Probing light exotics from a hidden sector at $c$-$\tau$ factories with polarized electron beams

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Future $c$-$\tau$ factories are natural places to study extensions of the Standard Model of particle physics (SM) with new long-lived feebly interacting particles light enough to be produced in electron-positron collisions. We investigate prospects of these machines in exploring such extensions emphasizing the role of polarized beams in getting rid of the SM irreducible background for the missing energy signature. We illustrate this on the example of $c$-$\tau$ project in Novosibirsk, where the electron beam is designed to be polarized to achieve much higher sensitivity to hadronic resonances and $\tau$-leptons. We investigate models with hidden photons, with millicharged particles (fermions and scalars), with $Z'$ bosons and with axion-like particles. We find that the electron beam polarization of 80% significantly improves the chances to observe the signal, especially with large statistics. We outline the regions of the model parameter space which can be reached at this factory in one year and in ten years of operation according with the scientific schedule of tuning the energy of colliding beams.

I. INTRODUCTION

Electron-positron colliders are probably the best tools to explore precisely the Zoo of hadronic resonances, especially if the energy of colliding leptons (the beam energy) may be tuned at will. The latter option is intrinsic to presently operating low-energy $e^+e^-$ machines in Novosibirsk (VEPP-2000, VEPP-4M) and Beijing (BEPC II) and proposed future super $c$-$\tau$ factories in China$^1$ and Russia$^2$.

The physical programs of these projects$^{[1, 2]}$ include thorough investigations of rare processes, which rates within the SM are strongly suppressed. In a realistic case of limited statistics of electron-positron collisions these processes give a higher chance to observe new physics. Among them the most encouraging are processes with missing energy, since they may be initiated by a direct production of new light feebly interacting particles either decaying promptly into invisible mode or long-lived enough to escape from the main detector. The absence of any clear evidences for such pattern in previous experiments may be naturally explained if they are only feebly coupled to the SM particles. We refer to recent reviews$^{[3–5]}$ for detailed discussion of relevant models of new physics, searches for the corresponding light hypothetical particles at previous experiments and further prospects with new projects. As to physical motivations, in brief, one may advertise the models with new light hypothetical particles because the SM fails to explain some phenomena like dark matter and neutrino oscillations and yet the quantum corrections from heavy new particles are generally dangerous for the SM Higgs boson mass, see e.g. Refs.$^{[6–8]}$.

To be of practical use in searches for new physics, the missing energy event must contain at least one observable particle to ensure that $e^+e^-$ collision happened indeed. The missing energy may be well explained without any new physics other than production of neutrinos avoiding any detection or by the detector failure in particle registration. The first class of events forms a so-called irreducible background for the searches of new physics events. The second class of events forms a so-called reducible background, which impact on the searches can be reduced by adjusting the phase space region where the interesting events are accounted for the data analysis. The lower is the total background, the better are our chances to observe new physics events and either measure or constrain parameters of the models with new light particles.

The colliding leptons may be polarized, which is actually a favorite option of the future projects, see e.g.$^{[9]}$. In particular, the Super Charm-Tau Factory$^{[2]}$ (hereafter we call it SCTF) plans to operate with 80% polarization of the electron beam, see e.g.$^{[10, 11]}$. The polarization helps to increase the factory’s potential in investigating the Zoo of hadronic resonances in 4-7 GeV energy range, measuring the weak mixing angle and exploring the $\tau$-lepton physics. Moreover, the direction of polarization (along the beam line) can be reversed at will for any bunch of accelerated electrons, which allows one to improve the particle recognition and keep under control subtle and evasive background processes.

Remarkably, the polarization can also enhance the factory’s sensitivity to light hypothetical particles via suppression of the irreducible background, see e.g.$^{[12, 13]}$. Here we illustrate this point on the example of missing energy events

\[ e^+e^- \rightarrow \gamma + \text{missing } E. \]  (1)

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The paper is organized as follows. In Sec. II we investigate the main processes which trigger the background events for the signal of a single photon and missing energy (1). We introduce the set of optimal cuts to suppress the background and improve the physics performance for the searches of new light particles with missing energy signature (1). Sections III-VI are devoted to models with light hidden photon, millicharged fermions (fermions and scalars), $Z'$-boson and axion-like particle, respectively. In each case we describe the model, give some physical motivation and relevant references to the origin of constraints on the model parameters in the interesting regions. Then we calculate the signal cross section, evaluated the number of signal events within the chosen cuts and compare the results with those expected from the background study. Further, we outline the expected at 95% C.L. exclusion regions in the corresponding model parameter space for the machine operating at thresholds of a set of hadronic resonances. Finally, we show the regions expected to be probed with joint analysis of all the data collected over one and ten years of operation. We conclude in Sec. VII and discuss additional options which might be useful in searches for new physics exploiting the missing energy signature (1).

