PROCEEDINGS OF SCIENCE

Gamma-ray Pulsars with DAMPE

Maria Munoz*
University of Geneva, Geneva, Switzerland
E-mail: maria.munoz@unige.ch

Xin Wu

University of Geneva, Geneva, Switzerland

Fabio Gargano

INFN, Bari, Italy

Kai-Kai Duan

Purple Mountain Observatory, Nanjing, China

Zhao-Qiang Shen

Purple Mountain Observatory, Nanjing, China

on behalf of the DAMPE collaboration†‡

The DArk Matter Particle Explorer (DAMPE) is a satellite-borne experiment successfully launched in December 2015. DAMPE has been taking data for over 3.5 years during which it has been observing the full gamma-ray sky above 1 GeV. The data used for this contribution considers the first 2 years of data within an energy range from 2 GeV to 100 GeV. Among all the pulsars observed by DAMPE we will present the measurement results for the 5 brightest gamma-ray pulsars which include Vela, Geminga and Crab. The light curves and energy spectra, including the phase averaged energy spectra will be presented for these 5 pulsars. From these results we will derive the timing precision of DAMPE, which is of importance for its other scientific goals, as well as the potential for future gamma-ray studies with DAMPE.

36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.

*Speaker.

†for collaboration list see PoS(ICRC2019)1177

‡The DAMPE mission is funded by the strategic priority science and technology projects in space science of Chinese Academy of Sciences. In China the data analysis is supported in part by the National Key Research and Development Program of China (No. 2016YFA0400200), the National Natural Science Foundation of China (Nos. 11525313, 11622327, 11722328, U1738205, U1738207, U1738208, 11851305), the strategic priority science and tech- nology projects of Chinese Academy of Sciences (No. XDA15051100), the 100 Talents Program of Chinese Academy of Sciences, and the Young Elite Scientists Sponsorship Program. In Europe the activities and the data analysis are supported by the Swiss National Science Foundation (SNSF), Switzerland; the National Institute for Nuclear Physics (INFN), Italy.

PoS(ICRC2019)587

1. Introduction

The DArk Matter Particle Explorer (DAMPE) is China's first astronomical satellite launched the 17th of December 2015. DAMPE has been successfully taking data for over 3.5 years. The satellite has a sun-synchronous orbit at an altitude of 500 km and has a period of 95 minutes i.e. 15 orbits per day. The instrument consists of four sub-detectors, from top to bottom: A Plastic Scintillator Detector (PSD) used as an anti-coincidence shield for photon identification and for charge measurement of heavy ions. A Silicon TracKer (STK) composed by six double layers of silicon: the first three layers are inter-layered by a tungsten foil to promote pair conversion of gamma-rays. A BGO Calorimeter for energy measurements and separation of electromagnetic/hadronic showers with a depth of ~ 32 radiations lengths. Finally a NeUtron Detector (NUD) for hadronic identification [7].

One of the main scientific objectives of DAMPE is the detection and study of high energy gamma-rays (above 1 GeV). One of the first detailed gamma-ray study using the DAMPE data focuses on pulsars. Pulsars are highly magnetized rotating neutron stars of great interest because of their characteristics. The time properties of pulsars makes them very reliable sources for timing calibration. The observation of Pulsars by DAMPE contributes to two key calibration points of the instrument, the confirmation of gamma-ray detection and the evaluation of the time performance in DAMPE. Previous searches of pulsars in γ-rays with space-based experiments have been made for example with EGRET, AGILE and FERMI[4], the latter still contributing to the discovery of γ-ray pulsars.

2. Data Selection

In a previous paper a method for resolving gamma-ray events detected by DAMPE has been presented [9], nevertheless for this work a different selection has been used. The reason for using a different selection is to increase our signal statistics at low energies to improve the detection of pulsars. As explained before, pulsars have a a very characteristic light curve and emission occurs at a defined known periodicity different for each pulsar. Therefore if the events detected are mistagged as photons they will over-all not contribute to the pulsar light curve measurements. Instead these events will smear-out into the background. Therefore for pulsar analysis a photon selection with a relatively higher electron contamination is permissible. The steps for the gamma-ray identification are similar to those presented in [9],

1. electron/proton separation: Using the BGO to search for characteristics signatures of electronic and hadronic shower, the objective is to reject hadrons. Knowing that $\sim 98\%$ of primary cosmic rays are hadrons it is important to reject them as first step.

