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PHYSICS WITH POLARIZED BEAMS IN e^+e^- COLLIDERS*

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ABSTRACT

The spin structure of the standard model of electroweak interactions is described, with emphasis on the relevance to polarized beam phenomena. The polarization dependence of the cross section, charge asymmetries, and examples of experimental measurements using longitudinal polarization are given. Longitudinal beam polarization is discussed in some detail, including electroweak radiative corrections. Applications to testing the standard model and looking beyond for additional gauge bosons are considered.

INTRODUCTION

The inherent left-handedness of the weak part of the electroweak interactions makes polarization phenomena at high energies an important experimental tool for studying the basic phenomenology. The use of polarized beams for studying electroweak phenomenology is described in this talk. It is emphasized that polarization phenomena exist even in the absence of beam polarization and that there exist interesting experiments which study these effects. This talk focusses however on the much broader class of polarization phenomena resulting from beam polarization. This talk is structured in the following way: (i) a brief discussion of the spin structure of the standard model with emphasis on the couplings and the polarization dependences; (ii) consequences of polarized beams and opportunities for experiments; (iii) status of radiative corrections; (iv) looking beyond the standard model.

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The experimental and technical problems in providing polarized beams for experiments have been studied at considerable length. In circular colliders depolarizing effects compete with the natural buildup of polarization. Equilibrium values of polarization depend on details of the machine. An active program to understand and control the depolarization in PETRA is underway, and has been discussed in this conference.[1] In linear colliders, production of polarization and depolarizing effects come from entirely different processes. These too have been studied in the SLC workshops and are rather well understood. Polarized beams are expected to exist eventually, if not in the early operations, at both LEP and the SLC at SLAC. This talk concerns some of the interesting phenomena associated with polarization.

THE SPIN STRUCTURE OF THE STANDARD MODEL

The electroweak part of the standard model, relevant to polarization, can be summarized in the well-known weak isospin structure, whereby left-handed fermions are placed in doublets and right-handed fermions in singlets:

$$\begin{pmatrix} \nu_e \\ e^-_L \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^-_L \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^-_L \end{pmatrix}, \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix} \qquad \text{(doublets)}$$

$$e^-_R, \mu^-_R, \tau^-_R, u_R, d_R, c_R, s_R, t_R, d_R \qquad \text{(singlets)}$$

Such structure is fundamental to minimal SU(2) × U(1). Right-handed currents are experimentally ruled out within this minimal structure, but may exist at higher energies if more gauge bosons exist. The couplings of a Z^o boson to a fermion pair $f\bar{f}$ are given by

$$\begin{aligned} g^f_L &= \frac{e}{\sin\theta_W \cos\theta_W} \left[T^f_{3L} - q^f \sin^2\theta_W\right] \\ g^f_R &= \frac{e}{\sin\theta_W \cos\theta_W} \left[T^f_{3R} - q^f \sin^2\theta_W\right] \end{aligned} \qquad (1)$$

where T_3 refers to the weak isospin with $T_{3L} = \pm 1/2$ and $T_{3R} = 0$. The electric charge of the fermion is q^f, and $\sin^2\theta_W$ is the weak mixing parameter. Note that $g^f_L \neq g^f_R$ because of the values of T_{3L} and T_{3R} being different. Parity violation in the neutral current interactions is the consequence of these couplings being unequal. Coupling strengths for left-handed fermions (i.e., longitudinal polarization with spin projection negative relative to momentum) to the Z^o are proportional to $(g^f_L)^2$, while for right-handed fermions, $(g^f_R)^2$. In the decay of an unpolarized Z^o, for example, the ratio of left-handed to right-handed polarized fermions is g^2_L/g^2_R. Table I shows the values for this ratio for four different

TABLE I. Neutral Current Couplings
($\sin^2\theta_W$ = .23)

fermion type	g_L^2/g_R^2
u	5.1
d	30.5
ν_e	∞
e^-	1.38

fermions and for the mixing parameter $\sin^2\theta_W = .23$. In this table we see the preference of the Z^o for the left-handed couplings. For neutrinos, neutral current couplings are purely left-handed. If right-handed neutrinos exist, which must be so if they are massive, they do not couple through the neutral currents in the standard model.