II. EXPECTED BACKGROUND

In the SM the colliding electron-positron pair may disappear producing the neutrino-antineutrino pair via either $s$-channel exchange of $Z$-boson or $t$-channel exchange of $W$-boson. If before disappearing a charged lepton emits a photon,

$$e^+e^−→γν\bar{ν},$$

it gives exactly the event mimicking what we are looking for (1), and hence forms the irreducible background to the search for light exotics. Fortunately, the neutrino production involves only weak interactions, and since (anti)neutrinos are (right)left-handed fermions, the chirality of initial lepton states can be adjusted to suppress the production rate of (2).

In our study we do not tune the lepton polarizations, but rather fix them in accordance with plans of SCTF, where the positron beam is unpolarized, while the electron beam polarization is 80%. The polarized electron spin is along the beam axis (the longitudinal polarization) and polarization of any electron bunch can be made either right-handed, positive, (the spin and 3-momenta directions coincide) or left-handed, negative, at will. We observe that the neutrino production (2) gets suppressed to the level negligible for the light exotic searches.

The main source of the background for the monophoton and missing energy signature (1) of light exotics is associated with non-ideality of the detector. Events with three SM particles in the final state like purely electromagnetic

$$e^+e^−→γl^+l^−, \ e^+e^−→γγγ$$

easily mimic the signal signature (1), if the lepton (electron and muon) pair or a couple of photons escapes detection. Indeed, apart from possible detector malfunctioning, there is always a chance that the lepton (photon) pair is produced in a specific part of the phase space with 3-momenta almost along the beam axis, where its detection is technically impossible.

Events of the type (3) form the reducible background, which impact on the light exotic searches can be diminished to some extent by choosing the appropriate cuts on the energy and direction of the single photon of signal event (1). To this end we use CalcHEP package [20] and simulate a set of collisions with a photon and an electron-positron (muon-antimuon) pair in the final state (3). We observe the muon contribution to be negligible as compared to that of the electron. We suppose that a produced lepton with 3-momentum forming an angle $θ$ with the beam direction can be detected and will not be missed if $|\cos θ|<0.95$, the distribution of photons over angle and energy is depicted in Fig. 1. Considering such events we find that for each angle $θ$, between the photon and beam axis the photon energy is limited from above by a certain value which depends on the angle, $E_{γ_{max}}(θ)$.

There are simply no events with more energetic photons. In what follows we constrain ourselves to the phase space region with photons obeying

$$|\cos θ_{γ}|<0.8,$$

with maximal energy inferred from the simulations we numerically approximate as a function of angle $θ$, and
FIG. 1. Distribution of photons over angle $\theta_\gamma$ and energy $E_\gamma$ in $e^+e^- \rightarrow \gamma e^+e^-$ with collision energy $\sqrt{s} = 3$ GeV and lepton angles obeying $|\cos \theta_l| > 0.95$.

present in Fig. 2. We checked that the same kinematic bounds reduce the background events from the second process in (3) as well. The maximal energy scales linearly with the collision energy, $E_{\gamma max} \propto \sqrt{s}$. The relevant kinematics of the electromagnetic processes (3) does not depend on the beam polarization.

Therefore, below, in our investigation of the signal events (1) expected in a set of SM extensions we limit the photon angle as (4) and photon energy as

$$E_\gamma(\theta_\gamma) > E_{\gamma max}(\theta_\gamma). \quad (5)$$

When the missing energy in the signal process (1) implies production of a single hypothetical particle, one can additionally suppress the background from neutrino production (2) using the fact that for processes with 2 particles in the final state the energy of signal photon $E_\gamma$ is actually fixed by kinematics. It equals

$$E_\gamma = \frac{s - m^2}{2\sqrt{s}}, \quad (6)$$

where $m$ is mass of the hypothetical particle. In practice, the electromagnetic calorimeter employed to determine the photon energy has a finite energy resolution, which in the case of SCTF is [21]

$$\sigma(E_\gamma) = E_\gamma \times \left(0.019 \times \left(\frac{1\text{ GeV}}{E_\gamma}\right)^{1/4} + 0.0033 \times \left(\frac{1\text{ GeV}}{E_\gamma}\right)^{1/2} + 0.0011 \times \left(\frac{1\text{ GeV}}{E_\gamma}\right)\right). \quad (7)$$

Therefore, to evaluate the background events we average the final photon energy with Gaussian distribution defined by the dispersion (7) and mean value (6). It enables us to greatly reduce the number of background events for the $2 \rightarrow 2$ signal processes.

