Prepared for submission to JHEP

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

Junjie Cao[a,b,c] **,Lei Feng**[d] **,Xiaofei Guo**[a] **,Liangliang Shang**[a] **,Fei Wang**[e] **,Peiwen Wu**[f]

[a] *College of Physics and Materials Science, Henan Normal University, Xinxiang 453007, China*
[b] *Center for High Energy Physics, Peking University, Beijing 100871, China*
[c] *Department of Applied Physics, Xi'an Jiaotong University, Xi'an 710049, China*
[d] *Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China*
[e] *School of Physics, Zhengzhou University, 450000, ZhengZhou, P.R.China*
[f] *School of Physics, KIAS, 85 Hoegiro, Seoul 02455, Republic of Korea*

E-mail: junjiec@itp.ac.cn, fenglei@pmo.ac.cn, guoxf@gs.zzu.edu.cn, shlwell1988@foxmail.com, feiwang@zzu.edu.cn, pwwu@kias.re.kr

Abstract: Recently, 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 the scalar dark matter (DM) annihilation scenario to explain the DAMPE data by extending $G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$ with additional $U(1)$ gauge symmetries while keeping anomaly free to generate $\chi\chi \to Z'Z' \to \ell\bar{\ell}\ell'\overline{\ell'}$, where $\chi, Z', \ell^{(\prime)}$ denote the scalar DM, the new gauge boson and $\ell^{(\prime)} = e, \mu, \tau$, respectively, with $m_\chi \sim m_{Z'} \sim 3.0 = 2\,E_\ell \sim 2 \times 1.5$ (TeV). We first illustrate that $G_{SM} \times U(1)_{Y'}$ with the above mass choices can explain the DAMPE excess but has been excluded by LHC constraints from the Z' searches. Then we study $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$ in which $U(1)_{Y''}$ mixes with $U(1)_{Y'}$ vie the kinetic term. We show that it can interpret the DAMPE data while passing other constraints including DM relic abundance, DM direct detection and collider bounds.

Contents

1 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]. If one assumes dark matter (DM) annihilation in a nearby clump halo into exclusive e^+e^- or equal e, μ, τ branching fractions (Brs) with $\langle\sigma v\rangle \sim 3 \times 10^{-26}\, cm^3/s$, the best fit values for the DM particle mass, and the DM clump mass and the annihilation luminosity $\mathcal{L} = \int \rho^2 dV$ are around 1.5 TeV, $10^{7-8}\, M_{\rm sun}$ and $10^{64-66}\, {\rm GeV}^2\, {\rm cm}^{-3}$, depending on the halo distance from earth [2].

Interestingly, excesses in cosmic positron flux have been previously announced in AMS-02 [3, 4], PAMELA [5, 6] and Fermi [7]. To interpret the positron anomaly both astrophysical (for a review see e.g. [8]) and DM origins (for a review see e.g. [9]) have be proposed. Since no confirmed source has been established, in this paper we assume DM annihilation with e, μ, τ to explain the DAMPE data.

The DM annihilation into e, μ, τ capable of interpreting the DAMPE data must satisfy the following four conditions:

- **I-ID**: *large* $\langle\sigma v\rangle_0 \sim 1 \times 10^{-26}\, cm^3/s$ with $v \sim 10^{-3}\, c$ in today's Universe.
- **II-RD**: *large* $\langle\sigma v\rangle_{FO} \sim 1 \times 10^{-26}\, cm^3/s$ with $v \sim 0.1\, c$ in early freeze out.
- **III-DD**: *small* DM-nucleon scattering σ^{SI}_{DM-p} to pass DM direct detection bounds.
- **IV-Collider**: *small* signals to pass relevant collider constraints.

If the DM particle is a singlet under the SM gauge group $G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$, a mediator sector is needed to connect the DM and the SM. To satisfy $\langle\sigma v\rangle_0 \sim \langle\sigma v\rangle_{FO} \sim 1 \times 10^{-26}\, cm^3/s$, the s-wave in $\langle\sigma v\rangle \sim a + b\, v^2$ must be dominant to avoid p-wave suppression. One must also avoid chiral suppression given the light lepton masses (see e.g. [10, 11]). One solution is to make DM annihilate dominantly into bosons in the first step, followed by bosons decaying into leptons. If DM annihilate into scalars ϕ', the new scalars usually mix with the SM Higgs and make it difficult to generate nearly equal e, μ, τ Brs. However, DM annihilation into new gauge vector bosons Z' can easily produce while being anomaly free. Moreover, the scalar DM can benefit from DM-DM-Z'-Z' contact interaction which is free of internal propagator suppression.

