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

Patomporn Payoungkhamdee
under supervision of
Asst. Prof. Warit Mitthumsiri

Mahidol University

patomporn.pay@gmail.com

6 January 2020

Overview

What are cosmic rays

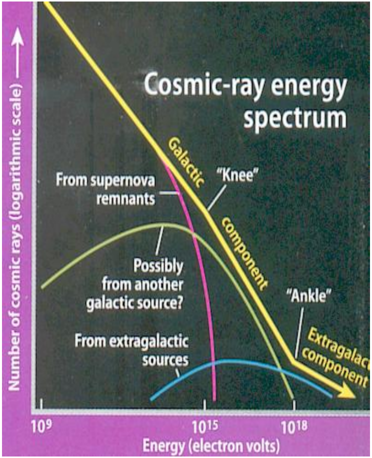


Figure: Cosmic ray feature : retrieved from universe-review.ca

- 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

Motivation

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

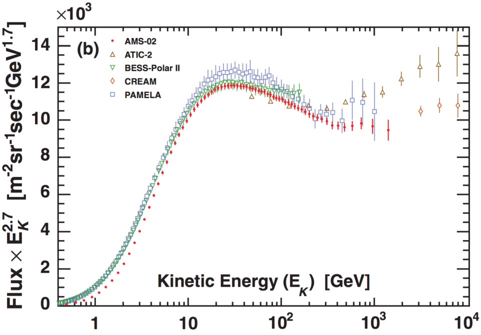
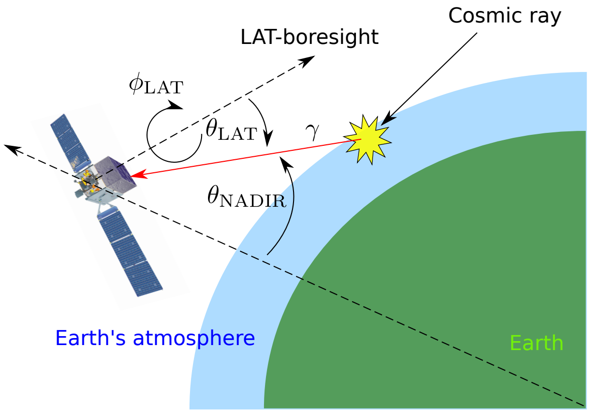


Figure: Cosmic rays proton flux : retrieved from M. Aguilar et al. (2015)

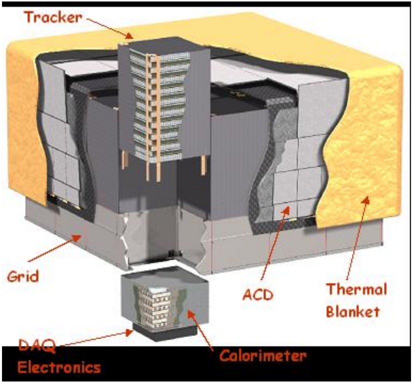
Schematics of limb γ-ray production



Objective

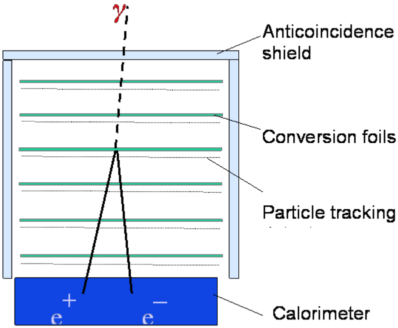
- Want to measure cosmic ray proton spectrum in range GV by using γ-ray data from *Fermi* Large Area Telescope (LAT) through Kachelrieβ and Ostapchenko model
- Some intruments claim that cosmic ray proton spectrum has discontinuity around 200-350 GV , then if our result agree with other intruments. Space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

Fermi Large Area Telescope



- 18 layers of silicon strip tracker on a horizontal plane
- Each calorimeter (CAL) contains CsI(TI) crystal scintillator
- Anti coincidence detector (ACD) frontend device
- Data acquisition (DAQ) module to digitize a signal

