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Forward-Backward Charge Asymmetry in $e^+e^- \rightarrow$ Hadron Jets

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The forward-backward asymmetry of quarks produced in e^+e^- annihilations, summed over all flavors, is measured at $\sqrt{s}$ between 50 and 60.8 GeV. Methods of determining the charge direction of jet pairs are discussed. The asymmetry is found to agree with the five-flavor standard model.

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The forward-backward asymmetry in the fermion (lepton and quark) pair production in e^+e^- annihilations is sensitive to the *interference* of γ and Z^0 as the mediating bosons. It is, therefore, an excellent test of the standard electroweak theory. Recently, the forward-backward charge asymmetry in $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ was measured in the $\sqrt{s} = 52$-57-GeV range.[1] This asymmetry is substantial, about 20%-40%. The asymmetry of $e^+e^- \to q\bar{q}$ is also predicted to be large in this energy range. Its measurement is complementary to the measurement in the lepton sector for a full test of the standard model.

The electroweak formalism of the production of a fermion pair $(f\bar{f})$ is summarized as follows. The differential cross section can be written in the form

$$\frac{d\sigma^f}{d\Omega} = \frac{\alpha^2}{4s}[R_f(1+\cos^2\theta_f) + B_f\cos\theta_f]\,, \qquad (1)$$

$$R_f = C_f[Q_f^2 - 8Q_f g_V^e g_V^f \chi + 16(g_V^{e2}+g_A^{e2})(g_V^{f2}+g_A^{f2})\chi^2]\,,$$

$$B_f = C_f(-16Q_f g_A^e g_A^f \chi + 128 g_V^e g_V^f g_A^e g_A^f \chi^2)\,,$$

$$\chi = \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\,\frac{s}{s-M_Z^2}\,,$$

where θ_f is the fermion production angle measured from the electron. The forward-backward asymmetry can be derived from (1). It is given by $A_f = 3B_f/8R_f$. In the standard model the vector and axial-vector coupling constants are $g_V^f = I_3^f - 2Q_f\sin^2\theta_W$ and $g_A^f = I_3^f$. C_f is the number of colors: three for quarks and one for leptons. The expected energy dependence of A_f for u-type (d-type) quarks is shown by the dot-dashed (dashed) curve of Fig. 1.

Measurement of the forward-backward asymmetry for an individual quark flavor is only feasible for heavy quarks, and then only with a reduced efficiency.[2,3] Alternatively, we combine all five quark flavors and study the asymmetry in hadron production by distinguishing between negatively charged jets (from d, s, b, $\bar{u}$, $\bar{c}$) and positively charged jets (from u, c, $\bar{d}$, $\bar{s}$, $\bar{b}$). We define the production angle θ to be between the incoming *electron* and the outgoing *negatively charged* jet. The *hadronic* asymmetry in $\cos\theta$ is $A_h = 3\sum_q' B_q/8\sum_q R_q$. We use $\sum'$ (instead of $\sum$) to denote the fact that we must now use $-B_q$ for the (positively charged) u and c. A_h can also be expressed in terms of $f_g = R_q/\sum_i R_i$, the fraction of q quarks in the sample, as $A_h = \sum_q' f_q A_q$. Combining two u-type (u,c) and three d-type (d,s,b) quark flavors results in a net positive A_h of 7%-10% in the $\sqrt{s} = 50$-60-GeV range, as shown by the solid curve of Fig. 1. Since the expected value for the hadronic asymmetry is due to the approximate cancellation between the large positive asymmetries of u-type quarks and the large negative ones of the d-type quarks in this energy region, the actual value of this asymmetry can be quite sensitive to new phenomena. For example, a 10% increase in cross section due to the production of additional u-type quarks

