Preliminary indirect measurement of cosmic-ray proton spectrum using Earth's γ-ray data from *Fermi* Large Area Telescope

Patomporn Payoungkhamdee

Department of Physics, Faculty of Science, Mahidol University

E-mail: patomporn.pay@gmail.com

Abstract. Cosmic rays (CRs) are high-energy particles, mostly protons, propagating in space. The rigidity (momentum per charge) spectrum of CRs is well described by a power law for which the spectral index is approximately 2.8 around 30 - 1000 GV. Recent measurements by PAMELA and AMS-02 indicate an abrupt change of the CR proton spectral index at about 340 GV. When CRs interact with the Earth's upper atmosphere, γ rays can be produced and detected by space-based detectors. Here we use the Earth's γ-ray data collected by the *Fermi* Large Area Telescope along with a proton-air interaction model to indirectly determine the CR proton spectral index and compare against observations by other instruments.

1. Introduction

Cosmic-ray are high energy particle which mainly come from the outer space which can penetrate and interact with the Earth's atmosphere [1, 2, 3]. The shark peak of gamma-ray emission from Earth's limb are mainly come from the interaction of CRs with the atmospheric molecules [4].

There are many possible phenomena of acceleration mechanism in the space that could produce high energy particles. The characteristic of acceleration mechanism could roughly be distinguished by a spectral index in the arrival of cosmic rays spectrum in rigidity. The breaking point of the spectrum mainly come from the overlapped region of acceleration mechanism that could be an evidence to explore a new candidate of cosmic ray source.

In 2011, PAMELA detector indicated that there is a breakpoint of cosmic-ray protons spectrum around 240 GV [5]. Furthermore, AMS-02 also found a drastic change of cosmic-ray proton spectrum at around 336 GV [6]. From the previous work, 5 years of *Fermi* Large Area Telescope (*Fermi*-LAT) observation data has been analyzed to trace back the characteristic of CR proton spectrum where the result imply that there is a breaking of spectral indice around 200 GeV where the statistical significance is around 2σ [7]. In this work, 9 years of *Fermi*-LAT data would be use for finding the spectral indices of CR proton between energy hundred MeV to a TeV range.

2. Methodology

2.1. Data selection and γ-ray flux extraction

Photon data with the latest reconstruction version (P8R2 ULTRACLEANVETO V6) of the telescope where the observation duration takes around 9 years (starts from 7 August 2008 to 16

October 2017). The energy range of photon is selected from 10 GeV to 1 TeV. The upper zone of earth's limb region could be determine by nadir angle from 68.4 to 70.0 where the coordinate figure has demonstrated in figure 1.

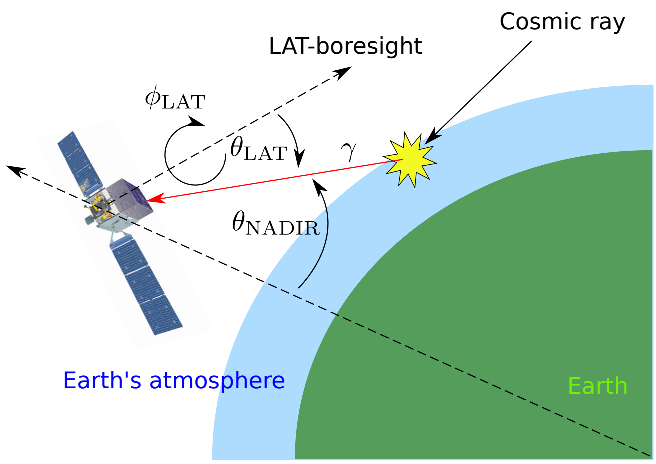

Figure 1. Schematic of γ-ray production

The observed flux is defined as differential flux where the governing equation for the calculation is represented as equation (1)

$$\textbf{Flux} \equiv \frac{dN_\gamma}{dE} = \frac{\int_{\text{Limb region}} (\text{Count map}/\text{Exposure map})}{\Delta\Omega\Delta E} \tag{1}$$

