Measurement of Charge Asymmetry in $e^+e^- \to \mu^+\mu^-$

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The measurement of the nonelectromagnetic forward-backward charge asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$ at $\sqrt{s} \sim 34.6$ GeV and in the angular region $0 < |\cos\theta| < 0.8$ is reported. With a systematic error less than 1%, we observe an asymmetry of (-8.1 ± 2.1)%. This is in agreement with the standard electroweak theory prediction of (-7.6 ± 0.6)%. The weak-current coupling constants are also reported.

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One of the most important advances in physics in the last two decades is the development of the electroweak theory.[1] Lepton-hadron experiments[2] in the last decade have shown agreement with this theory. These experiments are characterized by the following experimental conditions: (1) relatively low c.m. energy, namely, $s \approx 200\ \text{GeV}^2$; (2) relatively low momentum transfer $q^2 \approx -100\ \text{GeV}^2$ in the spacelike region; (3) the use of nuclear targets.

The reaction

$$e^+e^- \to \mu^+\mu^- \tag{1}$$

proceeds via timelike momentum transfers, and at high energies $q^2 = s \approx 1200\ \text{GeV}^2$ offers the possibility of observing directly the effect of the neutral vector boson $Z^0 \to \mu^+\mu^-$. According to electroweak theory,[1] reaction (1) proceeds through both photon and Z^0 intermediate states. The resulting differential cross section is[3]

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\,|(1+a_1)(1+\cos^2\theta) + a_2\cos\theta|, \tag{2}$$

where

$$a_1 = 2G|g_V|^2 + G^2(|g_V|^2 + |g_A|^2)^2,$$
$$a_2 = 4G|g_A|^2 + 8G^2|g_V|^2|g_A|^2, \tag{3}$$

and

$$G = \frac{G_F}{\sqrt{2}}\,\frac{s}{2\pi\alpha}\,\frac{m_Z^2}{s - m_Z^2},$$

with $G_F/\sqrt{2}$ the Fermi constant, m_Z the mass of the Z^0, and g_V and g_A the vector and axial couplings of the Z^0 to the lepton fields. At $\sqrt{s} = 34.6$ GeV, the term $a_2\cos\theta$ produces a measurable forward-backward charge asymmetry $a_2\cos\theta/(1+a_1)(1+\cos^2\theta)$. Using $\sin^2\theta_W = 0.23$, we have, after integration, the total asymmetry $A^W = -9.5\%$. After radiative corrections[4] including initial-state photon emission on interference terms we have $A^W = (-8.7 \pm 0.6)\%$. In the angular region of our experiment, $0 < |\cos\theta| < 0.8$, we have

$$A^W = (-7.6 \pm 0.6)\%. \tag{4}$$

Experimentally, the detectable effect of forward-backward asymmetry is

$$A^T = \frac{N(\theta < \pi/2) - N(\theta > \pi/2)}{N(\theta < \pi/2) + N(\theta > \pi/2)} = A + A^{\text{QED}}, \tag{5}$$

where N is the number of μ^- with a polar angle in the indicated range measured with respect to the e^- beam direction. To compare the measured asymmetry A from (5) with the neutral-current prediction from (4), the measured distributions are corrected for the small (α^3, positive) QED asymmetry A^{QED}.

For the present study[5,6] we have installed end-cap muon chambers, extending the muon acceptance to cover $|\cos\theta| < 0.9$, so that the region where the charge asymmetry is expected to be largest is well covered. Equal amounts of these data have been collected by using both magnetic field polarities of the detector. Our selection criteria for muon-pair events are (a) two minimum-ionizing particles emerging from within a cylindrical region of 20 cm length and 5 cm radius centered at the beam crossing point, penetrating 90 to 160 cm of magnetized iron, and reaching the outside drift chambers; (b) a time coincidence in the muon trigger counters to better than 5 nsec; (c) an acollinearity angle between the two tracks less than 20°; (d) $P_\mu > \sqrt{s}/4$ for at least one muon, where P_μ is the measured muon momentum. A total of 2435 $\mu^+\mu^-$ events were collected at $\sqrt{s} = 34.6$ GeV.

Much effort was spent to understand the systematic bias of the asymmetry measurement and to keep it <1%. We list some examples:

(1) *Uncertainty in momentum measurement.*—This uncertainty affects the determination of muon charge. The inverse-momentum resolution, $k = 1/P$, is $\sigma(k)/k = 30\%$ for $P = 17.5$ GeV/c. There are 50 observed events where both muons are measured to have the same charge (2.1% of the sample), which were removed. This suggests that in less than 0.1% of the events, the wrong charge assignment was made for both muons. As a further check of this (and other systematic errors), the data were processed by two completely independent analysis teams using different event selection and momentum fitting procedures. Event-by-event comparisons of the data obtained from each processing scheme indicate excellent agreement.