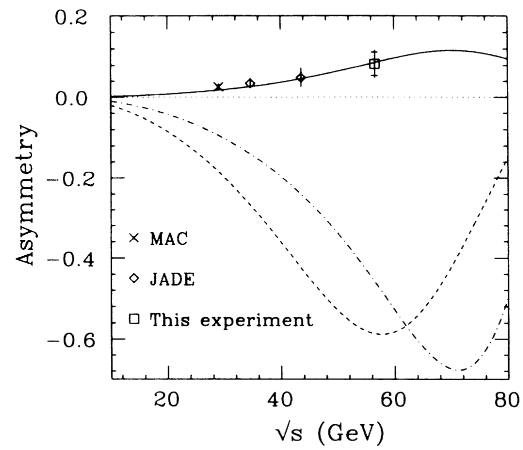

FIG. 1. Forward-backward asymmetry A_h of quark production in e^+e^- collisions compared with the standard-model values with $M_Z = 91$ GeV and $\sin^2\theta_W = 0.23$. The solid curve is the asymmetry in the charge distribution (for the angle between the incoming electron and the outgoing *negative charge*); it combines the asymmetries in two u-type (dot-dashed curve) and three d-type (dashed curve) quark production angular distributions (for the angle between the incoming electron and the outgoing *quark*). Error bars include both statistical and systematic errors. There is a mark specifying the contribution from statistical errors alone.

would result in a significantly larger A_h of 12%-15%.

We report a measurement of A_h at the KEK e^+e^- collider TRISTAN, for center-of-mass energies of 40-60.8 GeV ($\langle\sqrt{s}\rangle = 56.6$ GeV), by the AMY detector,[4] with a 27.4-pb^{-1} sample of 3211 multihadronic events.[5] The charged particles are tracked in a 3-T solenoidal field with good efficiency over the angular range $|\cos\theta| < 0.85$ for tracks with sufficient momentum transverse to the beam axis, $p_t > 0.4$ GeV. The momentum resolution is $\sigma_{p_t}/p_t \approx 0.7\% p_t$ (p_t in GeV). To assure a reasonably pure sample of two jet events, we used events with thrust $T > 0.8$, where t is determined using only the charged particles. To assure containment of the jets in the central detector, we require $|\cos\theta_T| < 0.65$. A total of 2071 events are selected. The angle θ_T is then used as the production angle θ_q of the quark pair. Monte Carlo studies show that $\cos\theta_T$ corresponds to $\cos\theta_q$ to within 0.1 unit.

We then divide the particles into two hemispheres (jets) by the plane perpendicular to the thrust axis and attempt to determine which jet corresponds to the positive quark-antiquark direction and which jet corresponds to the negative quark-antiquark direction. We have developed criteria to minimize the effect of misidentification of the jet charge as described below. We define P_q as the probability of correctly identifying the charge direction of the jet pair and $\bar{P}_q$ as the probability of incorrectly identifying it. Note that $P_q + \bar{P}_q < 1$, since jet charge for some events cannot be determined. Incorporating the misidentification probabilities for each flavor, the measured asymmetry is

$$A_h^M = \sum_q{}' \epsilon_q f_q^M A_q \,, \tag{2}$$

where $\epsilon_q \equiv (P_q - \bar{P}_q)/(P_q + \bar{P}_q)$, and $f_q^M = (P_q + \bar{P}_q) R_q / \sum_i (P_i + \bar{P}_i) R_i$ is the fraction of q events which contribute to the sum. The values ϵ_q and f_q^M clearly depend on the method used to determine the jets' charges. We determine these values using five-flavor simulated Monte Carlo events.[6] A good method is one which maximizes the ϵ_q's. However, ϵ_q could be different for different flavors. Because of the greater charge, higher ϵ_q is expected for u-type ($\frac{2}{3}$ charge) than d-type ($\frac{1}{3}$ charge) quarks. The values also depend on the (quark-mass-dependent) details of quark fragmentation. For example, the leading particle of a c jet could be a negative kaon, increasing the chance of a c jet being assigned a negative charge (see discussion of methods below). We therefore maximize ϵ_q in an average sense (for all flavors) and use the quantity $\langle\epsilon\rangle \equiv \sum_q \epsilon_q f_q^M$ as a figure of merit in the following discussion.

