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On a Z' signature at next high energy electron–positron colliders

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Abstract. The associated production of a Z' and a final hard photon in high energy electron–positron colliders is studied. It is shown that the hard-photon spectrum contains useful information on the Z' properties. This suggests that, if a new neutral gauge boson exists for $M_{Z'} < \sqrt{s}$, it will not be necessary to make a new energy run at the Z' mass in order to get most of its properties.

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1 Introduction

A general consequence of extended $SU(3) \otimes SU(2) \otimes U(1)$ gauge symmetry is the existence of additional gauge bosons. In the simplest extension one has only a new $U(1)$ neutral gauge boson Z'. This scheme has a natural place in grand unified theories and in some superstring models [1]. In other extended models, like left–right $SU_{\rm L}(2) \otimes SU_{\rm R}(2) \otimes U(1)$, there are new charged and neutral gauge bosons [2]. No experimental confirmation of these hypotheses has been found yet, but it is expected that the next generation of colliders will confirm, or rule out, these models. Following the success of the standard neutral gauge discovery of the Z boson, it is also expected that a clear sign of the existence of a Z' boson could be found in the resonant production of lepton pairs via $Z' \longrightarrow \ell^+\ell^-$ (with $\ell = e, \mu, \tau$), in the next high energy colliders [3–5]. These topics have been studied by many authors over the last years [5–7].

However, in the search for this new neutral gauge boson, there is a major difference with the standard model search for the usual Z. As the Z mass was theoretically predicted, colliders were built at the Z mass energies necessary to study its properties. Since the Z' mass is not known, colliders are considered at the highest feasible energy $\sqrt{s}$. If indications of a Z' signal are found with a mass lower than $\sqrt{s}$, a new run near the mass value would be necessary in order to study the Z' properties in detail. This could be experimentally a very complex, expensive or even an impossible operation. It is important to study alternative methods that could equally well disentangle the Z' properties without changing the collider energy. The soft-photon emission accompanying a new Z' is known [8] to imply logarithmic corrections to the cross section. For the standard neutral gauge boson production associated with a neutrino pair it was noted [9] that the Z pole would change its position. Recently [10] a study was presented of the process $e^+e^- \longrightarrow Z'n\gamma$. The effect of the multi-γ emission is to reduce the effective available energy and the consequent production of a real Z' with a mass below $\sqrt{s}$.

The purpose of this letter is to present an alternative signature for Z' production at the new electron–positron colliders, that could allow us to study its width, decay channels, couplings and so on, at a fixed collider energy $\sqrt{s} > M_{Z'}$.

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2 The model

Our main point is the associated production of a Z' and a hard photon in the process

$$e^+e^- \longrightarrow Z'\gamma. \tag{1}$$

This process is similar to the proposal of [8–10] but with an important difference. Whereas in [8–10] multi-soft photon emission is studied and the Z' properties are obtained from its direct decay products, in our proposal one has a single hard-photon emission and the Z' properties are studied from this hard photon. A similar proposal for a two body process, with one light particle and another very heavy one in the final state, has already been studied [11] for the case of two fermion production. In the present paper we discuss several advantages of the direct study of the hard-photon emission.

A very simple consequence of four-momentum conservation of process (1) is that the final high energy hard photon has an energy given by

$$E_\gamma \mp \Delta_\gamma = \frac{s - (M_{Z'} \pm \Delta_{Z'})^2}{2\sqrt{s}}, \tag{2}$$

where Δ_γ and $\Delta_{Z'}$ are the fluctuations in the photon energy E_γ and Z' mass distributions respectively.

The study of the hard-photon energy distribution gives the same information as the direct Z' decays, but in a simple and direct way, without the need to obtain the Z' mass from its decay products. In order to obtain numerical estimates and detector and hadronization effects, we will employ the canonical η, χ, ψ superstring-inspired E_6 models [7], but our arguments apply to any model with extra neutral gauge bosons as well, since it is based on the kinematical properties. We neglect Z–Z' mixing and consider that the Z' couples only to the usual fermions. Then there is only one unknown parameter in the above models – the extra Z' mass.

