Belle II constraints on sub-GeV dark matter

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We study the Belle II constraints on the sub-GeV dark matter that interacts with charged leptons. Two kinds of models with different interaction mechanisms between dark matter and charged leptons are considered in the analysis: the EFT operators and the light mediator models. The Belle II mono-photon constraints on the EFT operators are found to be of similar size as the LEP constraints. However, for the light mediator models, the Belle II mono-photon constraints can be much stronger than the LEP limits. For both EFT operators and the light mediator models, the Belle II limits can be several orders of magnitude stronger than the current dark matter direct detection limits, as well as the white dwarf limit. The light mediator can also be searched for in the leptonic decay final states, which is complementary to the mono-photon channel and can even become the better discovery channel for certain parameter space.

I. INTRODUCTION

Although dark matter (DM) makes up a quarter of the total energy density of the universe, its particle property remains unknown today. During the past decades, a great amount of theoretical and experimental efforts have been put into searches for the weakly interacting massive particles (WIMPs), which have constrained the DM-nucleus cross section to an unprecedented level. Recently, dark matter direct detection (DMDD) experiments have also started to provide compelling limits on sub-GeV dark matter particles. For sub-GeV dark matter, electronic signals become important in DMDD experiments. Scattered by DM, electrons in the target can be either ionized or excited. The DMDD experiments with an ionization signal include XENON10 [1], XENON100 [1], XENON1T [2], DarkSide-50 [3], and PandaX [4]; the experiments with an excitation signal include SENSEI [5], DAMIC [6], EDELWEISS [7], and SuperCDMS [8]. The excitation signal can have a lower energy threshold than the ionization signal, leading to a better sensitivity for lighter dark matter. Currently, the xenon target experiments and SENSEI provide the leading DMDD constraints to sub-GeV DM. Astrophysical processes can also give competitive constraints to sub-GeV DM, for example, heating constraints in white dwarfs due to DM [9–14]. Furthermore, interactions between sub-GeV DM and cosmic rays [15–17], and Sun [18, 19] can significantly alter the velocity of the DM particle, and thus enhance the sensitivity of the DMDD experiments.

In this paper, we study the Belle II constraints on sub-GeV dark matter that interacts with charged leptons. Belle II is operated at SuperKEKB which collides 7 GeV electrons with 4 GeV positrons [20]. In the 8-year data taking, Belle II is expected to accumulate 50 ab$^{-1}$ data [20], which is much more than other low energy electron-positron colliders, such as BaBar and BESIII. Moreover, the calorimeter of Belle II is much more hermetic with non-projective barrel crystals, which makes it an ideal detector for DM searches [20, 21].

Electron collider constraints on DM have been studied previously, including Belle II [20, 22–27, 27–30], LEP [31–35], and other electron colliders [36–56]. In this paper, we study the capability of the Belle II experiment in probing the parameter space of the sub-GeV dark matter models, including both the effective field theory (EFT) operators and the light mediator models. To our knowledge, Belle II constraints on various EFT operators between DM and charged leptons have not been thoroughly studied in the literature. Certain light mediator models, e.g., the dark photon model has been studied in Ref. [20]. Here we consider a more general light mediator model in which the light mediator has both vector and axial-vector couplings to fermions in the hidden sector and in the SM sector. Thus we carry out detailed Belle II analyses both for the EFT operators and for the light mediator models with different mass relations and different couplings. We compute the mono-photon constraints on the EFT operators and on the light mediator models, and further compare the limits to the DMDD constraints. We find that the Belle II mono-photon limits can be much stronger than current DMDD constraints, and can also constrain the proposed DM models to interpret the recent excess events in Xenon1T electron recoil data [57]. For the light mediator models, we further compute the Belle II limits due to the visible decay final states of the mediator, and find that the visible channel can be complementary to the mono-photon channel.

The rest of the paper is organized as follows. In Sec. II, we introduce two kinds of dark matter models: the EFT operators and the light mediator models. We discuss both the signal events and the SM background events in the mono-photon channel in Sec. III. We compute the Belle II mono-photon constraints for the EFT operators and for the light mediator models in Sec. IV and Sec. V respectively, and further compute them to the DMDD limits. We also analyze the di-muon limits on the light mediator models in Sec. VI. We summarize our findings in Sec. VII.
II. DARK MATTER MODELS AND THE MONO-PHOTON SIGNAL

In this paper, we consider two kinds of DM models: (1) DM interacts with charged leptons via EFT operators; (2) DM interacts with charged leptons via a light mediator. There are a variety of EFT operators between the SM and dark matter. Here we consider the fermionic dark matter that has four-fermion EFT interaction with charged leptons as follows

$$\mathcal{L} = \frac{1}{\Lambda_{\gamma}^2} \bar{\chi} \gamma_{\mu} \chi \ell \gamma^{\mu} \ell,$$  \tag{1}

$$\mathcal{L} = \frac{1}{\Lambda_{A}^2} \bar{\chi} \gamma_{\mu} \gamma_{5} \chi \ell \gamma^{\mu} \gamma_{5} \ell,$$  \tag{2}

$$\mathcal{L} = \frac{1}{\Lambda_{\chi}^2} \bar{\chi} \chi \ell \ell,$$  \tag{3}

$$\mathcal{L} = \frac{1}{\Lambda_{\chi}^2} \bar{\chi} \ell \ell \chi,$$  \tag{4}

where \( \chi \) is the Dirac DM, \( l \) denotes the SM charged lepton, \( \Lambda \) is the new physics scale. Here \( \Lambda_{\chi} \) (\( \Lambda_{A} \)) is the parameter for the vector (axial-vector) case, and \( \Lambda_{\gamma} \) (\( \Lambda_{t} \)) is the parameter for the case where an s-channel (t-channel) scalar mediator is integrated out. The differential cross sections at the electron colliders for the above four EFT operators have been computed in Ref. [42]; we collect these cross section formulas in Appendix A.

