~~PRELIMINARY~~ INDIRECT MEASUREMENT OF COSMIC-RAY PROTON SPECTRUM USING EARTH'S γ-RAY DATA FROM *FERMI* LARGE AREA TELESCOPE

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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.

KEY WORDS: EARTH'S GAMMA RAYS / COSMIC RAYS/ GEOMAGNETIC FIELD

39 pages

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CHAPTER I
INTRODUCTION

1.1 Overview

The space is full of questionable amazing phonomenon starting from why we have day and night, why the star bright to the advance question about existence of the dark matter. This influence to the mankind to start asking how it happen. Human curiosity bring us so far that now we could observe the sky with high resolution technique. However, the research to gather new knowledge by studying the space is endless and the answering one thing usually bring another mystery. Study of physical science also drag the technology for further step because the limitation of the instrument or technique to explore the nature is another challenging task.

Astrophysical research boundary is expanding through time pass by because the exploration of one thing does open the new door with the darky room waiting for human to shine a light to explore. There are various branch of astrophysical science from theoretical foundation, simulation and experimental physics where they are compliment each other for pushing the frontier of the human knowledge. To study high energy particle accelerators in the universe, the possibility of probing the source is nearly impossible in terms of current technology and resource that required to reach multiple galactic sources that could produce high energy particle called cosmic-rays (CRs). Nevertheless, the technology of observing the particles ~~that~~ arriving the Earth is more plausible for the scientist.

The way to observe cosmic-ray (CR) particles has divided into two ways. ~~One way is measuring the incoming charge particles on ground with a ground-base detector. Alternative way is gathering CRs on the space or basically orbiting spacecraft.~~ Performing analysis on CRs data allow us to interpret the physical properties of CRs particle for both quantatively and qualitatively by taking simulation and experimental results to compare.

Typically, the spectrum of the CRs would follow the power law with a specific spectral index depending on the rigidity of the charged particles where it was accelerated by a specific source. It is obvious that there will be multiple sources of the CRs in the space including unknown sources. The characteristic of spectrum would be indicated by the source from theoretical simulation and derivations. Consequencely, changing of the spectral index from one rigidity to another rigidity will find the discontinuity if there are the translation from one source type to another source from the superposition of multiple spectrums.

Fermi-LAT has been launched into the sky and orbiting around the Earth and looking around the space in γ-rays regions. It found that the ring of brightness around the Earth's limb where the major factor that cause this phenomenon is the intereaction of incoming CRs with the Earth's upper atmosphere as analyzed in Abdo et al. (2009). Then the spectrum of γ-rays that was induced by the incoming CRs highly related on the spectrum of CRs.

The first indirect measurement was conducted with 5 years of observations and indicate that there is breaking of spectral index around 302 GV with a significant level 1 σ. The significant level at this stage is not so strong to conclude the study. The reasons probably came from the nature of the CRs if there is no discontinuity in the incident CRs spectrum, the indirect could measurement distort the information so that the significant could be reducing or the exposure time during the observations is still not enough. In order to confirm that we did our best on the data collection side, performing the analysis with more data could also put us out doubt for the last clue.

1.2 Objectives

The objectives of this study are to

- To indirectly measure the cosmic ray proton spectrum in rigidity range gigaelectronvolt (GV)

- To put the weight on the previous study with more dataset
- To improve the optimizaiton technique by using heuristical methodology
- To reduce the calculation time by inventing a whole new parallel code in low level from scratch

1.3 Outline of Thesis

The dissertation would provide the various information from the overview introductory context to the technical detail that employ in this study as well as the result and interpretation. It is structured as follows.

Chapter I will introduce the reader about the overview of the long track from the historical analogy and zooming into the specific branch of research to get the reader to see where we are and what we are doing to fullfill the frontier of the research.

Chapter II is the background knowledge that will be used in this study. This chapter also have a brief of history in cosmic ray research community which contains an important finding and the impactful experiment that bring us to this far in the research field. Some theoretical detail will be provided on par with the historical discovery but the subchapter of the specific topic will describe more detail in depth of astroparticle physics that involving the high energy physics. Not only the concept of physical process but this chapter also have the apparatus informations where the majority of the content covering the detector part in the spacecraft to demonstrate how the apparatus gather the γ-rays data.

Chapter III is mainly consist of multiple literature reviews involving the study to clarify the theoretical idea as well as for filling the fundamental concept that takes reader to understand the next chapter in detail.

Chapter IV would cover the article reviewing. The content is staring from pioneering article of the field and the evolution that inspire this work.

Chapter V consists of datasets selection, flux calculation , problem optimizaiton and interpretation.

CHAPTER II
BACKGROUND

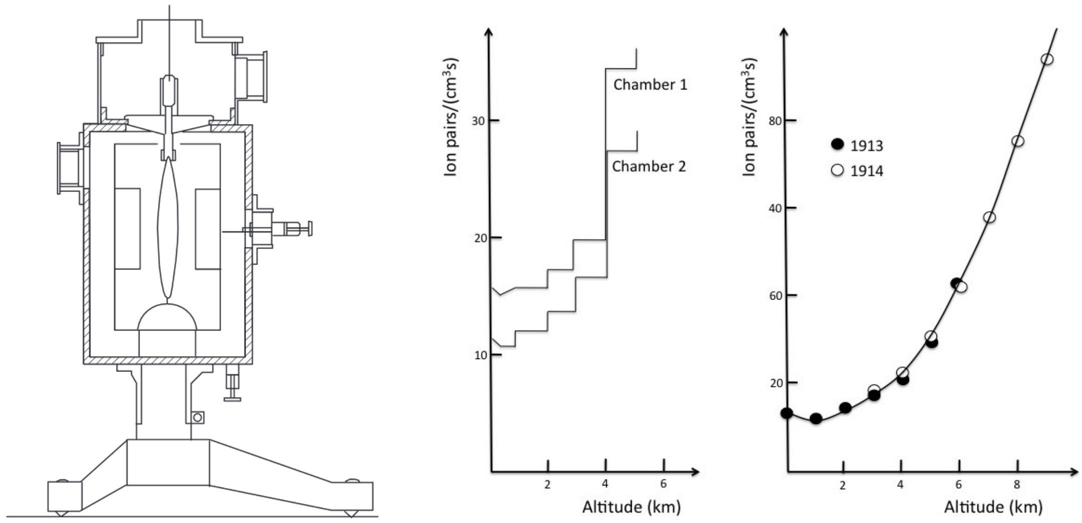
2.1 Cosmic-ray

This section consists of historical discovery, from the origin on this field of study until the latest impactful experiment. Not only historical content, it also contains the physical explaination with phenomenon that involving the CR reserch.