3 Results

In order to obtain the hard-photon energy distribution, which is particularly relevant to our analysis, Monte Carlo events were generated and selected by a set of realistic cuts. All final-state particles were required to emerge with a polar angle θ, measured with respect to the direction of the electron beam, in the range $|\cos\theta| \leq 0.995$. Events in which the hard-photon energy was less than 50 GeV were ignored. Since we are interested in hard-photon emission, this cut eliminates also most of the initial-state radiation. We also imposed a cut $m_{ij} > 5\,\mathrm{GeV}$ $(i, j = \gamma, \mu^+, \mu^-)$ on the invariant masses of the final particles. The $\cos\theta$ and m_{ij} cuts roughly reflect the detector limitations. We are assuming that the detector is "blind" for $|\cos\theta| \geq 0.995$ and for cluster with $m_{ij} < 5\,\mathrm{GeV}$.

As an example of future high energy electron–positron colliders we have chosen a new collider [6, 12] project at an energy $\sqrt{s} = 1\,\mathrm{TeV}$ and a typical yearly integrated luminosity of $100\,\mathrm{pb}^{-1}$.

A first example is given in Fig. 1, which shows the photon energy distribution in the channel $\gamma\mu^+\mu^-$ for two Z'

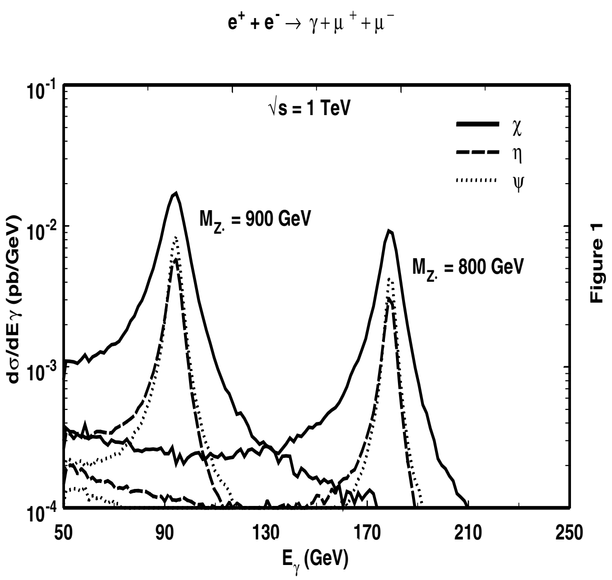

Fig. 1. The photon energy distribution in $e^+e^- \longrightarrow \gamma\mu^-\mu^+$ for $M_{Z'} = 800\,\mathrm{GeV}$ and $M_{Z'} = 900\,\mathrm{GeV}$ at $\sqrt{s} = 1\,\mathrm{TeV}$ for the χ, η and ψ models. The SM curve is below $10^{-4}\,\mathrm{pb/GeV}$

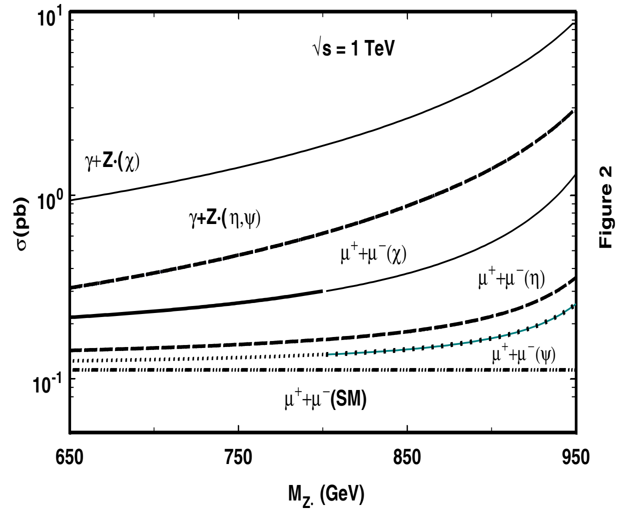

Fig. 2. The total cross section for $e^+e^- \longrightarrow \gamma Z'$ and $e^+e^- \longrightarrow \mu^+\mu^-$ for the χ , η, ψ and standard models