Event Reconstruction



- An incident photon hits the conversion foil and produce a pair of leptons
- Leptons pair be detected by scintillator crystals
- Process a track and deposit energy in CAL to reconstruction an event

Data selection

- P8R2_ULTRACLEANVETO_V6 data from 07/08/2008 to 16/10/2017 ($\sim$ 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
   - Treat photon energy bias 3.7% that be affected the energy range above 10 GeV
   - Adjust θ_{N} due to LAT altitude shift
3. Calculate exposure maps which include effective area and time that LAT field of view saw
4. Element-wise divide count map with exposure map
5. **Flux** $\equiv \frac{\int_{\text{Limb region}} (\text{Count map}/\text{Exposure map})}{\Delta\Omega\Delta E}$

Coordinate Transformations

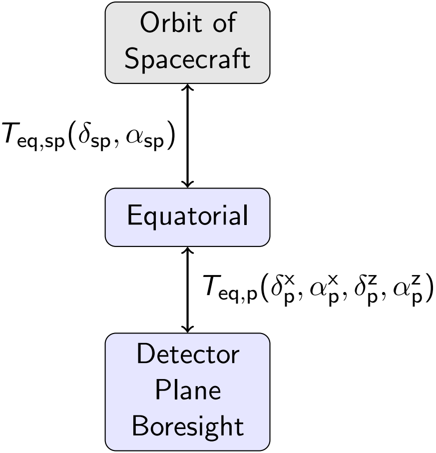


Figure: Three reference frames

Coordinate Transformations

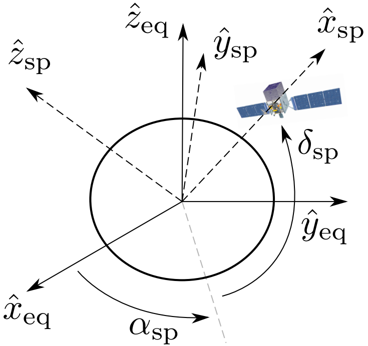


Figure: Coordinate transform between equatorial and spacecraft

Coordinate Transformations (SP-EQ)

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

$$
\begin{aligned}
\hat{x}_{\mathrm{sp}} &= \cos\delta_{\mathrm{sp}}\cos\alpha_{\mathrm{sp}}\hat{x}_{\mathrm{eq}} + \cos\delta_{\mathrm{sp}}\sin\alpha_{\mathrm{sp}}\hat{y}_{\mathrm{eq}} + \sin\delta_{\mathrm{sp}}\hat{z}_{\mathrm{eq}} \\
\hat{z}_{\mathrm{sp}} &= -\sin\delta_{\mathrm{sp}}\hat{y}_{\mathrm{eq}} + \cos\delta_{\mathrm{sp}}\hat{z}_{\mathrm{eq}} \\
\hat{y}_{\mathrm{sp}} &= \hat{z}_{\mathrm{sp}} \times \hat{x}_{\mathrm{sp}}
\end{aligned}
\tag{1}
$$

Transformation matrix could be extracted from the relation

$$
\hat{r}_{\mathrm{sp}} \equiv T_{\mathrm{eq}\to\mathrm{sp}}(\delta_{\mathrm{sp}}, \alpha_{\mathrm{sp}})\hat{r}_{\mathrm{eq}} \tag{2}
$$

Coordinate transformations (P-EQ)