2.1.1 History

In 1909, the famous experiment that pioneer the study of CR has been led by Theodor Wolf who take conduct the experiment of altitude variation by taking the apparatus to measure the rate of ionization from the ground to the top of the Eiffle Tower in Paris (Gray (1949)). The result shown that there the ionizaiton rate was slightly increase when the altitude is higher which gives the clues that the origin of cosmic-rays was came from the outer space rather than Earth's inner shell. Hörandel (2013)

However, the experiment of measuring the affect of altitude variation with a tiny altitude scale comparing to the Earth's atmosphere would not enough to consolidate the theory. In the same year, the ballon with a similar instrument has been released up to 1.3 kilometers by Karl Bergwitz to put more weight on the first experiment. They found that the ionization has increased by a quater comparing to ground level (De Angelis (2014)). Three years later, suicidal investigation was conducted by an Australian gentleman who brought the detector and himself to fly with the balloon. His name is Victor Hess, people might have no doubt why this name went so famous because he risk his life with the experiment and he was flying over 5 kilometers above the ground (Hess (1912)). Definitely, the result is strongly significant and impactful to the astrophysical research community. Risking life In 1914, Werner Kolhörster repeated the balloon experiment with higher altitude

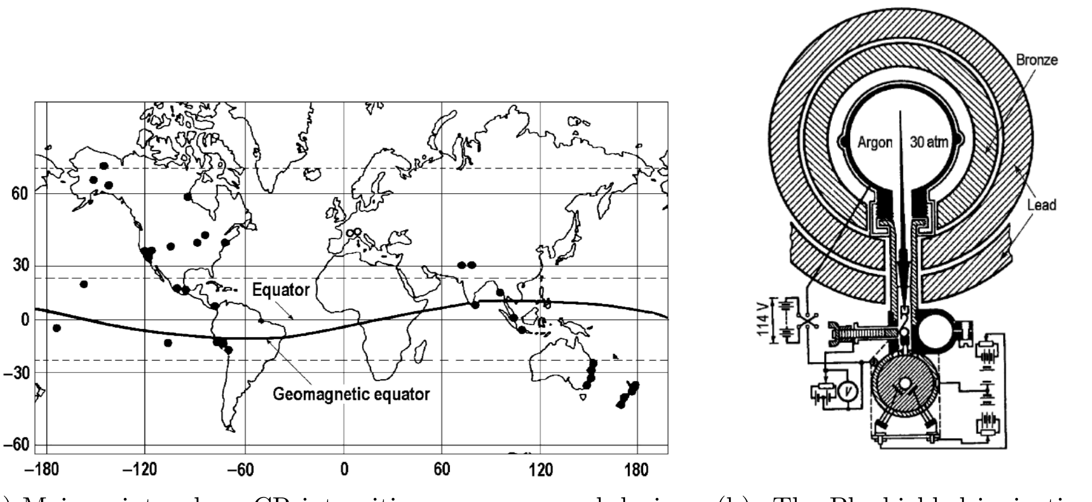


(a) An early version schematic view of electrometer used by Thedor Wulf (Hörandel (2013))

(b) Ionizaiton rate from Victor Hess (left) and Werner Kolhörster (right)

Figure 2.1: Wulf's apparatus and the ballon experimental results

which around 9 kilometers from the sea level and the ionizaiton rate still does increase when the ballon flown higher. This emphasize that the source of those ionizing ray came from Earth's upper atmosphere or the outer space.



(a) Main points where CR intensities were measured during eight Compton expeditions in 1932

(b) The Pb-shielded ionization chamber, organized by Compton (Dorman (2009))

Figure 2.2: Clay Experiment of geographical variation

Not only the altitude variable that related to the intensity of the CRs, but the geographic location of the obvervation also does affect to the measurement.

The first experiment has done done John Clay who sailed the ship across the ocean from Holland to Java (Clay (1927, 1928)). The geographical locations that used to measure the CR intensities and the apparatus schematicical draft is shown in Figure 2.2. The result shows that the further from equator, the higher CR intensity. Another exploration for the geographic variation was done by John Compton in the following five years. He basically sailed the ship from the Sydney (northern hemisphere) to Vancouver (the southern hemisphere) for various season during 1936 to 1937 back and forth (Compton & Turner (1937)). The Figure 2.3 demonstrates the latitude variation and the seasonality effects of the multiple trips from the experiment.

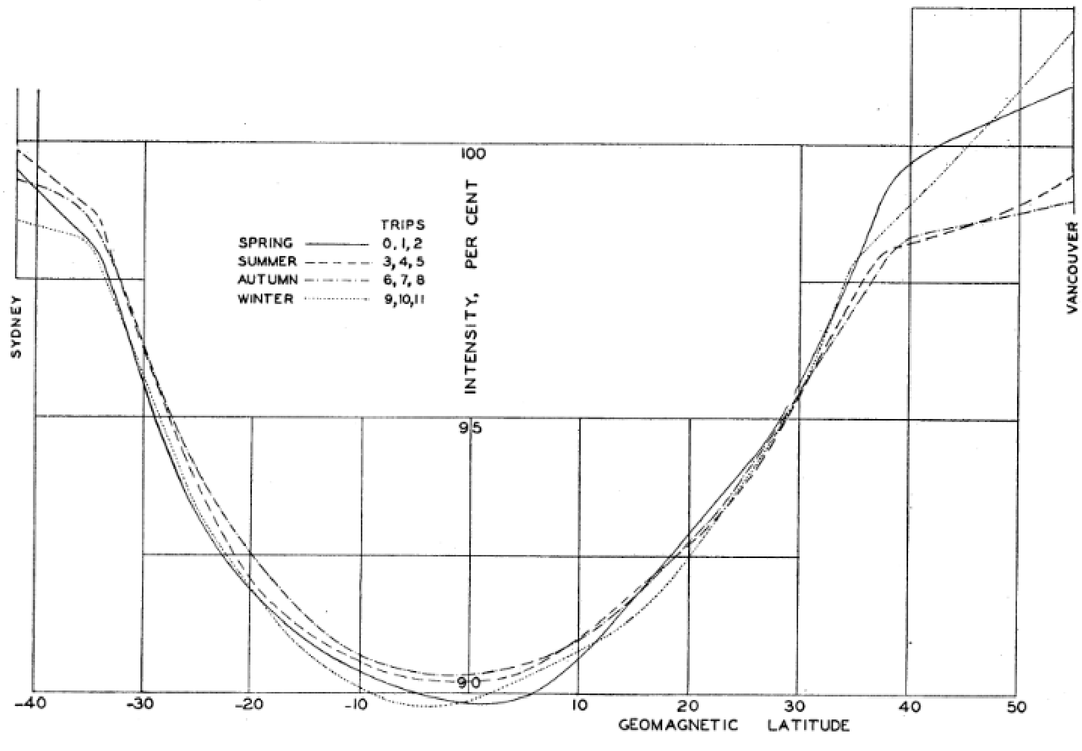


Figure 2.3: Latitude variation for various seasons (Compton & Turner (1937))

The first interpretation study from the discovery has been done by Carl Störmer. The explaination of the CR's altitude variation came from the trajectory of CR particles due to geomagnetic field (Störmer (1934)). In that period, the topic of geomagnetic field and the effects of CRs was quite famous. Another impactful study of the CRs trajectory and the relevant of Earth's magnetic field was conducted by Bruno Rossi for predicting an asymmetry of the East-West distribution of CR spectrum because the primary CRs does have a positive or negative charge then the cyclic moving direction of the particle was induced by Lorentz force where the direction of the Earth's magnetic field could be identified to determine the direction of the charged particles (Rossi & Greisen (1941)).

