CERN-TH.5499/89

T-ODD CORRELATION ON THE Z°-PEAK

J. Bernabéu*)

CERN-Geneva

and

N. Rius

Departament de Física Teòrica, Universitat de València,
e IFIC, Centre Mixt Univ. València-CSIC, 46100 Burjassot, Spain

ABSTRACT

T-odd observables can be due either to T-violation or to unitarity corrections. We find a non-vanishing expectation value of a T-odd operator for $Z^\circ \to f\bar{f}$ from one-loop electroweak corrections to the resonant decay and from interference with the background. For unpolarized beams, chirality conservation allows only one relevant absorptive part of the interference between different amplitudes. We identify this unique T-odd effect as the spin correlation $\langle S_T \bar{S}_N \rangle$, where S_T and $\bar{S}_N$ are the transverse (within the production plane) and normal (to the plane) spin components for f and $\bar{f}$, respectively. In the standard theory it is generated from the Z,W exchanges in the final vertex, from the Z-γ self-energy and from the tree-level Z-γ interference. Its value is -1.1% for $e^+e^- \to \tau^+\tau^-$ at 90°.

---

*) On leave of absence from University of Valencia, Spain.

CERN-TH.5499/89
August 1989

The advent of the SLC and LEP1 facilities will make possible to study with high precision and in extremely clean conditions a variety of processes [1] involving leptons and quarks. In this paper we address the question of whether the conditions are met in these processes to get on the Z°-peak effects associated with observables odd under time reversal. Momenta and polarizations are reversed by the time reversal operation, thus a scalar formed by the product of an odd number of these factors is a T-odd quantity. Its non-vanishing expectation value would be a signal of T-odd effects. Some general considerations about T-odd observables in e^+e^- colliders have been discussed recently [2-3]. The difficulty of finding suitable T-odd operators, with non-vanishing expectation values, for chiral conserving interactions has been pointed out. If this chirality restriction is abandoned by considering exotic chirality-flip couplings to fermions, such as those induced by P- and CP-violating electric or weak dipole moments [4], one finds more possibilities to build T-odd observables. We restrict our attention to gauge interactions with their chirality-conserving character.

T-odd effects can be due either to CP-violation or to unitarity corrections. Let us consider the transition matrix M for a given process $\alpha\to\beta$, expressed in terms of its Hermitian and anti-Hermitian components. Assuming that the interaction is invariant under the time reversal operator T, the effect of T gives

$$\langle\beta|M|\alpha\rangle = \eta\left\{\langle T\beta|\tfrac{1}{2}(M+M^+)|T\alpha\rangle^* - \langle T\beta|\tfrac{1}{2}(M-M^+)|T\alpha\rangle^*\right\} \qquad (1)$$

where η is a phase. In the lowest-order Born approximation, the transition matrix M=H is Hermitian and we have, from Eq. (1), an equal probability for a transition $\alpha\to\beta$ and for the transition between the time-reversed states $T\alpha\to T\beta$. For a T-odd observable this implies equal probability of finding positive or negative eigenvalues in its measurement. It follows that, if T is an exact symmetry, the expectation value of a T-odd observable vanishes. As a consequence, to first order in H, a non-vanishing expectation value of a T-odd observable is a signal of T non-invariance, that is, from the CPT theorem, a signal of CP violation. But higher-order terms in the Hamiltonian H induce an anti-Hermitian contribution to the transition matrix M, often referred to as unitarity correction because it is the absorptive part of the amplitude

$$(M-M^+)_{\alpha\beta} = i(2\pi)^4 \sum_\gamma M_{\alpha\gamma}\, M^+_{\gamma\beta}\, \delta^{(4)}(p_\alpha - p_\gamma) \qquad (2)$$

In the presence of Eq. (2), the probabilities for a transition and for the transition between the time-reversed states are no longer equal [5]. Non-vanishing

expectation values of T-odd observables are then allowed. Therefore, transition amplitudes with relative phases due either to unitarity corrections or to CP violation, or both, can lead to odd effects under time reversal.