Unit vector of detector plane on a basis of equatorial coordinate

$$\begin{aligned}\hat{x}_{\mathrm{p}} &= \cos\delta_{\mathrm{p}}^{\mathrm{x}} \cos\alpha_{\mathrm{p}}^{\mathrm{x}} \hat{x}_{\mathrm{eq}} + \cos\delta_{\mathrm{p}}^{\mathrm{x}} \sin\alpha_{\mathrm{p}}^{\mathrm{x}} \hat{y}_{\mathrm{eq}} + \sin\delta_{\mathrm{sp}}^{\mathrm{x}} \hat{z}_{\mathrm{eq}} \\ \hat{z}_{\mathrm{p}} &= \cos\delta_{\mathrm{p}}^{\mathrm{z}} \cos\alpha_{\mathrm{p}}^{\mathrm{z}} \hat{x}_{\mathrm{eq}} + \cos\delta_{\mathrm{p}}^{\mathrm{z}} \sin\alpha_{\mathrm{p}}^{\mathrm{z}} \hat{y}_{\mathrm{eq}} + \sin\delta_{\mathrm{sp}}^{\mathrm{z}} \hat{z}_{\mathrm{eq}} \\ \hat{y}_{\mathrm{p}} &= \hat{z}_{\mathrm{p}} \times \hat{x}_{\mathrm{p}}\end{aligned} \tag{3}$$

Then applying the following relation to get transformation matrix

$$\hat{r}_{\mathrm{p}} \equiv T_{\mathrm{eq}\to\mathrm{p}}(\delta_{\mathrm{p}}^{\mathrm{x}}, \alpha_{\mathrm{p}}^{\mathrm{x}}, \delta_{\mathrm{p}}^{\mathrm{z}}, \alpha_{\mathrm{p}}^{\mathrm{z}}) \hat{r}_{\mathrm{eq}} \tag{4}$$

Coordinate transformations from nadir angle

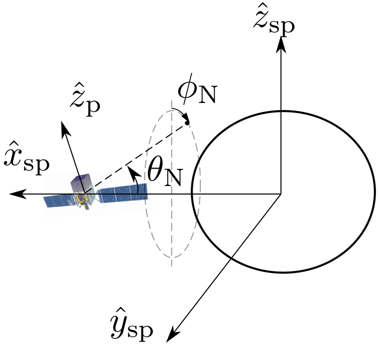


Figure: Coordinate transform between spacecraft and nadir angle

Coordinate transformations (nadir angle)

Consider each grid in nadir's solid angle map on basis of spacecraft

$$\hat{r}^{o}_{sp}(\theta_N, \phi_N) \equiv -\cos\theta_N \hat{x}_{sp} + \sin\theta_N \cos\phi_N \hat{z}_{sp} + \sin\theta_N \sin\phi_N \hat{y}_{sp} \quad (5)$$

Convert it back to the plane of detector

$$\hat{r}^{o}_{p}(\theta_N, \phi_N) = T_{eq\to p}(\delta^x_p, \alpha^x_p, \delta^z_p, \alpha^z_p)\left[T_{eq\to sp}(\delta_{sp}, \alpha_{sp})\right]^{-1} \hat{r}^{o}_{sp}(\theta_N, \phi_N) \quad (6)$$

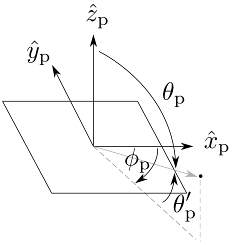


Figure: Detector's boresight in cartesian and polar coordinate

Effective Area

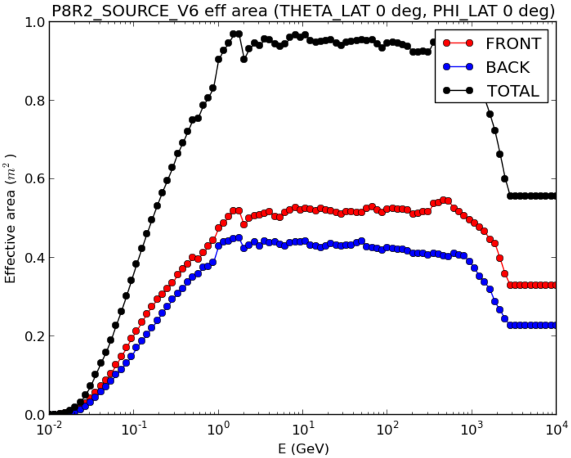


Figure: Effective area of Fermi-LAT

Power law (in rigidity)

