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The Fermi - LAT Measurement of the Cosmic-ray Proton Spectrum

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The Pass 8 gamma-ray simulation and reconstruction package for the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope has dramatically enhanced the ability of the LAT to perform gamma-ray science. The Pass 8 improvements have also allowed for the development of a new cosmic-ray proton analysis. Using the Pass 8 direction and energy reconstruction, we create a new proton event selection that has an acceptance of 1 m^2 sr over the incident proton energy ranges from 20 GeV to over 1 TeV. Applied to over 7 years of LAT observations, the proton data set provides high statistics for a spectral measurement. The systematic errors in the acceptance and energy reconstruction do require careful study. The event selection and spectral measurement of the Pass 8 proton analysis open the door to additional proton analyses with the LAT, such as the evaluation of proton anisotropy. We present a detailed study on the measurement of the cosmic-ray proton spectrum with Pass 8 data for the Fermi LAT.

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1. Introduction

Protons represent the largest fraction of cosmic rays across all energies and the largest portion of events downloaded from the Fermi Large Area Telescope (LAT). The proton event sample covers the entire LAT mission to date (more than six years of data) and extends to greater than TeV energies. The flux and spectrum of cosmic-ray protons are crucial to understanding galactic cosmic-ray origins and propagation. The Fermi Large Area Telescope is in a unique position to explore the spectral shape and investigate the spectral break at 300 GeV observed by Pamela and AMS-02 [1] [2]. We present the cosmic ray preliminary proton analysis for the Fermi Large Area Telescope.

2. The Large Area Telescope

The Large Area Telescope (LAT) is a pair conversion γ-ray telescope designed to measure high energy γ-rays from 20 MeV to more than 300 GeV. The LAT can be used to study more than γ-rays–its particle detector capability allows the study of protons to energies over 1 TeV. The three subsystems of the LAT are the tracker, calorimeter, and anti-coincidence detector. The LAT consists of 4 x 4 towers that measure incident direction and energy of incoming cosmic-rays. Each tower contains a tracker and a calorimeter module. A tracker module is 18 interlaced silicon strip detectors with 16 tungsten foil conversion layers. The tracker has a depth of 0.1 nuclear interaction lengths at normal incidence. The tracker's main purpose is to measure the direction of incoming cosmic ray, in addition the silicon strip detectors can measure time over threshold (ToT) of signal for each plane in the tracker which can be used to measure charge of the incident cosmic ray. Each calorimeter module consists of 96 CsI(Tl) crystals in a hodoscopic array of 8 layers and has a total depth at normal incidence of 0.5 λ_i. The calorimeter measures the deposited energy of the cosmic ray and its hodoscopic nature allows the imaging of the shower shape for distinguishing between hadronic and leptonic showers. The final subsystem is an anti-coincidence detector (ACD) composed of segmented plastic scintillator that tags > 99.97 % of charged particles and covers the tracker and calorimeter. The ACD can be used for measuring the charge of the incoming cosmic ray [3].

The Pass 8 Cosmic-Ray Electron studies provide an important framework for the preliminary proton analysis [4]. The main challenges of a proton spectrum measurement with the LAT include identification of protons from other cosmic-ray species such as electrons, helium, and other heavier ions ($Z > 1$); the poor energy resolution for hadronic showers due to the shallow depth of the calorimeter; and the systematic uncertainties in the acceptance and energy measurement.

3. Proton Event Selection

To perform the preliminary proton analysis, we use 3 months of Pass 8 data from February 3, 2012 to May 3, 2012 for a live-time of 5,929,558 seconds. This data set contains populations of predomintintly protons but also electron, positirons, helium ions, and heavier ions ($Z > 1$). We use three distinct Monte-Carlo simulations: protons from 4 GeV to 20 TeV, electrons from 10 GeV to 10 TeV, and a simulation of the background environment with realistic spectra and fluxes–containing protons, electrons, positrons, helium, and heavier ions up to iron.

To determine whether an event is valid for the event selection, we establish a set of basic quality cuts which ensures a well reconstructed direction and energy. The final step in the event selection is to reduce contamination of non-protons to a negligible level, providing a flight data sample of high purity protons.

3.1 Quality Cuts

We use a sequence of cuts to define a sample of high-quality proton events with well reconstructed direction and energy. The cuts require each event have a reconstructed track from the tracker which passes through at least 4 X_0 and deposit greater than 20 GeV of energy in the calorimeter. This takes advantage of the fact that the on-board filter is turned off for events with greater than 20 GeV energy deposited in the calorimeter, therefore this analysis does not need to take account of complicated and unknown filtering effects in the event rate and acceptance. A detailed explanation of the LAT on-board triggers and filter can be found in [5]. To remove Z> 1 ions from the data, we use two independent charge measurements, path-length corrected deposited energy in the ACD and ToT for the best track, to create a polygon around the desired phase-space as seen in Figure 1.