We consider a light mediator model in which the light mediator is a spin one particle with couplings to both hidden sector dark matter and charged leptons; the interaction Lagrangian is given by

$$\mathcal{L} = Z'_{\mu} \bar{\chi} \gamma^{\mu} (g_{\chi}^{\bar{\gamma}} - g_{a}^{\bar{\gamma}} \gamma_{5}) \chi + Z'_{\mu} \bar{l} \gamma^{\mu} (g_{l}^{\bar{\gamma}} - g_{a}^{\bar{\gamma}} \gamma_{5}) l,$$  \tag{5}

where \( Z' \) denotes the light mediator, \( \chi \) is the dark matter, \( l \) is the SM charged lepton, \( g_{\chi}^{\bar{\gamma}} (g_{l}^{\bar{\gamma}}) \) is the vector (axial-vector) coupling. The mono-photon cross section at the electron colliders for the process \( e^+ e^- \rightarrow \gamma Z' \rightarrow \gamma \chi \bar{\chi} \) is given by [47]

$$\frac{d\sigma}{dE_\gamma dz_\gamma} = \frac{\alpha \left[ (g_{\chi}^{\bar{\gamma}})^2 + (g_{l}^{\bar{\gamma}})^2 \right] \left[ (g_{\chi}^{\bar{\gamma}})^2 (1 + 2y) + (g_{a}^{\bar{\gamma}})^2 (1 - 4y) \right] s_{\gamma}^2 \beta_{\chi} \left[ 1 + x (1 + z^2_{\gamma}) \right]}{6\pi^2 s E_\gamma \left( s_{\gamma} - m_{Z'}^2 \right)^2 + m_{Z'}^4 \Gamma_{Z'}^2},$$  \tag{6}

where \( E_\gamma \) and \( \theta_{\gamma} \) are the photon energy and polar angle respectively in the center of mass frame, \( s \) is the square of the center of mass energy, \( z_{\gamma} = \cos \theta_{\gamma}, s_{\gamma} = s - 2\sqrt{s} E_\gamma, y = m_\gamma^2 / s_{\gamma}, x = E_\gamma / s_{\gamma}, \beta_{\chi} = (1 - 4y)^{1/2}, \) and \( m_{Z'} \) and \( \Gamma_{Z'} \) are the mass and the total decay width of the \( Z' \) boson. The \( Z' \) total decay width is given by

$$\Gamma_{Z'} = \Gamma (Z' \rightarrow \chi \bar{\chi}) + \sum_{l} \Gamma (Z' \rightarrow l \bar{l}),$$  \tag{7}

where \( \Gamma (Z' \rightarrow \chi \bar{\chi}) \) is the invisible decay width with DM in the final state, and \( \Gamma (Z' \rightarrow l \bar{l}) \) is the decay width with SM particles in the final state. The invisible decay width is given by

$$\Gamma (Z' \rightarrow \chi \bar{\chi}) = \frac{m_{Z'}}{12\pi} \sqrt{1 - 4 \frac{m_\gamma^2}{m_{Z'}^2}} \left[ (g_{\chi}^{\bar{\gamma}})^2 \left( 1 + 2 \frac{m_\gamma^2}{m_{Z'}^2} \right) + (g_{a}^{\bar{\gamma}})^2 \left( 1 - 4 \frac{m_\gamma^2}{m_{Z'}^2} \right) \right],$$  \tag{8}

\( \Gamma (Z' \rightarrow l \bar{l}) \) can be computed similarly by substituting the couplings and mass for lepton.

III. MONO-PHOTON SEARCH AT BELLE II

In this section, we use the mono-photon final state, \( e^+ e^- \rightarrow \chi \bar{\chi} \gamma \), to probe the DM models at Belle II. For each of the DM models, the number of signal events is calculated by the analytic expressions of the differential cross sections offered in section II. In our analysis, we consider both the reducible background and the irreducible background for the mono-photon process.

The mono-photon irreducible background is due to the \( e^+ e^- \rightarrow \gamma \nu \bar{\nu} \) process in the SM; the differential cross section of the \( e^+ e^- \rightarrow \gamma \nu \bar{\nu} \) process in the SM is given by [40, 58, 59]

$$\frac{d\sigma_{\gamma\nu\bar{\nu}}}{dE_\gamma dz_\gamma} = \frac{\alpha G_F^2 s_{\gamma}^2}{4\pi^2 s E_\gamma \left( 1 - z_{\gamma}^2 \right)} f (s_{\gamma}) \left[ 1 + \frac{E_\gamma^2}{s_{\gamma}} \left( 1 + z_{\gamma}^2 \right) \right],$$  \tag{9}
where $G_F$ is the Fermi constant, $s_W = \sin \theta_W$ with $\theta_W$ being the weak mixing angle, and $f(x) = 8x^4 - 4x^2/3 + 1$.

Photons at Belle II are detected in the ECL and KLM sub-detectors, both of which consist of three segments: the forward detector, the backward detector, and the barrel detector [20]. The mono-photon reducible backgrounds at the Belle II detector come from the SM processes in which one or more SM final state particles are not detected by the detector. The main reducible background in our analysis is due to the $e^+e^- \rightarrow \gamma\gamma\gamma$ process, where two of the final state photons are not detected because one photon escapes in the beam direction and the other escapes in the region where the detector has no coverage or a very low detection efficiency, for example, the gaps between different segments of the ECL and KLM sub-detectors, and the gap located at 90$^\circ$ of the ECL barrel [20]. We note that the reducible background events can be mitigated by setting certain kinematic conditions [22].

