Searching for new light gauge bosons at $e^+e^-$ colliders

I. Alikhanov

Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia
Institute of Applied Mathematics and Automation, Nalchik 360000, Russia

E. A. Paschos

Department of Physics, TU-Dortmund, 44221 Germany

Abstract

Searches for physics beyond the Standard Model are looking for new gauge bosons with masses below 1 GeV. Several models predict such low mass states. For example, models with light vector bosons are frequently discussed in the literature in order to explain the muon $(g-2)$ anomaly, rare meson decays, interaction between ordinary and dark matter and a number of astrophysical observations. Recently a 17 MeV peak in the invariant $e^+e^-$-mass distribution of $^8\text{Be}^*$ nuclear transitions has been reported by the Atomki Collaboration. The known nuclear theory does not accommodate this bump and a possible interpretation is the appearance of a new boson of mass $\simeq 17$ MeV decaying into a $e^+e^-$ pair. Electron–positron collision experiments, like BaBar, provide the most straightforward way to probe bosons of this kind. In the present article we study production of new light scalar and vector gauge bosons at $e^+e^-$ colliders operating at GeV center-of-mass energies. The reaction $e^+e^- \rightarrow e^+e^-Z'$ is analyzed in detail. We derive analytically useful observables like the energy spectra of the produced bosons and electrons, created in the subsequent decays $Z' \rightarrow e^+e^-$. It is shown that the discussed reaction can put constrains on the parameters of $Z'$ which are orders of magnitude more stringent than previously considered channels.
I. INTRODUCTION

The notion of gauge bosons has become an integral part of particle physics long ago. A gauge boson is electrically neutral or charged particle with spin one responsible for transmission of forces in a theory. The well known representatives with precisely established properties are the photon, $Z^0$ and $W^\pm$.

Many extensions of the Standard Model accommodate new gauge bosons. After the electroweak $SU(2) \times U(1)_Y$ model was proposed, there appeared numerous alternative theories with additional $U(1)'$ symmetries leading to associated new neutral $Z'$ bosons [1–3]. Production of heavy $Z'$s with masses in the TeV region have been studied [4, 5] and searched for directly at the LHC in the ATLAS and CMS experiments which put stringent limits on their masses and couplings to the Standard Model particles [6–9]. These bosons have also been indirectly probed using high-precision electroweak data [10].

Apart from heavy $Z'$, models with much lighter gauge bosons of masses around one GeV or even a few tens of MeV are extensively discussed in articles and are popular today [11]. Such models have been widely studied for various reasons. In particular, their existence is assumed to reconcile the measured value of the anomalous magnetic moment of the muon with theoretical calculations [12–17]. The bosons are also introduced to account for some cosmological and astrophysical observations [18–23]. Possible impact of a new gauge interaction with a light mediator on rare kaon decays [13, 24, 25] and the Higgs boson decay [26–31] has been studied as well.

Recently, the Atomki Collaboration reported the observation of an anomalous bump in the angular and invariant mass distributions of electron–positron pairs emitted in nuclear transitions, $^{8}\text{Be}^* \rightarrow ^8\text{Be} + e^+e^-$, with high statistical significance of $6.8\sigma$ [32]. The known nuclear theory predicts no such a bump. A possible explanation of this anomaly can be an additional channel of emission of a light neutral vector boson subsequently decaying into a $e^+e^-$ pair [32–36]. To describe the experimental distributions, the new boson should have mass $m_{Z'} = 16.70 \pm 0.35(\text{stat}) \pm 0.50(\text{sys})$ MeV [32]. In the last year, there appear a lot of works devoted to this hypothetical 17 MeV boson [37–48].

A search for a light boson in $\pi^0 \rightarrow Z' + \gamma$ by the NA48/2 experiment at CERN requires that $Z'$ should couple to $u$ and $d$ quarks very weakly [49], which means that such a boson should be, as usually dubbed in the literature, "protophobic". On the other hand, if the
Atomki anomaly is a manifestation of new physics, then the coupling of $Z'$ to electrons is nonzero and the boson could be produced in a reversed process, for example in $e^+e^- \rightarrow \gamma Z'$ \cite{18, 38}. Electron–positron collisions are the most straightforward reactions to probe $Z'$'s. At the same time, one should keep in mind that the value of the coupling must be compatible with other measurements in which $Z'$ may contribute as the electron magnetic dipole moment \cite{50}, beam dump experiments and $\nu e$ scattering \cite{51}.

