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

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Overview

Objective

- To measure CR proton spectrum between 60 GV - 2 TV using Earth's γ-ray data from *Fermi*-LAT through the interaction model by Kachelriess and Ostapchenko [2012]
- To test if the *Fermi*-LAT data to confirm the spectral break at around 340 GV as observed by some experiments

What are CRs

- High energy particles in space
- **Feature :** CR rigidity spectrum can be described well by power law (Flux $\propto$ Rigidity$^{-\text{index}}$)
- Changes of power-law indices may involve the superposition of different acceleration or propagation mehcanisms

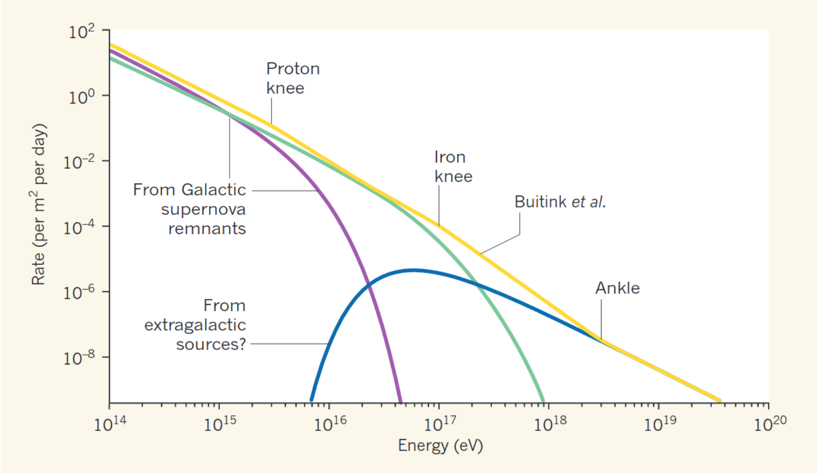


Figure: CR spectrum (figure from Taylor [2016])

Previous study

- In 2011, PAMELA claimed to discover a break in CR proton spectrum at around 300 GV. [Adriani et al., 2011]
- In 2014, *Fermi* LAT found some hint of this break though the results were inconclusive. [Ackermann et al., 2014]
- In 2015, the AMS-02 comfirmed this break.

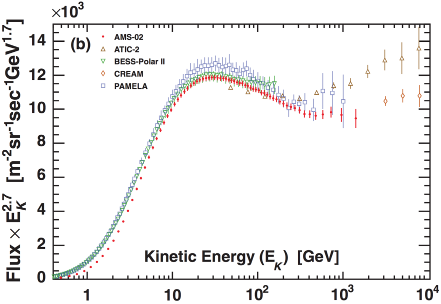
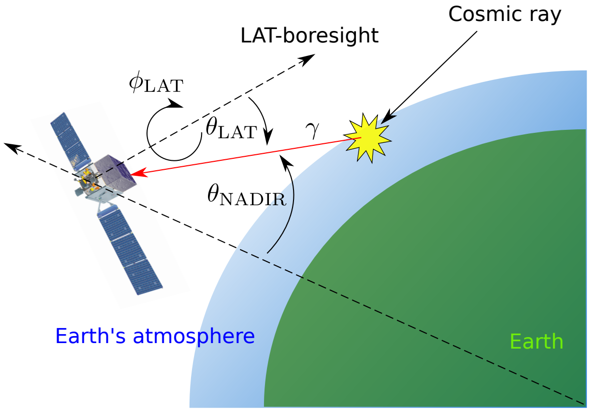


Figure: CR proton flux from Aguilar et al. [2015]

Earth's limb γ-ray production



Data selection

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

Flux calculation method

1. Analyze 50 bins in energy with equal logarithmic spacing between 10 GeV - 1 TeV
2. Create 2D histogram count maps from photon data for each energy bin
3. Create 2D histogram exposure maps (effective area $\times$ livetime) from spacecraft data for each energy bin
4. Calculate the Earth's γ-ray flux using the count and exposure maps by

$$\mathbf{Flux}(E_i) = \frac{dN}{dE}(E_i) = \left(\sum_{\text{pixel}} \frac{\text{Count}_i}{\text{Exposure}_i} \right) \frac{1}{\Delta\Omega\Delta E}$$

where $\Delta\Omega$ is the solid angle size of the Earth's limb region, ΔE is the energy bin width, and i is the ith energy bin.

