EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-228

14 December 1987

**A SCHEME TO MEASURE THE POLARIZATION ASYMMETRY
AT THE Z POLE IN LEP**

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Abstract

If longitudinally polarized beams are available in the Large Electron – Positron storage ring (LEP), it is shown that running with a specific sequence of polarized and depolarized bunches will allow both a measurement of the polarization asymmetry A_{LR} and the absolute calibration of the polarimeters. The resulting accuracy that one can expect is discussed.

(Submitted to Physics Letters)

1. Introduction

It has been shown [1] that the polarization asymmetry A_{LR} at the Z peak provides a measurement of $\sin^2\theta_w$ with a precision much superior to that which can be obtained with other asymmetries [2] and comparable in precision that expected from the Z mass measurement, $\Delta\sin^2\theta_w = 0.0002$ for $\Delta m_Z = 30\text{MeV}$ [3]. This is due to some remarkable properties of A_{LR} [4]: it is i) independent of the decay mode of the Z , allowing high statistical precision to be obtained, and ii) insensitive to both photonic and gluonic radiative effects, in contrast for instance with the unpolarized forward – backward asymmetries. On the other hand, A_{LR} is very sensitive to weak radiative corrections, allowing powerful tests of the theory to be performed [5].

Such a claim, however, relies on the possibility of measuring the longitudinal polarization P_L of the beams with a high accuracy. In this letter, a scheme is proposed, for performing this measurement in the Large Electron Positron (LEP) storage ring at CERN, in which the polarization of the beams is directly measured in the experiments; this renders unnecessary a high precision, absolutely calibrated, external measurement of the polarization. The cross – sections and existing proposals will be briefly reviewed, then the proposed scheme and the obtainable precision will be discussed.

2. Cross – sections and running modes

The total cross – section for the production of a pair of fermions, $e^+e^- \rightarrow f\bar{f}$, at the Z pole, has been calculated for polarized beams by Böhm and Hollik [6]. It can be reduced to

$$\sigma = \sigma_u [1 - P^+P^- + A_{LR} (P^+ - P^-)] \quad (1)$$

where $P^\pm$ are the longitudinal polarizations of the positron and electron, respectively; polarizations are positive if the spin is parallel to the particle's velocity. To a very good approximation, A_{LR} is independent of the decay mode of the Z :

$$\begin{aligned} A_{LR} &\cong 2v_e a_e / (v_e^2 + a_e^2) \\ &\cong 8 (0.25 - \sin^2\theta_w) \end{aligned}$$

where v_e and a_e are the vector and axial-vector couplings of the electron to the Z. Therefore A_{LR} can be extracted from measurements of the total cross-section for different combinations of beam helicity; given the high cross section (30 nb) at the top of the resonance, excellent statistical accuracy can be expected.

In the Stanford Linear Collider (SLC) [1], the polarization is created in the electron gun, where the light of a circularly polarized laser is sent onto a photoemissive cathode. It can be reversed on a pulse basis by reversing the laser polarization, given the relatively low rate of the linac (180Hz). The positrons, on the other hand, cannot be polarized. The SLC operation with polarized beams will therefore consist of colliding alternatively polarized electrons with unpolarized positrons:

electron bunches	$\Rightarrow$ 1	$\Leftarrow$ 2	etc.
positron bunches	1	2	etc.
cross sections	σ_1	σ_2	etc.
	$\sigma_1 = \sigma_u (1 - P^- A_{LR})$		
	$\sigma_2 = \sigma_u (1 + P^- A_{LR})$		
with	$A_{LR} = (1/P^-) (\sigma_1 - \sigma_2) / (\sigma_1 + \sigma_2)$		

How the beams will be polarized in LEP remains an open question. In any case, in a storage ring design, both electrons and positrons will be polarized, and by a similar amount: $P^+ \cong P^-$. The term in A_{LR} would vanish in eq.(1). Spin reversal is impractical, but it has been shown [7] that selective depolarization of any set of the four electron bunches and four positron bunches circulating in the machine is possible using existing equipment, with a residual polarization of $O(10^{-3} \times P)$ by continuously exciting an artificial depolarizing resonance. This feature is essential to obtain a non-zero polarization of the e^+e^- system. A sequence of polarizations equivalent to that of the SLC can thus be obtained by depolarizing every other bunch of each beam ('standard scheme'):

electron bunches	$\Rightarrow$ 1	2	$\Rightarrow$ 3	4	etc.
positron bunches	1	$\Leftarrow$ 2	3	$\Leftarrow$ 4	etc.
cross sections	σ_1	σ_2	σ_1	σ_2	etc.