The ground based detector is a great option for detecting the CRs where it include primary and secondary CRs. However, investigating the primary CRs is a challenging topic for ground based detector especially for low energy particles. Another interesting option to inspect the asymmetry of East-West could be done by using space based detector that orbiting around the Earth's at some radius in the higher altitude and definitely it would face a lower atmospheric density which consider to be an interesting choice to study the CRs with a lower effects of atmospheric interaction. In 2008, *Fermi* Large Area Telescope (LAT) has been launched to observed γ-ray and lightweight lepton particles which basically are electron and position. The East-West effects from geomagnetic induction was also emphasized by *Fermi*-LAT.

2.1.2 Physical properties

CRs are high energy particles that propagating through the space. The momentum of the particles came from various acceleration mechanism base on where it from such as supernovae, active galactic nuclei, quasars and gamma-ray bursts. The composition of CRs consists of 90% protons, 8% alphas and other nuclei of heavier elements (Dembinski et al. (2017)). Experimentally, many observations indicate that the spectrum of CRs for all particles and individually does follow the power law in rigidity (momentum per charge) with a specific spectral index depends on their energy range. Theoretically, the observed spectrum with a broad energy range would represented the superposition of arrival CRs with a diverse producers where each producer has their own specific character which is spectral index. By the end of the day, it is barely possible to distinguish the origin of CR particles one by one. Then it is more plausible to provenance the origin of CR particles in the macroscale rather than inspecting in the microscale.

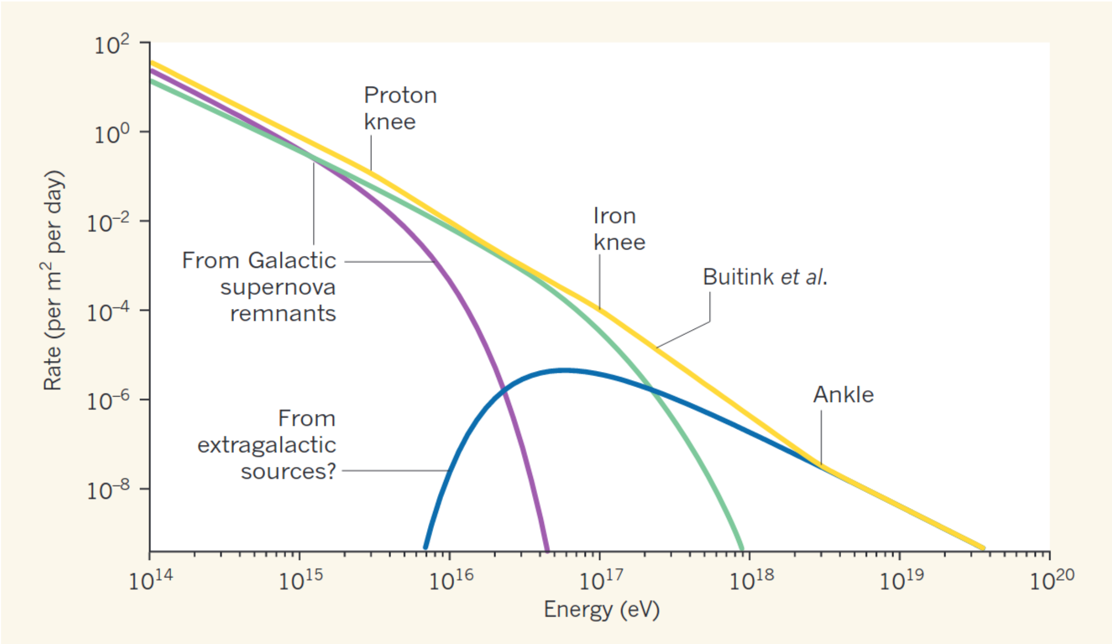


Figure 2.4: Superposition of CR spectrum (Taylor (2016))

As mentioned in an early paragraph, each souce of CR does reflect their own specific spectral index in the arrival CR spectrum. In order to validate the theoritical assumption, putting the simulation or calculation of each sources and check with the real data does compliment experimental observations. The superposition of various sources that yield a discontinuity of the spectral indices has been exploided in some energy ranges. Two well known breaking points are knee and ankle where it located in the energy order around 10^{15} eV and 10^{18} eV sequentially. Approximately, the rate to find one particle at knee is around one particle per square meter per year and the possibility that the apparatus could detect the particle in energy at ankle point is roughly one particle per kilometer per year. Figure 2.4 illustrate the concept of superposition from various sources and yield the arrival CR spectrum with a breaking spectral indices.

Not only the below ankle energy that has an interesting properties, but the CR that has energy beyond the ankle energy also has an identical properties. It knowns as ”ultra-high energy cosmic rays” (UHECR). One interesting point is that it does not that far from ankle in term of rigidity magnitude which higher around 1 or 2 order of magnitude. The widely known explaination why it could not go so far is the Greisen–Zatsepin–Kuzmin limit (GZK limit). The theory provides the description why it the UHECR could not propagte though the space but please note that some sources still could produce such a UHECR but the main issue here it the space does not empty. It contains some intermediate matter or dust and the microwave background radiation which it is believed that it came from the residue of the Big Bang or some greate explosion or expansion of the space that human never saw it (at least in the human lifetime). The main calculation of the CR kinetic energy limit from GZK was considered only proton particles and the main interaction that makes it stop is basically from the interaction with microwave background radiation that almost perfectly isotropically progating in the space with an order of traveling proton around hundred light years in the space (Greisen (1966)). The way of this kind of intereaction not only does slow down the CR proton by producing neutral pion where it mostly decay into a pair of γ-rays but it could also yield a neutron with a charged pion. Hence, it is also answer why we could see such a high energy neutron that does not only produced in the sky (shower effects) albeit it does not has any charge to be accelerated in the famouse acceleration mechanism such as shock acceleration.

The types of CRs could be divided into two kinds based on how they was produced which are

1. **Primary cosmic rays**: they mostly be produced from the Solar system, somewhere in the Milky ways, extragalactic sources and many more. When they interact with the Earth's atmosphere, with the hadronic interaction with the air molecules, they produce the secondary CR particles.

2. **Secondary cosmic rays**: as mentioned in collapsing of the primary CRs, secondary CRs consists of many particles from lightweight leptons to medium weight leptons and from mesons to hadron particles as well. The interaction of the proton with the atmospheric molecule looks simple but the precise calculation from derivation is extremely complicate since there are endless possibility of the (Feynman) path that also produce another products with a certain probability. By the end of the day, we definitely got a few certains

of particles from their likelihood of the occurence from the collision which mainly are electrons, positions, muons, pions and photons as demonstrates in Figure 2.5.

