

Explaining DAMPE results by dark matter with hierarchical lepton-specific Yukawa interactions^{*}

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Abstract: We propose to interpret the DAMPE electron excess at 1.5 TeV through scalar or Dirac fermion dark matter (DM) annihilation with doubly charged scalar mediators that have lepton-specific Yukawa couplings. The hierarchy of such lepton-specific Yukawa couplings is generated through the Froggatt-Nielsen mechanism, so that the dark matter annihilation products can be dominantly electrons. Stringent constraints from LEP2 on intermediate vector boson production can be evaded in our scenarios. In the case of scalar DM, we discuss one scenario with DM annihilating directly to leptons and another scenario with DM annihilating to scalar mediators followed by their decays. We also discuss the Breit-Wigner resonant enhancement and the Sommerfeld enhancement in the case where the s-wave annihilation process is small or helicity-suppressed. With both types of enhancement, constraints on the parameters can be relaxed and new ways for model building can be opened in explaining the DAMPE results.

Keywords: DAMPE, dark matter, Froggatt-Nielsen mechanism, Sommerfeld enhancement

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1 Introduction

The nature of dark matter (DM) is one of the most important questions in particle physics and cosmology. In fact, many new physics theories beyond the standard model (SM) can provide viable DM candidates. Apart from its various gravitational influences, DM has so far eluded all direct detection experiments through nucleon recoil, prompting experimentalists to find alternative ways to search for its existence. An important method of probing DM properties is via indirect detection, where we look for the appearance of particles like high energy gamma-rays, positrons or X-rays produced via annihilation or decay of DM concentrations in galaxies (satellites, dwarfs, or clusters).

In past few years, a positron excess has been reported by various experiments, such as AMS02 [1, 2], PAMELA [3, 4] and Fermi [5]. Recently, the DArk Mat-

ter Particle Explorer (DAMPE) satellite [6], which is a new cosmic ray detector with excellent energy resolution and hadron rejection power, published their measurements of the cosmic $e^+ + e^-$ flux up to 5 TeV and announced the finding of a sharp peak at ~ 1.5 TeV. Although both astrophysical (e.g., pulsars) and DM origins are possible as the required nearby mono-energetic electron sources, the DM explanation could potentially guide the search for DM particles in future direct detection and collider experiments. Many DM models have been proposed to explain the DAMPE results [7–35]. In the DM explanation (DM annihilation into electrons or equal amounts of lepton flavors), the best fit value of the DM mass should be 1.5 TeV if the nearby DM subhalo is located at $0.1 \sim 0.3$ kpc away from the solar system, and the DM annihilation cross section should be $\langle\sigma v\rangle \approx 3 \times 10^{-26} \text{cm}^3/\text{s}$. Besides, in order to guarantee the resulting electron/positron spectrum to be a narrow

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peak instead of a box shape spectrum, the required mass ratio between the mediator (to lepton pairs) and the DM mass is stringently constrained to be higher than 0.995 by numerical fitting to the DAMPE data [13].

In order to have a large DM annihilation cross section in the DM sub-halo and at the same time give the correct DM relic density, it is preferable to adopt Dirac DM scenarios because the Dirac DM annihilation into lepton pair final states via a vector leptophilic mediator will not be s -wave suppressed [36]. Scalar DM scenarios, where the DM can annihilate into vector mediator pairs followed by their late-time decays, can also explain the result. Both scenarios tend to adopt a leptophilic gauge boson which can couple universally to the lepton flavors as the mediator. On the other hand, the DM direct detection bounds as well as the electron/positron collider constraints on the vector mediator production will impose rather stringent constraints on these scenarios.

An alternative possibility is the scalar-portal DM scenario, in which the mediator will mainly couple to leptons. We propose to explain the DAMPE excess by a scalar or Dirac fermion DM candidate with lepton-specific Yukawa couplings. A horizontal family symmetry $U(1)_H$, which can be either global (with small explicit symmetry breaking terms) or local, is introduced for the lepton sector using the Froggatt-Nielsen mechanism [37, 38]. By properly choosing the $U(1)_H$ quantum numbers, the Yukawa couplings between the scalar mediators and the first family leptons can be unsuppressed, while other types may be suppressed, which is just what is needed for explaining the DAMPE result.