Universality of neutral current couplings is contained in Eq. (1). The coupling strengths are the same for e, μ, and τ as are those of u,c,t and d,s,b. Test of universality are important to checks of the standard model. These tests are underway at PETRA and PEP for the leptons e, μ and τ with reasonable accuracy, and for the quarks with less sensitivity. Precision tests of these relations await the production and decay of the Z^o. The relations of Eq. (1) imply large spin dependent effects at the Z^o occur because $|g_R - g_L| \sim O(g)$. Experimentally, this implies that polarization phenomena should lead to accurate studies of these parameters.

It is customary to define vector and axial-vector couplings to Z^o by

$$g_V^f = \frac{1}{2}\left(g_R^f + g_L^f\right)$$

and

$$g_A^f = \frac{1}{2}\left(g_R^f - g_L^f\right) \qquad (2)$$

Although relations (1) and (2) are equivalent, use of vector and axial-vector couplings has been more common. Notation and normalization of these couplings vary considerably in the literature. The values of these couplings depends on the value used for $\sin^2\theta_W$. The success of the standard model comes from the unification of widely differing interactions with one value of $\sin^2\theta_W$. The current experimental determination of this parameter is .230 ± .010.[2] For the future, electroweak studies at the Z^o promise to improve the accuracies in these couplings by a order-of-magnitude. One of the best determinations will be possible using polarized beams at the Z^o pole.

What can polarized beams do? Measurements with polarized beams can enhance the physics relative to that for unpolarized beams. Examples of physics phenomena enhanced by polarization are total cross sections, charge asymmetries, and final state lepton and quark polarizations. There are also measurements which are unique to polarization. Longitudinal asymmetries, an example of this, lead to sensitive tests for extra gauge bosons and tests of electroweak radiative corrections.

EXPERIMENTAL CONSEQUENCES OF POLARIZED ELECTRON BEAMS

The cross section, in lowest order, for $e^+e^- \to f\bar{f}$ is given by[3]

$$\begin{aligned}\frac{4s}{\alpha^2}\frac{d\sigma}{d\Omega} = &\left(1 - P_L^+P_L^-\right)\left[\sigma_u^\gamma + \sigma_u^{\gamma z} + \sigma_u^z\right] \\ &\left(P_L^+ - P_L^-\right)\left[\sigma_L^\gamma + \sigma_L^{\gamma z} + \sigma_L^z\right] \\ &\left(P_T^+P_T^- \sin^2\theta\, \cos\psi\right)\left[\sigma_T^\gamma + \sigma_T^{\gamma z} + \sigma_T^z\right] \\ &\left(P_T^+P_T^- \sin^2\theta\, \sin\psi\right)\left[\tilde{\sigma}_T^\gamma + \tilde{\sigma}_T^{\gamma z} + \tilde{\sigma}_T^z\right]\end{aligned} \tag{3}$$

where P_L^+ and P_L^- refer to longitudinal polarization of e^+ and e^- incident beams, P_T^+ and P_T^- refer to transverse components of the polarization, θ is the polar angle of the outgoing fermion, and $\psi = 2\phi - \varphi^+ - \varphi^-$, with ϕ the azimuthal angle of the outgoing fermion, and φ^+ and φ^- refer to the azimuthal angle of the transverse component of the spin of the e^+ and e^- beams. The superscripts γ, γz, and z refer to cross section terms from pure photon exchange, interference between photon and Z^o, and pure Z^o exchange, respectively.