2. Use of the PSD as anti-coincidence shield, gamma-rays leave no signal in the PSD. This is essential for electron rejection.

3. Search for tracks in the STK that interact after the first tungsten layer. To eliminate electrons and because of this cut we select only photons that convert within the STK.

4. Alongside the previous cuts, we also apply geometrical cuts to reject events that arrive from the sides or bottom of the detector. Searching for a well contained shower in the BGO for reliable energy measurement and photon directionality.

On top of the steps for photon identification, quality cuts are applied. First, events that cross the South Atlantic Anomaly are rejected. Lastly, the DAMPE instrument has a complex trigger system and an interacting particle can trigger one or more triggers, differentiation of this triggers is also taken into consideration. For this work we will focus on the Low Energy Trigger (LET) and the High Energy Trigger (HET). The HET has no pre-scale and as its name suggest is more efficient at higher energies. The LET is pre-scaled, meaning only a fraction of the events are stored, and it varies depending on the position of the DAMPE with respect to Earth. The Low Energy Trigger has a more lenient logic than the High Energy Trigger and therefore it has a pre-scaling dependent on the latitude, where for the low latitudes from -20 to 20 the pre-scale is set to 8 and for the other latitudes the pre-scale corresponds to 64.

The result of this selection can be observed in Figure 1, where results are shown for the two different triggers. The dependency on energy and the incoming angle of the photon in detector coordinates on the effective area are indicated.

The overall data set studied corresponds $\sim$ 39 months of observations. For this period of time a total of 354,985 events have been detected.

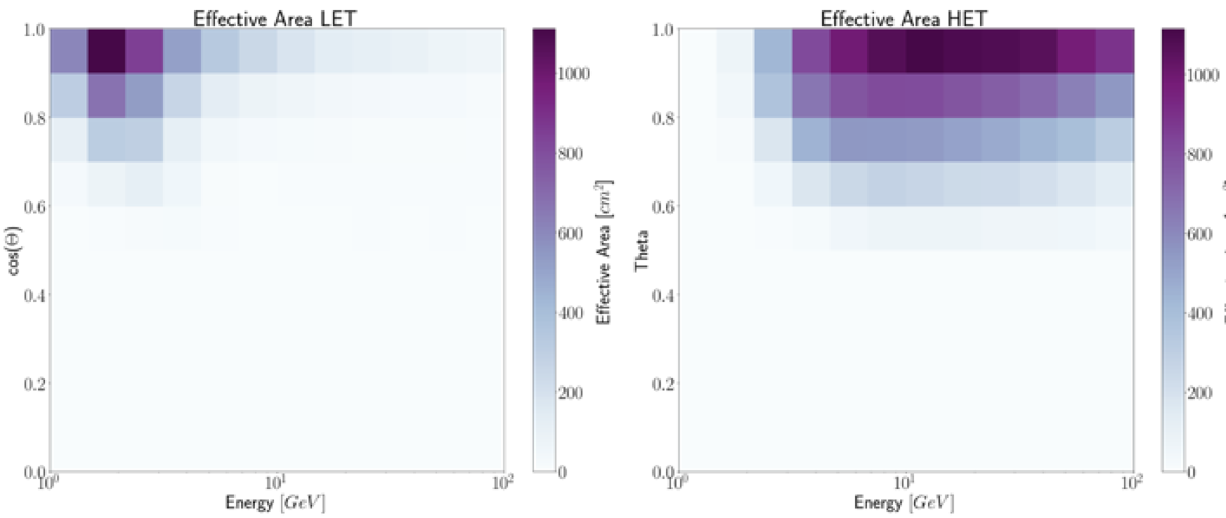


Figure 1: Effective area based on the applied selection, as a function of both the incoming angle(θ) and energy. From left to right, the effective area for Low Energy Trigger (LET) events and the High Energy Trigger events (HET).

3. Pulsars

Pulsars are highly magnetized and rapidly rotating neutron stars. Neutron stars are extremely dense objects, that are used as astrophysical laboratories that help to test the constant struggling relation between astrophysics, nuclear physics and particle physics.

In this section the methods applied to data for the light-curve calculation and the energy spectrum are presented.