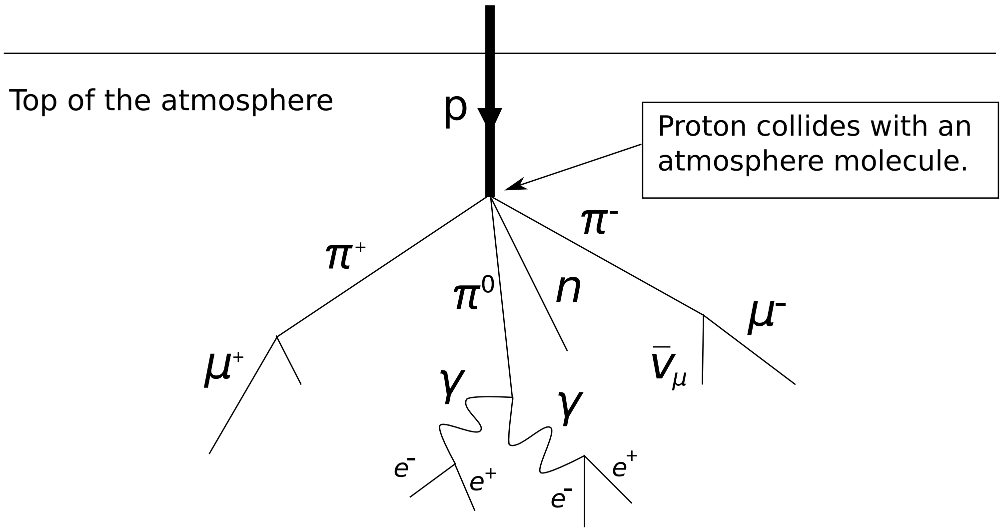


Figure 2.5: Cosmic rays shower from collision of primary CR with the atmospheric molecule

2.1.3 γ-ray production

The production of γ-ray particles happens all the time. It is mandatory to understand how a photon could gain a very high momentum from the nature. The procedure to acquire all those kinetic energy is quite different from how a charged particle obtains their momentum because a charged particle could earn their kinetic energy during their trip of propagating through the space with a Lorentzian force. The γ-rays mostly have only one chance to pick their kinetic energy and it happens when it was produced bacause it is barely interact with any other particles in the space especially high energy γ-ray. The scenarios that makes photon hold a high energy are listed in the following bullets.

Mechanism of γ-ray producing

- **Decaying of unstable matter**: Radioactive decay is one of the most well known phenomena for the γ-decay mode. One example of the heavy ion decay is the cobalt-60. It decays into excited state of nickle as

$${}^{60}_{27}\mathrm{Co} \longrightarrow {}^{60}_{28}\mathrm{Ni}^{*} + \mathrm{e}^{-} + \bar{\nu} + \gamma\,,$$

then the excited nickle decay another γ-ray to make it to the stable state

$${}^{60}_{28}\mathrm{Ni}^{*} \longrightarrow {}^{60}_{28}\mathrm{Ni} + \gamma\,.$$

The famous decay of a lower level from a small nuclei that consists of two quarks called "meson". To be more precise, it is known as the pion decay. The path diagram is demonstrated in Figure 2.6 where the neutral pion from the collision process that interact via Yukuwa's interaction. The neutral pion itself does not stable then it would have a short amount of lifetime before it dominately decays into two high energy photons. Definitely, neutral

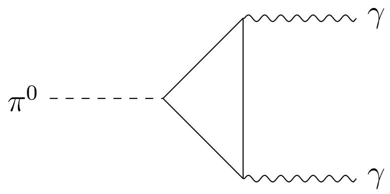
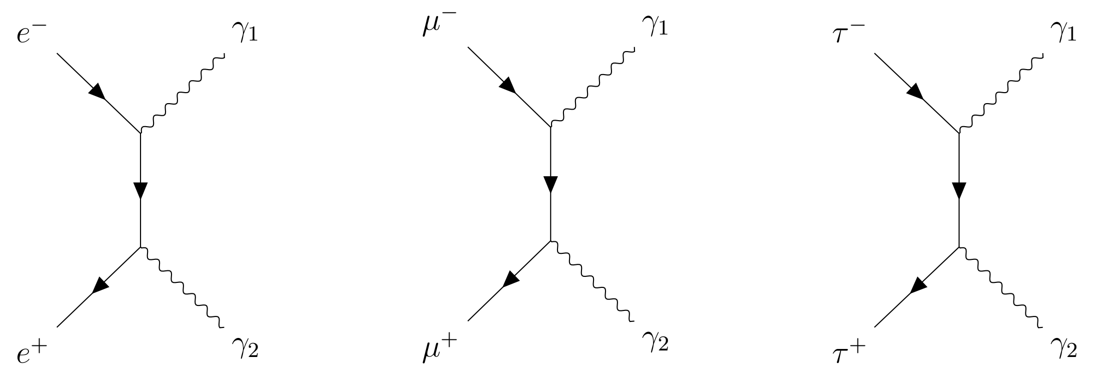


Figure 2.6: Feynman's diagram of neutral pion decays into two γ-rays

pion also could yield one γ-ray and a pair of lightweight leptons, a couple pair of lightweight leptons or even just a pair of lightweight leptons and much more as long as it conserve the momentum, energy and the quantum numbers. The main reason why the majority of their decaying process does yield only photons because the scattering amplitude as the Figure 2.6 does hold a branching ratio around 0.98823 and the rest of them is smaller than 1%. Another interesting property of this decay mode is the momentum vector of their pair γ-ray hold an opposite direction with the same amplitude in the reference frame.

- **electron–positron annihilation**: In the universe, there are some probability of the electron and position was forced to face each other by some chance from the electromagnetic force or randomly found each other. The intereaction when they facing each other dominate by electromagnetic interaction and definitely require a photon as a mediator to allow them talk to each other in quantum electro dynamics point of view. Definitely, there is a change when those pair of leptons decide to annihilate into high energy photons without runing any physical laws. Nevertheless, other kind of a pair of leptons like muon technically could deforms into two photons with much higher energy because their rest mass is higher. Surely, a pair of Tau is also allow to produces a pair of photons. However, the lifetime of those medium-weight and heavy-weight leptons could not last that long to survive in practical. The simplest Feynman's path of annihilation of leptons into a pair photons is illustrated in Figure 2.7 from light to heavy leptons sequentially.



(a) Lightweight leptons (b) Mediumweight leptons (c) Heavyweight leptons

Figure 2.7: Major lepton annihilation path diagram

- **Synchrotron radiation& Bremsstrahlung radiation**: The phenomena of turning momentum direction of charged particle or accelerate into another direction shares a similar description. Conservation of momentum has come into place when considering the bending charged particle that would emit the photon. Regarding the incoming direction of a charged particle and then turning it direction by $\pi/2$ radians. The question that comes into mild is where does those initial momentum in an incoming direction does since the momentum is conserved along the cartesian direction, not only the magnitude. Now the clue is here, they have to emit the photon to converse the momentum of the system.

Let walk through the first example called synchrotron radiation. Keeping some charged particle circulating around the donut-like apparatus have some cost to pay to make them stay without escaping the tunnel. Unquestionably, draging some moving particle circulating around some point requires a centripedal force. In this case, applying electromagnetic force without toucing it would yield a radiation called synchrotron emission.