We study obervables odd under T for the collision processes

$$e^-(k_1,\lambda_a) + e^+(k_2,\lambda_b) \to f(p_1,\lambda_1) + \bar{f}(p_2,\lambda_2) \qquad (3)$$

with $q^2=(k_1+k_2)^2=(p_1+p_2)^2$ around the Z°-resonance and the notation is self-explanatory. Our interest is focused on the imaginary parts of the interference between two terms of the amplitude. For unpolarized e^+e^- beams, the quantity to look for is an interference between amplitudes with different final helicities, averaging the observables over all possible initial helicities. Although there are in principle sixteen helicity amplitudes, in any theory like the Standard Model in which the fermions are coupled to vector bosons, chirality conservation in the limit of zero masses for the external legs implies $\lambda_b=-\lambda_a$, $\lambda_2=-\lambda_1$, so we are left with four independent helicity amplitudes. As a consequence, in our problem the only amplitudes which can interfere are those for total final helicity +1 and -1 and the odd effects under time reversal T would correspond to the following asymmetry

$$A = \frac{2\sum_{\lambda_i} Im\left\{M_{-1,\lambda_i} M^*_{1,\lambda_i}\right\}}{\sum_{\lambda_i,\lambda} |M_{\lambda,\lambda_i}|^2} \qquad (4)$$

where M_{λ,λ_i} is the transition amplitude from the initial state with total helicity $\lambda_i=\lambda_a-\lambda_b$ to a final state with total helicity $\lambda=\lambda_1-\lambda_2$.

The interference described by Eq.(4) is accessible through the following spin correlation between the outgoing fermions f and $\bar{f}$. Let us take the lab. reference frame (the Z° rest frame) and the moving frames for the outgoing f and $\bar{f}$ fermions at rest, with the coordinate systems as indicated in Fig. 1. The moving reference frames are obtained from the lab. frame with opposite velocity boosts, but the coordinate (x',y',z') system is chosen to be the same for both f and $\bar{f}$. For unpolarized beams, the collision process has cylindrical symmetry around the beam axis, so we define the coordinate (x,z) plane to be the collision plane and $y'\equiv y$. In the helicity basis of the final states, the information about the process is contained in the matrix

$$\rho_{\lambda_1\lambda_2;\lambda'_1\lambda'_2} = \sum_{\lambda_a,\lambda_b} M_{\lambda_1\lambda_2,\lambda_a\lambda_b} M^*_{\lambda'_1\lambda'_2,\lambda_a\lambda_b} \qquad (5)$$

When properly normalized, Eq.(5) becomes the density matrix of the final state, so the expectation value of the transverse (within the collision plane) - normal (to the collision plane) spin correlation for f and $\bar{f}$ is given by

$$\langle S_{x'} \bar{S}_{y'} \rangle = Tr(\rho S_{x'} \bar{S}_{y'})/Tr(\rho)$$
$$= 2 \, Im \, \rho_{-+;+-}/Tr(\rho) = A \qquad (6)$$

Equation (6) identifies the physical observable associated with the T-odd asymmetry Eq. (4).

One could think of applying the strategy of going to suppressed transitions to enhance the asymmetry that Eq. (4) could generate. In the Standard Model the tree-level amplitude for flavour changing neutral current transitions is forbidden and the first contribution to the M-amplitudes would be at the one-loop order. In this case one would expect both absorptive parts of the amplitudes and CP-violation in the electro-weak coupling parameters. Taken together, one predicts [6] a CP-violation asymmetry in the flavour-changing decay rates of the $Z°$, although desperately small to be observed with the expected luminosity of the e^+e^- machines. However, in order to build a T-odd asymmetry from Eq.(4) these ingredients are not enough: one needs a relative phase between the different helicity amplitudes. The flavour-changing neutral current vertex is [7], in the standard theory, of the form V-A for zero external masses and, therefore, purely left-handed. There is no option to find T-odd asymmetries in these suppressed transitions. We concentrate our study on the more promising processes of the leading decay modes of the $Z°$, the flavour diagonal channels for $f=\mu,\tau,u,c,d,s,b$.

For the flavour conserving collision process (3), the interference of the tree-level amplitudes for the resonant $Z°$-exchange and the background γ-exchange can contribute to an absorptive part of order Γ_Z/M_Z. Its contribution to Eq. (4) is

$$A^{(0)}(\theta) = \frac{2\sum_{\lambda_i}\{M^{(\gamma)}_{1,\lambda_i}\, Im\, M^{(0)}_{-1,\lambda_i} - M^{(\gamma)}_{-1,\lambda_i}\, Im\, M^{(0)}_{1,\lambda_i}\}}{\sum_{\lambda,\lambda_i} |M^{(0)}_{\lambda,\lambda_i}|^2} \qquad (7)$$

where $M^{(\gamma)}$ is the (real) γ-exchange amplitude and $M^{(0)}$ the resonant amplitude at tree level.