Coordinate Transformations

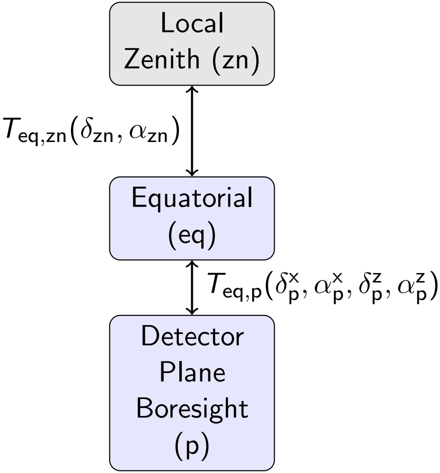
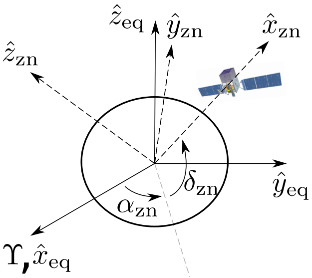


Figure: Three reference frames

where

- **Local zenith (zn)**: x-axis points to LAT's zenith, z-axis to Earth's North
- **Equatorial (eq)**: z-axis points along Earth's rotation axis, x-axis towards the vernal equinox
- **Detector plane bore sight (p)**: z-axis points along LAT's boresight, x-axis along one solar panel

Coordinate Transformation: zn-eq



Transformation matrix could be extracted from the relation

$$\hat{r}_{\rm zn} \equiv T_{\rm eq\to zn}(\delta_{\rm zn}, \alpha_{\rm zn})\hat{r}_{\rm eq}$$

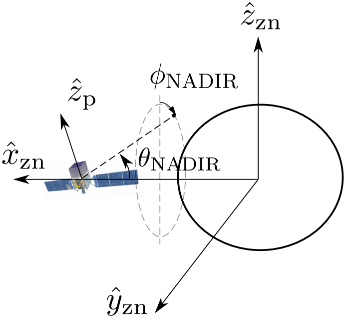
Write a unit vector of orbiting spacecraft on the basis of equatorial coordinate

$$\hat{x}_{\rm zn} = \cos\delta_{\rm zn}\cos\alpha_{\rm zn}\hat{x}_{\rm eq} + \cos\delta_{\rm zn}\sin\alpha_{\rm zn}\hat{y}_{\rm eq} + \sin\delta_{\rm zn}\hat{z}_{\rm eq}$$

$$\hat{z}_{\rm zn} = -\sin\delta_{\rm zn}\cos\alpha_{\rm zn}\hat{x}_{\rm eq} - \sin\delta_{\rm zn}\sin\alpha_{\rm zn}\hat{y}_{\rm eq} + \cos\delta_{\rm zn}\hat{z}_{\rm eq}$$

$$\hat{y}_{\rm zn} = \hat{z}_{\rm zn} \times \hat{x}_{\rm zn}.$$

Coordinate Transformation: p-eq



Transformation matrix is defined as

$$\hat{r}_{\rm p} \equiv T_{\rm eq\to p}(\delta^{\rm x}_{\rm p}, \alpha^{\rm x}_{\rm p}, \delta^{\rm z}_{\rm p}, \alpha^{\rm z}_{\rm p})\hat{r}_{\rm eq}$$

Then

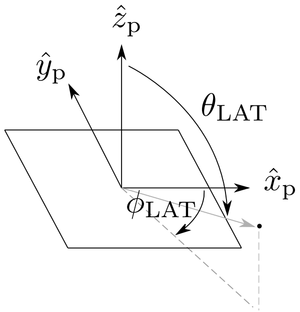
$$\hat{r}_{\rm zn}(\theta_{\rm NADIR}, \phi_{\rm NADIR}) \equiv -\cos\theta_{\rm NADIR}\hat{x}_{\rm zn} + \sin\theta_{\rm NADIR}\cos\phi_{\rm NADIR}\hat{z}_{\rm zn} + \sin\theta_{\rm NADIR}\sin\phi_{\rm NADIR}\hat{y}_{\rm zn}$$

