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

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Overview

What are cosmic rays

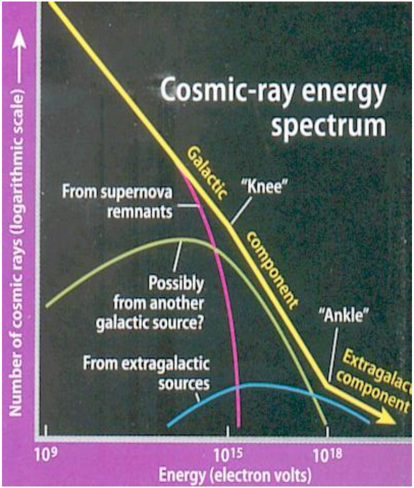


Figure: Cosmic ray feature : retrieved from universe-review.ca

- A high-energey 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

Previous study

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

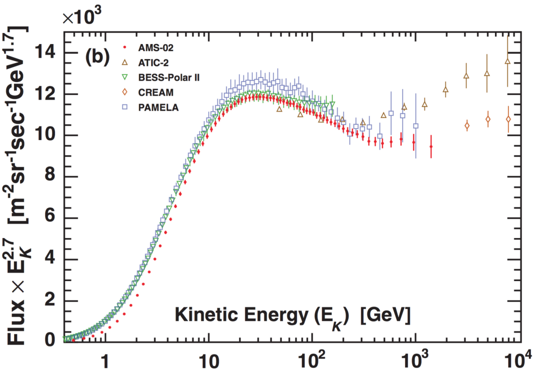
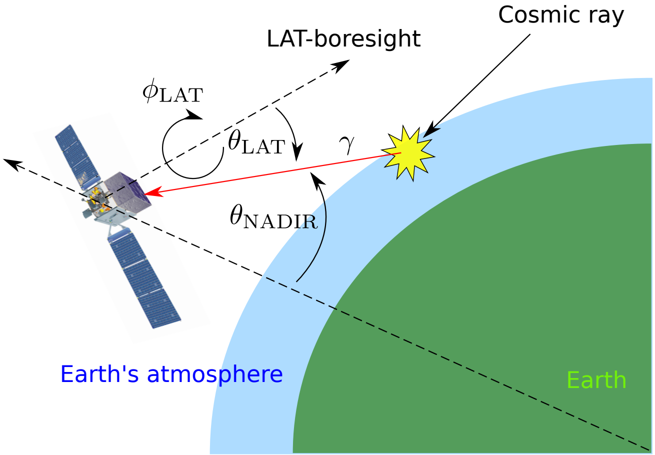


Figure: Cosmic rays proton flux : retrieved from M. Aguilar et al. (2015)

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 340 GV , then if our result agree with other intruments. There might be another acceleration mechanism that not widely known well.

Schematics of limb γ-ray production



Data selection

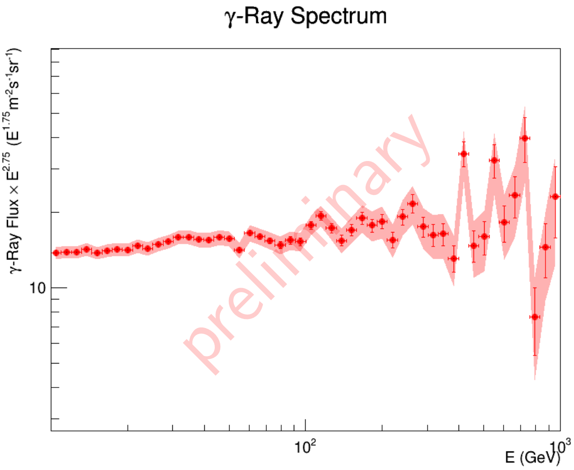
- P8R2_ULTRACLEANVETO_V6 data from 07/08/2008 to 17/10/2017 ($\sim$9 years)
- Collect photon energy range from 10 GeV up to 1 TeV
- $\theta_{\mathrm{NADIR}} \in 68.4^\circ$ - 70° (Earth's limb)
- Use $\theta_{\mathrm{LAT}} < 70^\circ$

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



Error bar show statistics error and red band including 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

