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Systematic Uncertainties on LEP Electroweak observables Due to Unknown Residual Longitudinal Beam Polarization

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Abstract

The consequences for electroweak observables of a residual longitudinal polarization are studied. For data recorded until 1994, all without spin-compensation of the experimental solenoids, the best estimate of longitudinal polarization of the e^+e^- system is zero, with upper limits of 0.06% at the Z peak and 0.2% at the $\pm$ 2 off-peak points. This results in a very safe upper limit on the additional systematic error on the Z mass and width of 0.2 MeV. Uncertainties on electroweak asymmetries are shown to enter as a modification of the initial state electron coupling $\mathcal{A}_e \equiv \frac{2g_{Ve}g_{Ae}}{g_{Ve}^2+g_{Ae}^2} \rightarrow \mathcal{A}_e + \Delta\mathcal{P}$. The value of the effective weak mixing angle $\sin^2\theta_{\rm w}^{\rm eff}$ is affected by an additional systematic error of at most ± 0.00008 when derived from the quark asymmetries and the τ forward-backward polarization asymmetry, ± 0.00004 for the lepton forward backward asymmetries, and not at all for the average τ polarization.
In case of a scan where data are taken for a fraction of the time at the off-peak energies with spin compensation of the experimental solenoids, allowing transverse polarization to build-up for energy calibrations, the additional systematic errors are well below the statistical accuracy of the data, both for cross-sections and asymmetries. Therefore calibrations with resonant depolarization in physics conditions are harmless off-peak from the point of view of systematics, and obviously useful from the point of view of integrated luminosity.

Contribution to the discussion on the 1995 scan.

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1 Introduction

In order to improve on the beam energy error for the 1995 scan, on foresees a large number of energy calibrations with resonant depolarization. Essentially, calibration should be tried for all fills. If these many calibrations have to be performed with separated beams, as has been done so far for operation, this might be perceived as a very heavy price to pay in terms of integrated luminosity. If each fill lasts 10 hours and a calibration takes about two hours, this would result in a loss of 20% of the off-peak data of 1995.

It has been shown several times in 1994 that polarization could be kept in collision mode [1], up to a polarization of 40% with a beam-beam tune shift of 0.04 in one collision point at the "peak-2" energy[1)] Although these results were obtained with somewhat specific tunes, it is now widely believed that one could keep in physics conditions a sufficient degree of polarization to perform energy calibrations without losing data.

There is a concern, however, that allowing transverse polarization would result in spurious longitudinal polarization, at the interaction point. This would affect in an unknown way the measurements of electroweak observables. This note will try to clarify this point and show that the resulting systematic uncertainty is always much smaller than the potential improvement in statistical errors.

The study shows that a spurious longitudinal polarization could also be present even if solenoids are not spin-compensated. The effect is quite relevant for the analysis of past data, since it is potentially strongly correlated among experiments. Safe upper limits to a possible effect are calculated for a number of electroweak observables and found to be very small.

2 Spurious Longitudinal Polarization

Prompted by my interrogations on this topic, Ralf Assmann Jean-Pierre Koutchouk have analysed this problem using the spin simulation programs [2]. There conclusions are the following. There are three sources of spurious longitudinal polarization.

1. Orbit imperfections in the arcs. These contribute to depolarization, so that they can only have a large effect when polarization is small and vice-versa. Due to this natural compensation, imperfections in the arcs give at most 0.2% longitudinal polarization at the IP's. This is essentially a random effect, uncorrelated between experiments.
2. Orbit imperfections in the interaction regions. This is by far the largest source. Because vertical orbit bumps in straight sections do not depolarize, one can be in a situation where one has large transverse polarization in the arcs and sizeable tilt of the spin vector in the IP's. This is indeed the principle of the spin rotators for LEP, within due proportions. What matters here is the tilt of the orbit at the IP w.r.t. the plane of LEP. Given the precision in the survey of LEP, and the accuracy of the pick-ups, an offset of 1.5 mm in the superconducting quadrupoles can certainly be present without hurting luminosity or polarization too much. This leads to a tilt of 375 μrad of the beam, and of 38 mrad of the spin vector. For 10% of transverse polarization, a longitudinal polarization of 0.4% results. This again is a random effect, uncorrelated between experiments. The offset in the quadrupoles can probably be suppressed by careful calibration of the pick-ups using the wobbling technique, reducing it by at least a factor 2.
3. Uncompensated solenoids. This effect is the most unexpected as it is not random, and fully correlated between experiments. Furthermore it occurs while solenoids are not spin-compensated,