Polarization - driving mechanisms occurring in circular colliders lead to transverse polarization of both e^+ and e^- beams. It is rather natural in circular rings for $P_T^+P_T^-$ terms to appear, and indeed these effects have been experimentally observed. Some discussion of the consequences of $P_T^+P_T^-$ terms are in literature.[3] For linear colliders, providing polarized electron beams is rather easy, but not easy for positron beams. Longitudinal polarization effects for electrons polarized and for positrons unpolarized lead to significant effects in at high energies. Those effects are the ones I wish to discuss here. They are important to polarized beams in the SLC. So for this talk, I will assume $P^+ = 0$. Equation (3) then reduces to

$$\frac{4s}{\alpha^2}\frac{d\sigma}{d\Omega} = \sigma_u^\gamma - P_L^-\left[\sigma_L^{\gamma z} + \sigma_L^z\right] \quad . \tag{4}$$

Note that the term σ_L^γ is 0 and that $\sigma_L^{\gamma z} \ll \sigma_L^z$, if the energy chosen is that of the Z^o-pole, $\sqrt{s} = M_Z$. For the discussion, neglect the contribution from $\sigma_L^{\gamma z}$. In the figures, however, this term remains. Figure 1 shows the total cross section for unpolarized

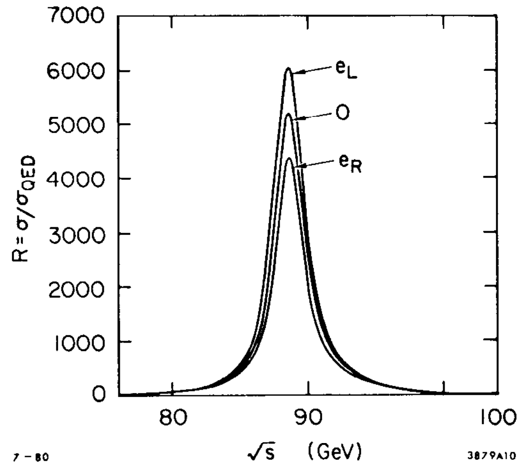

Fig. 1. The cross section ratio R in the vicinity of the Z^o, in lowest order, for three e^- beam polarization states. ($\sin^2\theta_W$ = .23)

beams, in lowest order. For polarized beams, at the Z^o-pole, the rate of production of Z^o's is proportional to $N_R g_R^2 + N_L g_L^2$, where N_R, N_L are the number of right-handed and left-handed incident electrons, and g_R^2, g_L^2 are the electron-Z^o couplings squared, respectively. The beam polarization is defined $P_e = (N_R - N_L)/(N_R + N_L)$. Using the definitions of Eq. (2), gives the rate of Z^o production proportional to $(g_V^2 + g_A^2 + 2P_e g_V g_A)$, where g_V and g_A are the vector and axial-vector electron couplings. The longitudinal asymmetry is defined

$$A_L = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$$

which becomes

$$A_L = \frac{g_R^2 - g_L^2}{g_R^2 + g_L^2} = \frac{2g_V/g_A}{(1 + g_V^2/g_A^2)} \quad . \tag{5}$$

A measurement of A_L through (5) provides a determination of g_V/g_A. For the mixing parameter value $\sin^2\theta_W$ = .23, the standard model predicts A_L = −.16. Figure 2 shows the polarization dependence of the cross section in the region $\sqrt{s} = M_Z$. Present experimental information lead to an accuracy on $\sin^2\theta_W = \pm.01$ at low energies. Longitudinal asymmetry measurements promise to provide accuracies an order-of-magnitude better for $\sin^2\theta_W$, and also similar improvements in g_V and g_A.

The Z^o's are polarized in polarized e^+e^- collisions. For a right-handed e^- beam, the Z^o spin aligns in the direction of the e^- beam. For left-handed e^- beams, the Z^o spin points in the opposite direction. That is, P_Z = +1 and −1 for these two cases.

