Extra neutral gauge bosons at a 5 TeV e^+e^- linear collider

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For a 5 TeV e^+e^- linear collider in the deep quantum regime, the energy loss due to beamstrahlung during the collision of the e^+e^- beams is expected to substantially influence the effective center-of-mass energy distribution of the colliding particles. In this paper, I have estimated the feasibility of the measurement of the extra neutral gauge bosons Z' on the Z' pole at a 5 TeV e^+e^- linear collider including the effects of the beam-beam interaction.

I. INTRODUCTION

One of the simplest gauge extensions of the standard model (SM) involves one or more additional $U(1)$ symmetries, $U(1)'$, and is to introduce their associated extra neutral Z' bosons [1,2]. They arise in extended gauge theories including grand unified theories (GUT's) or superstring theories, for example. The collider experiments for the Z' searches indicate that the low mass limit of a canonical Z' boson is about 600 GeV. If the center-of-mass energy of a future e^+e^- linear collider is large enough to produce Z' bosons after discovery of the Z' bosons, we will get precise information about its nature.

For a several TeV e^+e^- linear collider beyond the next linear colliders (NLC), one of the most important constraints is beamstrahlung [3–5] due to the beam-beam interaction [5]. Beamstrahlung is a synchrotron radiation produced by electrons and positrons as they pass through the collective electromagnetic field of the oncoming beam. The fields can be so strong due to the extremely high charge density that colliding particles may lose significant amount of their energy, causing severe luminosity degradation. The beamstrahlung photons may also turn to copious e^+e^- pairs and the pairs are strongly deflected as they continue moving through the collective field, causing troublesome background problem to the study of particle physics.

Recently the design study for 5 TeV linear colliders in the deep quantum beamstrahlung regime, for example, the laser driven e^+e^- linear colliders, has been started and it presents that the effects of quantum suppression of beamstrahlung due to the very short bunch length are effective [6–9]. In order to evaluate the feasibility of the measurement of the extra neutral gauge bosons Z' at a 5 TeV e^+e^- linear collider, we need to take account of the effects of the beam-beam interaction.

In this paper, we study the feasibility of the measurement of the extra neutral gauge bosons Z' on the Z' pole at a 5 TeV e^+e^- linear collider including the effects of the beam-beam interaction.

II. CROSS SECTION

There are many Extended Gauge Models (EGMs) which include the Standard model gauge group and at least an additional $U(1)$ group. Here we list some of the EGMs.

1. The E_6 effective rank-5 model (ER5M), which predicts a Z' whose couplings depend on a single parameter $-\pi/2 \le \theta \le \pi/2$ (with models ψ, χ, I, and η denoting specific θ values);
2. The Sequential Standard Model (SSM), wherein the new W' and Z' are just heavy versions of the SM particles;
3. The Ununified Model (UUM), based on the group $SU(2)_l \times SU(2)_q \times U(1)_Y$, which has a single free parameter $0.24 \le s_\phi \le 1$;
4. The Left-Right Symmetric Model (LRM), based on the group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, which also has a free parameter $\kappa = g_R/g_L$ of order unity which is the ratio of the gauge couplings;
5. The Alternative Left-Right Model (ALRM), based on the same extended group as the LRM but now arising from E_6.

In this paper, we compare the ER5Ms with ψ, χ, and η, the LRM with $\kappa = 1$, and the SM.

At e^+e^- colliders, the basic process is $e^+e^- \to f\bar{f}$ where f could be leptons (e, μ, τ) or quarks (u, d, c, s, b). The signal process of the ER5Ms and the LRM is

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

and that of the SM is

$$e^+e^- \to \gamma, Z \to \mu^+\mu^-. \tag{2}$$

These processes were calculated including the initial state radiation, radiative correction. Figure 1 shows the total cross sections of the ER5Ms with ψ, χ, and η, the LRM with $\kappa = 1$, and the SM. The mass of the Z' bosons is assumed as 5 TeV. From this figure, we see that the shape of the Z' bosons largely depend on the models and we need to take account of the luminosity degradation due to the beam-beam interaction for precision study of the Z' bosons.