Then, to estimate the sensitivity of the future $c\tau$ factory SCTF to the models with light exotic particles we adopt its planned operation schedule [19], which implies collecting a certain amount of $e^+e^-$ collisions at a given energy and then shifting to other energies. The collision energies are close to the thresholds of interesting resonances, see Tab. I. We find that with our chosen cuts

| $\sqrt{s}$, GeV | 3.097 | 3.554 | 3.686 | 3.770 | 4.170 | 4.650 |
|----------------|-------|-------|-------|-------|-------|-------|
| $L$, fb$^{-1}$ | 300   | 50    | 150   | 300   | 100   | 100   |

TABLE I. Annual operation schedule of SCTF: sets of the collision energy $\sqrt{s}$ and the corresponding integrated luminosity $L$.

(4) and (5), each of the six operation stages of Tab. I are background-free for our study: there are no contributions from both reducible (3) and irreducible (2) backgrounds for the statistics of electron-positron collisions expected to be collected at SCTF with 80% polarized electrons, see Tab. II. Hence, to estimate the sensitivity of the $c\tau$ factory to the new light particles in each model to be achieved at each of the operational stages, below we calculate the production of the single photon and corresponding light particles in electron-positron scattering and tune the model parameters to obtain 3 signal events (1). Within the Poisson statistics it implies that models with larger coupling constants will be excluded at 95% C.L. if no events are observed.
Moreover, after one year of operation in accordance with the plan of Tab. I, we can place stronger bounds on the models with light exotics performing a joint analysis of data from all six stages. The operation stages are independent, and so for each model we simply sum up the events from all the stages. However, the number of expected background events exceeds one in this analysis. We make use of the Feldman–Cousins approach [22, 23] to assess the prospects in testing the new models. In case of observed events with expected background events from the background, the number of signal events $S$ can be constrained at the $\alpha$ C.L. from the Poisson distribution as

$$1 - \alpha = \frac{e^{-B-S} \sum_{i=0}^{n} \frac{(B+S)^i}{i!}}{e^{-B} \sum_{i=0}^{n} \frac{B^i}{i!}}.$$  

(8)

Note that with $B = 0$ eq. (8) gives 3 for no events, $n = 0$, and $\alpha = 0.95$, as we use to get the bounds at 95% C.L. in the background-free case. Therefore, to evaluate the expected 95% C.L.-limit on the number of signal events to be obtained with small but non-zero background, $B \geq 1$, for several numbers of observed events $n$ we calculate the value of signal $S = S(n)$ from eq. (8) and then average them with the Poisson distribution for $n$ at zero signal as follows

$$\bar{S} = e^{-B} \sum_{n=0}^{\infty} \frac{S(n) B^n}{n!}.$$  

(9)

So, for each of the models we tune the model parameters to get the number of signal events equal $\bar{S}$: the models with stronger couplings will be excluded at 95% C.L. after one year of operation of SCFT following the schedule of Tab. I.

Finally, we estimate the reach of SCFT after 10 years of the operation with total integrated luminosity of $10 \text{ab}^{-1}$. To this end we sum separately signal and background events following the annual plan of Tab. I and apply eqs. (8), (9) in the models where the number of expected background events does not exceed ten. These are all the cases where the signal processes are $2 \rightarrow 2$. In the models with more particles in the final states the background is higher, the number of expected background events $B$ significantly exceeds ten, which one can realize from the estimates of the background events for one year of operation shown in Tab. II. Then we accept the Gaussian statistics, tune the parameters of the models with light hypothetical particles to obtain $S$ signal events, such that

$$\frac{S}{\sqrt{B}} = 2,$$

and say that all the models with larger couplings will be ruled out at 95% C.L.