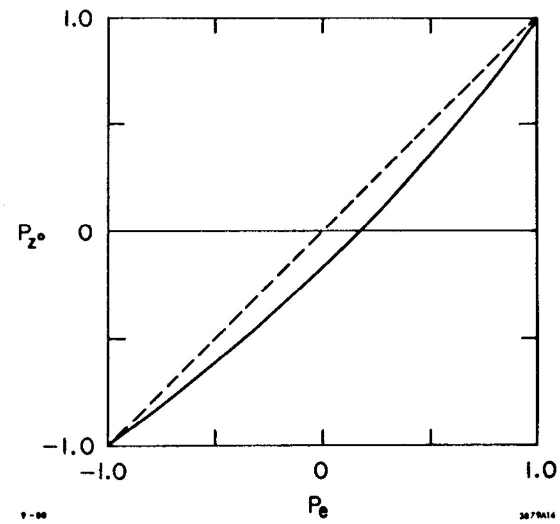

Fig. 2. The polarization of the Z^o in the e^- beam direction versus P_e for $\sin^2\theta_W = .23$. The dashed curve is for $\sin^2\theta_W = 1/4$.

However for unpolarized beams, the Z^o is still polarized. Why is this so? Because the Z^o prefers left-handed couplings, as shown in Table I. Figure 2 shows the polarization of the Z^o for P_e from −1 to +1. The form can be written as

$$P(Z^o) = (P_0(Z^o) + P_e)/(1 + P_eP_0(Z^o)) \quad (\text{at } \sqrt{s} = M_Z) \qquad (6)$$

where $P_0(Z^o)$ is the value for unpolarized beams. Figure 2 shows that Z^o's are highly polarized if the beam is highly polarized, and are polarized in the direction of the e^- beam even if $P_e = 0$.

Polarized Z^o's lead to nonzero charge asymmetries. Charge asymmetries for $e^+e^- \to f\bar{f}$ are defined as

$$A_{CH} = (N(f) - N(\bar{f}))/(N(f) + N(\bar{f}))$$

where $N(f)$, $N(\bar{f})$ refer to the observed number of primary fermions (such as $\mu^-\mu^+$, $\tau^-\tau^+$, ...) in a detector. Figure 3 shows the case of a Z^o aligned in one case parallel to the e^- beam, and in the other case antiparallel. The forward going μ^- has its spin aligned along its motion. The rate for this spin orientation is proportional to g_L^2, while for the forward going μ^+, the spin of the μ^- is opposite its motion, giving a rate proportional to g_R^2. So at 0^o, the charge asymmetry for $Z^o \to \mu^-\mu^+$ is

$$A_{CH} = P_Z \frac{2g_V^\mu/g_A^\mu}{\left(1 + (g_V^\mu/g_A^\mu)^2\right)} = \left\{ \begin{array}{ll} -.16 & \text{for } P_e = +1 \\ +.026 & \text{for } P_e = 0 \\ +.16 & \text{for } P_e = -1 \end{array} \right\}$$

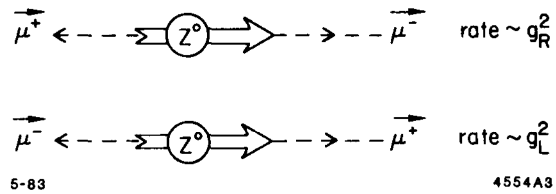

Fig. 3. Polarized Z^0's decaying into forward and backward μ's. The forward going μ^- has necessarily its spin aligned forward with a rate proportional to $g_R^{\mu 2}$. The backward going μ^- has a corresponding rate proportional to $g_L^{\mu 2}$.

for $\sqrt{s} = M_Z$ and $\sin^2\theta_W = .23$. Figure 4 shows the complete calculation in lowest order, including γ-exchange and average over $\cos\theta$ in a 4π detector. The angular dependence of A_{CH} is

$$A_{CH} = f(s) \frac{2\cos\theta}{1 + \cos^2\theta} \quad .$$

and is shown in Fig. 5. The forward and backward portions of the solid angle are most important for charge asymmetries. Numerical estimates show that 1/2 of the sensitivity comes from the forward cone inside 40^o (approximately), relatively independent of fermion type. Charge asymmetry measurements are best done by detectors which cover forward and backward regions of solid angle.