In this work we extend G_{SM} with one or more additional $U(1)$ gauge symmetries to generate $\chi\chi \to Z'Z' \to \ell\bar{\ell}\ell'\bar{\ell'}$, where $\chi, Z', \ell^{(\prime)}$ denote the scalar DM, the new gauge boson and $\ell^{(\prime)} = e, \mu, \tau$, respectively, with $m_\chi \sim m_{Z'} \sim 3.0 = 2\, E_\ell \sim 2 \times 1.5$ (TeV). We first illustrate that $G_{SM} \times U(1)_{Y'}$ with the above mass choices can explain the DAMPE excess but has been excluded by **IV-Collider**, i.e. LHC constraints from the Z' searches. Then we consider $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$ in which $U(1)_{Y''}$ mixes with $U(1)_{Y'}$ to interpret the DAMPE data while passing all four conditions **I-ID, II-RD, III-DD, IV-Collider**. Other DM approaches to DAMPE data can be found in [2, 12–15].

The paper is organized as follows. In Section 2 we show the failure of minimal extension $G_{SM} \times U(1)_{Y'}$. In Section 3 we discuss $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$ which is successful in

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

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

interpreting DAMPE data while satisfying other constraints. In Section 4 we present our conclusion.

2 $G_{SM} \times U(1)_{Y'}$, excluded by LHC

We propose to introduce a gauged $U(1)$ family symmetry in our scenarios. Although there are many possible ways for the charge assignments to guarantee anomaly cancelation, we adopt the minimal setting that predict equal e, μ, τ coupling strengths. The particle contents in this scenario with chiral anomaly cancellation are shown in Table.1, where we introduce 3 generations of right handed (RH) neutrinos $\nu_{R,\{1,2,3\}}$ and two complex scalars ϕ_s, ϕ_χ. Note that we will concentrate on the DM physics in light of the DAMPE data in this work and will not address the neutrino sector in detail. We require ϕ_s to develop a vacuum expectation value (vev) v_s to generate $m_{Z'}$. We also impose an odd Z_2 parity for ϕ_χ to generate a stable DM particle.

The most relevant Lagrangian to explain DAMPE data include

$$\begin{aligned} \mathcal{L} \supset\ & |D'_\mu \phi_\chi|^2 + |D'_\mu \phi_s|^2 - V(H,\, \phi_\chi,\, \phi_s) \\ & -\frac{1}{4}|F'_{\mu\nu}|^2 + g_{Y'} Z'_\mu (Y'_{f_R} \overline{f_R} \gamma^\mu f_R + Y'_{\nu_R} \overline{\nu_{R,i}} \gamma^\mu \nu_{R,i}) \end{aligned} \tag{2.1}$$

with

$$\begin{aligned} V(H,\, \phi_\chi,\, \phi_s) =\ & m_{\phi_\chi}^2 |\phi_\chi|^2 + m_{\phi_s}^2 |\phi_s|^2 + \lambda_{\phi_\chi} |\phi_\chi|^4 + \lambda_{\phi_s} |\phi_s|^4 \\ & + \lambda_{\chi H} |\phi_\chi|^2 |H|^2 + \lambda_{sH} |\phi_s|^2 |H|^2 \\ & + \lambda_{\chi s} |\phi_\chi|^2 |\phi_s|^2 + \lambda'_{\chi s} \Big((\phi_\chi^* \phi_s)^2 + h.c. \Big) \end{aligned} \tag{2.2}$$

in which $D'_\mu = \partial_\mu - i g_{Y'} Y' Z'_\mu$, $F'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$ and $f = u, d, \ell$. As mentioned above, when studying DM phenomenologies we will not discuss the neutrino sector including the neutrino mass terms or $U(1)_{Y'}$-induced new Yukawa interactions. To satisfy the condition **IV-Collider** related to the SM Higgs measurements, we set $\lambda_{\chi,H}, \lambda_{s,H}$ to be negligible and one-loop diagram will not give contributions to these couplings.

The terms $\lambda'_{\chi s}\Big((\phi^*_\chi \phi_s)^2 + h.c.\Big)$ in Eq.(2.2) can generate an important mass splitting between the real and imaginary component in ϕ_χ. Before v_s is developed we have

$$\phi_s \to \phi_{R,s} + \phi_{I,s}, \quad \phi_\chi \to \phi_{R,\chi} + \phi_{I,\chi}, \tag{2.3}$$

from which

$$\begin{aligned}
(\phi^*_\chi \phi_s)^2 + h.c. &= \Big((\phi_{R,\chi} - i\,\phi_{I,\chi})(\phi_{R,s} + i\,\phi_{I,s})\Big)^2 + h.c. \\
&= \Big((\phi_{R,\chi}\phi_{R,s} + \phi_{I,\chi}\phi_{I,s}) + i\,(\phi_{R,\chi}\phi_{I,s} - \phi_{I,\chi}\phi_{R,s})\Big)^2 + h.c. \\
&= 2(\phi_{R,\chi}\phi_{R,s} + \phi_{I,\chi}\phi_{I,s})^2 - 2(\phi_{R,\chi}\phi_{I,s} - \phi_{I,\chi}\phi_{R,s})^2 \\
&\supset 2\phi^2_{R,s}(\phi^2_{R,\chi} - \phi^2_{I,\chi}).
\end{aligned} \tag{2.4}$$

