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Multiple-photon effects in asymmetries: $\mu\bar{\mu}$ vs $b\bar{b}$

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We present an analysis of the effects of multiple-photon emission, in the context of Z^0 physics at the SLAC Linear Collider and the CERN e^+e^- collider LEP, on the forward-backward, left-right, and polarized forward-backward asymmetries for $e^+e^-\to\mu^+\mu^-+n(\gamma)$ and $e^+e^-\to b\bar{b}+n(\gamma)$. We focus on this Z^0-physics scenario in the presence of detector cuts. Realistic calculations are carried out with our Monte Carlo–based Yennie-Frautschi-Suura event-by-event approach to $SU_{2L}\times U_1$ radiative corrections at high energies. We conclude that the multiple-photon effects should be taken into account for high-precision Z^0 physics. We find further that, for high-luminosity unpolarized Z^0 physics, the $b\bar{b}+n(\gamma)$ final state looks much more promising as a way to measure the respective forward-backward asymmetry when it is compared to $\mu^+\mu^-+n(\gamma)$ insofar as radiative corrections are concerned.

I. INTRODUCTION

Recently,[1] the exciting era of high-precision Z^0 physics was initiated at the SLAC Linear Collider (SLC) and the CERN e^+e^- collider LEP and, already, the exciting result that N_ν, the number of massless neutrino generations, is three, is beginning to have its effect on the general direction of theoretical thought in the effort to unravel the fundamental dynamical principle which unifies all known elementary-particle forces. After the initial program of research on M_{Z^0}, Γ_{Z^0}, $\sigma_{\rm total}(e^+e^-\to f\bar{f})$, etc., statistics will reach the point where precise measurements of cross-section asymmetries are possible. At that point, a key issue will be the accuracy with which the radiative corrections to such asymmetries are known. Here, we wish to discuss this issue from the point of view of the large initial-state radiative effects which are already well understood[2] for the total cross sections in $e^+e^-\to\gamma,Z^0\to X$. The question is what are the effects of these corrections on the interesting cross-section asymmetries in the presence of realistic SLC/LEP-type detector cuts. We will use methods which we introduced in Ref. 3.

More specifically, we will employ the renormalization-group-improved[4] Monte Carlo–based Yennie-Frautschi-Suura (YFS) methods[3,5] in which the higher-order radiative effects are realized on an event-by-event basis, to all orders in α. The result of these methods is that the actual photon physical four-vectors for multiple-photon final states are listed among the final-particle four-vector list in the respective Monte Carlo simulation of $e^+e^-\to\gamma,Z^0\to X$. Hence, realistic detector cutoffs may be imposed on the simulation and the attendant effects assessed for physical parameters of interest. In this way, for the forward-backward, left-right polarization, and polarized forward-backward asymmetries, we present, for the first time, a realistic analysis of the interplay of detector cuts and multiple-photon radiation in a realistic scenario.

Here, we should note that some semianalytic work[6] and single- or two-initial- and one-final-photon Monte Carlo work has also been done in the presence of mild cuts, such as symmetric cuts on the cosine of the center-of-mass-system (c.m.s.) production angle in $e^+e^-\to f\bar{f}+(\gamma)$, for example. Thus, in what follows, we shall compare our multiple-photon YFS methods with representative work from the semianalytic or one-photon Monte Carlo approaches. In this way, we exhibit more explicitly the role of multiple-photon effects in asymmetry measurements in the presence of cuts.