### III. HIDDEN PHOTON

The new physics we are looking for may be located in a hidden sector, which is not connected with known physics, that is the SM sector, via known SM gauge interactions. However, some connection apart of via gravity still may exist, and for light feebly interacting particles from the hidden sector the most promising (as concerns direct searches) are those provided by portals, which are renormalizable dimension four interaction terms involving fields from the both sectors. In particular, so-called vector portal describes interaction between the SM high charge vector field $A'_\mu$, and a hidden vector field $A'_\mu$, [24]

$$\mathcal{L}_{\text{int}} \propto \varepsilon \times (\partial_\mu A'_\nu - \partial_\nu A'_\mu) (\partial_\mu A'_\nu - \partial_\nu A'_\mu).$$

with dimensionless parameter $\varepsilon \ll 1$. It mixes kinetic terms of the two vectors and is invariant with respect to Abelian gauge transformations in both sectors, $A'_\mu \rightarrow A'_\mu + \partial_\mu \alpha'$. At low energies relevant for $c\tau$ factories this mixing yields (upon field redefinition, see e.g. [25]) an effective interaction between the new light vector and the SM electromagnetic current. The interesting coupling is that to electrons and positrons,

$$\mathcal{L} = \varepsilon e A'_\mu \bar{e} \gamma^\mu e,$$

(10)

where $e$ is the electric charge of the positron. This coupling produces production of $A'_\mu$ in $e^+e^-$ scattering. Therefore, if $\varepsilon \ll 1$ and $A'$ is either stable or decays mostly into invisible particles from the hidden sector, one can suggest the signal (1) as a signature of this light vector.

In our study we adopt a minimal phenomenological model, where the light vector is characterized by its mass $m_{A'}$ and interaction (10), and we neglect the induced by (10) decay of $A'$ into SM fermions. In literature a light vector with tiny coupling is usually dubbed as paraphoton, hidden or dark photon [26]. It is predicted in SM extensions and may be related to some unexplained phenomena, including the dark matter [27], see Refs. [28, 29] for recent reviews. More complicated signatures than (1) can be advertised in particular models, see e.g. Ref. [30] for a recent investigation of SCTF prospects.

One can examine the production of a hidden photon associated with a single photon. It is the $2 \rightarrow 2$ process, see Fig. 3, and at each direction of the outgoing photon parametrized by the polar angle $\theta$, the photon energy is

| $\sqrt{s}$, GeV | 3.097 | 3.554 | 3.686 | 3.770 | 4.170 | 4.650 |
|-----------------|------|------|------|------|------|------|
| 2 particle f.s.  | 0.097 | 0.02 | 0.066 | 0.14 | 0.054 | 0.066 |
| 3 particle f.s.  | 2.8  | 0.63 | 2.1  | 4.4  | 1.8  | 2.3  |
fixed by the angle and the collision energy as (6). The corresponding differential cross section in the limit of zero electron mass reads
\[ \frac{d\sigma}{d\cos\theta_\gamma} = \frac{2\pi\varepsilon^2\alpha^2}{s} \left( 1 - \frac{m^2_{A'}}{s} \right) \frac{1 + \cos^2\theta_\gamma + \frac{4\varepsilon m^2_{A'}}{(s-m^2_{A'})^2}}{(1 - \cos^2\theta_\gamma)}. \]

(11)

Expectedly, the cross section of this pure electromagnetic process does not depend on the polarization of initial leptons.

Imposing the cut on photon angle (4) we integrate (11) over \( \theta_\gamma \) and obtain the number of signal events. Then, by setting it equal 3 we get the 95% C.L. exclusion limits outlined in Fig. 4 for a set of collision energies and integrated luminosities consistent with the working schedule of SCTF presented in Tab. I. Note that the limits in Fig. 4 become stronger with growing mass, which is anticipated from the term with denominator \( (s-m^2_{A'}) \) in (11), and corresponds to the almost resonant production, \( e^+e^- \rightarrow A' \), near the threshold. Technically, it is originated from the singularity in the \( t \)-channel fermion propagator. However, our cuts (4) and (5) exclude that kinematic region from the analysis, and so the maximum sensitivity is achieved at some mass near but not at the threshold.

One can estimate the entire prospects of probing the models with a light hidden photon at SCTF after one and ten years of operation in accordance with the schedule of Tab. I by making use of the procedure specified in Sec. II. The results are depicted in Fig. 5 together with existing experimental constraints and prospects of ongoing searches. The SCTF can explore a considerable region inaccessible to the ongoing searches. To emphasize the importance of searches for missing energy and monophoton signature (1) at SCTF we consider their value in a model where the hidden photon decays into visible modes (e.g. \( e^+e^- \)) as well, say in 50% cases. We call it as half-hidden (HH) case in what follows. Then searches for the visible decay modes are relevant as well as searches for the invisible mode. In this model our expected signal with missing energy is 2 times lower, therefore the upper limits on \( \varepsilon \) must be shifted by a factor \( \sqrt{2} \). Likewise the lower bounds on \( \varepsilon \) for the visible modes must be shifted by almost the same factor. The corrected in this way constraints from searches for the visible mode and the expected limits from future searches at SCTF for the invisible mode are presented in Fig. 6. One concludes that searches at SCTF for the invisible modes are competitive with ongoing searches for the visible modes, if the visible and invisible decay rates of the hidden photon are of the same order.