again,

$$A_{LR} = (1/P) (\sigma_1 - \sigma_2) / (\sigma_1 + \sigma_2), \quad \text{for } P \cong P^+ \cong P^-.$$

In both cases, the error on A_{LR} is dominated by statistics and the systematics on the polarization measurement:

$$(\Delta A_{LR})^2 = (1/P^2 N) + (A_{LR} \Delta P/P)^2$$

Other sources of error, such as dead time, luminosity and selection criteria, are expected to be very small [8] [9] because data with left and right polarization are taken at the same time with the same beam conditions. They will be neglected in this discussion where we concentrate on the effect of the polarization measurement.

It has been estimated that polarization could be measured with a relative precision of $\Delta P/P \geq 1\%$. For $\sin^2 \theta_w = 0.23$, yielding $A_{LR} = 0.16$, and a polarization of 50%, this error will dominate the error on A_{LR} for a total number $N_1 + N_2 = 10^6$ events. It will be shown in the following that in LEP, owing to the possibility of polarizing both electron and positron beams, there is a way around the challenge of measuring the beam polarization to an accuracy of 1%, and that the measurement of A_{LR} can be made free of that uncertainty.

3. The proposed scheme

Instead of depolarizing the electron bunches 2 and 4 as previously, one can depolarize the electron bunches 2 and 3 and obtain the following configuration ('4-bunch scheme') [10]:

electron bunches	$\Rightarrow$ 1	2	3	$\Rightarrow$ 4	etc.
positron bunches	1	$\Leftarrow$ 2	3	$\Leftarrow$ 4	etc.
cross sections	σ_1	σ_2	σ_3	σ_4	etc.

The experiment will measure four cross sections:

$$\sigma_1 = \sigma_u [1 - P^- A_{LR}] \quad (2a)$$

$$\sigma_2 = \sigma_u [1 + P^+ A_{LR}] \quad (2b)$$

$$\sigma_3 = \sigma_u \quad (2c)$$

$$\sigma_4 = \sigma_u [1 - P^+ P^- + (P^+ - P^-) A_{LR}] \quad (2d)$$

with statistics of N_1 , N_2 , N_3 , and N_4 events. Even if P^+ is different from P^- , these four numbers can be used to extract P^+ , P^- , and A_{LR} .

A first estimate of the statistical error can be obtained by assuming $P^+ = P^- = P$. Then the first two equations provide a measurement of A_{LR} as in the previous section, and the last two reduce to $\sigma_3 = \sigma_U$, and $\sigma_4 = \sigma_U[1 - P^2]$, providing a measurement of the polarization with a precision of

$$\Delta P/P = [(1 - P^2)/P^2] \sqrt{(1/N_3 + 1/N_4)}.$$

For an exposure of 40 pb^{-1} , yielding $N = N_1 + N_2 + N_3 + N_4 = 10^6$ events, one gets $\Delta P/P = 0.004$ and a negligible contribution to the statistical error.

4. Realistic experimental scenario

In practice the polarization will not be constant; it will vary with time, and it will not be equal for positrons and electrons as they circulate on slightly different orbits in the machine. One cannot even assume that the polarization of the various bunches in one beam would be identical. Therefore, constant monitoring with polarimeters will be required for both beams. It will be shown in this section that the method does provide absolute calibration of the polarimeters.

The polarimeters are expected to produce a luminosity weighted average polarization measurement P_i^m for each bunch i , which will be related to the true luminosity weighted average P_i^t by their calibration constants C^+ and C^- for electrons and positrons, respectively:

$$P_i^{t+} = P_i^{m+} C^+$$

$$P_i^{t-} = P_i^{m-} C^-,$$

which can be written as :

$$P_i^{t+} = P_i^{m+} (1 + \epsilon)(1 + \delta)$$

$$P_i^{t-} = P_i^{m-} (1 + \epsilon)(1 - \delta),$$

with $\epsilon = (C^+ + C^-)/2$ and $\delta = (C^+ - C^-)/(C^+ + C^-)$. Simulating an experimental error on N_1 , N_2 , N_3 , and N_4 , the four equations can be solved by a least-square fit. For the 40 pb^{-1} exposure, $A_{LR} = 0.16$, $P = 50\%$, one finds