For the interference between resonant amplitudes, the absorptive parts appear when electroweak radiative corrections are considered. To lowest order in pertubation theory we get for the T-odd observable

$$A^{(1)}(\theta) = \frac{2\sum_{\lambda_i} Im\{M^{(0)*}_{1,\lambda_i} M^{(1)}_{-1,\lambda_i} - M^{(0)*}_{-1,\lambda_i} M^{(1)}_{1,\lambda_i}\}}{\sum_{\lambda,\lambda_i} |M^{(0)}_{\lambda,\lambda_i}|^2} \qquad (8)$$

where $M^{(0)}_{\lambda,\lambda_i}$ is the resonant amplitude at tree level and $M^{(1)}_{\lambda,\lambda_i}$ its corresponding electroweak correction at one-loop order.

The calculation of the $M^{(1)}$ amplitudes has been made in the 't Hooft-Feynman gauge, for which the diagrams to be considered on the $Z°$ resonance are discussed now. The diagram with the exchange of the would-be Nambu-Goldstone boson $\sigma^{\pm}$ contributes only to the final vertex when the outgoing state is $b\bar{b}$, because the mass of the top quark is maintained different from zero. In the Feynman gauge, this diagram with σ-exchange is responsible for the particular behaviour of the $Z°\to b\bar{b}$ partial width, which is affected [8] by hard mass terms sensitive to the top quark mass. We neglect the (double) intergeneration mixings in the diagrams with (two) charged current couplings. To get non-vanishing absorptive parts, the intermediate states have to have their branch point below the physical value of M_Z^2. However, the explicit form of Eq. (8) indicates that not all the diagrams with non-vanishing absorptive parts are relevant for our T-odd observable, in the case of unpolarized beams. In general, with our assumptions the diagrams can be decomposed into a part corresponding to the Ze^+e^- vertex times another part associated with the $Zf\bar{f}$ vertex. Then all diagrams for which the one-loop corrected amplitude $M^{(1)}$ has a $Zf\bar{f}$ vertex proportional to that for $M^{(0)}$ do not contribute to the observable, because the induced absorptive part is common to both final total helicity amplitudes. Thus one does not need to consider the diagrams corresponding to the Ze^+e^- vertex corrections, to the γ,Z-Z self energy and to the γ-exchange in the $Zf\bar{f}$ vertex. One can convince oneself that the diagrams which are relevant for the T-odd observable we are considering are those depicted in Fig. 2. The absorptive part of the amplitude obtained from these diagrams can be written as

$$\mathrm{Im}\ \frac{M^{(1)}_{\lambda,\lambda_i}}{P(q^2)} = X^{(0)\mu}\ \bar{u}(p_1,\lambda_1)\gamma_\mu\{\mathrm{Im}\,F_V - \gamma_5\,\mathrm{Im}\,F_A\}\,v(p_2,\lambda_2) \tag{9}$$

in a normalization for which the tree-level amplitudes are given by

$$\frac{M^{(0)}_{\lambda,\lambda_i}}{P(q^2)} = X^{(0)\mu}\ \bar{u}(p_1,\lambda_1)\gamma_\mu\{v - \gamma_5 a\}\,v(p_2,\lambda_2) \tag{10}$$

The quantities

$$X^{(0)\mu} = \bar{v}(k_2,\lambda_b)\gamma^\mu\{v_e - \gamma_5 a_e\}\,u(k_1,\lambda_a)$$

$$P(q^2) = \frac{g^2}{\cos^2\theta_W}\ \frac{1}{q^2 - M_Z^2 + i\,M_Z\Gamma_Z} \tag{11}$$

are the e^+e^- vertex of the initial state and the Z°-propagator, respectively. The lowest order couplings v and a in Eq. (10) are given in terms of the weak isospin of the corresponding fermion

$$v = \frac{1}{2}\,I_3 - Q\,\sin^2\theta_W \quad ; \qquad a = \frac{1}{2}\,I_3 \tag{12}$$