When ϕ_s acquires a vev v_s we perform the following replacement

$$\phi_{R,s} \to v_s + \phi_{R,s}, \tag{2.5}$$

which implies

$$\lambda'_{\chi s}\Big((\phi^*_\chi \phi_s)^2 + h.c.\Big) \supset 2\,\lambda'_{\chi s} v_s^2 (\phi^2_{R,\chi} - \phi^2_{I,\chi}). \tag{2.6}$$

This indicates a mass splitting $\Delta m^2_{\chi,\chi'} = m^2_{\chi'} - m^2_\chi = 2\,\lambda'_{\chi s} v_s^2$ with $\chi' \equiv \phi_{R,\chi}, \chi \equiv \phi_{I,\chi}$, in which χ corresponds to the DM.

$\Delta m_{\chi,\chi'}$ has an important implication on the DM-nucleon scattering. To see this, we expand the covariant kinetic term in eq.(2.1)

$$\begin{aligned}
|D'_\mu \phi_\chi|^2 &= (\partial^\mu \phi_\chi - i g_{Y'} Y'_{\phi_\chi} Z'^\mu \phi_\chi)(\partial_\mu \phi^*_\chi + i g_{Y'} Y'_{\phi_\chi} Z'_\mu \phi^*_\chi) \\
&= \partial^\mu \phi_\chi \partial_\mu \phi^*_\chi + (g_{Y'} Y'_{\phi_\chi})^2 Z'^\mu Z'_\mu |\phi_\chi|^2 + i g_{Y'} Y'_{\phi_\chi} Z'_\mu (\phi^*_\chi \partial^\mu \phi_\chi - \phi_\chi \partial^\mu \phi^*_\chi) \\
&= \partial^\mu \phi_\chi \partial_\mu \phi^*_\chi + (g_{Y'} Y'_{\phi_\chi})^2 Z'^\mu Z'_\mu (\phi^2_{R,\chi} + \phi^2_{I,\chi}) - 2\,g_{Z'} Y'_{\phi_\chi} Z'_\mu (\phi_{R,\chi} \partial^\mu \phi_{I,\chi} - \phi_{I,\chi} \partial^\mu \phi_{R,\chi}).
\end{aligned} \tag{2.7}$$

The third term indicates there is only $Z' - \phi_{R,\chi} - \phi_{I,\chi}$, i.e. $Z' - \chi' - \chi$ interaction, but no $Z' - \chi - \chi$ or $Z' - \chi' - \chi'$. The same rule also applies to $Z - \phi_s - \phi_s$. Since we have required the Higgs portal $|\phi_\chi|^2 |H|^2$ to vanish to pass **IV-Collider**, DM χ can only scatter off the nucleon into χ' via t-channel Z' boson. To pass **III-DD** one can simply set $\Delta m_{\chi,\chi'} = m_{\chi'} - m_\chi$ to be much larger than the DM kinetic energy

$$E_{\chi,kin.} \sim \frac{1}{2} m_\chi v_\chi^2 \sim 0.5 \times (3 \times 10^3\,\text{GeV}) \times (10^{-3})^2 \sim 1\,\text{MeV}, \tag{2.8}$$

which will forbid the tree-level Z'-mediated inelastic scattering from happening. Elastic scattering can happen via box diagram involving double $U(1)_{Y'}$ gauge boson and light quark propagator which is suppressed by the light quark masses. The Spin-Independent (SI) direct detection cross section is estimated to be

$$\sigma^{SI}_{\chi-p} \sim \frac{1}{\pi}\frac{m_p^4}{m_\chi^2}\left(\sum_i f^p_{T_{q_i}}\frac{1}{4\pi^2}\frac{Y'^2_{\phi_\chi}}{9}\frac{g^4_{Y'}}{m^2_{\chi'}}\ln\left(\frac{m^2_{Z'}}{\mu^2}\right)\right)^2, \tag{2.9}$$

and our scenario can easily escape the current experiments with heavy $m^2_{\chi'}$.

