Study of cosmic-ray spectrum using γ-ray data from *Fermi* Large Area Telescope (*Fermi*-LAT)

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15 July 2018

Overview

What are cosmic rays

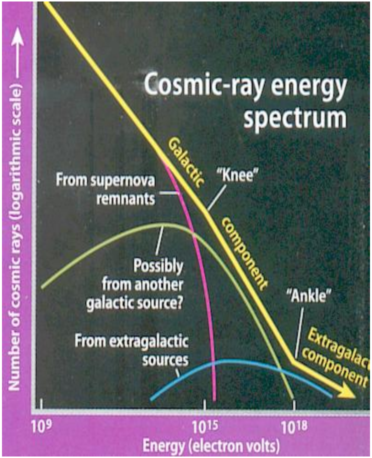


Figure: Cosmic ray feature : retrieved from universe-review.ca

- A high-energy particles that travelling through space
- **Criteria :** When we call flux it means differential flux
- **Feature :** CRs spectrum in rigidity follow power law
- Discontinuity in spectrum came from superposition of different acceleration mechanism

Trend in cosmic ray research

In 2015, the AMS collaboration claims that there is a broken in cosmic ray proton spectrum around 336 GV.

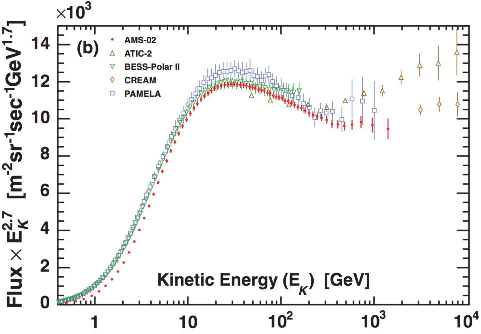
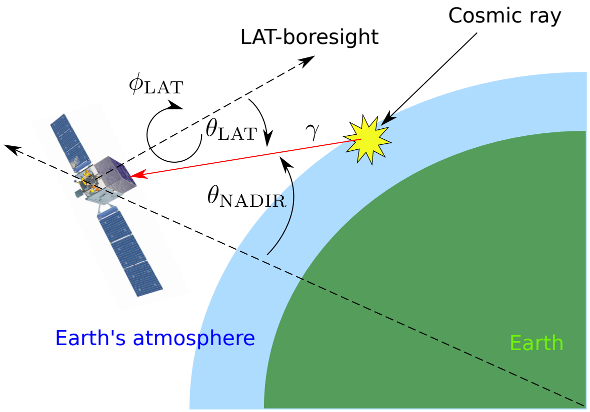


Figure: Cosmic rays proton flux : retrieved from M. Aguilar et al. (2015)

Objective

- Want to measure cosmic ray proton spectrum in range GV by using γ-ray data from *Fermi*-LAT through Kachelrieβ and Ostapchenko model
- Some intruments claim that cosmic ray proton spectrum has discontinuity around 200-350 GV , then if our result agree with other intruments. Space might have another acceleration mechanism that people did not know very well.

Schematics of limb γ-ray production



Data selection

- P8R2_ULTRACLEANVETO_V6 data from 07/08/2008 to 28/01/2015 (∼7 years)
- Collect photon energy range from 10 GeV up to 1 TeV
- $\theta_{\mathrm{NADIR}} \in 68.4^\circ$ - 70° (Earth's limb)
- Use $\theta_{\mathrm{LAT}} < 70^\circ$

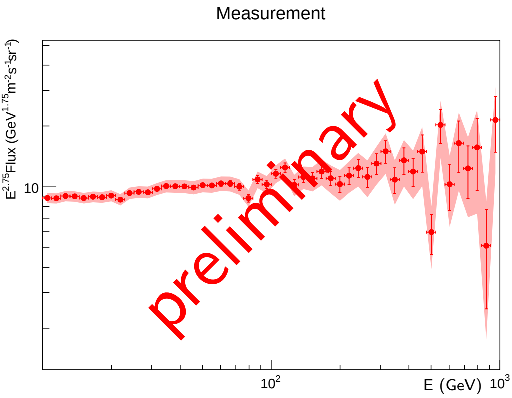
Calculation method

1. Make 2D histogram as much as energy bin that we want
2. Select photon data and fill in the 2D histogram
3. Calculate exposure maps which incldue effective area and time that LAT view can looking at Earth's limb

   $$\textbf{Flux} = \frac{dF}{dE} = \frac{\int_{\text{Limb region}} (\text{Count map}/\text{Exposure map})}{\Delta\Omega\Delta E}$$