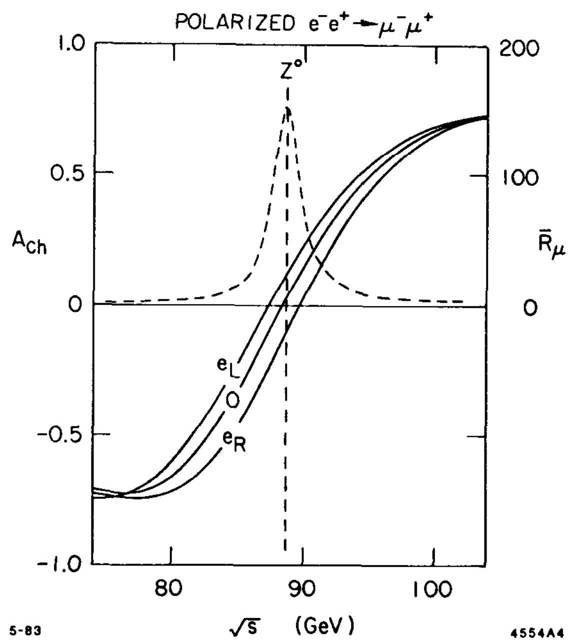

Fig. 4. A_{CH} for μ-pairs in the vicinity of the Z^0, for three polarizations of the e^- beam.

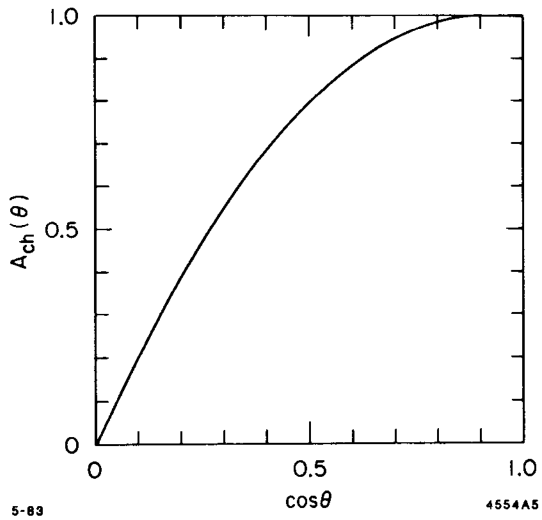

Fig. 5. The angular dependence for A_{CH}. Forward/backward directions are important to charge asymmetry measurements.

Figures 6(a) and 6(b) show charge asymmetries for hadron jets, separated into two cases; (i) primary quarks are $u\bar{u}$, $c\bar{c}$ and $t\bar{t}$, and (ii) $d\bar{d}$, $s\bar{s}$, and $b\bar{b}$. Charge asymmetries for jets are expected to be large, but sensitivity to values of $\sin^2\theta_W$ are not as large as for the leptons. Additional experimental problems of flavor identification, determination of the parent quark, and effects of gluon radiation make charge asymmetry measurements for the quarks harder than for the leptons. Semi-leptonic decays of the heavy quarks will be one area of work that will contribute to charge asymmetries.

Polarization of the final state fermions has the form

$$P_f = \frac{2g_V^f/g_A^f + P_Z\left(1 + (g_V^f/g_A^f)^2\right)}{\left(1 + (g_V^f/g_A^f)^2\right) + 2P_Z(g_V^f/g_A^f)} \qquad \begin{array}{l} \text{at } \sqrt{s} = M_Z \\ \theta = 0^{\circ} \\ \text{no } \gamma\text{-exchange} \end{array} \tag{9}$$

and the values of 1, -.31, -1. for P_e = 1,0,-1, respectively, for $\sin^2\theta_W$ = .23, and $f\bar{f} = \mu^-\mu^+$ or $\tau^-\tau^+$. Figure 7 shows the polarization of τ's for energies near the Z^o-pole, and averaging over 4π solid angle. Polarizations of the τ^- are large, even for unpolarized beams. Beam polarization permits a measure of control of the final state polarization. Studies of weak decays of heavy quarks should be substantially enhanced by this control.