For the numerical calculations, we use **SARAH** [16] to implement the model, **SPheno** [17, 18] to calculate the mass spectrum and **micrOMEGAs** [19, 20] to calculate DM relic abundance in which the threshold effects are important for $m_\chi \sim m_{Z'}$ [21]. We choose the following parameter settings in our numerical scan:

$$m_{\phi_\chi} \in (2500,\, 3500)\,\text{GeV}, \tag{2.10}$$
$$v_s \in (1000,\, 5000)\,\text{GeV}, \tag{2.11}$$
$$\lambda_{\phi_s} \in (0,\, 1), \tag{2.12}$$
$$g_{Y'},\, \lambda'_{\chi s} \in (0,\, 1), \tag{2.13}$$
$$\lambda_{\phi_\chi} = \lambda_{\chi s} = 0, \tag{2.14}$$
$$\lambda_{\chi,H} = \lambda_{s,H} = 0, \tag{2.15}$$

and require the mass eigenstates and DM observables [22] to satisfy

$$m_\chi \in 3000 \pm 100\,\text{GeV}, \tag{2.16}$$
$$m_{Z'} \in 3000 \pm 100\,\text{GeV}, \tag{2.17}$$
$$\Omega_\chi h^2 \in 0.1187 \pm 0.01198, \tag{2.18}$$
$$\langle\sigma v\rangle_0 \gtrsim 1\times 10^{-26}\, cm^3/s. \tag{2.19}$$

As for the other two physical real scalars $S \equiv \phi_{R,s}$ and χ' after v_s is developed, we require both of them to decay fast enough in the early Universe and not affect our discussion on the DAMPE data explanations in today's Universe. This can be easily fulfilled by $S \to Z'^{(*)}Z'^{(*)} \to$ SM and $\chi' \to \chi + Z^{(*)}$ via the $U(1)_{Y'}$ gauge interaction, as long as the mass spectrums are properly chosen. S can also decay into the neutrino sector via new Yukawa interactions under $U(1)_{Y'}$ such as $\phi_s\overline{\nu^c_{R,1}}\nu_{R,23}$, $\phi_s\nu^c_{R,i}\nu^c_{R,i}$, in which case the neutrino sector may bring additional constraints. In this work we do not address this possibility further and simply assume that a rich degree of freedom in $U(1)_{Y'}$-induced Yukawa couplings $y_{\phi_s,\nu_{ij}}$ can be tuned to evade any neutrino constraint.

This model $G_{SM} \times U(1)_{Y'}$ confronting the four conditions is shown in Table.2. The numerical results are provided in fig.1 on the plane of $m_{Z'}$ versus $g_{Y'}$, where the left regions of LEP and LHC bounds have been excluded. We can see that many samples with $\langle\sigma v\rangle_0 \gtrsim 1\times 10^{-26}\, cm^3/s$ to explain the DAMPE data can survive the LEP bounds on $e^+e^- \to Z' \to \mu^+\mu^-$ [23], but all of them fails to pass the LHC limits due to $q\bar{q} \to Z' \to \ell\bar{\ell}$ [24]. However, this LHC exclusion comes from the non-zero quark quantum numbers under $U(1)_{Y'}$, which could be easily evaded if one considers other anomaly-free $U(1)$ models such as $U(1)_{L_e - L_{\mu/\tau}}$ [14], in which case the SM quarks have no coupling to the new $U(1)$ gauge boson.

Table 2. $G_{SM} \times U(1)_{Y'}$ confronting the four conditions.

Condition	Result	Details
I-ID	$\surd$	$\chi\chi \to Z'Z' \to \ell\bar{\ell}\ell'\bar{\ell}'$ with $\ell, \ell' = e, \mu, \tau$ with $m_\chi \sim m_{Z'} \sim 3.0 = 2\,E_\ell \sim 2 \times 1.5$ (TeV). $Br(Z' \to q\bar{q})$ is small due to small Y'_q.
II-RD	$\surd$	Same as **I-ID**.
III-DD	$\surd$	$\Delta m_{\chi,\chi'} = m_{\chi'} - m_\chi \gg E_{\chi,kin}$ forbids tree-level inelastic scattering $\chi + SM \to \chi' + SM$ via t-channel Z'.
IV-Collider	$\times$	Excluded by $q\bar{q} \to Z' \to \ell\bar{\ell}$ at the LHC [24].