We should also note that, from the standpoint of the future physics objectives of SLC and LEP, the higher-order radiative effects in asymmetries are particularly interesting indeed. For, at the SLC, the initial components for the polarized beam capability for the electron have been installed and are being tested.[7] The objective will be a measurement of the electron left-right polarization asymmetry[8] in the $e^+e^-\to Z^0\to X$ cross section with 10^4–10^5 Z^0's. At LEP, there is the distinct possibility to raise the luminosity to $\gtrsim 1.4\times10^{32}/\text{cm}^2\text{s}$ so that samples of $\gtrsim 10^6$ tagged $b\bar{b}$ events would be available; this would afford a precise measurement of the unpolarized forward-backward asymmetry[9] for $b\bar{b}$ pairs. Both of these asymmetry measurements would provide yet another path to $\sin^2\theta_W$ and, hence, yet another precision test of the $SU_{2L}\times U_1$ theory in Z^0 physics. To set the quantitative level of the discussion here, note that the estimated statistics in these measurements, assuming a perfect knowledge of the radiative effects and assuming other possible systematic effects are under control as expected,[9,10] corresponds to $\delta\sin^2\theta_W\simeq0.001$, compared to the current best fit[11] $\sin^2\theta_W=0.2264\pm0.0054$. Thus, the radiative effects in these asymmetry measurements must be controlled at the level of $\lesssim 1\%$. Here, then, when we analyze the contribution of multiple-photon initial-state radiation to such asymmetries, we have an eye toward the next steps at SLC and LEP.

Accordingly, it is important to determine the flavor dependence, if any, of the interplay between cuts and higher-order multiple-photon effects in the asymmetries in $e^+e^-\to f\bar{f}+n(\gamma)$ in the SLC/LEP-type scenario. Here, we shall do this by considering $e^+e^-\to\mu^+\mu^-+n(\gamma)$ in comparison to $e^+e^-\to b\bar{b}+n(\gamma)$ in the presence of Mark II-type cuts; we take the latter to be representative of the typical detector scenario at SLC and LEP. We will see that, indeed, the flavor dependence is a nontrivial one and it emphasizes the importance of the $b\bar{b}+n(\gamma)$ final state for unpolarized high-luminosity scenarios.[9]

Our work is organized as follows. In the next section, we set our kinematical and notational conventions for the quantities of interest to us. In Sec. III, we focus on the effects of multiple photons on the asymmetries in $\mu^+\mu^-+n(\gamma)$ final states on the Z^0 pole in $e^+e^-\to Z^0\to X$ in comparison to the analogous effects for the $b\bar{b}+n(\gamma)$ final states. Section IV presents some overview remarks.

II. PRELIMINARIES

In this section, we wish to set our conventions and notation for our kinematics and for the quantities of interest to us. We start with the kinematics.

Specifically, our kinematical conventions for the process like $e^+e^-\to f\bar{f}+n(\gamma)$ are illustrated in Fig. 1.

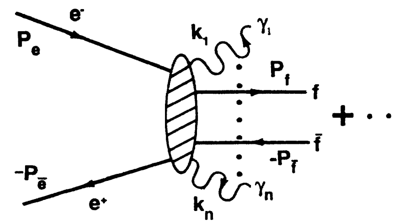

FIG. 1. A typical contribution to $e^+e^-\to f\bar{f}+n(\gamma)$.

Thus, p_A is the four-momentum of A and θ_A is the production angle of A relative to the direction of $\mathbf{p}_e$ in the e^+e^- center-of-momentum system. We define $s=(p_e+p_{\bar{e}})^2$ as usual. k_i is the four-momentum of photon i.

With our definition of θ_A, we define the forward-backward asymmetry of the respective cross section, $A_{FB}(f)$, to be

$$A_{FB}(f)=(\sigma_F-\sigma_B)/(\sigma_F+\sigma_B)\ , \tag{1}$$

where $\sigma_{F(B)}$ is the cross section for $e^+e^-\to f\bar{f}+n(\gamma)$ with $\cos\theta_f>0$ (<0). We emphasize that, here, $A_{FB}(f)$ may have further restrictions placed on it; for example, we may require that, in each σ_A, $|\cos\theta_f|<x_{\rm cut}$ for some value of $x_{\rm cut}$.

Similarly, we define the left-right polarization asymmetry to be the conventional:

$$A_{LR}=(\sigma_L-\sigma_R)/(\sigma_L+\sigma_R)\ , \tag{2}$$

where σ_H is the cross section for $e^+e^-\to f\bar{f}+n(\gamma)$ for polarized electrons with handedness H, $H=L,R$. Again, A_{LR} may have further restrictions placed on its σ_H, such as that, for each σ_H, $E_{\rm vis}>\alpha_{\rm cut}\sqrt{s}$, where $\alpha_{\rm cut}$ is some cut parameter and $E_{\rm vis}$ is defined to be the sum of all visible energy of the respective event which comprises σ_H. Here, visible means that it is seen by the respective SLC/LEP detector under study.