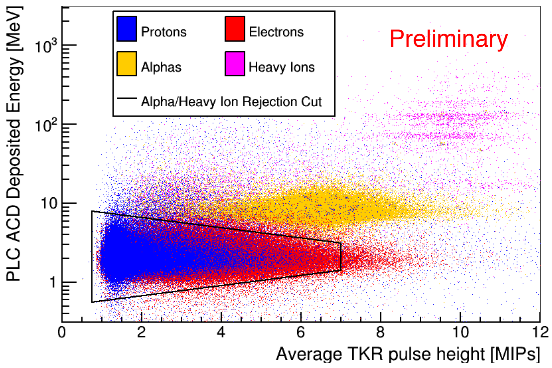

Figure 1: Path length corrected ACD deposited energy vs average time over threshold for best track from simulations show a clear separation between different cosmic-ray populations. The Alpha/Heavy ion rejection cut is also shown.

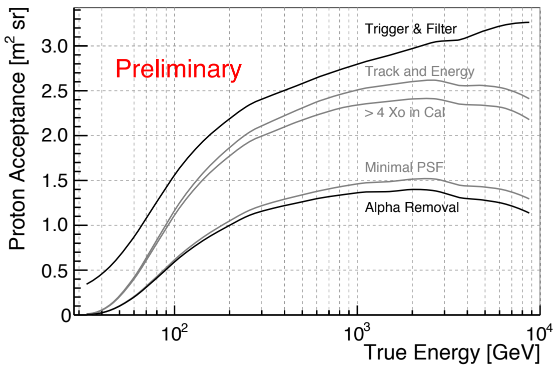

Figure 2: The effect each quality cut has on the proton acceptance measured in m^2 sr in true energy.

The effect each quality cut has on the proton acceptance can be seen in Figure 2. After all of the quality cuts have been applied, a maximum acceptance of 1.2 m^2 sr at TeV energies is left. These cuts leave a population of electrons as the last contamination source to be removed and a residual alpha/heavy ion contamination of $< 1\%$.

3.2 Proton Classifier

We use the TMVA package in ROOT to train a classification analysis based on boosted decision trees (BDTs) [6][7]. Applying the BDT classifier to the proton data set allows for the removal over residual electrons while maximizing proton efficiency.

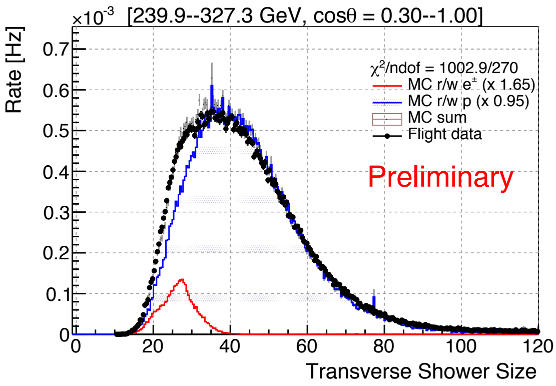

Figure 3: The data/simulation comparison of a variable (transverse shower size) used in the classification tree for one energy bin. Black points represent flight data, red and blue points represent reweighted models for electron/positron and proton.

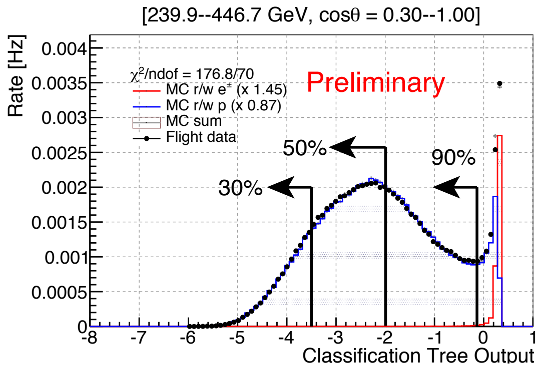

Figure 4: The data/simulation comparison for the output of the classification tree for one energy bin. Black points represent flight data, red and blue points represent reweighted models for electron/positron and proton. 90%, 50%, and 30% markers show the respected scanning proton efficiencies.

The first step in training our classifier is to select several variables that show separation between the electron and proton populations and have good agreement between flight data and simulations. Many of the variables used in the training the classifier originate from the Pass 8 shower profile fitter which uses the calorimeter's 3D imaging capability to measure the shape of the cosmic-ray showers. Variables such as the transverse shower size can be used to distinguish the intrinsically broader proton-initiated hadronic showers from the more compact electromagnetic showers from electrons and positrons. In Figure 3, the proton and electron simulations are reweighted to realistic cosmic-ray spectra and compared to flight data to show data/simulation comparisons for a variable used in the classification tree analysis.

We train the classifier with a signal of protons and background of electrons with a boosted decision tree. Selecting on the optimal value of the classifier output for each energy bin, we can build an energy-dependent cut with the classifier output to efficiently remove electrons from the proton data sample. Figure 4 shows the data/simulation comparison for the output of the classification tree, again using realistic spectra for proton and electrons for both the optimized selection on the classification tree and different proton scanning efficiencies used to study systematic uncertainties in the acceptance and contamination. We use a template fitter developed for the LAT cosmic-ray electron analysis group to measure the rate of electrons and positrons in flight data and subtract this background component from our proton sample [4].

