Prospects of Discovering a New Massless Neutral Gauge Boson at the ILC

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Prospects to search for a new massless neutral gauge boson, the paraphoton, in e^+e^- collisions at center-of-mass energies of 0.5 and 1 TeV are studied. The paraphoton naturally appears in models with abelian kinetic mixing. Interactions of the paraphoton with Standard Model fermion fields are proportional to the fermion mass and grow with energy, with however negligible couplings to ordinary matter. At the ILC, a potentially process to search for the paraphoton is its radiation off top quarks. Hence, the event topology of interest is a pair of acoplanar top quark jets with missing energy. Applying a multivariate method for signal selection limits for the top-paraphoton coupling could be derived. Arguments in favor of the missing energy as the paraphoton with spin 1 are shortly discussed.

1 Introduction

Modern elementary particle field theories are based on principe of the gauge invariance. It means that the Lagrangian of the theory should be invariant with respect to group transformation of the local symmetry which leads to a corresponding number of massless vector gauge boson fields. In the Standard Model (SM), based on the $U_Y(1) \times SU_L(2) \times SU_C(3)$ gauge symmetry group, 12 gauge vector bosons exist. Three of them, the electroweak bosons $W^\pm$ and Z^0, get masses due to the Higgs mechanism of spontaneous symmetry breaking. The eight massless strongly interacting gauge bosons, the gluons, are confined in hadrons and only one directly observed massless neutral vector boson, the well known photon, exists within the SM.

Although the Standard Model does not require any additional gauge fields it is possible to introduce gauge invariant operators in the Lagrangian which involve new gauge fields not forbidden by basic principe of gauge invariance. An example is given in [2] by the abelian kinetic mixing of the SM $U_Y(1)$ field with a new $U_P(1)$ field in a gauge invariant manner. The mixing term of the two $U(1)$ fields can be diagonalized and canonically normalized by an $SL(2,R)$ transformation in a way that one linear combination of the fields corresponds to the ordinary photon which couples in the usual manner to all electrically charged particles within the SM. The other linear combination appears as a massless spin-1 neutral particle, referred to as the "paraphoton" in [3] and denoted by γ' in this paper. The paraphoton couples only indirectly to the SM fields via higher mass-dimension operators.

In this study we follow an approach proposed in [4] where the effective Lagrangian of the interaction of the paraphoton with the SM fermion fields was proposed by considering higher dimensional operators. A possible lowest order Lagrangian which preserves both the new $U_P(1)$ and the SM gauge symmetries with the SM fermion cirality structure has the following form:

$$\frac{1}{M^2} P_{\mu\nu} \left(\bar{q}_L \sigma^{\mu\nu} C_u \tilde{H} u_R + \bar{q}_L \sigma^{\mu\nu} C_d H d_R + \bar{l}_L \sigma^{\mu\nu} C_e H e_R + h.c \right) , \qquad (1)$$

where q_L, l_L are the quark and lepton doublets, u_R, d_R the up and down-type $SU(2)$ singlet quarks, e_R the electrically-charged $SU(2)$-singlet leptons, and H is the Higgs doublet. An index labeling the three fermions generations is implicit here. The 3×3 matrices in flavor space, C_u, C_d, C_e, have dimensionless complex elements, and M is the mass scale where the operators are generated.

One can see that the interactions of the paraphoton with Standard Model fermions are suppressed by two powers of the mass scale M, but are directly proportional to the fermion mass m_f and the dimensionless coupling strength parameter C_f, with $f = u, d, e$. The coefficients C_f are unknown, but various phenomenological constraints exist. Discussions on possible lower limits on γ' interactions with fermions can be found in ref. [4].

From the Lagrangian, eq.(1), follows that γ' interaction with SM particles is strongest with the top quark, and small or negligible with light fermions. Therefore, the most interesting process to search for the paraphoton will be γ' radiation off the top. Since so far no constraint on c_t exists, access to $M/\sqrt{c_t}$ seems possible or corresponding limits might be set for the first time.