In this paper we focus our attention on the search for new light gauge bosons at $e^+e^-$ colliders in the following reaction:

$$e^+e^- \rightarrow e^+e^- Z'.$$  \hspace{1cm} (1)

This reaction contains subprocesses with the exchange of photons of small virtual mass leading to significant enhancement of the cross section, orders of magnitude larger than the cross section for the above mentioned channel $e^+e^- \rightarrow \gamma Z'$ \cite{18, 38}. Therefore, (1) could be used to make the existing constrains on the parameters of $Z'$ more stringent.

Assuming a general $V - A$ interaction we present an analytic study of the production cross section, the energy distribution for the final $Z'$'s as well their decay products. For completeness, we also calculate the same quantities in the case of a scalar theory considering the production of a spinless light boson $\phi$

$$e^+e^- \rightarrow e^+e^- \phi.$$  \hspace{1cm} (2)

The article is organized as follows. In Section \text{II}, we present the motivation of this work, carry out calculations of the cross section for vector boson production in full detail, derive the energy spectra of the bosons and electrons arising in the boson decay. In Section \text{III} we analyze the case of scalar boson production. Section \text{IV} considers a possibility of additional boson decay channels, like decays into neutrino–antineutrino pairs. In Section \text{V} we summarize our results and comment on a possibility of observation of the bosons at electron–positron colliders.
II. LIGHT VECTOR GAUGE BOSONS

A. The total cross section

Consider the production of a light vector gauge boson $Z'$ in reaction (1). We assume the general form of the electron–boson interaction:

$$L_e = -\varepsilon e \bar{u}_e \gamma_\mu (g_V - g_A \gamma_5) u_e Z'^\mu,$$

where $\varepsilon$ denotes the coupling strength of $Z'$ to the vector current, $e$ is the elementary electric charge. The leading Feynman diagrams are shown in Fig. [1].

We calculate the cross section in the Weizsäcker-Williams equivalent photon approximation (EPA). According to EPA we factorize (1) into two subprocesses. The first one is emission of a photon by the electron (positron), $e^\pm \rightarrow e^\pm + \gamma$, the second one is absorption of the emitted photon by the positron (electron) with production of a $Z'$ boson:

$$\gamma e^\pm \rightarrow e^\pm Z'.$$

(4)

Within EPA the sought-for total cross section is represented as

$$\sigma(s) = 2 \int_0^1 f_{\gamma/e}(\eta, s) \hat{\sigma}(\eta s) d\eta$$

(5)

where $s$ is the center-of-mass energy (cms), $f_{\gamma/e}(\eta, s)$ is the equivalent photon distribution of the electron (positron), $\eta$ is the fraction of the electron (positron) energy carried by the photon. The factor 2 arises because the distributions for electrons and positrons coincide. Throughout this paper we adopt [4]

$$f_{\gamma/e}(\eta, s) = \frac{\alpha}{2\pi} \frac{1 + (1 - \eta)^2}{\eta} \ln \left( \frac{s}{m_e^2} \right).$$

(6)

Here $\alpha$ is the fine structure constant.

Besides the unknown coupling $\varepsilon$ which varies over a wide range of values, depending on a model, EPA is quite good for order of magnitude estimations. In addition we emphasize that the interference between the two upper and two lower diagrams in Fig. [1] are negligibly small in the limit $s \gg m_Z^2$ (which is the condition for the cases we study). The point is that the $Z'$ boson will be predominantly emitted in the direction of the electron or positron so
that the processes become distinguishable. Thus the cross section will be determined by the square of the sum of the two upper diagrams plus that of the lower ones. This is another justification for using EPA which considerably simplifies calculations.

