Fermi-LAT Measurement of 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 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 m² sr over the incident proton energy range from 40 GeV to over 8 TeV. The systematic errors in the acceptance and energy reconstruction require careful study and will contribute significantly to the spectral measurement. We present a detailed study on the measurement of the cosmic-ray proton spectrum with Pass 8 data for the Fermi LAT.

Motivation

- The Fermi Large Area Telescope (LAT) collects a large sample (> 25 × 10^6 events for 3 months) of protons (which are removed from gamma-ray analysis)
- Pass 8 enables the development of a new cosmic-ray proton analysis with new observables that reduce contamination and improve the energy measurement and using techniques developed for the Pass 8 cosmic-ray electron (CRE) analysis
- Explore cosmic-ray protons with energy from 40 GeV to 8 TeV
- Recent AMS-02 measurements show break in spectrum ~300 GeV [2]
- Spectral properties very important for cosmic-ray propagation models

Measuring the Proton Spectrum

- Develop set of quality cuts which ensure well reconstructed direction and low contamination from heavy ions
- Build a proton event classifier for electron removal and event quality
- Estimate instrument response from proton Monte-Carlo simulations
- Use instrument response for redistribution of event energies and measure proton spectrum
- Event analysis and classification framework developed for the Pass 8 Electron analysis

Quality Cuts to Select Protons

- **Minimal Quality:** Event has a reconstructed track with well reconstructed direction, and ≥ $4X_0$ in the calorimeter (CAL)
- **Energy Cut**: Event has ≥ 20 GeV deposited energy in CAL
- Utilize Hi-Pass Filter: All events with CAL deposited energy ≥ 20 GeV downloaded from LAT. Sets a minimum true energy ~ 40 GeV

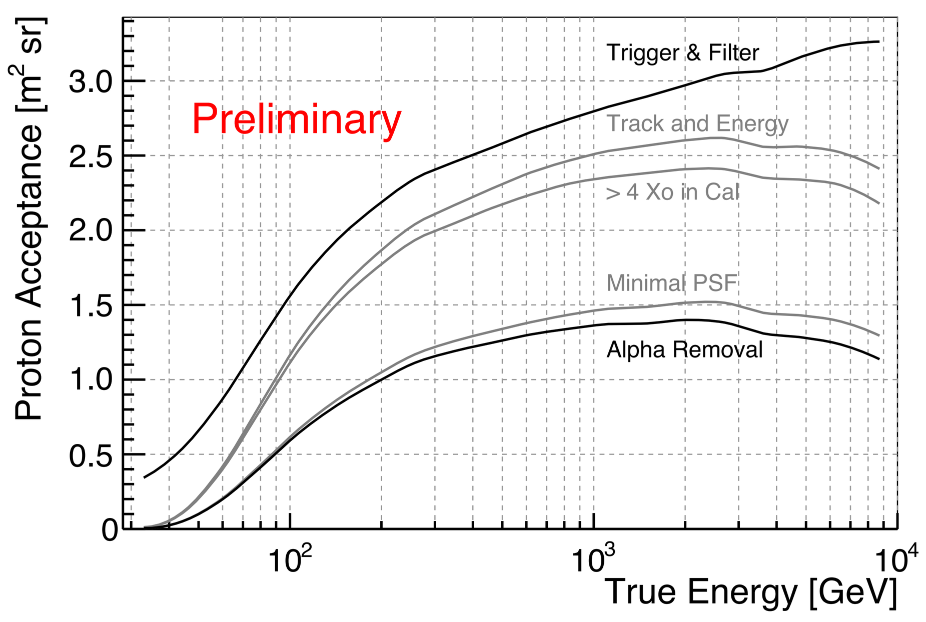

Figure 1: *Proton acceptance in m² sr for successively applied quality cuts*

- Remove Z > 1 CRs before training the proton classifier
  - Cut on path length corrected (PLC) ACD energy and average tracker (TKR) pulse height which both independently measure charge of incoming cosmic ray
- Contamination from Z>1 CRs is estimated at < 1%