Longitudinal asymmetries, defined in Eq. (5), are the quantities often called spin-flip asymmetries. The cross section in Eq. (5) may refer to total cross sections or to specific final states.

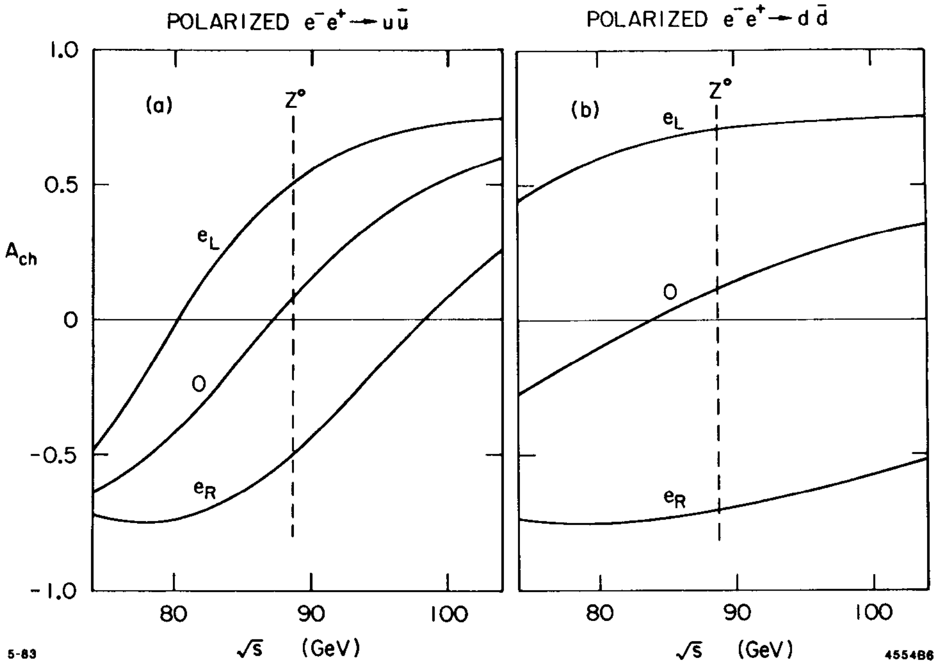

Fig. 6. A_{CH} for primary quarks in the vicinity of the Z^0, for three polarizations of the e^- beam.

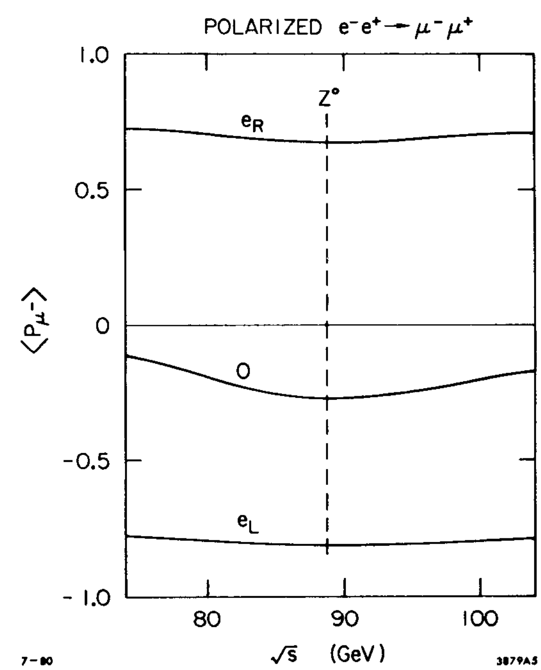

Fig. 7. Polarizations in the final state for μ-pairs or τ-pairs, near the Z^0, for the three beam polarizations indicated.