Finally, we will follow Ref. 12 and consider also the combination of (1) and (2), namely, the polarized forward-backward asymmetry

$$A_{FB,\rm pol}(f)=[\sigma_{LF}-\sigma_{LB}-(\sigma_{RF}-\sigma_{RB})]/(\sigma_{LF}+\sigma_{LB}+\sigma_{RF}+\sigma_{RB})\ , \tag{3}$$

where now the subscripts on the cross sections are fully defined below (1) and below (2).

The quantities A_{FB}, A_{LR}, and $A_{FB,\rm pol}$ are then the precise definitions of the asymmetries which we wish to consider in the context of the interplay between detector cuts and higher-order radiative effects. We turn next to our approach to these radiative effects.

III. MULTIPLE-PHOTON EFFECTS IN ASYMMETRIES

We describe in this section the interplay between higher-order multiple-photon effects on the one hand and detector cuts on the other. We do this in two steps. First, we compare the Monte Carlo expectations for A_{FB}, A_{LR}, and $A_{FB,\rm pol}$ for the $\mu^+\mu^-+n(\gamma)$ final state when we use a 1γ Monte Carlo simulation such as that in Ref. 13 with the same expectations when we use our YFS Monte Carlo methods as they are described in Ref. 3. This will isolate the dependence of the results on the multiple photon-type final states relative to the expectations for the more conventional (0,1)-photon-type final states. Secondly, we will compare our YFS results for the asymmetries in the $\mu^+\mu^-+n(\gamma)$ final states with those in $b\bar{b}+n(\gamma)$ final states. In this way, we get a view of the flavor dependence of the interplay of multiple-photon radiation and detector cuts insofar as asymmetries are concerned. We reemphasize that the $b\bar{b}+n(\gamma)$ asymmetries are of substantial interest in themselves. We consider now the first step.

Specifically, we compare in Table I the results of a 1γ Monte Carlo simulation of the type of Berends, Jadach, and Kleiss[13] (BJK) with those of our YFS2 FORTRAN Monte Carlo simulation, as it is described in Ref. 3, for the asymmetries in $e^+e^- \to \mu^+\mu^- + n(\gamma)$ at $\sqrt{s} = M_{Z^0} \cong 91$ GeV. We take the model that $\sin^2\theta_W = 0.2354$ here. We impose in Table I the Mark II–type cuts: $|\cos\theta_\mu| < 0.8$, $|\cos\theta_\gamma| < 0.95$, $E_\mu > 2$ GeV, $E_\gamma > 0.2$ GeV, and $E_{\text{vis}} > 0.1\sqrt{s}$. The cuts for the SLD and LEP detectors would be similar.[14] For the 1γ Monte Carlo simulation, which we provided via a switch in our earlier YFS1 FORTRAN program,[3] one has to set the value of the famous k_0 parameter which distinguishes simulated 1γ phenomena from quasi-two-body 1γ phenomena, i.e., from those 1γ phenomena which are so soft that they are counted as though they were virtual—indeed, these soft effects exactly cancel the respective virtual infrared divergence of the $O(\alpha)$ two-body cross section, as is well known. Here, we choose the 1γ Monte Carlo k_0 to be 3×10^{-3} so that we have a reasonable agreement between the overall normalization of the 1γ comparison Monte Carlo simulation and our rigorous YFS Monte Carlo simulation. Then, we may focus on the difference between the two Monte Carlo simulations for our asymmetries in $\mu^+\mu^- + n(\gamma)$ final states. It is in this way that we have arrived at the results in Table I, where the statistics is $\sim 10^5$ events per entry and where we also have applied the acollinearity cuts of 10°, 3°, and 1°.