Typically, cosmic ray spectrum follow power law in rigidity as

Single power law (SPL)

$$\frac{dN}{dR} = R_0 R^{-\gamma} \tag{7}$$

Broken power law (BPL)

$$\frac{dN}{dR} = \begin{cases} R_0 R^{-\gamma_1} & : \ E < E_{\text{Break}} \\ R_0 [R(E_{\text{Break}})]^{\gamma_2 - \gamma_1} R^{-\gamma_2} & : \ E \geq E_{\text{Break}} \end{cases} \tag{8}$$

Kachelrieβ and Ostapchenko model

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

$$\frac{dN_\gamma}{dE} \propto \sum_{E_{\mathrm{inc,i}}} \left[\frac{E_{\mathrm{inc,i}}}{E_{\gamma,\mathrm{i}}} \Delta(E_{\mathrm{inc,i}}) \right] \left[f_{pp} \frac{dN_{\mathrm{H}}}{dE_{\mathrm{inc,i}}} \left\{ 1 + \frac{\sigma_{\mathrm{HeN}}}{\sigma_{pN}} \left(\frac{dN_{\mathrm{H}}}{dR} \right)^{-1} \frac{dN_{\mathrm{He}}}{dR} \frac{dR_{\mathrm{He}}}{dR_{\mathrm{H}}} \right\} \right] \tag{9}$$

- 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

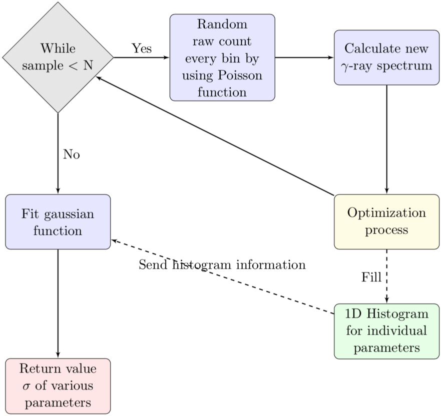
$$\mathcal{L} = \prod_{i=1}^{N} P_{\text{pois}}(n_{\text{i,model}}, n_{\text{i,measurement}}) \tag{10}$$

For numerically convenient, redefined into logarithmic form

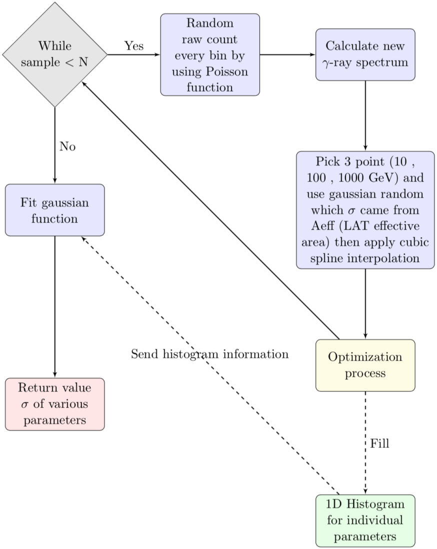
$$\log \mathcal{L} \equiv \sum_{i=1}^{N} -\log P_{\text{pois}}(n_{\text{i,model}}, n_{\text{i,measurement}}) \tag{11}$$

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

Monte Carlo Simulation (Statistical Error)



Monte Carlo Simulation (Total Error)