Here I will describe the luminosity distribution at a 5 TeV e^+e^- linear collider. There are two processes for $\gamma\gamma$ collisions in e^+e^- colliders. First, beamstrahlung is a synchrotron radiation induced by the collective fields of the oncoming colliding beams. The average Upsilon parameter, which is described as the ratio of the strength of the magnetic field in the bunch to that of the Schwinger critical field, is [5]

$$\Upsilon = \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha \sigma_z(\sigma_x + \sigma_y)}. \tag{3}$$

where N is the number of particles per bunch, r_e the classical electron radius, γ the Lorentz factor of the beams, α the fine structure constant, σ_z the rms bunch length, σ_x and σ_y the horizontal and vertical rms beam sizes at the IP, respectively.

Second, virtual photons are emitted by the collisions of individual particles. For the luminosity distribution between the virtual photons, the spectrum of the virtual photons from electron beams is given by the well-known equivalent photon approximation [10]

$$n_v(y) = \frac{\alpha}{2\pi}\left(\frac{1+(1-y)^2}{y}\ln\left[\frac{(1-y)P_{\mathrm{max}}^2}{m_e^2 y^2}\right] - \frac{2(1-y)}{y}\right), \tag{4}$$

where y and P_{max}^2 denote the energy fraction taken by the photon from the electron and the maximum photon virtuality, m_e the electron mass. In this article, the photon virtuality was restricted to $P_{\mathrm{max}}^2 = 0.01$ GeV^2 [10].

The beam parameters of an e^+e^- linear collider with the laser drive at $\sqrt{s}_{e^+e^-} = 5$ TeV are listed in Table I. The Υ parameter of the laser-driven e^+e^- collider is some hundreds, because σ_z is much smaller than that of conventional microwaves due to the typical wavelength of accelerating wakefield for laser wakefield acceleration, which is about 100 μm.

Figure 2 shows the luminosity distribution of a 5 TeV linear collider with $\Upsilon = 631$. The luminosity distribution of the e^+e^-, $e\gamma$, and $\gamma\gamma$ collisions (γ denotes beamstrahlung photons.) in Fig. 2 have been calculated by using the CAIN code [11]. CAIN is the fortran code which simulates the classical and quantum effects of the beam-beam interaction and the detail about the simulation results are written in the paper [8]. The maximum energy of the collisions between beamstrahlung photons reaches near $\sqrt{s} = 5$ TeV due to the large Υ parameter. Using the analytic formula of Eq.(4), that of the $\gamma^*\gamma^*$ collisions (γ^* denotes virtual photons.) was calculated by

$$L_{\gamma^*\gamma^*}(\sqrt{s}) = L_{ee}\int_0^1\int_0^1 n_v(y_1)n_v(y_2)\delta\left(s - 4y_1y_2E_0^2\right)dy_1dy_2, \tag{5}$$

where E_0 is the energy of initial electrons and L_{ee} the total luminosity of the e^+e^- collisions. The collisions between virtual photons over $\sqrt{s} > 1$ TeV is negligible in comparison with other collisions. It is needless to say that we will have to consider the superposition of the beamstrahlung and virtual photon spectrums.

The total luminosity of an e^+e^- linear collider with the laser drive at $\sqrt{s}_{e^+e^-} = 5$ TeV are listed in Table II. There is about a half of the total luminosity of the e^+e^- collisions with $\sqrt{s} > 4.975$ TeV and it presents a narrow width for precision study.

In order to evaluate the signal and background events including the luminosity distribution, the effective cross section is obtained by

$$\sigma_{\mathrm{eff}}(\sqrt{s}) = \frac{\sigma(\sqrt{s})}{L_{ee}}\frac{dL}{d\sqrt{s'}}\bigg|_{\sqrt{s'}=\sqrt{s}}, \tag{6}$$

and we can get easily the number of events by multiplying it by the amount of the luminosity. The effective cross sections of the ER5M with ψ and the SM are shown in Fig. 3. The tails of two peaks depend on the luminosity distribution including the beam-beam interaction, because the difference of the tails does not appear if no luminosity degradation.

