Front. Phys. 11(5), 111403 (2016)
DOI 10.1007/s11467-016-0541-1

REVIEW ARTICLE

Light dark sector searches at low-energy high-luminosity e^+e^- colliders

Peng-Fei Yin[1,†], **Shou-Hua Zhu**[2,3,4]

[1] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

[2] *Institute of Theoretical Physics & State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

[3] *Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*

[4] *Center for High Energy Physics, Peking University, Beijing 100871, China*

Corresponding author. E-mail: †*yinpf@ihep.ac.cn*

Received October 2, 2015; accepted November 27, 2015

Although the standard model (SM) is extremely successful, there are various motivations for considering the physics beyond the SM. For example, the SM includes neither dark energy nor dark matter, which has been confirmed through astrophysical observations. Examination of the dark sector, which contains new, light, weakly-coupled particles at the GeV scale or lower, is well motivated by both theory and dark-matter detection experiments. In this mini-review, we focus on one particular case in which these new particles can interact with SM particles through a kinematic mixing term between $U(1)$ gauge bosons. The magnitude of the mixing can be parameterized by a parameter ϵ. Following a brief overview of the relevant motivations and the constraints determined from numerous experiments, we focus on the light dark sector phenomenology at low-energy high-luminosity e^+e^- colliders. These colliders are ideal for probing the new light particles, because of their large production rates and capacity for precise resonance reconstruction. Depending on the details of a given model, the typical observed signatures may also contain multi lepton pairs, displaced vertices, and/or missing energy. Through the use of extremely large data samples from existing experiments, such as KLOE, CLEO, *BABAR*, Belle, and BESIII, the $\epsilon < 10^{-4}$–10^{-3} constraint can be obtained. Obviously, future experiments with larger datasets will provide opportunities for the discovery of new particles in the dark sector, or for stricter upper limits on ϵ. Once the light dark sector is confirmed, the particle physics landscape will be changed significantly.

Keywords dark photon, electron-positron collider, dark matter

PACS numbers 12.16.-i, 13.66.Hk, 95.35.+d

Contents

*Special Topic: Potential Physics at a Super τ-Charm Factory (Ed. Hai-Bo Li).

Frontiers of Physics

1 Introduction

Since the 1960s, the standard model (SM) has achieved great success. For example, one recent remarkable achievement is the discovery of the Higgs boson in 2012. However, many unresolved fundamental mysteries, such as the hierarchy problem, the unification problem, the origins of mass, flavor structure, and CP violation, and the nature of matter-antimatter asymmetry, dark energy and dark matter (DM), suggest the existence of new physics beyond the standard model (BSM) (see, e.g., [1–3]). Thus, searching for the BSM is a very important goal of modern physics.

There are three basic frontiers in particle physics, namely, the energy, intensity, and cosmic frontiers. A primary goal of the Large Hadron Collider (LHC) and other "energy frontier" experiments is exploration of the next energy scale above the electroweak symmetry breaking scale. Such experiments can be used to search for new particles predicted by the BSM with masses at or above several hundreds of GeV, which are directly produced by high-energy collisions. High-precision measurements of W, Z, and Higgs bosons, and top quarks, may also reveal the BSM at high energies. Terrestrial and satellite "cosmic frontier" experiments probe DM particle signatures, which are often assumed to indicate kinds of weakly interacting massive particles in the BSM. "Intensity frontier" experiments can be complementary to the other two kinds of experiments. Through the use of high-precision measurements with extremely large data samples, such research can indirectly facilitate exploration of a higher energy scale than that of high-energy colliders in some BSM scenarios (see, e.g., [4]). On the other hand, "intensity frontier" experiments can test the low-energy behavior of the BSM, even if such scenario would be firstly discovered in the other frontiers.

A well-motivated BSM scenario is the so-called "dark sector", which has a rich structure (see, e.g., [5]). Unlike conventional BSM scenarios, where new particles are often set at high energy scales, the dark sector may contain a series of new, light, weakly interacting particles. As illustrated in Fig. 1, some "portals" permitted by the SM symmetries can connect the dark sector to the SM, i.e., the vector, axion, Higgs, and neutrino portals. These portals are often described using various operators, including mixing terms between the SM particles and new light particles. In this mini-review, we focus on searches for the vector portal. In this scenario, the dark-sector particles can interact with the SM particles via a new, massive, spin-1 gauge boson named a "dark photon" A'[1]. The dark sector containing the light A' and other new particles has a rich and interesting phenomenology in the energy, cosmic, and intensity frontiers [4, 5].

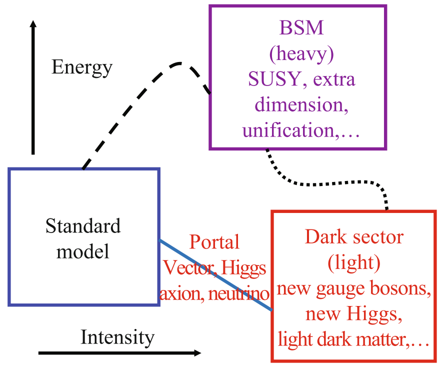

Fig. 1 The relation between the SM, BSM and light dark sectors considered in this mini-review.

The probing of new, light, weakly coupled particles at low-energy e^+e^- colliders has several particular advantages [6–12]. First, the A' production rate at a low-energy e^+e^- collider is large, as its production cross section is inversely proportional to the center-of-mass energy E_{cm}. Second, the high luminosity is ideal for collecting events from rare processes. Third, the environment of an e^+e^- collider is clean and well controlled. It is possible to reconstruct the masses of new light particles from the di-lepton invariant mass distribution. As no significant signals have been found in the extremely large datasets collected to date, the findings of low-energy high-luminosity e^+e^- collider experiments such as KLOE, CLEO, *BABAR*, Belle, and BESIII have set stringent upper limits on the mixing parameter between the photon and A', labeled ϵ, at a level of 10^{-4}–10^{-3}.

This review is organized as follows. In Section 2, we introduce the dark-sector model, in which new light particles couple to SM particles through a kinematic mixing term. In Section 3, we summarize the hints of the dark sector obtained from DM search experiments. In Section 4, we briefly discuss searches for A' with mass $m_{A'} > 1$ MeV, which involve low-energy tests, fixed-target experiments, and high-energy colliders. In Section 5, we discuss the production and decay processes of dark bosons at a low-energy e^+e^- collider. In Section 6, we introduce some current A' search results obtained at ϕ, B, and charm factories. The discussion and conclusions are given in the final section.

2 Model with kinematic mixing

A new Abelian gauge group $U(1)_D$ present in the dark

[1] This boson is also referred to as the heavy photon, hidden photon, or U boson (denoted by γ', or U) in the literature.

sector would mix with the SM $U(1)_Y$ [13]. This kinematic mixing term can be expressed as

$$\mathcal{L}_{mix} = \frac{1}{2}\epsilon' B_{\mu\nu}F'^{\mu\nu} = \frac{1}{2}\epsilon'(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu})F'^{\mu\nu}, \quad (2.1)$$

where ϵ' is a mixing coefficient, θ_W is the Weinberg angle, and $B_{\mu\nu}$, $F_{\mu\nu}$, $Z_{\mu\nu}$, and $F'_{\mu\nu}$ are the field strengths of the hypercharge field, photon, Z boson, and A', respectively. $\mathcal{L}_{mix}$ can be removed through a field redefinition of the photon and A'. These field shifts induce an order-ϵ coupling between A' and the electromagnetic current J^μ_{em} such that

$$\mathcal{L} = \epsilon' \cos\theta_W A'_\mu J^\mu_{em}. \quad (2.2)$$

Precise quantum electrodynamic (QED) measurements require an extremely small $\epsilon = \epsilon' \cos\theta_W$. If $U(1)_Y$ is embedded in a Grand Unified Theory (GUT) group at some high-energy scale, $\mathcal{L}_{mix}$ may be absent. At low energies below the scale of GUT breaking, the loop effects of particles charged under both SM and dark sectors can radioactively generate the mixing [14]. The heavy fields running in the loop can be removed through integration, and the kinematic mixing can then be expressed as [9, 15]

$$\epsilon' \sim \frac{g_Y g_D}{16\pi^2} \log\left(\frac{M}{M'}\right)^2, \quad (2.3)$$

where M and M' are the heavy-multiple component masses and g_D and g_Y are $U(1)$ couplings in the dark and SM sectors, respectively. If the mass ratio M/M' and gauge coupling g_D are assumed to have reasonable values, a small $\epsilon \sim 10^{-6}$–10^{-2} can be generated naturally. If $U(1)_D$ is also embedded in some GUT groups, ϵ is suppressed significantly as a result of higher-order effects [14]. Furthermore, an extremely small ϵ can be achieved in string theory [16, 17].

There may also exist other new particles in the dark sector. For example, a dark Higgs charged under $U(1)_D$ is required in order to generate the A' mass term $\frac{1}{2}m^2_{A'}A'^2$. In the supersymmetry (SUSY) scenario, the D-term mixing between $U(1)_D$ and $U(1)_Y$ induced by the kinematic mixing leads to an effective Fayet-Iliopoulos term with a scale of [15, 18]

$$\xi \sim \frac{1}{4}\epsilon' g_Y \cos 2\beta\, v^2. \quad (2.4)$$

Following $U(1)_D$ symmetry breaking, this term naturally generates a dark-particle mass scale of

$$g_D\xi \sim \text{GeV}^2, \quad (2.5)$$

for $\epsilon \sim 10^{-4}$–10^{-3}.