To find the cross section for the subprocess (4), there are two lowest order Feynman diagrams contributing to it shown in Fig. 2. Squaring these diagrams, averaging and summing over the spin states yield

\[ |M|^2(s, t, u) = -2(g_V^2 + g_A^2)\varepsilon^2 e^4 \left( \frac{u}{s} + \frac{s}{u} + \frac{2m_Z^2 t}{us} \right), \]

(7)

where \( t \) and \( u \) are the Mandelstam variables. After standard algebra one can obtain in the limit \( s \gg m_Z^2 \gg m_e^2 \) that

\[ \sigma(s) = \frac{4(g_V^2 + g_A^2)\varepsilon^2\alpha^3}{m_Z^2} \ln \left( \frac{m_Z^2}{m_e^2} \right) \ln \left( \frac{s}{m_e^2} \right). \]

(8)

Note that full consideration would also require taking into account diagrams of the same order depicted in Fig. 3. However they contain the exchange of an s-channel photon and produce terms of \( O(1/s) \) thus being greatly suppressed relative to the diagrams in Fig. 1. This happens because the t-channel photon exchange in Fig. 1 becomes highly dominating as the mass of the photon tends to zero. A notable property of the cross section (8) is the enhancement in models with light bosons due to the boson mass squared entering the denominator. In comparison with the cross section for the process \( e^+e^- \rightarrow \gamma Z' \) \[18, 38\], \( \sigma(s) \) may be orders of magnitude higher. This is clearly illustrated by the ratio of the cross sections in Fig. 4 at cms energies typical for experiments like BaBar \[52\] where the bosons can be searched. In Fig. 4 we set \( g_V = 1, g_A = 0 \) and \( m_Z = 17 \text{ MeV} \) as hinted by the recent observations of the Atomki Collaboration \[32\]. The main reason is that even though (1) is higher order in \( \alpha \) compared to \( e^+e^- \rightarrow \gamma Z' \), the suppression is compensated by the soft photon exchange in the t-channel. The same property produces the dependence on the \( Z' \) mass shown in figure 5 where one observes the significant dominance of reaction (1) as well. Thus, reaction (1) may be a promising channel for the production of new light gauge bosons that couple to electrons.
B. Energy spectrum of the produced bosons

We now describe some observables which may be useful for analyzing experimental data in order to probe $Z'$ bosons in $e^+e^-$ collisions. The first one is the energy distribution of the bosons produced in (1).

The cross section differential in the $Z'$ boson energy $E$ can be written as

$$\frac{d\sigma}{dE} = 2 \int_{\eta_{\text{min}}}^{\eta_{\text{max}}} f_{\gamma/e}(\eta, s) \frac{d\hat{\sigma}}{dE}(\eta s) d\eta, \quad (9)$$

where $\frac{d\hat{\sigma}}{dE}$ corresponds to the subprocess $\gamma e^\pm \rightarrow e^\pm Z'$. In order to find $\frac{d\hat{\sigma}}{dE}$ we start from the following formula:

$$\frac{d\hat{\sigma}}{dt}(\eta s) = \frac{1}{16\pi\eta^2 s^2} |M|^2(\eta s, t, u), \quad (10)$$

where $|M|^2(s, t, u)$ is given by (7). By definition

$$u = (p_e - p_Z)^2 = m^2_e + m^2_Z - 2E_e(E - p_L) = m^2_e + m^2_Z - \sqrt{s}(E - p_L). \quad (11)$$

Here $p_L$ is the longitudinal momentum of $Z'$ and we have used that $E_e = \sqrt{s}/2$. On the other hand

$$t = (p_\gamma - p_Z)^2 = m^2_Z - 2E_\gamma(E + p_L) = m^2_Z - \eta\sqrt{s}(E + p_L), \quad (12)$$

note that $E_\gamma = \eta E_e = \eta\sqrt{s}/2$. There is also the condition

$$\eta s + t + u = 2m^2_e + m^2_Z. \quad (13)$$

Adding (11) to (12) and using (13) yield

$$p_L = \frac{m^2_e - m^2_Z + E\sqrt{s}(1 + \eta) - \eta s}{\sqrt{s}(1 - \eta)}. \quad (14)$$

Substituting (14) into (12) we find the relation between $t$ and $E$

$$t = \frac{m^2_Z - \eta(m^2_e + 2E\sqrt{s} - \eta s)}{1 - \eta}. \quad (15)$$

Since
\[
\frac{d\hat{\sigma}}{d\hat{E}} = \frac{d\hat{\sigma}}{dt} \bigg| \frac{dt}{d\hat{E}}.
\]

we obtain

\[
\frac{d\hat{\sigma}}{d\hat{E}}(\eta_s) = \frac{1}{8\pi s^{3/2}} \frac{1}{\eta(1-\eta)} |M|^2(\eta_s, t, u).
\]

