The Simple and Natural Interpretions of the DAMPE Cosmic Ray Electron/Postitron Spectrum within Two Sigma Deviations

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The DArk Matter Particle Explorer (DAMPE) experiment has recently announced the first results for the measurement of total electron plus positron fluxes between 25 GeV and 4.6 TeV. A spectral break at about 0.9 TeV and a tentative peak excess around 1.4 TeV have been found. However, it is very difficult to reproduce both the peak signal and the smooth background including spectral break simultaneously. We point out that the numbers of events in the two energy ranges (bins) close to the 1.4 TeV excess have 1σ deficits. With the basic physics principles such as simplicity and naturalness, we consider the -2σ, $+2\sigma$, and -1σ deviations due to statistical fluctuations for the 1229.3 GeV bin, 1411.4 GeV bin, and 1620.5 GeV bin. Interestingly, we show that all the DAMPE data can be explained consistently via both the continuous distributed pulsar and dark matter interpretations, which have $\chi^2 \simeq 17.2$ and $\chi^2 \simeq 13.9$, respectively. These results are different from the previous analyses by neglecting the 1.4 TeV excess. Moreover, we present a $U(1)_D$ dark matter model with Breit-Wigner mechanism, which can provide the proper dark matter annihilation cross section and escape the CMB constraint. Furthermore, we suggest a few ways to test our proposal.

Introduction–Because of the strong radiative cooling via synchrotron and inverse Compton scattering (ICS) processes, the TeV electrons can only travel a short distance of about a few kpc in the Milky Way. Therefore, the nearby Cosmic Ray (CR) sources such as pulsars [1–5] and dark matter (DM) [6–8] can be probed via the high energy electrons and positrons. The spectra of the cosmic ray electrons and positrons (CREs) have been measured up to TeV energy scales by the ground-based and space-borne experiments, for example, HESS [9, 10], VERITAS [11], FermiLAT [12], AMS-02 [13], and CALET [14]. In particular, the excesses of the electrons [9, 15–17] and positrons [18–21] have been discovered as well.

Recently, the DArk Matter Particle Explorer (DAMPE), which is a new generation space-borne experiment to measure CRs and was launched in December 2015, has announced the first results of high energy CR electron plus positron ($e^- + e^+$) flux from 25 GeV to 4.6 TeV with unprecedentedly high quality [22]. The energy resolution of the DAMPE is better than 1.5% at TeV energies, and the hadron rejection power is about 10^5. Thus, DAMPE is able to reveal (fine) structures of the electron and positron fluxes. The main DAMPE spectrum can be fitted by a smoothly broken power-law model with a spectral break around 0.9 TeV, which confirms the previous results by HESS experiment [9, 10]. And there exists a tentative peak-like flux excess around 1.4 TeV. Thus, the DAMPE results have stimulated the extensive studies [23–54]. The spectral break can be explained by the broad distributed pulsars, pulsar wind nebulae (PWNe), supernova remnants (SNRs) [24, 26], and by the dark matter annihilation and decay in the galaxy halo [26, 34, 37, 53]. Also, the tentative peak is always interpreted by local pulsars, PWNe, and SNRs [24, 26, 54]), and by the DM sub-halos, clumps, and mini-spikes [23, 25, 27, 32–34, 37, 38, 46, 48].

However, one can easily show that it is impossible to explain both the spectral break and the tentative peak simultaneously [24, 26, 37, 38, 54]). In addition, we have 74, 93, and 33 events for three continuous bins or energy ranges [1148.2, 1318.3] GeV, [1318.3, 1513.6] GeV, and [1513.6, 1737.8] GeV, respectively, which for simplicity we shall call 1229.3 GeV bin, 1411.4 GeV bin, and 1620.5 GeV bin [22]. The number of events and fluxes for these bins are given in Table I. From Figure 2 of the DAMPE's paper [22], it is obvious that the 1411.4 GeV bin has a little bit more than 3σ excess, while the 1229.3 GeV bin and 1620.5 GeV bin have about 1σ deficits. Therefore, it is very difficult to explain the events in these three bins, especially the first two, no matter by the pulsar or dark matter interpretations.