In Table I, we note that, as the acollinearity cut is tightened, the radiative effects become less effective in A_{FB}, as expected. However, relative to the polarized asymmetries, the effect of the radiation is quite large in $A_{FB}(\mu)$, for both the 1γ and YFS Monte Carlo simulations. Indeed, the radiative effects on the polarized asymmetries are at the few % level at most, for both the 1γ and YFS Monte Carlo simulations. The analogous effect on $A_{FB}(\mu)$, however, is comparable to $A_{FB}(\mu)$ itself in size. We see that the 1γ and YFS results for A_{FB} are generally consistent with one another if one allows for the errors but that the results at no acollinearity are almost 2σ apart: This suggests, but does not prove, that they may be different. A higher-statistics sample is under investigation in this regard. We should note that, while the values of A_{LR} and $A_{FB,\text{pol}}$ are relatively close, the actual values of σ_{HA}, $A=F$, B, $H=L,R$ are different for the 1γ and YFS Monte Carlo results at the level of 3–4 %, so that the YFS methods are indeed necessary for the highest-precision work. Clearly, the large value of the effect on $A_{FB}(\mu)$ means that, to measure $A_{FB}(\mu)$, one must in fact observe a large enough sample of events to unravel this attendant radiative effect. From Table I, 10^5 $\mu\bar{\mu}$ pairs may not be sufficient—this of course depends on the level of accuracy one is seeking.

Turning next to the second step of our study, we focus on the same A_{FB}, A_{LR}, and $A_{FB,\text{pol}}$ asymmetries for the $b\bar{b}+n(\gamma)$ final states. Here, we again impose the μ-like cuts as we consider A_{LR}, $A_{FB,\text{pol}}$, and A_{FB}, where we consider A_{FB} for an acollinearity angle cut of 1° and for no acollinearity cut. Our results are all obtained with our YFS2 FORTRAN Monte Carlo program.[3] We see that, similarly to the $\mu^+\mu^- + n(\gamma)$ case, the percentage changes in A_{LR} and $A_{FB,\text{pol}}$ due to radiation are small. However, for A_{FB}, we see a dramatic change in the nature of the radiative effect. The respective percentage changes due to the radiation are -5.1% for no acollinearity cut and -2.75% for a 1° acollinearity cut. Hence, here, radiation leaves a relatively large asymmetry which would seem to be measurable with high precision, in view of the statistics in Table II, in high-luminosity unpolarized scenarios such as LEP and its planned upgrade.[9,15] We note that the results in Table II are entirely consistent with the semianalytic results of Djouadi *et al.* in Ref. 9. And, indeed, these authors have reached a similar conclusion concerning $A_{FB}(b)$ and its potential for an unpolarized LEP. Here, we have verified this conclusion in the presence of realistic detector cuts with rigorous $n(\gamma)$ radiation.

Thus, we conclude this section by emphasizing that in order to exploit the information in the asymmetries, one must accurately simulate the effects of the multiple-photon radiation on them in the presence of the detector cuts. We have illustrated that, at the level of the funda-

TABLE I. $\mu\bar{\mu}$ asymmetries.

No radiative corrections		
$A_{LR}=0.1164$, $A_{FB,\text{pol}}=0.0767$, $A_{FB}=0.008\,93$		
Radiative corrections		
$1\gamma \equiv (\text{BJK}, k_0 = 3\times10^{-3})$		$A_{LR}=0.1139\pm0.0012$
YFS		$A_{LR}=0.1137\pm0.0012$
$1\gamma \equiv (\text{BJK}, k_0 = 3\times10^{-3})$		$A_{FB,\text{pol}}=0.0753\pm0.0012$
YFS		$A_{FB,\text{pol}}=0.0755\pm0.0012$
1γ	(No acollinearity cut)	$A_{FB}=-0.007\,79\pm0.001\,66$
YFS	(No acollinearity cut)	$A_{FB}=-0.004\,63\pm0.001\,66$
1γ	10° acollinearity cut	$A_{FB}=-0.006\,85\pm0.001\,66$
YFS	10° acollinearity cut	$A_{FB}=-0.003\,98\pm0.001\,69$
1γ	3° acollinearity cut	$A_{FB}=-0.003\,73\pm0.001\,67$
YFS	3° acollinearity cut	$A_{FB}=-0.001\,30\pm0.001\,71$
1γ	1° acollinearity cut	$A_{FB}=0.001\,79\pm0.001\,72$
YFS	1° acollinearity cut	$A_{FB}=0.003\,31\pm0.001\,70$

TABLE II. $b\bar{b}$ asymmetries.