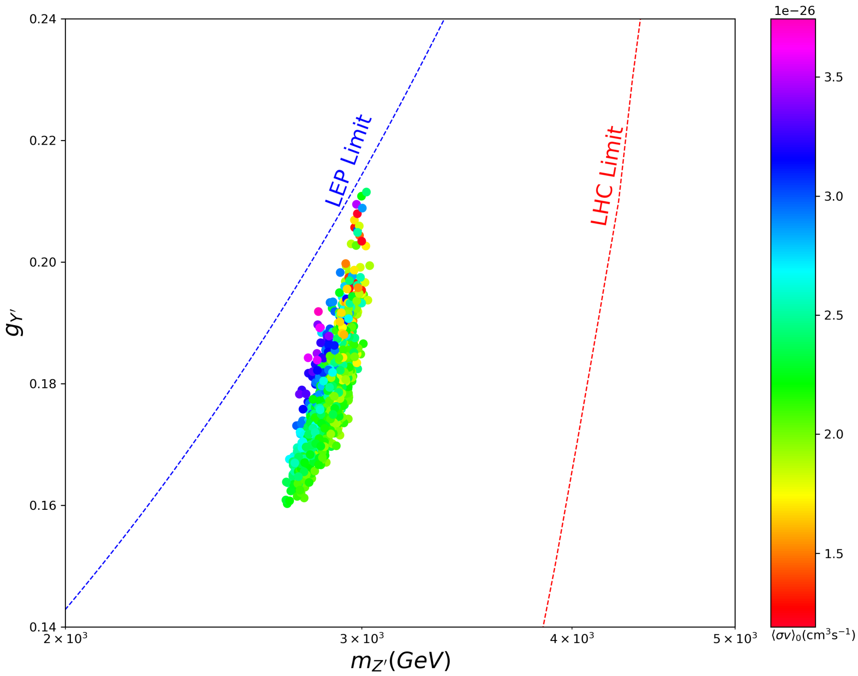

Figure 1. $G_{SM} \times U(1)_{Y'}$ is excluded by $q\bar{q} \to Z' \to \ell\bar{\ell}$ at the LHC [24].

3 $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$, allowed by LHC

To pass the LHC constraints in previous model $G_{SM} \times U(1)_{Y'}$, here we extend it with another $U(1)_{Y''}$ gauge group which mixes with $U(1)_{Y'}$, and one additional complex scalar ϕ_d. The particle contents in this model with chiral anomaly cancellation are shown in

Table 3. Particle contents in $G_{SM}\times U(1)_{Y'}\times U(1)_{Y''}$ model.

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

Table.3. Note that ϕ_χ is no longer charged under previous $U(1)_{Y'}$ and only ϕ_χ, ϕ_d are charged under $U(1)_{Y''}$. Similarly, we require ϕ_d to develop a vev v_d to generate the $U(1)_{Y''}$ gauge boson mass. We will not address in detail the origin and related particle sectors of the $U(1)_{Y'}-U(1)_{Y''}$ mixing, since it could be easily generated via loops of extra scalars/fermions charged under both of the two groups.

The most relevant Lagrangian to explain the DAMPE data include

$$\begin{aligned}\mathcal{L}\supset\ & |D_\mu^{(2)}\phi_\chi|^2+|D_\mu^{(2)}\phi_s|^2+|D_\mu^{(2)}\phi_d|^2-V(H,\,\phi_\chi,\,\phi_s,\,\phi_d)\\ &-\frac{1}{4}|F'_{\mu\nu}|^2-\frac{1}{4}|F''_{\mu\nu}|^2-\frac{\epsilon}{2}F'^{\mu\nu}F''_{\mu\nu}\\ &+g_{Y'}Y'_{f_R}\overline{f_R}\gamma^\mu f_R B'_\mu+g_{Y'}Y'_{\nu_R}\overline{\nu_{R,i}}\gamma^\mu\nu_{R,i}B'_\mu\\ &+g_{Y''}Y''_{f_R}\overline{f_R}\gamma^\mu f_R B''_\mu+g_{Y''}Y''_{\nu_R}\overline{\nu_{R,i}}\gamma^\mu\nu_{R,i}B''_\mu\end{aligned}\tag{3.1}$$

with

$$\begin{aligned}V(H,\,\phi_\chi,\,\phi_s,\,\phi_d)=\ & m_{\phi_\chi}^2|\phi_\chi|^2+m_{\phi_s}^2|\phi_s|^2+m_{\phi_d}^2|\phi_d|^2\\ &+\lambda_{\phi_\chi}|\phi_\chi|^4+\lambda_{\phi_s}|\phi_s|^4+\lambda_{\phi_d}|\phi_d|^4\\ &+\lambda_{\chi H}|\phi_\chi|^2|H|^2+\lambda_{sH}|\phi_s|^2|H|^2+\lambda_{dH}|\phi_d|^2|H|^2\\ &+\lambda_{\chi s}|\phi_\chi|^2|\phi_s|^2+\lambda_{\chi d}|\phi_\chi|^2|\phi_d|^2+\lambda_{sd}|\phi_s|^2|\phi_d|^2.\end{aligned}\tag{3.2}$$