More generally, the dark-sector gauge structure may contain some non-Abelian groups [14, 15]. In this case, there are extra charged and neutral gauge bosons in the dark sector. The Higgs bosons under both $U(1)$ and non-Abelian groups then make all the gauge bosons mix with each other. Therefore, the extra gauge bosons can also obtain masses of $\sim$ GeV and $\sim \mathcal{O}(10^{-3})$ couplings to the electromagnetic current.

3 Hints of light dark sector from dark-matter search experiments

Although the existence of DM has been confirmed via numerous past astrophysical and cosmological observations, the fundamental nature of DM particles remains unclear. DM detection experiments, including indirect, direct, and collider detections, attempt to discover the non-gravitational interactions between DM and SM particles. To date, the majority of these experiments have not detected DM signatures, but anomalies that may have been induced by DM particles have been reported in some cases. Interestingly, these results listed below provide strong support for the dark-sector scenario (see, e.g., [5, 19]).

1) In 2008, the PAMELA satellite-based telescope reported a cosmic-ray positron excess at energies of $\mathcal{O}(1)$–$\mathcal{O}(10^2)$ GeV with high significance [20]. This finding has since been confirmed by many other experiments, such as ATIC [21], Fermi [22], and AMS02 [23], and can be interpreted as being due to local exotic electron/positron sources. If these anomalous positrons are produced by DM annihilations in the Galaxy, two important points would be clarified. First, in order to explain these data, the DM annihilation cross section would be required to be $\sim 10^2$–10^3 times larger than that required by the thermal freeze-out mechanism $\sim 3 \times 10^{-26}$ $\text{cm}^3\cdot\text{s}^{-1}$. Second, the PAMELA antiproton measurement would be consistent with the astrophysical prediction at energies of $\mathcal{O}(10)$ GeV [24][2)]. This feature sets stringent constraints on the DM annihilation channels to quarks and gauge bosons. These two problems can be elegantly solved in the dark-sector scenario [26, 27]. According to that model, DM particles with masses of $\sim$ TeV annihilate to yield a pair of light bosons, which subsequently decay to charged leptons $\chi\bar{\chi} \to A'A' \to l\bar{l}l\bar{l}$. Thus, com-

[2)] The latest AMS02 antiproton measurement seems to leave room for DM products above ~ 100 GeV [25]. However, as the uncertainties arising from the antiproton production and propagation processes remain large, further precise data at high energies are required.

pared with the ordinary annihilation process in the early Universe, the long-range attractive force between incoming DM particles mediated by light bosons significantly enhances the DM annihilation cross section at low velocities in the Galaxy. This is the so-called "Sommerfeld enhancement." If the mass of new boson is smaller than the antiproton mass, the production of antiprotons is simply forbidden as a result of the associated kinematics.

2) The majority of direct-detection experiments have not found DM signatures. Instead, they have simply set strong bounds on the DM-nucleus scattering cross section. However, some experiments, such as DAMA [28], CoGeNT [29], and CRESSTII [30], have reported exotic signatures. For example, researchers at the DAMA scintillator experiment have reported observation of an annual modulation signal since the late 1990s. Although the DAMA apparatus can not distinguish the DM signal from the background exactly, the phase and amplitude of the modulation data are well explained as modulation of the DM-nuclei scattering rate, which is caused by the Earth's rotation around the Sun. If the scattering is elastic and spin independent, the DM mass and scattering cross section are required to be ~ 10 GeV and $\mathcal{O}(10^{-40})$ cm^2, respectively. This scattering cross section can be achieved through the t-channel exchange of a new light boson between the DM and nucleus (see, e.g., [31]). The corresponding parameter space is marginally consistent with that employed in the interpretation of the CoGeNT and CRESSTII results. In order to reconcile the tension between the DAMA signal and null results from other direct detection experiments, an "inelastic DM" scenario has been proposed, where the DM χ is scattered from a nucleus into a DM excited state χ^*, with mass splitting of $\delta \sim 10^2$ keV [32]. As discussed in Ref. [26], this small δ can be radiatively generated by the gauge bosons at the $\sim$ GeV scale in the dark sector.

3) The INTEGRAL telescope has detected a $\sim$ 511-keV gamma-ray line at the Galactic Center [33], which could be produced through annihilations of electrons and positrons with energies of $\sim \mathcal{O}(1)$ MeV [34]. These soft electrons and positrons can be explained as being due to the annihilation of light $\sim \mathcal{O}(1)$-MeV DM particles via a light A', where $\chi\bar{\chi} \to A' \to e^+e^-$. Another interesting interpretation is the so-called "exciting DM" model [35]. In this model, DM scattering may produce an excited DM state with $\delta \sim \mathcal{O}(1)$ MeV, which subsequently decays to the ground state and a soft e^+e^- pair, i.e., $\chi^* \to \chi e^+e^-$.

4) Through analysis of Fermi-LAT data, some groups have recently reported an excess of gamma rays at the GeV scale in the Galactic Center and inner galaxy [36, 37]. In the dark-sector scenario, light bosons from DM annihilations can decay into mesons and charged leptons. They can then produce gamma rays through meson decay, final-state radiation, and inverse Compton scattering processes [38, 39]. Compared with the ordinary interpretation of $\sim$ 30-GeV DM annihilation to yield $b\bar{b}$ for the GeV excess, DM annihilation into light bosons (e.g., $m'_A < 1$ GeV) would not produce antiprotons, because of the associated kinematics, and stringent antiproton constraints at the $\sim$ GeV scale would then be avoided.

Finally, it should be emphasized that all the above anomalies have non-DM explanations. For example, the extra high-energy cosmic-ray electrons and positrons mentioned above may be generated by nearby pulsars (see, e.g., [40]). Whether these exotic signals are generated from DM or from astrophysical sources remains debatable.

4 Constraints on light dark sector

Several experiments focused on the intensity and energy frontiers have been used to investigate the light particles in the dark sector over a long period of time [5]. New, high-precision, large-scale experiments are also being considered. As no A' signatures have been found, these projects, which involve electron and muon anomalous magnetic moment $(g-2)_l$ measurements, low-energy e^+e^- colliders, beam-dump experiments, fixed-target experiments, high-energy colliders, and so on, have set strong constraints on the dark-photon mass $m_{A'}$ and ϵ. Fig. 2 shows the limits for $m_{A'} > 1$ MeV obtained from anomalous $(g-2)_l$ measurements [41], *BABAR* [42, 43], KLOE [44, 45], WASA [46], HADES [47], MAMI A1 [48], APEX [49], PHENIX [50], NA48 [51], and reinterpretations of some older beam-dump-experiment results [52–54]. In this section, we provide a brief overview of these research efforts, which are focused on the intensity and energy frontiers. Some recent summaries of existing results can be found in Ref. [55–57]. For a more detailed review, we refer readers to Ref. [2].

4.1 Anomalous lepton magnetic moment and low-energy tests

In general, the coupling of A''s to electromagnetic states induces corrections to QED precision measurements. These corrections depend on the range of the dark force $\sim 1/m'_A$ and the system size r_{sys}, which is of order [10]

$$\sim \epsilon^2 e^2 \left(\frac{m_{A'}^{-1}}{r_{sys}}\right)^p, \tag{4.1}$$

where the parameter p depends on the system of mea-

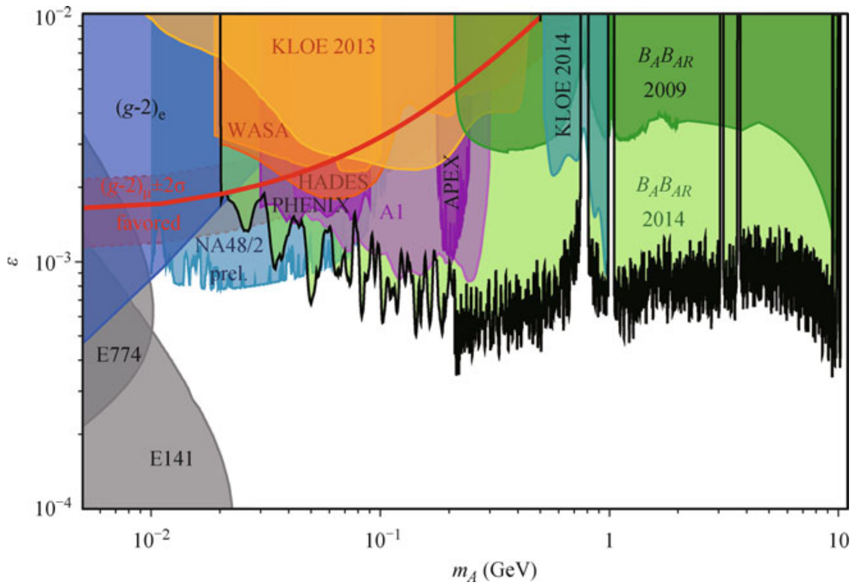

Fig. 2 Constraints on the mixing strength ϵ with the dark photon mass $m_{A'} > 1$ MeV from the measurements of electron and muon anomalous magnetic moments, low energy e^+e^- colliders, beam dump experiments and fixed target experiments. Reproduced from Ref. [55].

surement. For $m_{A'} \gg 1$ MeV, measurements of the atom system yield limits of order $\epsilon \sim 10^{-1}$ only; stricter constraints are obtained from smaller-scale systems [10, 58].