Figure 4,5, and 6 show the effective cross sections of e^+e^-, $e\gamma$, and $\gamma\gamma$ collisions. Here the total cross sections for the processes in the SM except for the $\gamma\gamma \to hadrons$ were calculated by the CompHEP and GRACE codes [12,13]. The cross section for the $\gamma\gamma \to hadrons$ from fitting the experimental data is described as [14]

$$\sigma_{\rm tot} = 156 s^{\epsilon} + 320 s^{-\eta_1} \text{ nb}, \tag{7}$$

where the exponents are $\epsilon = 0.095$ and $\eta_1 = 0.34$, respectively. The $\gamma\gamma$ luminosity except for $\gamma^*\gamma^* \to hadrons$ originate from beamstrahlung photons. At 5 TeV, the processes of $e^+e^- \to e\nu W$, $\nu\bar{\nu}Z$, $e^+e^-(|\cos\theta| < 0.99)$, and $e\gamma \to W\nu$ are dominant as well as $\gamma\gamma \to hadrons$. Especially, the events of $e^+e^- \to e\nu W$ is comparable to those of $\gamma\gamma \to hadrons$ at 5 TeV. The effective cross section of $\gamma\gamma \to hadrons$ from beamstrahlung photons is about 10^4 times larger than that of $\gamma\gamma \to W^+W^-$. When the collision energy is increasing, the effective cross sections of $\gamma\gamma$ collisions are almost decreasing.

Although the processes of $e^+e^- \to e\nu W$, $\nu\bar{\nu}Z$, $e^+e^-(|\cos\theta| < 0.99)$, $e\gamma \to W\nu$, and $\gamma\gamma \to hadrons$ are dominant at 5 TeV, the background candidates for the process $e^+e^- \to \gamma, Z, Z' \to \mu^+\mu^-$ are the processes $e^+e^- \to W^+W^- \to \nu\bar{\nu}\mu^+\mu^-$ and $\gamma\gamma \to W^+W^- \to \nu\bar{\nu}\mu^+\mu^-$. The branching ratio of $W \to \nu\mu^+$ is 10.2% [14] and $(W \to \nu\mu^+)^2 = 1.04\%$. Therefore the ratio is

$$e^+e^- \ or \ \gamma\gamma \to \nu\bar{\nu}\mu^+\mu^- \sim 1/100 \ (e^+e^- or \ \gamma\gamma \to W^+W^-), \tag{8}$$

and these backgrounds are negligible from Fig. 4 and 6.

The number of $\mu^+\mu^-$ events of the ER5Ms with ψ, χ, and η, the LRM, and the SM are listed in Table III. The integrated luminosity at a 5 TeV e^+e^- linear collider is assumed to be 100 fb^{-1}. The energy cut from the detector resolution 300 GeV (4.7$\sim$5.0 TeV) and the detector acceptance $|\cos\theta| < 0.95$ are applied as the adequate cuts. The number of the ER5M with ψ is largest in these models and the statistical significance of the ER5M with ψ, $\sqrt{S}$, where S is the number of signal, is 500. Therefore the 5 TeV e^+e^- collider would function as a Z' factory as listed in the table. From the table, we can not resolve the difference of the ER5M with η and the LRM from the number of events and need further information for distinguish of two models.

III. SUMMARY

I have estimated the feasibility of the measurement of the extra neutral gauge bosons Z' on the Z' pole at a 5 TeV e^+e^- linear collider including the effects of the beam-beam interaction. The beam-beam interaction for the 5 TeV e^+e^- linear collider in the deep quantum regime was simulated using the CAIN code and the luminosity distribution of e^+e^-,$e\gamma$, and $\gamma\gamma$ collisions were calculated. Taking account of the luminosity distribution, we estimated the effective cross section of the Z' boson production and standard model processes. For example, the number of $\mu^+\mu^-$ events of the ER5Ms with ψ is 250000 with the integrated luminosity of 100 fb^{-1}. Therefore the 5 TeV e^+e^- linear collider on the Z' pole could function as a Z' factory.

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TABLE I. Beam parameters of an e^+e^- linear collider with the laser drive at $\sqrt{s}_{e^+e^-}$=5 TeV [6].

Υ	P_b (MW)	$N_e(10^8)$	f_c (kHz)	ϵ_x/ϵ_y (nm)	$\beta_x/\beta_y(\mu$m)	σ_x/σ_y (nm)	σ_z (μm)
631	20	1.6	156	25/25	62/62	0.56/0.56	1

TABLE II. Total luminosity of an e^+e^- linear collider with the laser drive at $\sqrt{s}_{e^+e^-}$=5 TeV (Unit $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$).