It seems a priori very difficult to perform γ' searches at hadron colliders because of copious $t\bar{t}$ + multi-jet background production. The next generation e^+e^- linear collider (ILC) is ideally suited to evaluate prospects of a search for the paraphoton via the channel

$$e^+e^- \to t\ \bar{t}\ \gamma' . \qquad (2)$$

The search strategy relies on the property of the γ' to interact weakly with ordinary matter and its favored emission from top quarks. Hence, the signal signature consists of a pair of acoplanar top quark jets with missing transverse energy,$\not{E}_T$, carried away by the paraphoton. The rate of such events if noticed should clearly exceed the expected SM background.

Simulations of $t\bar{t}\gamma'$ signal events with a 'reasonable' value of the coupling parameter $M/\sqrt{c_t}$ and SM background reactions were performed at $\sqrt{s} = 0.5$ and 1.0 TeV and an integrated luminosity of 0.5, respectively, 1 ab^{-1}. These assumptions are in accord with the present design for the ILC, initially producing collisions at 0.5 TeV and in a second stage at 1 TeV [5].

2 The signal reaction $e^+e^- \to t\ \bar{t}\ \gamma'$

The characteristics of the signal reaction were computed and partonic events were generated by means of the program package CompHEP [8]. The Feynman rules for the fermion-fermion-γ' vertices following from the effective Lagrangian (1)

$$\frac{c_f}{M^2} \cdot m_f \cdot p_3^\nu \delta_{pq} \left(\gamma^\nu_{ac} \gamma^\mu_{cb} - \gamma^\mu_{ac} \gamma^\nu_{cb} \right) . \qquad (3)$$

have been implemented into CompHEP. An interface with PYTHIA 6.202 [9] allows to simulate initial and final state radiation and jet hadronization, needed at a later stage of the study. Also, beamstrahlung effects [10] are taken into account.

Table 1 shows the number of signal events expected at $\sqrt{s} = 0.5$ and 1 TeV as a function of

$M/\sqrt{c_t}$ $[TeV]$	$\sqrt{s} = 0.5\ TeV$	$\sqrt{s} = 1\ TeV$
0.2	5700	42500
0.3	1100	8500
0.5	40	1100
1	10	70

Table 1: $t\bar{t}\gamma'$ event rates for several values of $M/\sqrt{c_t}$ at $\sqrt{s}$ = 0.5 and 1 TeV and an integrated luminosity of 0.5, respectively, 1 ab^{-1}.

$M/\sqrt{c_t}$ for an accumulated luminosity of 0.5, respectively, 1 ab^{-1}. The event rates become rapidly smaller with increasing $M/\sqrt{c_t}$, so that simulations were only performed for $M/\sqrt{c_t}$ = 0.2 TeV.

In order to establish a search strategy for the paraphoton in $t\bar{t}$ events it is advantageous to know whether an off-shell or on-shell top quark radiates the γ'. Fig. 1 (left) shows the invariant mass of the $\gamma' Wb$ system of that top which radiates the paraphoton. Clearly, in most cases the paraphoton is radiated off a top being off-shell, and γ' search strategies should be based on on-shell top with $t \to Wb$ decays in association with the γ'. The energy of the γ' shown in Fig. 1 (right) at 1 TeV reveales that substantial energy is carried away by the paraphoton, so that large missing energy, $\not{E}$, will tag signal events.

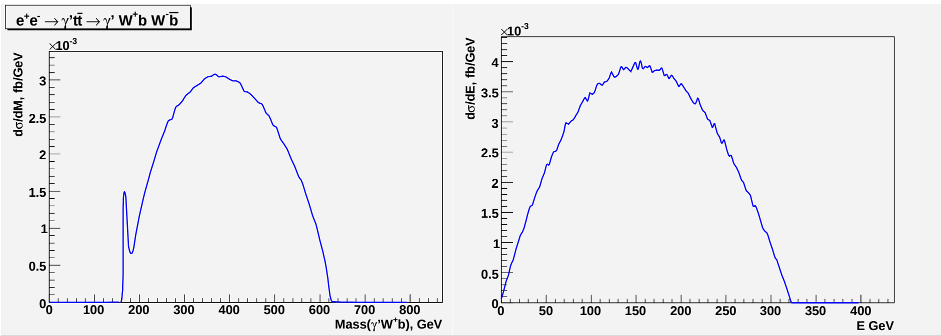

Figure 1: Left: Invariant mass of the $\gamma' Wb$ system. Right: γ' energy distributions at $\sqrt{s} = 1$ TeV.

