Nonlinear Dynamics and Applications. Vol. 25 (2019) 310-315

Model-independent analysis of new gauge boson effects in electron-positron annihilation processes

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The indirect effects of new neutral gauge bosons in the cross-section of scattering and forward-backward asymmetry of the di-muon generation process at the future international linear electron-positron Collider ILC are studied.

PACS numbers 12.60.–i, 12.90.+b
Keywords: Standard model, new gauge bosons, collider phenomenology

1. Introduction

Although the success of the standard model of particles (SM) is certainly unquestionable in describing the observed interactions of quarks and leptons, from the low energies involved in atomic physics parity violation experiments up to the high energies accessible at LEP and the LHC [1], other models with one or more additional gauge bosons (Z') are not ruled out [1,2]. A major objective of experiments at present and future high-energy accelerators is to search for new particles and interactions that would announce the onset of physics beyond the SM.

While open thresholds provide the most unambiguous signals of new physics, the mass range is in this case strictly limited by the available beam energy. In fact, at the future e^+e^- colliders, ILC and CLIC, a Z' would not be directly produced, because of the already existing mass limits [1]. A considerably larger mass range may be explored, however, through the study of virtual effects For masses much larger than the beam energy such indirect signatures are usually investigated within the frameworks of specific models. The consistency of experimental data with the SM is usually interpreted in terms of Z' mass limits [1] for specific models (e.g., E_6, the left-right symmetric model, the left-right alternative model, or the sequential standard model [1]). Such limits give a valuable feeling for the resolving powers of specific reactions and experiments, but the full information about a possible Z' can only be obtained by a model-independent analysis of the data [2]. In this regard, most attention has been given to the annihilation processes into the leptons and quarks, respectively

$$e^+ + e^- \to \mu^+ + \mu^-, \tag{1}$$

$$e^+ + e^- \to q^+ + q^-. \tag{2}$$

The reaction (1) which is very clean and with good statistics, is preferred for such a dedicated and model-independent analysis because it involves only leptonic couplings of the Z', in contrast to the process (2).

The purpose of this short note is to present a comparative and model-independent analysis of the potential to search for Z' interference effects at future e^+e^-- colliders ILC and CLIC. We concentrate on the muon pair production (1), which is particularly suitable for this purpose.

2. Basic formulae

A new neutral gauge boson induces additional neutral current interactions, the corresponding Lagrangian can be written as

$$-\mathcal{L}_{NC} = eJ_\gamma^\mu A_\mu + g_Z J_Z^\mu Z_\mu + g_{Z'} J_{Z'}^\mu {Z'}_\mu. \tag{3}$$

The neutral currents are

$$J_i^\mu = \Sigma_f \overline{\psi_f}\, \gamma^\mu (L_i^f P_L + R_i^f P_R)\psi_f = \Sigma_f \overline{\psi_f}\, \gamma^\mu (V_i^f + A_i^f \gamma_5)\psi_f, \tag{4}$$

where the coupling constants in SM can be written as

$$L_\gamma^f = Q_f,\ R_\gamma^f = Q_f,\ L_Z^f = I_{3L}^f - Q_f s_W^2,\ R_Z^f = -Q_f s_W^2,$$
$$V_\gamma^f = Q_f,\ A_\gamma^f = 0,\ V_Z^f = \frac{I_{3L}^f}{2} - Q_f s_W^2,\ A_Z^f = \frac{I_{3L}^f}{2}. \tag{5}$$

The lowest-order unpolarized differential cross section for the processes (1) and (2) is given by

$$\frac{d\sigma_{ff}}{d\cos\theta} = \frac{\pi\alpha^2}{2s}[(1+\cos^2\theta)F_1 + 2\cos\theta F_2]\ . \tag{6}$$