Finally, we perform calculations of the signal rate with the same angular and energy cuts and for the same beam energies as were done for a \( c-\tau \) factory in Ref. [14], where the colliding beams are considered to be unpolarized. The results are in agreement, since the signal does not depend on the polarization. As to the expected limits, they are the same for the small statistics, when the chosen
FIG. 6. The regions above the black bold and dashed lines will be probed in the HH case (see the main text for details) at 95% C.L. with $e^+e^- \rightarrow \gamma A'$ after one and ten years of operation, respectively. The existing limits (colored and outlined) and expected reaches of ongoing experiments (colored) on the visible mode are taken from Ref. [5].

Energy and angular cuts are enough to keep the number of expected background events (3) below one for the unpolarized beams. As we explained in Sec. II, exploiting polarized beams provides an additional tool to mitigate the background, and so for higher statistics our expected limits are stronger than the similar ones in [14], especially for ten years of operation.

IV. MILLISECOND CHARGED PARTICLES

Since quantization of the hypercharge of the SM particles may seem puzzling one can envisage hypothetical particles with arbitrary small hypercharge [32]. Consequently, at low energies there may be particles $\chi$ with arbitrary small electric charge, generically called millicharged particles (MCPs). In the case of fermions, their coupling to SM photon $A_{\mu}$ is

$$\mathcal{L} = \varepsilon e A_{\mu} \bar{\chi} \gamma^\mu \chi,$$

where the charge is written in terms of the positron electric charge $e$, and we assume $\varepsilon \ll 1$. It is worth noting that in the hidden sector scenario with vector portal described in Sec. III, any particles from the hidden sector charged under the Abelian group associated with the hidden photon $A'$ become MCPs upon proper redefinition of the vector fields $A_{\mu}$ and $A'_{\mu}$.

Interaction (12) gives rise to the MCP production associated with the photon, see the corresponding Feynman diagrams in Fig. 7. The outgoing MCPs with small charge cannot be observed (see however Ref. [33] for the special case of very slow MCPs), and so one can use the signature (1) to explore the models with MCPs. The signal process is $2 \rightarrow 3$, and hence both energy and angle of the measured photons are independent parameters. The corresponding differential production cross section can be written as [15]

$$\frac{d\sigma}{dE_{\gamma}d\cos \theta_{\gamma}} = \frac{8\varepsilon^2 \alpha^3 (1 + 2m_{\chi}^2/s_{\gamma}) \beta_{\chi}}{3sE_{\gamma}(1 - \cos^2 \theta_{\gamma})} \times \left[ 1 + \frac{E^2}{s_{\gamma}} (1 + \cos^2 \theta_{\gamma}) \right],$$

where $s_{\gamma} \equiv s - 2\sqrt{s}E_{\gamma}$, $\beta_{\chi} \equiv \sqrt{1 - 4m_{\chi}^2/s_{\gamma}}$. Integrating it over the photon energy and angle within the chosen cuts (4) and (5), one arrives at the expected at 95% C.L. limits presented in Fig. 8. The described in Sec. II combined analysis of all the data collected at the operation stages from Tab. I yields limits expected to be obtained (if no signal events are observed) after one and ten years of operation of SCTF. We outline them in Fig. 9 along with established experimental bounds and anticipated reaches of ongoing searches.

FIG. 7. The Feynman diagrams for the production of $\chi\bar{\chi}$ and a photon.

FIG. 8. The regions above the lines will be probed at 95% C.L. with $e^+e^- \rightarrow \gamma\chi\bar{\chi}$ in the particular operational modes.
To complete the task we consider the models with MCP mass. The models with light MCPs. Likewise, it well may increase the sensitivity in case of the longitudinally polarized electron beam of SCTF.

It is worth noting that with three particles in the final state the limiting curves in Figs. 8 and 9 rise up noticeably with MCP mass. The models with MCP masses close to the threshold, \( m_\chi = \sqrt{s}/2 \), can be probed by tracing the nonrelativistic MCPs along the lines of Ref. [33].