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

For numerically convenient, redefined into logarithmic form

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

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

Particle Swarm Optimization

For every iteration k, particle i move with velocity v_k^i where

$$v_{k+1}^i = \omega v_k^i + c^b r_k^b [b_k^i - x_k^i] + c^B r_k^B [B_k^i - x_k^i] \tag{6}$$

Update the new state of particle i with

$$x_{k+1}^i = x_k^i + v_{k+1}^i \tag{7}$$

where

- x_k^i represent variable that particle i hold
- b and B are best local and global parameter set along the optimization process
- Set $\omega = 0.2$, $c^b = 0.2$ and $c^B = 0.3$

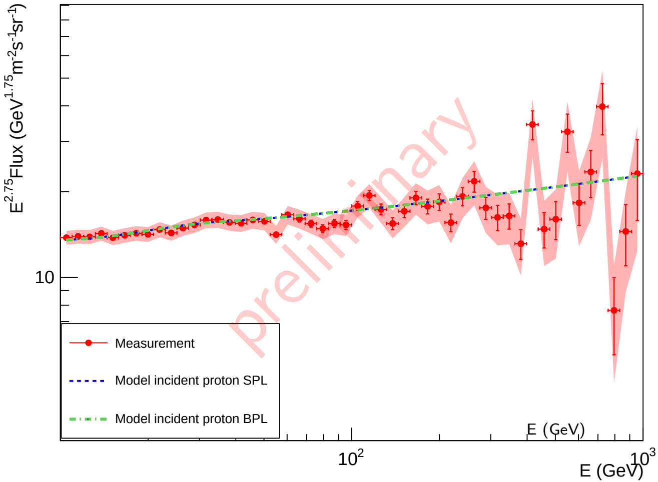
The iteration process would stop when standard deviation of fitness over any partilcle less than 0.1

Results

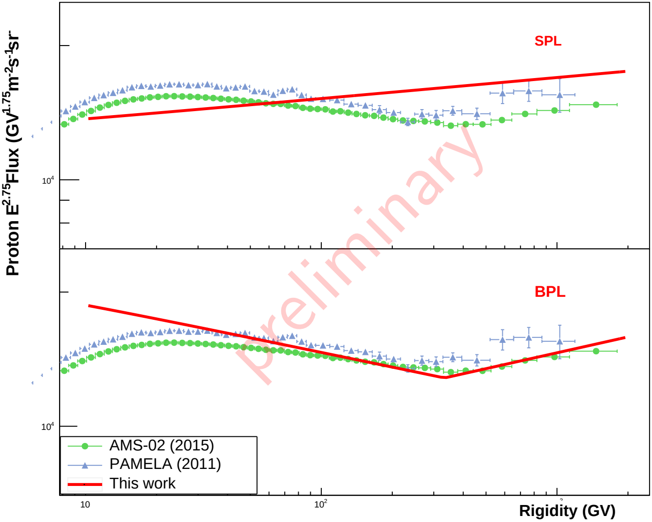
Best fits	γ_1	γ_2	E_{Break} (GeV)
SPL	2.70	-	-
BPL	2.86	2.63	333

Table: Optimization results

γ-ray spectrum



Proton spectrum



Future work

- Find the statistical significance
- Determine paramters error by performing a Monte Carlo Simulation

References

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[4] M. Aguilar et al. (AMS Collaboration), Phys. Rev. Lett. 115, 211101
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[6] L. Lyons, Statistics for nuclear and particle physicists

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Backup slide

Power law in energy

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

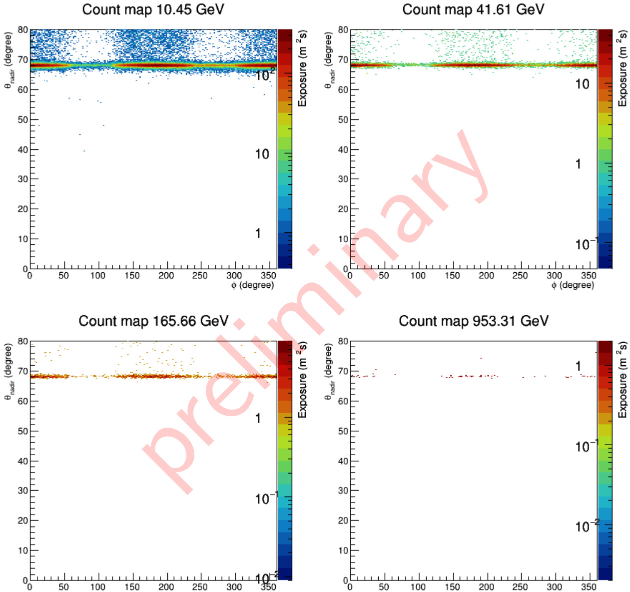
Single power law (SPL)