The second mechanism is Bremsstrahlung, where a charged particle or typically an electron moving path close to some opposite charged particle or typically a proton. The explaination from Coulomb's law would cover this scheme for the definition that the force is inverse proportional to the distance between two charges. Then moving pass by an opposite charged particle does induced the electron bending and emit the photon because the explained reason from the previous paragraph. This mechanism happens when an CR electrons moving through the matter of Sun's chronosphere and interact with a positive charged and produce some high energy photon but usually it produce in the X-ray energy range.

Mechanism of γ-ray gaining momentum

Even though, γ-ray usually does not prefer to talk to another fundamental particles because scattering amplitude of their interaction is pretty low. Nonetheless, there are some scenarios that γ could gain more kinetic energy and losing their kinetic energy when they traveling in the universe.

- **Inverse Compton scattering** The scattering of a photon (massless particle) with an electron (massive particle) could occur during their trip. Equation 2.1 demonstrate the symbolic relation of the scattering with the electromagnetic interaction and yield the same particles as an incoming particles.

$$e^-\gamma \rightarrow e^-\gamma \tag{2.1}$$

Interaction between an electron and a photon could make them converting the momentum via the scattering processs. Since the system momentum has to be conserved, then there will be one losing momentum and another one gaining momentum or kinetic energy. Suppose one photon is traveling and hit electron or a charged particle, it could transfer the kinetic energy to the particle and their wavelength will be longer. In another word, it is lossing the kinetic energy. On the other hand, this scenario could happen in the opposite way. There is situation when a high energy electron interacting with the photon and turn over it kinetic energy to the photon. After that, a photon could gain more kinetic energy during their trip. The latter scenario is called "Inverse Compton Scattering". The most likelihood choice of interaction of the scheme could be represented in Feynman's path as in Figure 2.8.

(a) First branch (b) Second branch

Figure 2.8: Trivial Feynman's path of (Inverse) Compton scattering

γ-ray production plants

- **Supernova ramnants (SNRs) and molecular cloud**: The supernova explosion is a huge expansion from that approximately expanding as a spherical shell that sweep the inter stellar medium (ISM) and decelerate at some radius after the enlargement. The kinetic energy that transfer from the momentum in the radial axis was modeled and belived to be the kinetic energy of the cosmic ray particles. There are three major processes that involves in this phenomenon which are nuclear pion production, nonthermal electron bremsstrahlung, and Compton scattering (Dermer & Powale (2013)). Last but not least, the shock acceleration could play an important role for this phenomenon.

- **Diffused γ-ray emission from galactic plane**: One of the bright source that does not locate too far from our teritory is the galactic plane. The first reasonable explaination is the distance of the productive objects does not far from Earth comparing to other extragalactic sources. In addition, there are many interesting CR sources in our galaxy. It might be pulsar, some flare of the event of an explosion and so on. The plot that shows the brightness of the galactic plane comparing to the outer space is shown in Figure 2.9.

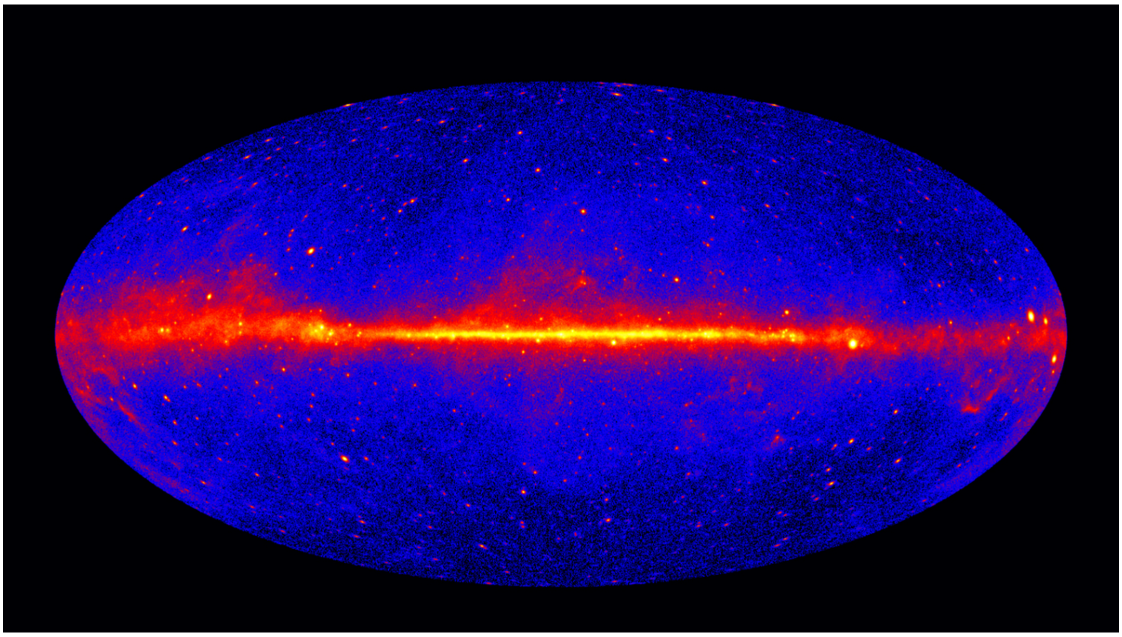


Figure 2.9: Intensity of γ-ray $>$ 1 GeV in galactic coordinate (Image credit: NASA/DOE/*Fermi* LAT Collaboration)

- **Earth's limb γ-ray production**: The closest γ-ray source is our Earth's atmosphere. To be more precise, the Earth's upper atmosphere is super bright in γ-ray exposure. The main reason that cause the shining of Earth's limb does came from the collision of the CR's massive particle such as protons and alphas. The interaction of those high energy CR massive particles yield many more particles and main contribution of the γ-ray dazzling came from the neutral pion decay which is the product from the collision process.

2.2 *Fermi* Large Area Telescope (LAT)

One of the famous space telescope that does see the sky in the visible wavelength is *Fermi* Large Area Telescope (LAT). Formerly, it was called Gamma-ray Large Area Space Telescope (GLAST). The mission of the satellite is to collect high energy photon data or γ-ray and it technically could detect the lightweight lepton particles namely electron and position. The orbiting radius is around 550 kilometers from the sea level. It is designed for observing the full-sky in γ-ray region. It also attach the Gamma-ray Burst Monitor (GBM) to study gamma-ray bursts for seeking an exotic event. The telescope was launched in 11 June 2008 at 16:05 UTC or 21:05 Bangkok time by abroading with Delta II 7920-H rocket.

