Fermi-LAT Measurement of Cosmic-ray Proton Spectrum
Paper Outline - Version 0

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Abstract

The Pass 8 gamma-ray simulation and reconstruction package for the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope has 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. This event selection has an acceptance of 1 m^2 sr over the incident proton energy range from 50 GeV to over 8 TeV and when applied to over 7 years of LAT observations provides over 700 million events for a spectral measurement. The systematic errors in the acceptance and energy reconstruction require careful study and will contribute significantly to the spectral measurement. The event selection and spectral measurement of the Pass 8 proton analysis opens 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.

1 Introduction

(I) Describe overview of LAT

- (A) Launch date to give early context of how much data there is available
- (B) Orbital parameters to show what kind of space environment we have to deal with
- (C) Development of Pass 8, short list of improvements and how this enables use to make a new proton analysis with the LAT

(II) Discuss recent developments of the CR proton spectrum from instruments

- (A) AMS-02 observes break in spectrum at 300 GeV
- (B) Potentially resolves discrepancy between satellite measurements in 100s GeV energy and balloon-borne measurements
- (C) But.... AMS-02 only goes to 1.8 TeV, statistics limited due to small acceptance and X years of flight
- (D) Gap left between 1.8 TeV of AMS-02 and 3 TeV of CREAM

(III) Goals of this analysis

- (A) Measure the cosmic-ray proton spectrum from 50ish GeV to several TeV
- (B) Fermi LAT in unique position to measure spectrum spanning between satellite measurements and balloon borne measurements
- (C) Also able to confirm spectral break as currently only seen by AMS-02 and possibly by Pamela
- (D) Create a new data set of cosmic-ray protons for future analysis (I'm not sure we really need this in the paper but might be nice to mention)

(IV) Event selection for high quality proton sample

(V) Energy reconstruction, biases, energy resolution, and limitations

(VI) Describe out instrument response: acceptance and contamination

(VII) Describe the methods used for spectral reconstruction: unfolding and forward folding using response matrix derived from MCs

(VIII) Describe evaluation of systematic uncertainties

- (A) Due to event selection: acceptance and contamination
- (B) Energy measurement: absolute energy scale and energy resolution
- (C) From hadronic model of Geant4 simulations
- (D) Spectral reconstruction: comparing unfolding and forward folding methods

(IX) Finally discuss observations and features of measured spectral, including possible spectral break and agreement with recent results (definitely need to but this in context with other measurements since while energy resolution is poor and systematics less precises than AMS-02 we can extend the energy further into the region of balloon-borne detectors which have never been done before and makes a quantitative connection between two different observation environments)

2 Event Analysis

(I) Overview

- (A) Description of the LAT
- (B) 4×4 array of towers which measure direction and energy of incoming cosmic-ray
- (C) Each tower is composed of TKR and CAL
- (D) TKR information
  - (i) Each TKR module is 18 x-y planes of silicon-strip detectors with tungsten converter foil
  - (ii) Total of 1.5 X_0 at normal incidence (should convert this to nuclear interaction length)
  - (iii) X-Y nature and depth of TKR allows for determination of initial direction of cosmic-ray
  - (iv) Additionally able to measure the time over threshold of CR
  - (v) ToT allows for measurement of signal $\propto \mathrm{Z}^2$
- (E) CAL information
  - (i) CAL is homogeneous electromagnetic calorimeter
  - (ii) Each CAL module is 96 CsI(Tl) crystals in an hodoscopic array in 8 layers.
  - (iii) The hodoscopic nature of the CAL allows for measuring the shape and evolution of each particle shower which can be used with a profile fitter to determine the incident energy of the cosmic-ray
  - (iv) At normal incidence the CAL is 0.5 λ_i lengths deep but at horizontal incidence is it 1.5 λ_i deep
- (F) Anti-coincidence detector (ACD) surrounds the 4×4 tower array
- (G) ACD information
  - (i) 89 segmented covering 5 sides of the tower array
  - (ii) Each tile independently measures deposited energy from CR
  - (iii) Deposited energy $\propto \mathrm{Z}^2$
- (H) LAT was not designed for accurate measurement of hadronic showers
  - (i) Very shallow homogeneous calorimeter not idea for fully capturing energy hadronic shower profile
  - (ii) Compare to CREAM and/or AMS-02