mass values. In order to account for real and virtual contributions for this process we have included all the twelve Feynman diagrams – eight from the standard model (SM) and four from the extra Z' contribution. We have performed the calculation with the CompHEP package [13]. The corresponding distribution for the SM is below $10^{-4}\,\mathrm{pb/GeV}$. A similar distribution, peaked at the photon energy, follows for any other decay channel $Z' \longrightarrow \bar{f}f$. The $\gamma Z'$ total cross section is shown in Fig. 2. The cross section for the more usual channel $e^+e^- \longrightarrow Z' \longrightarrow \mu^+\mu^-$ is also shown for comparison. It is important to observe that the $\gamma Z'$ cross section is greater than $\mu^+\mu^-$ production for all models, including the SM.

In Table 1 we give the Z' branching ratios for the fermionic decay channels. For the invisible channel we have summed all neutrinos whereas for the leptonic charged channel individual branching fractions are given. From this result we can estimate the total number of signal events.

With the purpose of accounting for the finite resolution of the detectors, we smeared the four-momenta of the final-state photons and leptons by means of the SMEAR routines [14]. The uncertainties in the energies of the final-state photons were simulated by Gaussian smearing of the energies of these particles with a half-width ΔE of the form $\Delta E/E = a + b/\sqrt{E}$. For the electromagnetic calorimeters proposed for the new linear colliders, $a = 1\%$, and b ranges from 10% to 15%. We used the value $b = 12\%$, which is representative of a electromagnetic calorimeter [12]. The

Table 1. Z' branching ratios (%) and total width for standard fermions channels in the χ, η and ψ models

	Models		
Channels	χ	ψ	η
Hadrons	65.1	79.0	86.0
Invisible	16.5	6.9	2.4
l^+l^-	6.1	4.7	3.9
$\Gamma_{\mathrm{total}}/M_{Z'}$	0.012	0.005	0.006

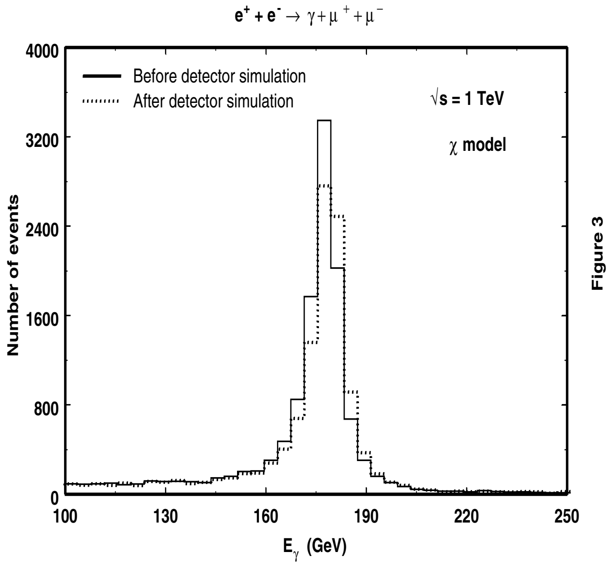

Fig. 3. Histogram for the photon energy before and after detector simulation in $\gamma\mu^+\mu^-$ when $M_{Z'} = 800\,\mathrm{GeV}$ for the χ model

