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Explaining the DAMPE data with scalar dark matter and gauged $U(1)_{L_e-L_\mu}$ interaction

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Abstract: We propose to adopt dark matter annihilation to explain the tentative peak structure at about 1.4 TeV in the recently released DAMPE measurement of the total cosmic $e^+ + e^-$ flux between 25 GeV and 4.6 TeV. By fitting the DAMPE data, we can determine the mass splitting between the DM and the mediator in case the mediators later decay into e, μ or e, τ final states, respectively. We introduce an additional $U(1)_{L_e-L_\mu}$ gauge symmetry to explain the DAMPE data through scalar DM annihilation $\chi\chi \to Z'Z' \to \ell\bar{\ell}\ell'\overline{\ell'}$, where $\chi, Z', \ell^{(\prime)}$ denote the scalar DM, the new gauge boson and $\ell^{(\prime)} = e, \mu$, respectively. We find that the most stringent constraint of our scenario comes from the LEP2 bounds on $M_{Z'}$ and the whole parameter space could be covered by ILC .

Contents

1 Introduction

One of the most important questions in current particle physics and cosmology is to understand the nature of cosmic dark matter (DM). Although many popular theories can predict viable DM candidates, no DM particle has been discovered by current collider or direct detection (DD)experiments so far. So, alternative ways, for example, indirect detection (ID) of DM by seeking the particles from DM annihilation or decay, can be valuable in understanding the nature of DM.

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 and reported strong indications for the existence of an excess of high-energy electrons and positrons spectrum at around 1.5 TeV [1, 2]. Although such excess may originate from certain new unobserved astrophysical sources, the data could also potentially indicate the discovery of annihilation products from cosmic DM. Relevant studies can be found in[3–19]. In fact, if one assumes that the electrons and positrons cosmic-ray spectrum originates directly from DM annihilation in a nearby clump halo, the best fit values for the DM particle mass, the DM clump mass and the annihilation luminosity are around 1.5 TeV, $10^{7-8} M_\odot$ and 10^{64-26} GeV^{2}cm^{-3}, depending on the halo distance from the earth.

If one wants to explain the DAMPE data with DM, one preliminary requirement is that DM today should annihilate dominantly into leptons (primarily electron and positron or annihilating democratically into e^+e^- and other generation lepton and antilepton pair). Other conditions include:

- **I-ID**: Current DM annihilation cross section $\langle \sigma v \rangle_0 \sim 1 \times 10^{-26}\, cm^3/s$ with $v \sim 10^{-3}\, c$ in DM halo.
- **II-RD**: DM relic density $\Omega_{DM} = 0.1199 \pm 0.0027$ [20, 21].
- **III-DD**: DM direct detection bounds on DM-nucleon scattering σ^{SI}_{DM-n}.
- **IV-Collider**: Collider constraints, especially LHC and LEP-II.

The first two requirements, which amount to $\langle \sigma v \rangle_0 \sim \langle \sigma v \rangle_{\text{freeout}} \sim 1 \times 10^{-26}\, cm^3/s$, prefer the DM annihilation processes to be s-wave dominant and at the same time without chiral suppression by light fermion masses [22, 23]. So a natural DM realization to explain the DAMPE excess is the Dirac DM scenario with certain lepton-specific gauge symmetry, which has been discussed in previous works. However, as indicated by these studies, rather stringent constraints on the DM couplings from DM direct detection make the minimal realizations less attractive.

On the other hand, the scenario with scalar DM pair annihilation into vector bosons $\chi\chi \to VV$, although potentially constrained by H.E.S.S, the Fermi-LAT as well as CMB data, can also satisfy the previous requirements. In our previous work [**?**] we proposed a scalar DM scenario with the gauge boson of an anomaly-free family symmetry $U(1)_{B-3(L_e-L_u-L_\tau)}$ as the mediators. The DM particles annihilate dominantly into the gauge bosons of the symmetry, followed by their decay into lepton pairs. We find that such a scenario can indeed explain the DAMPE results.

Scenarios of DM annihilation with vector portal may also be transported to other gauged family symmetries, e.g. the simplest lepton-specific family symmetry $L_e - L_\mu$, which is anomaly free even without right handed neutrinos. Such a gauged family symmetry, which imposes vanishing $U(1)_{L_e-L_\mu}$ charge assignments for the quarks, will have less stringent bounds from LHC and DM direct detection experiments. Besides, the discrepancy between theoretical predictions and E821 experiments[24] on muon anomalous magnetic momentum $g_\mu - 2$ can possibly be reconciled due to the new contributions from such new gauge interactions. As we will show in this work, such a framework can also be utilized to explain the excess.

