Bayesian Analysis of the break in DAMPE Lepton Spectra

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(Dated: April 27, 2018)

Recently, DAMPE has released its first results on the high-energy cosmic-ray electrons and positrons (CREs) from about 25 GeV to 4.6 TeV, which directly detect a break at \(\sim 1\) TeV. This result gives us an excellent opportunity to study the source of the CREs excess. In this work, we used the data for proton and helium flux (from AMS-02 and CREAM), \(p\/p\) ratio (from AMS-02), positron flux (from AMS-02) and CREs flux (from DAMPE without the peak signal point at \(\sim 1.4\) TeV) to do global fitting simultaneously, which can account the influence from the propagation model, the nuclei and electron primary source injection and the secondary lepton production precisely. For extra source to interpret the excess in lepton spectrum, we consider two separate scenarios (pulsar and dark matter annihilation via lepton channels) to construct the bump (\(\gtrsim 100\) GeV) and the break at \(\sim 1\) TeV. The result shows: (i) in pulsar scenario, the spectral index of the injection should be \(\nu_{\text{puls}} \sim 0.65\) and the cut-off should be \(R_{c} \sim 650\) GV; (ii) in dark matter scenario, the dark matter particle’s mass is \(m_{X} \sim 1208\) GeV and the cross section is \(\langle \sigma v \rangle \sim 1.48 \times 10^{-23}\) cm\(^3\) s\(^{-1}\). Moreover, in the dark matter scenario, the \(\pi^{\pm}\) annihilation channel is highly suppressed, and a DM model is built to satisfy the fitting results.

I. INTRODUCTION

Recently, DAMPE (DArk Matter Particle Explorer) Satellite, which has been launched on December 17, 2015, has released its first data on high-energy cosmic-ray electrons and positrons (CREs) \[3\]. DAMPE has measured the CREs (i.e., \(e^{-} + e^{+}\)) spectrum in the range of 25 GeV – 4.6 TeV with unprecedented energy resolution (better than 1.2\% \(\gtrsim 100\) GeV). The results shows a bumps at about 100 GeV – 1 TeV which is consistent with previous results \[4, 10\]. More interesting, a break at \(\sim 1\) TeV and a peak signal at \(\sim 1.4\) TeV have been detected. All of these features cannot be described by a single power law and provide us an opportunity to study the source of high-energy CREs.

The peak signal at \(\sim 1.4\) TeV has been studied by many works which employed nearby pulsars wind, supernova remnants (SNRs) and dark matter (DM) substructures \[10, 24\]. At the same time, considering the statistical confidence level of this signal is about 3\(\sigma\) which needs more counts in future, we exclude the peak signal and do a global fitting on the left points in DAMPE CREs spectrum in this work. As a result, if we refer to the DAMPE CREs flux in this work, the peak point is excluded except special emphasis.

In cosmic ray (CR) theory, the CR electrons are expected to be accelerated during the acceleration of CR nuclei at the sources, e.g. SNRs. But the CR positrons are produced as secondary particles from CR nuclei interaction with the interstellar medium (ISM) \[4, 25–27\]. From the results of the flux of positrons and electrons \[6, 28, 30\], we can infer that there should be some extra sources producing electron-positron pairs. This can be interpreted both by the astrophysical sources’ injection \[14, 21, 37\] and DM annihilation or decay \[38–44\].

As a result, the CREs data contains the primary electrons, the secondary electrons, the secondary positrons and the extra source of electron-positron pairs. If we want to study the properties of the extra source, we should deduct the primary electrons and secondary electrons/positrons first. The primary electrons are always assumed to have a power-law form injection and the secondary electrons/positrons are determined dominantly by the CR proton and helium particles interact with ISM. Consequently, we should do global fitting to these data simultaneously which can avoid the bias of choosing the lepton background parameters.

Considering the situations of high-dimensional parameter space of propagation model and precise data sets, we employ a Markov Chain Monte Carlo (MCMC) method (embedded by DRAGON) to do global fitting and sample the parameter space of all the related parameters to reproduce the CREs spectrum \[36, 49\].

