Scalar dark matter interpretation of the DAMPE data with U(1) gauge interactions

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Recently, the Dark Matter Particle Explorer (DAMPE) experiment released the new measurement of the total cosmic e^+e^- flux between 25 GeV and 4.6 TeV, which indicates a spectral softening at around 0.9 TeV and a tentative peak at around 1.4 TeV. We utilize a scalar dark matter (DM) model to explain the DAMPE peak by $\chi\chi \rightarrow Z'Z' \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$ with an additional anomaly-free gauged U(1) family symmetry, in which χ , Z' , and $\ell^{(\prime)}$ denote, respectively, the scalar DM, the new gauge boson, and $\ell^{(\prime)} = e, \mu, \tau$ with $m_\chi \sim m_{Z'} \sim 2 \times 1.5$ (TeV). We first illustrate that the minimal framework $G_{\text{SM}} \times U(1)_{Y'}$ with the above mass choices can explain the DAMPE excess, which, however, be excluded by LHC constraints from the Z' searches. Then, we study a nonminimal framework $G_{\text{SM}} \times U(1)_{Y'} \times U(1)_{Y''}$ in which $U(1)_{Y''}$ mixes with $U(1)_{Y'}$. We show that such a framework can interpret the DAMPE data and at the same time survive all other constraints including the DM relic abundance, DM direct detection, and collider bounds. We also investigate the predicted e^+e^- spectrum in this framework and find that the mass splitting $\Delta m = m_\chi - m_{Z'}$ should be less than about 17 GeV to produce the peaklike structure.

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I. INTRODUCTION

Recently, the Dark Matter Particle Explorer (DAMPE) experiment released the new measurement of the total cosmic e^+e^- flux between 25 GeV and 4.6 TeV, which indicates a spectral softening at around 0.9 TeV and a tentative peak at around 1.4 TeV [1,2]. The spectral softening, as was pointed out in Ref. [3], may be due to the breakdown of the conventional assumption of continuous source distribution or the maximum acceleration limits of electron sources, while the peak can be explained by dark matter (DM) annihilation in a nearby clump halo into exclusive e^+e^- or equal e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$ branching fractions (BRs) with $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ cm³/s. The best-fit values for the DM particle mass, the DM clump mass, and the annihilation

luminosity $\mathcal{L} = \int \rho^2 dV$ are around 1.5 TeV, $10^{7-8} m_\odot$ ($m_\odot$ denotes the mass of Sun), and 10^{64-66} GeV² cm⁻³, respectively, depending on the halo distance from Earth.

Interestingly, the excesses in cosmic positron flux have been previously announced by AMS-02 [4,5], PAMELA [6,7], and Fermi [8]. To interpret the positron anomaly, both astrophysical (for a review, see, e.g., Ref. [9]) and DM origins (for a review, see, e.g., Ref. [10]) have been proposed. Since no confirmed source has been established, in this paper, we assume DM to annihilate democratically into e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$ to explain the DAMPE data. This interpretation requires the following four conditions:

- (i) Indirect detection (ID): large $\langle\sigma v\rangle_0 \gtrsim 1 \times 10^{-26}$ cm³/s with $v \sim 10^{-3}c$ in today's Universe, meanwhile coinciding with other DM ID constraints.
- (ii) Relic density (RD): large $\langle\sigma v\rangle_{\text{FO}} \sim 1 \times 10^{-26}$ cm³/s with $v \sim 0.1c$ to generate the correct DM RD in early freeze-out (FO).
- (iii) Direct detection (DD): small DM-nucleon scattering $\sigma_{\text{DM}-p}^{\text{SI}}$ to pass the DM DD bounds.
- (iv) Collider: small signals to pass the relevant collider constraints.

If the DM particle is a singlet under the Standard Model (SM) gauge group $G_{\text{SM}} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$, a mediator sector is needed to connect the DM to the SM.

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FIG. 1. DM annihilation channels to interpret the DAMPE peak, where χ , Z' , B' , B'' , and $\ell^{(\prime)}$ denote the scalar DM, the new gauge bosons, and $\ell^{(\prime)} = e, \mu, \tau$, respectively. Left: model $G_{\text{SM}} \times U(1)_{Y'}$; right: model $G_{\text{SM}} \times U(1)_{Y'} \times U(1)_{Y''}$ with dots indicating the mixing between $U(1)_{Y''}$ and $U(1)_{Y'}$.

To satisfy $\langle \sigma v \rangle_0 \sim \langle \sigma v \rangle_{\text{FO}} \sim 1 \times 10^{-26} \text{ cm}^3/\text{s}$, the s -wave in $\langle \sigma v \rangle \simeq a + bv^2$ must be dominant to avoid p -wave suppression. One must also avoid chiral suppression given the light lepton masses (see, e.g., Refs. [11, 12]). One solution is to make DM annihilate dominantly into bosons in the first step, followed by the boson decays into leptons. If DM annihilates into a scalar pair, the new scalars usually mix with the SM Higgs, which makes it difficult to generate nearly equal e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$ BRs. However, the DM annihilation into a new anomaly-free family $U(1)$ gauge boson pair $Z'Z'$ can easily produce the required decay BRs. Moreover, scalar DM will annihilate efficiently from DM-DM- Z' - Z' contact interaction and be free of internal propagator suppression.