$$\hat{x}_{\rm p} = \cos\delta^{\rm x}_{\rm p}\cos\alpha^{\rm x}_{\rm p}\hat{x}_{\rm eq} + \cos\delta^{\rm x}_{\rm p}\sin\alpha^{\rm x}_{\rm p}\hat{y}_{\rm eq} + \sin\delta^{\rm x}_{\rm zn}\hat{z}_{\rm eq}$$

$$\hat{z}_{\rm p} = \cos\delta^{\rm z}_{\rm p}\cos\alpha^{\rm z}_{\rm p}\hat{x}_{\rm eq} + \cos\delta^{\rm z}_{\rm p}\sin\alpha^{\rm z}_{\rm p}\hat{y}_{\rm eq} + \sin\delta^{\rm z}_{\rm zn}\hat{z}_{\rm eq}$$

$$\hat{y}_{\rm p} = \hat{z}_{\rm p} \times \hat{x}_{\rm p}$$

Coordinate Transformation: Compact formula



$$\hat{r}_{\mathsf{p}}(\theta_{\mathsf{NADIR}}, \phi_{\mathsf{NADIR}}) = T_{\mathsf{eq}\to\mathsf{p}}(\delta^{\mathsf{x}}_{\mathsf{p}}, \alpha^{\mathsf{x}}_{\mathsf{p}}, \delta^{\mathsf{z}}_{\mathsf{p}}, \alpha^{\mathsf{z}}_{\mathsf{p}}) \times [T_{\mathsf{eq}\to\mathsf{zn}}(\delta_{\mathsf{zn}}, \alpha_{\mathsf{zn}})]^{-1} \, \hat{r}_{\mathsf{zn}}(\theta_{\mathsf{NADIR}}, \phi_{\mathsf{NADIR}})$$

Exposure calculation: procedures

Given a spacecraft log file (FT2) where it contains a row-like of the telescope status. The calculation steps are

- Pick a row in FT2
- Compute transformation matrices
- Mapping each nadir cell to the plane of detector
- Computes exposure time $\times$ effective area

Then iterate this process for all records from a selected timeframe.

Exposure calculation: parallel computing

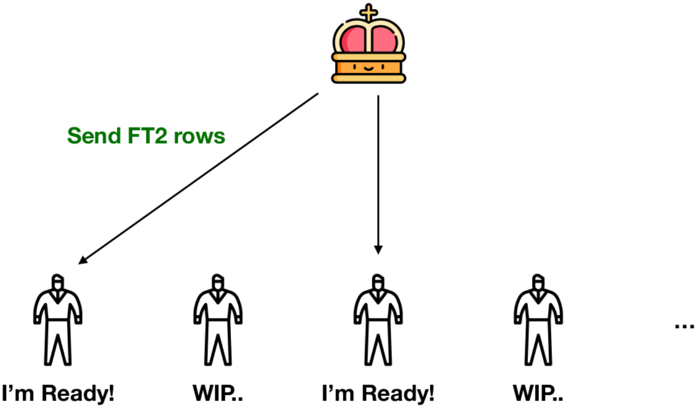


Figure: Demonstrations of Master-Slave technique. WIP stands for working in progress.

Power-law models (in rigidity)

We use 2 models of CR proton to fit the Earth's γ-ray data:

Single power law (SPL)

$$\frac{dN}{dR} = R_0 R^{-\Gamma}$$

Broken power law (BPL)

$$\frac{dN}{dR} = \begin{cases} R_0 R^{-\Gamma_1} & : \; E < E_{\mathrm{Break}} \\ R_0 [R(E_{\mathrm{Break}})]^{\Gamma_2 - \Gamma_1} R^{-\Gamma_2} & : \; E \geq E_{\mathrm{Break}} \end{cases}$$

Rigidity is defined by $R \equiv P/q$ where P is the momentum and q is the absolute value of the charge (in unit of proton charge) of a particle

Kachelrieβ and Ostapchenko model

This model can compute the γ-ray spectrum from a broad and smooth power-law spectrum of CR protons

$$\frac{dN_\gamma}{dE_\gamma} \propto \sum_{E_i'} \left[\frac{E_i'}{E_\gamma}\Delta(\ln E_i')\right]\left[f_{pp}\frac{dN_p}{dE_i'}\left\{1+\frac{\sigma_{\mathrm{HeN}}}{\sigma_{pN}}\left(\frac{dN_p}{dR}\right)^{-1}\frac{dN_{\mathrm{He}}}{dR}\frac{dR_{\mathrm{He}}}{dR_p}\right\}\right]$$