The paper is organized as follows. In Section 2, we show the required mass splitting between the DM and the mediator by fitting the DAMPE results with e, μ and e, τ final states, respectively. In Section 3, we discuss the scalar DM scenario with $U(1)_{L_e-L_\mu}$ gauged family symmetry as the portal to leptons. In Section 4, relevant constraints from LEP-II, ILC etc are discussed. In Section 5 we present our conclusion.

2 Required mass splitting for $e - \mu$ final states of DAMPE results

The reported excess in e^+e^- flux at 1.5 TeV by DAMPE satellite could be explained by DM annihilation. If the DM particles χ annihilate into intermediate mediator ϕ pairs followed by the mediator later decaying into electron/positron pairs, box-shaped spectrum will be generated if the mass splitting between χ and ϕ, namely $\Delta M \equiv m_\chi - m_\phi$, is large. Such box-shaped spectrum can be distinguished from other astrophysical process efficiently. As no significant signal of the DM annihilation into such box-shaped electrons/positrons are found by DAMPE, the value of $\Delta M/m_\chi$ is stringently constrained. On the other hand, if m_ϕ is comparable with the DM mass m_χ or $2m_e$, a narrow peak spectrum can be generated, which enable it to explain the excess. In the numerical fitting by[25], assuming the mediator decays into electron/positron pairs, the required mass ratio between the mediator m_ϕ and m_D is bounded to be larger than about 0.995. For a vector mediator, similar conclusion can be drawn.

If the mediator will not decay uniquely into electron/positron pairs and decays democratically into e, μ flavor final states, the later decaying of μ will tend to flat the sharp peak for pure electron flavor final states (siimlar conclusion should be applied to e, τ final states). So even stringent constraints for m_ϕ/m_D are anticipated. Her we would like to derive bounds on m_ϕ/m_D by fitting to DAMPE data for e, μ final states. To do this, we follow the procedure in [25]. Briefly speaking, we use the **LikeDM** package [26] to obtain the best-fit background. Then we add the contribution of local sub-halo directly by considering that such component only affect the energy bin around ~ 1.5TeV. The propagation of nearby e^+/e^- can be calculated analytically under the assumption of spherically symmetric geometry and infinite boundary conditions [27].

In the **left** panel of fig.1, we present the result of e, μ final states with mass splitting $\Delta M = 6$ GeV, 12 GeV and 18 GeV, respectively. The DM mass m_χ is fixed to be 3 TeV and the annihilation cross section is set to be $3 \times 10^{-26} cm^3 s^{-1}$. We also assume that the sub-halo with mass $1.9 \times 10^7 \mathrm{m}_\odot$ locate at 0.1 kpc away from our solar system. In the **right**

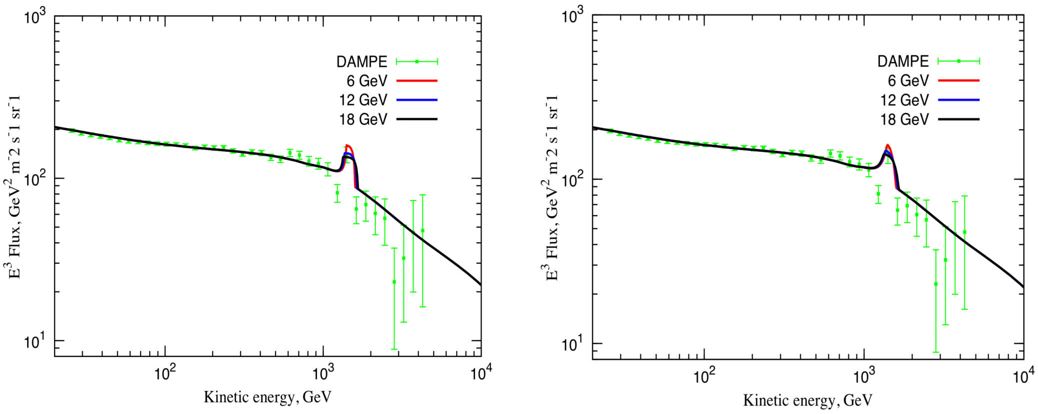

Figure 1. Cosmic $e^+ + e^-$ spectrum generated by $\Delta m_{\chi,Z'} = m_\chi - m_{Z'}$ for the process $\chi\chi \to Z'Z'$ with $Z' \to e^+e^-, \mu^+\mu^-$, which is compared to DAMPE data. The left panel correspond the sub-halo with mass $1.9 \times 10^7 \mathrm{m}_\odot$ and 0.1kpc away from our solar system, while the right panel correspond to the mass $1 \times 10^8 \mathrm{m}_\odot$ and the distance of 0.2kpc.