In this work, we consider anomaly-free extensions of G_{SM} with one or more additional gauged $U(1)$ family symmetries to generate $\chi\chi \rightarrow Z'Z' \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$, where χ , Z' , and $\ell^{(\prime)}$ denote the scalar DM, the new gauge boson, and $\ell^{(\prime)} = e, \mu, \tau$, respectively, with $m_\chi \sim m_{Z'} \sim 2 \times 1.5 \text{ (TeV)}$. We first illustrate that the minimal version $G_{\text{SM}} \times U(1)_{Y'}$ with the above mass choices can explain the DAMPE excess but has been excluded by condition iv, i.e., LHC constraints from the Z' searches. Then, we consider $G_{\text{SM}} \times U(1)_{Y'} \times U(1)_{Y''}$ in which $U(1)_{Y''}$ mixes with $U(1)_{Y'}$ to interpret the DAMPE data while passing all four conditions i–iv. Figure 1 shows the DM annihilation channels in two models to interpret the DAMPE peak. We note that some early studies on the DAMPE peak in terms of fermionic DM that annihilates directly into leptons [3, 13–17] did not explicitly include the anomaly-free condition for the theory, which is different from our assumption.

The paper is organized as follows. In Sec. II, we show the failure of the minimal extension $G_{\text{SM}} \times U(1)_{Y'}$ when confronting the LHC constraints. In Sec. III, we discuss the framework with the symmetry $G_{\text{SM}} \times U(1)_{Y'} \times U(1)_{Y''}$ which is successful in interpreting DAMPE data while satisfying other constraints. In Sec. IV, we investigate the e^+e^- spectrum predicted in our scenario and study the upper bound on the mass splitting between the DM and the new gauge boson if a peaklike structure is required. Finally, we draw our conclusion in Sec. V.

II. $G_{\text{SM}} \times U(1)_{Y'}$ FRAMEWORK

In this section, we extend the G_{SM} by one gauged $U(1)$ family symmetry to interpret the DAMPE peak. Although there are many possible ways for the charge assignments to guarantee anomaly cancellation, we adopt the minimal setting to predict equal e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$ coupling strengths for the new gauge boson, which was first proposed in Ref. [18]. The particle content of the model with chiral anomaly cancellation is shown in Table I, in which we introduce three generations of right-handed neutrinos $\nu_{R,\{1,2,3\}}$ and two complex scalars ϕ_s, ϕ_χ . We impose an odd Z_2 parity for ϕ_χ to generate a stable DM particle and require ϕ_s to develop a vacuum expectation value (vev) v_s to generate $m_{Z'}$. Since the neutrino physics of the model has been intensively studied in Ref. [18], we only concentrate on the DM physics to explain the DAMPE peak in our discussion.

The most relevant Lagrangian in our mechanism includes

$$\mathcal{L} \supset |D'_\mu \phi_\chi|^2 + |D'_\mu \phi_s|^2 - V(H, \phi_\chi, \phi_s) - \frac{1}{4} |F'_{\mu\nu}|^2 + g_{Y'} Z'_\mu (Y'_{f_R} \bar{f}_R \gamma^\mu f_R + Y'_{\nu_{R,i}} \bar{\nu}_{R,i} \gamma^\mu \nu_{R,i}), \quad (1)$$

where

$$V(H, \phi_\chi, \phi_s) = m_H^2 |H|^2 + m_{\phi_\chi}^2 |\phi_\chi|^2 + m_{\phi_s}^2 |\phi_s|^2 + \lambda_H |H|^4 + \lambda_{\phi_\chi} |\phi_\chi|^4 + \lambda_{\phi_s} |\phi_s|^4 + \lambda_{\chi H} |\phi_\chi|^2 |H|^2 + \lambda_{sH} |\phi_s|^2 |H|^2 + \lambda_{\chi s} |\phi_\chi|^2 |\phi_s|^2 + \lambda'_{\chi s} ((\phi_\chi^* \phi_s)^2 + \text{H.c.}), \quad (2)$$

with $D'_\mu = \partial_\mu - ig_{Y'} Y' Z'_\mu$, $F'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$, and $f = u, d, \ell$. To satisfy condition iv, we set $\lambda_{\chi H} = \lambda_{sH} = 0$ and choose proper m_H^2 and λ_H so that the properties of the H -dominated scalar are the same as those of the SM Higgs boson. The term $\lambda'_{\chi s} ((\phi_\chi^* \phi_s)^2 + \text{H.c.})$ in Eq. (2) can generate an important

TABLE I. Particle contents and their charge assignments in the $G_{\text{SM}} \times U(1)_{Y'}$ model.