- Red color terms are for incident proton spectrum
- Blue color term is the He spectrum from AMS-02 (2015)
- $f_{pp} \equiv E_\gamma(d\sigma^{pp\to\gamma}/dE_\gamma)$ is the interaction cross section table in the K&O model [Kachelriess and Ostapchenko, 2012]
- The cross-section ratio $\sigma_{\mathrm{HeN}}/\sigma_{pN}$ at high energy ($>$ 10GeV) is roughly constant (≈ 1.6) [Atwater and Freier, 1986]

Poisson likelihood function

We determine the incident proton spectrum that best fits the γ-ray masurement using the maximum likelihood (or minimum log likelihood) method

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

where P_{pois} is the Poisson probability of measuring $n_{\mathrm{i,measurement}}$ counts when the model predicts $n_{\mathrm{i,model}}$ counts for N energy bins

Fitting algorithm: Particle Swarm Optimization

- Randomly initiate many particles in a given range of the parameter space
- Check global and local best particle from a defined profit function
- The rest of them move toward the global and local particles
- Iterate the process until most of them yield nearly the same profit

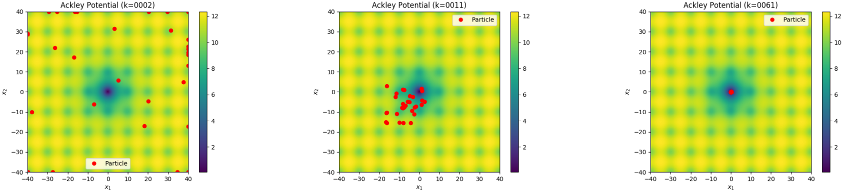


Figure: Example of particles in parameter space of Ackley potential

Particle Swarm Optimization

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

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

Update the new state of particle i with

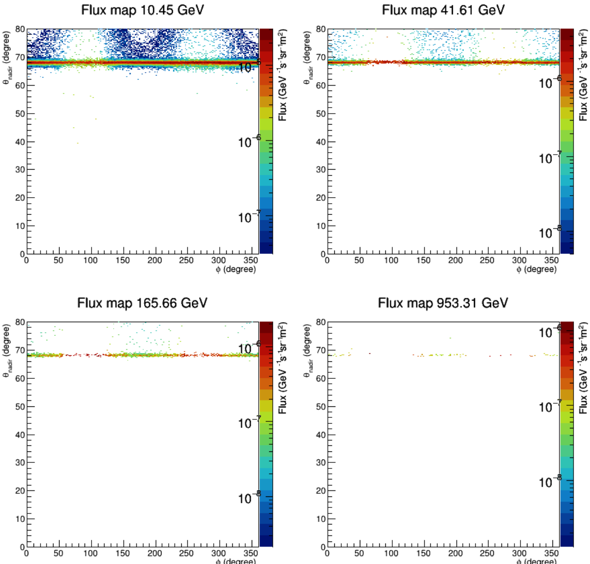
$$x_{k+1}^i = x_k^i + v_{k+1}^i$$

where

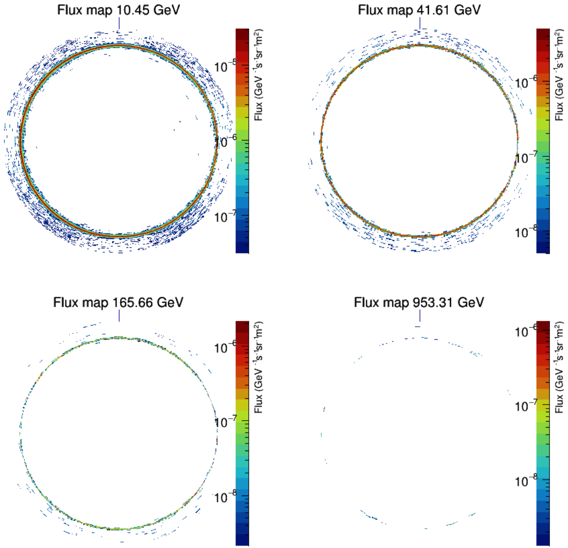
- x_k^i represent variable that particle i hold
- b and B are best local and global parameter sets along the optimization process
- Set $\omega = 0.2$, $c^b = 0.2$ and $c^B = 0.3$