Where count map is filled up with selected γ-ray and exposure map represent the exposure time as well as effective area of spacecraft where the angle of incident CR has taken into account. Procedure of computation is begin with the requirement of 25 bins of histogram of the γ-ray flux which contain a various median of energy in each bin. Consequently, the number of count map and exposure map will be exactly the same as the energy bins. The calculation of exposure map is done by using log file of the spacecraft combine with the responsiveness of the spacecraft which has to be consider in every step time while spacecraft is online. In addition, every step time of spacecraft require the coordinate transformation which cause a huge amount of computing process. That is the reason why paralleling processing with Master-Slave technique is applied in this work.

2.2. Interaction model

Incident CRs is modeled by a single power law (SPL) which contain one spectral indice and broken power law (BPL) where there is two spectral indices with a given breaking energy.

The model for a scattering amplitude from hadronic collision [8] that could produce a photon as a secondary product which could be detected by *Fermi*-LAT as equation 2.

$$\frac{dN_\gamma}{dE_\gamma} \propto \int_{E_\gamma}^{E_{\max}} dE' \frac{dN_p}{dE'} \frac{d\sigma^{pp\to\gamma}(E', E_\gamma)}{dE_\gamma} \tag{2}$$

For the real use case, the interaction of an alphaparticle with the air has a significant contribution to the secondary photon. A modification of He-air interaction could be applied by using a fraction of cross-section from a given atomic number [9]. The helium spectrum in rigidity is taken from the real measurement [10]. Then the input of the modified model is left only a proton spectrum.

$$\frac{dN_\gamma}{dE_\gamma}(E_\gamma) \propto \sum_{E_{\rm inc,i}} \left[\frac{E_{\rm inc,i}}{E_\gamma}\Delta(E_{\rm inc,i})\right] \left[f_{pp}\frac{dN_{\rm H}}{dE_{\rm inc}}(E_{\rm inc,i})\left\{1+\frac{\sigma_{\rm HeN}}{\sigma pN}\left(\frac{dN_{\rm H}}{dR}\right)^{-1}\frac{dN_{\rm He}}{dR}\frac{dR_{\rm He}}{dR_{\rm H}}\right\}\right] \quad (3)$$

2.3. Optimization

Optimizing a problem with multiple parameters might cause a local minimum which will cause an early stopping of the optimization proces before reaching to the global minimum. In this work, a simple gradient optimization with a set of different initial values yield a various output which implicitly imply that there are local minimum exists in this problem. To get rid of the local minimum, particle swarm optimization (PSO) is applied to find the best fit parameters [11].

3. Preliminary Results

The optimized parameters has shown in table 1. According to figure 2, secondary γ-ray product from both SPL and BPL model yield a similar product via hadronic collision in the atmosphere. In order to validate the indirect measurement of CR proton, comparing with a real observations is mandatory which has shown in figure 3. The normalization of this work is fitted PAMELA data to roughly scale the incident proton spectrum.