In the above $D_\mu^{(2)}=\partial_\mu-ig_{Y'}Y'B'_\mu-ig_{Y''}Y''B''_\mu$, $F'_{\mu\nu}=\partial_\mu B'_\nu-\partial_\nu B'_\mu$, $F''_{\mu\nu}=\partial_\mu B''_\nu-\partial_\nu B''_\mu$. ϵ is the kinetic mixing parameter between $U(1)_{Y'}$ and $U(1)_{Y''}$. Note that we can choose $Y''_{\phi_\chi}\neq Y''_{\phi_d}$ to forbid $\lambda'_{\chi s}$ terms in eq.(2.2), but for simplicity we take $Y''_{\phi_\chi}=Y''_{\phi_d}=6$ as in previous model and set $\lambda'_{\chi d}=0$ since we no longer have to rely on $\Delta m_{\chi,\chi'}$ to forbid tree-level Z'-mediated DM-nucleon scattering, which can be realized easily via small ϵ and heavy mediator. Simplifications of the neutrino sector and $\phi_{\chi,s,d} - H$ mixing are the same as in previous model. The interactions between the DM and the SM can be sketched as follows

$$\Big(\phi_\chi, \phi_d - [g_{Y''} Y''] - B''\Big) - [\epsilon] - \Big(B' - [g_{Y'} Y'] - \phi_s, \mathrm{SM}\Big). \tag{3.3}$$

Using mass eigenstates we have

$$\Big(\chi - [g_{Y''} Y''] - Z''\Big) - [\epsilon] - \Big(Z' - [g_{Y'} Y'] - \mathrm{SM}\Big), \tag{3.4}$$

in which we have ignored the scalar mass eigenstates $S \equiv \phi_{R,s}, D \equiv \phi_{R,d}$ after v_s, v_d are developed since we require them to decay fast enough in the early Universe and not affect our discussion on DAMPE data interpretation in today's Universe, as we argued for the previous model. We will focus on the complex scalar DM $\chi \equiv \phi_\chi$, two massive gauge boson mass eigenstates Z' (B'-dominant) and Z'' (B''-dominant) which couple mainly to SM and the DM, respectively.

We choose the following parameter settings in our numerical scan

$$\begin{aligned}
m_{\phi_\chi} &\in (2500,\, 3500)\,\mathrm{GeV}, && (3.5)\\
v_s &\in (1000,\, 5000)\,\mathrm{GeV}, &&\\
v_d &\in (1000,\, 5000)\,\mathrm{GeV}, &&\\
\lambda_{\phi_s},\, \lambda_{\phi_d} &\in (0,\, 1), &&\\
g_{Y''},\, \epsilon &\in (0,\, 1), &&\\
g_{Y'} &= 0.1, &&\\
\lambda_{\phi_\chi} &= \lambda_{\chi s} = \lambda_{\chi d} = \lambda_{sd} = 0, &&\\
\lambda_{\{\chi,s,d\},H} &= 0, && (3.6)
\end{aligned}$$

and require the mass eigenstates and DM observables to satisfy

$$\begin{aligned}
m_\chi &\in 3000 \pm 100\,\mathrm{GeV}, && (3.7)\\
m_{Z'} &\in 3000 \pm 100\,\mathrm{GeV}, &&\\
m_{Z''} &\gtrsim 4000\,\mathrm{GeV}, &&\\
\Omega_\chi h^2 &\in 0.1187 \pm 0.01198, &&\\
\langle \sigma v \rangle_0 &\gtrsim 1 \times 10^{-26}\, cm^3/s. &&
\end{aligned}$$

Here we clarify how the four conditions **I-ID, II-RD, III-DD, IV-Collider** are satisfied in the surviving samples:

- **I-ID**: $g_{Y''} \sim 0.2$ with $m_\chi \sim m_{Z''} \sim 3.0$ TeV to generate $\langle \sigma v \rangle_0 \sim 1 \times 10^{-26}\, cm^3/s$, followed by B'-component in Z'' decaying dominantly into nearly equal e, μ, τ Brs.
- **II-RD**: Same as **I-ID**.

Table 4. $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$ confronting the four conditions.

Condition	Result	Details
I-ID	$\surd$	$\chi\chi \to Z''Z'' \to \ell\bar{\ell}\ell'\bar{\ell}'$ with $\ell, \ell' = e, \mu, \tau$ with $m_\chi \sim m_{Z''} \sim 3.0 = 2\,E_\ell \sim 2 \times 1.5$ (TeV). $Br(Z'' \to q\bar{q})$ is small due to small Y'_q.
II-RD	$\surd$	Same as **I-ID**.
III-DD	$\surd$	$g_{Y'} = 0.1$, $\epsilon \lesssim 0.05$, $m_{Z'} \gtrsim 4\,\mathrm{TeV}$ can suppress the DM-nucleon scattering mediated by $\chi\chi - [g_{Y''}Y''] - Z'' - [\epsilon] - Z' - [g_{Y'}Y'] - q\bar{q}$
IV-Collider	$\surd$	$g_{Y'} = 0.1$, $m_{Z'} \gtrsim 4\,\mathrm{TeV}$ can suppress the Z' production at LEP and LHC via $f\bar{f} - [g_{Y'}Y'_f] - Z' - [g_{Y'}Y'_{f'}] - f'\bar{f}'$.