panel of fig.1, we present similar result by adopting the DM annihilation cross section $2.4 \times 10^{-26} cm^3 s^{-1}$ and sub-halo mass $1 \times 10^8 \mathrm{m}_\odot$ that located at 0.2 kpc away. These figures indicate that both scenarios can reproduce the observed spike peak at $\sim$ 1.4TeV but the mass splitting should not be too large. We checked that this conclusion also applies to $e + \tau$ final state if the sub-halo is less than about 0.2kpc away from our solar system.

3 Scalar DM scenario with gauged $U(1)_{L_e - L_\mu}$ portal

As mentioned previously, both e, μ and e, τ final states from DM annihilation could explain the DAMPE excess near 1.5 TeV. So it is preferable to assume that the mediator will participate in a typical e, μ (or e, τ) specific interaction. A gauged $U(1)_{L_e - L_\mu}$(or $U(1)_{L_e - L_\tau}$) family symmetry can play the role of such e, μ (or e, τ)-specific mediator. On the other hand, the long-standing muon anomalous magnetic momentum $g_\mu - 2$ discrepancy between theory and experiments may indicate the existence of new interactions involving μ. So we adopt the gauged $U(1)_{L_e - L_\mu}$ symmetry in this paper.

The particle contents in this scenario are shown in Table.1, where we introduce 3 generations of right handed (RH) neutrinos $\nu_{R,\{1,2,3\}}$ and a complex scalars ϕ_s. We will focus on the DM physics in this work and will not discuss the neutrino sector in detail. Besides, the choices of the $U(1)_{L_e - L_\mu}$ charge assignment for ϕ_s and ϕ_χ are not fixed and they are not necessarily equal. We require ϕ_s to acquire a vacuum expectation value (VEV) v_s to generate $m_{Z'}$. Although the stability of ϕ_χ DM is automatic in our scenario, an odd Z_2 parity is imposed for ϕ_χ to avoid further complications.

Table 1. Particle contents in $G_{SM} \times U(1)_{L_e - L_\tau}$ model.

Name	Spin	Gen.	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{L_e-L_\mu}$
H	0	1	$\mathbf{1}$	$\mathbf{2}$	-$\frac{1}{2}$	0
Q	1/2	3	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	0
d_R^*	1/2	3	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	0
u_R^*	1/2	3	$\bar{\mathbf{3}}$	$\mathbf{1}$	-$\frac{2}{3}$	0
L_1	1/2	1	$\mathbf{1}$	$\mathbf{2}$	-$\frac{1}{2}$	1
L_2	1/2	1	$\mathbf{1}$	$\mathbf{2}$	-$\frac{1}{2}$	-1
L_3	1/2	2	$\mathbf{1}$	$\mathbf{2}$	-$\frac{1}{2}$	0
$\ell_{R,1}^*$	1/2	1	$\mathbf{1}$	$\mathbf{1}$	1	1
$\ell_{R,2}^*$	1/2	1	$\mathbf{1}$	$\mathbf{1}$	1	-1
$\ell_{R,3}^*$	1/2	2	$\mathbf{1}$	$\mathbf{1}$	1	0
$\nu_{R,1}^*$	1/2	1	$\mathbf{1}$	$\mathbf{1}$	0	1
$\nu_{R,2}^*$	1/2	1	$\mathbf{1}$	$\mathbf{1}$	0	-1
$\nu_{R,3}^*$	1/2	2	$\mathbf{1}$	$\mathbf{1}$	0	0
ϕ_s	0	1	$\mathbf{1}$	$\mathbf{1}$	0	2
ϕ_χ	0	1	$\mathbf{1}$	$\mathbf{1}$	0	2