3.1 Pulsars Folding

The different ways to detect a pulsar depend on the acceptance of the instrument and its orbit. In the case of DAMPE we do a search based on known pulsars and then use timing models calculated by other experiments, normally in different wavelength such as radio, x-ray or even gamma rays. The pulsar timing solutions (ephemerides) of interest in this work were all provided by David A. Smith (Private Communication).

From the data selected as explained in the previous section, we make a sub-selection of events of interest for each pulsar. For this we search for events around the position of the pulsar of interest. The required information includes the timestamp and position of the satellite with respect to Earth where each event is detected. Precise position in the sky for the different sources is also needed, this position is given by other experiments mainly radio searches. This subset is then barycentered, meaning we convert the DAMPE timestamps that are given in Mission Elapsed Time (MET) to Coordinated Universal Time (UTC) to finally convert to Barycentric Dynamical Time (TDB). The conversion is necessary to correct for relativistic effects related to time dilatation this time variations are very small but important and takes into consideration effects such as Jupiter's and the Sun's orbit. To do this it is important to have precise arrival time stamps of the photons detected and accurate position of DAMPE at each given time. This information comes from the on-board GPS. The position of the known source also need to be accurate, therefore proper motion i.e. motion of the pulsar is also considered for the sources that require it. Because of the need of time precision and since GPS time doesn't consider leap seconds, we need to account for them as they happen. Since the start of the MET of DAMPE (01/01/2013) 2 leap seconds have been added.

Finally we fold the TDB times with the ephemerides given by other experiments. Pulsars are considered to be decelerating and this can be modeled giving rotation parameters, called the ephemerides, that can be applied to the data of different experiments. These rotation parameters can be very complex for different pulsars in particular for those that undergo "glitches" (irregular changes in the rotation parameters). Because of the complexity of the ephemerides the folding procedure is done using the TEMPO2 software package [6]. The TEMPO2 software validity has been widely proved [4] [2].

3.1.1 Light-curve Validation

Validation of the pulsars detection is required, for this we perform a statistical test that will allows to understand the significance of the pulsation, the statistical test used is called the H-test and it is widely used in the pulsar community.

This test has the capability to evaluate both the timing model and the quality of the data used. The H-test was presented for its application in the use of pulsars in 1989, a further modification of this test was presented in [5]. The test consists of searching for uniformity in the circular time periods, in other words evaluating the flatness as a function of the phase. Meaning the search for periodicity on a phase. From the H-Test we obtain an H-Value that can be translated to a probability. This can be used to determine that there is pulsation, we also need to verify the shape of the pulsation, for this we use the results from [4], and in the energy band of interest our results seem to be consistent. For more details on the method the reader is referred to [5].

3.2 Energy Spectrum

From the events detected we require to convert them between the measured distribution of energy and direction measured by DAMPE to the truth flux of gamma-rays on the sky. In order to do this we use the so-called Instruments Response Functions (IRFs). The IRFs can be separated into three parts:

- Effective Area $A_{eff}(E,\theta)$, as function of the true energy E and the true incoming angle θ. To calculate the effective area we use the following formula

$$\frac{\textbf{Events Passed the Selection}}{\textbf{All Events Generated}} \times \textbf{Generation Area} \tag{3.1}$$

  where the generation area will depend on the MC and depending on the MC we use, the integration on the solid angle will also vary. The effective Area results can be observed on Figure 1.

- Point Spread Function PSF $(\delta\theta; E, \theta)$, characterizes the error in the reconstruction of the direction $\theta = \theta' - \theta$. Where θ' and θ are the reconstructed incoming angle and the true incoming angle respectively.

- Energy Redistribution Function $ERF(E'; E, \theta)$, For the energy redistribution function we define the measured energy as function of the true energy and true incoming angle (θ). Once this is done, the correction is applied by using a Bayesian iterative method, where the response matrix is obtained from the normalized redistribution function.

To produce the response we depend on reliable GEANT4 simulations of the instrument for the different particles of interest.The true values are recovered from simulations. Also the IRFs will be dependent on the selection cuts applied to the data.

Finally, we also need to calculate the livetime of DAMPE. For this we applied a $\pm 60^\circ$ window around the source of interest and collect the amount of seconds the DAMPE has spend pointing at this area. The choice of the window is given by Field of View of DAMPE at anytime as a result of the photon selection explained in section 2.