[1)] The nomenclature for LEP energies around the Z pole is based on the corresponding spin-tune. One unit of spin-tune is 440.64 MeV in beam energy. "Peak" corresponds to a spin tune of about 103.5, "peak-2" to 101.5 etc...

e.g. one is not trying to establish transverse polarization. It is therefore present in data taken up to 1994 at all times. The estimate of Assmann and Koutchouk is that as much as 0.06% of longitudinal polarization could be present at the peak energy, coherently in all experiments. At the off-peak ± 2 points, the estimate is 0.2% with large cancelations amongst experiments. These estimates are upper limits, since they were calculated in a machine with no other depolarizing effect than the solenoids themselves.

In their study, Assmann and Koutchouk insist that positron and electron polarizations remain essentially opposite as long as their orbits are not too different. This should cancel any physics effect. In the case of energy calibrations, some bunches of electrons or positrons can be depolarized. Furthermore, in 1992 to 1994, the LEP operation with Pretzel resulted in somewhat different orbits for electrons and positrons. The above numbers will nevertheless be used to provide absolutely safe upper limits, although the best estimate is that the residual longitudinal polarization is zero.

In projection to the 1995 scan, the effect is compared with statistical errors corresponding to the maximum statistics one can reasonably hope for, i.e. 70 pb^{-1} on peak and 40 pb^{-1} off peak. The peak hadronic cross-section is 30 nb, the off-peak cross-section 10 pb.

3 Effects on total cross-sections

Total cross-sections are insensitive to transverse polarization, but parity violation in the Z couplings tells us that they depend on longitudinal polarization:

$$\sigma = \sigma_u(1 - \mathcal{P}_{e^+}\mathcal{P}_{e^-} + (\mathcal{P}_{e^+} - \mathcal{P}_{e^-})\mathrm{A_{LR}}) \tag{1}$$

where

$$\mathrm{A_{LR}} \simeq \mathcal{A}_e \equiv \frac{g_{Le}^2 - g_{Re}^2}{g_{Le}^2 + g_{Re}^2} = \frac{2 g_{Ve} g_{Ae}}{g_{Ve}^2 + g_{Ae}^2} \simeq 0.14 \tag{2}$$

A spurious polarization of $\Delta\mathcal{P}$ modifies the cross-section by:

$$(\frac{\Delta\sigma}{\sigma})_{\mathrm{Pol}} = \mathcal{A}_e \times \Delta\mathcal{P}. \tag{3}$$

Which is 7×10^{-4} for $\Delta\mathcal{P} = 0.5\%$.

Uncertainties in cross-sections affect three electroweak observables. The Z mass, $\mathrm{M_Z}$ the Z width Γ_Z, the peak-cross-section $\sigma_{\mathrm{had}}^{\mathrm{peak},0}$ – which is closely related to the derived number of light neutrinos N_ν. The ratio R_ℓ is unaffected. The Z mass would be sensitive to spurious polarization of opposite signs at the two off-peak points, the Z with to same sign polarization at these off-peak points, and the peak-cross-section to any effect at the peak point. For the sake of placing safe upper limits, the effects at the off-peak points are linearly added both for the mass and width. The error formulae for a scan at "peak $\pm$ 2" are then:

$$\Delta\mathrm{N}_\nu = (\frac{\Delta\sigma}{\sigma})_{\mathrm{Pol}} \times 8. \tag{4}$$

$$\Delta\mathrm{M_Z(MeV)} = (\frac{\Delta\sigma}{\sigma})_{\mathrm{Pol}} \times 1.2\ 10^3 \tag{5}$$

$$\Delta\Gamma_\mathrm{Z}(\mathrm{MeV}) = (\frac{\Delta\sigma}{\sigma})_{\mathrm{Pol}} \times 1.5\ 10^3 \tag{6}$$

4 Effects on Asymmetries

The formulae giving Z pole asymmetries with polarized beams can be found in any review of the subject [3]. The effective polarization of the e^+e^- system is given by

$$\mathcal{P} = \frac{\mathcal{P}_{e^-} - \mathcal{P}_{e^+}}{1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+}} \tag{7}$$

As mentioned before, it should be zero by symmetry between e^+ and e^- but will be assumed to take the full value of one beam polarization. In the case where only the e^- are polarized $\mathcal{P} = \mathcal{P}_e$. The polarization of the produced Z is modified:

$$\mathcal{P}_Z \to -\frac{\mathcal{A}_e - \mathcal{P}}{1 - \mathcal{A}_e\mathcal{P}} \simeq -\mathcal{A}_e + \mathcal{P} \tag{8}$$

The forward-backward asymmetry for a fermion of type f is modified to become

$$\mathrm{A}_{\mathrm{FB}}^{(f)} \simeq \frac{3}{4}\mathcal{P}_Z\mathcal{A}_f. \tag{9}$$

The effect is an apparent modification of the electron coupling but not of the final state coupling $\mathcal{A}_f$.