The most relevant Lagrangian to interpret the DAMPE data include

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

with

$$\begin{aligned} V(H,\, \phi_\chi,\, \phi_s) =\ & m_{\phi_\chi}^2 |\phi_\chi|^2 + m_{\phi_s}^2 |\phi_s|^2 + \lambda_{\phi_\chi} |\phi_\chi|^4 + \lambda_{\phi_s} |\phi_s|^4 \\ & + \lambda_{\chi H} |\phi_\chi|^2 |H|^2 + \lambda_{sH} |\phi_s|^2 |H|^2 \\ & + \lambda_{\chi s} |\phi_\chi|^2 |\phi_s|^2 + \lambda'_{\chi s} \Big((\phi_\chi^* \phi_s)^2 + h.c. \Big) \end{aligned} \tag{3.2}$$

in which $D'_\mu = \partial_\mu - i g_{Y'} Y' Z'_\mu$, $F'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$. As mentioned above, when investigating DM phenomenologies we will not discuss the neutrino sector such as the neutrino mass terms or $U(1)_{L_e - L_\mu}$-induced new Yukawa interactions. To meet the condition **IV-Collider** related to the SM Higgs measurements, we set $\lambda_{\chi H}, \lambda_{sH}$ to be zero and one-loop diagram will not generate these couplings.

Depending on whether the terms involving $\lambda'_{\chi s}$ vanish or not, we have the following two possibilities

- Complex scalar DM ϕ_χ without the term involving $\lambda'_{\chi s}$. In this case, the $U(1)_{L_e - L_\mu}$ charge assignment for ϕ_s and ϕ_χ can be fairly arbitrary. On the other hand, stringent constraints from LEP2 on the Z' gauge boson mass and DM direct detection bounds stringently constrained such minimal framework. Non-minimal framework, within which an additional $U(1)$ is introduced and mixes with the $U(1)_{L_e-L_\mu}$ gauge theory (or other $U(1)$ family symmetry as $U(1)_{B-3(L_e-L_u-L_\tau)}$), can survive all constraints and leave much allowed parameter space. The non-minimal framework had already been discussed in detail in our previous works[**?**] and we will not repeat the discussions here.

- Real scalar DM $\phi_{\chi,R}$ (or $\phi_{\chi,I}$) with $\lambda'_{\chi s} \neq 0$. As noted in our previous papers, possible mass splitting between the real $\phi_{\chi,R}$ and imaginary part $\phi_{\chi,I}$ of the complex scalar could be generated after ϕ_s develops a VEV. The lighter real scalars of $\phi_{\chi,R}$ and $\phi_{\chi,I}$ can act as a viable DM candidate. This scenario has the advantage of less stringent direct detection bounds because the DM-nucleon elastic scattering arise at two loop level (with vanishing quark $U(1)$ charge). Such a scenario with gauged $U(1)_{B-3(L_e+L_u-L_\tau)}$ had been ruled out by recent LHC data due to the non-trivial charge assignment for quarks. With the lepton-specific $U(1)_{L_e-L_\mu}$ interactions, however, this scenario can possibly revive as an explanation to the new DAMPE data.

We will concentrate on the second scenario with real scalar DM because it introduces least assumptions. We assume that the scalar corresponding to the imaginary part $\phi_{\chi,I}$ is the DM particle χ. The required mass splitting within the complex scalar ϕ_χ can be generated similarly as in our previous work.

Since we have required the Higgs portal interaction $|\phi_\chi|^2|H|^2$ to vanish to pass **IV-Collider**, DM particle $\phi_{\chi,I}$ can only scatter off the nucleon into $\phi_{\chi,R}$ state via t-channel Z' boson. To pass **III-DD**, one can simply require $\Delta m_{\chi I,\chi R} = m_{\phi_{\chi,R}} - m_{\phi_{\chi,I}}$ to be much larger than the DM kinetic energy (of order 1 MeV) so as to forbid the tree-level Z'-mediated inelastic scattering from happening. Elastic scattering can be generated via triangle and box diagrams involving double $U(1)_{L_e-L_\mu}$ gauge boson and lepton loops attached to quark propagators via intermediate photons. Generated at two loop order, the DM direct detection bounds will not impose any interesting constraints on the parameters of our scenario.