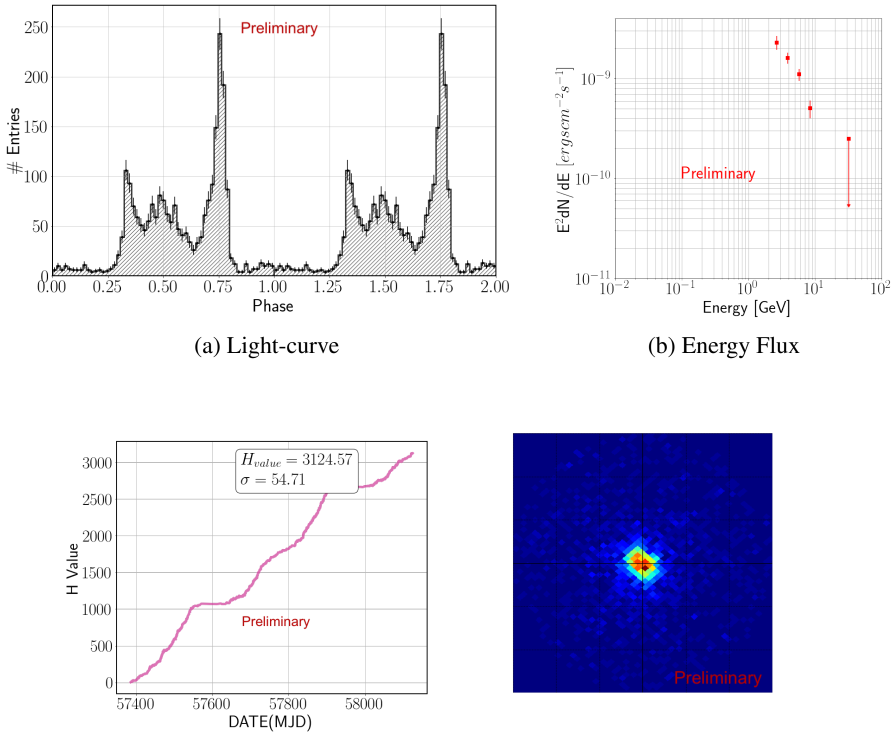
4. Results

In this sections the results of the analyzed pulsars will be presented. At the moment more than 20 pulsars have been studied with DAMPE data set, here we only present the first five. The complete pulsar studies will be presented in a future publication. The pulsars presented for this work were selected based on the number of events detected for each pulsar. The chosen pulsars have collected the higher number of photons in a two year observation period within a ROI of 1° around the known position of the source. However the analysis is applied for a ROI of 3°, and for the folding of the pulsars we use 2 years of data, from the 1st of January 2016 till the 1st of January 2018. Nevertheless for the energy spectrum we use 39 months of data, from the 1st of January

2016 til the 31st of March 2019. The current limitation on the 2 years of data for the light-curve calculation is due to the validity of the ephemerides.

The reason for a ROI of 3° is that the background or other γ-ray sources will not contribute to the phase shape but with a bigger window it increases our statistics that help us create more reliable light curves. The five pulsars presented here, have a sigma greater than five, confirming the detection of the pulsation.

The five pulsars studied were Vela, Geminga, J1709-4429, Crab and J0007+73703, and the results of the analysis can be observed in Figures 2, 3, 4, 5 and 6 respectively.