In general, models with s -wave suppressed DM annihilation cross section are not favored to interpret the DAMPE results. We note that, by adopting Breit-Wigner enhancement [39–41] or Sommerfeld enhancement [42–44], the s -wave (helicity or propagator) suppressed process can also be used to explain the DAMPE results because of a large enhancement factor. Therefore, new ways for model building in explaining the DAMPE results will be open with such an enhancement factor.

This paper is organized as follows. In Section 2, we introduce a scalar DM model to explain the DAMPE electron/positron excess. Effects of Breit-Wigner enhancement and Sommerfeld enhancement are discussed. In Section 3, a model with Dirac fermion DM is proposed. Finally, we draw our conclusions in Section 4.

2 Scalar dark matter with scalar mediator involving lepton-specific interactions

We propose to explain the DAMPE result with scalar DM and scalar mediators. The complex scalar S , which

is odd under a discrete Z_2 symmetry, will act as the DM candidate while other fields are even under Z_2 . Higgs-portal type interactions between S and scalar mediator T , which will couple only to leptons, will be introduced. To generate the Yukawa hierarchy so that the mediator decays dominantly to electrons, a global $U(1)_H$ with small explicit symmetry breaking terms or an anomaly free local $U(1)_H$ horizontal symmetry will be introduced to generate the required suppression factors via the Froggatt-Nielsen mechanism. The Lagrangian has the following form:

$$\begin{aligned} \mathcal{L} \supseteq & |\partial_\mu S|^2 + |D_\mu T|^2 - m_S^2 |S|^2 - m_T^2 |T|^2 - \frac{\lambda_1}{4} |S|^4 \\ & - \lambda_2 |S|^2 |T|^2 - \frac{\lambda_3}{4} |T|^4 \\ & - y_i \sum_i \left(\frac{U}{\Lambda} \right)^{Q_{ij}^E} (\bar{E}_{R,i}^c E_{R,j} T) + \dots, \end{aligned} \quad (1)$$

where

$$\begin{aligned} D_\mu T &= (\partial_\mu - iQ_Y^T g_Y B_\mu) T, \\ Q_{ij}^E &\equiv -\frac{Q_H(T) + Q_H(E_{R,i}^c) + Q_H(E_{R,j}^c)}{Q_H(U)}, \end{aligned} \quad (2)$$

with $Q_Y^T = 2$.

Non-renormalizable interactions involving the flavon field U , which transform non-trivially under $U(1)_H$, are generated after integrating out the heavy modes at the scale Λ . Due to the charge assignments of $U(1)_H$ horizontal symmetry for the SM fermions and T , the Yukawa coupling of the form $\bar{E}_{R,i}^c E_{R,i} T$ will appear only after the flavon acquires a VEV $\langle U \rangle$.

From the $U(1)_H$ quantum numbers given in Table 1, the Yukawa couplings between the scalar mediator and leptons have the following hierarchy:

$$\begin{aligned} \mathcal{L} \supseteq & -y_1 \bar{E}_{R,i}^c E_{R,i} T - y_2 \left(\frac{U}{\Lambda} \right)^6 (\bar{\mu}_R^c \mu_{R,i} T) \\ & - y_3 \left(\frac{U}{\Lambda} \right)^6 (\bar{\tau}_R^c \tau_{R,i} T). \end{aligned} \quad (3)$$

After U acquires a VEV so that $\langle U \rangle / \Lambda \sim \mathcal{O}(0.1)$, for $y_1 \simeq y_2 \simeq y_3 \sim \mathcal{O}(1)$, the resulting Yukawa couplings have the following hierarchy

$$y_e \gg y_\mu \approx y_\tau. \quad (4)$$

An alternative possibility is that we choose the following $U(1)_H$ quantum numbers

$$Q'(e, \mu) = 1, Q'(\tau) = -2, Q(T) = -2, Q(U) = 1. \quad (5)$$

The Yukawa couplings for e, μ are unsuppressed while that for τ is suppressed, so $y_e \simeq y_\mu \gg y_\tau$. Similarly, we could have $y_e \simeq y_\tau \gg y_\mu$.

Table 1. The local horizontal $U(1)_H$ quantum numbers for the SM matter content with the generation index $a=1,2,3$.