To complete the task we consider the models with scalars as particles carrying a small electric charge. We obtain for the differential cross section of the scalar MCPs production associated with a single photon the following expression,

\[
\frac{d\sigma}{dE_\gamma d\cos \theta_\gamma} = \frac{2\varepsilon^2 \alpha^2 \beta^3_\chi}{3sE_\gamma(1 - \cos^2 \theta_\gamma)} \times \left[ 1 + \frac{E^2_\gamma}{s} (1 + \cos^2 \theta_\gamma) \right],
\]  

(14)

where we use the same notations as in eq. (13). In the limit of small MCP masses the results differ by the number of final states, that is four. In Fig. 10 we depict the limits on \( \varepsilon \) expected to be reached after one and ten years of operation in accordance with the SCTF annual program of Tab. I.

V. \( Z' \) BOSON

There are SM extensions with a light exotic vector, which couples differently to right-handed and left-handed SM fermions, see e.g. Refs. [35–37]. This hypothetical particle is generically named as the \( Z' \) boson and its interaction with charged leptons can be parametrized with vector \( g_\nu \) and axial \( g_A \) couplings as

\[
\mathcal{L} = Z'_\mu \bar{e}_\mu^{\nu} (g_\nu - g_A \gamma_5) e. 
\]  

(15)

Then lepton scattering may produce \( Z' \) boson accompanied by a photon, which signature is (1) if the \( Z' \) boson is stable or decays mostly in an invisible mode. Since the strength of \( Z' \) coupling to SM fermions (15) depends on their chirality, so the production cross section does. With the unpolarized positron beam and electron beam polarization \( \varepsilon \in [-1; 1] \) one evaluates the differential cross section \( Z' \) as

\[
\frac{d\sigma}{d\cos \theta_\gamma} = \frac{\alpha}{2s} \times \left( g_A^2 + g_\nu^2 - 2\varepsilon g_A g_\nu \right) \times \left( 1 - \frac{m^2_{Z'}}{s} \right) \frac{1 + \cos^2 \theta_\gamma + \frac{4s m^2_{Z'}}{(s - m^2_{Z'} )^2}}{(1 - \cos^2 \theta_\gamma)}.
\]  

(16)

It is 2 \( \rightarrow \) 2 scattering, see Fig. 3, hence the photon energy \( E_\gamma \) is fixed by the collision energy at any angle \( \theta_\gamma \) as

FIG. 9. The regions above the black bold and dashed lines will be excluded at 95% C.L. with \( e^+e^- \rightarrow \gamma \bar{\chi}\chi \) after one and ten years of operation. The existing limits (colored and outlined) are taken from Ref. [5], prospects of MAPP-mCP and MilliQan (at the present stage of LHC operation, i.e. Run-3) are from Ref. [34], their prospects at LHC operation in high luminosity mode (HL-LHC) and prospects of FORMOSA are copied from Ref. [5].

FIG. 10. The regions above the black bold and dashed lines will be excluded at 95% C.L. with \( e^+e^- \rightarrow \gamma \bar{\chi}\chi \) with scalar MCP after one and ten years of operation.
Formula (16) transforms to (11) with unpolarized beams, $\epsilon = 0$, and also in the limit of pure vector-like coupling, $g_A \to 0$, where any dependence on the beam polarization disappears. The same is true for pure axial coupling. Then, if $Z'$ couples only to left-handed leptons like the SM $Z$-boson, we have $g_A = g_V$ and the cross section vanishes for the fully positively polarized electron beam, $\epsilon \to 1$. This illustrates our preference for the beam polarization, which guarantees the suppression of the irreducible background expected from the neutrino production (2).

Integrating the differential cross section (16) within the angular cuts (4) we evaluate the reach of the $c\tau$ factory to the $Z'$ boson couplings, which we show in Figs. 11–13 for a set of models with various relations between $g_V$ and $g_A$. Similar to the case of the hidden photon in Sec. III, the strongest sensitivity is exhibited to the model with mass of $Z'$ close to the threshold of nearly resonant production $e^+e^- \to Z'$.

FIG. 11. The parameter regions for models with $g_V = 0$ or $g_A = 0$ to be probed at 95% C.L. with $e^+e^- \to \gamma Z'$ and any polarization $\epsilon$ of the electron beam. The limits match those for the hidden photon presented in Fig. 4 upon replacement $g = \varepsilon e$. Recall that the irreducible background (2) gets suppressed with positive polarization, $\epsilon > 0$.

The signal dependence on the electron beam polarization may be exploited to reveal the nature of the hypothetical particle if the monophoton with missing energy events (1) are observed. Indeed, flipping the beam polarization will change the signal rate unless $Z'$ is pure vector or pure axial. In all other cases it couples differently to left-handed and right-handed SM fermions, and so the signal rate changes with reversing the electron beam polarization. This reversing also changes the rate of neutrino production and hence increases the irreducible background (2). Naturally, the sensitivity of this mode is weaker, see below. However, it is worth noticing that the signal rate also depends on the polarization and relative sign of $g_A$ and $g_V$, and hence the signal can be larger for negative $\epsilon$ in a subset of models.