The reducible BG at the Belle II detector has been analyzed by Ref. [20]. For the sub-GeV DM particles, we adopt the low-mass region given in Ref. [20] as the signal region in our analysis; recently a fitting function for the boundary of this region is given in Ref. [23]

$$\theta^{\text{low}}_{\text{min}} = 5.399^\circ E_{\text{CMS}}(\gamma)^2/\text{GeV}^2 - 58.82^\circ E_{\text{CMS}}(\gamma)/\text{GeV} + 195.71^\circ,$$

$$\theta^{\text{low}}_{\text{max}} = -7.982^\circ E_{\text{CMS}}(\gamma)^2/\text{GeV}^2 + 87.77^\circ E_{\text{CMS}}(\gamma)/\text{GeV} - 120.6^\circ,$$

where $\theta^{\text{low}}_{\text{min}}$ and $\theta^{\text{low}}_{\text{max}}$ are the minimum and maximum angles for the photon in the lab frame, namely $\theta^{\text{low}}_{\text{min}} < \theta^{\text{lab}} < \theta^{\text{low}}_{\text{max}}$. In the signal region, about 300 mono-photon events from the reducible backgrounds are expected with 20 fb$^{-1}$ data [20], corresponding to $\sim 7.5 \times 10^5$ mono-photon events with 50 ab$^{-1}$ data; there are about $1.9 \times 10^3$ mono-photon events from the irreducible background process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ with 50 ab$^{-1}$ data.

IV. MONO-PHOTON CONSTRAINTS ON EFT OPERATORS

We compute the Belle II 95% C.L. limits on the EFT operators, by using the criterion $N_s/\sqrt{N_b} = \sqrt{2.71}$, where $N_s$ ($N_b$) is the number of signal (background) events in the signal region. Fig. (1) shows the Belle II 95% C.L. lower bounds on the EFT operators, from the mono-photon channel with 50 ab$^{-1}$ integrated luminosity. As shown in the left panel figure of Fig. (1), the Belle II 95% C.L. lower bounds are $\sim 280$ GeV, for $\Lambda_V$, $\Lambda_A$, and $\Lambda_s$, and are about $\sim 220$ GeV for $\Lambda_t$. We further compare the Belle II limits to the LEP limits analyzed by Ref. [35]. Mono-photon data with 650 pb$^{-1}$ at various $\sqrt{s}$ from 180 GeV to 209 GeV have been collected by the DELPHI detector at LEP [35, 60]. The LEP mono-photon data are binned in 19 $x_{\gamma} = E_{\gamma}/E_{\text{beam}}$ bins [35], where $E_{\gamma}$ and $E_{\text{beam}}$ are the energy of photon and the beam energy respectively. The LEP 95% C.L. lower limits on EFT operator with sub-GeV mass, 2 are about 480 GeV for $\Lambda_V$ and $\Lambda_A$, 440 GeV for $\Lambda_s$, and 340 GeV for $\Lambda_t$ [35].

Although the expected integrated luminosity of Belle II is about five orders of magnitude larger than LEP, their limits on the EFT operators turn out to be of similar size. This is largely due to the fact that EFT operators and the SM processes depend on $\sqrt{s}$ in different ways. For the four-fermion EFT operators, the cross section is proportional to $s$ (to compensate the $s^4$ factor in the denominator), whereas for the QED process (responsible for the reducible background at Belle II), the cross section is inversely proportional to $s$. For that reason, the dominant reducible background at Belle II becomes totally negligible at LEP, whereas the cross sections of EFT operators at LEP are enhanced by a factor of $\sim 400$ as compared to Belle II. The weak processes that lead to the irreducible mono-photon backgrounds have a similar proportionality on $s$ as the EFT operators up to the $Z/W$ mass scale. Taking these effects into consideration, we find that LEP is expected to have similar constraints on the four-fermion EFT operators as Belle II.

We further compare the collider constraints on the EFT operators to other experimental constraints. We compute the DM-electron scattering cross section at the momentum transfer $q \equiv |q| = \alpha m_{\chi}$ [65, 66], by using the limit on $\Lambda$ in the EFT operators

$$\bar{\sigma}_e \equiv \frac{\mu^2_{\chi e}}{16\pi m^2_{\chi} m^2_e} |M_{\chi e}(q^2)|^2 |q = \alpha m_{\chi}|,$$

where $m_{\chi}$ is the DM mass, $m_e$ is the electron mass, $\mu_{\chi e}$ is the reduced mass. Here both DM and electron are assumed to be non-relativistic, and the dependence on $q$ is solely in the matrix element $M_{\chi e}$, which can be factorized as $|M_{\chi e}(q^2)|^2 = |M_{\chi e}(\alpha m_{\chi})|^2 |F_{\text{DM}}(q)|^2.$ We have $|M_{\chi e}(\alpha m_{\chi})|^2 \simeq 16 m^2_e m^2_{\chi}/\Lambda^4$ for all the four EFT operators.

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1 We use “slash” to denote a particle that is not detected by the detector.

2 We note that the 95% C.L. limits are actually quoted as the 90% C.L. limits in Ref. [35] due to a different convention.

3 See appendix B for the expression of $|M_{\chi e}(q)|^2$ for the EFT operators.
except $\Lambda_A$ which is 3 times larger. The form factor for the EFT operators considered in our analysis is found to be $F_{\text{DM}}(q) \simeq 1$. For the EFT operators the collider constraints from Belle II and LEP on sub-GeV DM are found to be much stronger than the DMDD limits, including the constraints from SENSEI [63], CDMS-HVeV [61], DAMIC [62], XENON10 [1], XENON1T [2], DMDD limits via solar reflection [18], and white dwarfs [9–14]. The constraint on $\bar{\sigma}_e$ from white dwarfs, as shown in Fig. (1), is computed via Eq. (12), by using of the lower bound on $\Lambda$ given in Ref. [9]. The gray dashed line in Fig. (1) shows the neutrino floor limit for silicon target detectors where the exposure is 1000 kg-year [64].

**V. MONO-PHOTON CONSTRAINTS ON LIGHT MEDIATOR MODEL**

We investigate the capability of the Belle II detector in probing the light mediator models in which the light mediator $Z'$ couples to both DM and charged leptons. Unlike the four-fermion EFT operators, the collider cross section in the light-mediator models is not proportional to $s$. For that reason, the Belle II is expected to explore some new parameter space in the light-mediator models that has not been probed by the LEP experiment.