Measurements of the anomalous $(g-2)_l$ can set stringent constraints on A'. For $m_{A'} \gg m_l$, the A' contribution to $(g-2)_l$ is of order (for a full formula, see, e.g., [7, 58])

$$\delta(g-2)_l \sim \epsilon^2 \frac{\alpha}{\pi} \frac{m_l^2}{m_{A'}^2}. \tag{4.2}$$

For the electron magnetic moment $(g-2)_e$, the upper limit is given by $\epsilon^2 \sim 10^{-5}(m_{A'}/10 \text{ MeV})^2$ [58]. For the muon $(g-2)_\mu$ and an $m'_A \sim 1$–10^3 MeV, the upper limit on ϵ is of order 10^{-3}. It should be mentioned that this constraint is a little ambiguous, because of the possible discrepancy between the measured and predicted $(g-2)_\mu$ in the SM. Note that the A' contribution can even be used to reconcile this deviation.

Some other low-energy experiments, such as νe scattering and atomic parity measurements, can constrain the mixing between A' and the Z boson [7, 10], which is suppressed by a factor of $(m_{A'}/m_Z)^2$, where m_Z is the mass of the Z boson. The upper limits set by these experiments are of order $\epsilon \sim 0.1$–1.

4.2 Fixed-target experiments

In electron fixed-target experiments, incoming electrons hitting target protons could produce A''s via initial- or final-state radiations. These A''s would then decay to e^+e^- in the detector. One advantage of such experiments is the large A' production rate, which can be coherently enhanced according to [59, 60]

$$\sigma_{eN\to eNA'} \sim \frac{\alpha^3 Z^2 \epsilon^2}{m_{A'}^2} \sim 100\,\text{pb}\left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{m_{A'}}{100\,\text{MeV}}\right)^{-2}. \tag{4.3}$$

The dominant QED background is composed of e^+e^- pairs from the radiative and Bethe-Heitler processes. In order to suppress this background, excellent reconstructions of the e^+e^- invariant mass distribution and/or the decay vertex of A' are required. Several electron fixed-target experiments have been proposed, such as APEX, HPS and DarkLight at the Jefferson Laboratory [61], and MAMI A1 in Mainz [48]. The reaches of these experiments are shown in Fig. 3. It is apparent that they are sensitive to the $\mathcal{O}(10^{-5}) < \epsilon < \mathcal{O}(10^{-3})$ region in the $\mathcal{O}(10) < m_{A'} < \mathcal{O}(100)$-MeV mass range, which are still permitted by current experimental constraints.

The results of electron beam-dump experiments can be used to search for light A''s with $m_{A'} < \mathcal{O}(100)$ MeV and small ϵ of $\mathcal{O}(10^{-7}) < \epsilon < \mathcal{O}(10^{-3})$ [54, 62, 63]. In these experiments, A''s are produced by a high-intensity electron beam dumped onto a target; they then decay into the detector after propagating through a sizable shield. In future, the limits on small ϵ can be further refined through the use of larger luminosity and longer shields.

Proton fixed-target experiments can be employed to search for A''s produced via decays of large numbers of mesons generated by proton-proton collisions. As the experimental principle in this case is similar to that of

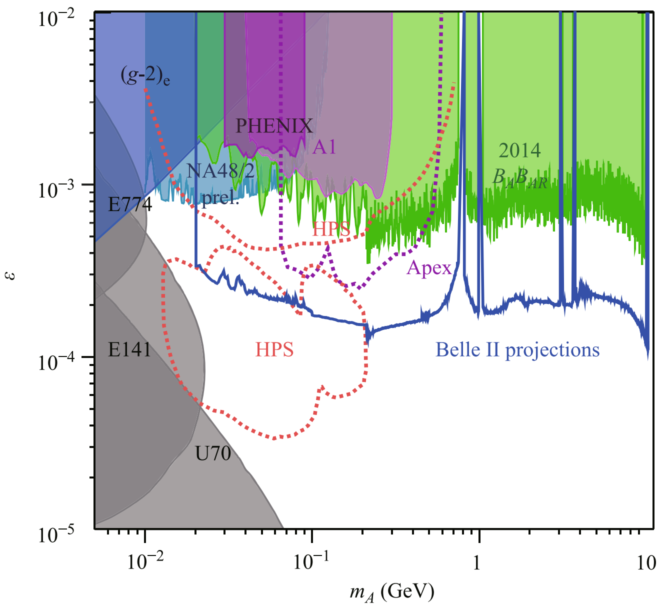

Fig. 3 Reaches of projected Belle-II and some electron fixed target experiments. Reproduced from Ref. [55].

neutrino experiments, several neutrino experiments can also be used to probe dark bosons [64, 65]; for example, CHARM, LSND, MINOS, and MiniBooNE.

4.3 High-energy colliders

In high-energy colliders, A''s can be directly produced via proton-proton collisions, or they can be indirectly produced through heavy-particle decays, including the decays of Z bosons, Higgs bosons, or some new BSM particles [14]. For prompt production, where $gq \to qA'$, resonance reconstruction of lepton pairs from A' decays is required. If the dark sector has a rich structure with several scalars and gauge bosons, it may be possible to find a large number of A''s in the final states of rare SM Z and Higgs boson decays, such as $Z \to A'h'(\to A'A')$ and $h \to A'A'$ [66]. In general, these two kinds of production processes are suppressed by a factor of ϵ^2 as a result of the small ϵ. The LHC at 14 TeV with high luminosity will be sensitive to A''s with masses larger than $\sim \mathcal{O}(1)$ GeV.

An interesting production mechanism is provided by the SUSY model. If the dark sector is also supersymmetric, the ordinary lightest neutralino may not be the actual lightest SUSY particle and it may be unstable. According to this theory and depending on the model sets, neutralinos and other SUSY partners decay into DM and several dark scalars and gauge bosons [14, 15, 67]. These processes can be guaranteed by the R-parity and are not suppressed by the small ϵ. A''s can also be produced through the final state radiation from other dark fermions [68, 69]. In such scenario, the final states also contain large missing energy induced by DM, which is useful for background suppression.

In high-energy colliders, particles in the dark sector experience high boosting. Consequently, lepton pairs generated via their decays have small invariant masses of $\sim$ GeV scale and small angular separations. Such objects are so-called "lepton-jets". Some technology for lepton jet identification has been developed via LHC [70–72] and Tevatron analyses [73].

5 Light dark sector phenomenology at low-energy high-luminosity e^+e^- colliders

5.1 Direct dark-photon production

Low-energy colliders such as B and charm factories are suited to searches for dark-sector particles, because of their large luminosities. Some A' production processes are shown in Fig. 4. A dominant direct A' production process is the $e^+e^- \to \gamma A'$ associated production, which is analogous to the $e^+e^- \to \gamma\gamma$ QED process. The signal cross section can be estimated using (for a full formula, see e.g., Ref. [9])

$$\sigma_{\gamma A'} \sim 2\pi \frac{\epsilon^2\alpha^2}{E_{cm}^2} \sim \epsilon^2\sigma_0, \tag{5.1}$$

where σ_0 is the production cross section of $e^+e^- \to \gamma\gamma$. As these experiments are predominantly used to search for lepton pairs from A' decays, the QED main background is $e^+e^- \to \gamma\gamma^* \to \gamma l^+l^-$. The background cross section around $m_{l^+l^-} = m_{A'}$ with window size δm is [10]

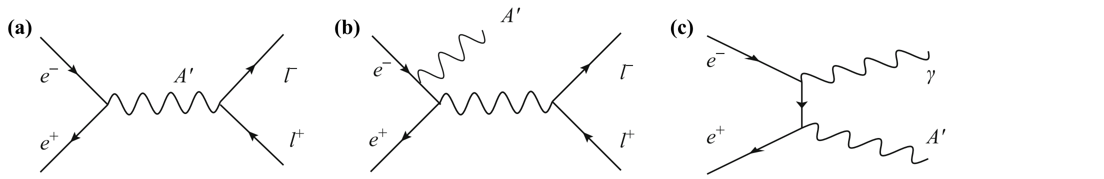

Fig. 4 The direct production processes of the dark photon at the e^+e^- collider: **(a)** $e^+e^- \to A'^{(*)}$, **(b)** $e^+e^- \to A'l^+l^-$, **(c)** $e^+e^- \to A'\gamma$.

$$\Delta\sigma_{bkg} \sim \frac{\alpha}{\pi}\sigma_0\frac{\delta m}{m_{A'}}. \tag{5.2}$$

The significance of the signal can be estimated from [10]

$$\frac{S}{\sqrt{B}} \sim \epsilon^2\sqrt{\mathcal{L}}\sqrt{\frac{\pi\sigma_0}{\alpha}}\sqrt{\frac{m_{A'}}{\delta m}}\mathrm{BR}(A' \to l^+l^-), \tag{5.3}$$

where $\mathcal{L}$ is the collider luminosity and $\mathrm{BR}(A' \to l^+l^-)$ is the branching ratio of the A' decay into leptons. For a collider with $\sigma_0 \sim 10^7$ fb, $\mathcal{L} \sim 100$ fb^{-1}, and $\delta m \sim 1$ MeV, the experimental reach on ϵ is $\sim 10^{-3}$. It is also apparent from Eq. (5.3) that the sensitivity to ϵ is improved by a factor of $(\mathcal{L}/E_{cm}^2)^{1/4}$ with increasing luminosity. This is why low-energy colliders are more sensitive to light A''s than high-energy colliders.