(iii) Unable to measure energy on an event by event basis, need to focus on a statistical ensemble approach with high event rate

(iv) Therefore need to be aware of limitation of energy measurement and associated systematic uncertainties

(II) Pass 8 Event Reconstruction

(A) I'm not 100% sure of the depth of this section but seeing as though we are using Pass 8 and that was a somewhat critical step into enabling this analysis's possibility I think having a dedicated section in the Event analysis chapter might make sense. If we put it anywhere it should be rather early before the simulations and after the describing the instrument

(B) Pass 8 is the new event reconstruction and simulation software developed by the Fermi LAT collaboration that drastically improves LAT's performance

(C) New event classification using boosted decision trees in TMVA

(D) More variables gives better separation between hadronic and leptonic showers in TMVA

(E) Improved profile to fitting to particle showers improves energy measurement

(F) New tree based TKR reconstruction allows for direction reconstruction at higher angles and larger energies

(G) New ACD reconstruction provides better particle identification, lowering the contamination of proton sample

(H) Is there something else I am missing from Pass 8? There is no Pass 8 paper to reference this so I am not sure how in depth I should go into this discussion.

(III) Monte Carlo simulations

(A) Need to stress the importance of the simulations since this is how we derive all of our instrument response functions

(B) Also use simulations for the development of TMVA selection to remove contamination for other CRs

(C) Simulations based on Geant4

(D) LAT instrument and spacecraft are fully simulated within Geant4

(E) Particles with distributions of energies, directions, and charges are generated and propagated with realistic physics models for interactions with the simulated LAT which create raw data

(F) Raw simulated data is processed through the same Pass 8 reconstruction software as flight data

(G) We preform extensive comparison between simulated data and flight data to ensure results from MC analyses can be reliably applied flight data

(H) Three types of simulations are used this analysis:

(I) Proton simulation

(i) Simulation run from 4 GeV to 20 TeV

(ii) Cover 4π sr

(iii) Created with an $dN/dE \propto E^{-1.5}$ spectral index

(iv) Original purpose to study Pass 8 CR rejection for studying extragalactic background light

(v) This produces a simulation event sample of over X million events

(J) Electron simulation

(i) 10 GeV to 10 TeV

(ii) Cover 2π sr (the top half of the instrument)

(iii) Created with a $dN/dE \propto E^{-1.0}$ spectral index

(iv) Original purpose of studying instrument response for cosmic-ray electron analysis

        (v) This produces a simulation event sample of over X million events
    (K) Background simulation
        (i) The background simulation was created to accurately simulate the cosmic-ray environment of the LAT during space flight
        (ii) It contains CR particle from Z = 1 to Z = 26, electrons, positrons, neutrons, and Earth albedo gamma-rays
        (iii) All particles are simulated with realistic fluxes using results from recent CR experiments
        (iv) The background simulation used in this analysis simulates about 8 days worth of livetime
        (v) Protons range: 4 GeV - 10 TeV and 4π sr
        (vi) Electrons/Positrons range: 4 GeV - 10 TeV and 4π sr
        (vii) Helium range: 4 GeV - 20 TeV and 4π sr
        (viii) Heavier CR range: 2 GeV/amu - 50 GeV/amu and 4π sr
        (ix) Fluxes are taken to be near solar minimum
    (L) All simulations are produces with an additional setting called overlay events
        (i) Overlay events are created from diagnostic events from flight data and signal is added on top of the simulated data
        (ii) This is mimic the effect of having two events simultaneous enter the LAT (for such high events rates at lower energies is a reasonable assumption)
        (iii) Pass 8 has many new algorithms to handle and reduce the effect of two simultaneous events interacting with the LAT

(IV) Event Selection

(V) Energy reconstruction

3 Spectral Analysis

(I) Instrument Acceptance

(II) Residual Contamination

(III) Spectral Reconstruction

(IV) Systematic Uncertainties

4 Results and Discussion