From the theoretical physics point of view, we would like to explain nature with basic principles such as simplicity and naturalness, or say truth and beauty! In the words of Sir Isaac Newton, "Truth is ever to be found in the simplicity, and not in the multiplicity and confusion of things." Therefore, to explain all the DAMPE data via a simple and natural way, we propose that the excess in the 1411.4 GeV bin and the deficits in the 1229.3 GeV bin and 1620.5 GeV bin arise from the $+2\sigma$, -2σ, and -1σ deviations due to statistical fluctuations, which happened frequently in collider experiments. Remarkably, we can indeed explain all the DAMPE data consistently via the pulsar and dark matter interpretations, which have $\chi^2 \simeq 17.2$ and $\chi^2 \simeq 13.9$, respectively. Our results are different from the previous analyses by neglecting the

Energy Bins (GeV)	N (original)	$\Phi(e^- + e^+) \pm \sigma_{\rm stat} \pm \sigma_{\rm sys}$ (original)	N (revised)	$\Phi(e^- + e^+) \pm \sigma_{\rm stat} \pm \sigma_{\rm sys}$ (revised)	ΔN	$\Delta N_{2\sigma}$
[1148.2, 1318.3]	74	$(4.38 \pm 0.53 \pm 0.14) \times 10^{-8}$	92	$(5.44 \pm 0.48 \pm 0.14) \times 10^{-8}$	+18	± 18
[1318.3, 1513.6]	93	$(4.99 \pm 0.53 \pm 0.17) \times 10^{-8}$	73	$(3.92 \pm 0.60 \pm 0.17) \times 10^{-8}$	-20	± 20
[1513.6, 1737.8]	33	$(1.52 \pm 0.28 \pm 0.06) \times 10^{-8}$	39	$(1.80 \pm 0.26 \pm 0.06) \times 10^{-8}$	+6	± 12

TABLE I: The original and revised numbers of events and fluxes, ΔN, and $\Delta N_{2\sigma}$ for the 1229.3 GeV bin, 1411.4 GeV bin, and 1620.5 GeV bin. Here, ΔN and $\Delta N_{2\sigma}$ are the adjusted numbers of events and the numbers of events for 2σ deviations from statistical fluctuations. Thus, we should require $|\Delta N| \leq |\Delta N_{2\sigma}|$.

1.4 TeV excess [53]. In addition, we present a $U(1)_D$ dark matter model with Breit-Wigner mechanism, which can provide the proper dark matter annihilation cross section and escape the CMB constraint. Furthermore, we suggest a few ways to test our proposal as well as the 1.4 TeV excess.

Statistical Fluctuations–In the DAMPE's paper [22], the numbers of events and the CRE fluxes with 1σ statistical and systematic errors have been given in its Table 1. To evaluate the uncertainties for numbers of the events, we need to understand their relations. The relation between the number of events and fluxes in each energy bin is [13, 22]

$$\Phi(e^- + e^+) = \frac{N(E) \cdot (1 - \varepsilon_{\rm bg}(E))}{A_{\rm eff}(E) \cdot T \cdot \Delta E} \cdot \varepsilon_{\rm other}(E), \tag{1}$$

where N is the number of $(e^- + e^+)$ events, $A_{\rm eff}$ is the effective detector acceptance, T is the operating time, ΔE is the energy range of the bin, $\varepsilon_{\rm bg}$ is the background fraction of the events, and $\varepsilon_{\rm other}$ represents the effects caused by other mechanisms which were not given in the Table 1 of Ref. [22].

Taking $T = 530$ days and $\varepsilon_{\rm other} = 1.3$, we can reproduce the corresponding results in the 1229.3 GeV bin, 1411.4 GeV bin, and 1620.5 GeV bin within the uncertainty $< 0.1\%$. Consequently, we use the formula

$$\Phi(e^- + e^+) = \frac{N(E) \cdot (1 - \varepsilon_{\rm bg}(E))}{A_{\rm eff}(E) \cdot T \cdot \Delta E} \cdot 1.3 \tag{2}$$

in this letter to calculate the fluxes in these bins.