Moreover, because of the significant difference in the slopes of proton and helium, of about \(\sim 0.1\) \[50–54\], has been observed, we use separate primary source spectra settings for proton and helium. Note also that we consider propagation of nuclei only up to \(Z = 2\) and neglect possible contributions from the fragmentation of \(Z > 2\) nuclei, which should be a good approximation since their
fluxes are much lower than the p and He fluxes \[55\]. In this condition, all the secondary particles (antiprotons and leptons) are produced from the interactions between proton, helium and ISM, which give us a self-consistent way to combine the nuclei and lepton data together.

This paper is organized as follows. We first introduce the setups of our work in Sec. II. The global fitting method and the chosen data sets and parameters is given in Sec. III. After present the fitting results and add some discussions in Sec. IV, we summarize our results in Sec. VI.

II. SETUPS

In this section, we just listed some of the most important setups in this work which is different from our previous work \[49\]. More detailed description can be found in Ref. \[49\].

A. Propagation model

In this work, we use the diffusion-reacceleration model which is widely used and can give a consistent fitting results to the AMS-02 nuclei data (see for e.g., \[48, 49\]). A uniform diffusion coefficient \(D_{xx} = D_0 \beta (R/R_0)^4\) is used in the whole propagation region.

At the same time, because high-energy CREs lose energy due to the process like inverse Compton scattering and synchrotron radiation, we parameterize the interstellar magnetic field in cylinder coordinates \((r, z)\) as

\[
B(r, z) = B_0 \exp \left( -\frac{r - r_\odot}{r_B} \right) \exp \left( -\frac{|z|}{z_B} \right),
\]

(1)
to calculate the energy loss rate. In Eq. 1, \(B_0 = 5 \times 10^{-10}\) Tesla, \(r_B = 10\) kpc, \(z_B = 2\) kpc \[50\], and \(r_\odot \approx 8.5\) kpc is the distance from the Sun to the galactic center.

B. Primary Sources

In this work, considering the fine structure of spectral hardening for primary nuclei at \(\sim 300\) GeV (which was observed by ATIC-2 \[50\], CREAM \[51\], PAMELA \[52\], and AMS-02 \[53, 54\]) and the observed significant difference in the slopes of proton and helium (of about \(\sim 0.1\) \[53, 54, 57\]), we use separate primary source spectra settings for proton and helium and each of them has 2 breaks at rigidity \(R_{A1}\) and \(R_{A2}\). The corresponding slopes are \(\nu_{A1}\) \((R \leq R_{A1})\), \(\nu_{A2}\) \((R_{A1} < R \leq R_{A2})\) and \(\nu_{A3}\) \((R > R_{A3})\). For cosmic-ray electrons primary source, we followed the same configuration as proton and helium. But due to the DAMPE lepton data range \((20\) GeV \(- 4\) TeV), we use 1 break \(R_c\) for electron primary source, and the corresponding slopes are \(\nu_{e1}\) \((R \leq R_c)\) and \(\nu_{e2}\) \(((R > R_c))\).

C. Secondary sources

The secondary cosmic-ray particles are produced in collisions of primary cosmic-ray particles with ISM. The secondary antiprotons are generated dominantly from inelastic pp-collisions and pHe-collisions. At the same time, the secondary electrons and positrons are the final product of decay of charged pions and kaons which in turn mainly created in collisions of primary particles with gas. As a result, the corresponding source term of secondary particles can be expressed as

\[
q_{sec} = \frac{c}{4\pi} \sum_{i=H,He} n_i \sum_j \int dp' \beta n_j(p') \frac{d\sigma_{pi,j}(p,p')}{dp} \]

(2)

where \(n_i\) is the number density of interstellar hydrogen (helium), \(d\sigma_{pi,j}(p,p')/dp\) is the differential production cross section, \(n_j(p')\) is the CR species density and \(p'\) is the total momentum of a particle.

To partially take into account the uncertainties when calculating the secondary fluxes, we employ a parameter \(c_p\) and \(c_{e^+}\) to re-scale the calculated secondary flux to fit the data \[17, 56–61\]. Note that the above mentioned uncertainties may not be simply represented with a constant factor, but most probably they are energy dependent \[62, 63\]. Here we expect that a constant factor is a simple assumption.

