The gluon condensation effects in the DAMPE cosmic ray spectrum of electrons and positrons

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Abstract

Gluons dominate the proton behavior at high energy collisions, they can be condensed at ultra high energy. The collisions of the accelerated high energy protons with interplanetary matter in cosmic rays will produce a huge number of secondary particles at the gluon condensate energy region, which break the primary power-law of cosmic rays. The above predictions seem to be consistent with the recent DAMPE data concerning the electron plus positron spectra. We find that the smoothly broken power-law at $\sim 0.9\ TeV$ and $3 \sim 4\ TeV$ in the DAMPE data can be understood as the gluon condensation effects in proton.

keywords: Gluon condensation; Broken power-law; DAMPE spectra

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Recently, the DArk Matter Particle Explorer (DAMPE) collaboration published their first result of the high energy electron plus positron spectrum from 25 GeV to 4.6 TeV [1]. The DAMPE data combining previous results of other group display a clear spectral break at $\sim 0.9 TeV$ and the possible complex structure after that. Besides, there is a suspect sharp peak at $\sim 1.4 TeV$.

We are pleasure to notice that the above mentioned spectral features broken power laws have been predicted by the gluon condensation (GC)-effects in our previous work [2], which is based on Refs.[3,4]: (a) this spectrum has a smoothly broken power-law at $\sim 0.9\ TeV$ and the curve is turning again at $3 \sim 4\ TeV$; (b) there is possible sharp peak around $\sim 1\ TeV$, which is arisen by $\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$ and $\mu^{\pm} \to e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_{\mu}(\nu_{\mu})$, although it was neglected in [2]. In this letter we try to improve the above estimations using the precise structure of the DAMPE spectra and emphasize the GC-effects in the cosmic ray electron spectra.

The gluon density in proton grows with decreasing Bjorken variable x (or increasing energy) according to the linear QCD evolution equations, where the correlations among the initial gluons are neglected. At a characteristic saturation momentum $Q_s(x)$, the non-linear recombination of the gluons becomes important and leads to an eventual saturation of parton densities [5]. Zhu, Shen and Ruan [3] pointed out that the above saturation state is unstable at the small x range if considering the corrections of a set of complete 2-2 and 1-3 amplitudes. Using the available saturation models as input, the new evolution equation presents the chaos solution with positive Lyaponov exponents. The chaotic oscillations of the gluon density raise both the strong negative and positive nonlinear corrections. They will result in a pair of closer and more stronger positive and negative corrections. In consequence, we observed the gluons condensation (GC) at (x_c, k_c^2) due to the extrusion of the shadowing and antishadowing effects in the QCD evolution [4].

A main primary product of hadronic processes in cosmic rays is pion via $p + p(A) \to N_{\pi}\pi + others$, where $\pi = (\pi^+, \pi^0, \pi^-)$. Then we have $\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$, $\mu^{\pm} \to e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_{\mu}(\nu_{\mu})$, $\pi^0 \to 2\gamma$ and $\gamma \to e^+ + e^-$. Considering lots of pions with a certain energy accumulate in a narrow space at per collision, they may transform each other in the formation time due to their wave-functions overlap, i.e., $\pi^+ + \pi^- \rightleftharpoons 2\pi^0$. However, the above balance will be broken since $m_{\pi^+} + m_{\pi^-} > 2m_{\pi^0}$, and the lifetime of π^0 (10^{-16} s) is much shorter than the typical weak decay lifetimes of $\pi^{\pm}$ ($10^{-6}\ s - 10^{-8}\ s$). Therefore we neglect temporarily the contributions of $\pi^{\pm}$. The isotropic measured electron and positron fluxes are (see [2] for details).