If the decay channels to other exotic particles are absent, the dominant decay products of the A' are charged leptons or hadrons. Thus, a narrow peak (e.g., $< \mathcal{O}(1)$ KeV) should appear in the di-lepton invariant mass distribution. The decay length of $A' \to l^+l^-$ in the rest frame can be roughly estimated as [9, 58]

$$c\tau_{A'\to l^+l^-} \sim \left(\frac{1}{3}\alpha\epsilon^2 m_{A'}\right)^{-1} \sim 10^{-6}\mathrm{cm}\left(\frac{m_{A'}}{\mathrm{GeV}}\right)^{-1}\left(\frac{\epsilon}{10^{-3}}\right)^{-2}. \tag{5.4}$$

For small $m_{A'}$ and ϵ, a displacing vertex may exist at the collider. The decay widths of the hadronic decay channels can be obtained from

$$\Gamma_{A'\to \mathrm{hadrons}} = \Gamma_{A'\to\mu^+\mu^-}R(s = m_{A'}^2), \tag{5.5}$$

where the R value is $R = \sigma_{e^+e^-\to\mathrm{hadrons}}/\sigma_{e^+e^-\to\mu^+\mu^-}$. In the regions near the resonances, such as ρ and ω, the dominant final states of the A' decay may be $\pi^+\pi^-$ or $\pi^+\pi^-\pi^0$. Therefore, the sensitivities to $A' \to l^+l^-$ decrease in these regions. The Γ and branching ratios of the A' to SM particle decays for $\epsilon = 10^{-2}$ are shown in Fig. 5 [8].

Dark photons can also be produced via the $e^+e^- \to e^+e^-A'$ process [10]. This process is significant at small $m_{A'}$, because of the large forward enhancement from Bhabha scattering. The dominant QED background is $e^+e^- \to e^+e^-l^+l^-$. Although efficient event triggering and the reconstruction of overly forward leptons is challenging, this search is complementary to $\gamma A'$ associated production for small $m_{A'}$.

5.2 Meson rare decay

Mesons can decay into an A' with a suppressed branching ratio

$$\mathrm{BR}(X \to Y + A') \sim \epsilon^2\mathrm{BR}(X \to Y + \gamma). \tag{5.6}$$

The large meson statistics at low-energy e^+e^- colliders can compensate for this suppressed BR. The dominant corresponding background for the $A' \to l^+l^-$ channel is $X \to Y + \gamma^* \to Y + l^+l^-$ with $m_{l^+l^-} \sim m_{A'}$, and the significance can be roughly estimated from [10]

$$\frac{S}{\sqrt{B}} \sim \sqrt{n_X}\epsilon^2\frac{\mathrm{BR}(X \to Y + \gamma)\cdot\mathrm{BR}(A' \to l^+l^-)}{\sqrt{\mathrm{BR}(X \to Y + \gamma^* \to Y + l^+l^-)}}$$

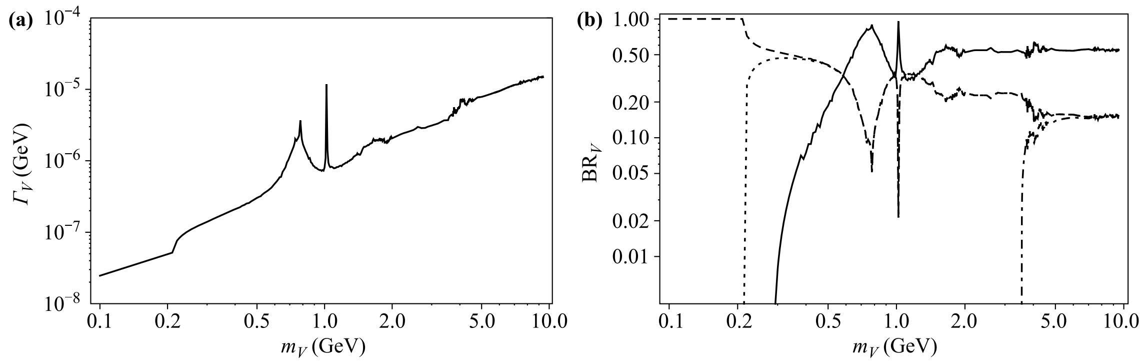

Fig. 5 **(a)** decay width of the dark photon to SM particles. **(b)** branching ratios of $A' \to e^+e^-$ (*dashed*), $A' \to \mu^+\mu^-$ (*dotted*), $A' \to \tau^+\tau^-$ (*dot-dashed*), and $A' \to$ hadrons (*solid*). ϵ is taken to be 10^{-2}. Reproduced from Ref. [8].

Table 1 The sensitivities to ϵ for several meson decay channels. The dark photon mass is taken to be $m_{A'} = 250$ MeV. Reproduced from Ref. [10].

$X \to YA'$	n_X	$m_X - m_Y$ (MeV)	BR($X \to Y\gamma$)	BR($X \to Y\ell^+\ell^-$)	$\epsilon \leqslant$
$\eta \to \gamma A'$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 A'$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta A'$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma A'$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ A'$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu A'$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8}	2×10^{-3}
$K^+ \to e^+ \nu A'$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

$$\cdot\sqrt{\frac{m_{A'}}{\delta m}\log\left(\frac{m_X - m_Y}{2m_l}\right)}, \tag{5.7}$$

where n_X is the number of mesons. Note that the sensitivity to ϵ is slowly improved by a factor of $n_X^{1/4}$. The ϵ sensitivities of several meson decay channels are summarized in Table 1 [10]. For BR($X \to Y + \gamma$) $\sim \mathcal{O}(10^{-2})$ and $n_X \sim \mathcal{O}(10^9)$, the experimental reach can be $\sim 10^{-3}$.

5.3 Production and decay of other dark particles

If the dark sector has a complex structure with many new light particles, a very rich phenomenology can be expected at the e^+e^- collider. For example, a light dark Higgs can be produced via a Higgs-strahlung process, $e^+e^- \to A'h'$, as shown in Fig. 6[3)]. The cross section of this process is estimated as (for $E_{cm} \gg m_{A'}, m_{h'}$, where the latter is the mass of the dark Higgs) [8]

$$\sigma_{A'h'} \sim \frac{\pi\alpha\alpha'\epsilon^2}{3E_{cm}^2} \sim 20\text{fb} \times \left(\frac{\alpha'}{\alpha}\right)\left(\frac{\epsilon}{10^{-2}}\right)^2\left(\frac{E_{cm}}{10\text{ GeV}}\right)^{-2}, \tag{5.8}$$

where $\alpha' \equiv \frac{e'^2}{4\pi}$ is defined by the $U(1)_D$ charge e' of A'. Compared with the $e^+e^- \to A'\gamma$ direct production, the production rate of the Higgs–Strahlung process depends on two additional parameters, α' and $m_{h'}$.

If the mixing term between the dark Higgs and SM Higgs at tree level (e.g., $\kappa h'^2 h^2$) is absent, the dark-Higgs decay mode depends on the relative mass of the dark Higgs and A'. For $m_{h'} \gg m_{A'}$, the dark Higgs decays into a pair of real A''s with a decay width of [8]

$$\Gamma_{h' \to A'A'} \sim \frac{\alpha' m_{h'}^3}{8m_{A'}^2}. \tag{5.9}$$

Therefore, the signature of the Higgs-strahlung process in this mass regime is three pairs of leptons with $m_{l^+l^-} \sim m_{A'}$. In addition, a peak is expected around $m_{h'}$ in the four-lepton invariant mass distribution $m_{2l^+l^-}$. Compared with the QED background $e^+e^- \to l^+l^-\gamma$ at $\mathcal{O}(\alpha^3)$ for the $e^+e^- \to A'\gamma \to l^+l^-\gamma$ direct production, the six-lepton background $e^+e^- \to 3l^+l^-$ for this process is only of order $\mathcal{O}(\alpha^6)$. Moreover, as the initial electrons and positrons in the background events may still have large energies along the beam pipe after the peripheral collision, cuts on the lepton angle and invariant mass would be very useful for background suppression [8]. For $m_{A'} < m_{h'} < 2m_{A'}$ and $m_{h'} < m_{A'}$, the decay channels through the virtual dark photon A'^*, i.e., $h' \to A'A'^* \to A'l^+l^-$ and $h' \to A'^*A'^* \to l^+l^-l^+l^-$, are suppressed by the phase-space factors. The dark Higgs can also directly decay into a pair of leptons via a loop containing A'^*'s. Consequently, this process is suppressed by a loop factor.

For a non-Abelian dark sector with gauged $SU(2)_D \times U(1)_D$, the vacuum may be maximally broken [15]. Therefore, all dark gauge bosons generically mix with each other. In this case, the production and decay processes of dark gauge and dark Higgs bosons may be very complex and depend on the detailed model [9, 15]. For example, the decay width of dark non-Abelian gauge bosons W' into charged SM particles depends on the mixing angles θ with $U(1)_D$ [9]

$$\Gamma_{W' \to l^+l^-} \sim \frac{1}{3}\epsilon^2\theta^2\alpha m_{W'}. \tag{5.10}$$

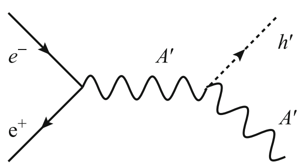

Fig. 6 The Higgs-strahlung process $e^+e^- \to A'h'$.