D. Extra sources

In this work, 2 kind of extra lepton sources are considered. The pulsar scenario account the extra lepton source to the pulsar ensemble in our galaxy, which is able to generate high energy positron-electron pairs from their magnetosphere. The injection spectrum of the CREs in such configuration can be parameterized as a power law with an exponential cutoff:

\[
q_{\nu_{e^+}}(p) = N_{\nu_{e^+}}(R/10\text{ GeV})^{-\nu_{e^+}} \exp \left(-\frac{R}{R_c}\right),
\]

(3)

where \(N_{\nu_{e^+}}\) is the normalization factor, \(\nu_{e^+}\) is the spectral index, \(R_c\) is the cutoff rigidity. The spatial distribution of this pulsar ensemble which provide continuous and stable CREs injection obeys the form as Eq. (5) in Ref. \[49\], with slightly different parameters \(a = 2.35\) and \(b = 5.56\) \[17\].

The DM scenario ascribe the extra lepton source to the annihilation of Majorana DM particles distributed in our galaxy halo, whose source term always has the form:

\[
Q(r, p) = \frac{\rho(r)^2}{2m_X^2} \langle \sigma v \rangle \int f \frac{dN^{(f)}}{dp},
\]

(4)

where \(\rho(r)\) present the DM density distribution, \(\langle \sigma v \rangle\) is the velocity-averaged DM annihilation cross section multiplied by DM relative velocity, and \(dN^{(f)}/dp\) is the injection energy spectrum of CREs from DM annihilating
into standard model (SM) final states through all possible channels \( f \) with \( \eta_f \) (the corresponding branching fractions). In this work, we considered DM annihilation via leptonic channels, the corresponding branching fractions for \( e^- e^+ \), \( \mu\mu \), and \( \tau\tau \) are \( \eta_e \), \( \eta_\mu \), and \( \eta_\tau \) respectively \((\eta_e + \eta_\mu + \eta_\tau = 1)\). We use the results from PPPC 4 DM ID \([64]\), which includes the electroweak corrections \([65]\), to calculate the electron (positron) spectrum from DM annihilation by different channels. At the same time, we use Einasto profile \([66–69]\) to describe the DM spatial distribution in our galaxy, which has the form:

\[
\rho(r) = \rho_\odot \exp \left[ -\left( \frac{2}{\alpha} \right) \left( \frac{r - r_\odot}{r_s} \right)^\alpha \right], \tag{5}
\]

with \( \alpha \approx 0.17 \), \( r_s \approx 20 \text{kpc} \) and \( \rho_\odot \approx 0.39 \text{GeV cm}^{-3} \) is the local DM energy density \([70–74]\).

E. Solar modulation

We adopt the force-field approximation \([75]\) to describe the effects of solar wind and heliospheric magnetic field in the solar system, which contains only one parameter the so-called solar modulation \( \phi \). Considering the charge-sign dependence solar modulation represented in the previous fitting \([49]\), we use \( \phi_{\text{nuc}} \) for nuclei (proton and helium) data and \( \phi_p \) for \( p \) data to do the solar modulation. At the same time, we use \( \phi_{e^\pm} \) to modulate the positron flux. Because the DAMPE lepton data \( \gtrsim 20 \text{GeV} \), we did not consider the modulation effects on electrons (or leptons).

F. Numerical tools

The public code DRAGON \([76]\) was used to solve the diffusion equation numerically, because its good performance on clusters. Some custom modifications are performed in the original code, such as the possibility to use specie-dependent injection spectra, which is not allowed by default in DRAGON.

In view of some discrepancies when fitting with the new data which use the default abundance in DRAGON \([77]\), we use a factor \( c_{\text{He}} \) to rescale the helium-4 abundance (which has a default value of \( 7.199 \times 10^3 \)) which help us to get a global best fitting.

The radial and \( z \) grid steps are chosen as \( \Delta r = 1 \text{kpc} \), and \( \Delta z = 0.5 \text{kpc} \). The grid in kinetic energy per nucleon is logarithmic between 0.1 GeV and 220 TeV with a step factor of 1.2. The free escape boundary conditions are used by imposing \( \psi \) equal to zero outside the region sampled by the grid.