$$\Phi_j(E_j) = \Phi_j^0(E_j) + \Phi_j^{GC}(E_j), \tag{1}$$

for $j = e^- + e^+$ and

$$\Phi_j^{GC}(E_j) = C_j \left(\frac{E_j}{1\ GeV}\right)^{-\beta_j} \int_{E_j} dE_\gamma \left(\frac{E_\gamma}{1\ GeV}\right)^{-\beta_\gamma} \int_{E_\pi^{min}}^{E_\pi^{max}} dE_\pi \left(\frac{E_{p-p(A)}}{E_{p-p(A)}^{GC}}\right)^{-\beta_p}$$
$$N_\pi(E_{p-p(A)}, E_\pi) \frac{d\omega_{\pi-\gamma}(E_\pi, E_\gamma)}{dE_\gamma} \frac{d\omega_{\gamma-e}(E_\gamma, E_e)}{dE_e}$$
$$= C_j(\frac{E_j}{1\ GeV})^{-\beta_j} \int_{E_j} \frac{dE_\gamma}{E_\gamma} \left(\frac{E_\gamma}{1\ GeV}\right)^{-\beta_\gamma} \int_{E_\pi^{GC}\ or\ E_\gamma}^{E_\pi^{max}} dE_\pi \left(\frac{E_{p-p(A)}}{E_{p-p(A)}^{GC}}\right)^{-\beta_p} N_\pi(E_{p-p(A)}, E_\pi) \frac{2}{\beta_\pi E_\pi}, \tag{2}$$

where the integral lower-limit takes E_π^{GC} (or E_γ) if $E_\gamma \leq E_\pi^{GC}$ (or if $E_\gamma > E_\pi^{GC}$). The normalized spectrum for $\pi^0 \to \gamma + \gamma$ is

$$\frac{d\omega_{\pi-\gamma}(E_\pi, E_\gamma)}{dE_\gamma} = \frac{2}{\beta_\pi E_\pi} H[E_\gamma; \frac{1}{2}E_\pi(1-\beta_\pi), \frac{1}{2}E_\pi(1+\beta_\pi)], \tag{3}$$

$\beta_\pi \equiv v_\pi/c$, $H(x; a, b) = 1$ if $a \leq x \leq b$, and $H(x; a, b) = 0$ otherwise. After taking average over possible directions, the energy of pair-produced electron-positron is uniformly distributed from zero to maximum value, i.e.,

$$\frac{d\omega_{\gamma-e}(E_\gamma, E_e)}{dE_e} = \frac{1}{E_\gamma}. \tag{4}$$

In Eq. (2) $N_\pi(E_{p-p(A)}, E_\pi)$ is pion-numbers with energies E_π at $p-p(A)$ collisions; $E_{p-p(A)}$ is the energy of incident proton in the rest frame of targeted proton. C_j incorporates the kinematic factor with the flux dimension and the percentage of $\pi^0 \to 2\gamma$ and $\gamma \to e^- + e^+$.

The sharp peak in the gluon momentum distribution caused by the GC-effects leads to an extreme enhancement of the multiplicity of gluon jets and number of secondary particles at $p-p(A)$ collisions, which can be larger than the normal value several orders of magnitude as we have examined in Ref. [4]. In general, the more the larger number of gluons, the more the secondary pions. However, energy conservation restricts the creation number of massive particle, unlike the number of gluons which can increase indefinitely. The secondary particles (they are mostly pions) have a saturated number $N_{\pi,max}$, where all available kinetic energies of the colliding protons are almost used to create pions in the center-of-mass (CM) system. A lot of gluons converge at a critic momentum and once they participate in the collisions, the resulting pions may reach this saturation limit. Thus, we write the relativistic invariant and energy conservation

$$(2m_p^2 + 2E_{p-p}m_p)^{1/2} = 2m_p + N_\pi m_\pi, \tag{5}$$

$$E_{p-p} + m_p = [2m_p + N_\pi m_\pi]\gamma \tag{6}$$

at the saturation limit; γ is the CM Lorentz factor. Note that although a small part of particles may still take a large momentum tail, but it does not affect our following discussions. One can easily get the solutions $N_\pi(E_{p-p(A)}, E_\pi)$ for $p-p(A)$ collisions in GeV-unit

$$\ln N_\pi = 2.3 + 0.5 \ln E_{p-p(A)}, \quad \ln N_\pi = 4.6 + \ln E_\pi. \tag{7}$$

This extra power-law describes the GC-effects in cosmic ray spectra, and it results in the broken power-law.

Figure 1 is a new result fitting data including the DAMPE $e^- + e^+$ spectrum, where using $E_\pi^{GC} = 880\ GeV$ for $p-A$ collisions and $E_\pi^{GC} = 24\ TeV$ for $p-p$ collisions, respectively. $\Phi^0_{e^-+e^+}$ is refers to [6], where we reduce the background line to lower than the data at $E > 1\,TeV$. The data from AMS02 [7], Fermi [8], HESS [9] and VERITAS [10] are added. The sky survey DAMPE data are consistent with the HESS and VERITAS data on the ground at high energy band ($> 3\ TeV$) since high energy particles have a strong penetrating power in the atmosphere. We present a smoothly broken power at $0.9\ TeV$ and the curve is turning again at $3 \sim 4TeV$.