In this analysis, we are interested in the $Z'$ mass below the Belle II $\sqrt{s} \simeq 10$ GeV. Thus we consider three $Z'$ masses in the MeV-GeV mass range: 10 MeV, 0.6 GeV, and 5 GeV. We note that for ultralight mediators, constraints from cosmic microwave background (CMB) and baryon acoustic oscillations (BAO) are usually much more stringent than collider searches [68].

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*Our white dwarf constraint on $\bar{\sigma}_e$ is different from Ref. [9] where the cross section is evaluated at the momentum/energy scale relevant for DM captures in white dwarfs [67]. The white dwarfs limits are $\Lambda_V \simeq \Lambda_A \simeq 200$ GeV and $\Lambda_s \simeq 200$ MeV when $m_\chi > 100$ MeV as given in Ref. [9].

*The neutrino floors for Xe and Ge targets are higher than Si.*
Figure 2: The expected Belle II 95\% C.L. upper bound (solid lines) with 50 ab$^{-1}$ integrated luminosity on $g'_2$ (left panel) and $\bar{\sigma}_e$ (right panel) in light mediator models where only vector couplings are assumed. Three $Z'$ masses are considered for the Belle II analysis: $m_{Z'} = 5$ GeV (red), $m_{Z'} = 6.6$ GeV (blue), and $m_{Z'} = 10$ MeV (green). The LEP constraints (dashed lines) with 650 pb$^{-1}$ integrated luminosity are also shown for two $Z'$ masses: $m_{Z'} = 5$ GeV (red), and $m_{Z'} = 6.6$ GeV (blue). Constraints from DMDD experiments with $F_{DM}(q) = 1$ (valid for $m_{Z'} \gg m_\chi$) are also shown: SENSEI [63], XENON10 [1] and XENON1T [2], CDMS-HVeV [61], DAMIC [62], and solar reflection [18]. The gray dashed line shows the neutrino floor limit for silicon detectors [64].

Figure 3: Same as Fig. (2) but for light mediator models where only axial-vector couplings are assumed.

We compute the Belle II 95\% C.L. limits on the light-mediator models using the same criterion as the EFT operators, namely by setting $N_s/\sqrt{N_b} = \sqrt{2.7}I$, where $N_s$ is obtained by integrating Eq. (6) in the signal region. The expected Belle II 95\% C.L. upper bounds with 50 ab$^{-1}$ data on the gauge coupling are shown on left panel figure of Fig. (2) and Fig. (3), where we only consider vector couplings and axial-vector couplings respectively. The collider signals depend strongly on the mass relations between the light mediator and DM. There are two categories:

- $m_{Z'} > 2m_\chi$. The $Z'$ boson mainly decays into dark matter. Thus the $Z'$ boson can be produced on-shell in the $e^+e^- \to \chi\bar{\chi}$ process and is exhibited as a resonance in the mono-photon energy spectrum (see e.g. [39] [38] [51] [47]). The mono-photon cross section can be approximated by $\sigma_{\gamma\gamma} \approx \sigma_{Z'} \times BR(Z' \to \chi\bar{\chi})$. Because the branching ratio $BR(Z' \to \chi\bar{\chi}) \approx 1$ in the parameter space of interest in this analysis, and the cross section of $Z'\rightarrow \gamma\gamma$ is proportional to $(g')^2$, the mono-photon cross section depends on $g'_2$, but not on $m_\chi$ or $g^v$. The $m_\chi$ independence can be seen in Fig. (2) and Fig. (3) in the mass range $m_\chi < m_{Z'}/2$.

- $m_{Z'} < 2m_\chi$. The $Z'$ boson can only decay into the SM particles. Thus the $Z'$ boson is produced off-shell
in the $e^+e^- \rightarrow \chi\chi$ process without a resonance in the mono-photon energy spectrum. In this case, $\sigma_{\chi\chi}$ is proportional to $\left(g^{\prime}_{\chi}g_{\chi}\right)^2$ and depends on $m_{\chi}$, which can be seen in Fig. (2) and Fig. (3).

For both the vector-only case and the axial-vector-only case, the Belle II upper limits are about $g^{\prime} \sim 3 \times 10^{-5}$ when $m_{Z'} > 2m_{\chi}$, as shown in Fig. (2) and Fig. (3). For the vector-only case, the sensitivity is highly enhanced if $m_{Z'} = 2m_{\chi}$. We further compare the Belle II limits to the LEP limits. LEP constraints on light mediator models with $m_{Z'} > 10$ GeV have been studied in Ref. [35]. Here we analyze the LEP constraints to the region where $m_{Z'} < 10$ GeV, following the analysis of Ref. [35]; the details of our LEP analysis are given in section C. As shown in Fig. (2) and Fig. (3), the LEP constraints are about $3 \times 10^{-2}$ for both vector and axial-vector couplings when $m_{Z'} > 2m_{\chi}$, which are three orders of magnitude stronger than Belle II. Unlike the EFT operators, there are resonance signals in the mono-photon energy spectrum, which correspond to the Breit-Wigner resonance of the $Z'$ boson, in the light mediator models. One could select the events near the resonance to further improve the significance of the searches.

Similar to the analysis for the EFT operators, we compare the collider limits on the light mediator models to DMDD limits on the right panel figures of Figs. (2) and (3). In the non-relativistic limit, the amplitude for the light mediator models is given by

$$|M_{\chi e}|^2 \simeq 16m_{\chi}^2m_{\chi}^2\left(g^{\prime}_{\chi}g_{\chi}\right)^2 + 3g^{\prime 2}_{\chi}g^{2}_{\chi}\left(m_{Z'}^2 + q^2\right)^2.$$  

(13)

Thus we have $F_{DM}(q) \simeq 1$ for $m_{Z'} \gg m_{\chi}c$, which is the case for the model points considered in our study. The reference amplitude $|M_{\chi e} (q = am_{\chi})|^2$ is obtained by neglecting $q^2$ term in the denominator of Eq. (13), resulting in an $m_{Z'}^4$ dependence in the reference cross section $\sigma_{\chi}$. We find that for the light mediator in the GeV scale, the Belle II limits can be several orders of magnitude stronger than the DMDD limits, including SENSEI [63], CDMS-HVeV [61], DAMIC [62], XENON10 [1], XENON1T [2], and DMDD limits via solar reflection [18]. For example, Belle II can explore the parameter space well below the neutrino floor for silicon detectors [64], for the case where $m_{Z'} \gtrsim 5$ GeV. However, for the mediator mass at the MeV scale, the Belle II limits become somewhat weaker due to the $m_{Z'}^4$ dependence. For example, the parameter space to be probed by Belle II for the $m_{Z'} \sim 10$ MeV case has already been excluded by the current DMDD limits, except the parameter space in the vicinity of $m_{Z'} \simeq 2m_{\chi}$ in the vector-coupling-only case, where the Belle II limits are significantly enhanced.