Here,

$$F_1 = F_1^{SM} + \Delta F_1$$
$$F_2 = F_2^{SM} + \Delta F_2 \tag{7}$$

$$F_1^{SM} = Q_e^2 Q_f^2 + 2Q_e v_e Q_f v_f Re\chi_Z + (v_e^2 + a_e^2)(v_f^2 + a_f^2)|\chi_Z|^2$$
$$F_2^{SM} = 2Q_e a_e Q_f a_f Re\chi_Z + 4v_e a_e v_f a_f |\chi_Z|^2$$
$$\Delta F_1 = 2Q_e v_e' Q_f v_f' Re\chi_{Z'} + (v_e'^2 + a_e'^2)(v_f'^2 + a_f'^2)|\chi_{Z'}|^2 + 2(v_e v_e' + a_e a_e')(v_f v_f' + a_f a_f')Re(\chi_Z \chi_{Z'}^*)$$
$$\Delta F_2 = 2Q_e a_e' Q_f a_f' Re\chi_{Z'} + 4v_e' a_e' v_f' a_f' |\chi_{Z'}|^2 + 2(v_e v_e' + a_e a_e')(v_f v_f' + a_f a_f')Re(\chi_Z \chi_{Z'}^*). \tag{8}$$

The normalized coupling constants can be written as

$$v_f = \frac{g_Z}{e} V_Z^f = \frac{1}{2s_W c_W}(I_{3L}^f + Q_f s_W^2)$$
$$a_f = \frac{g_Z}{e} A_Z^f = \frac{1}{2s_W c_W} I_{3L}^f$$
$$v_f' = \frac{g_{Z'}}{e} V_{Z'}^f$$
$$a_f' = \frac{g_{Z'}}{e} A_{Z'}^f. \tag{9}$$

The total cross section reads

$$\sigma_{ff} = \int_{-1}^{1} \frac{d\sigma_{ff}}{d\cos\theta} d\cos\theta = \sigma_{pt} F_1, \tag{10}$$

and the forward-backward asymmetry

$$A_{FB} = \frac{\int_0^1 (d\sigma_{ff}/d\cos\theta) d\cos\theta - \int_{-1}^0 (d\sigma_{ff}/d\cos\theta) d\cos\theta}{\int_0^1 (d\sigma_{ff}/d\cos\theta) d\cos\theta + \int_{-1}^0 (d\sigma_{ff}/d\cos\theta) d\cos\theta} = \frac{3}{4}\frac{F_2}{F_1}. \tag{11}$$

3. Interference pattern and concluding remarks

In order to explain qualitatively, in as simple terms as possible, the interference pattern induced by a Z', we shall first present Born-level results. We shall furthermore focus on the leptonic channel (1) due to its remarkable phenomenological features as compared with the process (2). In particular, assuming leptonic universality, one avoids further assumptions on the couplings. In general, there are then only three independent parameters to describe the leptonic process, the vector and axial-vector fermionic couplings and the mass of Z'.

The energy dependence of the cross section and forward-backward asymmetry for the SSM model, SM as well as the deviation of the cross section from the SM prediction are shown in Fig.3.1 and Fig.3.2, respectively.

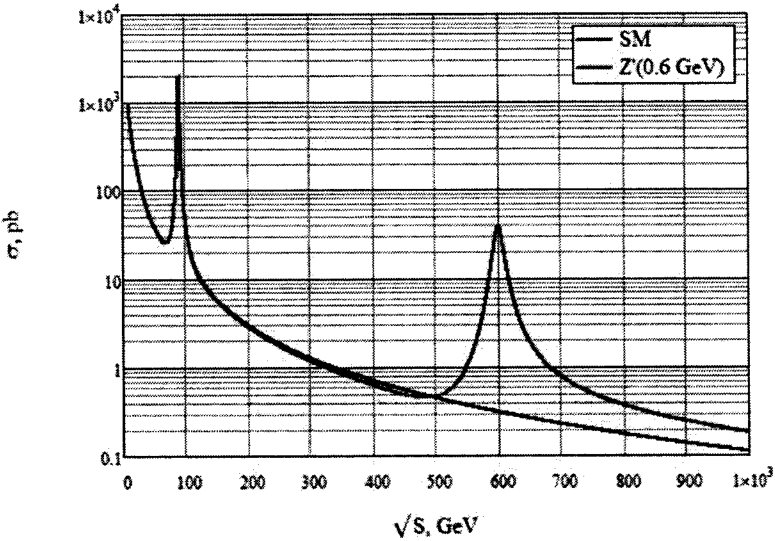

Figure 3.1 Total cross section for process (1) as a function of c.m. energy within the framework of the CM (blue curve) and SSM with M_Z=600 GeV (red curve).