The vertex functions F_V and F_A to one-loop order in Eq. (9) depend on the final fermion considered. They are obtained as a sum of the contributions from the different diagrams of Fig. 2:

$$F_{V,A} = \sum_{j=a,\dots,d} F^{(j)}_{V,A} \tag{13}$$

The diagram (a) gives an absorptive contribution in terms [9] of purely neutral current couplings for the selected fermion channel

$$\mathrm{Im}\ F_V^{(a)} = \frac{\alpha}{\sin^2\theta_W\cos^2\theta_W}\ v\,(v^2 + 3a^2)\left(2\ln 2 - \frac{5}{4}\right)$$

$$\mathrm{Im}\ F_A^{(a)} = \frac{\alpha}{\sin^2\theta_W\cos^2\theta_W}\ a\,(a^2 + 3v^2)\left(2\ln 2 - \frac{5}{4}\right) \tag{14}$$

The diagram (b) and (for the $b\bar{b}$ channel) the diagram (c) provide [6,7] an effective $Zf\bar{f}$ vertex of the V-A type, i.e., $F_V^{(j)} = F_A^{(j)}$ for j=b,c. The calculation in the Feynman gauge gives for the absorptive parts

$$\mathrm{Im}\,[F^{(b)}_{V,A} + F^{(c)}_{V,A}] = -\frac{\alpha}{16\sin^2\theta_W}\left\{(v'+a')F_1(r) - (v'-a')\,r\,F_2(r)\right\} \tag{15}$$

where the neutral current couplings appearing in Eq. (15) refer to the partner, in the $SU(2)_L$ doublet, of the f fermion and $r\equiv(m/M_W)^2$, where m is the mass of this intermediate partner fermion. We have $r\neq 0$ only for $f\bar{f}\equiv b\bar{b}$, associated with the mass of the top. The two functions $F_{1,2}(r)$ are

$$F_1(r) = \Theta(1-4r/s)\Big\{(1-4r/s)^{1/2}\left[3 + \frac{2(1-r)}{s}\right]$$

$$+ \frac{1}{s}\left[2s + (2-r)^2 + 2\,\frac{(1-r)^2}{s}\right]\ln\frac{2(1-r)+s-(s(s-4r))^{1/2}}{2(1-r)+s+(s(s-4r))^{1/2}}\Big\}$$

$$F_2(r) = \theta(1-4r/s)\left\{-(1-4r/s)^{1/2}\left[\frac{1}{2} + \frac{r-1}{s}\right] + \frac{1}{s}\left[2 + \frac{(1-r)^2}{s}\right] \ln \frac{2(1-r)+s-(s(s-4r))^{1/2}}{2(1-r)+s+(s(s-4r))^{1/2}}\right\} \tag{16}$$

where $s \equiv (M_Z/M_W)^2 = 1/\cos^2\theta_W$ and θ is the step function. As explained before, $r=0$ or $r=r_t$ depending on the channel.

Finally, the diagram (d) of mixing between the two neutral gauge bosons (Z,γ) gives a contribution [9] which is obtained after the sum over all fermions in the loop, including the three possible colours for quarks. We write the absorptive part in terms of the vector neutral current couplings for charged leptons, d-type quarks and u-type quarks :

$$\mathrm{Im}\; F_V^{(d)} = \alpha Q \left\{ v_e + v_d - \frac{4}{3} v_u - \frac{2}{3} v_u \left(1+\frac{2r}{s}\right)\left(1-\frac{4r}{s}\right)^{1/2} \theta\left(1-4\frac{r}{s}\right)\right\}$$

$$\mathrm{Im}\; F_A^{(d)} = 0 \tag{17}$$

where $r=r_t$ here.

Once the amplitudes contributing to the T-odd observable on the Z° peak have been determined, we have to extract their helicity dependence. We obtain the helicity amplitudes as traces of products of γ's, which can be evalutated by means of standard procedures. In the CM frame and, in the limit of zero external masses with chirality conserving interactions, for opposite helicity of fermion and antifermion we can use the following equality satisfied by the four spinors [10]

$$u(\vec{p},\lambda')\,\bar{v}(-\vec{p},\lambda) = \frac{i}{2}\,\not{p}\,[\not{t} + \sigma^2_{\lambda\lambda'}\not{n}]\,\gamma^0 \quad ; \quad \lambda \neq \lambda' \tag{18}$$

where σ^2 is the (second) Pauli matrix and t^μ and n^μ are the polarization vectors associated with the transverse and normal directions, respectively. If Eq. (18) [actually its adjoint] is applied to the outgoing fermions, in the reference system (x,y,z) with the choice indicated in Fig. 1 we have

$$t^\mu = (0, \cos\theta, 0, -\sin\theta) \quad ; \quad n^\mu = (0,0,1,0) \tag{19}$$

Similarly, when applied to the incoming fermions, Eq. (18) has to be taken for $\vec{p}\to\vec{k}$ and $\theta\to 0$.