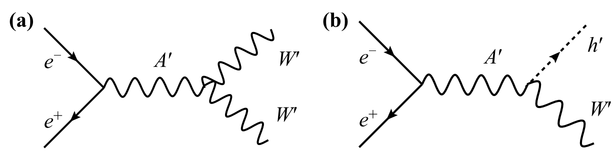

Fig. 7 The production processes of the dark $SU(2)$ gauge bosons at the e^+e^- collider: **(a)** $e^+e^- \to W'W'$, **(b)** $e^+e^- \to W'h'$.

3) For discussion of the A' production associated with the SM Higgs $e^+e^- \to A'h$ in future high-energy e^+e^- colliders, see Ref. [74].

The possible dark-boson production processes include $e^+e^- \to A'^* \to W'W'$ and $e^+e^- \to A'^* \to W'h'$, as shown in Fig. 7. Depending on the parameters, a dark gauge boson will subsequently decay into the lightest dark bosons. Therefore, the typical signatures of the non-Abelian dark sector always have high lepton multiplicities with or without photons. It is possible to suppress the QED background through full reconstruction of E_{cm} or displaced vertices [9].

If the non-Abelian sector is confined to a Λ_D scale, the dark quarks induced by the e^+e^- collision produce a high multiplicity of dark hadrons after the shower and hadronization processes [9]. This scenario is similar to the hidden-valley scenario [75–77]. Further, many collimated lepton jets from dark-hadron decays at the detector should appear. The final-state distribution depends on the E_{cm}/Λ_D ratio.

5.4 Missing energy

In the above discussions, we have focused on searches for charged lepton (or hadron) pairs from dark-boson decays. In this subsection, we discuss signatures containing missing energy or displaced vertices. For example, for $m_{A'} \gg m_{h'} \gg 2m_l$, the decay length of the dark Higgs is [8]

$$c\tau_{h'} \sim \left(\frac{\alpha'\alpha^2\epsilon^4 m_{h'}}{2\pi^2}\frac{m_l^2}{m_{A'}^2}I\right)^{-1} \sim 10^2\text{cm}\left(\frac{\alpha}{\alpha'}\right)\left(\frac{\epsilon}{10^{-2}}\right)^{-4}\left(\frac{m_{h'}}{\text{GeV}}\right)\left(\frac{m_{A'}}{2m_l}\right)^2, \quad (5.11)$$

where I is a loop factor for $h' \to l^+l^-$ through a triangle diagram containing A'^*'s. Therefore, the dark Higgs is a very long-lived particle in this mass region. Depending on the realistic parameter set, the dark Higgs may decay in the detector with a displaced vertex, or it may escape from the detector. In the latter case, the signature contains several leptons and missing energy.

Another important possibility is the invisible decay of A' into light DM particles [6, 7, 78–80]. In this case, the DM interacts with the SM particles through the A'. At the e^+e^- collider, the possible signatures are the invisible decay of mesons or the mono-photon from $e^+e^- \to \textit{missing energy} + \gamma$. The event rate depends on the DM mass and DM coupling to the A'. Compared with the visible channel $e^+e^- \to A' + X \to l^+l^- + X$ (X denotes any particle), which is suppressed by a factor of $\mathcal{O}(\epsilon^4)$ at least, the suppression of the $e^+e^- \to A' + X \to \textit{missing energy} + X$ invisible channel may be only $\mathcal{O}(\epsilon^2)$, if the A' has a large interaction with DM. The irreducible backgrounds are comprised of processes containing neutrinos. The mis-measurement of ordinary particles may also induce so-called "fake missing energy".

If there are more fermions in the dark sector, DM can be produced via cascade decays through the on- or off-shell A', such as $f' \to \chi A' \to \chi l^+l^-$ [9, 14, 15]. In that case, it is possible to reconstruct an endpoint in the dilepton invariant mass distribution.

6 Current status of light sector searches at high-luminosity low-energy e^+e^- colliders

In this section, we discuss results from several e^+e^- colliders. These experiments operate at different E_{cm} values of 1–10 GeV. Their enormous datasets are ideal for the investigation of new particles in the dark sector and their interactions with SM particles.

6.1 ϕ factories

The DAΦNE e^+e^- collider is a ϕ factory running at an E_{cm} of $\sim$ 1020 MeV. From 2000 to 2006, the KLOE detector operated at DAΦNE collected 2.5 fb^{-1} of data. The KLOE collaboration has searched for A''s in the $\phi \to \eta A'$ rare decay. In Ref. [81], 1.5 fb^{-1} of data (corresponding to 5×10^9 ϕ mesons) and the tagging decay channel $\eta \to \pi^+\pi^-\pi^0$ are considered. The dominant background is the Dalitz decay of $\phi \to \eta l^+l^-$. This process has a cross section of $\sim$ 0.7 nb in $M_{ll} < 470$ MeV with a branching ratio of BR($\phi \to \eta l^+l^-$) $\sim 1.14 \times 10^{-4}$, whereas the production cross section of $\phi \to \eta A'$ is $\sim$ 40 fb for $\eta = 10^{-3}$. As the $e^\pm$ can be easily identified using a time-of-flight technique, the KLOE collaboration has focused on the $A' \to e^+e^-$ decay channel. Hence, as no excess has been found in the dilepton invariant mass distribution following background subtraction, the KLOE researchers have set an upper limit on ϵ^2 of 2×10^{-5} for $50 < m_{A'} < 420$ MeV at 90% confidence level (C.L.).

In Ref. [44], the KLOE search for the $\phi \to \eta A' \to \eta l^+l^-$ decay was reported, which was conducted using the $\eta \to \pi^0\pi^0\pi^0$ tagging decay for a 1.7-fb^{-1} data sample. Combined with the previous study of $\eta \to \pi^+\pi^-\pi^0$, improved upper limits on ϵ^2 of 1.7×10^{-5} for $30 < M_{A'} < 400$ MeV or 8×10^{-6} for $50 < m_{A'} < 400$ MeV were reported.

The KLOE collaboration has also probed A''s through the $e^+e^- \to \gamma A'$ direct production with $A' \to \mu^+\mu^-$ and $A' \to e^+e^-$. These searches have set upper limits on ϵ^2 of 8.6×10^{-7}–1.6×10^{-5} for $520 < m_{A'} < 980$ MeV [45] and $\sim 10^{-6}$–10^{-4} for $5 < m_{A'} < 520$ MeV [82], respectively.

6.2 B factories

The *BABAR* experiment at PEP-II and the Belle experiment at KEK-B have collected an enormous amount of data ($\sim$ 1.4 ab^{-1}) at and in the vicinity of the Υ resonances. The *BABAR* collaboration has searched for the light CP-odd Higgs A^0 in the next minimal SUSY model in Υ decays such as $\Upsilon(2S, 3S) \to A^0\gamma$ and $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^- \to A^0\gamma\pi^+\pi^-$, which are followed by $A^0 \to \mu^+\mu^-$ [43, 83], $A^0 \to \tau^+\tau^-$ [84, 85], or $A^0 \to$ invisible [86, 87]. The results of searches for $\Upsilon(2S, 3S) \to A^0\gamma \to \mu^+\mu^-\gamma$ based on an $\sim$ 40 fb^{-1} dataset can be reinterpreted as providing constraints on the A' signature $\Upsilon(2S, 3S) \to A'\gamma \to \mu^+\mu^-\gamma$, as a result of the same final states (see e.g., [59, 60]). The corresponding upper limit on ϵ^2 is of order $\sim 10^{-5}$. A similar search for $\Upsilon(1S) \to \gamma A^0$ with $A^0 \to \mu^+\mu^-$ or $\tau^+\tau^-$ has also been performed at CLEO, based on 1.1 fb^{-1} of data [88].

As the CP-odd Higgs A^0 only has large coupling to heavy quarks via the Yukuawa interaction, it is preferable to search for this particle in narrow resonance decays, such as $\Upsilon(2S)$ and $\Upsilon(3S)$. However, for A''s with "universal" couplings to all fermions, the continuum production around a broader resonance is also significant [10]. In Ref. [42], the *BABAR* collaboration study of the $e^+e^- \to \gamma A'$ production with A' decay into e^+e^- or $\mu^+\mu^-$ is reported. This search was based on 514 fb^{-1} of data, primarily at and in the vicinity of the $\Upsilon(4S)$ resonance. The constraints on ϵ for a broad mass region of $0.02 < m_{A'} < 10.2$ GeV are shown in Fig. 2. It is apparent that the *BABAR* limits are at the level of $\epsilon \sim \mathcal{O}(10^{-4})$, and are, therefore, stronger than many previous experimental results. Note that the parameter region favored by the explanation of the discrepancy between the predicted and measured $(g-2)_\mu$ has been almost completely excluded[4)].

For other light particles in the dark sector, the *BABAR* collaboration has probed the $e^+e^- \to W'W' \to l^+l^-l^+l^-$ di-boson production using 536 fb^{-1} of data [89]. In this search, two dark gauge bosons were assumed to have similar mass. The W' couplings to electrons and muons were also assumed to be equal. Note that, for a small mass region, the upper limits on $\alpha_D\epsilon^2$ can be set to the level of $\mathcal{O}(10^{-10})$.

The *BABAR* search for dark Higgs production in the Higgs-strahlung process $e^+e^- \to A'h' \to A'A'A'$ is presented in Ref. [90]. Several different A' and dark Higgs mass combinations were taken into account in the $0.8 < m_{h'} < 10$ GeV and $0.25 < m_{A'} < 3$ GeV ranges, with the constraint that $m_{h'} > 2m_{A'}$. The A' and dark Higgs can be either fully reconstructed in the $3(l^+l^-)$, $2(l^+l^-)\pi^+\pi^-$, and $2(\pi^+\pi^-)l^+l^-$ final states, or partially reconstructed in the $2(\mu^+\mu^-) + X$ and $e^+e^-\mu^+\mu^- + X$ (X denotes any particle) final states. Depending on the A' and dark Higgs masses, the upper limits on $\alpha_D\epsilon^2$ can be $\sim 10^{-10}$–10^{-7}.