	Q_L^a	U_R^a	D_R^a	$L_{L,e}, e_R$	$L_{L,\mu}, \mu_R$	$L_{L,\tau}, \tau_R$	S	T	U
$U(1)'$	0	0	0	-2	1	1	0	4	-1

For the DM annihilation, we have two possibilities.

1) Scenario I

The DM particles annihilate into the scalar mediators $SS^* \rightarrow T^{++}T^{--}$, followed by their decays into lepton pairs $T^{--} \rightarrow l_R l_R$. The dark matter mass should then satisfy $m_\chi \equiv m_S > m_T$ and the range of $m_T \in [0.995, 1] \times m_S$ to fit the peak shape electron/positron spectrum required to fit the DAMPE data.

Our numerical results are shown in Fig. 1. We can see that the Higgs portal coupling λ_2 is constrained to lie near 1.7, which is quite large but within the perturbative regime.

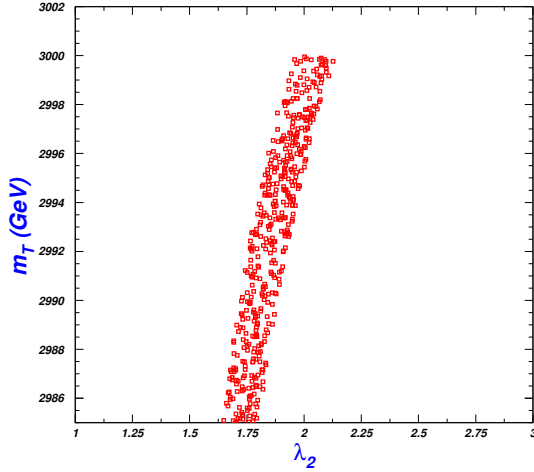


Fig. 1. (color online) The range of the parameter λ_2 vs m_T to explain the DAMPE result without enhancements in the case of scalar DM.

In previous papers with typical leptophilic $U(1)$ gauge bosons as DM mediator [18, 27], the LEP2 bounds on vector boson production will rule out many simplest scalar DM models. In our setting, the LEP2 constraints will be relaxed because the T scalar with double electric charge would not have been produced directly at the electron/positron collider LEP2. It is therefore fairly advantageous to use such a doubly charged scalar as the DM mediator.

Naively, the DM can scatter off the light quarks at one-loop order through T scalar loops that connect to the quark lines via photons. However, the one-loop diagram can be proved to vanish. So the leading order contributions arise at two-loop order. The DM direct detection cross sections are thus suppressed at two-loop order. By matching to the effective operator after integrating out

the scalar T

$$\mathcal{L}_{\text{eff}} \approx \frac{2}{3} \alpha_{\text{em}}^2 \lambda \frac{\chi^\dagger \chi}{m_T^2} \frac{F^{\mu\nu} F_{\mu\nu}}{e^2}, \quad (6)$$

we can estimate the scalar DM-nucleon scattering amplitudes to be

$$\mathcal{M} \approx \frac{\kappa}{12} \alpha_{\text{em}}^2 \frac{\lambda}{m_T^2} Z^2 \tilde{F}(q^2) \left(\bar{u}'_N \frac{1}{2} (1 + \gamma^0) u_N \right). \quad (7)$$

Following the methods in Ref. [45], we can estimate the DM direct detection cross section

$$\frac{d\sigma}{dE_d} \approx \left(\frac{\alpha_{\text{em}} Z}{\pi} \right)^4 \frac{m_N \lambda^2}{2\pi v^2} \left(\frac{\pi^2}{12} \right)^2 \frac{m_N^2}{m_T^2} v_d^2 \tilde{F}(q^2), \quad (8)$$

with the DM velocity $v \sim 10^{-3}c$ and the velocity of the recoiled nucleus $v_d = \sqrt{2E_d/m_N}$. With $m_T \sim 3$ TeV, the DM-nucleon scattering cross section, which can be estimated to be of order 3×10^{-16} pb, can easily survive the DM direct detection bounds given by LUX [46] and PandaX [47].

2) Scenario II

The DM particles annihilate directly into four leptons $S^*S \rightarrow (T^{++})^* (T^{--})^* \rightarrow l^- l^- l^+ l^+$ if the scalar mediator is heavier than 3 TeV. Such an annihilation cross section will in general be suppressed by the mediator propagator.