The tau polarization as a function of polar angle,

$$\mathcal{P}_\tau(cos\theta) \simeq -\frac{\mathcal{A}_\tau - \frac{2cos\theta}{1+cos^2\theta}\mathcal{P}_Z}{1 - \frac{2cos\theta}{1+cos^2\theta}\mathcal{P}_Z\mathcal{A}_\tau}, \tag{10}$$

from which one can derive the average, integrated over polar angle,

$$\langle\mathcal{P}_\tau\rangle \simeq -\mathcal{A}_\tau, \tag{11}$$

which is not modified by beam polarization, and the forward-backward polarization asymmetry

$$\mathrm{A}_{\mathrm{FB}}^{\mathrm{pol}(\tau)} = \frac{(\sigma_{\mathcal{P}_\tau=1,F} - \sigma_{\mathcal{P}_\tau=-1,F}) - (\sigma_{\mathcal{P}_\tau=1,B} - \sigma_{\mathcal{P}_\tau=-1,B})}{(\sigma_{\mathcal{P}_\tau=1,F} + \sigma_{\mathcal{P}_\tau=-1,F}) + (\sigma_{\mathcal{P}_\tau=1,B} + \sigma_{\mathcal{P}_\tau=-1,B})} \simeq \frac{3}{4}\mathcal{P}_Z, \tag{12}$$

which measures the Z polarization and is therefore fully modified.

So altogether the situation is rather simple: change all $\mathcal{A}_e$ into $\mathcal{A}_e - \mathcal{P}$ when $\mathcal{A}_e$ is the initial state coupling, and change nothing else.

Because QED is parity conserving, the interference term is unchanged by initial state polarization and the forward-backward asymmetry as function of energy

$$\mathrm{A}_{\mathrm{FB}}^{(f)}(s) \simeq \frac{3}{4}\mathcal{A}_e\mathcal{A}_f + \frac{s - \mathrm{M}_{\mathrm{Z}}^2}{\mathrm{M}_{\mathrm{Z}}^2}\frac{3}{2}Q_fQ_e \cdot 4\sin^2\theta_{\mathrm{w}}^{\mathrm{eff}}\cos^2\theta_{\mathrm{w}}^{\mathrm{eff}}\frac{g_{Ae}g_{Af}}{(g_{Ae}^2 + g_{Ve}^2)(g_{Af}^2 + g_{Vf}^2)}. \tag{13}$$

is only modified by a change again of $\mathcal{A}_e$ to $\mathcal{A}_e - \mathcal{P}$, corresponding in an upward or downward shift by

$$\Delta\mathrm{A}_{\mathrm{FB}}^{(f)}(s) = \frac{3}{4}\mathcal{P}\mathcal{A}_f \tag{14}$$

around the Z pole.

The effect of the spurious longitudinal polarization has been calculated for the lepton asymmetry, the tau asymmetries, the b-asymmetry, as well as for the combined $\sin^2\theta_{\mathrm{w}}^{\mathrm{eff}}$. The results are shown in table 1. Since the measurements are sensitive in different ways to the beam polarization, the effect could in principle be observed as an apparent violation of universality. It is, however, much too small compared to experimental errors.

5 Conclusions

The resulting effects are estimated for one experiment and the average of the four LEP experiments in table 1. The resulting very safe upper limits on uncertainties in the LEP average of data taken up to 1994 with uncompensated solenoids are

$$\Delta \mathrm{M_Z} \ll 0.2\mathrm{MeV} \quad (15)$$

$$\Delta \Gamma_\mathrm{Z} \ll 0.2\mathrm{MeV} \quad (16)$$

$$\Delta \mathrm{N}_\nu \ll 0.0007 \quad (17)$$

$$\Delta \sin^2 \theta_\mathrm{w}^\mathrm{eff} \ll 0.00004 \ \ (\mathrm{from\ all\ asymmetries}) \quad (18)$$

These number were obtained under very conservative assumptions that the polarizations of the two beams do not compensate each other as they should, and that effects are totally reproducible from day to day. Worst case correlations between energy points were assumed for estimating the errors on the line shape parameters.