Name	Spin	Generation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$
H	0	1	1	2	$-\frac{1}{2}$	0
Q	1/2	3	3	2	$\frac{1}{6}$	$\frac{1}{3}$
d_R^*	1/2	3	$\bar{3}$	1	$\frac{1}{3}$	$-\frac{1}{3}$
u_R^*	1/2	3	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{1}{3}$
L_1	1/2	1	1	2	$-\frac{1}{2}$	3
$L_{\{2,3\}}$	1/2	2	1	2	$-\frac{1}{2}$	-3
$\ell_{R,1}^*$	1/2	1	1	1	1	-3
$\ell_{R,\{2,3\}}^*$	1/2	2	1	1	1	3
$\nu_{R,1}^*$	1/2	1	1	1	0	-3
$\nu_{R,\{2,3\}}^*$	1/2	2	1	1	0	3
ϕ_s	0	1	1	1	0	6
ϕ_χ	0	1	1	1	0	6

mass splitting between the real and imaginary components in ϕ_χ . To be more explicit, we have

$$\phi_s \rightarrow \frac{1}{\sqrt{2}}(\phi_{R,s} + i\phi_{I,s}), \quad \phi_\chi \rightarrow \frac{1}{\sqrt{2}}(\phi_{R,\chi} + i\phi_{I,\chi}), \quad (3)$$

before v_s is developed, and consequently, we have

$$\begin{aligned} & (\phi_\chi^* \phi_s)^2 + \text{H.c.} \\ &= \frac{1}{4}((\phi_{R,\chi} - i\phi_{I,\chi})(\phi_{R,s} + i\phi_{I,s}))^2 + \text{H.c.} \\ &= \frac{1}{4}((\phi_{R,\chi}\phi_{R,s} + \phi_{I,\chi}\phi_{I,s}) + i(\phi_{R,\chi}\phi_{I,s} - \phi_{I,\chi}\phi_{R,s}))^2 + \text{H.c.} \\ &= \frac{1}{2}(\phi_{R,\chi}\phi_{R,s} + \phi_{I,\chi}\phi_{I,s})^2 - \frac{1}{2}(\phi_{R,\chi}\phi_{I,s} - \phi_{I,\chi}\phi_{R,s})^2 \\ &\supset \frac{1}{2}\phi_{R,s}^2(\phi_{R,\chi}^2 - \phi_{I,\chi}^2). \end{aligned} \quad (4)$$

When ϕ_s acquires a vev, v_s , we perform the replacement

$$\phi_{R,s} \rightarrow v_s + \phi_{R,s}, \quad (5)$$

which implies

$$\lambda'_{\chi s}((\phi_\chi^* \phi_s)^2 + \text{H.c.}) \supset \frac{1}{2}\lambda'_{\chi s}v_s^2(\phi_{R,\chi}^2 - \phi_{I,\chi}^2). \quad (6)$$

This induces a mass splitting $\Delta m_{\chi'\chi}^2 = m_{\chi'}^2 - m_\chi^2 = 2\lambda'_{\chi s}v_s^2$ with $\chi' \equiv \phi_{R,\chi}$ and $\chi \equiv \phi_{I,\chi}$. Note that χ corresponds to the DM candidate for a positive $\lambda'_{\chi s}$. In our discussion, we use the minimization condition of the scalar potential to replace m_{ϕ_s} in Eq. (2) with v_s as the theoretical input parameter.

The mass splitting $\Delta m_{\chi'\chi}$ has an important implication on the DM-nucleon scattering. To see this, we expand the covariant kinetic term in Eq. (1) as

$$\begin{aligned} |D'_\mu \phi_\chi|^2 &= (\partial^\mu \phi_\chi - ig_{Y'} Y'_{\phi_\chi} Z'^\mu \phi_\chi)(\partial_\mu \phi_\chi^* + ig_{Y'} Y'_{\phi_\chi} Z'_\mu \phi_\chi^*) \\ &= \partial^\mu \phi_\chi \partial_\mu \phi_\chi^* + (g_{Y'} Y'_{\phi_\chi})^2 Z'^\mu Z'_\mu |\phi_\chi|^2 \\ &\quad + ig_{Y'} Y'_{\phi_\chi} Z'_\mu (\phi_\chi^* \partial^\mu \phi_\chi - \phi_\chi \partial^\mu \phi_\chi^*) \\ &= \partial^\mu \phi_\chi \partial_\mu \phi_\chi^* + (g_{Y'} Y'_{\phi_\chi})^2 Z'^\mu Z'_\mu (\phi_{R,\chi}^2 + \phi_{I,\chi}^2) \\ &\quad - 2g_{Y'} Y'_{\phi_\chi} Z'_\mu (\phi_{R,\chi} \partial^\mu \phi_{I,\chi} - \phi_{I,\chi} \partial^\mu \phi_{R,\chi}), \end{aligned} \quad (7)$$

where the third term indicates that there is no $Z'\chi\chi$ or $Z'\chi'\chi'$ interaction but only $Z'\chi'\chi$ interaction exists. This observation implies that if the mass splitting $\Delta m_{\chi'\chi} = m_{\chi'} - m_\chi$ is much larger than the typical DM kinetic energy $E_{\chi,\text{kin}}$,

$$\frac{1}{2}m_\chi v_\chi^2 \sim 0.5 \times (3 \times 10^3 \text{ GeV}) \times (10^{-3})^2 \sim 1 \text{ MeV}, \quad (8)$$

the inelastic scattering process $\chi N \rightarrow \chi' N$ is kinematically forbidden (see the left panel of Fig. 2), where N denotes the SM nucleon.