The searches conducted at Belle are similar to those at *BABAR*. As the sensitivity to ϵ is scaled as the fourth root of the luminosity, the Belle investigations using $\sim \mathcal{O}(10^2)$-fb^{-1} data also set similar constraints to those given by *BABAR*. Recently, the Belle collaboration reported the results of searches for $e^+e^- \to A'h' \to A'A'A'$ with $A' \to e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-$ in the $0.1 < m_{A'} < 3.5$ GeV and $0.2 < m_{h'} < 10.5$ GeV mass ranges [91]. Based on 977 fb^{-1} of data, the upper limit on ϵ was set to $\sim 8 \times 10^{-4}$ for $\alpha_D = \alpha$, $m_{h'} < 8$ GeV, and $m_{A'} < 1$ GeV. As shown in Fig. 3, the future Belle-II, which will have 100 times more luminosity than *BABAR* and superior trigger efficiency and mass resolution, will yield several-fold tighter limits for ϵ [12, 56].

6.3 Charm factories

The BESIII detector is operated at the BEPCII e^+e^- collider, which has a design peak luminosity of 10^{33} cm^{-2} s^{-1}. Using a large sample of J/ψ, $\psi(2S)$, and $\psi(3770)$, BESIII can be used to perform searches for light A' and other new light particles.

In Ref. [92], the BESIII collaboration search for a light A^0 in the $\psi' \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\gamma A^0$ process was reported, where $A^0 \to \mu^+\mu^-$. This study was based on 1.06×10^8 events at the ψ' resonance peak. Depending on m_{A^0}, upper limits on the BR$(J/\psi \to \gamma A^0) \times$ BR$(A^0 \to \mu^+\mu^-)$ branching ratio ranging from 4×10^{-7} to 2.1×10^{-5} were set. These results can be used to set constraints on A'. Note that the A^0 couplings to quarks are proportional to the quark masses. Therefore, B factories are more sensitive to searches for such particles because of their larger production rates. However, charm factories are ideal for probing A', as this particle's couplings to SM leptons are "universal".

The BESIII collaboration has performed a search for invisible η and η' decays in $J/\psi \to \phi\eta$ and $\phi\eta'$, based on a data sample of $2.25 \times 10^8 J/\psi$ events [93]. The invisible η and η' decays were tagged by $\phi \to K^+K^-$. As no signals were found, this analysis set constraints on the invisible decay branching ratios of BR$(\eta \to 1.0 \times 10^{-4})$ and BR$(\eta' \to 5.3 \times 10^{-4})$.

Some previous phenomenological studies have discussed the possibility of probing A' via several processes at BESIII, such as $e^+e^- \to \gamma A'$, $J/\psi \to A'l^+l^-$, $\psi(2S) \to A'\chi_{c1,2}$, and $J/\psi \to A'h'$, with the leptonic or

4) If A''s decayed into particles in the dark sector, the constraints would be weaker.

invisible decay of A' [11, 79, 94]. Several experimental analyses are still in progress. For example, the BESIII collaboration is searching for A' in the $e^+e^- \to \gamma_{ISR}A'$ initial-state radiation process, with $A' \to e^+e^-$ or $\mu^+\mu^-$, based on 2.9 fb^{-1} of $\psi(3770)$ data [95]. In this analysis, the initial-state radiation photon is emitted at a small polar angle and is not detected by the electromagnetic calorimeter. Through use of this so-called "untagged" photon method, the constraints set by BESIII in the 1.5–3.4-GeV mass range are comparable with those given by *BABAR*.

7 Discussion and conclusions

Although the SM has achieved considerable success in the past, the existence of the BSM is well supported by many unresolved fundamental questions in high-energy physics. Thus, a new sector consisting of a series of light, weakly coupled particles at low energies may exist. The findings of DM detection experiments, such as the cosmic-ray electron-positron excess, the DAMA modulation signal, and gamma-ray excess in the Galactic center, provide indications of the dark sector. In the proposed scenario, a $\sim \mathcal{O}(1)$ GeV A' couples DM to SM particles through kinematic mixing, which can be probed in both intensity and high-energy experiments.

Low energy e^+e^- colliders are ideal tools for searching for A' and other related light bosons, as they have provided extremely large collected data samples on the GeV scale. A' can be identified by a narrow peak in the di-lepton invariance mass distribution, and the production of other dark bosons induces even more lepton pairs in the final states. Furthermore, highly suppressed dark-boson decay into leptons or invisible decay into DM particles should leave a displaced vertex or missing energy signature at the detector. These features provide a very rich and interesting phenomenology at e^+e^- colliders.

Some current high-luminosity experiments at different E_{cm}, such as KLOE, CLEO, *BABAR*, Belle, and BESIII, have searched for A' in the $e^+e^- \to \gamma A' \to \gamma l^+l^-$ process and in some meson rare decays. As no significant signatures have been found, upper limits can be set on ϵ at a level of $\sim 10^{-3}$. These limits are complementary to those set by fixed-target and beam-dump experiments. Furthermore, the parameter region favored by the explanation of the discrepancy between the predicted and measured $(g-2)_\mu$ has been almost completely excluded by current low-energy e^+e^- collider results.

As the sensitivity to ϵ scales as the fourth root of the integrated luminosity, colliders with higher luminosities are required in future in order to probe the light dark sector. Upgraded Super-B factories will collect approximately two orders of magnitude more data than current B factories. Further, proposed super-tau-charm factories are designed to achieve a luminosity of 10^{35} cm^{-2}·s^{-1}. These experiments will improve the current experimental sensitivities to ϵ. In addition, detailed data analysis to determine signatures containing multi-lepton pairs or missing energy will also provide an opportunity to further reveal the properties of the dark sector.

Finally, we note that new light particles may also be searched for using the cosmic-ray signatures produced in the earth or in the sun [96–100]. By combining results from experiments targeted at the three basic frontiers of particle physics, it will be possible to establish a universal picture of the new physics in the future [101].

Acknowledgements This work was supported by the National Basic Research Program of China (973 Program) under Grant No. 2013CB837000, and the National Natural Science Foundation of China under Grants Nos. 11475189, 11135003, and 11375014.

References

1. S. H. Zhu, Recent progress in physics beyond the standard model, *Front. Phys.* 8, 241 (2013)
2. Y. Hu, Y. K. Wang, P. F. Yin, and S. H. Zhu, On physics beyond standard model, *Front. Phys.* 8, 516 (2013)
3. S. H. Zhu, A new paradigm: Role of electron-positron and hadron colliders, arXiv: 1410.2042 [hep-ph]
4. J. L. Hewett, H. Weerts, R. Brock, J. N. Butler, B. C. K. Casey, et al., Fundamental physics at the intensity frontier, arXiv: 1205.2671 [hep-ex]
5. R. Essig, J. A. Jaros, W. Wester, P. H. Adrian, S. Andreas, et al., Dark sectors and new, light, weakly-coupled particles, arXiv: 1311.0029 [hep-ph]
6. N. Borodatchenkova, D. Choudhury, and M. Drees, Probing MeV dark matter at low-energy e^+e^- colliders, *Phys. Rev. Lett.* 96, 141802 (2006), arXiv: hep-ph/0510147
7. P. Fayet, U-boson production in e^+e^- annihilations, psi and upsilon decays, and light dark matter, *Phys. Rev. D* 75, 115017 (2007), arXiv: hep-ph/0702176 [hep-ph]
8. B. Batell, M. Pospelov, and A. Ritz, Probing a secluded U(1) at B-factories, *Phys. Rev. D* 79, 115008 (2009), arXiv: 0903.0363 [hep-ph]
9. R. Essig, P. Schuster, and N. Toro, Probing dark forces and light hidden sectors at low-energy e^+e^- colliders, *Phys. Rev. D* 80, 015003 (2009), arXiv: 0903.3941 [hep-ph]
10. M. Reece and L.-T. Wang, Searching for the light dark gauge boson in GeV-scale experiments, *J. High Energy Phys.* 0907, 051 (2009), arXiv: 0904.1743 [hep-ph]
11. P.-F. Yin, J. Liu, and S.-H. Zhu, Detecting light leptophilic gauge boson at BESIII detector, *Phys. Lett. B* 679, 362 (2009), arXiv: 0904.4644 [hep-ph]