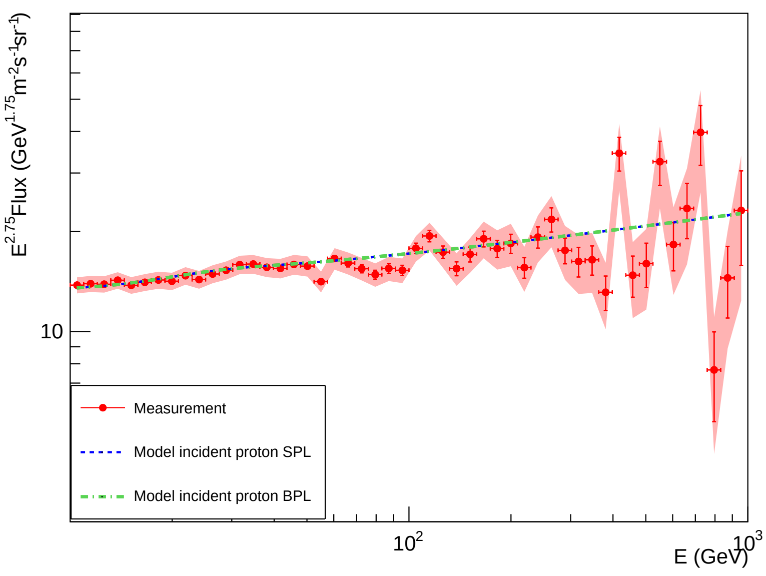

Figure 2. Measured γ-ray flux and the product from incident CRs

Table 1. Best fitted parameters

Proton CR model	Index 1	Index 2	E_{break} (GeV)
SPL	2.70	-	-
BPL	2.86	2.63	333

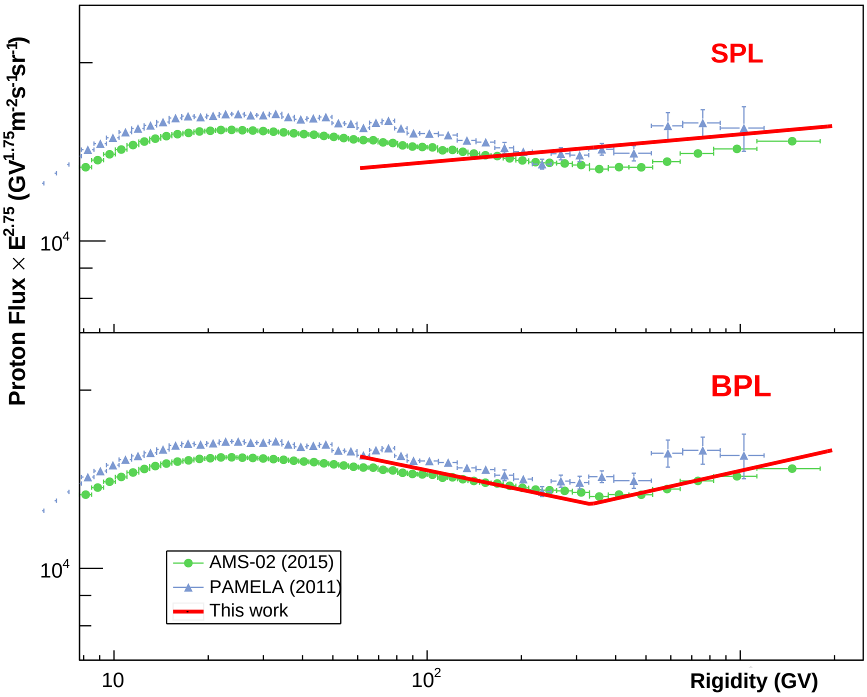

Figure 3. Best fitted proton CRs versus real observations

4. Discussion and future work

From the figure 2, a trend of incident proton model demonstrated that BPL has more consistency than SPL. Nevertheless, to determine the significance between two models require likelihood ratio test to evaluate the statistical level of confidence. In addition, statistical and total error including the instrument will be determined by performing Monte Carlo Simulation.

References

[1] Hess V F 1936 (The Nobel Foundation)

[2] Pacini D 1912 *Il Nuovo Cimento* **3** 93 URL `https://doi.org/10.1007/BF02957440`

[3] Clay J 1927 *Proceedings of the Section of Sciences, Koninklijke Akademie van Wetenschappen te Amsterdam* **30** 1115–1127

[4] Abdo A A, Ackermann M, Ajello M, Atwood W B, Baldini L, Ballet J, Barbiellini G, Bastieri D, Baughman B M, Bechtol K, Bellazzini R, Berenji B, Bloom E D, Bonamente E, Borgland A W, Bouvier A, Bregeon J, Brez A, Brigida M, Bruel P, Buehler R, Burnett T H, Buson S, Caliandro G A, Cameron R A, Caraveo P A, Casandjian J M, Cecchi C, Çelik O, Charles E, Chekhtman A, Chiang J, Ciprini S, Claus R, Cohen-Tanugi J, Conrad J, de Palma F, Digel S W, do Couto e Silva E, Drell P S, Dubois R, Dumora D, Farnier C, Favuzzi C, Fegan S J, Focke W B, Fortin P, Frailis M, Fukazawa Y, Funk S, Fusco P, Gargano F, Gehrels N, Germani S, Giebels B, Giglietto N, Giordano F, Glanzman T, Godfrey G, Grenier I A, Grondin M H, Grove J E, Guillemot L, Guiriec S, Hays E, Horan D, Hughes R E, Jóhannesson G, Johnson A S, Johnson T J, Johnson W N, Kamae T, Katagiri H, Kataoka J, Kawai N, Kerr M, Knödlseder J, Kuss