$$\frac{dN}{dE} = N_0[E_k(E_k + 2m_p)]^{-\gamma/2}\left(\frac{E_k + m_p}{\sqrt{E_k(E_k + 2m_p)}}\right) \tag{8}$$

Broken power law (BPL)

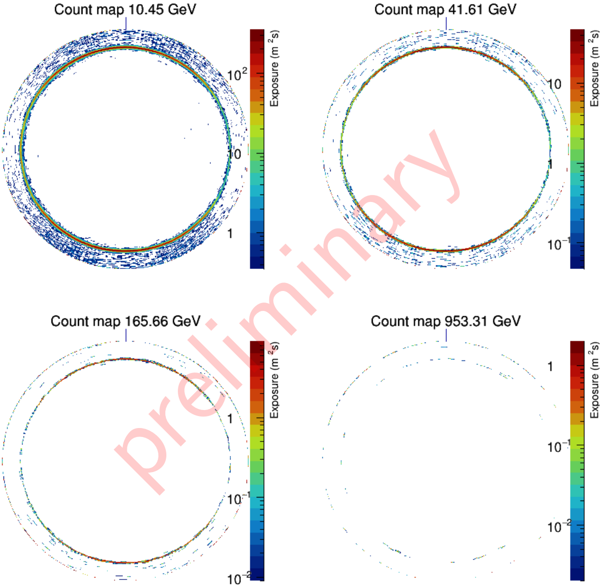
$$\frac{dN}{dE} = \begin{cases} N_0[E_k(E_k + 2m_p)]^{-\gamma_1/2}\left(\frac{E_k+m_p}{\sqrt{E_k(E_k+2m_p)}}\right) & : \; E < E_{\text{Break}} \\ N_0[E_b(E_b + 2m_p)]^{(\gamma_2-\gamma_1)/2}[E_k(E_k + 2m_p)]^{-\gamma_2/2}\left(\frac{E_k+m_p}{\sqrt{E_k(E_k+2m_p)}}\right) \\ : \; E \geq E_{\text{Break}} \end{cases} \tag{9}$$

Count map



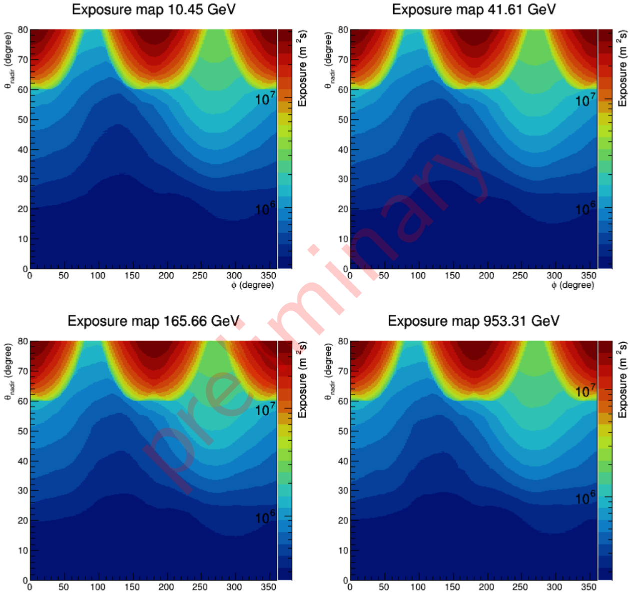
Count map 10.45 GeV
Count map 41.61 GeV
Count map 165.66 GeV
Count map 953.31 GeV
θ_{nadir} (degree)
ϕ (degree)
Exposure ($m^2 s$)
preliminary