3 Signal event selection

After event generation using CompHEP, PYTHIA and the CompHEP-PYTHIA interface packages [12] an approximate response of an ILC detector was simulated by means of SIMDET_v4 [13]. Including a simple particle flow algorithm, the output of SIMDET denoted as 'energy flow objects' was subject to our search studies.

Basic properties of the signal process as discussed in the previous section may suggest that a reasonable separation of signal events from large SM background should be possible. The most important background consists of $t\bar{t} + (\gamma)$ events, where the γ from initial state radiation (ISR) is very often not detected. The number of events expected for both energies are given in Table 2. They exceed substantially the number of signal events for interesting $M/\sqrt{c_t}$ values.

The next significant background to consider is the channel $e^+e^- \to t\bar{t} + \nu\bar{\nu}$, with a signature similar to that of the signal due to escaping neutrinos in the final state. The corresponding event numbers also given in Table 2 are comparable to the signal event rates for not too small $M/\sqrt{c_t}$ values. An invariant mass cut of e.g. $M_{\nu\bar{\nu}} < 80$ GeV, i.e. a cut on the event missing mass, removes most of these events. Additional SM background with a topology of a pair of acoplanar top quark jets and large $\not{E}_T$ is not needed to be addressed.

In a first attempt for signal event selection, a conventional method was applied by using consecutive cuts on kinematical variables based on either the energy flow objects or, utilizing a jet finder, the 4-momenta of jets consistent with the $t\bar{t} \to (Wb)(Wb) \to (q\bar{q})b\ (q\bar{q})b$ decay chain. Jets were reconstructed by means of the routine PUCLUS from PYTHIA which relies on a cluster analysis method using particle momenta. The 'jet-resolution-power' was adjusted to provide 7- and 8-jet event rates in accord with expectations from gluon radiation. The method of consecutive cuts, however, was found to be inefficient to select signal from background because of the failure of distinct properties between signal and background events.

background	$\sqrt{s} = 0.5\ TeV$	$\sqrt{s} = 1\ TeV$
$t\bar{t}(\gamma)$	276675	200310
$t\bar{t}\nu\bar{\nu}$	75	930

Table 2: Background events at $\sqrt{s} = 0.5$ and 1 TeV for an integrated luminosity of 0.5, respectively, 1 ab^{-1}.

Under such circumstances one needs to pursue more sophisticated strategies to extract the signal. Out of several powerful multivariate selection methods we used the following. Kinematical variables as discussed above were combined into a global discriminant variable P_P, designed to give a measure of the 'Paraphoton-likeness' of any particular event. This quantity was constructed from large statistics signal and background event samples, and for each event, signal and background probabilities were then calculated, and by multiplication of all signal probabilities the sensitivity for an event to be a paraphoton candidate was maximized. The quantity so obtained was constraint to lie in the region [0;1]. Background events are preferentially distributed at low P_P values while for signal events P_P is close to unity. The distributions of P_P for both energies considered are shown in Fig. 2. Clear accumulations of γ' candidate events can be recognized near P_P = 1, with some non-negligible background in particular at 0.5 TeV. A cut of $P_P > 0.98$ was applied to select signal events. This method resulted in a γ' selection efficiency of 49%