III. FITTING PROCEDURE

A. Bayesian Inference

As our previous works \([49]\), we take the prior PDF as a uniform distribution and the likelihood function as a Gaussian form. The algorithms such as the one by Goodman and Weare \([78]\) instead of classical Metropolis-Hastings is used in this work for its excellent performance on clusters. The algorithm by Goodman and Weare \([78]\) was slightly altered and implemented as the Python module emcee \([79]\) by Foreman-Mackey et al. \([79]\), which makes it easy to use by the advantages of Python. Moreover, emcee could distribute the sampling on the multiple nodes of modern cluster or cloud computing environments, and then increase the sampling efficiency observably.

B. Data Sets and Parameters

In our work, the proton flux (from AMS-02 and CREAM \([51, 54]\)), helium flux (from AMS-02 and CREAM \([51, 54]\)) and \( p/p \) ratio (from AMS-02 \([80]\)) are added in the global fitting data set to determine not only the propagation parameters but also the primary source of nuclei injections which further produce the secondary leptons. The CREAM data was used as the supplement of the AMS-02 data because it is more compatible with the AMS-02 data when \( R \gtrsim 1 \text{TeV} \). The errors used in our global fitting are the quadratic summation over statistical and systematic errors.

On the other hand, the AMS-02 positrons flux \([30]\) is added to set calibration to the absolute positron flux in DAMPE CREs flux \([3]\). Although the electron energy range covered by AMS-02 is under TeV and there are systematics between the AMS-02 and DAMPE CREs data, fittings to the AMS-02 leptonic data provide a self-consistent picture for the extra source models. As the extra sources accounting for the AMS-02 results may provide contribution to the TeV scale, the AMS-02 data could also constrain the properties of the predicted \( e^- + e^+ \) spectrum above \( \sim \text{TeV} \). Considering the degeneracy between the different lepton data, we use the positron flux from AMS-02 and CREs flux from DAMPE together to constraint the extra source properties. The systematics are dealt with by employing a re-scale factor \( c_{e^\pm} \) on positron flux.

Altogether, the data set in our global fitting is

\[
D = \{ D^{\text{AMS-02}}_p, D^{\text{AMS-02}}_{\text{He}}, D^{\text{AMS-02}}_{p/p}, D^{\text{CREAM}}_{\text{He}}, D^{\text{CREAM}}_{e^\pm}, D^{\text{DAMPE}}_{e^- + e^+} \}.
\]

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1. https://github.com/cosmicrays/DRAGON
2. https://dan.iel.fm/emcee/
The parameter sets for pulsar scenario is

$$\theta_{\text{psr}} \equiv \{D_0, \delta, z_h, v_A, |N_p, R_{p_1}, R_{p_2}, \nu_{p_1}, \nu_{p_2}, \nu_{p_3}, R_{He1}, R_{He2}, \nu_{He1}, \nu_{He2}, \nu_{He3}, |e_p, c_{He}, \phi_{\text{psr}}, \phi_{\text{He}}; |N_{e_1}, R_{e_1}, \nu_{e_1}, \nu_{e_2}; |m_h, \langle \sigma v \rangle, \eta_e, \eta_\mu, \eta_\tau; |c_e^+, \phi_e^+; \},$$

for DM scenario is

$$\theta_{\text{DM}} \equiv \{D_0, \delta, z_h, v_A, |N_p, R_{p_1}, R_{p_2}, \nu_{p_1}, \nu_{p_2}, \nu_{p_3}, R_{He1}, R_{He2}, \nu_{He1}, \nu_{He2}, \nu_{He3}, |e_p, c_{He}, \phi_{\text{psr}}, \phi_{\text{He}}; |N_{e_1}, R_{e_1}, \nu_{e_1}, \nu_{e_2}; |m_h, \langle \sigma v \rangle, \eta_e, \eta_\mu, \eta_\tau; |c_e^+, \phi_e^+; \}. $$

Note that, most of these 2 scenarios’ parameters in the set $\theta_{\text{psr}}$ and $\theta_{\text{DM}}$ is the same with each other except those who account the extra sources of lepton.