Count map

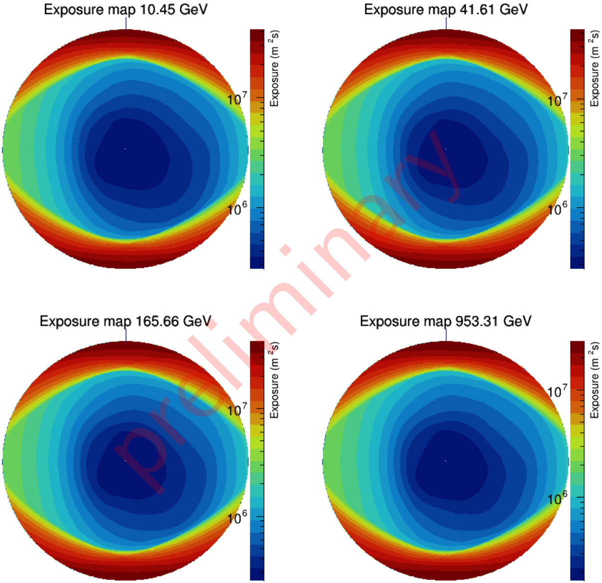


Count map 10.45 GeV
Exposure (m^{2}s)
10^2
10
1
Count map 41.61 GeV
Exposure (m^{2}s)
10
1
10^{-1}
Count map 165.66 GeV
Exposure (m^{2}s)
1
10^{-1}
10^{-2}
Count map 953.31 GeV
Exposure (m^{2}s)
1
10^{-1}
10^{-2}
preliminary

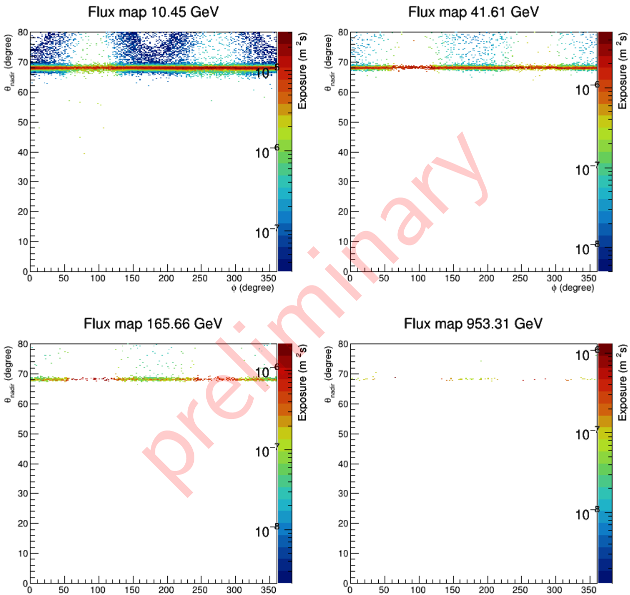
Exposure map



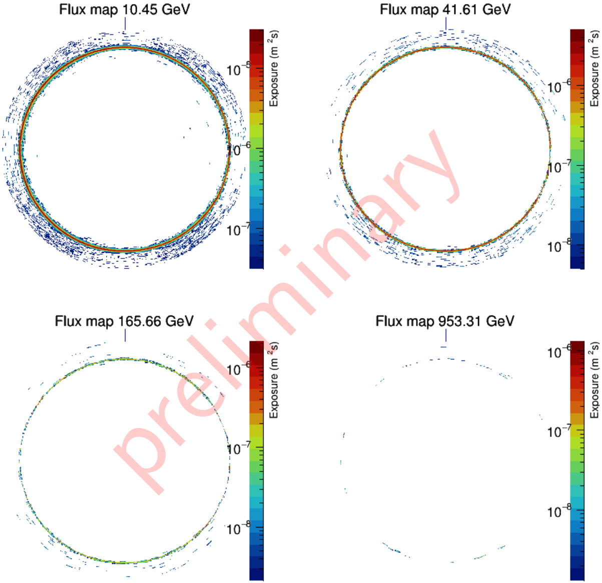
Exposure map



Flux map


Flux map 10.45 GeV
Flux map 41.61 GeV
Flux map 165.66 GeV
Flux map 953.31 GeV
θ_{nadir} (degree)
ϕ (degree)
Exposure ($m^2 s$)
preliminary

Flux map



Flux map 10.45 GeV
Flux map 41.61 GeV
Flux map 165.66 GeV
Flux map 953.31 GeV
Exposure (m^{2}s)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
preliminary