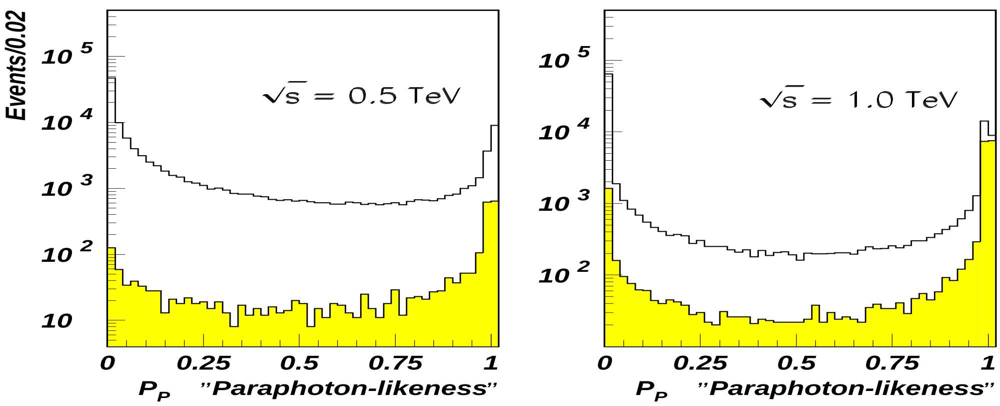

Figure 2: Distributions of the discriminant variable P_P for $t\bar{t}\gamma'$ signal events (shaded) and the sum of signal and background events at $\sqrt{s} = 0.5$ (left) and 1 TeV (right).

(76%) at $\sqrt{s} = 0.5$ (1) TeV, while only 9% of background events survived. In the following, we rely on the results of this method and demand $P_P > 0.98$ as the principal cut in the study.

At $\sqrt{s} = 0.5$ TeV, S$/\sqrt{B} = 11.96$ for $M/\sqrt{c_t} = 0.2$ TeV, while S$/\sqrt{B} = 162.6$ at 1 TeV, i.e. the chance of measuring the signal event rates as a result of a background fluctuation is $0.5 \cdot 10^{-12}$ and $< 10^{-15}$ at 0.5, respectively, 1 TeV, using Gaussian sampling of uncertainties.

Fig. 3 shows the $\not{E}_T$ and $\not{p}_T$ distributions at 0.5 and 1 TeV for the signal events (shaded) and the sum of signal and background events, surviving the cut $P_P > 0.98$. As apparent from Fig. 3, convincing excess of γ' events is evident in both distributions at 1 TeV and the ratio $S/\sqrt{B}$ can be further enhanced by demanding, for example, $\not{E}_T > 330$ GeV or $\not{p}_T > 100$ GeV. In this way, an almost background-free signal event sample can be extracted for further measurements. The situation is much less convenient at 0.5 TeV.

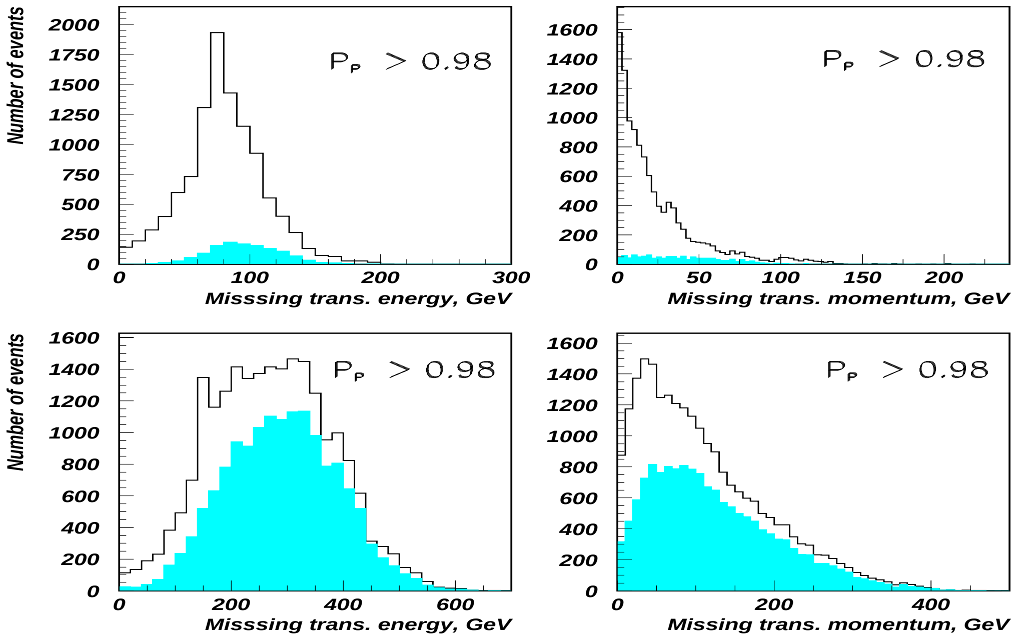

Figure 3: $\not{E}_T$ and $\not{p}_T$ distributions of $t\bar{t}\gamma'$ signal events (shaded) and the sum of signal and background events at $\sqrt{s} = 0.5$ (top) and 1 TeV (bottom).