IV. FITTING RESULTS AND DISCUSSION

The MCMC algorithm was used to determine the parameters in the 2 scenarios. When the Markov Chains have reached their equilibrium state, we take the samples of the parameters as their posterior PDFs. The best-fitting results and the corresponding residuals of the proton flux, helium flux and $\bar{p}/p$ ratio for 2 scenarios are showed in Fig. 1 and the corresponding results of the positron and CREs flux are showed in Fig. 2. The best-fit values, statistical mean values, standard deviations and allowed intervals at 95% CL for parameters in set $\theta_{\text{psr}}$ and $\theta_{\text{DM}}$ are shown in Table I and Table II, respectively. For best fit results of the global fitting, we got $\chi^2/d.o.f = 255.24/298$ for pulsar scenario and $\chi^2/d.o.f = 276.56/296$ for DM scenario.

In Fig. 1 we can see that the nuclei data is perfectly reproduced, which would provide a good precondition for the subsequent fitting on the lepton data. The proton and helium particles $\gtrsim$ TeV would produce the secondary particles (including anti-protons and positrons) in lower energy range. Although the CREAM proton and helium data in $\gtrsim$ TeV has a relative large uncertainties, the spectral hardening at $\sim 300$ GeV is accounted and then its influence on secondary products is included.

The best-fitting results and the corresponding residuals of the lepton and positron spectra are showed in Fig. 2. The corresponding best-fit values, statistical mean values, standard deviations and allowed intervals at 95% CL for these parameters are shown in Table III and Table IV.

In Fig. 2 the lepton data can be fitted within fitting uncertainties. Although we got smaller reduced $\chi^2$ from global fitting on pulsar scenario, if we consider the DAMPE CREs flux alone, the best fit results shows $\chi^2 = 21.89$ for pulsar scenario and $\chi^2 = 14.63$ for DM scenario.

A. Propagation parameters

The results of posterior probability distributions of the propagation parameters are shown in Fig. 3 (for pulsar scenario) and Fig. 4 (for DM scenario).

In this work, we adapt the widely used diffusion-reacceleration model to describe the propagation process, and the relevant propagation parameter are $D_0$, $\delta$, $z_h$, and $v_A$. The obtained posterior PDFs are different from previous works to some extent. The classical degeneracy between $D_0$ and $z_h$ is not obvious due to the data set in this work, but both of them get larger best fit values than previous works. This is because (i) the $D_0$ defined in the DRAGON (which represents the perpendicular diffusion coefficient $D_\perp$) is not the same as that in GALPROP (which represents the isotropic diffusion coefficient); (ii) the sensitivity region which could breaks the degeneracy between $D_0$ and $z_h$ is different between $\bar{p}/p$ ($10 - 100$ GeV) and B/C ($\lesssim 10$ GeV). The observed AMS-02 $\bar{p}/p$ ratio favors larger $D_0$ and $z_h$ values.

The $\delta$ value obtained in this work is smaller than some of the previous works because we use one more break in the primary source injection of proton ($\sim 240$ GV) and helium ($\sim 420 - 500$ GV) to account for the observed hardening in their observed spectra, other than use only one break and let $\delta$ compromise the different slopes in high energy regions ($\gtrsim 240 - 500$ GV) (see, e.g., Niu and Li 19). In such configuration, we also got smaller fitting uncertainties on $\delta$ ($\sim 0.03$).

Moreover, the fitting results favor relative large values of $v_A$, which may not only comes from the constraints of nuclei data in low energy regions, but also the positron data as well.

B. Primary source injection parameters

The results of posterior probability distributions of the primary source parameters are shown in Figs. 5 (proton and helium, for pulsar scenario), 6 (proton and helium, for DM scenario), and Figs. 7 (electron, for pulsar scenario), 8 (electron, for DM scenario).

Benefited from the 2 independent breaks injection spectra for proton and helium, the observed data has been reproduced perfectly. The fitting result shows that the rigidity breaks and the slopes are obviously different between proton and helium spectra. This indicates that the cosmic ray physics has entered a precision-driven era.
and all these differences should be treated carefully in future studies. On the other hand, we want to point out that the hardening of the nuclei spectra ~ 300 GeV could also be reproduced by other proposals, which focus on the propagation and diffusion effects rather than ascribing it to the acceleration near the source. These solutions include proposing a spatial dependent diffusion coefficient \[84\,85\], or adding a high-rigidity break in the diffusion coefficient \[84\,86\]. With the precise data obtained in future extending to higher energy regions, we would expect more details can be revealed on this theme.