With all the collected ingredients, it is straightforward to calculate from Eqs.(9) and (10) the explicit helicity dependence of the amplitudes. We obtain the scattering angle dependence for the amplitudes at one-loop order

$$\frac{M^{(1)}_{\lambda,\lambda_i}}{P(q^2)} = -q^2 (v_e - \lambda_i a_e)\left\{F_V - \lambda F_A\right\}(\lambda\lambda_i + \cos\theta) \tag{20}$$

and similarly for $M^{(0)}_{\lambda,\lambda_I}$ taking $F_V\to v$ and $F_A\to a$. Using the same method, the helicity amplitudes for γ-exchange are

$$M^{(\gamma)}_{\lambda,\lambda_i} = e^2 Q\,(\lambda\lambda_i + \cos\theta) \tag{21}$$

where Q is the charge, in natural units, of the final fermion. The angular distribution of the amplitudes shows the anticipated conservation of the total helicity in the forward direction and the opposite total helicity restriction in the backward direction.

The helicity amplitudes thus calculated have been combined in our Eqs. (7) and (8) for the T-odd observable. The angular distribution of the transverse-normal spin correlation for outgoing $f\bar{f}$ fermions is

$$A(\theta) = A^{(0)}(\theta) + A^{(1)}(\theta)$$

$$A^{(0)}(\theta) = -\frac{\Gamma_Z}{M_Z}\,\frac{2\,Q\cos^2\theta_W\sin^2\theta_W\,v_e\,a\,\sin^2\theta}{(v_e^2+a_e^2)(v^2+a^2)(1+\cos^2\theta)+8\,v_e a_e v a\cos\theta} \tag{22}$$

$$A^{(1)}(\theta) = \frac{2\{a\,\mathrm{Im}\,F_V - v\,\mathrm{Im}\,F_A\}\sin^2\theta}{(v^2+a^2)(1+\cos^2\theta)+8\,\frac{v_e v a_e a}{v_e^2+a_e^2}\cos\theta}$$

where the relevant absorptive parts are given in Eqs. (13-17), generated by the diagrams of Fig. 2. We present in Fig. 3 the scattering angle dependence of the observable (22) for all final states of interest: $f=\mu,\tau$; $f=u,c$; $f=d,s$; $f=b$, as indicated in the four curves. We have used $\sin^2\theta_W=0.23$, $M_Z=91$ GeV, $\Gamma_Z=2.5$ Gev and a top quark not produced at the Z° peak. In all cases the angular distribution for the T-odd asymmetry is approximately symmetric around the maximum (in absolute values) obtained for $\theta=\pi/2$. The reason, as seen from Eq. (22), is the small forward-backward asymmetry for all channels on the Z° peak due to the small v_e.

The present experimental lower bound for the top quark mass is [11] $m_t>41$GeV, although its value is likely to be above 60 GeV, both from the experimental collider limits [12] and from the simplest interpretation of the large $B^\circ\bar{B}^\circ$ mixing [13]. If $r_t>s/4$ the top quark intermediate states decouple in the absorptive parts of both the vertex diagrams (b)+(c) of Fig. 2 and the off-diagonal self-enery diagram (2.d). We have studied the value of the T-odd observable as function of the top quark mass below the branch point value $r_t=s/4$, and for the same set of final states. One finds a very mild dependence of the results on the top quark mass.

