Instrument simulation for the analysis of cosmic ray electron with the Fermi LAT

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Abstract. The Fermi LAT collaboration has built up a detailed Monte Carlo simulation to characterize the instrument response and tune its performance. The simulation code is built around the widely used GEANT4 toolkit and was carefully validated against beam test and flight data. This poster shows how the full LAT simulation is used to develop the event selection for the Cosmic-Ray Electron (CRE) analysis so as to optimize the instrument performance. In particular, we will show in detail the determination of the geometry factor and the residual hadron contamination. The very accurate MC simulation proved to be fundamental to control the systematic uncertainties on the CRE spectrum measured by the Fermi LAT.

Keywords: Cosmic ray electrons; spectral analysis; Monte Carlo.

I. INTRODUCTION

The Fermi Large Area Telescope (LAT) is designed to provide an accurate measurement of the incoming direction, energy and time of incident γ-rays that convert in $e^+ + e^-$ pairs within the instrument. The LAT is composed of three detector subsystems. A tracker-converter made of silicon strip detector layers interleaved with tungsten foils to enhance the photon conversion probability. A calorimeter composed of CsI crystals arranged in a hodoscopic array in order to image the development of the electromagnetic shower and measure the energy of the incoming γ-ray. A scintillator tiled anticoincidence detector that surrounds the tracker and provides the main identification of charged vs. neutral incoming particles. More details on the instrument can be found in [1].

Due to its capability to reconstruct electromagnetic showers and separate them from hadronic showers, the LAT is naturally a cosmic ray electron detector. No dedicated event reconstruction is required since the topology of electron initiated showers is very similar to the one of photon initiated showers.

The main advantage of this instrument with respect to previous ones is the large collection area and the long operation time that allows the accumulation of large statistics during its life time. The main disadvantage is that electron-positron separation is not possible.

The event analysis to identify electron candidates as well as the evaluation of the instrument response functions is studied and optimized using a detailed Monte Carlo (MC) simulation. This paper describes the simulations required for the CRE study and how they are used for the spectrum reconstruction [2].

II. INSTRUMENT MODEL

The Fermi LAT collaboration uses a very detailed MC simulation to study the instrument performance and the response to celestial sources. The software code uses a precise description of the LAT geometry that includes the position and the material of all the detector elements, both active and passive. The simulation is based on the GEANT4 [3] toolkit, widely used in high-energy physics experiments, to model particle propagation and interaction through the instrument (energy loss, multiple scattering, etc.) and therefore the energy deposition in the active detector elements. A digitization algorithm takes care of converting this information into raw detector quantities that can be processed, by the reconstruction algorithms, in the same way of the real data. The digitization algorithm has the capability of including detector “defects” like sensors misalignment, real gain and noise level, non lineairities etc. In this way the reconstruction algorithm can use the actual calibration constants and the MC can provide a very accurate representation of the instrument response.

The MC simulation has been extensively used for the design of the instrument and optimization of the event reconstruction and background rejection analysis. The Instrument Response Functions that are used in the γ-ray analysis are evaluated using the MC. A similar scheme is employed in the CRE analysis and therefore the role of the simulation is crucial.

No Monte Carlo simulation is perfect, hence both the physical processes and the geometry implementation have to be validated by comparing the simulation results with real data. The LAT MC has been verified on ground with cosmic rays and with a series of beam tests on a Calibration Unit (CU) at CERN PS and SPS and at the GSI heavy ion accelerator laboratories [4]. The Calibration Unit, composed of flight spare LAT modules (corresponding to about 1/8 of the LAT), has been exposed to beams of electrons, hadrons and heavy ions in several configurations of beam energy and incoming

1In this paper the word “electron” refers to the combination of positrons and electrons.
angle. Figure 1 shows an example of data-MC comparison for one of the tracker quantities that are relevant for CRE analysis. The overall agreement between the MC simulations of the CU and the beam test data are good. A further verification of the agreement between LAT data and MC simulation is performed using on-orbit simulation.

III. ON-ORBIT ENVIRONMENT SIMULATION

The detection of the CRE with the LAT takes advantage of the on-orbit particle environment model built by the LAT collaboration. This highly detailed model has been intensively used to develop all the γ-ray background rejection algorithms, both on-orbit and off-line. The model includes cosmic rays and earth albedo γ-rays starting from 10 MeV and is valid outside the South Atlantic Anomaly (since the LAT does not take data inside). The particle fluxes are chosen to fit experimental data of several past experiments, more details can be found in [1]. In addition to the primary component of the cosmic radiation, the model includes the secondary particles produced by the interaction with the atmosphere and the Earth magnetic field taking into account the geomagnetic cutoff and East-West effect.