$$\Delta A_{LR} = 0.0028,$$

$$\Delta \varepsilon = 0.009,$$

$$\Delta \delta = 0.033.$$

The errors correspond to the full 68% confidence level interval for each variable. This result is insensitive to the assumption that all bunches are polarized identically, provided the calibration constant is the same for all bunches belonging to the same beam. One can see that the parameter δ is very poorly determined, the reason being that it almost decouples from the equations. A priori knowledge of δ to better than 1% could probably be assumed, considering that the calibration constant of two nearly identical polarimeters functioning in very similar conditions cannot be very different. Imposing that constraint one finds

$$\Delta A_{LR} = 0.0027,$$

$$\Delta \varepsilon = 0.004.$$

Note that the error on A_{LR} has not improved much, and that the result of the previous section is retrieved.

The request on polarimetry can be phrased in the following way: the method will provide an absolute calibration of the polarimeters, provided it is the same for different bunches of the same beam. It is found that in order to infer a systematic error on A_{LR} of no more than 0.001, this statement must be true to 3×10^{-3} . No difference at all is expected for beams circulating in the same ring at the same time, but this point must be studied carefully.

The presence of a term in P^+P^- in eq.(4) leads to some constraints on the polarimeters: the measurement of polarization will be read in short time intervals Δt , and a bias could be introduced if the average over this interval of P^+P^- , $\langle P^+P^- \rangle$ is substantially different from the product of the averages, $\langle P^+ \rangle \langle P^- \rangle$. Statistical errors, being uncorrelated between the two polarimeters, will not contribute. The common time evolution of the polarization will however produce a bias. The normal polarization build-up time of 80 minutes in LEP at Z energies will produce a (correctable) bias of less than 10^{-3} for Δt less than 11 minutes. If a drop in the polarization occurred during the reading time it would have to be larger than $\Delta P = 0.1$ to induce a bias as large as 10^{-3} on the value of A_{LR} deduced from that particular interval. One would have to be capable of eliminating a time interval containing such a drop, but the polarimeters under study [11] being capable of a statistical accuracy of $\pm 2\%$ in 2 minutes seem perfectly adequate on that respect.

Figure 1: Comparison of the 4-bunch scheme proposed in this letter with the standard scheme, where the polarization measurement error is $\Delta P/P$, as a function of the polarization level $\langle P \rangle$:

- a) accuracy obtained for an exposure yielding 3×10^6 Z events;
- b) total integrated luminosity required to reach $\Delta A_{LR} = 0.002$.

Finally, the dependence of the precision on A_{LR} upon the polarization level, defined as

$$\langle P \rangle = \sqrt{(\int P(t)^2 \cdot \mathcal{L}(t) dt) / \int \mathcal{L}(t) dt},$$

is shown in figure 1, as well as the total integrated luminosity necessary to reach $\Delta A_{LR} = 0.002$. The 'optimized 4-bunch scheme' corresponds to devoting only the fraction of the data-taking to the spin configurations (2c) and (2d) that is needed to calibrate the polarimeters with sufficient accuracy. This optimum fraction varies from 50% for $\langle P \rangle = 0.2$ to 10% for $\langle P \rangle = 0.8$.

The advantage of the scheme presented here in comparison with the standard scheme is that it does not rely on the measurement of the polarization. Which scheme is best will depend on the values of A_{LR} , $\Delta P/P$, $\langle P \rangle$ and the integrated luminosity. An increase of any of these parameters will favour the 4-bunch scheme.

5. Conclusion

Owing to the possibility of selectively polarizing and depolarizing both electrons and positrons in LEP, the measurement of A_{LR} can be made potentially free of experimental systematics coming from the polarization measurement. The importance of this measurement as a test of the Standard Electroweak Model makes the effort of implementing longitudinally polarized beams highly worth while.

Acknowledgments

I gratefully acknowledge a stimulating discussion I had with H. Steiner on the SLC proposal, and the encouragement and support of J. Thresher, D. Treille, and of my friends from the ALEPH Polarization Working Group.

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