One can see that (17) coincides with equation (53) of [4] at \(q(x, P^2) = \delta(x - 1)\). The integration limits in (9) are the solutions of the following equations:

\[
t_{\max} - t_{\min} = \frac{m_Z^2 - \eta_{\max}^2 (m_e^2 + 2 E \sqrt{s} - \eta_{\max}^2 s)}{1 - \eta_{\max}^2}.
\]

In the limit \(s \gg m_Z^2 \gg m_e^2\) one can obtain that

\[
\eta_{\max}^2 = \frac{E}{\sqrt{s}} \left( 1 \pm \sqrt{1 - \frac{m_Z^2}{E^2}} \right).
\]

Using (17) in (9) we find

\[
\frac{d\sigma}{dE} = 32 (g_V^2 + g_A^2) \alpha^2 \frac{E^2 - m_Z^2}{m_Z^2 s} \frac{2 E^2 - 2 E \sqrt{s} + s}{m_Z^2 - 2 E \sqrt{s} + s} \ln \left( \frac{s}{m_e^2} \right),
\]

which actually determines the energy spectrum of \(Z'\) bosons. The \(Z'\) energy varies in the range

\[
m_Z \leq E \leq \frac{s + m_Z^2 - m_e^2}{2 \sqrt{s}}.
\]

Note that the boson mass is kept in the denominator of (20) so that the cross section behaves correctly at \(E \rightarrow E_{\max}\). A plot of the energy distribution of \(Z'\) bosons given by (20) for the cms energy of the BaBar experiment and \(m_Z = 17\ MeV\) is shown in Fig. 6.

C. Energy spectrum of electrons from \(Z'\) decays

The produced \(Z'\) bosons may decay back into electron–positron pairs and another convenient measurable quantity is the energy spectrum of these electrons. We compute it as

\[
\frac{d\sigma}{dE_e} = \int_{E_{\min}}^{E_{\max}} \frac{d\sigma}{dE} \frac{d\Gamma}{dE_e} dE.
\]
where $E_e$ is the electron energy, $\Gamma$ denotes the decay width of the $Z'$ boson with energy $E$, $\frac{d\sigma}{dE}$ is given by (20). The latter equation leads to

$$\frac{d\sigma}{dE_e} = \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{1}{\sqrt{E^2 - m_Z^2}} \frac{d\sigma}{dE} dE$$

(23)

with integration limits defined as

$$E_{\text{min}} = \frac{4E_e^2 + m_Z^2}{4E_e}, \quad E_{\text{max}} = \frac{s + m_Z^2 - m_e^2}{2\sqrt{s}}.$$  

(24)

The lower limit $E_{\text{min}}$ is a consequence of the condition $\cos \theta \leq 1$ with $\theta$ being the angle between the three-momenta of $Z'$ and the electron from the decay. In contrast to $E_{\text{min}}$, where the electron mass can be safely neglected (as we have done), in $E_{\text{max}}$ the mass should be kept to ensure the regular behavior of the electron spectrum in the upper edge.

The integration in (23) yields the distribution of the electrons arising from the decay $Z' \rightarrow e^+e^-$:

$$\frac{d\sigma}{dE_e} = \frac{4(g_Y^2 + g_A^2)e^2\alpha^3}{m_Z^2 s^{3/2}} \left[ (\sqrt{s} - 2E_e)^2 + 2s \ln \left( \frac{(\sqrt{s} - 2E_e)(2E_e\sqrt{s} - m_Z^2)}{2E_e m_e^2} \right) \right] \ln \left( \frac{s}{m_e^2} \right).$$  

(25)

We plot the electron spectrum (25) in Fig. 7. It is shown that for an integrated luminosity $\sim 500$ fb$^{-1}$ for the BaBar experiment there may be produced $\sim 10^3$ $Z'$ bosons with the mass 17 MeV and coupling $\varepsilon = 10^{-5}$. This would allow to set stringent constrains on the parameters of the bosons. Even for $\varepsilon = 10^{-6}$ there could be more than 10 events observed. Figure 8 demonstrates the dependence of the spectrum on the boson mass at a fixed electron energy $E_e = 2$ GeV.