We take the net average of the charges of all charged particles in each jet. Leading particles are given heavier weighting as they are expected to retain properties of the quark. Two weighting variables have been used. The MAC Collaboration[7] used rapidity $\eta \equiv \frac{1}{2} \ln[(E+P_\parallel)/(E-P_\parallel)]$ with respect to the thrust (quark-antiquark) axis. The JADE Collaboration[8] used fractional momentum $\zeta \equiv P/E_{\text{beam}}$. We have examined the average charges of jets using both of these variables.

Rapidity weighting.— We define the charge of a jet to be the sum over the n particles in the jet of the charges weighted by a function of the η of each particle. This is divided by the total weighting to obtain an effective charge;

$$Q = \sum_{j=1}^{n} Q_j \eta_j^\kappa \Big/ \sum_{j=1}^{n} \eta_j^\kappa \,, \tag{3}$$

where κ is a parameter ≥ 0. We use $\langle\epsilon\rangle$ as our figure of merit to find an optimum value of κ, and find the maximum $\langle\epsilon\rangle$ near $\kappa=1$. We further improve $\langle\epsilon\rangle$ by requiring a minimum charge difference $\Delta Q_{\min}=0.15$ between the two jets. Table I shows the performance of the method on individual quark flavors.

Momentum weighting.— We define the charge of a jet to be the sum over the n particles in the jet of their charges weighted by their ζ, dividing by the total weighting to obtain an effective charge, i.e., using ζ instead of η in Eq. (3). A maximum $\langle\epsilon\rangle$ occurs near $\kappa=0.5$. Although we can reach the same maximum of $\langle\epsilon\rangle$ as in the rapidity weighting case, the peak is narrow and therefore the systematic uncertainty due to the choice of κ could be larger. Table I shows the performance of the method. We note that the momentum and rapidity weighting methods give significantly different values of ϵ for heavy flavors (c and b). In particular, momentum weighting is worse for identifying the charge of c jets, and ϵ_c is far below ϵ_u. We will use only rapidity weighting for the remainder of this paper.

TABLE I. Performance of the rapidity ($\kappa=1.0$, $\Delta Q_{\min}=0.15$) and momentum ($\kappa=0.5$, $\Delta Q_{\min}=0.15$) weighting methods. All values are in percent.

Flavor	P_q	$\bar{P}_q$	ϵ_q	f_q^M
		Rapidity weighting		
u	61.5 ± 1.6	12.5 ± 0.6	66.3 ± 1.4	33.5 ± 0.5
d	48.9 ± 2.4	20.0 ± 1.4	42.0 ± 3.1	11.6 ± 0.3
s	53.2 ± 2.5	17.5 ± 1.2	50.5 ± 2.8	11.9 ± 0.4
c	55.7 ± 1.5	14.6 ± 0.7	58.5 ± 1.6	31.7 ± 0.5
b	47.8 ± 2.4	19.4 ± 1.4	42.2 ± 3.1	11.2 ± 0.3
		Momentum weighting		
u	63.6 ± 1.8	12.9 ± 0.7	66.4 ± 1.5	33.4 ± 0.6
d	49.6 ± 2.8	20.6 ± 1.6	41.4 ± 3.5	11.6 ± 0.4
s	55.8 ± 2.9	16.8 ± 1.4	53.6 ± 3.1	11.9 ± 0.4
c	52.8 ± 1.6	19.4 ± 0.9	46.3 ± 1.9	31.3 ± 0.6
b	55.1 ± 3.0	17.6 ± 1.5	51.5 ± 3.3	11.9 ± 0.4