4. Divide every single grid of couple histogram (count map and exposure map)
5. Sum over limb region of this map then divided by solidangle and energy bin width
6. Now we got γ-ray flux

γ-ray spectrum from measurement



Notice that error bar came from statistics error and the red band already take into account instrument error

Power law (in rigidity)

Typically, cosmic ray spectrum follow power law in rigidity as

Single power law (SPL)

$$\frac{dN}{dR} = R_0 R^{-\gamma} \tag{1}$$

Broken power law (BPL)

$$\frac{dN}{dR} = \begin{cases} R_0 R^{-\gamma_1} & : \ E < E_{\text{Break}} \\ R_0 [R(E_{\text{Break}})]^{\gamma_2 - \gamma_1} R^{-\gamma_2} & : \ E \geq E_{\text{Break}} \end{cases} \tag{2}$$

Note for someone who not familiar with rigidity : it just defined by $R \equiv P/q$ when P, q is a momentum and charge of particle

Kachelrieβ and Ostapchenko model

Is the model which can compute spectrum of γ-ray from a known incident proton

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

- Red color terms is using for incident proton spectrum
- Use helium spectrum from AMS-02 measurement (2015)
- $f_{pp} \equiv E_\gamma (d\sigma^{pp\to\gamma}/dE_\gamma)$ is a table in K&O model which behave like a scattering amplitude that depend on the energy of incident particle
- Crossection $\sigma_{\mathrm{HeN}}/\sigma_{pN}$ at high energy ($>$ 10GeV) is almost remain constant (≈ 1.6)

Poisson likelihood function

On the previous slide, we want to find the incident proton.
Let define some loss function to compare model and measurement

$$\mathcal{L} = \prod_{i=1}^{N} P_{\text{pois}}(n_{\text{i,model}}, n_{\text{i,measurement}}) \tag{4}$$

For numerically convenient, redefined into logarithmic form

$$\log \mathcal{L} \equiv \sum_{i=1}^{N} -\log P_{\text{pois}}(n_{\text{i,model}}, n_{\text{i,measurement}}) \tag{5}$$

This part is the hard work of computer to find best incident cosmic ray proton that match the spectrum from measurement.