Algorithm

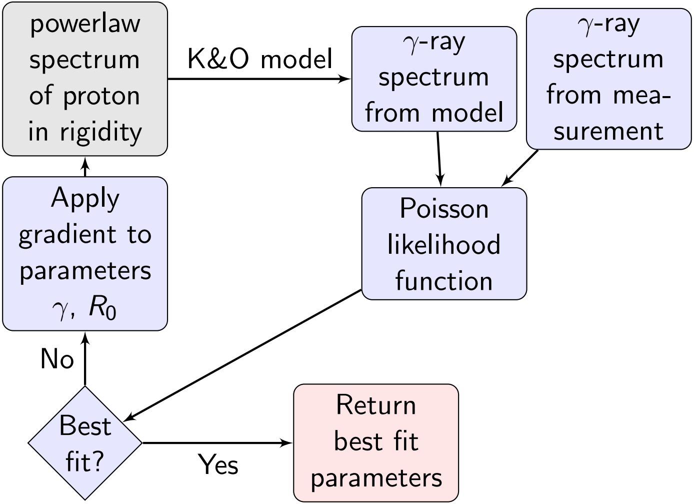
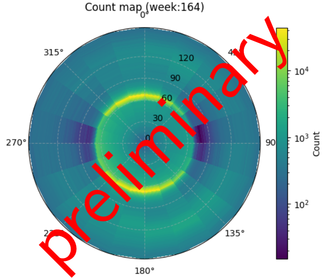


Figure: Flow chart of optimization process

Count map and distribution



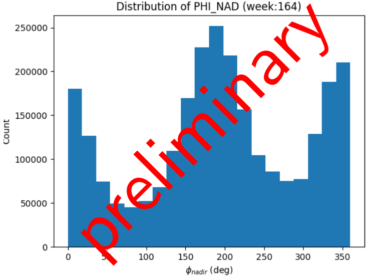
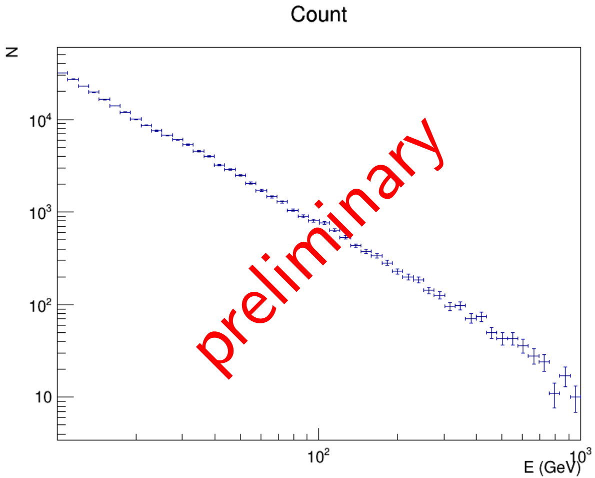
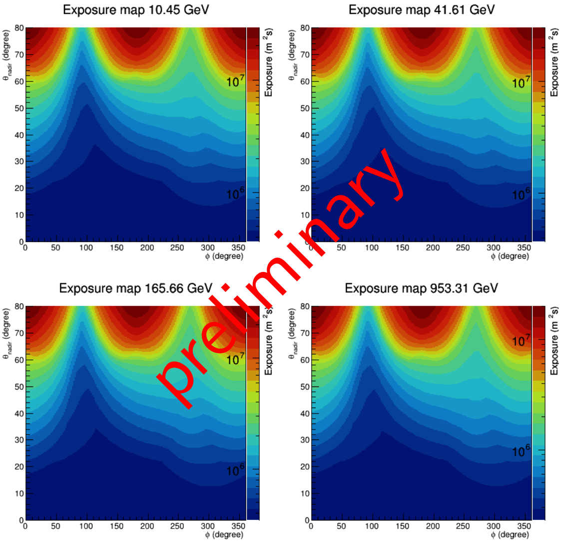