We calculate the 2σ deviations for the number of events ($\Delta N_{2\sigma}$) from the flux statistical fluctuations as follows

$$\Delta N_{2\sigma} = \frac{\Delta\Phi(e^- + e^+)_{2\sigma_{\rm stat}}}{\Phi(e^- + e^+)} \cdot N \ . \tag{3}$$

Thus, for the 1229.3 GeV bin, 1411.4 GeV bin, and 1620.5 GeV bin, we obtain $\Delta N_{2\sigma} = \pm 18, \ \pm 20, \ \pm 12$, respectively. Assume -2σ, $+2\sigma$, and -1σ deviations for these bins from statistical fluctuations, we have $\Delta N = +18, \ -20, \ +6$, respectively. Therefore, the revised numbers of events for the 1229.3 GeV bin, 1411.4 GeV bin, and 1620.5 GeV bin, are 92, 73, and 39, respectively.

Furthermore, we reestimate the statistical uncertainties in these bins based on the revised numbers of events via the formula

$$\Delta N_{1\sigma} \simeq \frac{1}{\sqrt{N}} \ , \tag{4}$$

and then calculate the corresponding fluxes and their statistical uncertainties. The systematical uncertainties are assumed to be invariant. All the detailed information for these three bins are given in Table I. By the way, as a cross check, with Eq. (4), we have reproduced similar 1σ statistical uncertainties of the original fluxes in the DAMPE's paper [22].

Fitting Procedure–As in Ref. [53], we perform a global fitting on the data set including the proton fluxes from AMS-02 and CREAM [55, 56] helium flux from AMS-02 and CREAM [56, 57], $\bar{\rm p}/{\rm p}$ ratio from AMS-02 [58], positrons flux from AMS-02 [13], and CRE flux from DAMPE [22], which could account for the primary electrons, the secondary leptons, and the extra leptons in a self-consistent way. Moreover, the employed AMS-02 positron flux is used to calibrate the positron contribution in the DAMPE CRE flux in energy region $\lesssim 300\,{\rm GeV}$. The framework of the fitting procedure is the same as our previous work [53], where the details can be found.

We consider both pulsar and DM scenarios to generate the CRE excesses in the observed spectrum by the DAMPE experiment. For the pulsar scenario, a continuous distributed pulsar background was used [53, 59]. The injection spectrum of such sources is assumed to be a power law with an exponential cutoff

$$q_e^{\rm psr}(p) = N_{\rm psr}(R/10\,{\rm GeV})^{-\nu_{\rm psr}} \exp\left(-R/R_{\rm c}\right), \tag{5}$$

where $N_{\rm psr}$ is the normalization factor, $\nu_{\rm psr}$ is the spectral index, and $R_{\rm c}$ is the cutoff rigidity. For the DM scenario, we employ the Einasto profile [60–63]

$$\rho(r) = \rho_\odot \exp\left[-\left(\frac{2}{\alpha}\right)\left(\frac{r^\alpha - r_\odot^\alpha}{r_s^\alpha}\right)\right], \tag{6}$$

with $\alpha \approx 0.17$, $r_s \approx 20\,{\rm kpc}$, and $\rho_\odot \approx 0.39\,{\rm GeV\,cm^{-3}}$ is the local DM relic density [64–68]. And the source term, which we use to add the CRE particles from the annihilations of the Majorana DM particles, is

$$Q(\boldsymbol{r}, p) = \frac{\rho(\boldsymbol{r})^2}{2m_\chi^2}\langle\sigma v\rangle \sum_f \eta_f \frac{dN^{(f)}}{dp}, \tag{7}$$

where $\langle\sigma v\rangle$ is the velocity-averaged DM annihilation cross section multiplied by DM relative velocity (referred as cross section), $\rho(\boldsymbol{r})$ is the DM density distribution, and $dN^{(f)}/dp$ is the injection energy spectrum of CREs from DM annihilating into the Standard Model (SM) final states via leptonic channels $f\bar{f}$ (e^-e^+, $\mu\bar{\mu}$, and $\tau\bar{\tau}$) with η_f (η_e, η_μ, and η_τ) the corresponding branching fractions. Here, we normalized η_f as $\eta_e+\eta_\mu+\eta_\tau=1$.