M, Lande J, Latronico L, Lemoine-Goumard M, Longo F, Loparco F, Lott B, Lovellette M N, Lubrano P, Makeev A, Mazziotta M N, McEnery J E, Meurer C, Michelson P F, Mitthumsiri W, Mizuno T, Monte C, Monzani M E, Morselli A, Moskalenko I V, Murgia S, Nolan P L, Norris J P, Nuss E, Ohsugi T, Okumura A, Omodei N, Orlando E, Ormes J F, Paneque D, Panetta J H, Parent D, Pelassa V, Pepe M, Pesce-Rollins M, Piron F, Porter T A, Rainò S, Rando R, Razzano M, Reimer A, Reimer O, Reposeur T, Rochester L S, Rodriguez A Y, Roth M, Sadrozinski H F W, Sander A, Saz Parkinson P M, Sgrò C, Share G H, Siskind E J, Smith D A, Smith P D, Spandre G, Spinelli P, Strickman M S, Suson D J, Takahashi H, Tanaka T, Thayer J B, Thayer J G, Thompson D J, Tibaldo L, Torres D F, Tosti G, Tramacere A, Uchiyama Y, Usher T L, Vasileiou V, Vilchez N, Vitale V, Waite A P, Wang P, Winer B L, Wood K S, Ylinen T and Ziegler M (Fermi-LAT Collaboration) 2009 *Phys. Rev. D* **80**(12) 122004 URL `https://link.aps.org/doi/10.1103/PhysRevD.80.122004`

[5] Adriani O, Barbarino G C, Bazilevskaya G A, Bellotti R, Boezio M, Bogomolov E A, Bongi M, Bonvicini V, Borisov S, Bottai S, Bruno A, Cafagna F, Campana D, Carbone R, Carlson P, Casolino M, Castellini G, Pascale M P D, Santis C D, Simone N D, Felice V D, Formato V, Galper A M, Grishantseva L, Karelin A V, Koldashov S V, Koldobskiy S, Krutkov S Y, Kvashnin A N, Leonov A, Malakhov V, Marcelli L, Mayorov A G, Menn W, Mikhailov V V, Mocchiutti E, Monaco A, Mori N, Nikonov N, Osteria G, Palma F, Papini P, Pearce M, Picozza P, Pizzolotto C, Ricci M, Ricciarini S B, Rossetto L, Sarkar R, Simon M, Sparvoli R, Spillantini P, Stozhkov Y I, Vacchi A, Vannuccini E, Vasilyev G, Voronov S A, Yurkin Y T, Wu J, Zampa G, Zampa N, Zverev V G, Potgieter M S and Vos E E 2013 *The Astrophysical Journal* **765** 91 URL `http://stacks.iop.org/0004-637X/765/i=2/a=91`

[6] Aguilar M (AMS Collaboration) 2015 *Phys. Rev. Lett.* **114**(17) 171103 URL `https://link.aps.org/doi/10.1103/PhysRevLett.114.171103`