Figure 3 shows that the largest T-odd effects correspond to leptonic final states ($\mu\bar{\mu}$ or $\tau\bar{\tau}$) and they are about -1.1%. For quarks of up-type the results are somewhat smaller, about -0.6%. For quarks of down-type they are still smaller, about -0.2% for d,s and -0.1% for b. The reason for the larger value in the leptonic channel is that there the effect is dominated by the absorptive part Im $F_V^{(d)}$ of the off-diagonal self-energy diagram (2.d). For quarks v~a and there are other terms of opposite sign which tend to diminish the value of the T-odd

observable. On the other hand, the W-exchange vertex correction Im $F_{V,A}^{(b+c)}$ vanishes for $r>s/4$, so the $b\bar{b}$ final state has a signal of T-odd effects somewhat smaller than that for the other down-type quarks. In all cases, the two sources of the T-odd effect, $A^{(0)}$ and $A^{(1)}$ in Eq. (22), have opposite sign and $A^{(1)}$ is somewhat larger in magnitude. For the interesting $\tau^-\tau^+$ final state one gets $A(\theta=\pi/2)=(+1.27-2.37)\times10^{-2}=-1.1\%$. Neither $A^{(0)}$ not $A^{(1)}$ have a strong energy dependence through the resonance region.

To summarize, we have singled out a T-odd correlation for the leading decay channels of the Z° boson with unpolarized e^+e^- beams. It is manifested by a non-vanishing expectation value of the transverse-normal component of the spin correlation between the outgoing fermion and antifermion. This T-odd effect is due to the generation of absorptive parts in the resonant amplitudes from electroweak radiative corrections to the final vertex and from the Z-γ self energy, as well as from the tree-level interference of the resonant and non-resonant amplitudes. These contributions provide a relevant relative phase between helicity amplitudes for different total final helicity. We have calculated the observable for the different fermions in the final state, charged leptons and quarks. In the standard theory the spin correlation is larger for the $\tau^-\tau^+$ channel, with a value of -1.1% at the scattering angle $\theta=90°$. It would be interesting to explore the presence of this T-odd spin correlation at the e^+e^- colliders around the Z°, where this spin effect on the $\tau^+\tau^-$ could be translated into energy or angular correlations [14] between their corresponding decay products. An easier alternative to the proposal for T-odd effects discussed in this paper would be possible if transverse polarization of the e^+e^- beams were available at the SLC and/or LEP1 facilities. A strong transverse polarization program is the first step [15] to get longitudinal polarization at LEP for other precision tests of the Standard Model.

Acknowledgements

The authors are indebted to F.J. Botella, A. De Rújula, M.B. Gavela, J.J. Gómez-Cadenas, J.J. Hernández, C. Jarlskog, A. Pich and A. Sirlin for the interesting discussions and questions about the subject of this paper. One of us (J.B.) acknowledges the hospitality of the CERN Theory Division, the other (N.R.) the fellowship of the Ministerio de Educación y Ciencia, Spain. This work has been financially supported by CICYT, under Grant AEN-88/021.

REFERENCES

[1] See, for example, Physics with LEP, CERN 86-02 (1986), Eds. J. Ellis and R. Peccei.

[2] J.F. Donoghue and G. Valencia, Phys. Rev. Lett. 58 (1987) 451; E60 (1988) 243.

[3] M.B. Gavela, F. Iddir, A. Le Yaouanc, L. Oliver, O. Pène and J.C. Raynal, Phys. Rev. D39 (1989) 1870;
Y. Kizukuri, Phys. Lett. B193 (1987) 339;
J. Bernabeu and M.B. Gavela, in CP Violation, Ed. C. Jarlskog, World Scientific (1989).

[4] F. Hoogeveen and L. Stodolsky, Phys. Lett. B212 (1988) 505;
W. Bernreuther, M.J. Duncan, E.W.N. Glover, R. Kleiss, J.J. van der Bij, J.J. Gomez-Cadenas and C.A. Heusch, CERN-TH 5484/89.

[5] A. De Rujula, J. Kaplan and E. de Rafael, Nucl. Phys. B35 (1971) 365.

[6] J. Bernabeu, A. Santamaria and M.B. Gavela, Phys. Rev. Lett. 57 (1986) 1514;
W.S. Hou, N. Deshpande, G. Eilam and A. Soni, Phys. Rev. Lett. 57 (1986) 1406.

[7] A. Axelrod, Nucl. Phys. B209 (1982) 349;
M. Clemens, C. Footman, A. Kronfeld, S. Navasimhan and D. Photiadis, Phys. Rev. D27 (1983) 570;
V. Ganapathi, T. Weiler, E. Laerman, I. Schmitt and P.M. Zerwas, Phys. Rev. D27 (1983) 579;
G. Eilam, Phys. Rev. D28 (1983) 1202;
M.J. Duncan, Phys. Rev. D31 (1985) 1139; CERN-TH 5429/89.