12. L. Barze, G. Balossini, C. Bignamini, C. M. Carloni Calame, G. Montagna, O. Nicrosini, and F. Piccinini, Probing dark forces at GeV-scale colliders, *Acta Phys. Polon. B* 42, 2461 (2011)
13. B. Holdom, Two U(1)'s and epsilon charge shifts, *Phys. Lett. B* 166, 196 (1986)
14. N. Arkani-Hamed and N. Weiner, LHC signals for a superunified theory of dark matter, *J. High Energy Phys.* 0812, 104 (2008), arXiv: 0810.0714 [hep-ph]
15. M. Baumgart, C. Cheung, J. T. Ruderman, L.-T. Wang, and I. Yavin, Non-Abelian dark sectors and their collider signatures, *J. High Energy Phys.* 0904, 014 (2009), arXiv: 0901.0283 [hep-ph]
16. S. A. Abel, M. D. Goodsell, J. Jaeckel, V. V. Khoze, and A. Ringwald, Kinetic mixing of the photon with hidden U(1)s in string phenomenology, *J. High Energy Phys.* 0807, 124 (2008), arXiv: 0803.1449 [hep-ph]
17. M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, Naturally light hidden photons in LARGE volume string compactifications, *J. High Energy Phys.* 0911, 027 (2009), arXiv: 0909.0515 [hep-ph]
18. C. Cheung, J. T. Ruderman, L.-T. Wang, and I. Yavin, Kinetic mixing as the origin of light dark scales, *Phys. Rev. D* 80, 035008 (2009), arXiv: 0902.3246 [hep-ph]
19. M. A. Deliyergiyev, Recent progress in search for hidden/dark photon, arXiv: 1510.06927 [hep-ph].
20. O. Adriani, et al. (PAMELA Collaboration), An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV, *Nature* 458, 607 (2009), arXiv: 0810.4995 [astro-ph]
21. J. Chang, J. H. Adams, H. S. Ahn, G. L. Bashindzhagyan, M. Christl, et al., An excess of cosmic ray electrons at energies of 300–800 GeV, *Nature* 456, 362 (2008)
22. A. A. Abdo, et al. (Fermi LAT Collaboration), Measurement of the cosmic ray e^+ plus e^- spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope, *Phys. Rev. Lett.* 102, 181101 (2009), arXiv: 0905.0025 [astro-ph.HE]
23. M. Aguilar, et al. (AMS Collaboration), First result from the alpha magnetic spectrometer on the international space station: Precision measurement of the positron fraction in primary cosmic rays of 0.5C350 GeV, *Phys. Rev. Lett.* 110(14), 141102 (2013)
24. O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, et al., A new measurement of the antiproton-to-proton flux ratio up to 100 GeV in the cosmic radiation, *Phys. Rev. Lett.* 102, 051101 (2009), arXiv: 0810.4994 [astro-ph]
25. AMS Collaboration, Talks at the "AMS Days at CERN", April 15–17, 2015
26. N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, A theory of dark matter, *Phys. Rev. D* 79, 015014 (2009), arXiv: 0810.0713 [hep-ph]
27. M. Pospelov and A. Ritz, Astrophysical signatures of secluded dark matter, *Phys. Lett. B* 671, 391 (2009), arXiv: 0810.1502 [hep-ph]
28. R. Bernabei, et al. (DAMA Collaboration), First results from DAMA/LIBRA and the combined results with DAMA/NaI, *Eur. Phys. J. C* 56, 333 (2008), arXiv: 0804.2741 [astro-ph]
29. C. E. Aalseth, et al. (CoGeNT Collaboration), Results from a search for light-mass dark matter with a P-type point contact germanium detector, *Phys. Rev. Lett.* 106, 131301 (2011), arXiv: 1002.4703 [astro-ph.CO]
30. G. Angloher, M. Bauer, I. Bavykina, A. Bento, C. Bucci, et al., Results from 730 kg days of the CRESST-II dark matter search, *Eur. Phys. J. C* 72, 1971 (2012), arXiv: 1109.0702 [astro-ph.CO]
31. P. Draper, T. Liu, C. E. M. Wagner, L. T. Wang, and H. Zhang, Dark light Higgs, *Phys. Rev. Lett.* 106, 121805 (2011), arXiv: 1009.3963 [hep-ph]
32. S. Chang, G. D. Kribs, D. Tucker-Smith, and N. Weiner, Inelastic dark matter in light of DAMA/LIBRA, *Phys. Rev. D* 79, 043513 (2009), arXiv: 0807.2250 [hep-ph]
33. A. W. Strong, R. Diehl, H. Halloin, V. Schoenfelder, L. Bouchet, P. Mandrou, F. Lebrun, and R. Terrier, Gamma-ray continuum emission from the inner galactic region as observed with INTEGRAL/SPI, *Astron. Astrophys.* 444, 495 (2005), arXiv: astro-ph/0509290
34. C. Boehm, D. Hooper, J. Silk, M. Casse, and J. Paul, MeV dark matter: Has it been detected? *Phys. Rev. Lett.* 92, 101301 (2004), arXiv: astro-ph/0309686
35. D. P. Finkbeiner and N. Weiner, Exciting dark matter and the INTEGRAL/SPI 511 keV signal, *Phys. Rev. D* 76, 083519 (2007), arXiv: astro-ph/0702587
36. L. Goodenough and D. Hooper, Possible evidence for dark matter annihilation in the inner Milky way from the Fermi gamma ray space telescope, arXiv: 0910.2998 [hep-ph]
37. T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. K. N. Portillo, N. L. Rodd, and T. R. Slatyer, The characterization of the gamma-ray signal from the central Milky way: A compelling case for annihilating dark matter, arXiv: 1402.6703 [astro-ph.HE]
38. D. Hooper, N. Weiner, and W. Xue, Dark forces and light dark matter, *Phys. Rev. D* 86, 056009 (2012), arXiv: 1206.2929 [hep-ph]
39. J. Liu, N. Weiner, and W. Xue, Signals of a light dark force in the galactic center, *J. High Energy Phys.* 1508, 050 (2015), arXiv: 1412.1485 [hep-ph]
40. D. Hooper, P. Blasi, and P. D. Serpico, Pulsars as the sources of high energy cosmic ray positrons, *J. Cosmol. Astropart. Phys.* 0901, 025 (2009), arXiv: 0810.1527 [astro-ph]
41. M. Endo, K. Hamaguchi, and G. Mishima, Constraints on hidden photon models from electron g-2 and hydrogen spectroscopy, *Phys. Rev. D* 86, 095029 (2012), arXiv: 1209.2558 [hep-ph]
42. J. P. Lees, et al. (BaBar Collaboration), Search for a dark photon in e^+e^- collisions at BaBar, *Phys. Rev. Lett.* 113(20), 201801 (2014), arXiv: 1406.2980 [hep-ex]