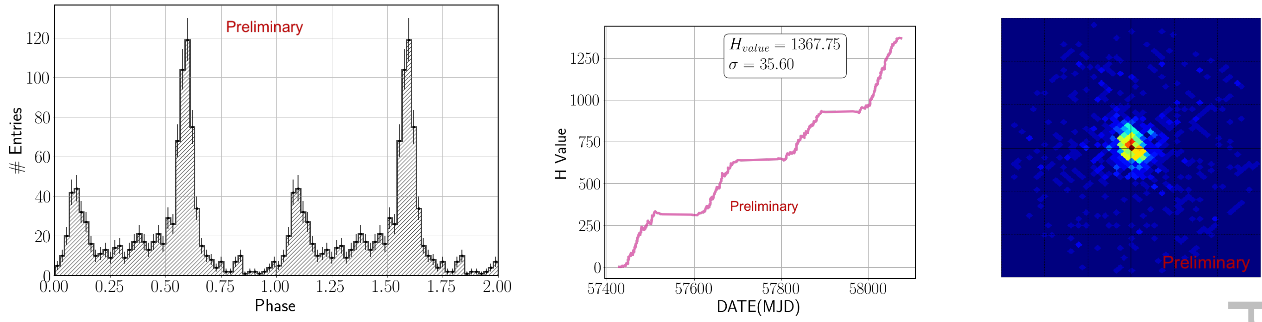
(a) Light-curve (b) Energy Flux

(c) H-Test (d) 2D Projection

Figure 2: Results of the pulsar J0835-4510, a) shows its characteristic light curve. The pulsating detection has a $\sigma = 54.71$ b) Energy Spectrum as measured for this analysis by DAMPE in red from 2 GeV to 100 GeV, c) Plot showing the H-Value progression as a function of time, d) 2D projection of photons detected within a 3° ROI around the pulsar of interest.

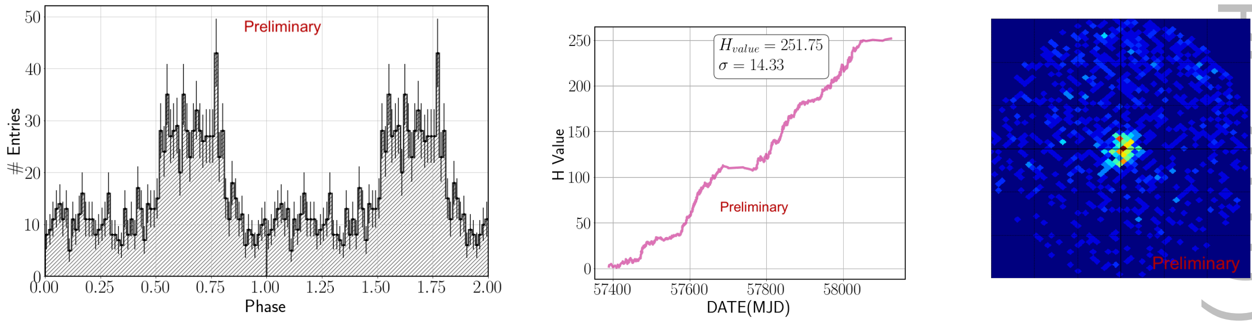
5. Conclusions and future scope

With 24 months of data, we showed DAMPE's capability to measure gamma-rays in an energy range from 2-100GeV. We also show its timing capabilities for the identification and analysis of pulsars. In the future we aim to perform spectral analysis in the pulse and off-pulse regions, observe the evolution of light curves as a function of energy. We also have shown the broad possibilities for research and study of gamma-ray sources such as the galactic plane, SNRs, AGNs, GRBs among others.



(a) Phase information (b) H-Test (c) 2D Projection

Figure 3: Results of the pulsar J0633+1746 also known as Geminga, a) shows its characteristic light curve. b) Plot showing the H-Value progression as a function of time, c) 2D projection of photons detected within a 3° ROI around the pulsar of interest.



(a) Phase information (b) H-Test (c) 2D Projection

Figure 4: Results of the pulsar J1709-4429, a) shows its characteristic light curve. b) Plot showing the H-Value progression as a function of time, c) 2D projection of photons detected within a 3° ROI around the pulsar of interest.

6. Acknowledgements

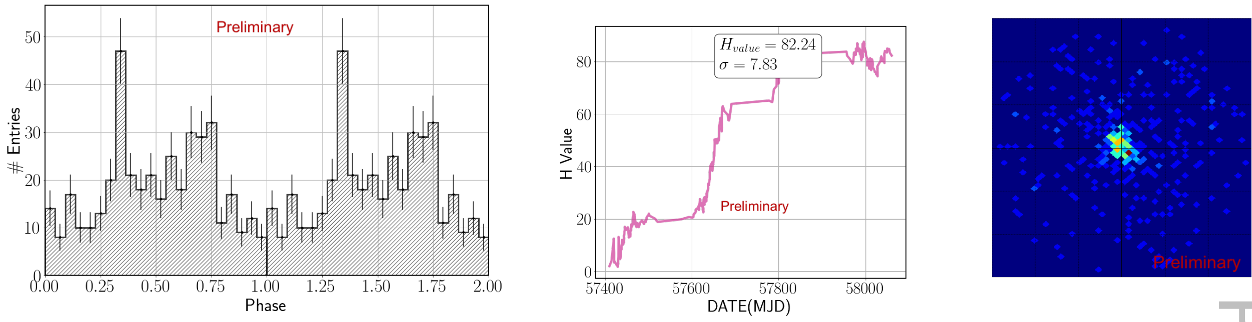
MMS expresses her gratitude to David A. Smith for providing the ephemerides applied for this analysis along with invaluable discussions that have help further this work.