We propose two ways of enhancing the DM annihilation cross section to explain the DAMPE data in this scenario.

Resonant annihilation with Breit-Wigner enhancement

If the scalar mediator mass lies slightly higher than the DM mass m_S , the direct 4-lepton final state annihilation will be enhanced by the Breit-Wigner resonant effect [39]. The resonant annihilation cross sections are given as

$$\begin{aligned} \sigma v_{\text{rel}} &\approx \frac{\lambda_2^2}{4m_\chi^2} \left[\frac{2m_T \Gamma_T}{(p^2 - m_T^2)^2 + m_T^2 \Gamma_T^2} \right]^2, \\ &\approx \frac{\lambda_2^2}{4m_\chi^2} \left[\frac{8\gamma}{(v_{\text{rel}}^2 - 2\epsilon)^2 + 4\gamma^2} \right]^2, \end{aligned} \quad (9)$$

with

$$p^2 \approx m_\chi^2 + \frac{1}{2} m_\chi v_{\text{rel}}^2, \quad \epsilon = \frac{m_T^2 - m_\chi^2}{m_T^2}, \quad \gamma = \frac{m_T \Gamma_T}{m_T^2}.$$

It is known that for $\gamma \ll 1$ and $\gamma^2 \ll (v_{\text{rel}}^2 - 2\epsilon)^2$, we have the approximation

$$\lim_{\gamma \rightarrow 0} \frac{8\gamma}{[(v_{\text{rel}}^2 - 2\epsilon)^2 + 4\gamma^2]} = 4\pi \delta(v_{\text{rel}}^2 - 2\epsilon). \quad (10)$$

We can see that we could have **double** enhancement near the threshold due to the apparent $\delta(0)$. We need to cut the apparent infinity with the decay width of T , which is estimated to be given by

$$\Gamma_T \approx \frac{y_E^2 m_T}{32\pi}. \quad (11)$$

So we have the cut for the delta function

$$\delta(v_{\text{rel}}^2 - 2\epsilon) \rightarrow \frac{m_T}{\pi\Gamma_T} \approx \frac{32}{y_E^2}. \quad (12)$$

Using the standard formula for DM relic density [41], Ωh^2 is given by

$$\Omega h^2 \approx 2.755 \times 10^8 \sqrt{\frac{45}{\pi g_*}} \frac{1}{M_{\text{pl}} J_f} \text{GeV}^{-1}, \quad (13)$$

with

$$\begin{aligned} J_f &= \int_0^\infty dv_{\text{rel}} \frac{v_{\text{rel}}^2 (\sigma v_{\text{rel}})}{2\pi^{1/2}} \int_{x_f}^\infty dx x^{-1/2} e^{-x^2 v_{\text{rel}}^2/4}, \\ &\approx \frac{4\pi^2 \lambda_2^2}{m_\chi^2} \text{erfc}\left(\sqrt{\frac{x_f \epsilon}{2}}\right) \delta(0), \\ &\approx \frac{4\pi^2 \lambda_2^2}{m_\chi^2} \text{erfc}\left(\sqrt{\frac{x_f \epsilon}{2}}\right) \frac{32}{y_E^2}. \end{aligned} \quad (14)$$

So we can obtain a universal $\langle \sigma v \rangle$ at the freeze-out time. The thermal averaged cross section today can also be readily obtained from J_f with $\epsilon \rightarrow 0$. So, if this scalar DM scenario is to explain the DAMPE data, the range of λ_2 can be much smaller if y_E is small because of the double enhancement effects near resonance. We should note that the resonant enhancement will affect the annihilation cross section at both the freeze-out temperature and today. The DM-nucleon scattering cross section will be suppressed by a tiny coupling λ_2 , so DM direct detection experiments may not see any signal in the near future.

DM annihilation with Sommerfeld enhancement

There is an alternative possibility, in which the DM annihilation in the early universe may be helicity-suppressed (by light fermion masses) at the s -wave and the DM relic density is determined mainly by p -wave processes. Suppressed by the low relative velocity $v \sim 10^{-3}c$, the p -wave process will not give dominant contributions to the DM annihilation in the sub-halo. So, in order to explain the observed electron/positron excess reported by DAMPE, we need to enhance the suppressed s -wave contributions to the DM annihilation today.