43. B. Aubert, et al. (BaBar Collaboration), Search for Dimuon decays of a light scalar boson in radiative transitions upsilon — gamma A^0, *Phys. Rev. Lett.* 103, 081803 (2009), arXiv: 0905.4539 [hep-ex]
44. D. Babusci, et al. (KLOE-2 Collaboration), Limit on the production of a light vector gauge boson in phi meson decays with the KLOE detector, *Phys. Lett. B* 720, 111 (2013), arXiv: 1210.3927 [hep-ex]
45. D. Babusci, et al. (KLOE-2 Collaboration), Search for light vector boson production in $e^+e^- \to \mu^+\mu^-\gamma$ interactions with the KLOE experiment, *Phys. Lett. B* 736, 459 (2014), arXiv: 1404.7772 [hep-ex]
46. P. Adlarson, et al. (WASA-at-COSY Collaboration), Search for a dark photon in the $\pi^0 \to e^+e^-\gamma$ decay, *Phys. Lett. B* 726, 187 (2013), arXiv: 1304.0671 [hep-ex]
47. G. Agakishiev, et al. (HADES Collaboration), Searching a dark photon with HADES, *Phys. Lett. B* 731, 265 (2014), arXiv: 1311.0216 [hep-ex]
48. H. Merkel, et al., Search at the Mainz Microtron for light massive gauge bosons relevant for the muon g-2 anomaly, *Phys. Rev. Lett.* 112(22), 221802 (2014), arXiv: 1404.5502 [hep-ex]
49. S. Abrahamyan, et al. (APEX Collaboration), Search for a new gauge boson in electron-nucleus fixed-target scattering by the APEX experiment, *Phys. Rev. Lett.* 107, 191804 (2011), arXiv: 1108.2750 [hep-ex]
50. A. Adare, et al. (PHENIX Collaboration), Search for dark photons from neutral meson decays in $p+p$ and d+Au collisions at $\sqrt{s_{NN}}$=200 GeV, *Phys. Rev. C* 91(3), 031901 (2015), arXiv: 1409.0851 [nucl-ex]
51. E. Goudzovski (NA48/2 Collaboration), Search for the dark photon in π^0 decays by the NA48/2 experiment at CERN, *EPJ Web Conf.* 96, 01017 (2015), arXiv: 1412.8053 [hep-ex]
52. E. M. Riordan, et al., A search for short lived axions in an electron beam dump experiment, *Phys. Rev. Lett.* 59, 755 (1987)
53. A. Bross, M. Crisler, S. H. Pordes, J. Volk, S. Errede, and J. Wrbanek, A search for shortlived particles produced in an electron beam dump, *Phys. Rev. Lett.* 67, 2942 (1991)
54. S. Andreas, C. Niebuhr, and A. Ringwald, New limits on hidden photons from past electron beam dumps, Phys. Rev. D 86, 095019 (2012), arXiv: 1209.6083 [hep-ph]
55. G. Eigen (BaBar Collaboration), Direct searches for new physics particles at BABAR, *J. Phys. Conf. Ser.* 631(1), 012034 (2015), arXiv: 1503.02860 [hep-ex]
56. A. Soffer, Constraints on dark forces from the B factories and low-energy experiments, arXiv: 1409.5263 [hep-ex]
57. A. Soffer, Searches for light scalars, pseudoscalars, and gauge bosons, arXiv: 1507.02330 [hep-ex]
58. M. Pospelov, Secluded U(1) below the weak scale, *Phys. Rev. D* 80, 095002 (2009), arXiv: 0811.1030 [hep-ph]
59. J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, New fixed-target experiments to search for dark gauge forces, *Phys. Rev. D* 80, 075018 (2009), arXiv: 0906.0580 [hep-ph]
60. R. Essig, P. Schuster, N. Toro, and B. Wojtsekhowski, An electron fixed target experiment to search for a new vector boson A′ decaying to e^+e^-, *J. High Energy Phys.* 1102, 009 (2011), arXiv: 1001.2557 [hep-ph]
61. J. Balewski, J. Bernauer, W. Bertozzi, J. Bessuille, B. Buck, et al., DarkLight: A search for dark forces at the Jefferson laboratory free-electron laser facility, arXiv: 1307.4432
62. J. Blumlein and J. Brunner, New exclusion limits for dark gauge forces from beam-dump data, *Phys. Lett. B* 701, 155 (2011), arXiv: 1104.2747 [hep-ex]
63. J. Blmlein and J. Brunner, New exclusion limits on dark gauge forces from proton Bremsstrahlung in beam-dump data, *Phys. Lett. B* 731, 320 (2014), arXiv: 1311.3870 [hep-ph]
64. B. Batell, M. Pospelov, and A. Ritz, Exploring portals to a hidden sector through fixed targets, *Phys. Rev. D* 80, 095024 (2009), arXiv: 0906.5614 [hep-ph]
65. R. Essig, R. Harnik, J. Kaplan, and N. Toro, Discovering new light states at neutrino experiments, *Phys. Rev. D* 82, 113008 (2010), arXiv: 1008.0636 [hep-ph]
66. D. Curtin, R. Essig, S. Gori, and J. Shelton, Illuminating dark photons with high-energy colliders, *J. High Energy Phys.* 1502, 157 (2015), arXiv: 1412.0018 [hep-ph]
67. C. Cheung, J. T. Ruderman, L. T. Wang, and I. Yavin, Lepton jets in (supersymmetric) electroweak processes, *J. High Energy Phys.* 1004, 116 (2010), arXiv: 0909.0290 [hep-ph]
68. Y. Bai and Z. Han, Measuring the dark force at the LHC, *Phys. Rev. Lett.* 103, 051801 (2009), arXiv: 0902.0006 [hep-ph]
69. A. Gupta, R. Primulando and P. Saraswat, A new probe of dark sector dynamics at the LHC, *J. High Energy Phys.* 1509, 079 (2015), arXiv: 1504.01385 [hep-ph]
70. S. Chatrchyan, et al. (CMS Collaboration), Search for light resonances decaying into pairs of muons as a signal of new physics, *J. High Energy Phys.* 1107, 098 (2011), arXiv: 1106.2375 [hep-ex]
71. G. Aad, et al. (ATLAS Collaboration), Search for long-lived neutral particles decaying into lepton jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *J. High Energy Phys.* 1411, 088 (2014), arXiv: 1409.0746 [hep-ex]
72. G. Aad, et al. (ATLAS Collaboration), Search for new light gauge bosons in Higgs boson decays to four-lepton _nal states in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC, arXiv: 1505.07645 [hep-ex]
73. V. M. Abazov, et al. (D0 Collaboration), Search for dark photons from supersymmetric hidden valleys, *Phys. Rev. Lett.* 103, 081802 (2009), arXiv: 0905.1478 [hep-ex]
74. S. Biswas, E. Gabrielli, M. Heikinheimo, and B. Mele, Higgs-boson production in association with a dark photon in e^+e^- collisions, *J. High Energy Phys.* 1506 (2015) 102, arXiv: 1503.05836 [hep-ph]
75. M. J. Strassler and K. M. Zurek, Echoes of a hidden valley at hadron colliders, *Phys. Lett. B* 651, 374 (2007), arXiv: hep-ph/0604261

76. M. J. Strassler, Possible effects of a hidden valley on supersymmetric phenomenology, arXiv: hep-ph/0607160

77. T. Han, Z. Si, K. M. Zurek, and M. J. Strassler, Phenomenology of hidden valleys at hadron colliders, *J. High Energy Phys.* 0807, 008 (2008), arXiv: 0712.2041 [hep-ph]

78. P. Fayet, U-boson detectability, and light dark matter, arXiv: hep-ph/0607094

79. S.-H. Zhu, U-boson at BESIII, *Phys. Rev. D* 75, 115004 (2007), arXiv: hep-ph/0701001

80. R. Essig, J. Mardon, M. Papucci, T. Volansky, and Y. M. Zhong, Constraining light dark matter with low-energy e^+e^- colliders, *J. High Energy Phys.* 1311, 167 (2013), arXiv: 1309.5084 [hep-ph]

81. F. Archilli, et al. (KLOE-2 Collaboration), Search for a vector gauge boson in phi meson decays with the KLOE detector, *Phys. Lett. B* 706, 251 (2012), arXiv: 1110.0411 [hep-ex]

82. A. Anastasi, D. Babusci, G. Bencivenni, M. Berlowski, C. Bloise, et al., Limit on the production of a low-mass vector boson in $\mathrm{e}^+\mathrm{e}^- \to \mathrm{U}\gamma$, $\mathrm{U} \to \mathrm{e}^+\mathrm{e}^-$ with the KLOE experiment, *Phys. Lett. B* 750, 633 (2015), arXiv: 1509.00740 [hep-ex]

83. J. P. Lees, et al. (BaBar Collaboration), Search for di-muon decays of a low-mass Higgs boson in radiative decays of the (1S), *Phys. Rev. D* 87(3), 031102 (2013) [*Phys. Rev. D* 87(5), 059903 (2013)], arXiv: 1210.0287 [hep-ex]

84. B. Aubert, et al. (BaBar Collaboration), Search for a low-mass Higgs boson in Y(3S) → gamma A^0, A^0 → tau^+ tau^- at BABAR, *Phys. Rev. Lett.* 103, 181801 (2009), arXiv: 0906.2219 [hep-ex]

85. J. P. Lees, et al. (BaBar Collaboration), Search for a low-mass scalar Higgs boson decaying to a tau pair in single-photon decays of $\Upsilon(1S)$, *Phys. Rev. D* 88(7), 071102 (2013), arXiv: 1210.5669 [hep-ex]

86. B. Aubert, et al. (BaBar Collaboration), Search for invisible decays of a light scalar in radiative transitions $\upsilon_{3S} \to \gamma\ \mathrm{A}^0$, arXiv: 0808.0017 [hep-ex]

87. P. del Amo Sanchez, et al. (BaBar Collaboration), Search for production of invisible final states in single-photon decays of $\Upsilon(1S)$, *Phys. Rev. Lett.* 107, 021804 (2011), arXiv: 1007.4646 [hep-ex]

88. W. Love, et al. (CLEO Collaboration), Search for very light CP-odd Higgs boson in radiative decays of Upsilon(S-1), *Phys. Rev. Lett.* 101 (2008) 151802, arXiv: 0807.1427 [hep-ex]

89. B. Aubert, et al. (BaBar Collaboration), Search for a narrow resonance in e^+e^- to four lepton final states, arXiv: 0908.2821 [hep-ex]

90. J. P. Lees, et al. (BaBar Collaboration), Search for low-mass dark-sector Higgs bosons, *Phys. Rev. Lett.* 108, 211801 (2012), arXiv: 1202.1313 [hep-ex]

91. I. Jaegle (Belle Collaboration), Search for the dark photon and the dark Higgs boson at Belle, *Phys. Rev. Lett.* 114(21), 211801 (2015), arXiv: 1502.00084 [hep-ex]

92. M. Ablikim, et al. (BESIII Collaboration), Search for a light Higgs-like boson A^0 in J/ψ radiative decays, *Phys. Rev. D* 85, 092012 (2012), arXiv: 1111.2112 [hep-ex]

93. M. Ablikim, et al. (BESIII Collaboration), Search for η and η' invisible decays in $\mathrm{J}/\psi \to \phi\eta$ and $\phi\eta'$, *Phys. Rev. D* 87(1), 012009 (2013), arXiv: 1209.2469 [hep-ex]

94. H.-B. Li and T. Luo, Probing dark force at BES-III/BEPCII, *Phys. Lett. B* 686, 249 (2010), arXiv: 0911.2067 [hep-ph]

95. V. Prasad, H. Li, and X. Lou, Search for low-mass Higgs and dark photons at BESIII, arXiv: 1508.07659 [hep-ex]

96. P. F. Yin and S. H. Zhu, Detecting light long-lived particle produced by cosmic ray, *Phys. Lett. B* 685, 128 (2010), arXiv: 0911.3338 [hep-ph]

97. S. H. Zhu, V-particle again? *Int. J. Mod. Phys. D* 20, 1399 (2011)

98. B. Batell, M. Pospelov, A. Ritz and Y. Shang, Solar gamma rays powered by secluded dark matter, *Phys. Rev. D* 81, 075004 (2010), arXiv: 0910.1567 [hep-ph]

99. P. Schuster, N. Toro, N. Weiner and I. Yavin, High energy electron signals from dark matter annihilation in the Sun, *Phys. Rev. D* 82, 115012 (2010), arXiv: 0910.1839 [hep-ph]

100. P. Meade, S. Nussinov, M. Papucci and T. Volansky, Searches for long lived neutral particles, *J. High Energy Phys.* 1006, 029 (2010), arXiv: 0910.4160 [hep-ph]

101. S. H. Zhu, Dark matter signature from the sky and at colliders, *PoS ICHEP* 2010, 451 (2010), arXiv: 1008.3963 [hep-ph]