A first observation that can be made from is that only squares of leptonic vector coupling constants appear. It follows that the signs of the interference terms due to the Z', and the deviation of the cross section from the SM prediction, are governed by the propagators of the Z and Z'. This is rather unique, as compared with the process (2). Furthermore, in certain energy regions, the magnitudes of these propagators will be quite different, such that one of them will dominate.

The first term of the deviation of the cross section describes γ-Z' interference. It is given by the squared vector coupling,, and the real part of the Z' propagator. The second term of cross section deviation describes Z-Z' interference. In contrast to the former, it depends only on the axial coupling squear. Since it is proportional to the product of two propagator factors, it will be positive below the SM Z, and negative above. It should be emphasized that all these features are model independent. However, the quantitative interference pattern will depend on the coupling strengths, and thus be model dependent.

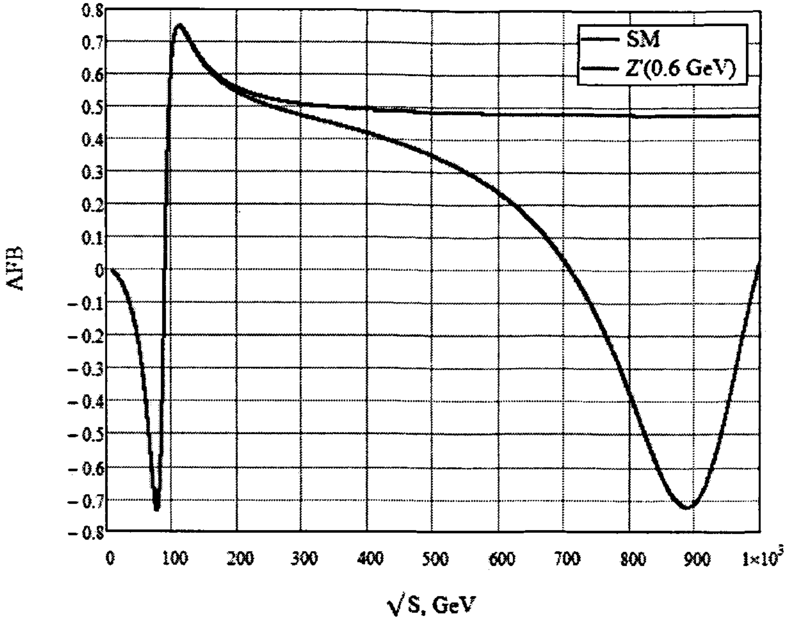

Figure 3.2 Forward-backward asymmetry for process (1) as a function of c.m. energy within the framework of the CM (blue curve) and SSM with M_Z=600 GeV (red curve).

Analogous considerations apply to the forward-backward asymmetry. This asymmetry, as a function of energy, is shown in Fig.~3.2.

Up to now we studied the indirect (propagator) effects of new neutral bosons on the cross section and forward-backward asymmetry. We note that the deviations from the SM predictions are small, which is indeed the case in our analysis, we can directly confront our observables in the Born approximation with the radiatively corrected data. While the contribution of the weak loop corrections will only change the overall normalization, the photonic corrections and in particular those due to initial state radiation give very large contributions which depend on the experimental set-up. Due to the radiative return to the Z resonance at c.m. energy above the CM Z boson peak, the energy spectrum of the radiated photons is peaked around $1\text{-}M_Z^2/s$. In order to increase the Z' signal, events with hard photons should be eliminated from a Z' search by a cut on the photon energy.

In conclusion, we have reviewed the interference effects induced by an extra neutral gauge boson Z' in the process $e^+ + e^- \to \mu^+ + \mu^-$. Assuming lepton universality, the lepton channel has the advantage over the quark pair production channel that the signs of the interference terms are given very simply by the propagators of Z and Z'. This is caused by the fact that the observables under consideration, total cross section and forward-backward asymmetry depend only on squares of coupling constants.

Acknowledgments
This research has been partially supported by the Abdus Salam ICTP (TRIL Programme).

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