Additionally, the electron primary source injection spectra can be described by a break power-law from 20 GeV to \(10^4\) GeV (DAMPE data), with \(\nu_{e1} \in [2.54, 2.57]\),
Consequently, the DM annihilation is about 3 orders larger than that of thermal DM [90].

This may indicate: (i) there is something wrong or inaccurate in the extra source parameters; (ii) more attention should be paid in future researches.

In standard pulsar models, the injection spectrum indices of CREs from pulsars are always in the range $\nu_{\text{psr}} \in [1.0, 2.4]$ [77,89]. As a result, more attention should be paid in future researches. This may indicate: (i) there is something wrong or inaccurate with the classical pulsar CRE injection model; (ii) the CRE excess is not contributed dominantly by pulsars.

Moreover, we have $\eta_e \simeq 0.484$, $\eta_\mu \simeq 0.508$, and $\eta_\tau \simeq 0.008$, which is obviously different from the fitting results obtained from AMS-02 lepton data alone (see for e.g., Lin et al. [17]). Consequently, the DM annihilation into $\tau\tau$ is highly suppressed, which provides some hints to construct an appropriate DM model (see for e.g., [91]).

Because we have $\eta_e \simeq 0.484$, $\eta_\mu \simeq 0.508$, and $\eta_\tau \simeq 0.008$, the constraints from the Fermi-LAT observations on dwarf spheroidal galaxies [23,92,96] can be avoided [17]. In order to escape the constraints from the Planck observations of CMB anisotropies [97], the Breit-Wigner mechanism [88,105] could be employed and the dark $U(1)_D$ model (where the SM fermions and Higgs fields are neutral under it) is considered. We introduce one SM singlet field $S$, one chiral fermionic dark matter particle $\chi$, and three pairs of the vector-like particles $(X E_i, \widehat{X E}_i)$, whose quantum numbers under the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_D$ are

$$S : (1,1,0,2) , \quad \chi : (1,1,0,-1)$$

$$X E_i : (1,1,-1,-2) , \quad \widehat{X E}_i : (1,1,1,2) .$$  \hspace{1cm} (6)
The relevant Lagrangian is

\[-\mathcal{L} = -m_{3/2}^2 |S|^2 + \frac{\lambda}{2} |S|^4 + \left( M_Y^i \vec{X} E_i^c \vec{X} E_j \right) + y_{ij} S \vec{E}_i^c \vec{X} \vec{E}_j + y S \chi \chi + \text{H.c.} \] (7)

where \( \vec{E}_i^c \) are the right-handed charged leptons.

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

\[
\left( \begin{array}{c} E_i^c \\
X E_i^c \end{array} \right) = \left( \begin{array}{cc} \cos \theta_i & \sin \theta_i \\
-\sin \theta_i & \cos \theta_i \end{array} \right) \left( \begin{array}{c} \vec{E}_i^c \\
\vec{X} \vec{E}_i^c \end{array} \right),
\]

where \( \tan \theta_i = -y(S)/M_Y^i \).

Neglecting the charged lepton masses again, we obtain

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

where \( m_\chi = y(S) \), 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

\[
\Gamma_{Z'} = \frac{\sum_{i=1}^{3} g'^2 \sin^2 \theta_i}{6\pi} m_{Z'}. 
\]

To explain the DM best fit results, we can choose proper values of \( g' \), \( \frac{m_{Z'} - 2m_\chi}{m_{Z'}} \), \( \sin \theta_e \), \( \sin \theta_\mu \), and \( \sin \theta_\tau \) to reproduce the values of \( m_\chi \), \( \langle \sigma v \rangle \) and \( \eta_e : \eta_\mu : \eta_\tau \) like that in Niu et al. [106].

\[\text{TABLE II: The same as Table. I, but for the ones in set } \theta_{DM}. \text{ With } \chi^2/d.o.f = 276.56/296 \text{ for best fit result.}\]
D. Nuisance parameters

In Figs. 11 and 12 the results of posterior probability distributions represent the necessity to introduce them in the global fitting.