FIG. 2. DM-nucleon scattering processes in the model $G_{\text{SM}} \times U(1)_{Y'}$. Left: inelastic scattering proceeds at tree level; middle and right: elastic scattering starts from one-loop level.

On the contrary, the elastic scattering process $\chi N \rightarrow \chi N$ starts from one-loop level, including the triangle diagram involving $\chi\chi Z'Z'$ interaction (see the middle panel of Fig. 2), as well as the box diagrams involving the double $U(1)_{Y'}$ gauge boson and light quark propagator (see the right panel of Fig. 2). Obviously, the rates of the elastic processes are suppressed by a loop factor, light quark mass, and the small coupling between Z' and light quarks. To estimate the scattering rate, we first choose the degenerate limit $\Delta m_{\chi'\chi} = 0$, in which case the scattering $\chi N \rightarrow \chi' N$ proceeds mainly via the tree-level Z' -mediated diagram. We utilize the package MICROMEGAS [19,20] to calculate the scattering rate, and the result is about $9 \times 10^{-43} \text{ cm}^2$ for $m_\chi \simeq m_{Z'} = 3 \text{ TeV}$ and $g_{Y'} \simeq 0.2$, which is the benchmark parameter choice needed to produce the observed DM relic density while explaining the DAMPE peak (see the below). We conclude that, although this rate is about 40 times larger than the current bound from the DM direct search experiments such as XENON-1T [21] and PandaX-II [22], the nondegenerate case $\Delta m_{\chi'\chi} \gg 1 \text{ MeV}$ can easily turn off the inelastic scattering and make our model pass constraint iii.

For the numerical calculations, we use SARAH [23] to implement the model, SPHENO [24,25] to calculate the mass spectrum and MICROMEGAS [19,20] to calculate the DM relic abundance in which the threshold effects may be important for $m_\chi \sim m_{Z'}$ [26]. We set $\lambda_{\phi_\chi} = \lambda_{\chi s} = \lambda_{\chi H} = \lambda_{sH} = 0$ and scan the following parameters space using the package EASYSCAN-HEP [27], which is based on the Markov chain Monte Carlo sampling technique [28],

$$\begin{aligned} & 0 \leq \lambda_{\phi_s}, \quad g_{Y'}, \quad \lambda'_{\chi s} \leq 1, \\ & 2.9 \text{ TeV} \leq m_{\phi_\chi} \leq 3.1 \text{ TeV}, \quad 1 \text{ TeV} \leq v_s \leq 5 \text{ TeV}. \end{aligned} \quad (9)$$

In the mass spectrum calculation, we have included the radiative correction to m_χ ; i.e., we have $m_\chi \neq m_{\phi_\chi}$ even with $\lambda_{\chi s} = \lambda'_{\chi s} = 0$. We further impose the constraints [29]

$$\begin{aligned} & m_\chi \in (3000 \pm 10) \text{ GeV}, \quad m_{Z'} \in (2.7, 3) \text{ TeV}, \\ & m_{\phi_{R,s}}, m_{\chi'} > 3 \text{ TeV}, \quad \langle \sigma v \rangle_0 \gtrsim 1 \times 10^{-26} \text{ cm}^3/\text{s}, \\ & \Omega_\chi h^2 \in 0.1187 \pm 0.01198, \end{aligned} \quad (10)$$

where both of the two physical scalars $S \equiv \phi_{R,s}$ and χ' are required to be heavier than 3 TeV so that they do not

TABLE II. The framework $G_{\text{SM}} \times U(1)_{Y'}$ confronting the four conditions.

Condition	Result	Details
(i)	✓	$\chi\chi \rightarrow Z'Z' \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$ with $\ell, \ell' = e, \mu, \tau$ with $m_\chi \sim m_{Z'} \sim 2 \times 1.5$ (TeV). BR($Z' \rightarrow l_i^+ l_i^-$) $\simeq 2/9$ and BR($Z' \rightarrow \nu_i \bar{\nu}_i$) $\simeq 1/9$ for $i = e, \mu, \tau$; BR($Z' \rightarrow q\bar{q}$) is small due to the small charge assignment for quarks.
(ii)	✓	Same as (i) since the annihilation is s -wave dominated.
(iii)	✓	$\Delta m_{\chi',\chi} = m_{\chi'} - m_\chi \gg E_{\chi,\text{kin}}$ forbids tree-level inelastic scattering $\chi N \rightarrow \chi' N$ via t -channel exchange of Z' .
(iv)	×	Excluded by $q\bar{q} \rightarrow Z' \rightarrow \ell\bar{\ell}$ at the LHC [30].

significantly affect the explanation of the DAMPE peak. The scalar S may decay into $Z'^{(*)}Z'^{(*)}$ or neutrinos via the new Yukawa interactions under $U(1)_{Y'}$ such as $\phi_s \bar{\nu}_{R,1}^c \nu_{R,23}, \phi_s \bar{\nu}_{R,i}^c \nu_{R,i}$ [18], and the scalar χ' may decay via $\chi' \rightarrow \chi + Z'^{(*)}$ through the $U(1)_{Y'}$ gauge interaction.