(2) *Uncertainty in detector acceptance.*—This may cause a given solid angle for positive muons to be different for negative muons. The systematic error due to detector acceptance can be significantly decreased by alternating the polarity of the detector magnetic field. Any acceptance asymmetry will produce effects which are equal and opposite for positive and negative magnet polarities. Therefore, the difference between the measured asymmetries with each field polarity displays twice this systematic bias. To measure the detector asymmetry, we collected a sample of 20 000 cosmic-ray muons with momentum greater than 10 GeV. Most of these cosmic-ray data were collected during normal data-taking periods, thus appropriately reflecting any possible time-dependent changes in detector response. After correction for the different time of flight and energy loss, the detector response to a cosmic-ray muon going through the interaction region is equivalent to that for a collinear muon pair of the same energy. From a detailed study of these cosmic-ray muon data,[7] we calculate the detector asymmetry as a function of the polar angle θ, as shown in Fig. 1(a), and thus conclude that the detector contribution to the charge asymmetry is less than 1%. Furthermore, this detector asymmetry is eliminated by collecting data in equal amounts with both magnet polarities, thereby canceling to the first order all systematic errors which relate to the charge measurement of muons.

(3) *Trigger inefficiency.*—From the measurement of muon yields from redundant triggers, we observe a <0.5% uncertainty in the total muon-pair rate. This implies that the uncertainty in muon asymmetry will be <0.1%.

(4) *Tau pairs.*—The contamination from e^+e^-

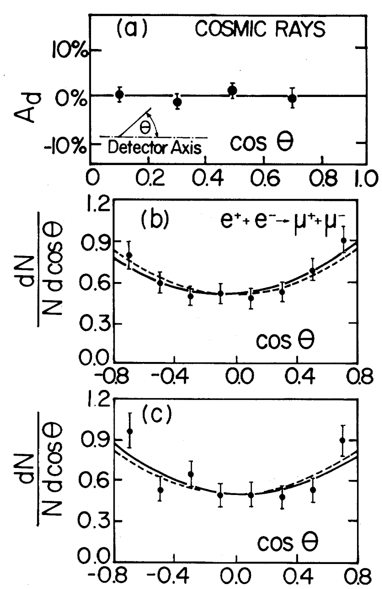

FIG. 1. (a) The measured detector asymmetry A_d defined as the percentage difference in acceptance for positive and negative muons as a function of the polar angle, as determined from 20 000 cosmic-ray events with momenta between 10 and 50 GeV/c. The angular distribution of muon-pair events as a function of the cosine of the scattering angle, for (b) $\sqrt{s} = 14$ GeV and (c) $\sqrt{s} = 22$ GeV, corrected for detector acceptance and the α^3 QED angular asymmetry. The full curves are fits to the data, under the assumption of Eq. (2). The dashed curves represent the angular distribution due to the lowest-order QED alone.

$\to \tau^+\tau^- \to \mu^+\mu^-\nu_\mu\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$ is about 1%[8] and yields a similar angular distribution to that from muon pairs.

(5) *Two-photon process.*—Muon pairs from $e^+e^- \to e^+e^-\mu^+\mu^-$ are characterized by lower muon momenta and by muon acollinearity angles that are roughly uniform up to 90°.[9] We calculate that the rate of such events satisfying the above criteria is less than 0.2% of the muon-pair rate.

(6) *Cosmic rays.*—From coincidence timing, we estimate a cosmic-ray contamination to the muon-pair sample of less than 0.4%.

From these studies, we conclude that by taking equal amounts of data at both magnetic polarities, the total systematic error is < 1%.

As a consistency check on the systematic errors, Figs. 1(b) and 1(c) display the distribution of $\mu^+\mu^-$ events as a function of the scattering angle[10] for $\sqrt{s}=14$ and 22 GeV. As seen, the deviations from QED angular distributions are small at $\sqrt{s}=14$ and 22 GeV; the asymmetry values are $A=(+5.3\pm5.0)\%$ and $A=(-4.3\pm6.1)\%$, respectively. This is consistent with the expected s dependence of the asymmetry.

The total cross sections for $e^+e^-\to\mu^+\mu^-$ at $\sqrt{s}=14$, 22, and 34.6 GeV, normalized to the expectations from QED (after α^3 radiative corrections),[3] are measured to be $\sigma_{\mu\mu}/\sigma_{\rm QED}=1.04\pm0.05$, 1.02 ± 0.05, and 0.99 ± 0.02, respectively. The corresponding luminosities are 1.57, 3.12, and 48.3 pb^{-1}. The systematic error for all three values, due primarily to the luminosity measurement error, is 3%. QED cutoff-parameter[6] limits are $\Lambda_+=180$ GeV and $\Lambda_-=163$ GeV (95% confidence level).