The parameters related to the extra source of the leptons for pulsar scenario is $(N_{\rm psr},\nu_{\rm psr},R_c)$, and for DM scenario is $(m_\chi,\langle\sigma v\rangle,\eta_e,\eta_\mu,\eta_\tau)$.

Results–The fitting results of the pulsar and DM scenario on the DAMPE CRE spectrum are given in Figs. 1 and 2, respectively. From these figures, we can conclude that both scenarios could provide the excellent fittings to the DAMPE CRE spectrum within 3σ fitting deviation, which do not need to employ extra local sources. For the best fit result on the DAMPE CRE spectrum, we have $\chi^2\simeq 17.2$ and $\chi^2\simeq 13.9$ for pulsar and DM scenarios, respectively.

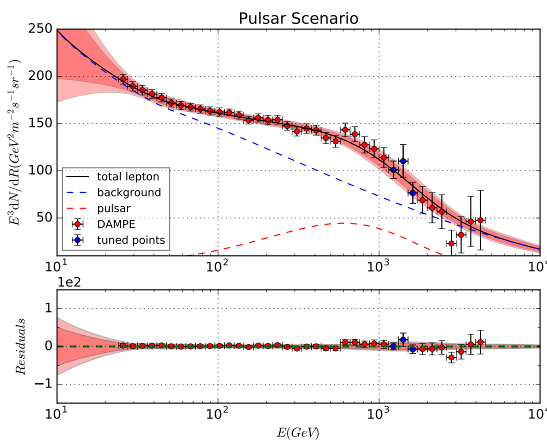

FIG. 1: The global fitting results and the corresponding residuals to the DAMPE lepton flux for pulsar scenario. The 2σ (deep red) and 3σ (light red) bounds are also shown in the figure. The three relevant bins with revised fluxes are plotted as blue dots. And we have $\chi^2\simeq 17.2$.

For the pulsar scenario, the fitting results give $\nu_{\rm psr}\simeq 0.62$, which is obviously different from the fitting results in previous works (see for e.g., [69]). In standard pulsar models, the injection spectrum indices of CREs from pulsars are always in the range $\nu_{\rm psr}\in[1.0,2.4]$ [70–72]. As a result, more attention should be paid in future researches. This may indicate: (i) there is something wrong or inaccuracy with the classical pulsar CRE injection model; (ii) the CRE excess is not contributed primarily by pulsars. Moreover, the cut-off is $R_c\simeq 692$ GV. In the previous work [53] where the 1.4 TeV peak excess was neglected, we obtained that the spectral index of the injection is $\nu_{\rm psr}\simeq 0.65$ and the cut-off is $R_c\simeq 650$ GV. Thus, there exist about $+5\%$ and -5% deviations for $\nu_{\rm psr}$ and R_c, respectively.

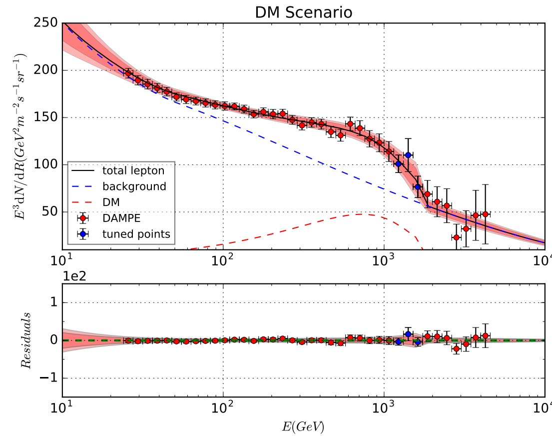

FIG. 2: The global fitting results and the corresponding residuals to the DAMPE lepton flux for DM scenario. The color code is the same as Fig. 1, and we have $\chi^2\simeq 13.9$.

