bar{c}$ events. From the Monte Carlo we find $\eta_b = 0.13 \pm 0.02$, $\eta_{cb} = 0.03 \pm 0.01$, and $\eta_c = 0.37 \pm 0.07$ which results in a predicted asymmetry of $A_{\rm tot} = 0.018 \pm 0.007$ if we assume standard model values of A_b and A_c and no B^0-$\bar{B}^0$ mixing effects. Including the effect of B^0-$\bar{B}^0$ mixing ($\chi = 0.21$) changes the prediction only slightly to $A_{\rm tot} = 0.024 \pm 0.007$. For the data we find $A = 0.027 \pm 0.025$ in good agreement with either prediction.

We have performed several checks against bias in the detector and analysis. A sample of 1392 $e^+e^- \to e^+e^-\mu^+\mu^-$ events was analyzed with the same procedure used for the multihadron data. The asymmetry was found to be $A = -0.004 \pm 0.023$ consistent with the expected null result. Multihadron and $e^+e^-\mu^+\mu^-$ asymmetries were also measured with only the positive or negative muons in the events; variations were within 1σ. The magnetic fields in the MAC detector were reversed periodically during the course of data collection to cancel any possible asymmetric bias in the detector; however, as an additional check against detector bias the data were divided into two subsamples, one with each magnetic polarity. No significant differences were found between the asymmetries of the subsamples for either

♯1 In the usual convention A_c is negative; however, in our analysis it is positive since we calculate the asymmetry assuming that the muons result from decays of beauty hadrons.

$e^+e^-\mu^+\mu^-$ or multihadron events. Asymmetry analyses have also been performed on large samples ($> 10,000$) of $\mu^+\mu^-$ and $\tau^+\tau^-$ events [11] collected with the MAC detector concurrently with the multihadron data. Detector bias in those analyses was found to be negligible compared to the statistical precision (± 0.008 for $\mu^+\mu^-$). As a final simple check of bias we note that the total numbers of muons in the forward and backward hemispheres, ignoring muon charge, are 344 and 337 and the total numbers of positively and negatively charged muons, ignoring production angle, are 351 and 330. We conclude that there are no indications of significant bias in the detector or analysis procedure. However, we assign a systematic uncertainty of 0.02 in the asymmetry due to possible detector bias—observed variations in the asymmetries of $e^+e^-\mu^+\mu^-$ subsamples are less than this value.

Solving Eq. 3 for A_b^{obs} and using $A_c = 0.09$ and the Monte Carlo predicted values of η_b, η_{cb}, and η_c we obtain

$$A_b^{\text{obs}} = 0.034 \pm 0.070 \text{ (statistical) } \pm 0.035 \text{ (systematic).}$$

The systematic error is dominated by the contribution from possible detector bias discussed above. A review of other measurements of the b-quark asymmetry is found in reference [12]; the most significant is the measurement of JADE $A_b^{\text{obs}} = -0.228 \pm 0.060 \pm 0.025$ at $\sqrt{s} = 34.6\,\text{GeV}$ [2] (expected value without mixing $= -0.252$).

Our result may be interpreted as a measurement of χ. By using Eq. 2 with $A_b = -0.16$ we obtain $\chi = 0.61 \pm 0.24$; however, it must be noted that the maximum allowed value of χ is 0.5 and that for a data sample containing only neutral B mesons. Nonetheless, this result is indicative of substantial B^0-$\bar{B}^0$ mixing (at 95% confidence level, $\chi > 0.21$). It reinforces our previous result of $\chi = 0.21^{-0.15}_{+0.29}$ based on an analysis of dimuon events [9], but it disagrees with the 90% C.L. limits found by Mark II from dilepton events ($\chi < 0.12$) [13] and by JADE from their measurement of the b-quark asymmetry ($\chi < 0.13$) [2]. It is not directly comparable with the measurements of ARGUS ($\chi_d = 0.17$) [14] and CLEO ($\chi_d = 0.15$) [15]

which measure mixing of B_d^0 only, because the proportions of B_s^0 and B_d^0 mesons in our data are unknown.

To summarize, we have measured the value of the b-quark forward-backward charge asymmetry to be $A_b = 0.034 \pm 0.070 \pm 0.035$. The expected value without B^0-$\bar{B}^0$ mixing is -0.16. Assuming the standard model couplings, this measurement may be interpreted to give a limit on B^0-$\bar{B}^0$ mixing of $\chi > 0.21$ at 95% C.L.

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FIGURE CAPTIONS

1. Log likelihood of A_{tot}. The maximum likelihood at $A_{\mathrm{tot}} = +0.034$ is indicated. The uncertainty of the measurement σ is determined from the points A_{tot} at which $\ln \mathcal{L}(A_{\mathrm{tot}}) = \ln \mathcal{L}(0.034) - 0.5$.