Figure: Example distributions of γ-ray from a single week

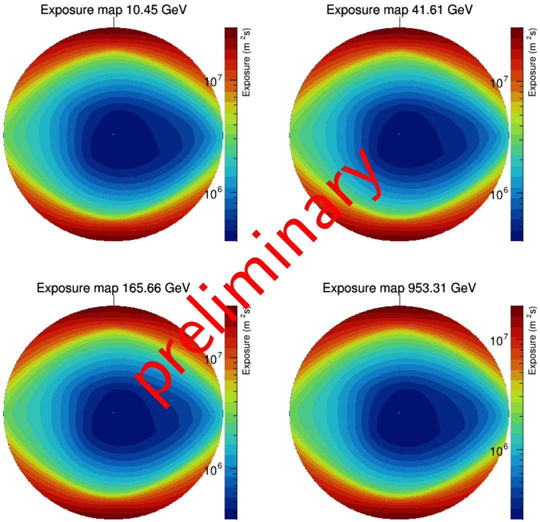
Count map and distribution



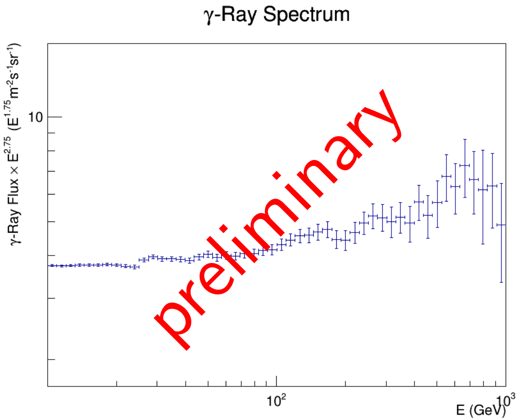
Exposure maps



Exposure maps



γ-ray spectrum



Please note that the error bar is statictical error and systematic error does not include in this figure.

Outlook

- Find a breaking point of cosmic ray proton spectrum and determine level of confidence
- Put weight on the previous study that the brightenss of γ-ray from Earth's high atmosphere could be use to perform an indirect measurement

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)

$$\frac{dN}{dE} = N_0[E_k(E_k + 2m_p)]^{-\gamma/2}\left(\frac{E_k + m_p}{\sqrt{E_k(E_k + 2m_p)}}\right) \tag{12}$$

Broken power law (BPL)

$$\frac{dN}{dE} = \begin{cases} N_0[E_k(E_k + 2m_p)]^{-\gamma_1/2}\left(\frac{E_k+m_p}{\sqrt{E_k(E_k+2m_p)}}\right) & : \; E < E_{\mathrm{Break}} \\ N_0[E_b(E_b + 2m_p)]^{(\gamma_2-\gamma_1)/2}[E_k(E_k + 2m_p)]^{-\gamma_2/2}\left(\frac{E_k+m_p}{\sqrt{E_k(E_k+2m_p)}}\right) \\ : \; E \geq E_{\mathrm{Break}} \end{cases} \tag{13}$$

Error determination

Statictical error (Random error)

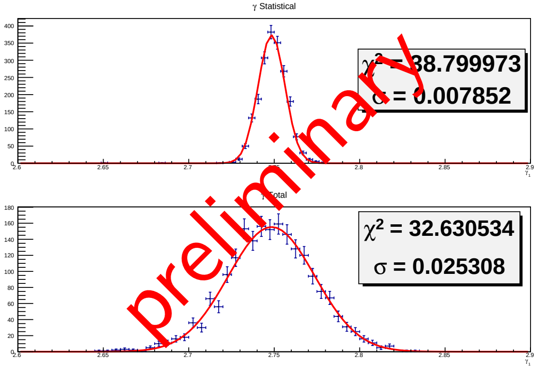
1. Get back to raw count and random new count in each energy bin by Poisson random function
2. Recalculate proton spectrum
3. Optimize it and store the parameter that we got
4. do it over thoundsand time and fill in histogram to interpret error by saying sigma of gaussian function

Total error (take into account instrument)

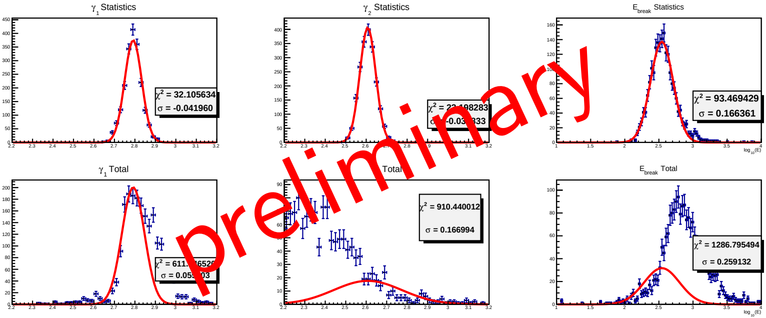
1. Get back to raw count and random new count in each energy bin by Poisson random function
2. Random value we got again by systematic error (Apparatus)
3. Recalculate proton spectrum
4. Optimize it and store the parameter that we got
5. do it over thoundsand time and fill in histogram to interpret error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