Algorithm

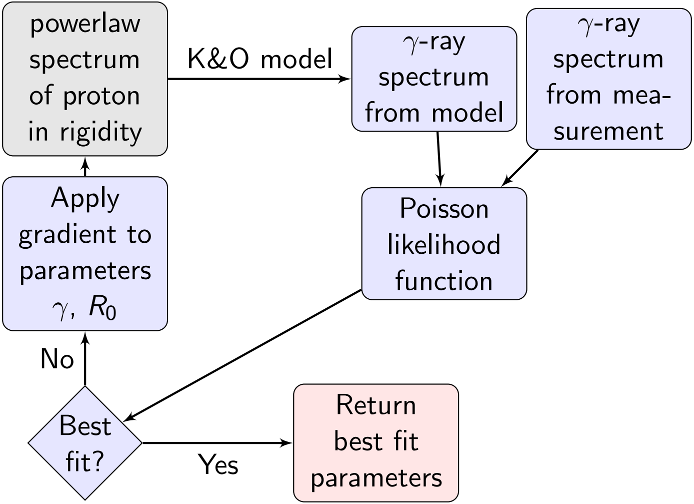


Figure: Flow chart of optimization process

Results

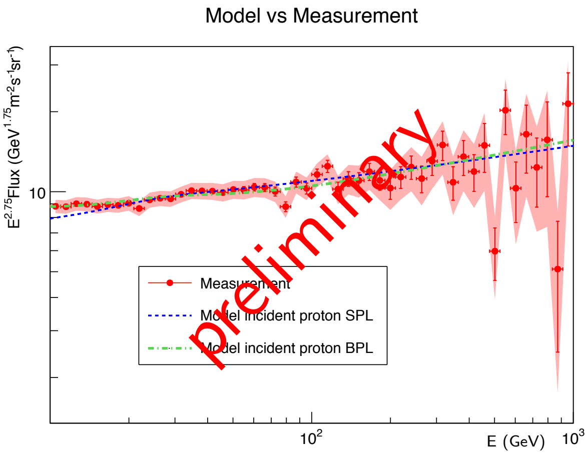
Best fits	γ_1	γ_2	E_{Break} (GeV)
SPL	$2.68 \pm 0.01(0.03)$	-	-
BPL	$2.84 \pm 0.04(0.06)$	$2.64 \pm 0.04(0.17)$	$328 \pm 151(267)$

Table: Optimization results

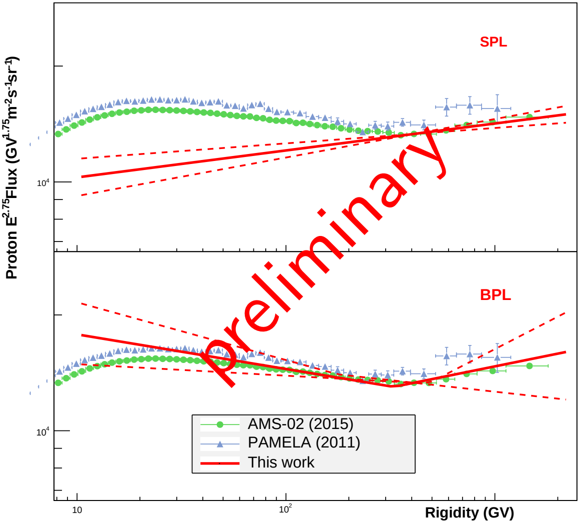
- Likelihood Ratio Test (LRT) $\Rightarrow$ BPL better than SPL with a significant level of 3.3σ

Where 1σ of systematic error and total error (take into account instrumental error) was shown in the table consequently.
Notice that error of parameters came from Monte Carlo Simulation

γ-ray spectrum



Proton spectrum



Conclusion

- We found an energy break point around 328 GeV with a significant level of 3.3σ which agree with other measurement
- Put weight on the previous study [M. Ackermann et al. (2014)] that we could take a benefit of brightness γ-ray from Earths high atmosphere to indirectly observe cosmic ray spectrum which cause it's luminosity

References

[1] O. Adriani et al., Science 332, 69 (2011) [2] M. Ackermann et al. (Fermi LAT Collaboration), Phys. Rev. Lett. 112, 151103
[3] Kachelriess & Ostapchenko, Phys. Rev. D 86
[4] M. Aguilar et al. (AMS Collaboration), Phys. Rev. Lett. 115, 211101
[5] M. Aguilar et al. (AMS Collaboration), Phys. Rev. Lett. 114, 171103
[6] L. Lyons, Statistics for nuclear and particle physicists

Acknowledgement

- Dr. Warit Mitthumsiri
  Mahidol University, Thailand
- Dr. Francesca Spada
  University of Pisa, Italy
- People in the Space Physics laboratory at Mahidol University and the Fermi lab at the University of Pisa
- Development and Promotion of Science and Technology Talents Project (DPST)
- Partially supported by the Thailand Research Fund Award RTA5980003

Backup slide

Power law in energy

In our case, we use power in energy then we need to convert by relativistic energy-mass relation

Single power law (SPL)

$$\frac{dN}{dE} = N_0[E_k(E_k + 2m_p)]^{-\gamma/2}\left(\frac{E_k + m_p}{\sqrt{E_k(E_k + 2m_p)}}\right) \tag{6}$$

Broken power law (BPL)

$$\frac{dN}{dE} = \begin{cases} N_0[E_k(E_k + 2m_p)]^{-\gamma_1/2}\left(\frac{E_k+m_p}{\sqrt{E_k(E_k+2m_p)}}\right) & : \ E < E_{\mathrm{Break}} \\ N_0[E_b(E_b + 2m_p)]^{(\gamma_2-\gamma_1)/2}[E_k(E_k + 2m_p)]^{-\gamma_2/2}\left(\frac{E_k+m_p}{\sqrt{E_k(E_k+2m_p)}}\right) \\ : \ E \geq E_{\mathrm{Break}} \end{cases} \tag{7}$$