The different values of $\phi_{\text{nuc}}, \phi_p$, and $\phi_{e^+}$ from the best-fit results represent not only the charge-sign dependent solar modulation (which has also been claimed by some previous works, see, e.g., Niu and Li [49], Clem et al. [107], Boella et al. [108]), but also a species dependent solar modulation to some extent. As claimed in our previous works [49], the force field approximation could not describe the effects of solar modulation to all the species by a single $\phi$, but as an effective model, we can use an independent $\phi$ for each of the species. The different values of the $\phi$s for different species could reveal the hints to improve the propagation mechanisms of them in the heliosphere. Additionally, the proton, helium, and positron data have been collected from AMS-02 in the same period with a suggested $\phi$ from 0.50 - 0.62 GV [30, 53, 54], which is based on data from the world network of sea level neutron monitors [109]. More details in this field can be gotten in Corti et al. [110].

The value of $c_p \sim 1.4 - 1.5$ could be explained by the uncertainties on the antiproton production cross section [58-61] [111].

The DRAGON primary source isotopic abundances are inherited from GALPROP, which are taken as the solar system abundances and iterated to achieve and agreement with the propagated abundances as provided by ACE at $\sim 200$ MeV nucleon. It is naturally that the normalized factor is different in different energy regions. On the other hand, we always focus on the shape of the spectrum, and $c_{\text{He}}$ could be considered as an independent normalized factor as $N_{p}$, which is just identified as an nuisance parameter to get a better fitting result and

\[ E^{3}dN/dR(GeV^{2}m^{-2}s^{-1}sr^{-1}) \]

\[ \chi^{2} = 21.89 \]

Pulsar Scenario
total lepton
background
pulsar
DAMPE
peak point
E(GeV)
Residuals
$1e_{2}$

\[ E^{3}dN/dR(GeV^{2}m^{-2}s^{-1}sr^{-1}) \]

\[ \chi^{2} = 14.63 \]

Pulsar Scenario
total lepton
background
pulsar
AMS-02
peak point
E(GeV)
Residuals
$1e_{1}$

\[ E^{3}dN/dR(GeV^{2}m^{-2}s^{-1}sr^{-1}) \]

\[ \chi^{2} = 14.63 \]

DM Scenario
total lepton
background
DM
DAMPE
peak point
E(GeV)
Residuals
$1e_{2}$

\[ E^{3}dN/dR(GeV^{2}m^{-2}s^{-1}sr^{-1}) \]

\[ \chi^{2} = 21.89 \]

DM Scenario
total lepton
background
DM
AMS-02
peak point
E(GeV)
Residuals
$1e_{1}$

FIG. 2: The global fitting results and the corresponding residuals to the AMS-02 positron flux and DAMPE lepton flux. The 2σ (deep red) and 3σ (light red) bound are also showed in the figures. The first column shows the fitting results of pulsar and the second shows the fitting results of DM. For DAMPE CREs flux only, we got $\chi^{2} = 21.89$ for pulsar scenario and $\chi^{2} = 14.63$ for DM scenario.

It is naturally that the low energy proton and helium spectra precisely under the precision of current data.

\[ \phi_{\text{nuc}} \]

\[ \phi_p \]

\[ \phi_{e^+} \]
FIG. 3: Fitting 1D probability and 2D credible regions of posterior PDFs for the combinations of all propagation parameters for pulsar scenario. The regions enclosing $\sigma$, $2\sigma$ and $3\sigma$ CL are shown in step by step lighter blue. The red cross lines and marks in each plot indicates the best-fit value (largest likelihood).

FIG. 4: Same as Fig. 3 but for DM scenario.

V. CONCLUSION

In this work, we did Bayesian analysis on the newly released CREs flux (exclude the peak signal at $\sim 1.4$ TeV) from DAMPE to study the extra source properties in it. In order to deduct the primary electrons, secondary leptons in CREs flux consistently and precisely, we did a global fitting to reproduce the proton flux (from AMS-02 and CREAM), helium flux (from AMS-02 and CREAM), $\bar{p}/p$ ratio (from AMS-02), positron flux (from AMS-02) and CREs flux (from DAMPE) simultaneously. Two independent extra source scenarios are considered, which account the excess of leptons to continuously distributed pulsars in the galaxy and dark matter annihilation (via leptonic channels) in the galactic halo. Both of these scenarios can fit the DAMPE CREs flux within the fitting uncertainties, while DM scenario gave a smaller $\chi^2$ and a obvious break at $\sim 1$ TeV.