- **III-DD**: $g_{Y'} = 0.1$, $\epsilon \lesssim 0.05$, $m_{Z'} \gtrsim 4\,\mathrm{TeV}$ can suppress the DM-nucleon scattering mediated by $\chi\chi - [g_{Y''}Y''] - Z'' - [\epsilon] - Z' - [g_{Y'}Y'] - q\bar{q}$.
- **IV-Collider**: $g_{Y'} = 0.1$, $m_{Z'} \gtrsim 4\,\mathrm{TeV}$ is sufficient to suppress the $f\bar{f} - [g_{Y'}Y'_f] - Z' - [g_{Y'}Y'_{f'}] - f'\bar{f}'$ production at both LEP and LHC [23, 24], with f, f' being SM fermions.

This model $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$ confronting the four conditions is shown in Table.4. The numerical results are provided in fig.2 on the plane of ϵ versus SI DM-nucleon scattering rate σ^{SI}_{DM-p}, where we also show the latest PandaX-II bounds [25]. We can see that surviving samples with $\langle\sigma v\rangle_0 \sim 1 \times 10^{-26}\,cm^3/s$ can still exist without violating other constraints.

4 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 $G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$ with additional $U(1)$ gauge symmetries while keeping anomaly free to generate $\chi\chi \to Z'Z' \to \ell\bar{\ell}\ell'\bar{\ell}'$, where $\chi, Z', \ell^{(')}$ denote the scalar DM, the new gauge boson and $\ell^{(')} = e, \mu, \tau$, respectively, with $m_\chi \sim m_{Z'} \sim 3.0 = 2\,E_\ell \sim 2 \times 1.5$ (TeV). We first illustrate that $G_{SM} \times U(1)_{Y'}$ 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 $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$ in which $U(1)_{Y''}$ mixes with $U(1)_{Y'}$. We showed that it can interpret the DAMPE data while passing other constraints including DM relic abundance, DM direct detection and collider bounds.

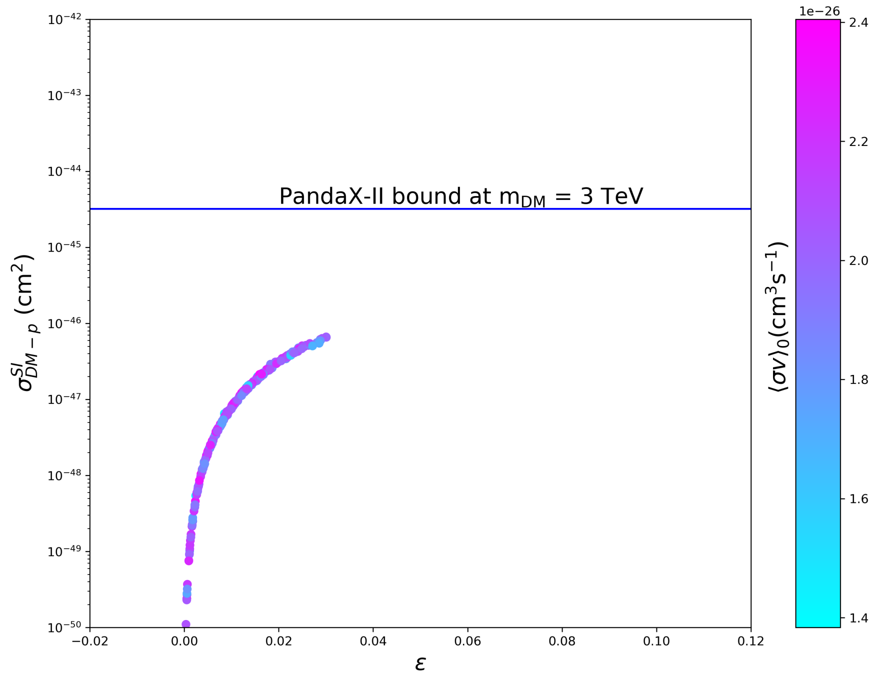

Figure 2. $G_{SM} \times U(1)_{Y'} \times U(1)_{Y''}$ can interpret the DAMPE data while passing all conditions.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (NNSFC) under grant No. 11575053. This work is also supported by the Natural Science Foundation of China under grant numbers 11675147 and by the Innovation Talent project of Henan Province under grant number 15HASTIT017.