The model $G_{\text{SM}} \times U(1)_{Y'}$ confronting the four conditions is shown in Table II, and the numerical results are provided in Fig. 3 on the plane of $m_{Z'}$ versus $g_{Y'}$, where the left regions of large electron-positron collider (LEP) and LHC bounds have been excluded. In the model $G_{\text{SM}} \times U(1)_{Y'}$, the LEP bound on $m_{Z'}$ comes from the process $e^+e^- \rightarrow Z' \rightarrow \mu^+\mu^-$, which requires $m_{Z'} \gtrsim g_{Y'}/0.1 \times 1.4$ TeV [18]. The LHC bound on the mass arises from the ATLAS search for a dilepton signal at 13 TeV LHC [30], and we get the corresponding curve in Fig. 3 by simulating the analysis in Ref. [30] (for details, see Sec. 10.3 and Fig. 6 of Ref. [30]). This figure indicates that for $m_\chi \sim m_{Z'} \sim 2 \times 1.5$ (TeV) $g_{Y'}$ should be around 0.2 to produce the observed DM relic density and meanwhile to explain the DAMPE peak. In this case, $\langle\sigma v\rangle_0$ varies between 1.0×10^{-26} and approximately 3.5×10^{-26} cm³/s. This figure also shows that the samples

with $\langle\sigma v\rangle_0 \gtrsim 1 \times 10^{-26}$ cm³/s to explain the DAMPE peak can survive the LEP bound from $e^+e^- \rightarrow Z'^* \rightarrow \mu^+\mu^-$ [18] but fail to pass the LHC limits on $q\bar{q} \rightarrow Z' \rightarrow \ell\bar{\ell}$ [30]. Note that the exclusion from the LHC for this model originates from the chosen quark quantum numbers under the $U(1)_{Y'}$, which is due to the gauge anomaly-free requirement and the assumption of Z' democratic decays into e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$.

III. $G_{\text{SM}} \times U(1)_{Y'} \times U(1)_{Y''}$ FRAMEWORK

To pass the LHC constraints frustrating the minimal framework $G_{\text{SM}} \times U(1)_{Y'}$, we extend it with another $U(1)_{Y''}$ gauge group mixing with the $U(1)_{Y'}$ group and one additional complex scalar ϕ_d to break the $U(1)_{Y''}$ symmetry. The particle contents in this model with chiral anomaly cancellation are shown in Table III. Note that ϕ_χ is no longer charged under the previous $U(1)_{Y'}$ and only ϕ_χ and ϕ_d are charged under $U(1)_{Y''}$.

The most relevant Lagrangian to explain the DAMPE data includes

FIG. 3. Samples surviving the constraints in Eq. (10), which are projected on $m_{Z'} - g_{Y'}$ plane. The bounds on $m_{Z'}$ from the LEP experiment and LHC experiment are also shown with the left regions of the curves being excluded.

TABLE III. Particle contents in $G_{\text{SM}} \times U(1)_{Y'} \times U(1)_{Y''}$ model.

Name	Spin	Generation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$	$U(1)_{Y''}$
H	0	1	1	2	$-\frac{1}{2}$	0	0
Q	1/2	3	3	2	$\frac{1}{6}$	$\frac{1}{3}$	0
d_R^*	1/2	3	$\bar{3}$	1	$\frac{1}{3}$	$-\frac{1}{3}$	0
u_R^*	1/2	3	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{1}{3}$	0
L_1	1/2	1	1	2	$-\frac{1}{2}$	3	0
$L_{\{2,3\}}$	1/2	2	1	2	$-\frac{1}{2}$	-3	0
$\ell_{R,1}^*$	1/2	1	1	1	1	-3	0
$\ell_{R,\{2,3\}}^*$	1/2	2	1	1	1	3	0
$\nu_{R,1}^*$	1/2	1	1	1	0	-3	0
$\nu_{R,\{2,3\}}^*$	1/2	2	1	1	0	3	0
ϕ_s	0	1	1	1	0	6	0
ϕ_χ	0	1	1	1	0	0	Y''_{ϕ_χ}
ϕ_d	0	1	1	1	0	0	Y''_{ϕ_d}

$$\mathcal{L} \supset |D_\mu \phi_\chi|^2 + |D_\mu \phi_s|^2 + |D_\mu \phi_d|^2 - V(H, \phi_\chi, \phi_s, \phi_d) - \frac{1}{4} |F'_{\mu\nu}|^2 - \frac{1}{4} |F''_{\mu\nu}|^2 - \frac{\kappa}{2} F'^{\mu\nu} F''_{\mu\nu}, \quad (11)$$

where

$$D_\mu \phi = [\partial_\mu + iY'_\phi (g_{Y'Y'} B'_\mu + g_{Y'Y''} B''_\mu) + iY''_\phi (g_{Y''Y'} B'_\mu + g_{Y''Y''} B''_\mu)] \phi, \quad (12)$$

$$F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu, \quad F''_{\mu\nu} = \partial_\mu B''_\nu - \partial_\nu B''_\mu, \quad (13)$$

and

$$V(H, \phi_\chi, \phi_s, \phi_d) = m_H^2 |H|^2 + m_{\phi_\chi}^2 |\phi_\chi|^2 + m_{\phi_s}^2 |\phi_s|^2 + m_{\phi_d}^2 |\phi_d|^2 + \lambda_H |H|^4 + \lambda_{\phi_\chi} |\phi_\chi|^4 + \lambda_{\phi_s} |\phi_s|^4 + \lambda_{\phi_d} |\phi_d|^4 + \lambda_{\chi H} |\phi_\chi|^2 |H|^2 + \lambda_{sH} |\phi_s|^2 |H|^2 + \lambda_{dH} |\phi_d|^2 |H|^2 + \lambda_{\chi s} |\phi_\chi|^2 |\phi_s|^2 + \lambda_{\chi d} |\phi_\chi|^2 |\phi_d|^2 + \lambda_{sd} |\phi_s|^2 |\phi_d|^2. \quad (14)$$

