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Electroweak effects for polarized Z boson in $e^+e^- \to ZH$ reaction

A. Arbuzov[1,2], S. Bondarenko[*,1,2], L. Kalinovskaya[2,3], R. Sadykov[1], V. Yermolchyk[1,2,4]

[1] Joint Institute for Nuclear Research, Dubna, Russia

[2] Dubna State University, Dubna, Russia

[3] Lomonosov Moscow State University, Moscow, Russia

[4] Belarusian State University, Minsk, Belarus

e-mail: bondarenko@jinr.ru

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Abstract

Electroweak effects for the helicity states of the final Z boson in $e^+e^- \to ZH$ reaction are considered. The Born cross section and complete one-loop electroweak corrections to it are calculated. Effects due to polarization of the initial electron/positron beams are also investigated. Numerical calculations are performed by means of the Monte Carlo generator `ReneSANCe`.

Introduction

The Standard Model (SM) successfully describes various phenomena in high-energy physics. In spite of this, for many reasons the SM is considered to be an effective theory, i.e., a low-energy approximation of the true fundamental theory. Finding the boundaries of the applicability of the SM is one of the most valuable problems in modern physics. In this context, the study of the Higgs boson sector of the SM is of crucial importance for testing the mechanism of spontaneous symmetry breaking and for a deeper understanding of the properties of the SM at the energies of future accelerators.

The time has come for ultra-precise experiments at future e^+e^- colliders. Special attention will be paid there to the effects related to the polarization of the initial and final particles. The pair production of helicity-polarized weak bosons serves as a powerful probe of the Standard Model, potential new physics, and the properties of quantum systems. In fact, the information on boson polarization in the final state can be recovered from the decay products, e.g., for the case of the decay of the Z boson into a lepton pair. Dealing with the polarization of Z bosons is challenging due to not so much efficient of its analysis through the decay channel $Z \to l^+ l^+$, since the couplings of Z to left-handed and right-handed leptons are nearly the same. Consequently, the analyzing power in leptonic Z boson decays is approximately 15%, compared to 100% for $W \to l\nu$ (based on the results of the LHC analysis [1]). Nevertheless, high statistics, advanced detectors, and analysis technique at the future experiments will allow to perform accurate studies of polarization effects.

The study of cross sections corresponding to spin states of the final bosons makes it possible to investigate angular distributions of the produced leptons [2]. It is especially important in the study of anomalous trilinear gauge boson couplings [3]. In general, since the gauge bosons are spin-1 particles, the full spin density matrix parameterized by the vector and tensor polarization parameters should be used [4]. However, even the cross sections with a definite helicity state of the final boson are of interest.

In paper [5] weak one-loop virtual corrections to asymmetries and cross sections with polarized final Z bosons were considered, and in papers [6, 7] the electroweak (EW) ones with soft photon emission were evaluated in addition.

The capabilities of the `SANC` system for calculation of electroweak corrections by means of the Monte-Carlo tools `MCSANC` and `ReneSANCe` at lepton-lepton colliders have been detailed in various publications (see references in our recent paper [8]). The radiative corrections (RCs) and higher order QED effects to $e^+e^- \to ZH$ process with polarized initial particles were presented in [9, 10].

This paper further explores this process by detailing the spin/helicity states of the final Z boson. The Born (leading order, LO) and complete one-loop EW (next-to-leading-order, NLO) calculations are performed for cross sections with definite helicity of the final Z boson in the $e^+e^- \to ZH$ reaction. Using the helicity formalism, it is possible to distinguish final particle spin states. Also, the impact of the polarization of the initial electron/positron beams can be investigated.

Numerical calculations in this paper are performed with the help of the Monte Carlo (MC) generator of unweighted events `ReneSANCe` [11, 12]. The angular distributions of the cross sections for polarized Born and hard bremsstrahlung are cross-checked with the corresponding results of the `WHIZARD` [13].