No radiative corrections	
$A_{FB}=0.0708$, $A_{LR}=0.116$, $A_{FB,\mathrm{pol}}=0.609$	
Radiative corrections	
5×10^5 events (YFS2)	
$A_{LR}=0.1126\pm0.0012$	
$A_{FB,\mathrm{pol}}=0.6143\pm0.0013$	
$A_{FB}=0.0672\pm0.0012$	No acollinearity cut
$A_{FB}=0.0689\pm0.0012$	1° acollinearity cut

mental fermions themselves, we have methods which allow us to do this. What we have not discussed in the $b\bar{b}+n(\gamma)$ case, of course, are the effect of tagging, hadronization (QCD), etc. Such matters are discussed for the semianalytic work of Djouadi *et al.* in Ref. 9 to some extent. What one needs to do next is to combine our YFS2 Monte Carlo program with a state-of-the-art QCD generator such as the LUND Monte Carlo program,[16] augmented with a realistic detector simulation scenario. In this way, a complete assessment of $A_{FB}(b)$ in Z^0 physics with unpolarized beams can be made. We hope to participate in such an assessment in the not-too-distant future. Here, we have provided and illustrated the first phase of this complete assessment—the Monte Carlo simulation of the effects of the $n(\gamma)$ final states on an event-by-event basis.

IV. CONCLUSIONS

We have analyzed the interplay between detector cuts on the one hand and multiple-photon radiation on the other on asymmetries in Z^0 production and decay. We see phenomena which are consistent with known analytic and semianalytic theoretical expectations but which, of course, for all practical purposes can only be calculated precisely via Monte Carlo methods of the type we have used in our analysis. Thus, we find these circumstances encouraging.

Specifically, we find that the fundamental cross-section asymmetries have very interesting sensitivities to radiation in $e^+e^-\to f\bar{f}+n(\gamma)$, in the presence of realistic detector cuts—cuts of the SLC/LEP-type detector scenarios. Indeed, the $\mu^+\mu^-+n(\gamma)$ final state, in the presence of cuts, has a small correction to its polarized asymmetries A_{LR} and $A_{FB,\mathrm{pol}}$ but a large correction to A_{FB}. This is true for both our YFS multiple-photon Monte Carlo simulation and the comparison 1γ simulation with $k_0=3\times10^{-3}$. We emphasize that there is a known[17] dependence of the 1γ *total* cross sections to k_0 so that only by using the YFS simulation can one really assess the true interplay between cuts and radiation, in a k_0-independent manner. The two sets of Monte Carlo results for the $\mu^+\mu^-+n(\gamma)$ asymmetries A_{LR} and $A_{FB,\mathrm{pol}}$ (we always understand that $n=1$ for the 1γ simulation) are relatively close; however, the various cross sections σ_{HA} are different at the level of 3–4%, $H=L,R$, $A=F,B$. Thus, for high-precision work, the YFS methods are essential.

The acollinearity cut on $A_{FB}(\mu)$ has the effect of reducing the effect of the radiation on it. Indeed, at no acollinearity cut, the effect of the radiation is maximal for both the 1γ and the YFS Monte Carlo simulation. The two results are almost 2σ apart at this point of maximal effect. We cannot claim, however, that they are actually different with any appreciable confidence. A higher-statistics sample is under investigation in this connection. Our point would be here that, even though the two simulations may be relatively close for acollinearity cuts $\lesssim 10°$, one would want to use our YFS methods in any case in high-precision work to obtain k_0-independent predictions. For these quantities A_{LR}, A_{FB}, $A_{FB,\mathrm{pol}}$, the 1γ simulation does not make a *severe* error *if* $k_0=3\times10^{-3}$, for example. Without our YFS methods, it would have been impossible to know this with certainty.