We further display the Belle II mono-photon constraints on $\sigma_{\chi}$ with 50 ab$^{-1}$ for each model point in the $m_{\chi} - m_{Z'}$ plane for the vector-coupling-only case, as shown in Fig. (4). Because the $\sigma_{\chi}$ value to be probed by Belle II is proportional to $m_{Z'}^{-4}$, the DM models with a smaller $m_{Z'}$ is less constrained, for example $\sigma_{\chi} > 10^{-30}$ cm$^2$ is still allowed for a sub-MeV mediator. We also find that the constraint decreases with the DM mass $m_{\chi}$ and becomes very strong in the vicinity of the $m_{Z'} = 2m_{\chi}$ line.

Recently, excess events in the electron recoil data are observed in the Xenon1T experiment [57]. A number of papers have used DM to explain such an excess, some of which require a sizable DM-electron interaction cross section [69–72]. We note that for EFT operators between DM and electron, and for the GeV-mediated models, such strong DM-electron interaction cross sections are likely to be constrained by Belle II. However, for the models with a relatively light mediator, the DM-electron cross section can be significantly large, for example, $\sigma_{\chi} \gtrsim 0(10^{-30})$ cm$^2$ for the mediator mass below MeV is likely to remain unconstrained with the Belle II data.

VI. DILEPTON SIGNALS IN LIGHT MEDIATOR MODELS

Because for the light mediator that couples to leptons, it is inevitable that the mediator can decay into a pair of final state leptons if kinematically allowed, one can search for the dark matter via the visible decay of the light mediator. Here we choose the process $e^+e^- \rightarrow \gamma\mu^+\mu^-$ to search for the $Z'$ resonance in the di-muon invariant mass spectrum.

We use MADGRAPH [73] to generate $10^5$ events for the $e^+e^- \rightarrow \gamma\mu^+\mu^-$ process for each new physics model point and for the SM. The main SM backgrounds are from $e^+e^- \rightarrow \gamma\mu^+\mu^-$ mediated by photon, since the center of mass energy is much smaller than the mass of $Z$ boson. We use the following preselection cut for MADGRAPH simulations: we select photons that are within the angle coverage of ECL such that $12.4^\circ < \theta_{\gamma\mu}^\ell < 155.1^\circ$, and muons within the angle coverage of KLM such that $25^\circ < \theta_{\mu\mu}^\ell < 155^\circ$ [20]. We adopt the “three isolated clusters” [24] as the trigger condition, which requires that (i) at least three isolated calorimeter clusters with a minimum distance of $d_{\text{min}} = 30$
Figure 4: The expected Belle II upper bound on $\bar{\sigma}_{e}$ for each model point in the $m_{\chi} - m_{Z'}$ plane, in the mono-photon channel with 50 ab$^{-1}$, where only vector couplings are considered. We have estimated the limits in the vicinity of $m_{Z'} = 2m_{\chi}$, where the Belle II sensitivity is highly enhanced. The limits along the $m_{Z'} = 2m_{\chi}$ line are shown for illustrative purposes only; the more accurate values require a detailed analysis which is beyond the scope of the current work.

Table I: Selection cuts for photons and muons adopted from Ref. [23].

| Cuts | Conditions |
|------|-------------|
| muons | (i) both $p_T(\mu^+)$ and $p_T(\mu^-) > 0.05$ GeV  
(ii) opening angle of pair $> 0.1$ rad  
(iii) invariant mass of pair $m_{\mu\mu} > 0.03$ GeV  
(iv) $m_{\mu\mu} < 0.480$ GeV or $m_{\mu\mu} > 0.520$ GeV |
| photons | (i) $E_{\text{lab}} > 0.5$ GeV  
(ii) $17^\circ < \theta_{\text{lab}} \leq 150^\circ$ |

We compute the Belle II sensitivity (95% C.L. upper bound) to the new physics model in the di-muon channel with 50 ab$^{-1}$ integrated luminosity, by using the condition $N_{s}/\sqrt{N_{b}} = \sqrt{2.71}$, where $N_{s}$ is the number of new physics signal events, and $N_{b}$ is the number of SM background events. The expected 95% C.L. upper bounds on $g_{l}$ are shown on the left panel figure of Fig. (5) where we take $g_{l}^{d} = g_{l}^{s} = 0$ and $g_{l}^{v} = 1$; the corresponding limits on $\bar{\sigma}_{e}$ are shown on the right panel figure of Fig. (5). We consider two new physics models with the following $Z'$ masses: $m_{Z'} = 0.6$ GeV and $m_{Z'} = 5$ GeV. For the $m_{Z'} = 5$ GeV case, the expected 95% C.L. upper bound on $g_{l}^{d}$ in the di-muon channel is $g_{l}^{d} \lesssim 10^{-3}$ in the MeV-GeV DM mass range, which is about two orders of magnitude weaker than in the mono-photon channel. The $m_{Z'} = 0.6$ GeV case is similar to the $m_{Z'} = 5$ GeV except in the mass range $m_{\chi} > 0.3$ GeV.