[7] Ackermann M, Ajello M, Albert A, Allafort A, Baldini L, Barbiellini G, Bastieri D, Bechtol K, Bellazzini R, Blandford R D, Bloom E D, Bonamente E, Bottacini E, Bouvier A, Brandt T J, Brigida M, Bruel P, Buehler R, Buson S, Caliandro G A, Cameron R A, Caraveo P A, Cecchi C, Charles E, Chaves R C G, Chekhtman A, Chiang J, Chiaro G, Ciprini S, Claus R, Cohen-Tanugi J, Conrad J, Cutini S, Dalton M, D'Ammando F, de Angelis A, de Palma F, Dermer C D, Digel S W, Di Venere L, do Couto e Silva E, Drell P S, Drlica-Wagner A, Favuzzi C, Fegan S J, Ferrara E C, Focke W B, Franckowiak A, Fukazawa Y, Funk S, Fusco P, Gargano F, Gasparrini D, Germani S, Giglietto N, Giordano F, Giroletti M, Glanzman T, Godfrey G, Gomez-Vargas G A, Grenier I A, Grove J E, Guiriec S, Gustafsson M, Hadasch D, Hanabata Y, Harding A K, Hayashida M, Hayashi K, Hewitt J W, Horan D, Hou X, Hughes R E, Inoue Y, Jackson M S, Jogler T, Jóhannesson G, Johnson A S, Kamae T, Kawano T, Knödlseder J, Kuss M, Lande J, Larsson S, Latronico L, Longo F, Loparco F, Lovellette M N, Lubrano P, Mayer M, Mazziotta M N, McEnery J E, Mehault J, Michelson P F, Mitthumsiri W, Mizuno T, Moiseev A A, Monte C, Monzani M E, Morselli A, Moskalenko I V, Murgia S, Nemmen R, Nuss E, Ohsugi T, Okumura A, Orienti M, Orlando E, Ormes J F, Paneque D, Panetta J H, Perkins J S, Pesce-Rollins M, Piron F, Pivato G, Porter T A, Rainò S, Rando R, Razzano M, Razzaque S, Reimer A, Reimer O, Ritz S, Roth M, Schaal M, Schulz A, Sgrò C, Siskind E J, Spandre G, Spinelli P, Strong A W, Takahashi H, Takeuchi Y, Thayer J G, Thayer J B, Thompson D J, Tibaldo L, Tinivella M, Torres D F, Tosti G, Troja E, Tronconi V, Usher T L, Vandenbroucke J, Vasileiou V, Vianello G, Vitale V, Werner M, Winer B L, Wood K S, Wood M and Yang Z (Fermi LAT Collaboration) 2014 *Phys. Rev. Lett.* **112**(15) 151103 URL `https://link.aps.org/doi/10.1103/PhysRevLett.112.151103`

[8] Kachelrieß M and Ostapchenko S 2012 *Phys. Rev. D* **86**(4) 043004 URL `https://link.aps.org/doi/10.1103/PhysRevD.86.043004`

[9] Atwater T W and Freier P S 1986 *Phys. Rev. Lett.* **56**(13) 1350–1353 URL `https://link.aps.org/doi/10.1103/PhysRevLett.56.1350`

[10] Aguilar M, Aisa D, Alpat B, Alvino A, Ambrosi G, Andeen K, Arruda L, Attig N, Azzarello P, Bachlechner A, Barao F, Barrau A, Barrin L, Bartoloni A, Basara L, Battarbee M, Battiston R, Bazo J, Becker U, Behlmann M, Beischer B, Berdugo J, Bertucci B, Bindi V, Bizzaglia S, Bizzarri M, Boella G, de Boer W, Bollweg K, Bonnivard V, Borgia B, Borsini S, Boschini M J, Bourquin M, Burger J, Cadoux F, Cai X D, Capell M, Caroff S, Casaus J, Castellini G, Cernuda I, Cerreta D, Cervelli F, Chae M J, Chang Y H, Chen A I, Chen G M, Chen H, Chen H S, Cheng L, Chou H Y, Choumilov E, Choutko V, Chung C H, Clark C, Clavero R, Coignet G, Consolandi C, Contin A, Corti C, Gil E C, Coste B, Creus W, Crispoltoni M, Cui Z, Dai Y M, Delgado C, Della Torre S, Demirköz M B, Derome L, Di Falco S, Di Masso L, Dimiccoli F, Díaz C, von Doetinchem P, Donnini F, Duranti M, D'Urso D, Egorov A, Eline A, Eppling F J, Eronen T, Fan Y Y, Farnesini L, Feng J, Fiandrini E, Fiasson A, Finch E, Fisher P, Formato V, Galaktionov Y, Gallucci G, García B, García-López R, Gargiulo C, Gast H, Gebauer I, Gervasi M, Ghelfi A, Giovacchini F, Goglov P, Gong J, Goy C, Grabski V, Grandi D, Graziani M, Guandalini C, Guerri I, Guo K H, Haas D, Habiby M, Haino S, Han K C, He Z H, Heil M, Hoffman J, Hsieh T H, Huang Z C, Huh C, Incagli M, Ionica M, Jang W Y, Jinchi H, Kanishev K, Kim G N, Kim K S, Kirn T, Korkmaz M A, Kossakowski