Using rapidity weighting with $\kappa=1$ and $\Delta Q_{\min}=0.15$ for our data, the angular distribution of the jet pairs is shown in Fig. 2. A minimum χ^2 fit gives a measured asymmetry of $A_h^M=(9.3\pm3.1\pm2.0)\%$ ($\chi^2=7.9/8$ degrees of freedom). For comparison, the standard-model prediction at 56.6 GeV, with the misidentification probabilities included, is $A_h^M=(9.7\pm0.6)\%$. (The error is due to the uncertainty in the misidentification probabilities.) b-$\bar{b}$ mixing would increase this predicted asymmetry by reducing the b quark's contribution. For example, assuming 20% mixing of B_d and 100% mixing of B_s, the

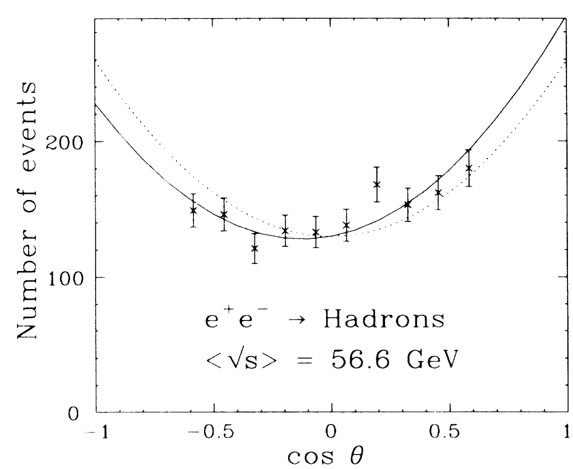

FIG. 2. Production angular distribution using rapidity weighting with $\kappa=1$ and $\Delta Q_{\min}=0.15$. The solid curve is a minimum χ^2 fit ($\chi^2=7.9/8$ degrees of freedom) giving an asymmetry of 9.3%. The dotted curve is the corresponding symmetric distribution which has $\chi^2=17.2/9$ degrees of freedom and is below the data for $\cos\theta>0$ and above the data for $\cos\theta<0$.

predicted asymmetry becomes $A_h^M = 10.9\%$. This increase in asymmetry, however, is less than our measurement uncertainty in A_h^M.

The systematic error in A_h^M arises from uncertainties in the parameters in the Monte Carlo event generator used to determine the values for the ϵ_q's. We estimate the error by changing parameters in the event generator, particularly the parameters of the string fragmentation scheme and the ratio of s to u and d quarks in the sea. The analysis is repeated with Monte Carlo data generated using reasonably extreme values of these parameters, without a detector simulation. The resulting difference is added linearly to the error arising from the uncertainty in the misidentification probabilities to obtain the estimate of the systematic error in A_h^M.

Since A_h^M depends on the method used to determine the jets' charges, we unfold a method-independent asymmetry. This is accomplished by allowing one parameter in the standard-model predictions of Eq. (1) for the A_q's in Eq. (2) to vary until the predicted A_h^M matches the measured value. That parameter value is then used to calculate A_h. Assuming universality, the magnitudes of the axial-vector couplings for all fermions are the same ($=|g_A|$). Then g_A^2 is a good parameter to use in extracting A_h. Our measured A_h^M corresponds to $g_A^2 = 0.23^{+0.29+0.12}_{-0.10-0.06}$. This is to be compared with the standard-model value of $g_A^2 = |I_3|^2 = \frac{1}{4}$. From this g_A^2 we calculate the method-independent asymmetry $A_h = (8.3 \pm 2.9 \pm 1.9)\%$.[9] For comparison, the standard-model prediction at 56.6 GeV is $A_h = 8.7\%$. In Fig. 1, A_h is compared to the standard-model prediction and the values at the energies of the SLAC and DESY storage rings PEP and PETRA, which we calculated from the values of g_A published in similar works by the MAC and JADE Collaborations. The higher-energy data continue to agree well with the standard model for five flavors.

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[9] The corresponding number unfolded from the momentum weighting method is $A_h = (7.0 \pm 3.7 \pm 2.8)\%$.