Result from 7 years of data

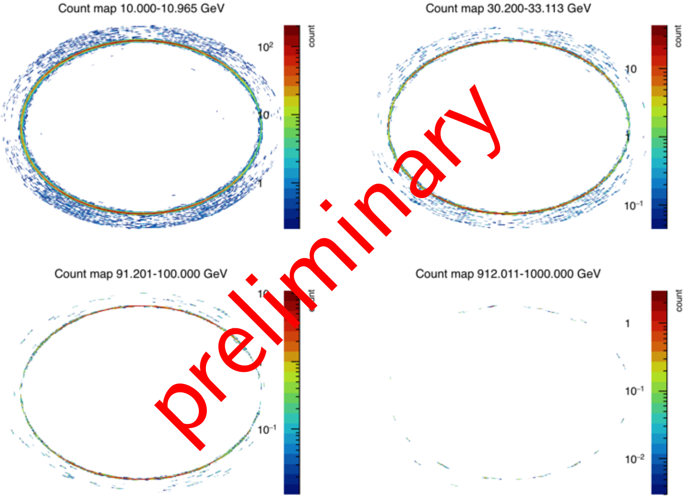
Single power law (SPL)



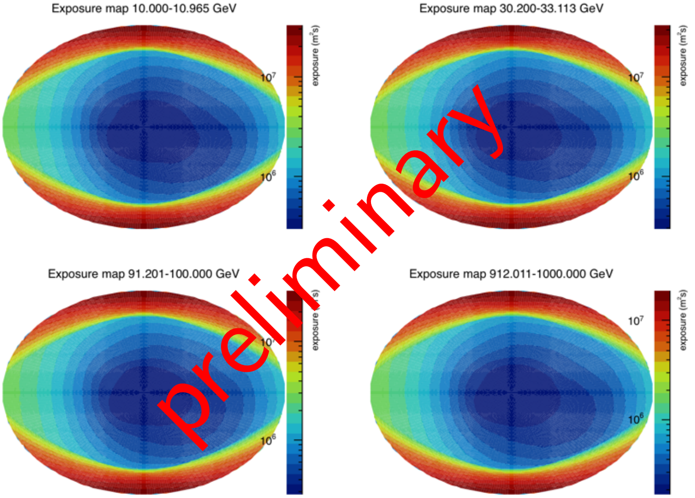
Broken power law (BPL)



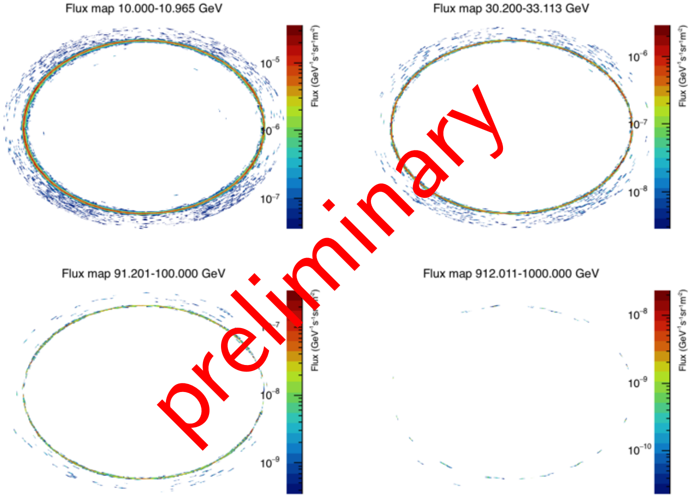
Count map


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