Error determination

Statictical error (Random error)

1. Get back to raw count and random new count in each energy bin by Poisson random function
2. Recalculate proton spectrum
3. Optimize it and store the parameter that we got
4. do it over thoundsand time and fill in histogram to interpret error by saying sigma of gaussian function

Total error (take into account instrument)

1. Get back to raw count and random new count in each energy bin by Poisson random function
2. Random value we got again by systematic error (Apparatus)
3. Recalculate proton spectrum
4. Optimize it and store the parameter that we got
5. do it over thoundsand time and fill in histogram to interpret error by saying sigma of gaussian function

Monte Carlo Simulation

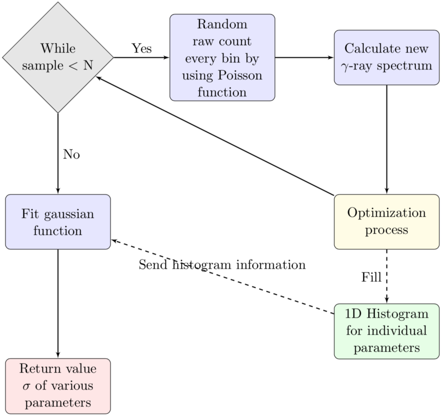


Figure: Statictical error determination

Monte Carlo Simulation

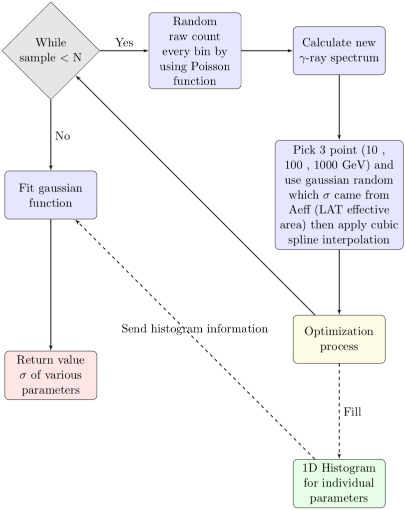
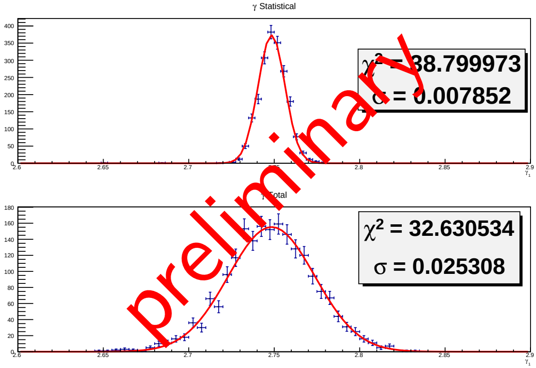
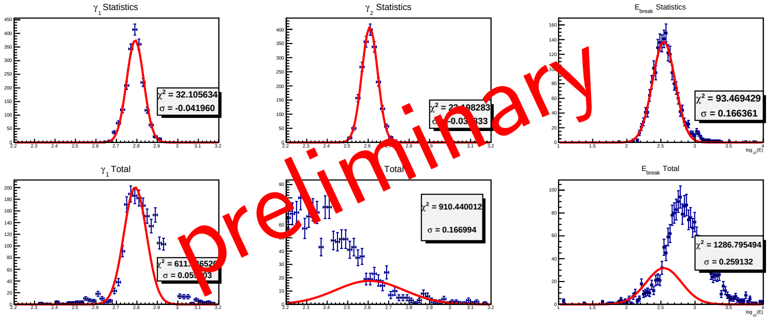