Figure 2 displays the distribution of muon-pair events as a function of the scattering angle for $\sqrt{s}=34.6$ GeV. The data show a distinct asymmetry. Indeed, the total asymmetry A^T, resulting from the simple counting of events forward and backward in θ for $0<|\cos\theta|<0.8$, is $A^T=(-6.7\pm2.1)\%$. The asymmetry due to QED $A^{\rm QED}=(1.4\pm0.5)\%$. Therefore we observe a non-QED asymmetry

$$A=(-8.1\pm2.1)\%.$$

Our result agrees with the Glashow-Weinberg-Salam prediction [Eq. (4)]

$$A^W=(-7.6\pm0.6)\%.$$

Our results limit the mass of Z^0 to $m_Z>51$ GeV with 95% confidence. If we fit the form of Eq. (2) to the data, as indicated by the solid curve, we obtain the asymmetry value extrapolated to all angles. The resulting value is $A=(-9.8\pm2.3)\%$ with $\chi^2=7.2$ for six degrees of freedom. This result can be compared with the corresponding $A^W=(-8.7\pm0.6)\%$ and with the value of Brandelik *et al.*,[5] $A=(-16.1\pm3.2\%)$, and the value of Bartel *et al.*,[5] $A=(-12.8\pm3.8)\%$.

In Table I we display the asymmetry values for $\sqrt{s}\approx34.6$ GeV obtained from each polarity individually, and for two regions of $\cos\theta$. The compatibility of these values indicates the insensitivity to variations in detection and measurement efficiencies. Assuming μ-e universality, we have used the measured charge asymmetry values and the total $\mu^+\mu^-$ cross sections to calculate the two coupling constants g_V and g_A of Eq. (2). For $m_Z=90$ GeV we obtain

$$g_V^2=0.01\pm0.05,\quad g_A^2=0.28\pm0.06.$$

The systematic error in g_V^2 (±0.06) comes from the systematic error in luminosity measurement of 3%. The upper limit in the systematic error in g_A^2 (±0.03) comes from the upper limit in the systematic error of 1% in the charge asymmetry measurement.

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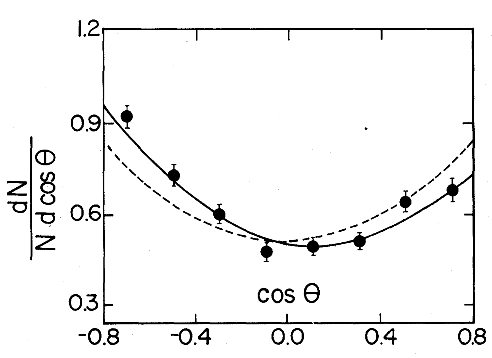

FIG. 2. Same as Figs. 1(b) and 1(c) at $\sqrt{s}=34.6$ GeV, showing the electroweak effect.

TABLE I. Charge asymmetry for both magnet polarities and for various angular regions ($\int L\,dt$ in units pb^{-1}).

Polarity	$\int L\,dt$	$0<\lvert\cos\theta\rvert<0.8$ A(%)	$0.2<\lvert\cos\theta\rvert<0.8$ A(%)
−	22.4	-7.8 ± 3.1	-11.4 ± 3.5
+	25.9	-8.4 ± 2.8	-10.1 ± 3.1
Sum	48.3	-8.1 ± 2.1	-10.7 ± 2.3
$A^W=$		-7.6 ± 0.6	-9.0 ± 0.6

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[5]R. Brandelik *et al.*, Phys. Lett. 110B, 173 (1982); H. J. Behrend *et al.*, Deutsches Elektronen-Synchrotron Report No. 82/019 (to be published); W. Bartel *et al.*, Phys. Lett. 92B, 206 (1980), and 99B, 281 (1981), and 108B, 140 (1982); Ch. Berger *et al.*, Phys. Lett. 99B, 489 (1981), and Z. Phys. C 7, 289 (1981); The MARK-J collaboration, Phys. Rep. 63, 337 (1980); D. P. Barber *et al.*, Phys. Rev. Lett. 45, 1904 (1981).

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[10]Since the two muons are not precisely collinear, we use the mean angle of the two polar angles to define θ for the event.

Indices, Triality, and Ultraviolet Divergences for Supersymmetric Theories

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Transverse rotation-group representation indices are shown to appear in one-loop radiative corrections. Some conjectures are made on how such index structure generalizes to higher orders. An unusual correlation between the absence of UV divergences in supersymmetric theories and the equality of such indices for fermions and bosons is described. This correlation is argued to be a fundamental indicator of higher-order UV behavior for $D=10$ ($N=4$) supersymmetric Yang-Mills theory and $D=11$ ($N=8$) supergravity. Within this context, the significance of O(8) triality is discussed.

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In this Letter I discuss some striking group-theoretical features which appear in radiative corrections as computed perturbatively for relativistic quantum field theories. These features seem to be very general in character, and may lead to further simplifications in the rules used to determine the UV structure of field theories. Although I expect wider applications, I will primarily discuss supersymmetric theories in this Letter, since their UV structure is of paramount theoretical interest.

I shall show how radiative corrections involve "transverse rotation-group representation indices" by giving a simple one-loop example. On the basis of such low-order perturbation theory results, I conjecture that higher-loop processes involve generalized higher-order representation indices. I also suggest a factorized form for the dependence of higher-loop corrections on boson and fermion indices in supersymmetric theories such that generalized indices are a direct indicator of certain higher-order effects. I observe that these conjectures are consistent with an otherwise unusual correlation between the equality of group representation indices for the fermions and bosons found in certain supersymmetric theories