Generically, one can determine both $g_A$ and $g_V$ from the combined analysis of the signal events obtained with electron beam polarization of both signs.

The best sensitivity is exhibited by the $c\tau$ factory performing the joint analysis of data collected over all the operation stages, as we explained in Sec. II. The constraints, expected after one and ten operation years in accord with the plan depicted in Tab. I, are outlined in Figs. 14 and 15 for a set of models and positive and nega-
tive polarization modes. Recall that for purely vector and for purely axial $Z'$ coupling the sensitivity coincides with that for the hidden photon outlined in Fig. 5. The signal rates are the same for models with opposite signs of the product $g_A g_V$ at SCTF operating with electron beams of opposite polarizations. However, the background rate is 1.5 times higher for the electron beam with negative longitudinal polarization, $\epsilon = -0.8$, and so the required number of signal events, according to (8), is 1.15 times bigger at high statistics, when the numbers of expected background events exceed one. It gives a 7% weaker sensitivity in this case (read the captions of Figs. 14 and 15).

The searches at SCTF look very promising, and we further illustrate their power in Figs. 16 and 17 with the HH model case introduced in Sec. III.

At a $c-\tau$ factory operating with unpolarized lepton beams, the signal rate may be higher or lower as compared to that at SCTF, depending on the relative sign of the product $g_A g_V$ entering eq. (16). The background is higher than that of SCTF with positive polarization $\epsilon = 0.8$ and lower than that with negative polarization $\epsilon = -0.8$. Therefore, while at small statistics (when the searches are effectively background-free) the factory with unpolarized beams may exhibit higher sensitivity to models with a specific sign of $g_A g_V$ as compared to the polarized case, with growing statistics the SCTF becomes superior in testing the model with light $Z'$ for all values of the coupling constants.
VI. NEUTRAL (PSEUDO)SCALAR

While only one spin-zero fundamental particle, the SM Higgs boson, has been discovered so far, the nature may hide some other scalars and/or pseudoscalars. They can originate from the extended SM Higgs sector, high energy grand unification theory, scalar potential of a hidden sector, etc. They may be naturally light, with the mass term protected from the quantum corrections by symmetry arguments, e.g. like (pseudo-)Goldstone bosons, the QCD axion providing the well-known example. Alternatively, they may be light just because the entire hidden sector is light. Within the portal paradigm, a scalar \( s \), singlet with respect to the SM gauge group, can couple to the visible sector via a so-called scalar portal: dimension-3 and dimension-4 renormalizable interaction terms with the SM weak Higgs doublet. At low energies this portal coupling induces the non-renormalizable interactions with photons, see e.g. \[39\]

\[
\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma} s F_{\mu\nu} F^{\mu\nu}, \tag{17}
\]

where parameter \( g_{a\gamma\gamma}^{-1} \) has dimension of mass. Similar coupling is predicted for light pseudoscalar \( a \) or axion-like particles (ALPs) including the QCD axion,

\[
\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} F^{\mu\nu} \tag{18}
\]

where \( \tilde{F}^{\mu\nu} \) is the tensor dual to \( F^{\mu\nu} \).

In \( e^+e^- \) collisions the non-renormalizable couplings (17) and (18) produce via \( s \)-channel photon exchange the (pseudo)scalar associated with a photon. If the new particle is stable or decays predominantly into invisible particles (e.g. from the hidden sector), it exhibits the signature (1) to be exploited in searches for these particles. As far as these searches are concerned, there are no differences between the scalar and pseudoscalar particle cases, and below we perform the calculations in the ALP case, for concreteness. The same formulas are applicable in the scalar case as well.

The process under study is \( 2 \rightarrow 2 \), see the diagram in Fig. 18, so at a given angle \( \theta_\gamma \) of the outgoing photon its energy \( E_\gamma \) is fixed as (6). The corresponding differential cross section reads \[40\]

\[
\frac{d\sigma}{d\cos\theta_\gamma} = 4\pi^2 \alpha g_{a\gamma\gamma}^2 \left( 1 - \frac{m_a^2}{s} \right)^3 \left( 1 + \cos^2\theta_\gamma \right). \tag{19}
\]

One observes absence of any amplification of (19) in the limit \( m_a^2 \rightarrow s \) contrary to the vector (11) and pseudovector (16) cases: the resonant (pseudo)scalar production, \( e^+e^- \rightarrow a \) cannot proceed through the \( s \)-channel exchange of the spin-1 particle, photon. There is no dependence on the electron polarization, similar to other processes considered in Secs. III and IV.