Fortunately, the Sommerfeld enhancement has the desired behavior: it is enhanced at low velocities and therefore can boost the present day annihilation cross section. The DM annihilation in the early universe will be affected only slightly. We should note that although

chemical recoupling [44] implies suppressed indirect detection signals for near-resonance regions, the Sommerfeld enhancement can still enhance the suppressed annihilation up to a factor $10^2 \sim 10^3$ to account for the DAMPE signal.

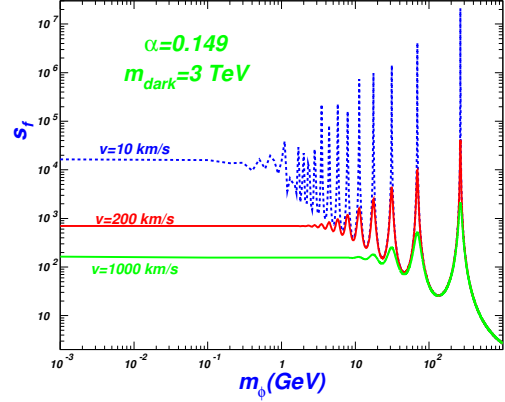


Fig. 2. (color online) The Sommerfeld enhancement factor S_f vs the light gauge boson mass m_ϕ for $\alpha_X \approx 0.149$ and DM mass $m_S = 3$ TeV. Here $v = 10$ km/s, 200 km/s, and 1000 km/s corresponds to the characteristic speeds of dwarf halos, the Milky Way and clusters, respectively.

In this scenario, although the s -wave of DM annihilation is not suppressed, the requirement to give a correct DM relic density will stringently constrain the couplings involved. Considering the Sommerfeld enhancement can explain the DAMPE results with much smaller coupling strengths. Therefore, the DM direct detection bounds can be evaded very easily.

We can introduce an additional $U(1)_X$ gauge group with the gauge coupling strength g_X and the gauge boson mass m_X . The complex DM particle $\chi \equiv S$ will transform non-trivially under $U(1)_X$ with the corresponding charge Q_S . The Sommerfeld enhancement factor can be approximated by [43]

$$\tilde{S} \approx \frac{g_X^2 m_S}{4\pi m_X}. \quad (15)$$

for a massive gauge boson mediator A_μ^X . While the DM annihilation is dominantly by $S^*S \rightarrow XX$ via t, u -channel S , the resulting cross section

$$\langle \sigma v_{\text{rel}} \rangle \approx \frac{g_X^4 Y_S^4}{48\pi m_S^2} \quad (16)$$

must give the correct DM relic density, which is given by the Planck satellite data $\Omega_{\text{DM}} = 0.1199 \pm 0.0027$ [48] in combination with the WMAP data [49] (with a 10% theoretical uncertainty). So we must have $\alpha_X Y_S^2 \approx 0.149$ for the DM mass $m_S = 3$ TeV. For simplicity, we choose the DM $U(1)_X$ charge $Y_S = 1$. Numerical results for the value of the Sommerfeld enhancement factor are given in

Fig. 2. We can see that, given an appropriate mass of the mediator ϕ , a sufficient enhancement factor can be achieved for different cosmic objects, such as the dwarf halos, Milky Way and the clusters.

It is shown in Ref. [44] that the DM can annihilate into $A_\mu^X \phi$, with ϕ being the hidden Higgs that breaks the $U(1)_X$ gauge symmetry. The mass of ϕ is argued to be $m_\phi \lesssim 10m_X$ by perturbative requirements. However, we can introduce additional Higgs portal terms, which can contribute to the mass of ϕ , so that the simple relation between m_ϕ and m_X is released. So we will neglect the effect of hidden Higgs ϕ in our estimation of $\langle\sigma v_{\text{rel}}\rangle$ by tuning ϕ to be very heavy. Opening both annihilation channels will introduce uncertainty in the parameter g_X because of the free parameter m_ϕ .