	L_{ee}	L_{ee} ($\sqrt{s} > 4.975$ TeV)	$L_{e\gamma}$	$L_{\gamma\gamma}$	$L_{\gamma^*\gamma^*}$ ($\sqrt{s}$ >1 GeV)
Total	1.3	0.61	0.49	0.21	0.34

TABLE III. Number of $\mu^+\mu^-$ events of the ER5Ms with ψ, χ, and η, the LRM, and the SM. The integrated luminosity at a 5 TeV e^+e^- linear collider is assumed to be 100 fb^{-1}.

SM	ER5M ψ	ER5M χ	ER5M η	LRM
5300	78000	250000	60000	60000

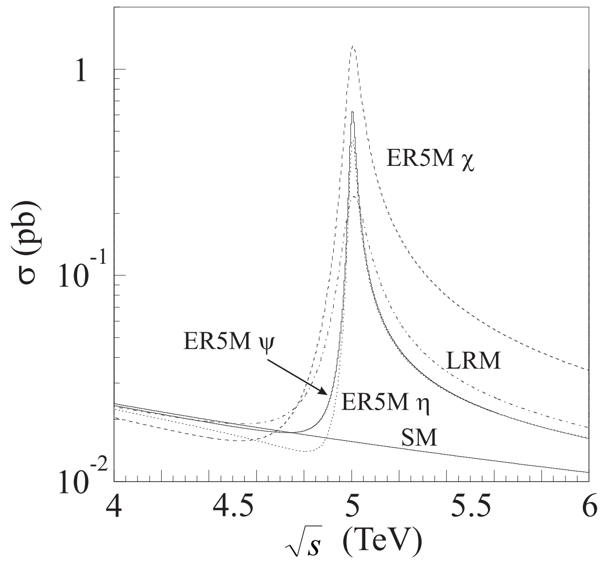

FIG. 1. Total cross sections of $\mu^+\mu^-$ events of the ER5Ms with ψ, χ, and η, the LRM, and the SM. The mass of Z' bosons are assumed as 5 TeV.

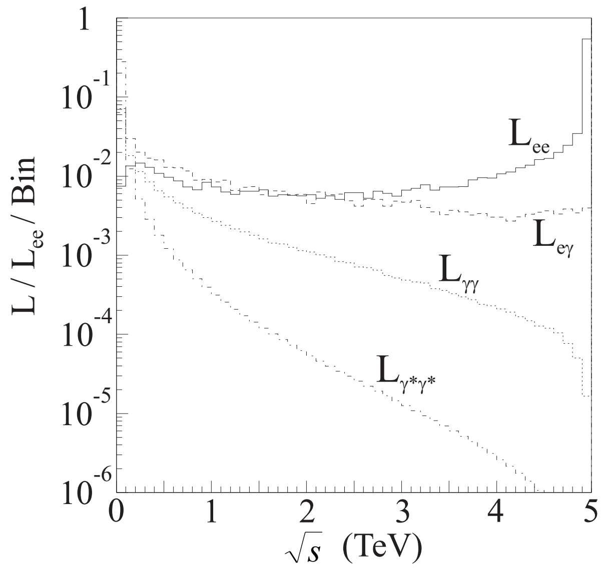

FIG. 2. Luminosity distribution of a 5 TeV e^+e^- linear collider with $\Upsilon = 631$. The vertical axis is normalized by the total luminosity of the e^+e^- collisions. The bin size is 100 GeV.

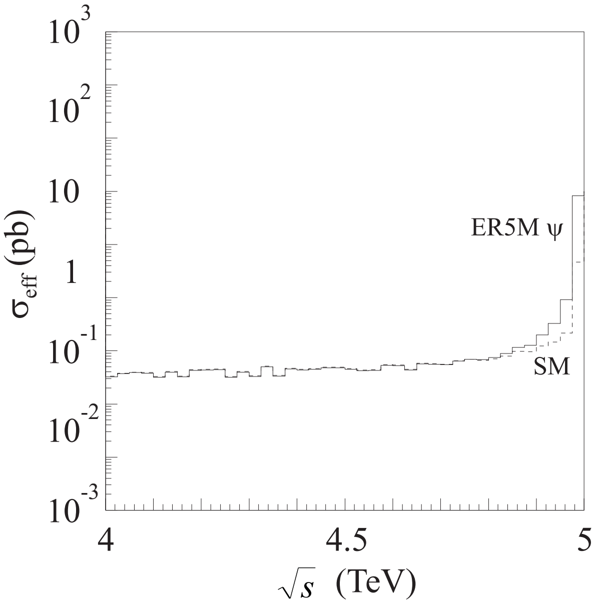

FIG. 3. The effective cross sections of the ER5M with ψ and the SM at a 5 TeV e^+e^- linear collider. The bin size is 20 GeV.