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6 We use the incident position on the first layer of the ECL detectors to compute $d_{\text{min}}$. The inner surface of the barrel region of the detector is $r = 125$ cm away from the beam and with the polar angle $32.2^\circ < \theta < 128.7^\circ$; the forward (backward) detector is placed at $r = 196 (-102)$ cm with $12.4^\circ < \theta < 31.4^\circ (130.7^\circ < \theta < 155.1^\circ)$ [20].

7 In the $e^+e^- \rightarrow \gamma \mu^+\mu^-$ process at the electron colliders, the di-muon invariant mass is related to the photon energy via $m_{\mu\mu}^2 = s - 2\sqrt{E_{\gamma}}$, and the uncertainty is given by $\sigma_{m_{\mu\mu}} = \sigma_{E_{\gamma}}/\sqrt{m_{\mu\mu}}$, where $\sigma_{E_{\gamma}}/E_{\gamma} = 2\%$ [20]. Thus, for $m_{Z'} = 5$ GeV case, we have $\sigma_{m_{\mu\mu}}/m_{\mu\mu} \approx 6.4\%$ from the photon energy measurement, which is of the same order as the di-muon invariant mass measurement.
GeV, where the di-muon limit becomes stronger than the mono-photon limit. This is due to the fact that for the case where $m_{Z'} = 0.6$ GeV and $m_\chi > 0.3$ GeV, dileptons can be produced on the $Z'$ resonance, but DM can only be produced off the $Z'$ resonance. The di-muon limit for the $m_{Z'} = 5$ GeV case is comparable to the neutrino floor limit of the silicon detectors [64] and is several orders of magnitude stronger than the current DMD limits, which includes SENSEI [63], XENON10 [1] and XENON1T [2], CDMS-HVeV [61], DAMIC [62], and solar reflection [18]. The expected 95\% C.L. upper bound on $g_\ell'$ is about three times weaker than $g_\ell$ in the low DM mass range.

The different limits on $g_\ell'$ and $g_\ell$ are primarily due to different behaviors in the photon-$Z'$ interference terms in the cross section. The total amplitude square of the $e^+e^- \rightarrow \mu^+\mu^-\gamma$ process can be parameterized as $|\mathcal{M}|^2 = |\mathcal{M}_\gamma + \mathcal{M}_{Z'} + \mathcal{M}_Z|^2$, where $\mathcal{M}_\gamma$, $\mathcal{M}_{Z'}$, and $\mathcal{M}_Z$ denote the amplitudes mediated by the photon, $Z'$, and $Z$ respectively. Since $m_{Z'}$ is much larger than $\sqrt{s}$ of Belle II, we neglect $\mathcal{M}_Z$ here. Hence, the $e^+e^- \rightarrow \mu^+\mu^-\gamma$ cross section receives three contributions: $\sigma = \sigma_\gamma + \sigma_{Z'} + \sigma_Z$, where $\sigma_\gamma$ denotes the SM background mediated by the photon, $\sigma_{Z'}$ denotes the cross section due to the $\gamma - Z'$ interference term, and $\sigma_Z$ denotes the cross section due to the $Z'$ term. The expressions of $\sigma_{Z'}$ are similar in the vector only case and in the axial-vector only case; the $\sigma_Z$ contributions, however, are very different. For example, we have $\sigma_{Z'} = 2.36$ (0.379) fb and $\sigma_Z = 0.472$ (0.603) fb for the case where $g_\ell' (g_\ell) = 0.01$, $m_{Z'} = 5$ GeV, and $m_\chi = 1$ GeV. Therefore the total cross section in the vector case is about one order of magnitude larger than the axial-vector case. Although we have imposed detector cuts to select events from the $Z'$ resonance, the contribution from $\sigma_{Z'}$ turns out to be comparable to that from $\sigma_Z$, because the NP couplings ($g_\ell'$ and $g_\ell$) are much smaller than the QED coupling constant $e$.

We further compare the 95\% C.L. upper bound on $g_\ell'$ from the mono-photon channel and from the di-muon channel on the $g_\ell' - g_\ell$ plane in Fig. (7), where we consider the vector-only case and take $m_{Z'} = 0.6$ GeV. For the case where $m_\chi = 0.1$ GeV, the $Z'$ boson can decay into a pair of DM particles. For that reason, Belle II can probe a much smaller $g_\ell'$ in the mono-photon channel than in the di-muon channel, in the range of $g_\ell' \gtrsim 5 \times 10^{-5}$; only for very small $g_\ell'$ values (namely $g_\ell' \lesssim 5 \times 10^{-5}$), the di-muon channel becomes the better channel to constrain the parameter space. We further compare the sensitivities from these two channels for all the model points on the $g_\ell' - g_\ell$ plane, and find that the parameter space can be approximately divided by the line $g_\ell' = 2g_\ell$ into two regions: model points on the left-upper side of the line typically receive a stronger constraint from the di-muon channel than from the mono-photon channel; model points on the right-lower side of the line, on the other hand, are better constrained by the mono-photon channel. We also estimate the di-muon sensitivity curve by neglecting the $\gamma - Z'$ interference term, as indicated by the blue dotted line in the left panel figure of Fig. (7). We find that the $\gamma - Z'$ interference term cannot be neglected for the parameter range of $g_\ell' > 0.1$ and produces the dominant contribution to the di-muon

Figure 5: The expected Belle II 95\% C.L. upper bound via visible search (dashed) with 50 ab$^{-1}$ integrated luminosity on $g_\ell'$ (left panel) and $\sigma_\ell$ (right panel) in light mediator models where only vector couplings are assumed. Two $Z'$ masses are considered for the di-muon search analysis: $m_{Z'} = 5$ GeV (red) and $m_{Z'} = 0.6$ GeV (blue). The Belle II mono-photon search constraints (solid) are shown for the two $Z'$ masses. Constraints from DMD experiments with $F_{\text{DDDM}}(g) = 1$ (valid for $m_{Z'} \gg \text{ome}_\gamma$) are also shown: SENSEI [63], XENON10 [1] and XENON1T [2], CDMS-HVeV [61], DAMIC [62], and solar reflection [18]. The gray dashed line shows the neutrino floor limit for silicon detectors [64].
signal for the parameter range of $g_\chi^X \sim 1$ (in the vicinity of the sensitivity curve).