2. Angular distribution of acceptance corrected data (points with error bars). The curve is $N(1 + \cos^2\theta + \frac{8}{3}A_{\mathrm{tot}}\cos\theta)$ where $A_{\mathrm{tot}} = 0.034$, the measured value, and N is an arbitrary normalization constant.

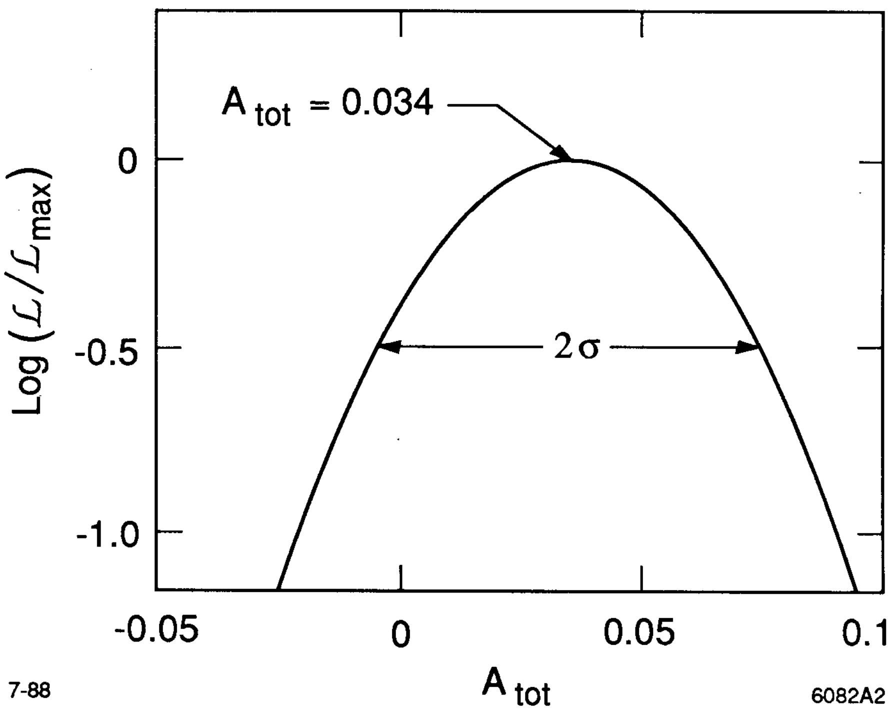

Fig. 1

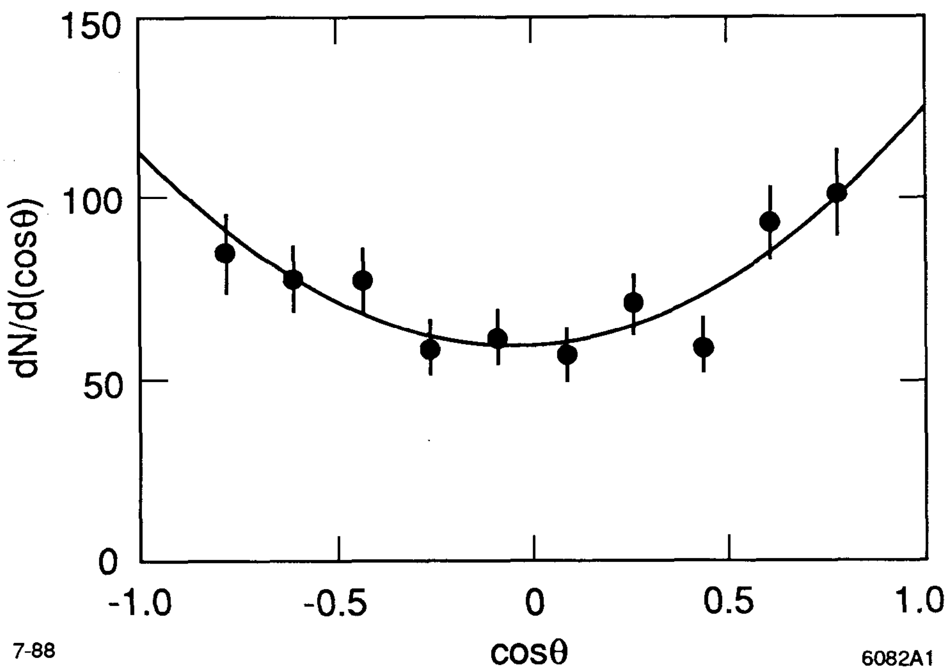

Fig. 2