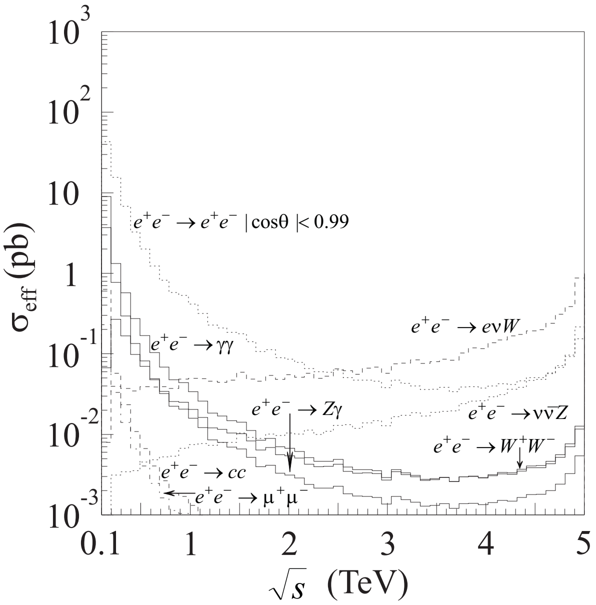

FIG. 4. The effective cross section of e^+e^- collisions at a 5 TeV e^+e^- linear collider.

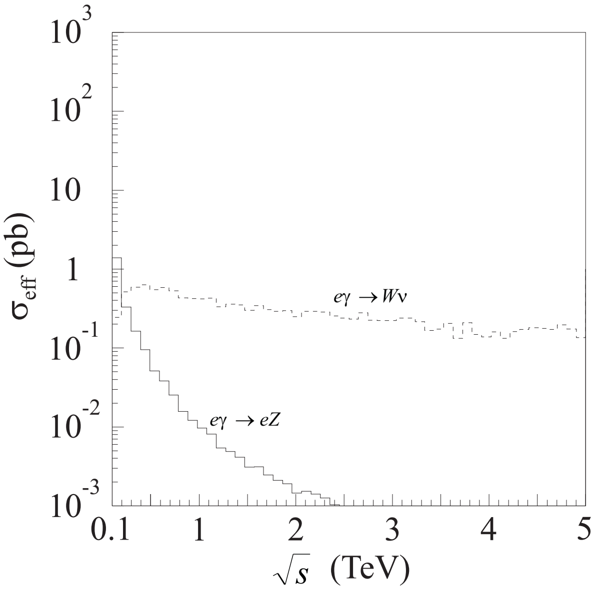

FIG. 5. The effective cross section of $e\gamma$ collisions at a 5 TeV e^+e^- linear collider.

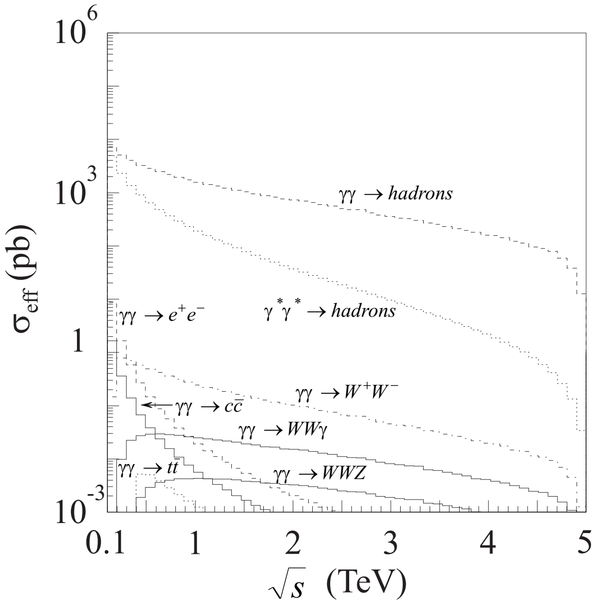

FIG. 6. The effective cross section of $\gamma\gamma$ collisions at a 5 TeV e^+e^- linear collider.

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