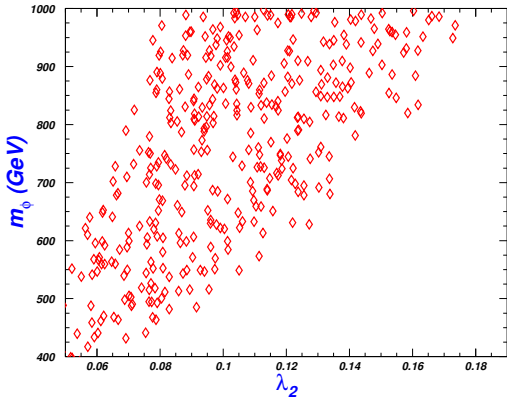


Fig. 3. (color online) The allowed parameter λ_2 versus the light gauge boson mass m_ϕ when the Sommerfeld enhancement is considered in the case of scalar DM.

The Sommerfeld enhancement factor is determined by the DM wave-function obtained from the non-relativistic Schrodinger equation:

$$\tilde{S} = \left| \frac{\chi(\infty)}{\chi(0)} \right|^2, \quad (17)$$

with which the approximate analytic results can be obtained after approximating the Yukawa potential by the Hulthen potential [50]. The enhancement factor is thus approximated by

$$\tilde{S} \approx \frac{\pi^2 \alpha_X m_X}{6 m_\chi v^2} \quad (18)$$

at the resonance and is proportional to v^{-1} away from the resonance. In order to avoid chemical recoupling, we will adopt mainly the v^{-1} enhancement behavior in our numerical study. In Fig. 3 we can see that the coupling strength λ_2 can be reduced to a much smaller value with such an enhancement. As the DM annihilation cross sections into leptons are enhanced by the Sommerfeld factor, the reduced coupling strengths of λ will easily pass the DM direct detection constraints.

3 Dirac fermion dark matter with scalar mediator involving lepton-specific interactions

We also propose to explain the DAMPE results by introducing a Dirac DM scenario which can annihilate into leptons via a scalar portal. It is also possible to adopt the s -wave suppressed Majorana DM scenario with Sommerfeld enhancement and we will discuss that possibility in our subsequent studies.

The Lagrangian with Yukawa hierarchy from the Froggatt-Nielsen mechanism is written as

$$\begin{aligned} \mathcal{L} \supseteq & \frac{1}{2}(\partial_\mu S)^2 + |D_\mu T|^2 - \frac{1}{2}m_S^2 S^2 - m_T^2 |T|^2 - \lambda S^2 |T|^2 \\ & - \lambda_2 S^4 - \lambda_3 |T|^4 - a_1 S |T|^2 + i\bar{\chi}\gamma^\mu D_\mu \chi - m_\chi \bar{\chi}\chi \\ & - y_\phi \bar{\chi}\chi S - \sum_a y_a \left(\frac{U}{\Lambda}\right)^Q (\bar{E}_{R,a}^c E_{R,a} T) + \dots, \quad (19) \end{aligned}$$

with Dirac DM χ and an additional real scalar S as a portal to a doubly charged complex scalar T that couples to the lepton species. The discrete Z_2 parity is imposed only for the DM particle χ .

Similar to the preceding section, we can have different annihilation modes, depending on the mass of S and T :

1) For $m_S \simeq 6$ TeV and $m_T \in [0.995, 1] \times m_\chi$, the DM can annihilate directly into TT^* pairs. This case is similar to scenario I of the scalar DM scenario. A new feature here is that resonant enhancement annihilation is possible when m_S is very near $2m_\chi$. The discussions are similar to those of scenario II in the preceding section, except that the m_S can be slightly lighter than $2m_\chi$, resulting in a negative ϵ parameter. In this case, the reduced coupling strength λ can still give the correct DM relic density and at the same time explain the DAMPE results. Numerical results for the parameters a_1, y_ϕ , which can account for both the DAMPE data and DM relic density, are given in Fig. 4.

2) For $m_S \simeq 6$ TeV and $m_T \gtrsim m_\chi$, the DM particles will annihilate directly into four leptons $\bar{\chi}\chi \rightarrow S \rightarrow (T^{++})^*(T^{--})^* \rightarrow l^- l^- l^+ l^+$. This case is similar to the corresponding discussion in the preceding section. Both Sommerfeld enhancement and resonance can be used to avoid the propagator suppression. Due to the fact that three internal propagators exist, we could have triple enhancement due to the resonance. Sommerfeld enhancement is also possible by introducing an additional light scalar or gauge boson. It is therefore possible that the s -wave suppressed DM annihilation cross section could be enhanced enough to explain the DAMPE results. Besides, the reduced coupling strength λ is also possible with a large (mass dimension) trilinear coupling a_1 . Figure 5 shows the scattering plot of $\langle\sigma v\rangle$ with/without

Sommerfeld enhancement in the case of Dirac fermion DM. The allowed range of a_1 versus the light gauge boson mass m_ϕ with Sommerfeld enhancement is shown in Fig. 6.