1 Differential cross section

The process under investigation is

$$e^+(p_1, \lambda_1) + e^-(p_2, \lambda_2) \to Z(p_3, \lambda_3) + H(p_4, \lambda_4). \tag{1}$$

The corresponding cross section of the scattering of longitudinally polarized e^+ and e^- with polarization degrees P_{e^+} and P_{e^-}, respectively, can be expressed as follows:

$$\sigma(P_{e^-}, P_{e^+})_{\lambda_Z} = \frac{1}{4} \sum_{\lambda_1, \lambda_2} (1 + \lambda_1 P_{e^+})(1 + \lambda_2 P_{e^-}) \sigma_{\lambda_1 \lambda_2 \lambda_Z}, \tag{2}$$

where $\lambda_i = \pm 1$ corresponds to the lepton with left (right) helicity, and $\lambda_Z = \pm 1, 0$ describes the spin states of the final Z boson, see [14, 15].

NLO corrections involve the calculation of one-loop amplitudes, renormalization of their UV divergences (by dimensional regularization) [16], regularization of IR divergencies, and the combination of virtual and real-emission contributions in order to cancel them. The complete one-loop cross section $\sigma^{\rm NLO}$ consists of four components: the Born cross-section $\sigma^{\rm Born} \equiv \sigma^{\rm LO}$, the contribution from virtual (loop) corrections $\sigma^{\rm virt}(\lambda)$, and the contributions from real corrections, which include both the soft photon emission component $\sigma^{\rm soft}(\lambda, \bar{\omega})$ and the hard photon bremsstrahlung component $\sigma^{\rm hard}(\bar{\omega})$. (here the hard photon energy $E_\gamma > \bar{\omega}$). Auxiliary parameters λ ("photon mass") and $\bar{\omega}$ are canceled out after summation.

To compute the virtual component at the one-loop level using the foundational procedure of `SANC`, we begin by examining the covariant amplitude (CA). The covariant one-loop amplitude is derived from a standard calculation involving all diagrams that contribute to a specific process at the one-loop level. The CA is expressed in a particular basis consisting of combinations of Dirac matrices and/or external momenta (structures) that are contracted with the polarization vectors of vector bosons, when applicable. CA can be explicitly represented using scalar form factors and structures. Scalar coefficients before structures are called as scalar form factors. They encapsulate all dependencies related to masses, kinematic factors, coupling constants, and other parameters. Meanwhile, the structures featuring Lorentz indices, composed of strings of Dirac matrices, are defined by the chosen basis. The number of form factors corresponds to the number of independent structures in the calculation. Loop integrals are expressed in terms of standard scalar Passarino-Veltman functions, namely A_0, B_0, C_0, and D_0 [17]. We have our own library `SANClib` [18] for computing scalar loop integrals, but also use third-party library LoopTools [19]. The helicity approach is used for all contributions. A detailed description of the renormalization, the calculation of one-loop integrals, and the evaluation of one-loop covariant and helicity amplitudes, along with other specifics necessary for computing complete electroweak radiative corrections for the process (2), can be found in [9].

2 Results and discussion

Comparison

The results of comparison of integral Born and hard photon emission cross sections at several c.m. energies and polarized initial beams were discussed in [9].

Also a comprehensive analysis of the sum of virtual and soft photon emission components of cross-sections given in [7] was performed. Although we lack their precise input parameters, our results show a good qualitative agreement for cross section with polarized final Z boson, for the A_{LR} and A^{pol} asymmetries with various final Z boson helicity $\pm 1, 0$ angular distributions at $\sqrt{s} = 1$ TeV with polarized and unpolarized initial beams.

Numerical results

The results for the angular distributions of the RCs to the cross section are presented below. The calculated angular distributions are plotted as a ratio of the cross section $\sigma_{\lambda_Z}^{\text{LO,NLO}}$ with definite final Z boson helicities to the corresponding unpolarized cross section $\sigma_{\text{unp}}^{\text{LO,NLO}}$:

$$R_{\lambda_Z}^{\text{LO,NLO}} = \sigma_{\lambda_Z}^{\text{LO,NLO}} / \sigma_{\text{unp}}^{\text{LO,NLO}}. \tag{3}$$

For NLO corrections, the relative corrections

$$\delta_{\lambda_Z} = \sigma_{\lambda_Z}^{\text{NLO}} / \sigma_{\lambda_Z}^{\text{LO}} - 1 \tag{4}$$

in percents are also shown. In (3) and (4) the dependence on the degree of polarization of the initial beams is omitted.