R, Kounina O, Kounine A, Koutsenko V, Krafczyk M S, La Vacca G, Laudi E, Laurenti G, Lazzizzera I, Lebedev A, Lee H T, Lee S C, Leluc C, Li H L, Li J Q, Li J Q, Li Q, Li Q, Li T X, Li W, Li Y, Li Z H, Li Z Y, Lim S, Lin C H, Lipari P, Lippert T, Liu D, Liu H, Liu H, Lolli M, Lomtadze T, Lu M J, Lu S Q, Lu Y S, Luebelsmeyer K, Luo F, Luo J Z, Lv S S, Majka R, Mañá C, Marín J, Martin T, Martínez G, Masi N, Maurin D, Menchaca-Rocha A, Meng Q, Mo D C, Morescalchi L, Mott P, Müller M, Nelson T, Ni J Q, Nikonov N, Nozzoli F, Nunes P, Obermeier A, Oliva A, Orcinha M, Palmonari F, Palomares C, Paniccia M, Papi A, Pauluzzi M, Pedreschi E, Pensotti S, Pereira R, Picot-Clemente N, Pilo F, Piluso A, Pizzolotto C, Plyaskin V, Pohl M, Poireau V, Putze A, Quadrani L, Qi X M, Qin X, Qu Z Y, Räihä T, Rancoita P G, Rapin D, Ricol J S, Rodríguez I, Rosier-Lees S, Rozhkov A, Rozza D, Sagdeev R, Sandweiss J, Saouter P, Schael S, Schmidt S M, von Dratzig A S, Schwering G, Scolieri G, Seo E S, Shan B S, Shan Y H, Shi J Y, Shi X Y, Shi Y M, Siedenburg T, Son D, Song J W, Spada F, Spinella F, Sun W, Sun W H, Tacconi M, Tang C P, Tang X W, Tang Z C, Tao L, Tescaro D, Ting S C C, Ting S M, Tomassetti N, Torsti J, Türkoğlu C, Urban T, Vagelli V, Valente E, Vannini C, Valtonen E, Vaurynovich S, Vecchi M, Velasco M, Vialle J P, Vitale V, Vitillo S, Wang L Q, Wang N H, Wang Q L, Wang R S, Wang X, Wang Z X, Weng Z L, Whitman K, Wienkenhöver J, Willenbrock M, Wu H, Wu X, Xia X, Xie M, Xie S, Xiong R Q, Xu N S, Xu W, Yan Q, Yang J, Yang M, Yang Y, Ye Q H, Yi H, Yu Y J, Yu Z Q, Zeissler S, Zhang C, Zhang J H, Zhang M T, Zhang S D, Zhang S W, Zhang X B, Zhang Z, Zheng Z M, Zhuang H L, Zhukov V, Zichichi A, Zimmermann N and Zuccon P (AMS Collaboration) 2015 *Phys. Rev. Lett.* **115**(21) 211101 URL `https://link.aps.org/doi/10.1103/PhysRevLett.115.211101`

[11] Kennedy J and Eberhart R 1995 *Proceedings of ICNN'95 - International Conference on Neural Networks* vol 4 pp 1942–1948 vol.4