For the case where $m_\chi = 1$ GeV, the $Z'$ boson cannot decay into a pair of DM particles. For that reason, the sensitivity on $g_\ell^L$ from the di-muon channel is always better than the mono-photon channel for the entire $g_\chi^Y$ range shown in the right panel figure of Fig. (7). We also find that the di-muon limits in the $m_\chi = 1$ GeV case are better than the $m_\chi = 0.1$ GeV case, since in the former case the $Z'$ boson can only decay into visible final states.

VII. SUMMARY

We investigate the capability of the Belle II experiment in probing the parameter space of the DM models in which DM only interacts with charged leptons in the SM. Our analyses focus on the sub-GeV DM, which is less constrained than WIMPs by the current DMDD experiments. We consider two different mechanisms to mediate the interactions between DM and charged leptons: EFT operators and light mediators in the MeV-GeV scale.

We compute the Belle II limits in the mono-photon channel on the EFT operators. Our analysis shows that $\Lambda_\ell \lesssim 220$ GeV can be probed by Belle II with 50 ab$^{-1}$ data, and $\Lambda \lesssim 280$ GeV can be probed for $\Lambda_V$, $\Lambda_A$ and $\Lambda_\chi$. We find
that the expected Belle II limits on EFT operators are of similar size to the LEP limits. The Belle II and LEP limits for sub-GeV DM can be several orders of magnitude stronger than the current DMDD limits, as well as the white dwarf limit.

The light mediator models can be searched for both in the mono-photon channel and in the di-muon channel. We compute the Belle II limits from both channels on the light mediator models. The mono-photon limits are analyzed for $m_{Z'} = 10$ MeV, 0.6 GeV and 5 GeV. The gauge coupling $g' \simeq 3 \times 10^{-5}$ (both vector and axial-vector) can be probed by the Belle II mono-photon data, when $m_\chi < m_{Z'}/2$ and $g^\chi = 1$. The di-muon channel is complementary to the mono-photon channel and sometimes can be much better, for example in the parameter where $m_\chi > m_{Z'}/2$. Unlike the EFT operators, the expected Belle II limits on the light mediator models can be several orders of magnitude stronger than the LEP limits, in the mono-photon channel. We also find that the collider limits have a rather weak dependence on the mediator mass; the DMDD cross section, however, is inversely proportional to $m_{Z'}$. For both the EFT operators and the light mediator models, the Belle II limits can be well below the “neutrino floor” expected in silicon detectors in DMDD. Thus the Belle II collider can probe the parameter space which is beyond the capability of current DMDD experiments, unless the neutrino floor can be mitigated in a satisfactory way.

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Appendix A: the differential cross sections of EFT operators

The differential cross section of $e^+e^- \rightarrow \chi \bar{\chi} \gamma$ for the four EFT operators in our analysis have been computed in Ref. [42]. Here we collect the expressions of the cross section for the $e^+e^- \rightarrow \chi \bar{\chi} \gamma$ process given in Ref. [42]. For the vector case, the cross section is

$$ \frac{d\sigma}{dE_\gamma d\cos \theta_\gamma} = \frac{\alpha \sqrt{s}}{12\pi^2 \Lambda_4^2} \frac{(1 - z + 2\mu^2)}{z \sin^2 \theta_\gamma} \sqrt{1 - z - 4\mu^2} \left[ 4(1 - z) + z^2 \left( 1 + \cos^2 \theta_\gamma \right) \right]. $$ (A1)

For the axial-vector case, the cross section is

$$ \frac{d\sigma}{dE_\gamma d\cos \theta_\gamma} = \frac{\alpha \sqrt{s}}{12\pi^2 \Lambda_4^2} \frac{(1 - z)}{z \sin^2 \theta_\gamma} \left( \frac{1 - z - 4\mu^2}{1 - z} \right)^{3/2} \left[ 4(1 - z) + z^2 \left( 1 + \cos^2 \theta_\gamma \right) \right]. $$ (A2)

For the “s-channel” scalar case, the cross section is

$$ \frac{d\sigma}{dE_\gamma d\cos \theta_\gamma} = \frac{\alpha \sqrt{s}}{8\pi^2 \Lambda_4^2} \frac{(1 - z)}{z \sin^2 \theta_\gamma} \left( \frac{1 - z - 4\mu^2}{1 - z} \right)^{3/2} \left[ 2(1 - z) + z^2 \right]. $$ (A3)

For the “t-channel” scalar case, the cross section is

$$ \frac{d\sigma}{dE_\gamma d\cos \theta_\gamma} = \frac{\alpha \sqrt{s}}{192\pi^2 \Lambda_4^2} \frac{1}{z \sin^2 \theta_\gamma} \sqrt{1 - z - 4\mu^2} \left[ \left( 2 - z + 2\mu^2 \right) \left( 3z^2 - 6z + 4 \right) - 8\mu^2 \\
+ 8 \left( 1 - z + 2\mu^2 \right) \left( 1 - z \right) + 2z^2 \left( 1 - z + 2\mu^2 \right) \left( 1 + \cos^2 \theta_\gamma \right) - \frac{1 - z + 2\mu^2}{1 - z} \cos^2 \theta_\gamma \right]. $$ (A4)

Here $z = 2E_\gamma/\sqrt{s}$ and $\mu = m_\chi/\sqrt{s}$, where $E_\gamma$ is the energy of photon, $m_\chi$ is mass of dark matter, $s$ is the square of the center of mass energy and $\theta_\gamma$ is the angle of photon with respect to the direction of the initial electron.
Appendix B: Matrix element for EFT operators in DMDD