Three cases of polarization are considered: unpolarized initial beams and polarized $(P_{e^+} = 0.0, P_{e^-} = -0.8)$ and $(P_{e^+} = 0.3, P_{e^-} = -0.8)$ beams. The center-of-mass energy $\sqrt{s} = 250$ GeV is used in the analysis.

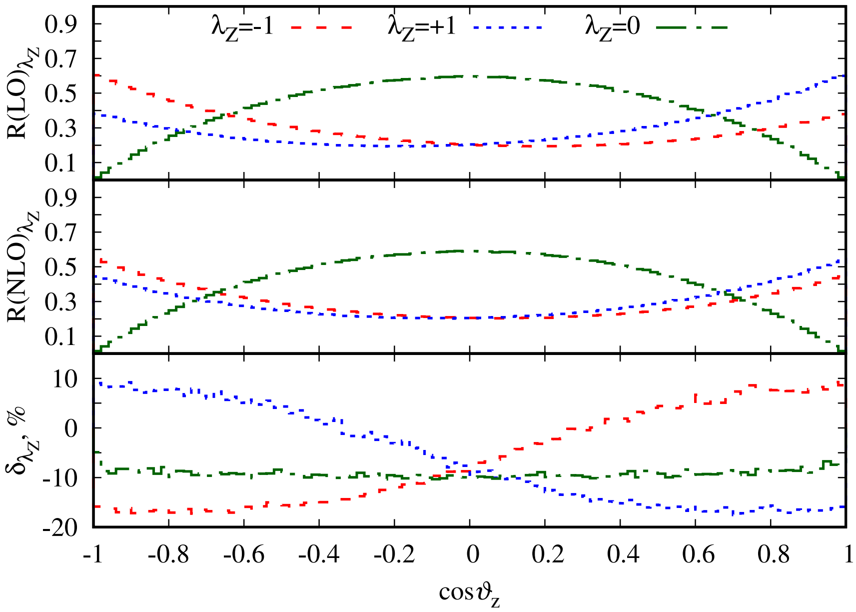

Figure 1: Ratios and relative corrections for $\sqrt{s} = 250$ GeV for unpolarized initial beams.

In Figure 1 the ratios and relative corrections for unpolarized initial beams are shown. The components of the Born cross section with $\lambda_Z = \pm 1$ give the asymmetric contributions from 40 to 60% with the minimum value of about 20% at the central value of $\cos\theta_Z = 0$. The $\lambda_Z = 0$ component gives the symmetric contributions from 0 to 60% with the maximum at $\cos\theta_Z = 0$. The components of the NLO cross section have behavior similar to the LO ratios, but components with $\lambda_Z = \pm 1$ become closer to each other. The relative corrections for $\lambda_Z = 0$ component are negative and constant about -10% in $\cos\theta_Z$ while the $\lambda_Z = \pm 1$ components vary from -15% to $+10\%$.

In Figure 2 the ratios and relative corrections for polarized initial beams with $P_{e^+} = 0.0, P_{e^-} = -0.8$ are shown. As in the case of unpolarized initial beams, the components of the Born cross section with $\lambda_Z = \pm 1$ give the asymmetric