In the above expressions, Y'_ϕ, Y''_ϕ denote the $U(1)_{Y'}$ and $U(1)_{Y''}$ charge of ϕ , respectively. g_{ab} with $a, b = Y', Y''$ are the coupling constants, while κ parametrizes the kinetic mixing between $U(1)_{Y'}$ and $U(1)_{Y''}$. Note that for a $U(1)_1 \times U(1)_2$ gauge theory D_μ is usually presented in a compact form, [31–33] which is given by $D_\mu \phi = [\partial_\mu + i \sum_a \sum_b Y_\phi^a g_{ab} B_\mu^b] \phi$, with $a, b = 1, 2$, and g corresponding to a coupling matrix. In our notations, we expand the summation explicitly. The appearance of a coupling matrix g instead of one single gauge coupling for each $U(1)$ group is a special feature of the theory with multiple $U(1)$ groups. In fact, even if g is not included in the tree-level Lagrangian, the kinetic mixing term κ and the g_{ab} couplings will be generated in the effective action through radiative corrections if there exist fields charged under both of the groups. Also note that we can choose $Y''_{\phi_\chi} \neq Y''_{\phi_d}$ to forbid $\lambda'_{\chi s}$ terms in Eq. (2), but for comparison, we take $Y''_{\phi_\chi} = Y''_{\phi_d} = 6$ as we did for previous model and set $\lambda'_{\chi d} = 0$ since we no longer need to rely on nonzero $\Delta m_{\chi' \chi}$ to forbid tree-level Z' -mediated DM-nucleon scattering, which is helpful to evade the DM direct search constraints (see the discussion below).

In the following, we denote $g_{Y'} \equiv g_{Y'Y'}, g_{Y''} \equiv g_{Y''Y''}, \epsilon \equiv g_{Y'Y''} = g_{Y''Y'}$ and neglect the explicit kinetic mixing term κ for simplicity. As illustrated in Refs. [33,34], including the mixing corresponds to a redefinition of the fields and does not essentially change the results in this work. Then, in the basis (B', B'') , the mass matrix of the new gauge bosons is given by

$$M_V^2 = 36 \times \begin{pmatrix} g_{Y'}^2 v_s^2 + \epsilon^2 v_d^2 & \epsilon(g_{Y'} v_s^2 + g_{Y''} v_d^2) \\ \epsilon(g_{Y'} v_s^2 + g_{Y''} v_d^2) & \epsilon^2 v_s^2 + g_{Y''}^2 v_d^2 \end{pmatrix}.$$

After diagonalization, one can obtain the mass eigenstates Z' and Z'' , which are B'_μ and B''_μ dominated, respectively. Similar to the minimal framework of $G_{\text{SM}} \times U(1)_{Y'}$, charge assignments in Table III make Z' and Z'' decay dominantly into $l_i^+ l_i^-$ and $\nu_i \bar{\nu}_i$ if the CP -even scalars dominated by $\phi_{s,d}$ are sufficiently heavy. In this new framework, we will focus on the complex scalar DM $\chi \equiv \phi_\chi$ and utilize the process $\chi\chi \rightarrow Z'' Z'' \rightarrow \ell \bar{\ell} \ell' \bar{\ell}'$ with $\ell, \ell' = e, \mu, \tau$ to explain the DAMPE peak. The sensitive parameters, as we discussed in the minimal framework, are $m_\chi, m_{Z''}, g_{Y''}$, and also ϵ . The parameter ϵ affects not only the masses and the B'_μ, B''_μ components of the new gauge bosons but also the $\chi N \rightarrow \chi N$ scattering rate which proceeds via the tree-level t -channel exchange of Z' and Z'' .

As what we did in previous section, we explore the parameter space of the nonminimal framework $G_{\text{SM}} \times U(1)_{Y'} \times U(1)_{Y''}$ to interpret the DAMPE peak. First, we set $\lambda_{\{\chi, s, d\}, H} = \lambda_{\phi_\chi} = \lambda_{\chi s} = \lambda_{\chi d} = \lambda_{sd} = 0$, $g_{Y'} = 0.1$ to simplify our analysis and also to ensure that the H -dominated CP -even scalar acts as the SM Higgs boson. Then, we scan the parameter space

$$\begin{aligned} 0 &\leq \lambda_{\phi_s}, \quad \lambda_{\phi_d}, \quad g_{Y''}, \\ \epsilon &\leq 1, \quad 2.9 \text{ TeV} \leq m_{\phi_\chi} \leq 3.1 \text{ TeV}, \\ 6(2) \text{ TeV} &\leq v_s(v_d) \leq 10(5) \text{ TeV} \end{aligned}$$

with the following requirements:

$$\begin{aligned} m_\chi &\in (3000 \pm 10) \text{ GeV}, \quad m_{Z''} \in (2.7, 3) \text{ TeV}, \\ m_{\phi_{R,s}}, m_{\phi_{R,d}} &> 3 \text{ TeV}, \quad m_{Z'} > 4 \text{ TeV}, \\ \Omega_\chi h^2 &\in 0.1187 \pm 0.01198, \quad \langle \sigma v \rangle_0 \gtrsim 1 \times 10^{-26} \text{ cm}^3/\text{s}. \end{aligned} \quad (15)$$