4 Numerical results

In the numerical calculations, we use **SARAH** [28] to implement the model, **SPheno** [29, 30] to obtain the mass spectrum and **micrOMEGAs** [31, 32] to calculate DM relic abundance in which the threshold effects are important when $m_\chi \equiv m_{\phi_{\chi,R}} \sim m_{Z'}$ [33]. We choose the following parameter settings in our numerical scan:

$$m_{\phi_\chi} \in (2500,\, 3500)\,\text{GeV}, \tag{4.1}$$

$$v_s \in (1000,\, 5000)\,\text{GeV}, \tag{4.2}$$

$$\lambda_{\phi_s} \in (0,\, 1), \tag{4.3}$$

$$g_{Y'},\, \lambda'_{\chi s} \in (0,\, 1), \tag{4.4}$$

$$\lambda_{\phi_\chi} = \lambda_{\chi s} = 0, \tag{4.5}$$

$$\lambda_{\chi,H} = \lambda_{s,H} = 0, \tag{4.6}$$

and require the mass eigenstates and DM related observables [20, 21] to satisfy

$$m_\chi \in 3000 \pm 100\,\mathrm{GeV}, \tag{4.7}$$

$$m_{Z'} \in 3000 \pm 100\,\mathrm{GeV}, \tag{4.8}$$

$$\Omega_\chi h^2 \in 0.1187 \pm 0.01198, \tag{4.9}$$

$$\langle \sigma v \rangle_0 \gtrsim 1 \times 10^{-26}\, cm^3/s. \tag{4.10}$$

As for the other two physical real scalar particles $S \equiv \phi_{R,s}$ and $\phi_{\chi,R}$ after v_s is developed, we require both of them to decay fast enough in the early universe so as not to affect our discussion. This can be easily satisfied by $S \to Z'^{(*)} Z'^{(*)} \to$ SM and $\phi_{\chi,R} \to \phi_{\chi,I} + Z^{(*)}$ via the $U(1)_{L_e - L_\mu}$ gauge interaction, as long as the mass spectrums are properly chosen.

The model $G_{SM} \times U(1)_{L_e - L_\mu}$ confronting the four conditions is shown in Table.2. The numerical results are provided in fig.2 on the plane of $m_{Z'}$ versus $g_{Y'}$, where the upper regions of LEP-II bounds [34, 35] have been excluded. Note that since the SM quarks are singlets under $U(1)_{L_e - L_\mu}$, there is no longer Drell-Yan constraints on Z' from the LHC [36] which is different from our previous model [**?**]. We can see that most samples with $\langle \sigma v \rangle_0 \sim 1 \times 10^{-26}\, cm^3/s$ to explain the DAMPE data can survive the LEP-II bounds, which can be expressed as

$$\frac{g_{Z'}}{m_{Z'}} \lesssim 2.14 \times 10^{-4}\,\mathrm{GeV}^{-1}, \tag{4.11}$$

which implies that a typical benchmark $\frac{g_{Z'}}{m_{Z'}} \sim \frac{0.6}{3\,\mathrm{TeV}} \sim 2 \times 10^{-4}\,\mathrm{GeV}^{-1}$ in our samples is on the edge of exclusion. As for the future detection potential of Z' at ILC with $\sqrt{s}$ up to 1 TeV and a luminosity of 500 fb^{-1}, one can expect the following stronger bound [37]

$$\frac{g_{Z'}}{m_{Z'}} \lesssim 2.2 \times 10^{-5}\,\mathrm{GeV}^{-1}, \tag{4.12}$$

in which case the current scenario in fig.2 will be detected. To gain a more complete picture, we also show the modified production cross section $\sigma(e^+e^- \to \mu^+\mu^-)$ in fig.3 for $m_{Z'} = 3$ TeV with different $g_{Z'} = 0.6, 0.5$.

The $U(1)_{L_e - L_\mu}$ interactions will contribute to the muon anomalous magnetic momentum as

$$\Delta a_\mu \approx \frac{3 g_{Z'}^2}{4\pi^2} \frac{m_\mu^2}{M_{Z'}^2}. \tag{4.13}$$

In our scenario, the contribution is estimated to be $\Delta a_\mu \approx 3.35 \times 10^{-11}$, which is too small to account for the discrepancy.

5 Conclusion

We propose to adopt dark matter annihilation to explain the tentative peak structure at about 1.4 TeV in the recently released DAMPE measurement of the total cosmic $e^+ + e^-$ flux between 25 GeV and 4.6 TeV. By fitting the DAMPE data, we can determine the mass splitting between the DM and the mediator in case the mediators later decay into e, μ or

Table 2. $G_{SM} \times U(1)_{L_e - L_\mu}$ confronting the four conditions.