[8] A.A. Akhundov, D. Yu. Bardin and T. Riemann, Nucl Phys. B276 (1986) 1;
J. Bernabeu, A. Pich and A. Santamaria, Phys. Lett. B200 (1988) 569;
W. Beenakker and W. Hollik, Z. Physik C40 (1988) 141.

[9] M. Böhm, W. Hollik and H. Spiesberger, Fortschr. Phys. 34 (1986) 687.

[10] J.A. Penarrocha, Ph.D. Thesis, University of Valencia (1980), unpublished.

[11] C. Albajar et al., UA1 collaboration, Z. Phys. C37 (1988) 505;
G. Altarelli, M. Diemoz, G. Martinelli and P. Nason, Nucl. Phys. B308 (1988) 724.

[12] CDF, UA1 and UA2 Collaborations, preliminary results.

[13] P.J. Franzini, Physics Reports 173 (1989) 1.

[14] Yung-Su Tsai, Phys Rev. D4 (1971) 2821;
S. Kawasaki, T. Shirafuji and S.Y. Tsai, Prog. Theor. Phys. 49 (1973) 1656;
T. Hagiwara, So-Young Pi and A.I. Sanda, Ann. Phys. (N.Y.) 106 (1977) 134;
C.A. Nelson, Phys. Rev. D40 (1989) 123.

[15] A. Blondel, in Polarization at LEP, CERN 88-06 (1988), Eds. G. Alexander, G. Altarelli, A. Blondel, G. Coignet, E. Keil, D.E. Plane and D. Treille.

FIGURE CAPTIONS

Fig. 1. Coordinate systems chosen for the Z° rest frame (x,y,z) and for the moving frame (x',y',z'). The axis y≡y' is normal to the collision plane.

Fig. 2. Diagrams in the 't Hooft-Feynman gauge contributing to the one-loop order amplitude $M^{(1)}$ for the T-odd asymmetry discussed in Eq. (8). (2.a) gives the Z-exchange correction to the final vertex, (2.b+2.c) the W-exchange correction to this vertex and (2.d) the Z-γ self-energy contribution to the process.

Fig. 3. Angular distribution of the T-odd asymmetry for the different decay modes of the Z°. Continuous line (——): μ,τ leptons; dashed-dotted line (-·-·): u,c quarks; dashed line (---): d,s quarks; dotted line (....): b quark. The results are given for $\sin^2\theta_W$=0.23, M_Z=91GeV and Γ_Z=2.5 GeV.