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

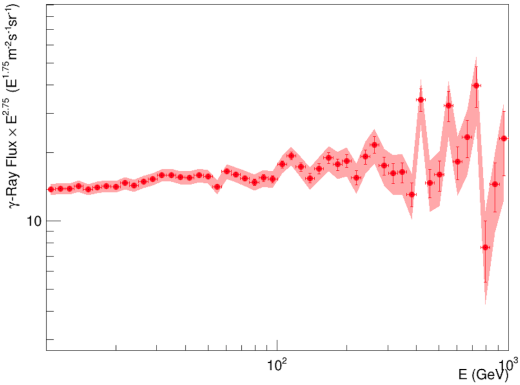
Flux maps


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)
Flux (GeV^{-1}s^{-1}sr^{-1}m^{2})

Flux maps


Flux map 10.45 GeV
Flux map 41.61 GeV
Flux map 165.66 GeV
Flux map 953.31 GeV
Flux (GeV^{-1}s^{-1}sr^{-1}m^{2})

Earth's limb γ-ray spectrum from measurement



Error bars show statistical uncertainties and red bands show total (statistical + systematic) uncertainties. Systematic error is 5% from 10 GeV to 100 GeV and $5\% + 10\% \times (\log_{10}(E/\mathrm{MeV}) - 5)$ above 100 GeV.

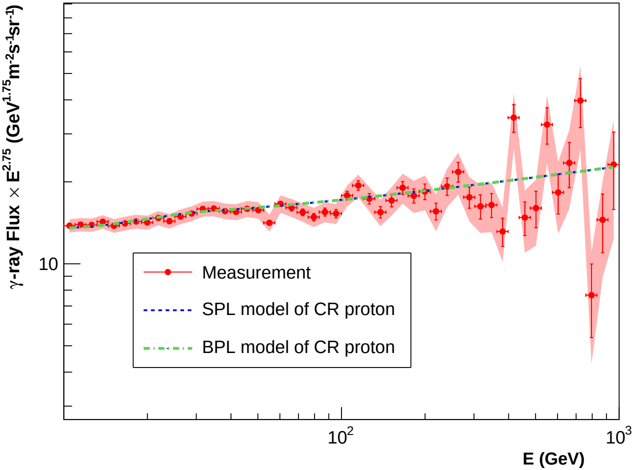
Results

Best fits	Γ_1	Γ_2	E_{Break} (GeV)
SPL	2.70	-	-
BPL	2.86	2.63	333

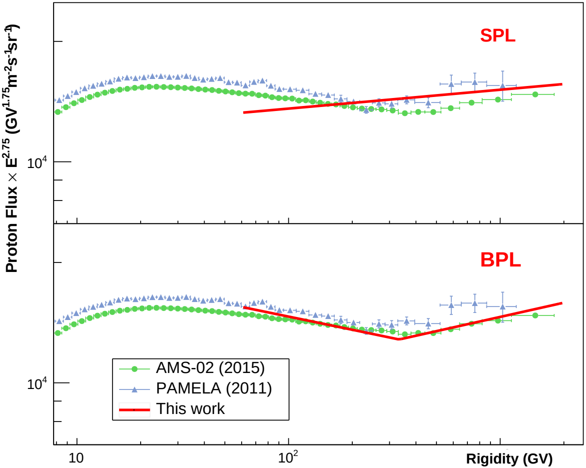
Table: Optimization results.

From the hypothesis testing of BPL versus SPL, it yields a confidence level at 1.38σ (92%).