III. LIGHT SCALAR BOSONS

We can extend the analysis and study the production of neutral scalar boson $\phi$ in $e^+e^-$ collisions. We introduce the following interaction:

$$\mathcal{L}_S = -ge \bar{u}_e u_e \phi,$$  

(26)

where $g$ is a Yukawa coupling.
As in the previous section, we consider first the subprocess $e^\pm \gamma \to e^\pm \phi$. The corresponding Feynman diagrams are the same as in Figs. 1 and 2 when one replaces $Z'$ by $\phi$. Then the amplitude squared is

$$|M_S|^2(s, t, u) = -g^2e^4 \left( \frac{u}{s} + \frac{s}{u} + \frac{2m^2_t}{su} + 2 \right).$$  \hspace{1cm} (27)

The part $-2g^2e^4$ in (27) gives a term in the total cross section decreasing as $1/s$, so that the calculations become similar to the case of the vector boson. For example, one can anticipate that the cross section for $e^+e^- \to e^+e^- \phi$ has the following form analogous to equation (8):

$$\sigma_S = 2g^2\alpha^3 m^2_\phi \ln \left( \frac{m^2_\phi}{m^2_e} \right) \ln \left( \frac{s}{m^2_e} \right).$$  \hspace{1cm} (28)

Proceeding exactly as before, we find the distribution of the boson energy:

$$\frac{d\sigma_S}{dE} = 16g^2\alpha^3 \sqrt{E^2 - m^2_\phi} \left[ 1 + \frac{2E^2 - 2E\sqrt{s} + s}{m^2_\phi - 2E\sqrt{s} + s} \right] \ln \left( \frac{s}{m^2_\phi} \right),$$  \hspace{1cm} (29)

as well as the energy spectrum of electrons coming from the boson decay $\phi \to e^+e^-$:

$$\frac{d\sigma_S}{dE_e} = \frac{2g^2\alpha^3}{m^2_\phi s^{3/2}} \left[ (\sqrt{s} - 2E_e)(5\sqrt{s} - 2E_e) + 2s \ln \left( \frac{(\sqrt{s} - 2E_e)(2E_e\sqrt{s} - m^2_\phi)}{2E_em^2_e} \right) \right] \ln \left( \frac{s}{m^2_e} \right).$$  \hspace{1cm} (30)

These spectra are plotted in figures 6 and 7 for $g = 10^{-5}$, $m_\phi = 17$ MeV and $\sqrt{s} = 10.5$ GeV. Figure 8 demonstrates dependence of the spectra on the boson mass at a fixed energy $E_e = 2$ GeV. One can observe an order of magnitude coincidence with the light vector boson production rates as well as similar behavior of the spectra.

IV. SWITCHING ON ADDITIONAL DECAY CHANNELS

So far we considered a model with only one decay mode, namely $Z' \to e^+e^-$. In principle, the boson may couple to other leptons, for example neutrinos. In this case there is a possibility that reaction (1) will be followed by the decay

$$Z' \rightarrow \nu \bar{\nu}.$$  \hspace{1cm} (31)
In a $e^+e^-$ collision experiment this channel can be observed as a missing energy. It is easy to generalize our results to include this possibility. Since the production of $Z'$ and its subsequent decay $Z' \rightarrow \nu \bar{\nu}$ are independent processes, the missing energy distribution will read

$$\frac{d\sigma}{dE_{\text{miss}}} = \text{Br}(Z' \rightarrow \nu \bar{\nu}) \frac{d\sigma}{dE}\bigg|_{E = E_{\text{miss}}},$$

(32)

where $\text{Br}(Z' \rightarrow \nu \bar{\nu})$ is the branching ratio of the decay $Z' \rightarrow \nu \bar{\nu}$ and $\frac{d\sigma}{dE}$ is given by equation (20). Therefore, the missing energy spectrum will have exactly the same shape as shown in Fig. 6, but normalized by the branching fraction.

V. CONCLUSIONS

New light neutral gauge bosons beyond the Standard Model are of interest today as a possible explanation of several anomalies recently observed in experiments. These bosons may have non-zero couplings to electrons so that the most straightforward way to probe them is in $e^+e^-$ collisions.

In this paper, we have described two processes for electron–positron collision experiments to study the production of scalar and vector bosons with masses in the range MeV to GeV. We have analyzed the reaction $e^+e^- \rightarrow e^+e^-Z'$ in detail. We have considered a model with a single $Z'$ that directly decays into a $e^+e^-$ pair. The analysis indicates that the discussed reaction may be the most favorable channel for the production of light gauge bosons at $e^+e^-$ colliders, because the corresponding cross section is larger by orders of magnitude compared to similar reactions proposed in articles. Since all the production rates are much higher, the experimental results can put stringent bounds on the parameters of $Z'$ or observe it. For example, the rates are discussed for the BaBar experiment. For an integrated luminosity of $\sim 500$ fb$^{-1}$ the production of $\sim 10^3$ $Z'$ bosons is predicted with a mass of 17 MeV and a coupling $\varepsilon = 10^{-5}$. Even for a smaller coupling $10^{-6}$ there are still $\sim 10$ events produced.