This model plays a fundamental role in the CRE analysis. It provides a realistic simulation of the background particles, mainly protons, for the LAT on-orbit. Together with the electron simulation described in section IV, it has been used to identify the quantities, in the event reconstruction, that are most sensitive to the difference between electromagnetic and hadronic shower topologies. The CRE event selection is, thus, based on the information provided by the simulation of the LAT in the true orbital environment. Notice that the CRE event selection (described in more details in [5]) uses a Classification Tree technique which was trained on MC simulation. Figure 2 shows the output of the Classification Trees on a sample of electrons and hadrons simulated using this detailed cosmic ray model. The comparison with real LAT data shows a good agreement.

The on-orbit background model was also used to evaluate and subtract the residual contamination in the electron event sample. Because the model describes a realistic on-orbit environment, it can be used to estimate the residual background rate as a function of the measured energy by dividing the number of events that survive the event selection by the simulated collection time. This estimate of the background rate is subtracted from the total event rate measured by the LAT as shown in figure 3. The residual contamination, evaluated as the ratio between residual background rate and the candidate CRE rate, provides a useful figure of merit for the quality of the analysis (fig. 4). With this procedure the residual contamination depends only on the model of primary protons and its systematic uncertainty on the absolute scale is taken into account in the total systematic uncertainty. The production of this MC sample was one of the most important and time consuming activities for the CRE spectrum measurement. Because of the required high rejection power, about $10^3 - 10^4$ simulated events are needed to obtain one event that leaks through the selection and can be used for residual background rate evaluation. The power law spectrum in $E^{-2.7}$ of primary protons (the main background source) makes it even harder to populate the high energy region of the spectrum. To evaluate the residual background rate used in the CRE spectrum measurement, about 400 CPUs for 80 days of computing time were used.

IV. ELECTRON SIMULATION

Together with the background model, a pure electron model was used to simulate the LAT response to CRE. This model does not include all the details of the LAT on-orbit, but provides an isotropic flux in the LAT reference frame. In this way the evaluation of the
The energy dispersion is another important figure of merit to quantify the effect of the low energy tail. The energy resolution of the LAT for each energy bin, using the on-orbit environment contamination required an intense but successful work. Also, the production of the large amount of simulated data required for the electron selection (together with the background model), but without exceeding 30% at 1 TeV. A further check on the energy reconstruction is done evaluating the most probable value by fitting the peak with a LogNormal function and verifying that it does not differ significantly from 1 in the whole energy range. This ensures an unbiased response at least up to 1 TeV.

The electron simulation was used to develop the event selection (together with the background model), but also to evaluate the LAT performance and the response functions for spectrum deconvolution. These response functions parametrize the energy response of the LAT and its geometrical acceptance as a function of true (MC) energy. The acceptance (geometry factor) is calculated as proportional to the fraction of events surviving the selection in each energy bin. The normalization constant depends on the area and the angle over which the events have been generated. The result of this calculation is shown in figure 4. The sharp increase just after 30 GeV is mainly due to the on-board event selection designed to remove charged particles with deposited energy lower than 20 GeV. The shape of the geometry factor is almost entirely due to the event selection that must obtain a good background rejection power in the whole energy range.

The energy dispersion is another important figure of merit to quantify the LAT capability as an electron spectrometer. It is evaluated dividing, event by event, the reconstructed energy by the true energy. The resulting rate (in black) is deconvolved with instrument response functions to provide the electron spectrum. 

response functions does not depend on orbital details while the isotropic distribution of incoming electrons is a good assumption also for real operation. The energy distribution in this model is a power law with index $-1$, so that we can accumulate high statistics in the whole energy range in a relatively short simulation time. 

The Monte Carlo simulation has a central role in the measurement of the cosmic ray electron spectrum. It was used to develop the electron selection algorithm and to evaluate the instrument response functions for spectrum reconstruction. The LAT collaboration made a large effort to build such a detailed description of the instrument and its on-orbit behavior. Also, the production of the large amount of simulated data required for the electron analysis and in particular the evaluation of residual contamination required an intense but successful work. This extensive simulation, supported by beam test data...
and verified with flight data, allowed the measurement of the most precise electron spectrum in the energy range 20 GeV to 1 TeV.

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**References**

[1] W. B. Atwood et al., *The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission*, submitted to The Astrophysical Journal (arXiv:0902.1089v1)

[2] A. A. Abdo et al., *Measurement of the Cosmic Ray e⁺ + e⁻ spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope*, Phys. Rev. Lett., 102, (2009) 181101

[3] J. Allison et al., *Geant4 developments and applications*, IEEE Trans. Nucl. Sci., vol. 53 no. 1 (2006) 270-278

[4] L. Baldini et al., *Preliminary results of the LAT Calibration Unit beam tests*, Proceedings of the first GLAST symposium, AIP Conference Proceedings Vol. 921 (2007) 190-204

[5] M. N. Mazziotta, *Data analysis for the measurement of high energy cosmic ray electron/positron spectrum with Fermi-LAT*, these proceedings