2.2.1 Overview

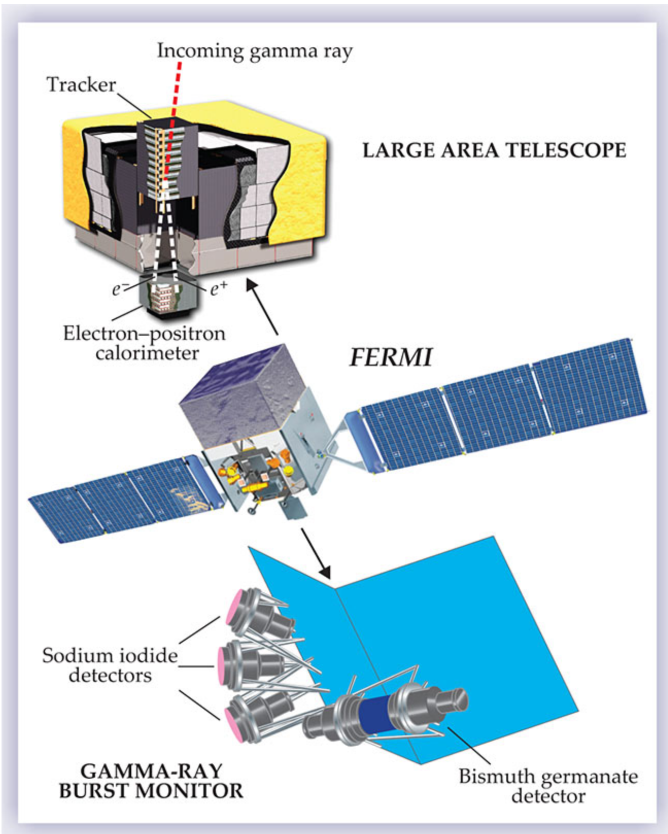


Figure 2.10: Main components of *Fermi*-LAT (Image taken from Michelson et al. (2010))

According to Figure 2.10, each components of the *Fermi* telescope was designed for a purpose since there is no ideal detector module that could detect kind of particles. There are two main parts where the first part if the major component called Large Area Telescope (LAT) for detecting the γ -ray and the second part is Gamma-ray Burst Monitor (GBM) for seeking an interesting event in the sky. In fact, both of them does detect the γ-ray but in the different energy scale. LAT is the main component where it detect the γ-ray in a few dozen of GeV up to a digit of TeV. For GBM part, the visible photon energy for them is around 8 keV to 40 MeV. The GBM consists of two sub components which are sodium iodide detector for low-energy photons (8 keV to 1 MeV) and bismuth germenate detector for high-energy photons (0.2 MeV to 40 Mev). GBM detectors distribute around the telescope to be a closed circuit camera and looking for a flare of the γ-ray. The actual purpose of GBM is not a detector for collecting a high quality data but it is attached in the spacecraft to assist the LAT for mainly looking at an interesting events that could produce a huge amount of γ-rays. The content in this chapter will deep down into more detail of LAT in depth and would not provide more detail of GBM.

2.2.2 Large Area Telescope (LAT)

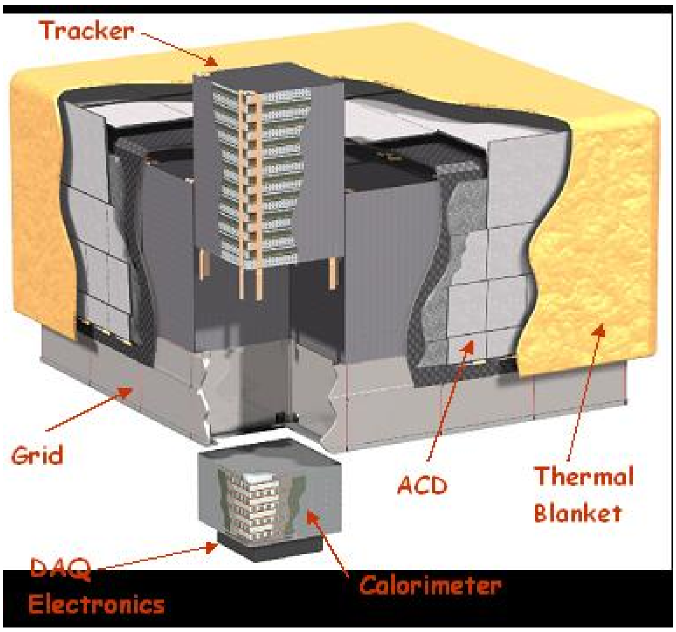


Figure 2.11: Instrument structure (Image taken from https://fermi.gsfc.nasa.gov)

LAT consists of tracker (TKR) module for tracing the incoming photon, calorimeter (CAL) for measuring the kinetic energy after the particle has been passed through the tracker because a charged particle interact with the CAL and dissipate since it enter the module and anti-coincidence Detector (ACD) for rejecting the background signal. The last part is the on-boarding data acquisition (DAQ) module for investigating the particle's footprint and digitize the signal.

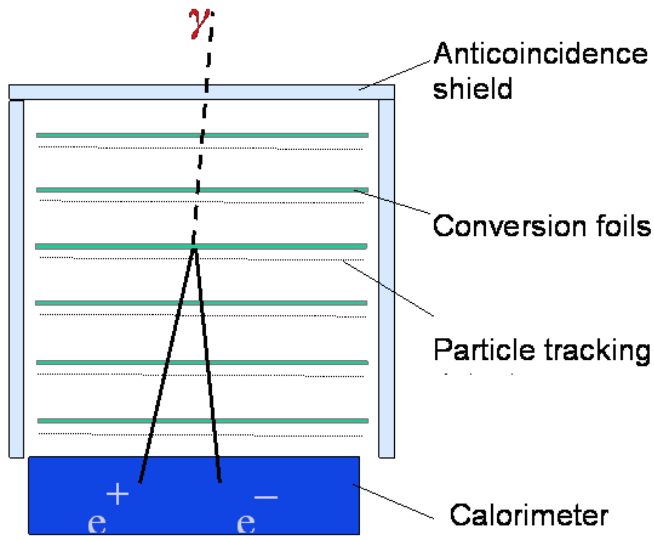


Figure 2.12: Schematic structure of the LAT (Image taken from https://fermi.gsfc.nasa.gov)

Tracker

Higher energy photon or γ-ray talk to the LAT by converting the kinetic energy into a pair of lightweight leptons or e^+e^- pair. The converter-tracker has 16 planes of a large atomic numbers for making the incident γ-ray convert into a pair of e^+e^- as demonstrated in Figure 2.12. After that, a pair of leptons would leave a footprint as an electromagnetic induction in particle tracker where it sensitive for the moving charge particle.