This parameter is easiest to measure experimentally. For example, A_L does not require charge identification (possibly difficult for forward-backward μ-pairs), or flavor identification in the case of hadron jets. A_L is extremely sensitive to effects from heavy Z^0's (such as contained in $SU(2) \times U(1)$, for example) and most importantly, this asymmetry is little affected by electroweak radiative corrections. This latter point is most significant, because distinguishing between radiative corrections and influences of extra gauge bosons may be difficult. The influence of radiative corrections on charge asymmetries is relatively large, making these measurements much more sensitive to such higher order effects.

RADIATIVE CORRECTIONS

Radiative corrections have been treated at different levels by a number of authors.[4] For polarized beams, the best work currently is that of M. Bohm and W. Hollik.[3] Their calculations include bubbles, vertex corrections, box diagrams, and soft bremsstrahlung of photons. Diagrams containing more than one heavy gauge boson are excluded, but are expected to be small. Figure 8 shows examples of electroweak processes which contribute to the radiative corrections. Comparison of radiative corrections for A_L and A_{CH} are given in Fig. 9. The conclusion, important to future experiments, is that

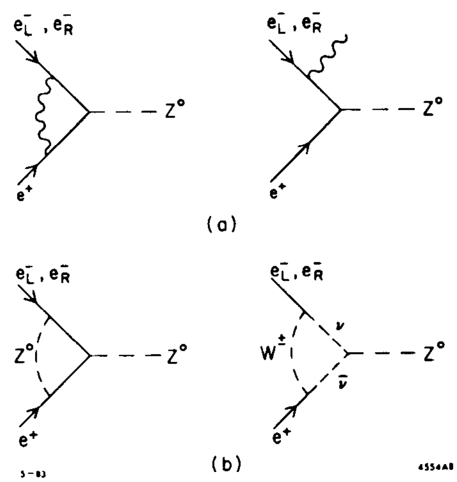

Fig. 8. Processes important to radiative corrections. The first two diagrams are examples which do not contribute to A_L, while the latter two are examples which do. Existing calculations of radiative corrections to A_L do not include the latter diagrams, but they are expected to be quite small.