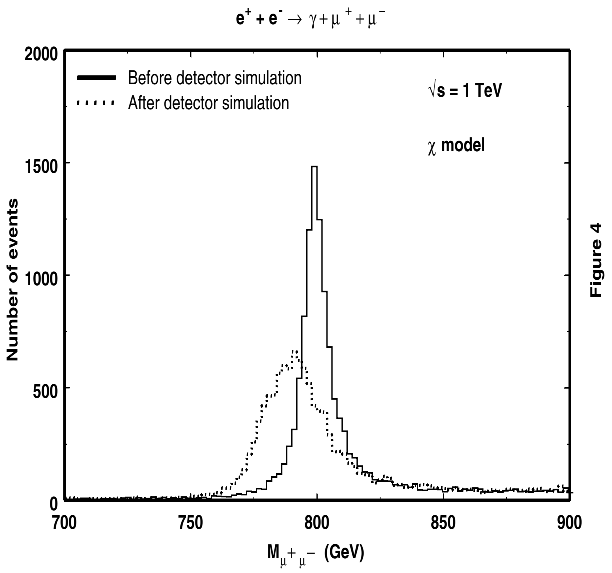

Fig. 4. Histogram for the invariant $\mu^-\mu^+$ mass before and after detector simulation when $M_{Z'} = 800\,\mathrm{GeV}$ for the χ model

directions of the final-state photons were smeared in a cone around the directions of their original three-momenta, according to a Gaussian distribution with half-width equal to 10 mrad. As far as the detection of muons is concerned, one has to consider the momentum resolution of the muon tracker and the multiple scattering effects on the transverse momentum p_{T} and azimuth ϕ of the muons. The details of the procedure to incorporate these effects by Gaussian smearing of $1/p_{\mathrm{T}}$ and ϕ can be found in [14] and references therein.

The hard-photon energy distribution gives a very clear indication of the Z' parameters. This is shown in Fig. 3 for the channel $e^+e^- \longrightarrow Z' \longrightarrow \gamma\mu^+\mu^-$. The hard-photon energy distribution shows practically no difference between the exact theoretical curve and the estimate for the possible data whereas in the reconstructed $\mu^+\mu^-$ invariant mass distribution there is a much larger distortion and the peak shifted to the left as shown in Fig. 4. This distortion can lead to experimentally sophisticated invariant mass correction methods increasing the uncertainties for the $M_{Z'}$ and its width.

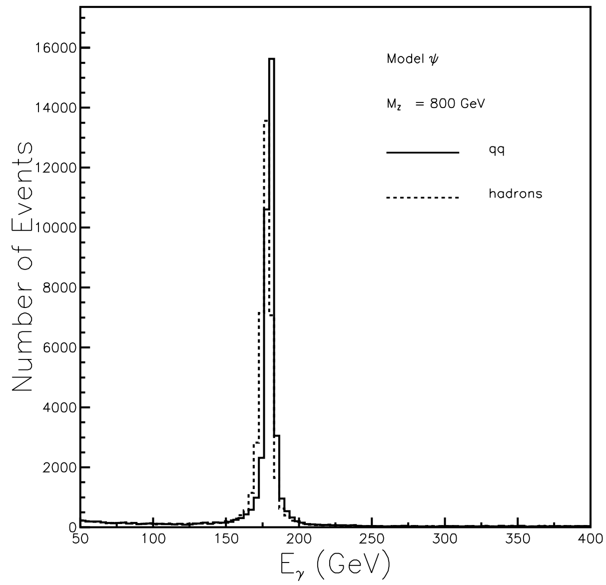

Fig. 5. Histogram of the photon energy in the γ jet–jet channel before and after hadronization when $M_{Z'} = 800\,\mathrm{GeV}$ for the ψ model

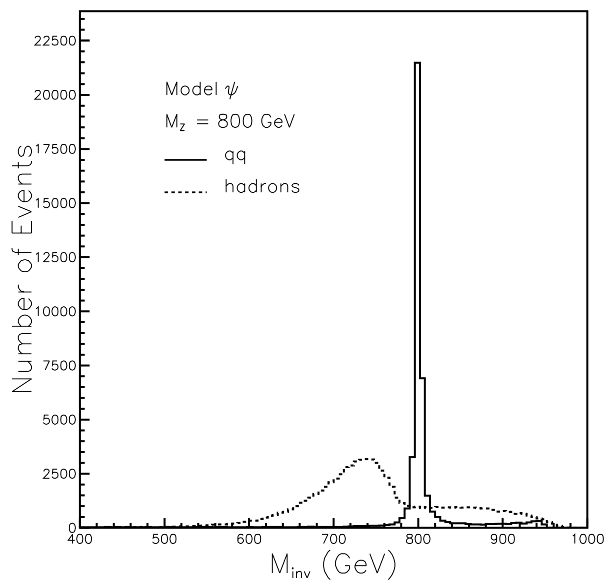

Fig. 6. Histogram of the jet–jet invariant mass before and after hadronization when $M_{Z'} = 800\,\mathrm{GeV}$ for the ψ model