Now we consider the contributions of $\pi^\pm \to \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$ and $\mu^\pm \to e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$.

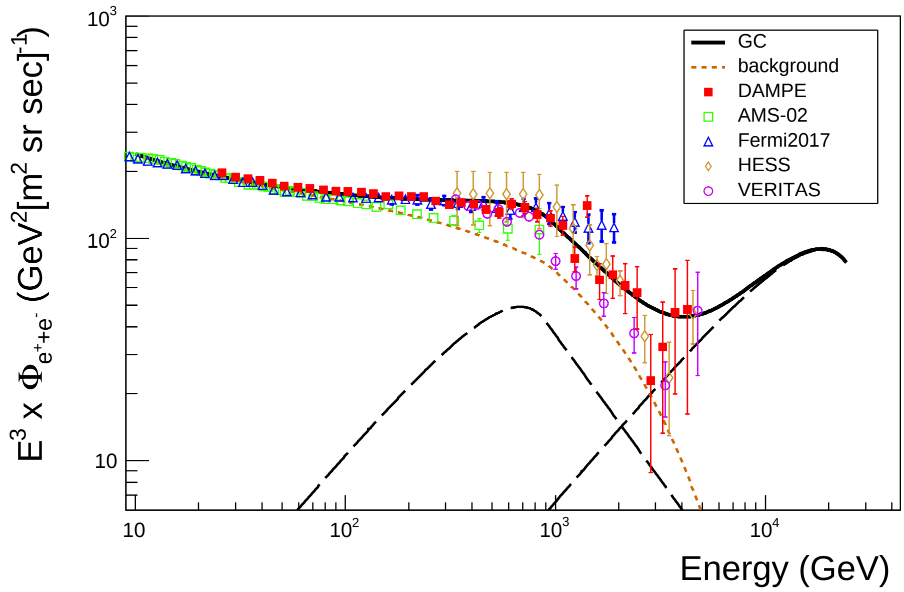

Figure 1: Predicted cosmic ray electron+positron spectrum using Eq.(2) and multiplied by $E^{3.0}$ as a function of energy (solid line). The data are taken from [1,7-10]. Broken lines present the broken power-law of the GC-effects. $\Phi^0_{e^-+e^+}$ (dashed line) refers to [6]. The free parameters $\beta_p = 1.7, \beta_\gamma = 1.3, \beta_e = 0.6, C_{880\ GeV} = 1.15 \times 10^{-6}$ and $C_{24\ TeV} = 2.0 \times 10^{-9}$.

This process was neglected before as discussed above. However, the contributions of this process may be found in a precise measurement. Therefore, we add the corrections from $\pi^\pm$. Similar to Eq. (2), we have

$$\Phi_e^{GC}(E_e) = C_e \left(\frac{E_e}{1\ GeV}\right)^{-\beta_e} \int dE_\mu \int_{2.5E_e\ or\ E_\pi^{GC}}^{E_\pi^{max}} dE_\pi \left(\frac{E_{p-p(A)}}{1\ GeV}\right)^{-\beta_p} N_{\pi^\pm}(E_{p-p(A)}, E_\pi)$$
$$\frac{d\omega_{\pi-\mu}(E_\pi, E_\mu)}{dE_\mu} \frac{d\omega_{\mu-e}(E_\mu, E_e)}{dE_e}, \tag{8}$$

where the integral lower-limit takes $2.5E_e$ (or E_π^{GC}) if $E_e > 0.4E_\pi^{GC}$ (or if $E_e \leq 0.4E_\pi^{GC}$). The normalized spectra are

$$\frac{d\omega_{\pi-\mu}(E_\pi, E_\mu)}{dE_\mu} = \delta(E_\mu - 0.8E_\pi), \tag{9}$$

and

$$\frac{d\omega_{\mu-e}(E_\mu, E_e)}{dE_e} = 4(\frac{2E_e}{E_\mu})^2(1.5 - \frac{2E_e}{E_\mu}), \quad E_e \leq \frac{E_\mu}{2}. \tag{10}$$

An interacting distinguish is that the spectra break at $\sim 0.9\ TeV$ is smoothed, while there is a sharp peak at $\sim 1.4\ TeV$. One can simply understand these different behaviors