The particle tracking is made from silicon-strip. Tracking information would leave the track in 2-D plane of a particle tracking. In order to trace back and gaining data as the 3-D moving direction, 16 particle tracker has to be taken in account for constructing the electron or positron path. Despite one layer of particle

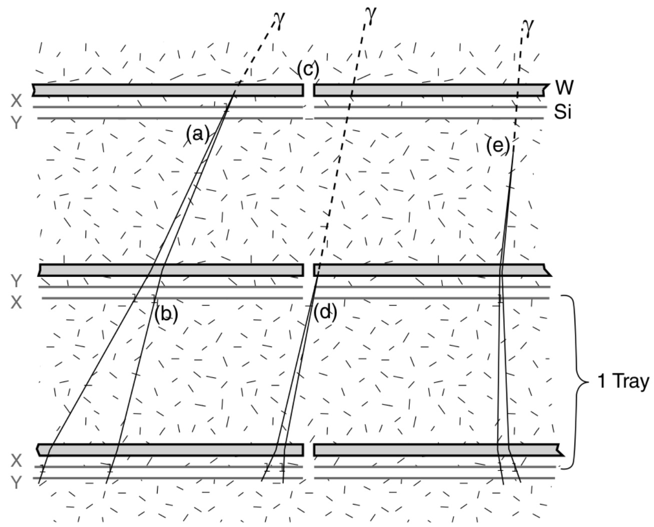


Figure 2.13: LAT's particle tracker (Image taken from Atwood et al. (2009))

tracking could obtain the information about incoming leptons for x-y plane only, but techinical design of LAT does put a 2 layers of silicon-based tracker with a very narrow gap between them. This kind of design could make the LAT performing measurement precision in the angular resolutiom better than a single layer of a wide gap which affects in the point-spread function (PSF) of the probability distribution from reconstruction direction. According to Figure 2.13, top and the bottom of silicon trackers and the heavy-nuclei conversion layer called "Tray". Case (a) and (b) in the figure is the ideal case where the γ-ray hit the conversion layer and multiple footprints are recorded. Nevertheless, there is an edge case as in (d) and (e) where the γ-ray has a probability to skip an early layer and choose to covert in the secondary conversion layer and will be detected in the upcoming tracking layer. The major benefit of deploying multiple conversion layers is quite obvious for the better event gathering.

Calorimeter

Unlike particle tracker that talk to a charged particle by utilizing the EM induction without (or barely) disturbing the particle state, calorimeter is a starving component. It consume a lepton and produce electronic readout of the energy from radiation of the lepton in the crystal scintillator. Definitely, size of this part is mainly considered from the radiation lengths of the electron and position particles becasue it has to record the shower that happen during the decaying process. However, the radiation length highly depends on the kinetic energy of the particle. The LAT itself has been designed for detecting photon energy range between MeV to a few hundred GeV. Hence, the exposure of photon energy beyond TeV is probably not promising in this case.

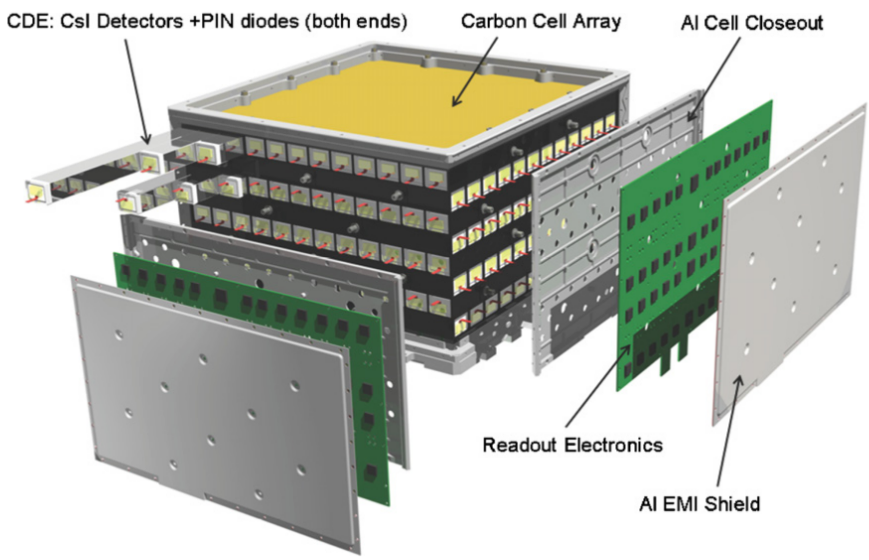


Figure 2.14: LAT's calorimeter (Image taken from Atwood et al. (2009))

The overview apparatus structure is illustrate in Figure 2.14. Each calorimeter module consists of 96 CsI(Tl) scintillator crystal size 2.7 cm x 2.0 cm x 32.6 cm and PIN photodiodes at both ends which connect to the readout electronic components for translate an amount of light that has been sparked in the crystal to digitized signal. Each horizontal layer is combined from 12 crystal component and stack them 8 times by rotate them 90°each for boosting the angular resolution from the sparking lights. The carbon cell was build for supporting the structure of low mass particle tracker due to the properties of high stiffness, thermal conductivity and thermal stability. An electron, position or γ-ray will deposit the energy in the calorimeter as the scintillated lights via electromagnetic intereaction. The segmented crystal also allow LAT to trace the shower as the spatial imaging.

Anti-coincidence Detector (ACD)

The main objective of ACD is to support the charged-particle background rejection of the CRs. It is cover the tracker over the LAT field of view (FoV) for 4 side and the top part of the LAT. It consists of 89 plastic scintillator tiles with 5×5 array on top and 4 sides of 16 tiles. Each tile component contains two photomultiplier and wanelength shifting fibers embedded in the scintillator. The tile is overlapping another one in one-dimension to reduce the effect of the gaps between them. To be more prcise, there are two sets of four called scintillator ribbon for covering the top-down side and a pair around their center. The ACD is required to has 0.9997 efficientcy for detecting an incoming charged particle of FoV of the LAT. However, the γ-ray induce the shower that calorimeter will absorb but there is a scenario called "backsplash effect" where the secondary particles in keV range from the electromagnetic shower could interact with the incoming photon and Compton scattering in ACD. Then it could create a veto signal from the recoil electron. In order to solve this issue, the ACD with their neighborhood would take the incident candidate photon into account and could dramatically reduce the effect of the backsplashing.

Data Acquisition System (DAQ)

To acquire an interesting event, event selection could not be done on software on the ground level from the whole raw signal of subsystems because the limitation of the hardware in the current edge. In order to collect an event, raw data will be selected from filtering algorithm on board. The hierarchical structure of data acquisition system (DAQ) was invented for seeking an transient event as shown in Figure 2.15.

The lowest level is tower electronic modules (TEMs) to serve as an interface for the tracker and calorimeter. All TEMs create event buffering and communicates with Event Builder Module (EBM) which is a component of Global-trigger/ACD-module/Signal distribution Unit (GASU). Command Response Unit (CRU) was built to communicate the software execution in DAQ system. Lastly,

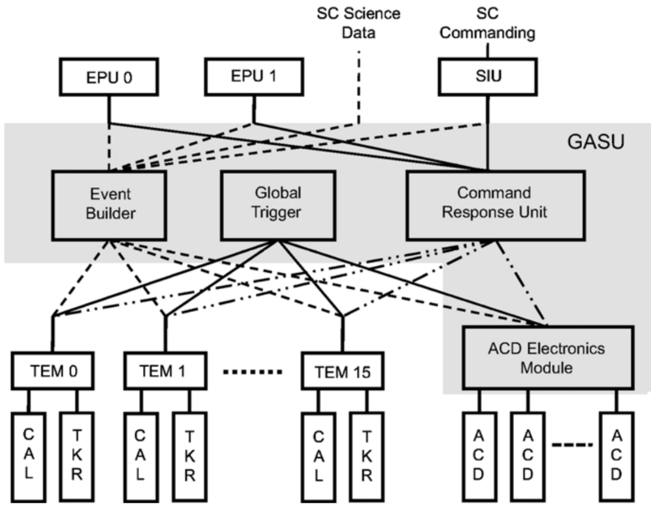


Figure 2.15: Flow chart of LAT's data acquisition system (DAQ) (Image taken from Atwood et al. (2009))

Event Processing Unit (EPU) will process a selecting event from TEM and ACD Electronics Module (AEM). Filtering an event could reduce the information flowing rate from a few kHz to around 400 Hz which will be sent back to the ground level.