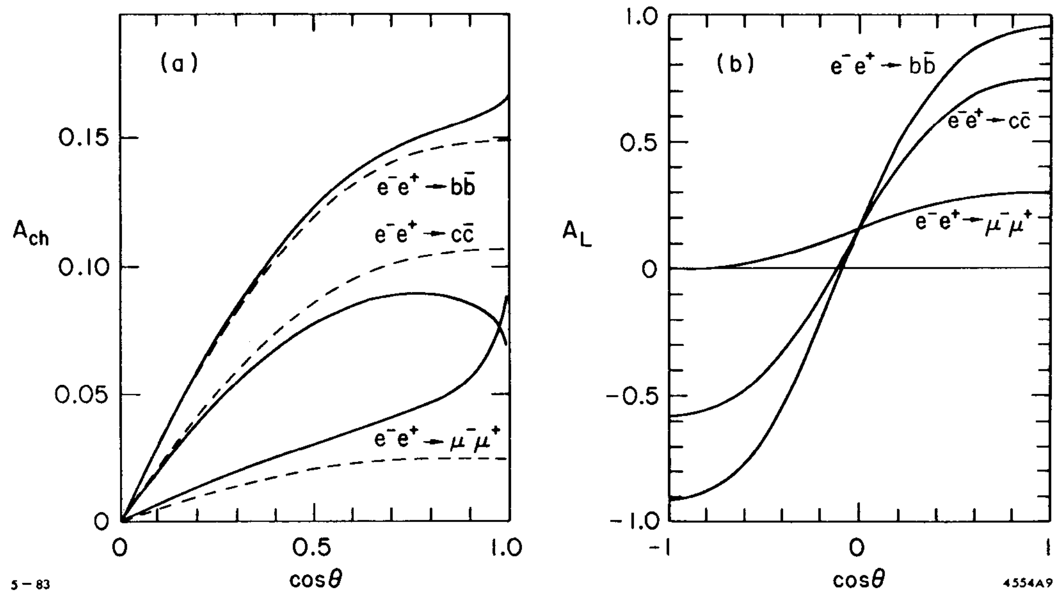

Fig. 9. (a) The on-resonance ($\sqrt{s} = M_Z$) unpolarized charge asymmetries for $e^-e^+ \to \mu^-\mu^+$, $c\bar{c}$, $b\bar{b}$ in lowest order (dashed curve) and corrected, with $\Delta E/E = 0.01$ (solid curve) (from Ref. 3). (b) The on-resonance ($\sqrt{s} = M_Z$) longitudinal polarization asymmetries A_L for $e^-e^+ \to \mu^-\mu^+$, $c\bar{c}$, $b\bar{b}$. Lowest order and corrected curves with $\Delta E/E = 0.01$ are practically identical (from Ref. 3).

radiative corrections to A_L are expected to be small. The measurement of A_L should provide an accurate measure of $\sin^2\theta_W$, insensitive to theoretical uncertainties. Combining two independent measurements, A_L and M_Z, should provide a precise check of electroweak radiative corrections.

LOOKING BEYOND THE STANDARD MODEL

Longitudinal asymmetries are sensitive to the presence of heavy gauge bosons lying well above the standard model Z^o. The effects arise through the interference between the Z^o and a heavier $Z^{o\prime}$, in analogy to the effects of γ-Z^o interference at low energies. Precision measurements of A_L may be possible. Studies of the sensitivity to heavy $Z^{o\prime}$'s have been carried out at the SLC Workshop[5] and elsewhere.[6] Figure 10 is the result of the SLC Workshop, showing that polarization measurements are sensitive to $Z^{o\prime}$'s with masses up to 400 GeV. The conclusions depend on details of gauge models, of course, but in fact occur in similar fashion in several models studied.

Let me then conclude. Polarization phenomena play a significant role in high energy processes of the future because the weak

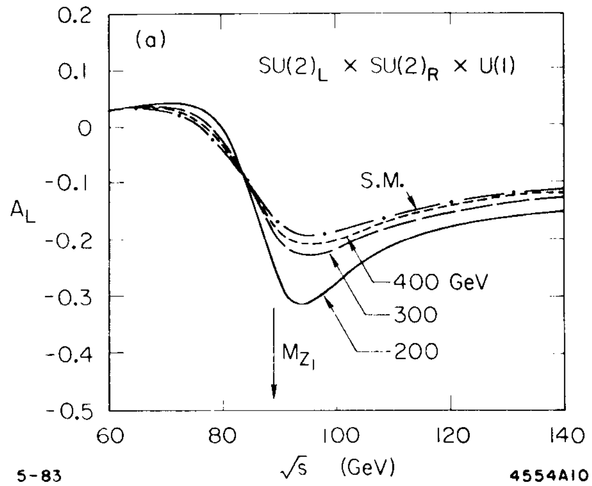

Fig. 10. Longitudinal asymmetry calculated in the standard model (S.M.) and in the $SU(2)_L \times SU(2)_R \times U(1)$ model. The numbers 200, 300 and 400 GeV refer to the mass of the second Z^o.

interactions become dominant and have an intrinsic spin structure that leads to large spin effects. Longitudinal polarization enhances many measurements such as total cross sections, charge asymmetries, and final state polarizations. Longitudinal asymmetries add additional possibilities for experiments not available to experiments without polarized beams. We can expect to see interesting work resulting from use of polarized beams at high energies.

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