The matrix elements of the four EFT operators, given in Eqs. (1, 2, 3, 4), in the DMDD experiments are given by

\[ \Lambda^4 \left| M_{\chi e} \right|^2 = (t - 4m_e^2)(t - 4m_e^2), \quad (B1) \]
\[ \Lambda^4 \left| M_{\chi e} \right|^2 = ((m_e - m_\chi)^2 - s)^2, \quad (B2) \]
\[ \Lambda^4 \left| M_{\chi e} \right|^2 = 4(m_e^2 + m_\chi^2 - s)^2 + 4st + 2t^2, \quad (B3) \]
\[ \Lambda^4 \left| M_{\chi e} \right|^2 = 2(2m_e^4 + 4m_e^2(5m_\chi^2 - s - t) + 2m_\chi^4 - 4m_\chi^2(s + t) + 2s^2 + 2st + t^2), \quad (B4) \]

where \( s \) and \( t \) are Mandelstam variables. For the typical momentum transfer at the DMDD experiments \( q = \alpha m_e \), the first three matrix elements become \( 16m_e^2m_\chi^2 \), and the last one becomes \( 48m_e^2m_\chi^2 \), where we have assumed \( v \ll c \) and \( m_\chi \gg \alpha m_e \), which is valid for DM mass in the MeV-GeV range. The DM form factor is \( F_{DM}(q) \simeq 1 \) in DMDD experiments for these EFT operators.

Appendix C: LEP analysis

In this section, we describe our LEP analysis, which closely follows the analysis in Ref. [35]. To properly take into account the initial state radiation effect, we use CalcHEP [74] to generate \( 10^9 \) events for each model point for the process of \( e^+e^- \rightarrow \chi \bar{\chi} \gamma \) at \( \sqrt{s} = 200 \text{ GeV} \) (with 100 GeV for each beam).\(^8\) The DELPHI detector has three main electromagnetic calorimeters: the Small angle Tile Calorimeter (STIC), the Forward ElectroMagnetic Calorimeter (FEMC), and the High density Projection Chamber (HPC). We smear the photon events by using the gaussian distributions with the energy resolutions given in Table II. Following Ref. [35], an additional Lorentzian energy smearing

\[ L(E) = \frac{\Gamma/2}{\pi (E - E_\gamma)^2 + (\Gamma/2)^2}, \quad (C1) \]

where \( \Gamma = 0.052E_\gamma \) is further performed. We analyzed the events with the preselection cuts shown in Table II.

| \( \sigma_{E_\gamma}/E_\gamma \) | Preselection cuts |
|----------------|------------------|
| STIC 0.0152 \( \oplus \) (0.135/\( \sqrt{E_\gamma} \)) | (i) \( x_\gamma > 0.3 \)
| | (ii) \( \theta_\gamma > 9.2^\circ - 9^\circ x_\gamma \) when \( 3.8^\circ < \theta < 8^\circ \)
| | \( 180^\circ - \theta_\gamma > 9.2^\circ - 9^\circ x_\gamma \) when \( 172^\circ < \theta < 176.2^\circ \) |
| FEMC 0.03 \( \oplus \) (0.12/\( \sqrt{E_\gamma} \)) \( \oplus \) (0.11/\( E_\gamma \)) | (i) \( x_\gamma > 0.1 \)
| | (ii) \( \theta_\gamma > 28^\circ - 80^\circ x_\gamma \) when \( 12^\circ < \theta < 32^\circ \)
| | \( 180^\circ - \theta_\gamma > 28^\circ - 80^\circ x_\gamma \) when \( 148^\circ < \theta < 168^\circ \) |
| HPC 0.043 \( \oplus \) (0.32/\( \sqrt{E_\gamma} \)) | (i) \( x_\gamma > 0.06 \)
| | (ii) \( 45^\circ < \theta < 135^\circ \) |

Table II: Preselection cuts and energy resolution for the three sub-detectors in the electromagnetic calorimeters in DELPHI: STIC, FEMC, and HPC [60]. Here \( E_\gamma \) is in unit of GeV, and \( x_\gamma = E_\gamma/E_{\text{beam}} \).

We further take into account other efficiency factors beyond the detector cuts given in Table II, as analyzed in Ref. [35]. They include the trigger efficiency, the analysis efficiency, and an overall factor of 90%, which is found to be necessary for the simulations in Ref. [35] to match the simulations in Ref. [60]. For HPC, the trigger efficiency is a linear interpolation function with 52% at \( E_\gamma = 6 \) GeV, 77% at \( E_\gamma = 30 \) GeV, and 84% at \( E_\gamma = 100 \) GeV; the analysis efficiency is a linear interpolation function with 41% at \( E_\gamma = 6 \) GeV and 78% at \( E_\gamma > 80 \) GeV [35]. For FEMC, the trigger efficiency is a linear interpolation function with 93% at \( E_\gamma = 10 \) GeV and 100% at \( E_\gamma > 15 \) GeV; the analysis efficiency is a linear interpolation function with 51% at \( E_\gamma = 10 \) GeV and 67% at \( E_\gamma = 100 \) GeV [35]. For STIC, the product of the trigger efficiency and the analysis efficiency is 48% for \( E_\gamma > 30 \) GeV [35].

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\(^8\) Ref. [35] found that using \( \sqrt{s} = 200 \text{ GeV} \) only introduces a small deviation from the full analysis.
We bin the data in 19 bins with $0.05 < x_\gamma < 1$, where $x_\gamma = E_\gamma/E_{\text{beam}}$ and compute the $\chi^2$ via

$$\chi^2 = \sum_{i=1}^{19} \frac{(N_i^s + N_i^b - N_i^o)^2}{\sigma_i^2},$$

where $N_i^s$ is the number of signal events, $N_i^b$ is the number of background events, $N_i^o$ is the number of observed data events, and $\sigma_i$ is the uncertainty. Here the dominant background process is the $e^+ e^- \rightarrow \nu \nu \gamma$ process. We take $N_i^b$, $N_i^o$, and $\sigma_i$ from Refs. [35, 60]. The LEP limits at 95% CL on light mediator models are obtained by $\chi^2/dof = 27.2/19$.

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