Condition	Result	Details
I-ID	$\surd$	$\chi\chi \to Z'Z' \to \ell\bar{\ell}\ell'\bar{\ell'}$ with $\ell, \ell' = e, \mu$ with $m_\chi \sim m_{Z'} \sim 3.0 = 2\,E_\ell \sim 2 \times 1.5$ (TeV).
II-RD	$\surd$	Same as **I-ID**.
III-DD	$\surd$	$\Delta m_{\chi I, \chi R} = m_{\phi_{\chi,R}} - m_{\phi_{\chi,I}} \gg E_{\chi,kin}$ forbids tree-level inelastic scattering $\phi_{\chi,I} + SM \to \phi_{\chi,R} + SM$ via t-channel Z'.
IV-Collider	$\surd$	Small $Y'_{\phi_\chi} = 2$ combined with proper $g_{Y'} \lesssim 0.6$ and $m_{Z'} \sim 3$ TeV.

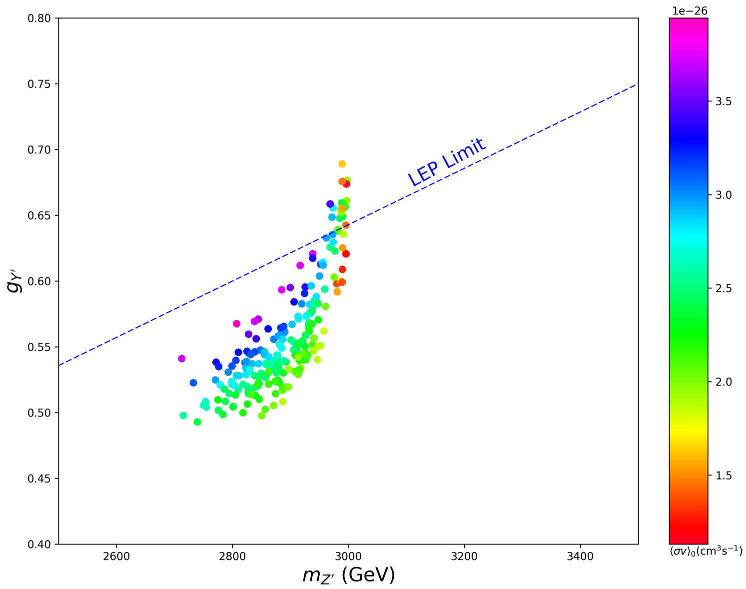

Figure 2. Samples with $\langle \sigma v \rangle_0 \sim 1 \times 10^{-26}\, cm^3/s$ with color bar denoting the DM indirect detection rate. The LEP-II bound on the plan is also plotted with the right side of the line is experimentally allowed. [34, 35].

e, τ final states, respectively. We introduce an additional $U(1)_{L_e - L_\mu}$ gauge symmetry to explain the DAMPE data through scalar DM annihilation $\chi\chi \to Z'Z' \to \ell\bar{\ell}\ell'\overline{\ell'}$, where $\chi, Z', \ell^{(')}$ denote the scalar DM, the new gauge boson and $\ell^{(')} = e, \mu$, respectively. We find that the most stringent constraint of our scenario comes from the LEP2 bounds on $M_{Z'}$ and the whole parameter space could be covered by ILC .

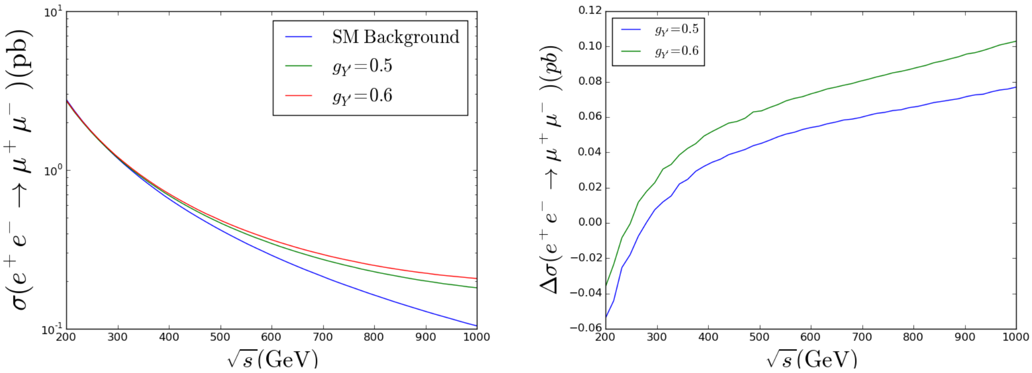

Figure 3. Modified production cross section $\sigma(e^+e^- \to \mu^+\mu^-)$ relevant to future detection potential of Z' at ILC.

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