The possible uncertainties resulting from taking 20% of the off-peak data with compensated solenoids can be obtained from in table 1. They would be smaller than – and uncorrelated with – the uncertainties in the sample taken with uncompensated solenoids. On the contrary, the additional statistics potentially available makes calibration in physics highly worthwhile.

The conclusion is clear: spurious Polarization leads to negligible systematic errors at the peak if solenoids are not spin compensated, and off-peak in all cases. At the peak with compensated solenoids, the very generous upper limits given here would be at the limit of significance. If one wanted to run with high transverse polarization at the peak, more work would be needed to correct the alignment of the beam around the IP's to reduce the resulting errors on electroweak quantities to a small level.

6 Acknowledgements

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References

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[2] R. Assmann and J.-P. Koutchouk, 'residual Longitudinal Polarization in LEP' SL Note 94-37 (AP).

[3] A. Blondel 'Beam Polarization in e^+e^- annihilation', CERN-PPE/93-125, to appear in "precision tests of the Standard Model", World scientific P. Langacker ed.

[4] The LEP collaborations, 'Combined Preliminary data on Z parameters from the LEP experiments and constraints on the Standard Model', CERN-PPE/94-187.

Table 1: Summary of systematic errors from spurious longitudinal polarization on important electroweak measurements from ONE experiment, or from the average of the four LEP experiments. For the line shape measurements the resulting errors on $\mathrm{N}_\nu, \mathrm{M}_\mathrm{Z}, \Gamma_\mathrm{Z}$ is extracted assuming worse case correlations between energy points. For each asymmetry the equivalent $\sin^2\theta_\mathrm{w}^\mathrm{eff}$ errors have been given. The effect of these fully correlated effects on the combined $\sin^2\theta_\mathrm{w}^\mathrm{eff}$ is also given.

		PEAK			OFF-PEAK		
Quantity	solenoids spin compensation	Pol. Level (%)	Pol Syst. (1exp.) (10^{-4})	Pol. syst. (4 exp.) (10^{-4})	Pol. Level (%)	Pol Syst. (1 exp.) (10^{-4})	Pol. syst. (4 exp.) (10^{-4})
σ^had	OFF	0.06	0.8	0.8	0.2	2.8	1.4
	ON	0.5	7	3.5	0.5	7	3.5
N_ν	OFF	0.06	7	7	–	–	–
	ON	0.5	56	28	–	–	–
M_Z (MeV)	OFF	0.06	–	–	0.2	0.34	0.17
	ON	0.5	–	–	0.5	0.8	0.4
Γ_Z (MeV)	OFF	0.06	–	–	0.2	0.4	0.2
	ON	0.5	–	–	0.5	1.	0.5
$\mathrm{A}_\mathrm{FB}^{(\ell)}$	OFF	0.06	0.6	0.6	0.2	2.1	1.
	ON	0.5	5.	2.5	0.2	5.3	2.6
$\sin^2\theta_\mathrm{w}^\mathrm{eff}$	OFF	0.06	0.4	0.4	–	–	–
	ON	0.5	3.	1.5	–	–	–
$\mathcal{P}_\tau$	OFF	0.06	0.	0.	0.2	0.	0.
	ON	0.5	0.	0.	0.5	0.	0.
$\sin^2\theta_\mathrm{w}^\mathrm{eff}$	OFF	0.06	0.	0.	–	–	–
	ON	0.5	0.	0.	–	–	–
$\mathcal{A}_e$ from τ	OFF	0.06	6	6	0.2	20	10
	ON	0.5	50	25	0.5	50	25
$\sin^2\theta_\mathrm{w}^\mathrm{eff}$	OFF	0.06	0.8	0.8	–	–	–
	ON	0.5	6.2	3.1	–	–	–
$\mathrm{A}_\mathrm{FB}^{(b)}$	OFF	0.06	4	4	0.2	14	7
	ON	0.5	35	17	0.5	35	17
$\sin^2\theta_\mathrm{w}^\mathrm{eff}$	OFF	0.06	0.8	0.8	–	–	–
	ON	0.5	6.2	3.1	–	–	–
$\sin^2\theta_\mathrm{w}^\mathrm{eff}$ (combined)	OFF	0.06	0.4	0.4	–	–	–
	ON	0.5	3.1	1.5	–	–	–