For the DM scenario, we obtain $\langle\sigma v\rangle\simeq 4.07\times 10^{-23}\,{\rm cm^2\,s^{-1}}$ and $m_\chi\simeq 1884\,{\rm GeV}$. The value of $\langle\sigma v\rangle$ is about 3 orders larger than that of thermal DM [73]. To explain this discrepancy, we will present a concrete model in the next section. Moreover, we have $\eta_e\simeq 0.465$, $\eta_\mu\simeq 0.510$, and $\eta_\tau\simeq 0.025$. So the DM annihilation into $\tau\bar{\tau}$ is highly suppressed, which provides some hints to construct an appropriate DM model. In our previous work [53] where the 1.4 TeV peak excess was neglected, we have $\langle\sigma v\rangle\simeq 1.48\times 10^{-23}\,{\rm cm^2\,s^{-1}}$, $m_\chi\simeq 1208\,{\rm GeV}$, $\eta_e\simeq\eta_\mu\simeq 0.5$, while η_τ is highly suppressed. Thus, we have similar results on branching fractions, but different DM masses and annihilation cross sections.

Model Building–Because we have $\eta_e\sim 0.465$, $\eta_\mu\sim 0.510$, and $\eta_\tau\sim 0.025$, the constraints from the Fermi-LAT observations of dwarf spheroidal galaxies [74–78] can be avoided [26]. To escape the constraints from the Planck observations of CMB anisotropies [79], we employ the Breit-Wigner mechanism [80–85]. We consider the dark $U(1)_D$ model where the SM fermions and Higgs fields are neutral under it. We introduce one SM singlet Higgs field S, one chiral fermionic dark matter particle χ, and three pairs of the vector-like particles $(\widehat{XE}_i,\widehat{XE}_i^c)$, whose quantum numbers under the $SU(3)_C\times SU(2)_L\times U(1)_Y\times U(1)_D$ are

$$
\begin{aligned}
&S:(\mathbf{1},\mathbf{1},\mathbf{0},\mathbf{2})~,\quad \chi:(\mathbf{1},\mathbf{1},\mathbf{0},\mathbf{-1})\\
&\widehat{XE}_i:(\mathbf{1},\mathbf{1},\mathbf{-1},\mathbf{-2})~,\quad \widehat{XE}_i^c:(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})~.
\end{aligned}
\tag{8}
$$

The relevant Lagrangian is

$$-\mathcal{L} = -m_S^2|S|^2 + \frac{\lambda}{2}|S|^4 + \Big(M_{ij}^V \widehat{XE}_i^c \widehat{XE}_j + y_{ij} S \widehat{E}_i^c \widehat{XE}_j + y S\chi\chi + \text{H.C.}\Big) \ , \quad (9)$$

where $\widehat{E}_i^c$ are the right-handed charged leptons. For simplicity, we choose $M_{ij}^V = M_i^V \delta_{ij}$ and $y_{ij} = y_i \delta_{ij}$. After S acquires a Vacuum Expectation Value (VEV), the $U(1)_D$ gauge symmetry is broken down to a Z_2 symmetry under which χ is odd. Thus, χ is a DM matter candidate. For simplicity, we assume that the mass of $U(1)_D$ gauge boson is about twice of χ mass, *i.e.*, $M_{Z'} \simeq 2m_\chi$, while the Higgs field S and vector-like particles are heavier than $M_{Z'}$. Moreover, $\widehat{E}_i^c$ and $\widehat{XE}_i^c$ will be mixed due to the $M_i^V \widehat{XE}_i^c \widehat{XE}_i$ and $y_i S \widehat{E}_i^c \widehat{XE}_i$ terms, and we obtain the mass eigenstates E_i^c and XE_i^c by neglecting the tiny charged lepton masses

$$\begin{pmatrix} E_i^c \\ XE_i^c \end{pmatrix} = \begin{pmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{pmatrix} \begin{pmatrix} \widehat{E}_i^c \\ \widehat{XE}_i^{c\prime} \end{pmatrix} \ , \quad (10)$$

where $\tan\theta_i = -y\langle S\rangle / M_i^V$.