Earth's limb γ-ray spectra from best-fit models



Proton spectrum



The normalization of this work is fitted AMS-02 data

Summary

- Our best BPL fit indicates the spectral hardening of CR proton at 333 +/- xx GV
- This breaking point is consistent with the direct measurement by AMS-02 at 340 +/- xx GV and the previous indirect measurement by Fermi LAT at 302 +/- 96 GV
- The BPL model fits the measured Earth's γ-ray spectrum better than the SPL model does at the significance level of 1.37σ (compared to 1.0σ in previous LAT analysis)
- Though with more than 2x increase in the amount of data, the spectral break cannot be concluded exclusively by this work
- This indirect detection method may reach its limitation due to the systematic uncertainties

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- The results shows a consistency with direct measurement (AMS-02) where breaking point is $\sim$ 340 GV (ours 333 GV)
- The significant level is 1.37σ (previous work 1.0σ)

References

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Backup slide

Power law in energy

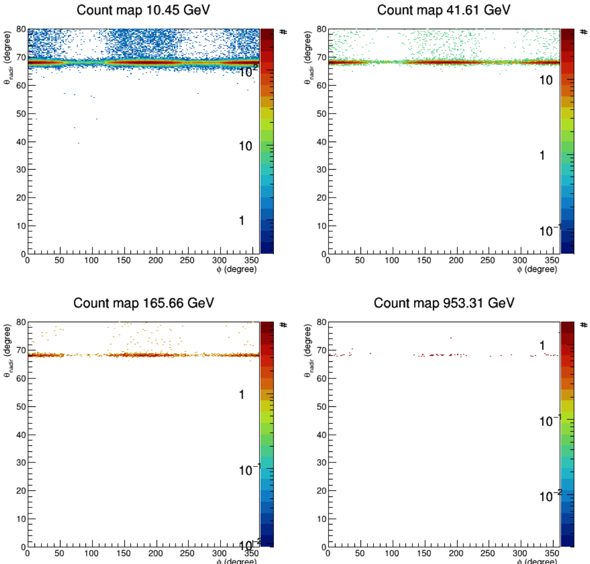
Converting the power law in rigidity to energy, we obtain **Single power law (SPL)**

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

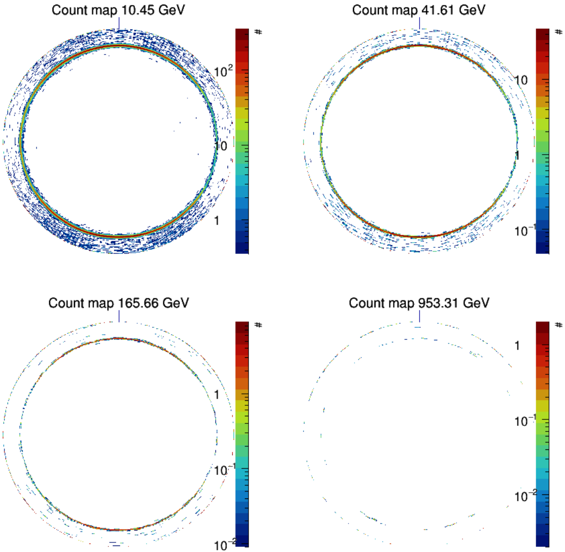
Broken power law (BPL)

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

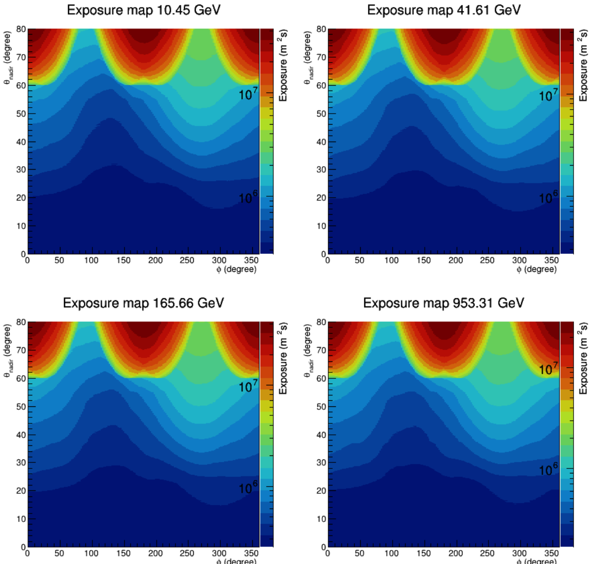
Count map


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)
#

Count maps


Count map 10.45 GeV
#
10^2
10
1
Count map 41.61 GeV
#
10
1
10^{-1}
Count map 165.66 GeV
#
1
10^{-1}
10^{-2}
Count map 953.31 GeV
#
1
10^{-1}
10^{-2}

Exposure maps



Exposure maps