2.2.3 Event reconstruction

In an early day, the reconstruction algorithm for tracing a photon is Monte Carlo (MC) simulation. Modeling the incident γ-rays and the background has been simulated in the orbiting-like environment before it launch. Meaning that background rejection property already embedded in the LAT since the developing process. The simulation could be use for the detector calibration since the simulation software provide an interaction physical process.

The main logic of the reconstruction is started by tracking the footprint in the tracker and expect the output in calorimeter cube as physical process would yield. After that the event classificaiton mainly consider from the ACD part to classify an event types.

The result from processed data on the fly is level 0 and it will pass down to Earth and reconstructing the photon data called level 1. The more LAT orbiting around the Earth's, the more understanding of the LAT environment and it brings the software improvement for the reconstruction algorithm to exploid the technique of pattern recognitions. First official released is LAT data is Pass 6 and Pass 7 after has been released with the same level 0 data but the reconstructed event is more efficient than the older one by software level. The newest version and likely to be the final version is Pass 8. Not only the reconstruction algorithm that has been devided but the event class is also an crucial concept. As mentioned earlier, the photon is clsssified into a specific class. There is no free lunch to think that the detector see the particle as a binary classificaiton. It will mix with a likelihood or probability to distinguish the specific kind of interesting event. That is the main reason why *Fermi*-LAT team split the event into multiple classes which mainly are TRANSIENT, SOURCE, ULTRACLEAN and ULTRACLEANVETO.

Definitely, lesser photon candidates has been selected in the ULTRACLEANVETO. Then there is no certain right or wrong for picking the class from researcher point of view. The main criteria would be the objectives of the analysis. If the analyzer want a huge events and could accept some noisy event, then SOURCE or TRANSIENT class is suitable for the analysis and vice versa.

2.2.4 Detector performance and their characteristics

""will be add after done Methodology""

CHAPTER III
LITERATURE REVIEW

CR induced γ-ray emission $\rightarrow$ Abdo et al. (2009)

One of the most impactful study of CR's acceleration mechanism was conducted by Enrico Fermi (Fermi (1949)). He describe how high energy CR particle gain such a huge momentum from shock wave that was generated by supernovae or a great explosion from the heavy dense star. How it gains the kinetic energy could be described as a first order shock acceleration

$$\frac{dN(E)}{dE} \propto E^{-\gamma} \tag{3.1}$$

...

CHAPTER IV
METHODOLOGY

Procedure of getting data to perform an analysis from the collected data is very important. In order to get a precise Earth's limb γ-ray spectrum to trace back the incident proton spectrum, it is crucial to carefully determine the selection criteria from raw data in many angle base on the objectives. This chapter will begin by giving information of γ-ray flux extraction by providing information of data filtering and the extracting process from scratch. Secondly, hadronic collision model that forwardly yield the γ-ray spectrum will be discuss and tracing the incident CR's proton spectrum algorithm from heuristic optimization. Lastly, the last sub-chapter contains details of statistical analysis.

4.1 Data selection

In this work, 9 years of LAT's flight data has been used to analyze reconstructed photon and their metadata of spacecraft log recorded in a similar format periodically every half minutes. The reconstructed algorithm version is the latest version which is Pass 8 with the cleanest photon events that exists from *Fermi*-LAT data catalogues called ULTRACLEANVETO. To be more precise, the photon data is collected from publically available raw FITs file from the

Only high energy limb's photon will be selected from 10 GeV up to 1 TeV. It makes the tracebacking analysis for gaining the information of CR proton spectrum in rigidity between 60 GV to 2 TV. The definition of γ-ray's limb regiom is obtained from Abdo et al. (2009) in a given nadir angle from 68.4°to 70.0°. The maximum of incident angle (θ_{LAT}) that was measured from the z-axis of the LAT's foresight is 70°.

4.2 Flux extraction

There are multiple step from trivial to complex calculation to obtain the differential flux. The definition when saying flux is actually a differential flux that be calculated one chunk of energy range at a time as Equation 4.1

$$\textbf{Flux} \equiv \frac{dN_\gamma}{dE} = \frac{\int_{\text{Limb region}}(\text{Count map}/\text{Exposure map})}{\Delta\Omega\Delta E}. \tag{4.1}$$

Since the CR spectrum follows a power law as the exponential form $dN/dR \propto R^\gamma$ as mentioned in the background section. Then the log-log relation of the flux versus rigidity would behave like a trivial linear trend in the plot. Not only the rigidity, but in the high energy CR like 10 GeV also makes the energy of the particle almsot the same as the rigidity does. Consequently, the γ-ray spectrum is equally divived in the energy space in the log scale for 50 bins.

To get the spectrum, it is obvious to construct the histogram with 50 bins in a given energy scale as explained in the previous paragraph. The flux of each bin could be computed separately by initializing the empty count map and the exposure map where it represents the exposure time and the effectiveness of the spacecraft when looking at each angle in the sky. Let regards the following example for a deeper understanding. The ideal scenario is when incident γ-ray walk pass through the LAT in a normal line of the detector. Definitely, the performance would be the highest as it could do. On the other hand, if the incident γ-ray arrive with high tile angle from the LAT's plane (High θ_{LAT}). An angle resolution is selected to be 2°in ϕ_{NADIR} and 0.1°in θ_{NADIR}. The reason behind these number is simply from the toy experiment of plotting the result in the 2D histogram and it is selected to be the one as the bin value is not too noist. In another words, it should not be too small so that the result is not too noisy and it is should not so big due to the limb region could not be seen clearly which leads to the matched photon mixed up with the Earth's γ-rays and collecting too many primary CR photon.

Basically, the procedure is summarized in these following steps.

1. Make 2D histograms with 25 bins per decade of energy

2. Select photon data and fill in the 2D histograms

3. Calculate exposure maps which include the effective area and livetime of the LAT as it observed the Earth

4. Compute the flux by applying Equation 4.1 in for bin

5. Taking consider background subtraction from a average uniform background photon distribution by treating bin by bin

4.2.1 Exposure map gathering

In fact, step 3 is the most complicate stage in this work. Practically, *Fermi*-LAT was designed for observing the space which makes the spacecraft logging in equatorial coordinates not for the Earth's polar coordinates. The LAT position is recorded in equatorial coordinates as well as the normal line of the detector plane to log their orientation during the orbit. Basically, there are three coordinates. First

4.3 Optimization

4.4 Monte Carlo Simulation

4.5 Likelihood ratio test (LRT)

CHAPTER V

RESULTS AND DISCUSSION

5.1 Limb's angle correction

5.2 γ-ray measurement

5.3 Best fit result

5.4 Error determination

CHAPTER VI
CONCLUSION

example cite Curie (1923)

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APPENDICES

APPENDIX A
BLA

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BIOGRAPHY

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