The immediate conclusion from our $\mu^+\mu^-+n(\gamma)$ analysis is that the program of the SLC to measure A_{LR} is robust from the standpoint of multiple-photon radiation even in the presence of detector cuts. The measurement of $A_{FB}(\mu)$ will require the careful treatment of the respective large radiative corrections. One loses a substantial amount of one's would-be signal due to the radiative effects (at points near $\sqrt{s}=M_{Z^0}$, the signal actually vanishes). Thus, very high statistics would be required, as one can see from Table I. Hence, it is imperative to look also at $A_{FB}(f), f\neq\mu$, from the standpoint of unpolarized high-precision Z^0 physics.

Here, we considered the case $f=b$. What we have found is encouraging and corroborates the semianalytic results in Ref. 9. Specifically, we find that, in $b\bar{b}+n(\gamma)$ in the presence of detector cuts, the polarized asymmetries are, like those in the $\mu^+\mu^-+n(\gamma)$ final states, relatively mildly affected by the radiation. In addition, we find that $A_{FB}(b)$ is only moderately affected by the radiation, so that it was quite well known in our simulations with our YFS2 FORTRAN Monte Carlo program of 5×10^5 events. Hence, apparently $A_{FB}(b)$ can be used[18] to arrive at another precise measurement of $\sin^2\theta_W$, for example, at an unpolarized relatively high-luminosity scenario such as that at LEP and its upgrade in comparison to the measurement of $\sin^2\theta_W$ via A_{LR} at the SLC. We understand that such a measurement at LEP is under active consideration and we encourage the experimentalists to pursue this consideration.

The methods used in our analysis of the $b\bar{b}+n(\gamma)$ asymmetries may be interfaced to the respective QCD and detector simulations to assess the effects of tagging, hadronization, etc. The preliminary indication of Djouadi *et al.* in Ref. 9, which is a semianalytic assessment of the QCD effects, is that the effects considered there are under control. We hope to be a part of a report on a more complete detector-based study elsewhere.

We should emphasize that our results are in agreement with the semianalytic work of Jadach and Was and the $\leq 3\gamma$ Monte Carlo results of Campagne and Zitoun in Ref. 6 and with the recent initial pioneering measurements[19] of the Mark II and L3 Collaborations for $A_{FB}(\mu)$. In the latter measurements, the errors on $A_{FB}(\mu)$ are comparable to (or larger than) the measured value of $A_{FB}(\mu)$ itself; thus, these measurements do not address the level of precision of our discussion in the text.

They are in agreement with theoretical expectations so that they do set the stage for the next level of precision.

Before we end our discussion, we should also note that the YFS2 Monte Carlo program used in our analysis realizes only the initial-state aspects of the YFS-theory predictions for $e^+e^- \to f\bar{f}+n(\gamma)$. The omitted final-state-related radiative effects (including the respective interference effects) are estimated[6,9,20] to be below 0.18% for A_{FB} for cutoffs such as those in our work; they should be even smaller for A_{LR} and $A_{FB,\mathrm{pol}}$ due to the relative insensitivity to such effects.

In summary, realistic assessments at the level of the fundamental fermions have been made of the interplay of multiple-photon radiation and detector cuts in the context of the asymmetries in $e^+e^- \to f\bar{f}+n(\gamma)$ in the SLC/LEP-type scenarios. We await the impending observations wherein these assessments may be used to facilitate the tests of the $SU_{2L} \times U_1$ theory in high-precision Z^0 physics.

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[1] G. S. Abrams *et al.*, Phys. Rev. Lett. **63**, 2173 (1989); ALEPH Collaboration, D. Decamp *et al.*, Phys. Lett. B **231**, 519 (1989); **235**, 399 (1990); DELPHI Collaboration, P. Aarnio *et al.*, 1989 (unpublished); L3 Collaboration, B. Adeva *et al.*, 1989 (unpublished); OPAL Collaboration, M. Akrawy *et al.*, 1989 (unpublished).