For the surviving samples, we present the details of how the four conditions i–iv are satisfied:

- (i) ID: $g_{Y''} \sim 0.2$ with $m_\chi \sim m_{Z''} \sim 3.0$ TeV can generate $\langle \sigma v \rangle_0 \gtrsim 1 \times 10^{-26} \text{ cm}^3/\text{s}$, followed by Z'' decaying into nearly equal $e^+ e^-$, $\mu^+ \mu^-$, and $\tau^+ \tau^-$ BRs. In this case, we checked that for $\epsilon = 0.04$ and $m_{Z'} = 5$ TeV the Z'' -lepton couplings are $\mathcal{O}(0.1)$ and the width of Z'' is about 3 GeV, which means the lifetime of Z'' is short enough and does not affect the evolution of the early Universe.
- (ii) RD: Same as (i) since the DM annihilation is an s -wave process.
- (iii) DD: $g_{Y'} = 0.1$, $\epsilon \lesssim 0.05$, and $m_{Z'} \gtrsim 4$ TeV can suppress the DM-nucleon scattering $\chi N \rightarrow \chi N$, which proceeds via the t -channel exchange of Z' and Z'' . In Fig. 4, we project the surviving samples on the plane of ϵ versus spin-independent (SI) DM-nucleon scattering rate $\sigma_{\text{DM}-p}^{\text{SI}}$. This figure indicates that for $\epsilon \lesssim 0.05$, the scattering rate is far below its current

FIG. 4. DM-nucleon scattering rate as a function of ϵ in the framework $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$ with the color bar denoting DM annihilation rate at present time.

bound from the PandaX-II experiment. We checked that a larger ϵ can change significantly m_χ by radiative correction so that it violates the requirement of $m_\chi \simeq 3$ TeV.

- (iv) Collider: Our choice $g_{Y'} = 0.1$, $m_{Z'} \gtrsim 4$ TeV is sufficiently heavy to suppress the process $e^+e^- \rightarrow Z'^* \rightarrow \mu^+\mu^-$ at LEP and $pp \rightarrow Z'^{(*)} \rightarrow l_i^+ l_i^-$ at the 13 TeV LHC. Consequently, the collider constraints can be evaded (see details of collider constraints in the previous section).

Before we end this section, we note that the DM explanation of the DAMPE peak is consistent with the other DM indirect detection constraints, as pointed out in Ref. [35]. These include the H.E.S.S. data on the annihilation $\chi\chi \rightarrow VV \rightarrow 4e$ [36,37], the Fermi-LAT data in the direction of the dwarf spheroidal galaxies [38], the Planck cosmic microwave background (CMB) data that are sensitive to energy injection to the CMB from DM annihilations [39,40], and the IceCube data on DM annihilation into neutrinos [41]. It also survives the upper bounds of XENON-10 and XENON-100 experiments on the DM scattering with electron [42].

IV. e^+e^- SPECTRUM IN OUR EXPLANATION

It is well known that if DM annihilates into intermediate particles ϕ that subsequently decay into e^+e^- the e^+e^- spectrum will exhibit a box-shaped feature that is distinguishable from other astrophysical process. To explain the DAMPE peak by the process $\chi\chi \rightarrow Z''Z'' \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$ considered in this work, the mass splitting $\Delta m \equiv m_\chi - m_{Z''}$ should be small (see, e.g., Ref. [43]), and the subhalo where DM annihilates should be located near the Earth.

In this section, we study the e^+e^- spectrum predicted by $\chi\chi \rightarrow Z''Z'' \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$ and investigate the upper bound on

Δm when explaining the DAMPE peak. We adopt the parametrization of the cosmic ray background by the formulas presented in Ref. [43] and use the LIKEDM package [44] to calculate the propagation of the e^+e^- in the background. The relevant data to determine the parameters for the background are taken from the e^+ fraction and e^+e^- fluxes of the AMS-02 results and the e^+e^- flux of DAMPE data. Then, we add the contribution of the local subhalo by assuming that such a component only affects the energy bin ~ 1.5 TeV. We adopt a Navarro-Frenk-White profile [45] with a truncation at the tidal radius [46] for DM density distribution inside the subhalo and use the subhalo mass as an input to determine the profile (for the relevant method, see the Appendix of Ref. [3]). The propagation of

FIG. 5. Cosmic e^+e^- spectrum generated by $\Delta m \equiv m_\chi - m_{Z''} = 6, 12, 18$ GeV, respectively, for the process $\chi\chi \rightarrow Z''Z''$ with Z'' democratic decays into e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$ final states and $m_\chi = 3$ TeV. The DAMPE data is also plotted for comparison. The top panel corresponds to the choice $\langle\sigma v\rangle_0 = 3.2 \times 10^{-26}$ cm³ s⁻¹, $M_{Halo} = 1.9 \times 10^7$ $m_\odot$ (the subhalo mass), and $l = 0.1$ kpc (the distance of the subhalo away from our solar system), while the bottom panel corresponds to $\langle\sigma v\rangle_0 = 1.2 \times 10^{-26}$ cm³ s⁻¹, $M_{Halo} = 3.0 \times 10^8$ $m_\odot$, and $l = 0.2$ kpc.