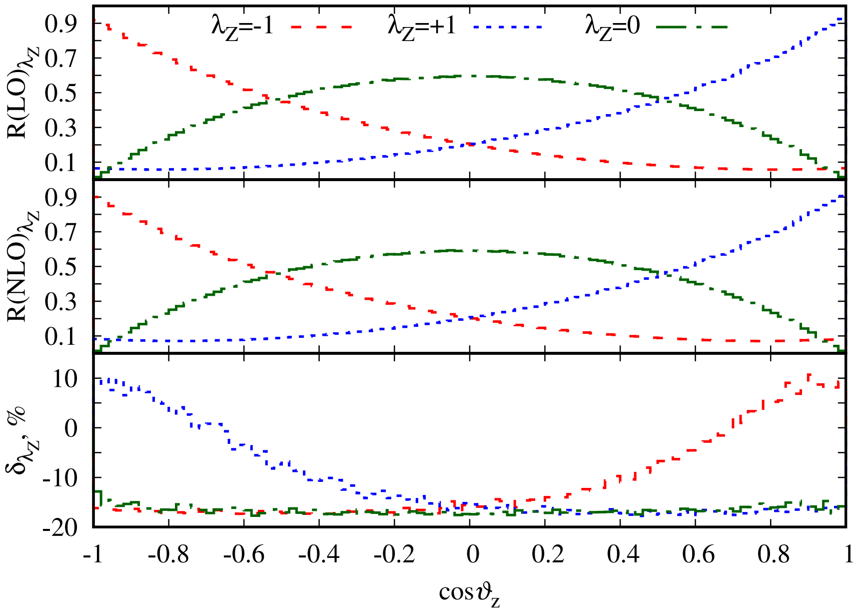

Figure 2: Ratios and relative corrections for $\sqrt{s} = 250$ GeV with polarized initial beam $P_{e^+} = 0.0, P_{e^-} = -0.8$.

contributions from 5% to 90% with 20% at the central value of $\cos\theta_Z = 0$. The $\lambda_Z = 0$ component gives the symmetric contributions from 0 to 60% with a maximum at $\cos\theta_Z = 0$. The rations for NLO are very similar to LO ones. The relative correction varies from -20% to $+10\%$ for $\lambda_Z = \pm1$ components and is constant -20% for $\lambda_Z = 0$ component.

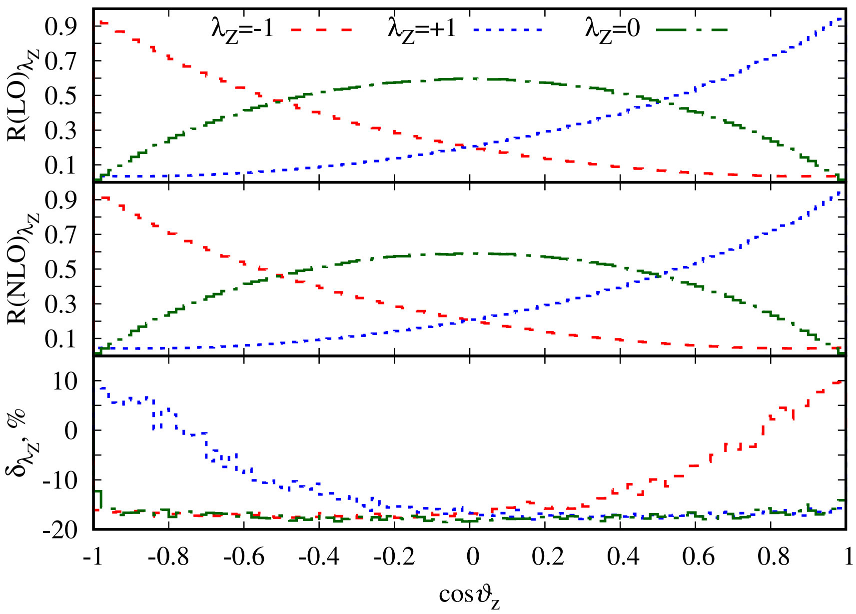

Figure 3: Ratios and relative corrections for $\sqrt{s} = 250$ GeV with polarized initial beam $P_{e^+} = 0.3, P_{e^-} = -0.8$.

In Figure 3 the ratios for polarized initial beams with $P_{e^+} = 0.3, P_{e^-} = -0.8$ are shown. The results are slightly changed compared to the previous case. The influence of the positive positron polarization appears to be very weak.

Conclusions

The polarization effects were examined through the leading-order and next-to-leading-order electroweak calculations by means of the Monte Carlo event generator `ReneSANCe`. The angular distributions of the cross sections with the final Z boson helicities in the reaction $e^+e^- \to ZH$ are considered at the c.m. energy $\sqrt{s} = 250$ GeV. The NLO corrections to the Z polarized cross section are found to be significant; they vary from -15% to $+10\%$ in terms of the Born cross section depending on the component and the initial beam polarization. Theoretical investigations with a careful account of radiative corrections open the way to a better experimental analysis and more deeper insights into the spin structure of vector bosons and into their interactions with different fermions. The possibility to fully reconstruct the rest frame of each Z boson gives access to the lepton decay angles, which are the most direct probes of the polarization states of decayed bosons. To a good precision, the subsequent decays of (polarized) Z bosons can be described within the pole approximation [2].

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