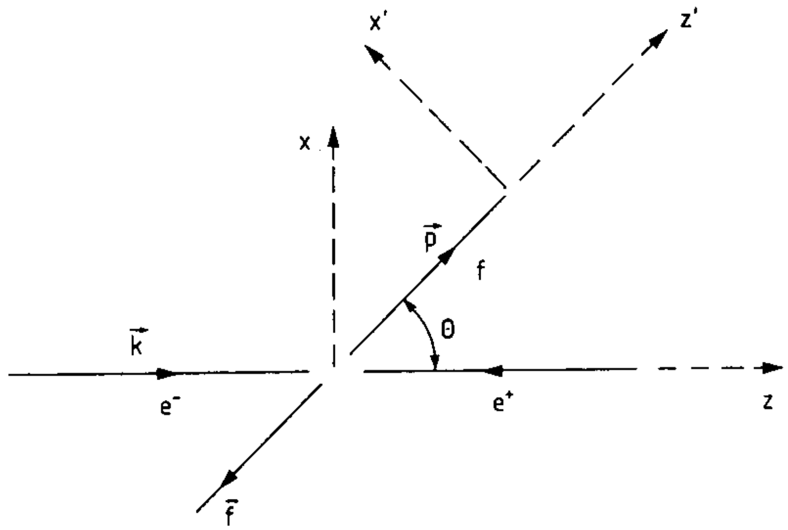
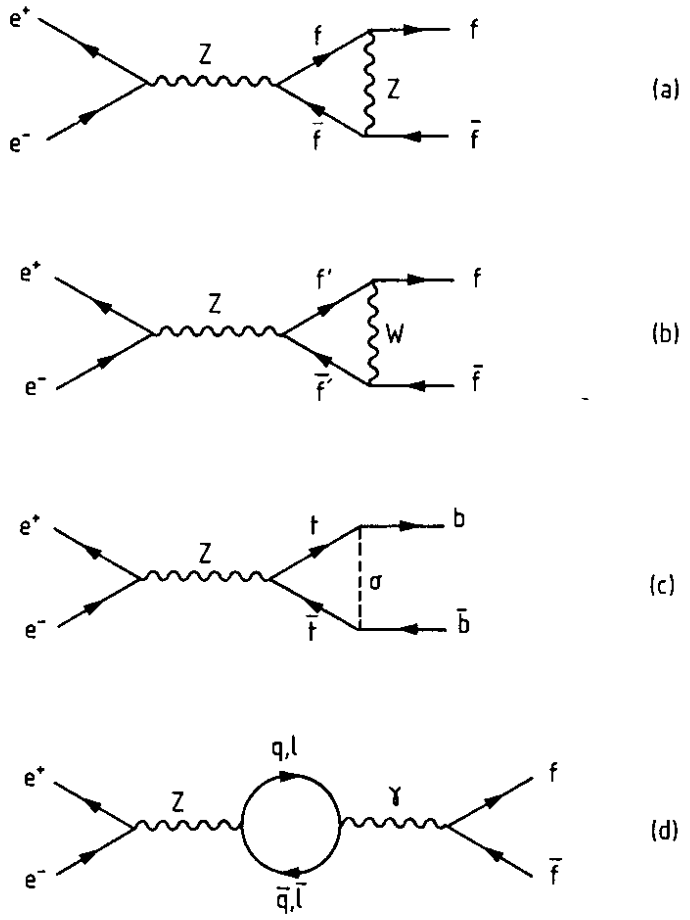
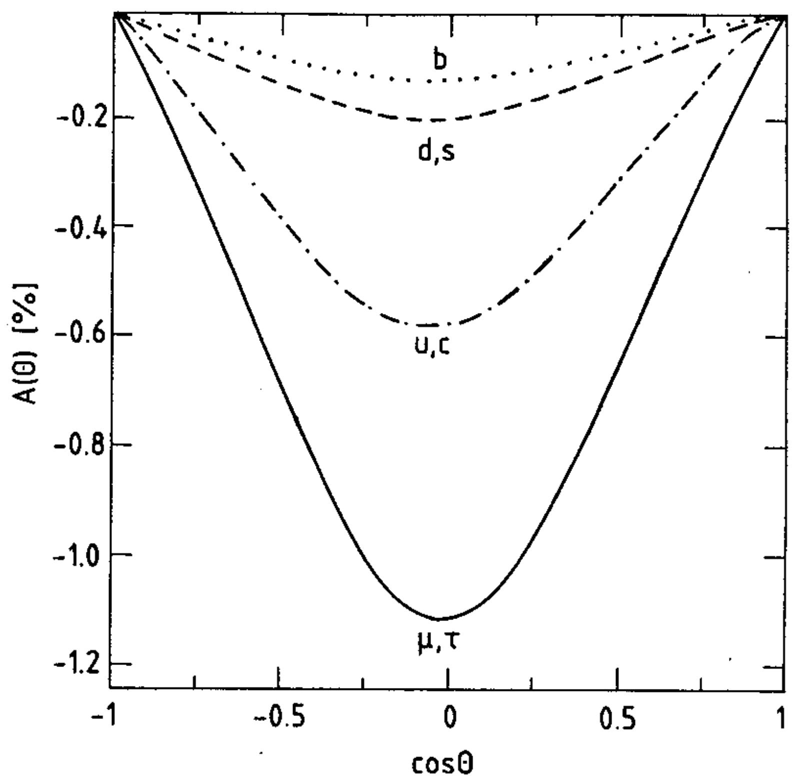


Fig. 1



e⁺
e⁻
Z
f
f̄
f
f̄
(a)
f′
f̄′
W
(b)
t
t̄
σ
b
b̄
(c)
q,l
q̄,l̄
γ
(d)

Fig. 2



A(Θ) [%]
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1
-0.5
0
0.5
1
cosΘ
b
d,s
u,c
μ,τ

Fig. 3