We integrate eq. (19) over the photon angle \( \theta_\gamma \) within the adopted cuts (4) and requiring 3 events obtain the expected sensitivity at 95% C.L. The results are presented in Fig. 19. The limiting lines are flat at small masses, and they steadily grow up with the mass approaching the reaction threshold.

The data, collected over one and ten years of operation allows one to place stronger constraints on the light axion coupling to photons. Performing the calculations outlined in Sec. II, we obtain the expected limits presented in Fig. 20 (see Fig. 21 for HH case) along with current bounds and constraints expected from the ongoing experiments.

The same sensitivity as in Figs. 19 and 20 will be exhibited by SCTF to coupling (17) of a light singlet scalar and photons.

Note in passing that since the signal differential cross section (19) does not depend on the beam polarization, the signal rate must be the same for a \( \tau+\tau \) factory with unpolarized beams. The usage of polarized beams enables one to additionally suppress the background. Therefore, similar to the case of a hidden photon described in Sec. III, for the unpolarized beams we would obtain somewhat lower sensitivity to the axion coupling, especially for the joint analysis of ten-years statistics.
FIG. 19. The regions above the lines will be tested at 95% C.L. with $e^+e^- \rightarrow \gamma a$.

FIG. 20. Bounds on the axion coupling constant to photons $g_{a\gamma\gamma}$. The regions above the black bold and dashed lines will be explored at 95% C.L. with $e^+e^- \rightarrow \gamma a$ after one and ten years of operation, correspondingly. The existing limits (colored and outlined) and expected reaches of FASER, Belle2 ($3\gamma$) and Accelerator experiments (colored) are taken from Ref. [41]. Limits from Belle and LEP are taken from Ref. [42].

FIG. 21. Bounds on the axion coupling constant to photons $g_{a\gamma\gamma}$ in the HH model. The regions above the black bold and dashed lines will be explored at 95% C.L. with $e^+e^- \rightarrow \gamma a$ after one and ten years of operation, correspondingly. The existing limits (colored and outlined) and expected reaches of FASER, Belle2 ($3\gamma$) and Accelerator experiments (colored) are taken from Ref. [41]. Limits from Belle and LEP are taken from Ref. [42]. Limits from Belle and LEP are taken from Ref. [42].

VII. DISCUSSION

To summarize, we estimate the sensitivity of the proposed super $e\tau$ factory SCTF [2, 10, 19] to physical parameters of a set of models with hypothetical light particles whose production in $e^+e^-$ collisions can be associated with a single photon and missing energy events. The electron beam in the project of SCTF will be polarized, which mitigates the background and gives better chances to probe the models with smaller couplings as compared to the factory exploiting unpolarized beams. We find the SCTF can explore models with one-two orders of magnitude smaller couplings that the previous experiments. Depending on the model and parts of the model parameter space the SCTF prospects in searches for the new particles are either complementary to those of the project under construction or more promising. Note, there are other signatures which may be promising for testing at SCTF particular models with light feebly interacting particles. Our study reveals that even in models with presence of noticeable visible decay modes of the light exotic particles, searches for the invisible channels at SCTF are still competitive even with the ongoing searches for the visible modes.

The reversibility of the electron beam polarization can be effectively used to reveal the nature of the hypothetical particles. In most cases the sensitivity to the new particle couplings are almost mass-independent for sufficiently light particles. If the signal is observed, the mass of new particles can be measured for the moderate range of masses with accurate determination of the photon energy. However, the resolution of the electromagnetic calorimeter is always finite, and for light particles it will allow one to place only an upper limit on mass of the hypothetical particle possibly responsible for the signal events. A specific investigation can yield a lower bound on the mass of some hypothetical candidates (or discover its nature and measure its mass): the very light millicharged particles start to interact inside the detector material, see e.g. [43], light hidden photons oscillate...
to visible photons, see e.g. [44], etc.

It is worth mentioning that while we present our numerical estimates for a particular project of the super $e$-$\tau$ factory developing in BINP (Novosibirsk), the similar study can be performed for the project of super $\tau$-$e$ factory in China. A brief look through the literature shows that at the present stage of development of both projects the main ingredients essential to the present study (beam polarization, beam energy range, calorimeter energy resolution, etc) are very similar, and hence similar chances are observed to observe the new exotic particles.

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