4. Instrument Performance

We determine the optimal event selection in each energy bin by minimizing electron contamination while maximizing proton acceptance. The optimal proton event selection are used to determine the acceptance, residual electron/positon contamination, and energy resolution for the

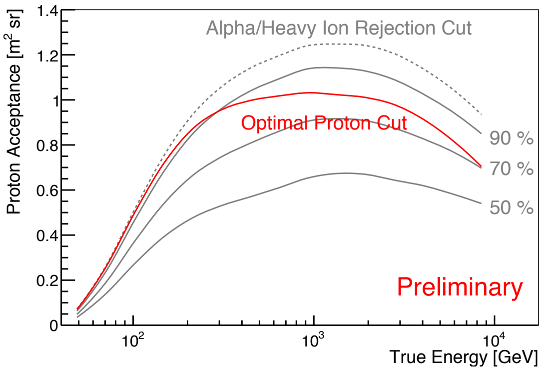

Figure 5: The acceptance for optimized classification tree cut (red line) and cuts with constant proton efficiency (gray lines) as shown in Figure 4.

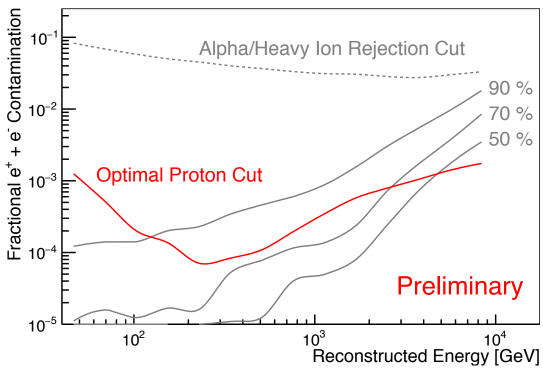

Figure 6: The contamination for optimized classification tree cut (red line) and cuts with constant proton efficiency (gray line) as shown in Figure 4.

proton analysis. The different constant proton efficiencies are used to establish the stability of the proton event class and probe systematic uncertainty in the acceptance and contamination.

4.1 Acceptance and Contamination

To estimate the acceptance using the proton simulation the following formula is used:

$$\mathscr{A}_{eff}(E) = 4\pi\ sr\ \times A_{gen} \times \frac{N_{acc}(E)}{N_{gen}} \tag{4.1}$$

where A_{gen} is the generating area in m^2, N_{acc} are the number of events passing the total event selection for each energy bin, N_{gen} are the number of events generated.

The estimated proton acceptance, Figure 5, and residual electron contamination, Figure 6, are shown for different selection cuts: optimized (red line), constant proton efficiency (solid gray lines), and no classification tree cut (dashed gray line). The classification tree efficiently removes electron contamination to negligible levels while maintaining high proton acceptance.

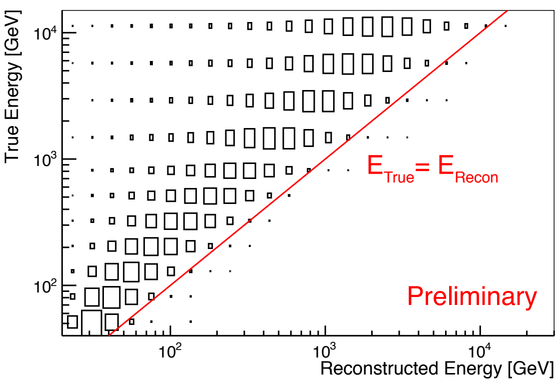

Figure 7: The detector response for protons of the LAT in Reconstructed Energy [GeV] vs True Energy[GeV] from proton simulations.

4.2 Energy Resolution

One of the difficult challenges with a proton spectral measurement with the Fermi-LAT is the energy measurement. Since the LAT's calorimeter has a depth of only 0.5 λ_i at normal incidence, there is little probability of capturing a full hadronic shower development. We estimated the energy of the incident proton using Pass 8's shower profile fitter which fits the shower with an electromagnetic profile and corrects for shower leakage out of the calorimeter. The profile fitter passively selects for hadronic showers which have large and early electromagnetic components in the calorimeter. As seen in Figure 7, the reconstructed energy exhibits an offset from the true energy and an energy resolution of $\sim 30\%$.

The energy resolution is the currently sufficient to measure the cosmic-ray proton spectrum but improvements in the energy resolution will improve the scientific significance. In order to measure the counts spectrum in true energy, one needs to use the detector response in Figure 7 to account for the redistribution of event energies in the measured counts spectrum.

5. Conclusion

The preliminary Fermi-LAT Proton analysis is able to produce a high purity sample of protons with $< 1\%$ contamination from electrons and heavier ions with acceptance on the order of 1 m^2 sr out to TeV energies. This large data sample of high purity protons can be used for a variety of scientific purposes including spectral and anisotropy analyses. With this preliminary proton analysis we will measure the cosmic-ray proton spectrum from 50 GeV to several TeV.

Acknowledgments

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