FIG. 6. Best fits of the e^+e^- spectrum generated by the process $\chi\chi \rightarrow Z''Z'' \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$ (with $\ell, \ell' = e, \mu, \tau$) to the AMS-02 and DAMPE data, which are projected on $\Delta m - \chi^2$ plane for fixed $m_\chi = 3$ TeV, $l = 0.1$ kpc, and $M_{\text{Halo}} = 1.9 \times 10^7 m_\odot$. From this figure, one can infer that the 95% upper limit on Δm in explaining the DAMPE peak is about 17 GeV.

the nearby e^+e^- can be calculated analytically under the assumption of spherically symmetric geometry and infinite boundary conditions [47]. We note that the method to obtain the DM spectrum has been described in detail in Refs. [35,48,49].

In the top panel of Fig. 5, we present the spectrum of e^+e^- with $\Delta m = 6, 12$, and 18 GeV, respectively. In producing this plot, we set $m_\chi = 3$ TeV and $\langle\sigma v\rangle_0 = 3.2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ and take the distance and the mass of the hypothesized subhalo as $l = 0.1$ kpc and $M_{\text{Halo}} = 1.9 \times 10^7 m_\odot$. The parameters for the background are chosen to be the same as those in Table I of Ref. [43]. The bottom panel of Fig. 5 is the same as the top panel, except that we take $\langle\sigma v\rangle_0 = 1.2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$, $l = 0.2$ kpc, and $M_{\text{Halo}} = 3.0 \times 10^9 m_\odot$. Note that the height of the spectrum is determined by $\langle\sigma v\rangle_0$ and M_{Halo} , while the increase of the distance l and/or Δm will make the spectrum more box shaped. Moreover, we note from our calculation that if the mediator decays exclusively into e^+e^- the peak is sharper than the mixed-channel case considered in Fig. 5. This is understandable since the later Z'' decays into $\mu^+\mu^-$ and $\tau^+\tau^-$ tend to flatten the peak. Figure 5 shows that the process we considered can generate the peak structure to explain the DAMPE excess.

To obtain the upper limit on Δm , we perform best fits of the e^+e^- spectrum generated by our explanation of the AMS-02 and DAMPE data. For each chosen Δm , we fix $m_\chi = 3$ TeV, $l = 0.1$ kpc, and $M_{\text{Halo}} = 1.9 \times 10^7 m_\odot$ and vary the background parameters and $\langle\sigma v\rangle_0$ to get the maximum value of the constructed likelihood function. This procedure is the same as used in Ref. [43]. The χ^2 s obtained in this way are projected on the $\Delta m - \chi^2$ plane in Fig. 6. This figure indicates that the minimum value of χ^2 is located at $\Delta m \simeq 5$ GeV. By requiring $(\chi^2 - \chi^2_{\text{min}}) \leq 2.71$, which can be used to set a 95% upper bound on Δm , we get $\Delta m \lesssim 17$ GeV in order to produce an acceptable peaklike e^+e^- spectrum.

V. CONCLUSION

In this work, we utilized the dark matter annihilation scenario to explain the tentative peak structure at around 1.4 TeV in the recently released DAMPE measurement of the total cosmic e^+e^- flux between 25 GeV and 4.6 TeV. We extended $G_{\text{SM}} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$ with an additional gauged $U(1)$ family symmetry to generate $\chi\chi \rightarrow Z'Z' \rightarrow \ell\bar{\ell}\ell'\bar{\ell}'$, where χ , Z' , and $\ell^{(\prime)}$ denote the scalar DM, the new gauge boson, and $\ell^{(\prime)} = e, \mu, \tau$, respectively, with $m_\chi \sim m_{Z'} \sim 2 \times 1.5$ (TeV). We first illustrated that the minimal framework $G_{\text{SM}} \times U(1)_{Y'}$ with the above mass choices can explain the DAMPE excess but has been excluded by the LHC constraints from the Z' searches. Then, we studied the nonminimal framework $G_{\text{SM}} \times U(1)_{Y'} \times U(1)_{Y''}$ in which the $U(1)_{Y''}$ group mixes with the $U(1)_{Y'}$ group. We showed that it can interpret the DAMPE data and pass other constraints including DM relic abundance, DM direct detection, and collider bounds. We also studied the e^+e^- spectrum predicted by the DM annihilation process we consider. By performing spectrum fits to the relevant experimental data, we found that the mass splitting $\Delta m \equiv m_\chi - m_{Z''}$ between the scalar DM and the mediator vector boson should be less than about 17 GeV to explain the observed peak.

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