References

[1] A. A. Abdo *et al.* [Fermi-LAT Collaboration], "Fermi LAT Observations of the Vela Pulsar," Astrophys. J. **696**, 1084 (2009) [arXiv:0812.2960 [astro-ph]].

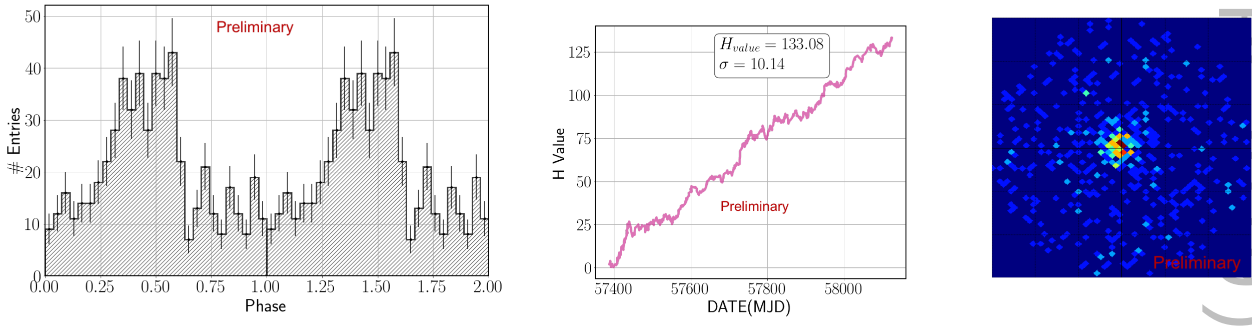
[2] A. A. Abdo *et al.* [Fermi-LAT Collaboration], "Fermi LAT observations of the Geminga pulsar," Astrophys. J. **720**, 272 (2010) [arXiv:1007.1142 [astro-ph.HE]].

[3] A. A. Abdo *et al.*, "PSR J0007+7303 in the CTA1 SNR: New Gamma-ray Results from Two Years of Fermi-LAT Observations," Astrophys. J. **744**, 146 (2012) [arXiv:1107.4151 [astro-ph.HE]].



(a) Phase information (b) H-Test (c) 2D Projection

Figure 5: Results of the Crab (J0534+2200), a) shows its characteristic light curve. b) Plot showing the H-Value progression as a function of time, c) 2D projection of photons detected within a 3° ROI around the pulsar of interest.



(a) Phase information (b) H-Test (c) 2D Projection

Figure 6: Results of the pulsar J0007+7303, a) shows its characteristic light curve. b) Plot showing the H-Value progression as a function of time, c) 2D projection of photons detected within a 3° ROI around the pulsar of interest.

[4] A. A. Abdo *et al.* [Fermi-LAT Collaboration], “The Second Fermi Large Area Telescope Catalog of Gamma-ray Pulsars,” Astrophys. J. Suppl. **208**, 17 (2013) [arXiv:1305.4385 [astro-ph.HE]]

[5] de Jager, O.C, BuÌĹsching, I ”The H-test probability distribution revisited: Improved sensitivity” arxiv.:005.4867

[6] Hobbs, G. B. and Edwards, R. T. and Manchester, R. N., "TEMPO2, a new pulsar-timing package - I. An overview", astro-ph/0603381,

[7] J. Chang *et al.* [DAMPE Collaboration], “The DArk Matter Particle Explorer mission,” arXiv:1706.08453 [astro-ph.IM].

[8] J. P. Halpern, E. V. Gotthelf, F. Camilo, D. J. Helfand and S. M. Ransom, “X-ray, radio, and optical observations of the putative pulsar in the supernova remnant CTA 1,” Astrophys. J. **612**, 398 (2004) [astro-ph/0404312].

[9] Xu, Z.*et al.*, "An algorithm to resolve γ-rays from charged cosmic rays with DAMPE" arxiv.:1712.02939