[2] See, for example, G. Altarelli, in *Physics at LEP*, LEP Jamboree, Geneva, Switzerland, 1985, edited by J. Ellis and R. Peccei (CERN Report No. 86-02, Geneva, 1985); E. A. Kuraev and V. Fadin, Yad. Fiz. **41**, 733 (1985) [Sov. J. Nucl. Phys. **41**, 466 (1985)]; F. Berends *et al.*, Nucl. Phys. **B297**, 429 (1988); O. Nicrosini and L. Trentadue, Z. Phys. C **39**, 479 (1988); M. Greco *et al.*, Nucl. Phys. **B101**, 234 (1975), and references therein.

[3] See, for example, S. Jadach and B. F. L. Ward, Phys. Rev. D **38**, 2897 (1988); **39**, 1472 (1989); Phys. Lett. B **220**, 611 (1989); Phys. Rev. D **40**, 3582 (1989); Comput. Phys. Commun. **56**, 351 (1990); S. Jadach, Max-Planck-Institut Report No. MPI-PAE/PTH 6/87 (unpublished); B. F. L. Ward, Phys. Rev. D **36**, 939 (1987); S. Jadach and B. F. L. Ward, Report No. CERN-TH. 5399/89 (unpublished); University of Tennessee Report No. UTHEP-89-0703 (unpublished), and references therein.

[4] S. Weinberg, Phys. Rev. D **8**, 3497 (1973); G. 't Hooft, Nucl. Phys. **B61**, 455 (1973), and references therein.

[5] D. R. Yennie, S. C. Frautschi, and H. Suura, Ann. Phys. (N.Y.) **13**, 379 (1961); see also K. T. Mahanthappa, Phys. Rev. **126**, 329 (1962).

[6] See, for example, the contributions of the Forward-Backward Asymmetry Working Group and of the Electroweak Generators Working Group, in *LEP 100 Workshop Proceedings*, edited by G. Altarelli, R. Kleiss, and C. Verzegnassi (CERN, Geneva, 1989), and references therein.

[7] K. C. Moffeit, R. Prepost, M. Swartz, and M. Woods (private communication).

[8] See, for example, G. Altarelli, in *Proceedings of the 1989 Lepton-Photon Conference*, edited by R. Taylor (SLAC, Stanford, 1989); P. Rankin, in *Proceedings of the Mark II SLC Pajaro Dunes Workshop*, edited by J. Hu (SLAC, Stanford, 1989); University of Colorado Report No. COLO-HEP-204, 1989 (unpublished), and references therein.

[9] See, for example, B. Atwood, in *Proceedings of the B-Factories Workshop*, edited by D. Cline and A. Fridman (New York Academy of Sciences, New York, 1989); A. Djouadi *et al.*, Max-Planck-Institut Report No. MPI-PAE/48/89 (unpublished), and references therein.

[10] See, for example, K. C. Moffeit, in *Proceedings of the Mark II Granlibakken Workshop*, edited by K. Krieger (SLAC, Stanford, 1986), p. 128.

[11] P. Langacker, Phys. Rev. Lett. **63**, 1920 (1989), and references therein.

[12] A. Blondel *et al.*, Nucl. Phys. **B304**, 438 (1988), and references therein.

[13] F. A. Berends, S. Jadach, and R. Kleiss, Comput. Phys. Commun. **29**, 185 (1983).

[14] T. Kozanecka (private communication).

[15] See, for example, P. Mattig, in *Procceedings of the B-Factories Workshop* (Ref. 9).

[16] See, for example, the report of the QCD Generators Working Group, in *Proceedings of the LEP 100 Workshop* (Ref. 6).

[17] See, for example, S. Jadach and B. F. L. Ward, University of Tennessee Report No. UTHEP-89-1001 (unpublished); R. Kleiss, in *Proceedings of the Brighton Workshop*, edited by N. Dombey and F. Boudjema (Plenum, London, 1989).

[18] Here, we need to recall our precautionary remarks concerning the possible nonperturbative QCD effects and detector efficiency-type effects in Sec. IV.

[19] G. Abrams *et al.*, Phys. Rev. Lett. **63**, 2780 (1989); L3 Collaboration, B. Adeva *et al.*, Report No. L3-005, 1990 (unpublished).

[20] Z. Was and S. Jadach, Phys. Rev. D **41**, 1425 (1990).