4 Discussion of the results

If an excess of signal events over the SM background has been established, limits on $M/\sqrt{c_t}$ accessible for a significance[a] of $S/\sqrt{B} = 5$ can be derived. We consider this figure as sufficient for discovery the paraphoton. The number of surviving γ' events for 5σ discovery amounts to 508 (450) at 0.5 (1) TeV for an integrated luminosity of 0.5 (1.0) ab^{-1}. These numbers

[a]We quantify the discovery potential of the γ' in the usual way of $significance = signal/\sqrt{background}$, where signal and background imply the number of corresponding events passing all cuts.

can be converted into a limit for the 'coupling' parameter $M/\sqrt{c_t}$ of 0.33 (0.61) TeV, with the 1 TeV value of 0.61 TeV as the most stringent limit accessible at the ILC.

We will also discuss the signal-to-background ratio, S/B, as it will be important for attempting to understand the nature of the excess events. At $\sqrt{s}$ = 0.5 TeV, S/B of 0.11 does not favor such studies, while at 1 TeV S/B of 1.79 is sufficiently large so that background contamination should not be a major worry. If we require in addition $\not{E}_T > 330$ GeV, S/B results to $5231/2654 = 1.97$.

In order to demonstrate the spin-1 nature of the γ', we follow studies performed to establish the vector nature of the gluon in 3-jet e^+e^- annihilation events at PETRA [14–17] and LEP [18–20] energies, based on predictions that a spin-$\frac{1}{2}$ quark radiates the spin-1 gluon.

In a first step, we calculated the Ellis-Karliner angle [21] for each accepted event at 1 TeV. Distinction between the vector and scalar particle interpretations is made only on the basis of the shape of the distribution. We found that spin-1 assignment for the paraphoton is highly favored over spin 0.

Alternatively, after interpreting a signal candidate event as a 3-jet event, the polar angle distribution of the normal to the three-jet plane, θ_N, was proposed to distinguish between the vector and scalar hypothesis of the emitted particle [26, 27]. The θ_N distributions for various thrust cut-off values, corrected for background and detector effects, were fitted to the expression predicted for vector particle emission [28]. Good agreement between the data and the theoretical expectation was found.

5 Conclusions

Some realistic extensions of the Standard Model of elementary particle physics suggest the existence of a new massless neutral gauge boson, denoted as the paraphoton γ' in this study. This particle is similar to the ordinary photon, but the couplings of the γ' are very distinct: interactions with Standard Model fermions are negligible except those to the top quark. Hence, if the paraphoton is radiated off the top the signature of γ' events in the channel $e^+e^- \to t\,\bar{t}\,\gamma'$ consists of a pair of acoplanar top quark jets with missing transverse energy, $\not{E}_T$, carried away by the paraphoton. Only the all-hadronic top decay mode was selected to ensure a high signal-to-background ratio and to avoid complications due to final state neutrinos in leptonic W decays.

Based on a multivariate search strategy[b] prospects to discover the γ' at the ILC are studied. Maximizing the probability of each event to be a γ' candidate the method selected 49% (76%) of the signal (S) at 0.5 (1) TeV and strongly suppressed the background (B), resulting to a $S/\sqrt{B}$ larger than 150 at $\sqrt{s} = 1$ TeV. Allowing for a 5σ paraphoton discovery significance, e^+e^- collisions at 1 TeV will bound the γ'-top quark 'coupling' to $M/\sqrt{c_t} \lesssim 0.61$ TeV, which seems to be the most stringent limit accessible at the next generation colliders.

For the sake of demonstration two angular variables, the Ellis-Karliner angle and the polar angle of the normal to the $t\,\bar{t}\,\gamma'$ plane as a function of a thrust cut-off, were studied to establish the vector nature of the γ'. Both angular distributions are in accord with the spin-1 assignment of the paraphoton and inconsistent with e.g. a scalar hypothesis.

[b]This method was necessary to pursue because of large $t\bar{t}(\gamma)$ SM background, small signal event rates and little discrimination power of variables.

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