Figure: Total error determination

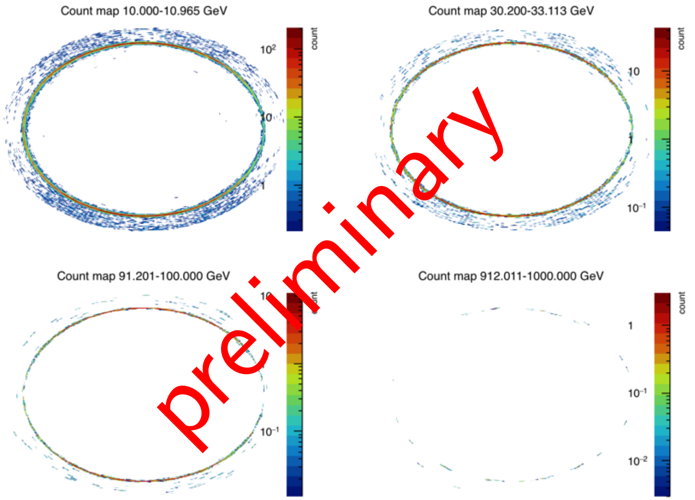
Single power law (SPL)



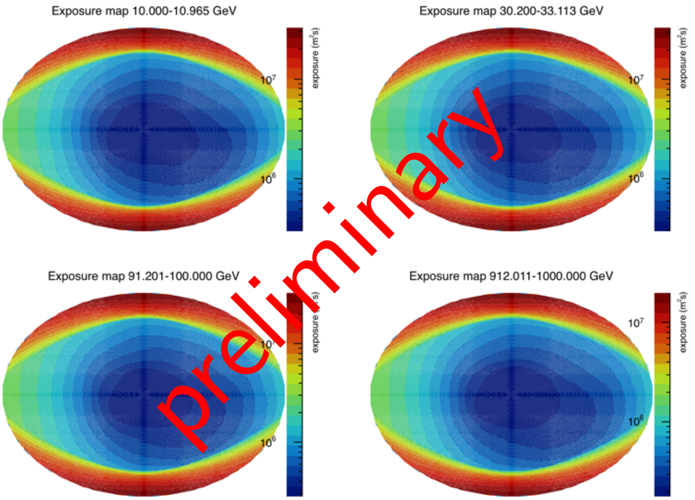
Broken power law (BPL)



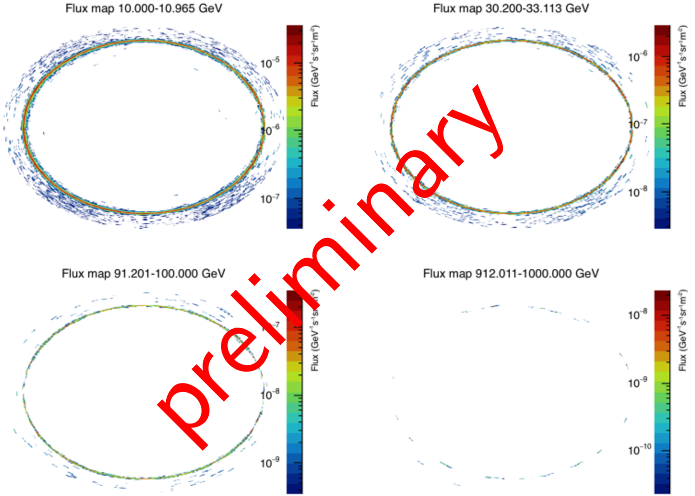
Count map


Count map 10.000-10.965 GeV
Count map 30.200-33.113 GeV
Count map 91.201-100.000 GeV
Count map 912.011-1000.000 GeV
count
10^2
10
1
10^{-1}
10^{-2}
preliminary

Exposure map



Flux map


Flux map 10.000-10.965 GeV
10^{-5}
10^{-6}
10^{-7}
Flux (GeV^{-1}s^{-1}sr^{-1}m^{-2})
Flux map 30.200-33.113 GeV
10^{-6}
10^{-7}
10^{-8}
Flux (GeV^{-1}s^{-1}sr^{-1}m^{-2})
Flux map 91.201-100.000 GeV
10^{-8}
10^{-9}
Flux map 912.011-1000.000 GeV
10^{-8}
10^{-9}
10^{-10}
Flux (GeV^{-1}s^{-1}sr^{-1}m^{-2})
preliminary