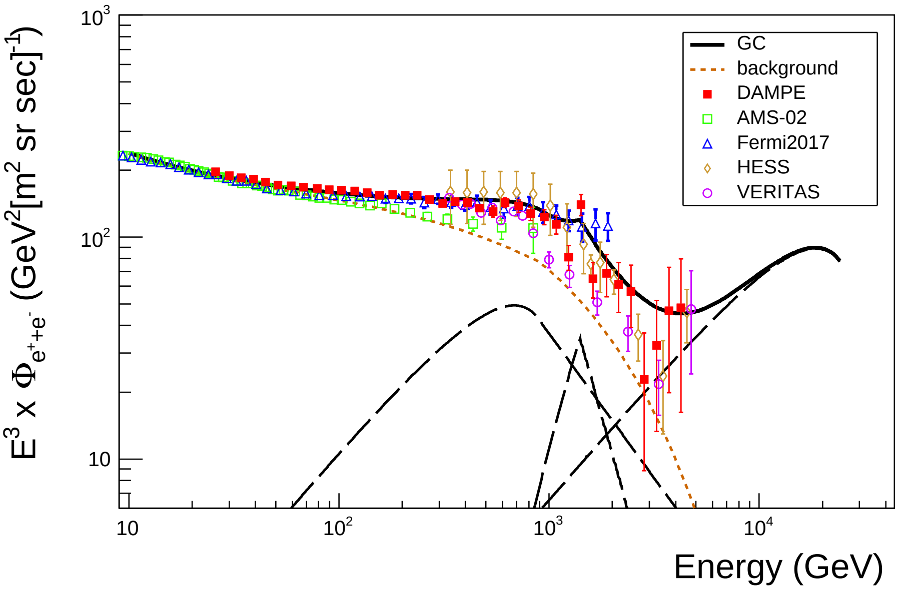

Figure 2: As similar to Fig. 1 but added the corrections of Eq. (8). The added parameters for the peak at 1.4 TeV: $\beta_p = 3.9$ and $C_{1.4\ TeV} = 8.0 \times 10^{-14}$.

as follows. The integral of E_γ in Eq. (2) smooths the corner, while Eq. (8) lacks such smooth factor since Eq. (9). Therefore, a sharp peak at the TeV-band is permissible. However, as we have mentioned that the probability of $\pi^\pm$ decay is much smaller than that of π^0 decay due to the accumulation of a lot of pions at $p-p(A)$ collisions. Therefore, we prefer that $\pi^\pm$ decay is almost suppressed, however, it is still possible to be measured with the sharp peak but with a small probability. Nevertheless, the DAMPE data at 1.2, 1.4 and 1.6 TeV are obviously deviated from our predicted curve. We expect the further experimental data.

In summary, by comparing our previous predictions with the new DAMPE electron-positron spectra, we confirm that the smoothly broken power-laws at two places (0.9 TeV and 3 $\sim$ 4 TeV) in high energy electron spectra origin from the GC-effects in proton. And a suspect sharp peak at $\sim$ 1.4 TeV in the DAMPE data is discussed in the same framework.

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References

[1] G. Ambrosi et. al., [The DAMPE Collaboration], Nature, **552**.

[2] W. Zhu, J. Lan, J.H. Ruan and F. Wang, hep-ph/1709.03897.

[3] W. Zhu, Z.Q. Shen and J.H. Ruan, Chin. Phys. Lett. **25**, 3605 (2008); W. Zhu, Z.Q. Shen and J.H. Ruan, Nucl. Phys. **B911**, 1 (2016).

[4] W. Zhu and J. Lan, Nucl. Phys. **B916**, 647 (2017).

[5] J. Jalilian-Marian, A. Kovner, L. McLerran, and H. Weigert, Phys. Rev. **D55**, 5414 (1977); J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, Nucl. Phys. **B504**, 415 (1977); H. Weigert, Nucl. Phys. **A703**, 823 (2002).

[6] Q. Yuan, et. al., astro-ph/1711.10989.

[7] M. Aguilar, et. al., [The AMS Collaboration], Phys. Rev. Lett.**117**, 091103 (2016).

[8] S. Abdollahi,et al. [The Fermi LAT Collaboration], Phys. Rev. **D95**, 082007 (2017).

[9] F. Aharonian1, et. al., [The H.E.S.S. Collaboration], Astron. Astrophys. **508**, 561, (2009) astro-ph/0905.0105.

[10] D. Staszak for The VERITAS Collaboration, the Proceedings of the 34th International Cosmic Ray Conference (ICRC2015), The Hague, The Netherlands astro-ph/1508.06597.