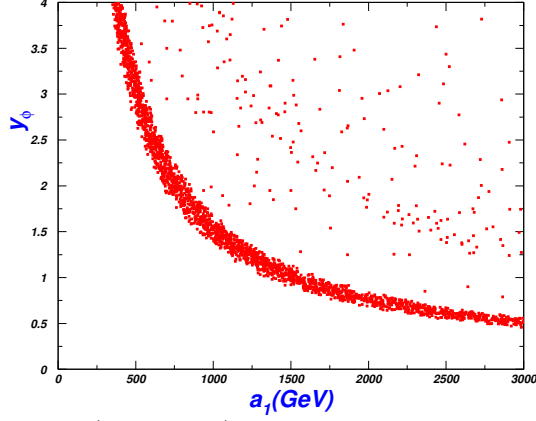


Fig. 4. (color online) The allowed parameter space for a_1 vs y_ϕ to explain both the DAMPE results and DM relic density in the case of Dirac DM without Breit-Wigner or Sommerfeld enhancement.

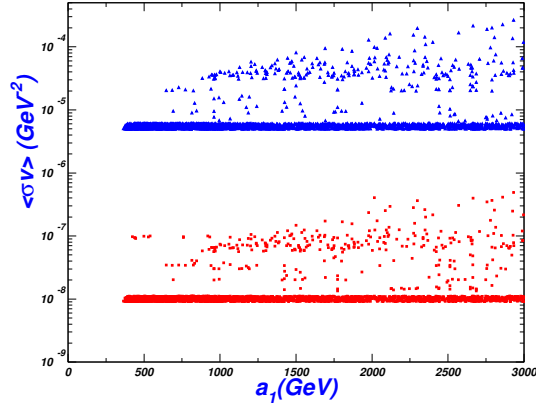


Fig. 5. (color online) The scattering plot of the allowed parameter space for a_1 vs $\langle\sigma v\rangle$ to explain both the DAMPE results and DM relic density in the case of Dirac DM with (blue) and without (red) Sommerfeld enhancement. The $U(1)_X$ gauge boson is fixed to be $m_\phi=10$ GeV.

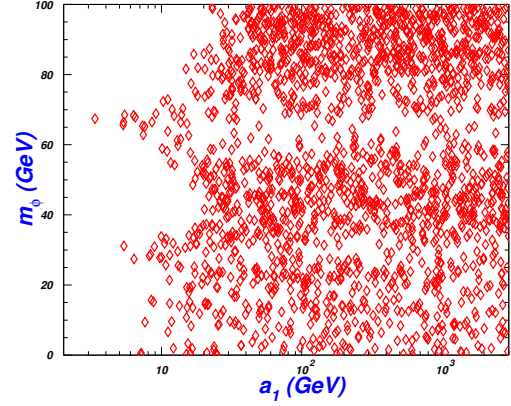


Fig. 6. (color online) The allowed parameters a_1 vs the light gauge boson mass m_ϕ when the Sommerfeld enhancement factor is introduced in the case of Dirac DM.

4 Conclusions

In this work we proposed to interpret the DAMPE electron excess at 1.5 TeV through scalar (or Dirac fermion) dark matter (DM) annihilation with doubly charged scalar mediators that have lepton-specific Yukawa couplings. Hierarchical lepton-specific Yukawa couplings are generated through the Froggatt-Nielsen mechanism, so that the dark matter annihilation products can be dominantly electrons. Stringent constraints from LEP2 on intermediate vector boson production can be evaded in our scenarios. In the case of scalar DM, we discussed two scenarios: one scenario with DM annihilating directly to leptons and the other one with DM annihilating to scalar mediators followed by their decays. We also discussed the Breit-Wigner resonant enhancement and Sommerfeld enhancement in the case that the s -wave annihilation process is small or helicity-suppressed. With both types of enhancement, the constraints on the parameters can be relaxed and new ways for model building can be opened in explaining the DAMPE results.

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