Neglecting the charged lepton masses again, we obtain

$$\sigma v = \sum_{i=1}^{3} \frac{g'^4 \sin^2\theta_i}{6\pi} \frac{s - m_\chi^2}{(s - m_{Z'}^2)^2 + (m_{Z'}\Gamma_{Z'})^2} \ , \quad (11)$$

where $m_\chi = y\langle S\rangle$, and g' and $M_{Z'}$ are the gauge coupling and gauge boson mass for $U(1)_D$ gauge symmetry.

For $m_{Z'} \simeq 2m_\chi$, Z' decays dominantly into leptons, and the decay width is

$$\Gamma_{Z'} = \sum_{i=1}^{3} \frac{g'^2 \sin^2\theta_i}{6\pi} m_{Z'} \ . \quad (12)$$

To explain the DM best fit results, we choose

$$g' \simeq 0.028, \ m_\chi \simeq 1884 \text{ GeV}, \ \frac{m_{Z'} - 2m_\chi}{m_{Z'}} \simeq 3.0 \times 10^{-6},$$
$$\sin\theta_e \simeq 0.21 \ , \quad \sin\theta_\mu \simeq 0.22 \ , \quad \sin\theta_\tau \simeq 0.05 \ . \quad (13)$$

And then we obtain $\langle\sigma v\rangle \simeq 4.07 \times 10^{-23}\text{cm}^3\text{s}^{-1}$, and $\eta_e : \eta_\mu : \eta_\tau \simeq 0.465 : 0.510 : 0.025$. Of course, there exists fine-tuning between $m_{Z'}$ and m_χ , which deserves further study. For some solutions, see Ref. [84].

Discussions and Conclusion–First, we would like to point out that if the numbers of events in the 1229.3 GeV bin and 1411.4 GeV bin are exchanged, we can also explain the DAMPE's data similarly. Of course, the most important question is how to test our proposal that there exists statistical fluctuations in the 1229.3 GeV bin, 1411.4 GeV bin, and 1620.5 GeV bin. For the data analyses, we suggest that one chooses different energy ranges to study the data again. For example, we can shift the energy ranges by ±50 GeV and ±100 GeV for the high energy bins, and then study the corrsponding events and fluxes. In the future, DAMPE will provide us more accurate spectrum data reaching up to $\sim 10\,\text{TeV}$, which can give us a unprecedented opportunity to study the origin and propagation of CREs. We predict that the CRE spectrum would be more continuous. In particular, the peak excess in the 1411.4 GeV bin as well as the deficits in the 1229.3 GeV bin and 1620.5 GeV bin will all decrease! Moreover, if the 1.4 TeV peak signal was proved to be correct, we do need a local source of high energy CREs. Other experiment is needed as a cross check if such signal arises from DM annihilation, for example, our recent work [86] proposed a novel scenario to probe the interaction between DM particles and electrons for the DM mass range $5\,\text{GeV} \lesssim m_\chi \lesssim 10\,\text{TeV}$.

In summary, with the simplicity and naturalness physics principle, we proposed that there exists the -2σ, $+2\sigma$, and -1σ deviations due to statistical fluctuations for the 1229.3 GeV bin, 1411.4 GeV bin, and 1620.5 GeV bin of the DAMPE data. Interestingly, we showed that all the DAMPE data can be explained consistently via both the pulsar and dark matter interpretations, which have $\chi^2 \simeq 17.2$ and $\chi^2 \simeq 13.9$, respectively. These results are different from the previous analyses by neglecting the 1.4 TeV excess. Moreover, we presented a $U(1)_D$ dark matter model with Breit-Wigner mechanism, which can provide the proper dark matter annihilation cross section and escape the CMB constraint. Furthermore, we suggested a few ways to test our proposal. The details for global fittings will be given elsewhere [88].

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