A similar effect can be seen in the hadronic channels. We have performed the full hadronization procedure for the $Z' \longrightarrow \gamma q\bar{q}$ by using the Pythia program. The results are shown in Figs. 5 and 6. Here again the photon peak is practically unchanged, whereas the jet–jet peak presents a much larger distortion. One can also perform the smearing

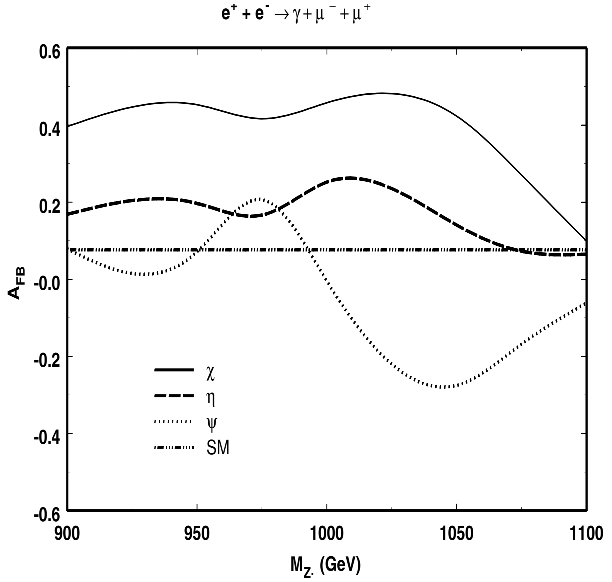

Fig. 7. Forward–backward asymmetry as a function of $M_{Z'}$ for the μ^- relative to the initial e^- in $e^+e^- \longrightarrow \gamma\mu^-\mu^+$ for the χ, η and ψ and standard models at $\sqrt{s} = 1\,\mathrm{TeV}$

process in the hadronic channels. This will increase even more the distortion in the Z' invariant mass reconstruction.

In the hard-photon channel one can also study model differences in the charge forward–backward asymmetry, defined relative to the final μ^- angular distribution relative to the incoming electron. The result is shown in Fig. 7.

4 Conclusions

In this paper we have shown that the energy distribution of a hard photon in $e^+e^- \longrightarrow \gamma f\bar{f}$ can give a very clear indication of a new neutral gauge boson with mass $M_{Z'} < \sqrt{s}$ using the simple kinematical expression (2), instead of the reconstruction of the Z' mass from the final fermions. We have simulated the finite resolution of the detectors for final-state photons and leptons and found that the hard-photon energy distribution remains essentially the same. The reconstructed $M_{l^+l^-}$ invariant mass distribution is flatter and its peak is moved from the real Z' mass value. Analyzing hadronization effects for the channel $e^+e^- \longrightarrow Z' \longrightarrow \gamma q\bar{q}$, it is seen that the quark hadronization introduces experimental uncertainties, strongly modifying the distribution that is not present in the hard-photon distribution. Analyzing the hard-photon distribution it is also possible to sum over all final fermions contributions, increasing substantially the Z' mass statistics and its resolution.

The forward–backward asymmetry of the final muons can be used to establish the relevant theoretical origin of a new possible Z'.

The hard-photon energy distribution approach could also be very useful in the case of more than one new neutral gauge boson with mass smaller than $\sqrt{s}$. Two or more peaks in the hard-photon energy distribution will indicate two or more new neutral gauge bosons, without the need to tune the accelerator energy to the resonant values. This analysis can be applied to any extended model with extra neutral gauge bosons and to any future high energy lepton colliders such as the NLC, TESLA or CLIC.

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