Additionally, in the DM scenario, the fitting result gives a dark matter particle’s mass $m_\chi \sim 1208$ GeV and a cross section $\langle \sigma v \rangle \sim 1.48 \times 10^{-23}$ cm$^3$ s$^{-1}$. This is benefited from the break at $\sim 1$ TeV. In such situations, the cross section in this work still should have a suppress factor to meet the value $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3$ s$^{-1}$. This discrepancy can be resolved by some proposed mechanisms like the non-thermal production of the DM [115–117], the Sommerfeld enhancement mechanism [118–120], and Breit-Wigner type resonance of the annihilation interaction [121,122]. What’s more interesting, the constraints on the annihilation branching fraction shows the $\tau\bar{\tau}$ annihilation channel is strongly suppressed, while the $e^-e^+$ and $\mu\bar{\mu}$ channels are almost equally weighted ($\eta_e = 0.484$, $\eta_\mu = 0.508$, and $\eta_{\tau} = 0.008$). This would give some hints for constructing DM models, and we tried to build one in this work to meet the fitting results.

Note: In this work, we can see that the CREs spectrum from DAMPE without the peak can be reproduced by DM scenarios precisely. On the other hand, the spectrum with the peak also can be reproduced by DM an-
FIG. 5: Fitting 1D probability and 2D credible regions of posterior PDFs for the combinations of nuclei primary source injection parameters for pulsar scenario. The regions enclosing $\sigma$, $2\sigma$ and $3\sigma$ CL are shown in step by step lighter blue. The red cross lines and marks in each plot indicates the best-fit value (largest likelihood).
FIG. 6: Same as Fig. 5 but for DM scenario.
FIG. 7: Fitting 1D probability and 2D credible regions of posterior PDFs for the combinations of electron primary source injection parameters for pulsar scenario. The regions enclosing $\sigma$, $2\sigma$ and $3\sigma$ CL are shown in step by step lighter blue. The red cross lines and marks in each plot indicates the best-fit value (largest likelihood).

FIG. 8: Same as Fig. 7 but for DM scenario.

FIG. 9: Fitting 1D probability and 2D credible regions of posterior PDFs for the combinations of extra lepton source parameters from for pulsar scenario. The regions enclosing $\sigma$, $2\sigma$ and $3\sigma$ CL are shown in step by step lighter blue. The red cross lines and marks in each plot indicates the best-fit value (largest likelihood).

FIG. 10: Same as Fig. 9 but for DM scenario.
nihilation from a local DM sub-structure [17, 23, 123-126]. Both of these situations call for DM particles with \( m_\chi \sim 1 - 2 \text{ TeV} \). Other independent detection strategy is needed to distinguish the excess in the CREs spectrum which can also be produced from some astrophysical sources [16, 17, 127]. Our recent works [128] proposed a novel scenario to probe the interaction between DM particles and electrons with \( 5 \text{ GeV} \lesssim m_\chi \lesssim 10 \text{ TeV} \).

FIG. 11: Fitting 1D probability and 2D credible regions of posterior PDFs for the combinations of nuisance parameters for pulsar scenario. The regions enclosing \( \sigma \), \( 2\sigma \) and \( 3\sigma \) CL are shown in step by step lighter blue. The red cross lines and marks in each plot indicates the best-fit value (largest likelihood).

FIG. 12: Same as Fig. 11 but for DM scenario.

ACKNOWLEDGMENTS

We would like to thank Maurin et al. [129] to collect database and associated online tools for charged cosmic-ray measurements, and Foreman-Mackey et al. [130] to provide us the tool to visualize multidimensional samples using a scatterplot matrix. Many thanks for the referees valuable and detailed suggestions, which led to a great progress in this work. This research was supported in part by the Projects 11475238 and 11647601 supported by National Science Foundation of China, and by Key Research Program of Frontier Sciences, CAS. The calculation in this paper are supported by HPC Cluster of SKLTP/ITP-CAS.

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