References

[1] DAMPE Collaboration, *Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons,* http://dx.doi.org/10.1038/nature24475, *Nature* (nov, 2017) .

[2] Q. Yuan, L. Feng, P.-F. Yin, Y.-Z. Fan, X.-J. Bi, M.-Y. Cui et al., *Interpretations of the DAMPE electron data*, 1711.10989.

[3] AMS collaboration, M. Aguilar et al., *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** (2013) 141102.

[4] AMS collaboration, L. Accardo et al., *High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5C500 GeV with the Alpha Magnetic Spectrometer on the International Space Station*, *Phys. Rev. Lett.* **113** (2014) 121101.

[5] PAMELA collaboration, O. Adriani et al., *An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV*, Nature **458** (2009) 607–609, [0810.4995].

[6] O. Adriani et al., *A statistical procedure for the identification of positrons in the PAMELA experiment*, Astropart. Phys. **34** (2010) 1–11, [1001.3522].

[7] Fermi-LAT collaboration, M. Ackermann et al., *Measurement of separate cosmic-ray electron and positron spectra with the Fermi Large Area Telescope*, Phys. Rev. Lett. **108** (2012) 011103, [1109.0521].

[8] P. D. Serpico, *Astrophysical models for the origin of the positron 'excess'*, Astropart. Phys. **39-40** (2012) 2–11, [1108.4827].

[9] M. Cirelli, *Indirect Searches for Dark Matter: a status review*, Pramana **79** (2012) 1021–1043, [1202.1454].

[10] S. Chang, R. Edezhath, J. Hutchinson and M. Luty, *Effective WIMPs*, Phys. Rev. **D89** (2014) 015011, [1307.8120].

[11] A. Berlin, D. Hooper and S. D. McDermott, *Simplified Dark Matter Models for the Galactic Center Gamma-Ray Excess*, Phys. Rev. **D89** (2014) 115022, [1404.0022].

[12] K. Fang, X.-J. Bi and P.-F. Yin, *Explanation of the knee-like feature in the DAMPE cosmic e^-+e^+ energy spectrum*, 1711.10996.

[13] G. H. Duan, L. Feng, F. Wang, L. Wu, J. M. Yang and R. Zheng, *Simplified TeV leptophilic dark matter in light of DAMPE data*, 1711.11012.

[14] P.-H. Gu and X.-G. He, *Electrophilic dark matter with dark photon: from DAMPE to direct detection*, 1711.11000.

[15] Y.-Z. Fan, W.-C. Huang, M. Spinrath, Y.-L. S. Tsai and Q. Yuan, *A model explaining neutrino masses and the DAMPE cosmic ray electron excess*, 1711.10995.

[16] F. Staub, *Exploring new models in all detail with SARAH*, Adv. High Energy Phys. **2015** (2015) 840780, [1503.04200].

[17] W. Porod, *SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e+ e- colliders*, Comput. Phys. Commun. **153** (2003) 275–315, [hep-ph/0301101].

[18] W. Porod and F. Staub, *SPheno 3.1: Extensions including flavour, CP-phases and models beyond the MSSM*, Comput. Phys. Commun. **183** (2012) 2458–2469, [1104.1573].

[19] G. Blanger, F. Boudjema, A. Pukhov and A. Semenov, *micrOMEGAs4.1: two dark matter candidates*, Comput. Phys. Commun. **192** (2015) 322–329, [1407.6129].

[20] G. Belanger, F. Boudjema and A. Pukhov, *micrOMEGAs : a code for the calculation of Dark Matter properties in generic models of particle interaction*, in *The Dark Secrets of the Terascale: Proceedings, TASI 2011, Boulder, Colorado, USA, Jun 6 - Jul 11, 2011*, pp. 739–790, 2013. 1402.0787. DOI.

[21] K. Griest and D. Seckel, *Three exceptions in the calculation of relic abundances*, Phys. Rev. D **43** (May, 1991) 3191–3203.

[22] Planck collaboration, P. A. R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, Astron. Astrophys. **594** (2016) A13, [1502.01589].

[23] H.-S. Lee and E. Ma, *Gauged $B - x_i L$ origin of R Parity and its implications*, Phys. Lett. **B688** (2010) 319–322, [1001.0768].

[24] ATLAS collaboration, M. Aaboud et al., *Search for new high-mass phenomena in the dilepton final state using 36 fb*$^{-1}$ *of proton-proton collision data at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *JHEP* **10** (2017) 182, [1707.02424].

[25] PandaX-II collaboration, A. Tan et al., *Dark Matter Results from First 98.7 Days of Data from the PandaX-II Experiment*, *Phys. Rev. Lett.* **117** (2016) 121303, [1607.07400].