The dominant background to the considered reactions is the production of QED pairs, $e^+e^- \rightarrow e^+e^-e^+e^-$. This background can be reduced by selecting $e^+e^-$ pairs whose vertices are clearly separated from the collision point of the incoming $e^+$ and $e^-$ beams [53, 54]. For the bounds on $\varepsilon$ and $m_Z$ presently available, the lifetime of the $Z'$ in the laboratory frame
is sizable. In fact for $\varepsilon \leq 10^{-3}$, $m_Z = 17$ MeV at the BaBar energy of $\sqrt{s} = 10.5$ GeV the separation between the $Z'$ and the vertex can reach $\sim 10$ cm, which exceeds the spatial separation of the beams at the interaction point; this is illustrated in Fig. 9. The energy spectra for the produced boson and for the electrons or positrons, derived in this article, correlated with the $e^+e^-$ vertex should be helpful for designing the interaction region in a way that maximizes the sensitivity to $Z'$ events.

We have also analyzed the possibility of the boson decay into neutrino–antineutrino pairs. In this case, the boson will manifest itself as missing with a characteristic spectrum.

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FIG. 1. Leading Feynman diagrams that contribute to $e^+e^- \rightarrow e^+e^-Z'$.

FIG. 2. Leading Feynman diagrams that contribute to subprocesses $\gamma e^\pm \rightarrow e^\pm Z'$. 
FIG. 3. Feynman diagrams with an $s$-channel photon exchange that contribute to $e^+e^- \rightarrow e^+e^-Z'$. 
FIG. 4. Ratio of the cross section for $e^+e^- \rightarrow e^+e^-Z'$ to that for $e^+e^- \rightarrow \gamma Z'$ as a function of the cms energy at different values of $m_Z$: 17 MeV (the Atomki result), 50 MeV and 100 MeV. The dotted vertical line indicates the position of the BaBar cms energy.
FIG. 5. Ratio of the cross section for $e^+e^- \rightarrow e^+e^-Z'$ to that for $e^+e^- \rightarrow \gamma Z'$ as a function of the boson mass $m_Z$. The cms energy is fixed and equal to that of the BaBar experiment. The dotted vertical line indicates the position of the Atomki result ($m_Z = 17$ MeV).
FIG. 6. Energy spectrum of light vector (solid curve) and scalar (dashed curve) bosons produced in $e^+e^- \rightarrow e^+e^-Z'(\phi)$ at the BaBar energy ($\sqrt{s} = 10.5$ GeV), $m_Z = m_\phi = 17$ MeV and $\varepsilon = g = 10^{-5}$. 
\[ \sqrt{s} = 10.5 \text{ GeV (BaBar)} \]

\[ \varepsilon = g = 10^{-5} \]

\[ m_Z = m_\phi = 17 \text{ MeV} \]

FIG. 7. Energy spectrum of electrons from decays of vector (solid curve) and scalar (dashed curve) bosons produced in \( e^+e^- \rightarrow e^+e^-Z'(\phi) \) at the BaBar energy (\( \sqrt{s} = 10.5 \text{ GeV} \)), \( m_Z = 17 \text{ MeV} \) and \( \varepsilon = g = 10^{-5} \).
FIG. 8. Dependence of the energy spectra of electrons from decays of vector (solid curve) and scalar (dashed curve) bosons produced in $e^+e^- \rightarrow e^+e^- Z'(\phi)$ on the boson mass at the BaBar energy ($\sqrt{s} = 10.5$ GeV), $E_e = 2$ GeV and $\varepsilon = g = 10^{-5}$. The dotted vertical line indicates the position of the Atomki result ($m_Z = 17$ MeV).
FIG. 9. A schematic illustration of the QED background and the signal. For the QED process the $e^+e^-$ vertex is located near the collision point of the beams (left figure); for the $Z'$ decay the $e^+e^-$ vertex is displaced (right figure).