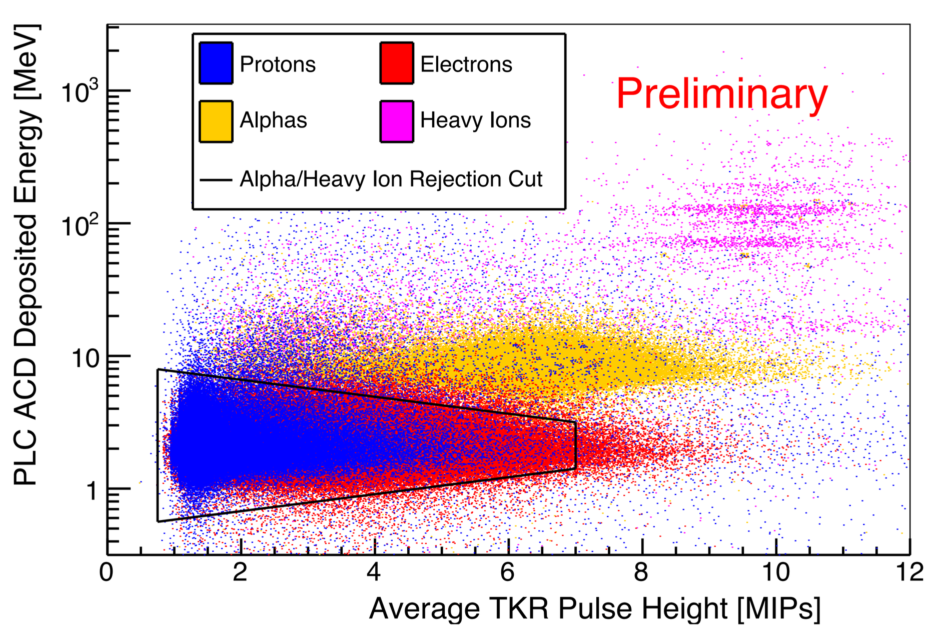

Figure 2: *PLC ACD energy vs average TKR pulse height from simulations show separation between cosmic-ray populations*

The Proton Classifier

- Use multivariate analysis to remove residual electrons
  - Trained on simulations of e± as background and protons as signal
  - Use variables that measure shower shape and energy evolution in CAL
- Use output to decide if event is proton or e±
  - Optimize cut on classifier by selection on signal vs background efficiency

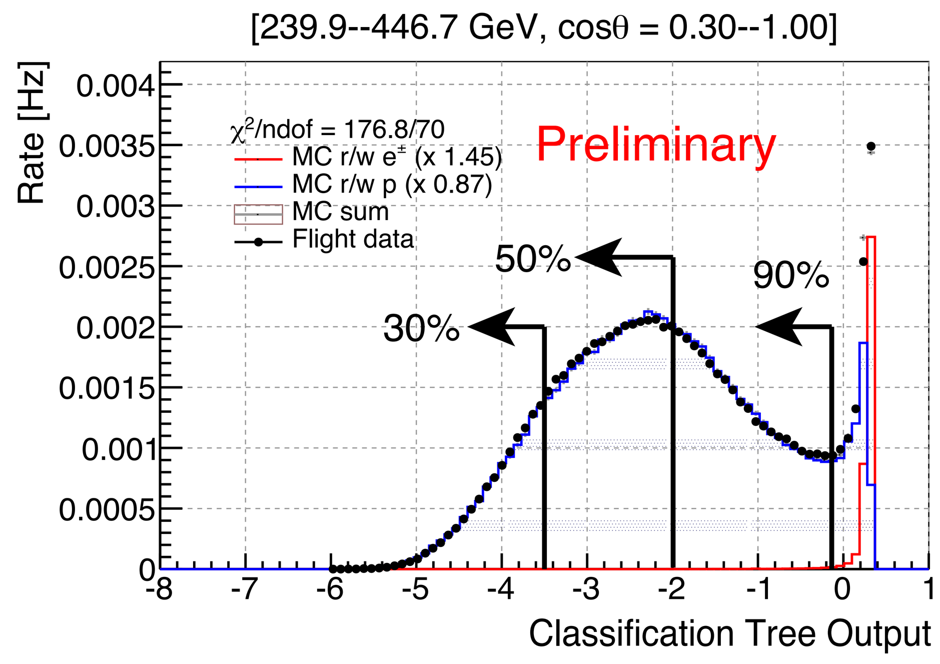

Figure 3: *Data/simulation comparison for the classifier output for 240 GeV to 450 GeV*

- Scanning several constant signal efficiencies (90%, 70%, 50%, etc...) allows to estimate systematic errors in the acceptance and contamination

Instrument Response for Protons

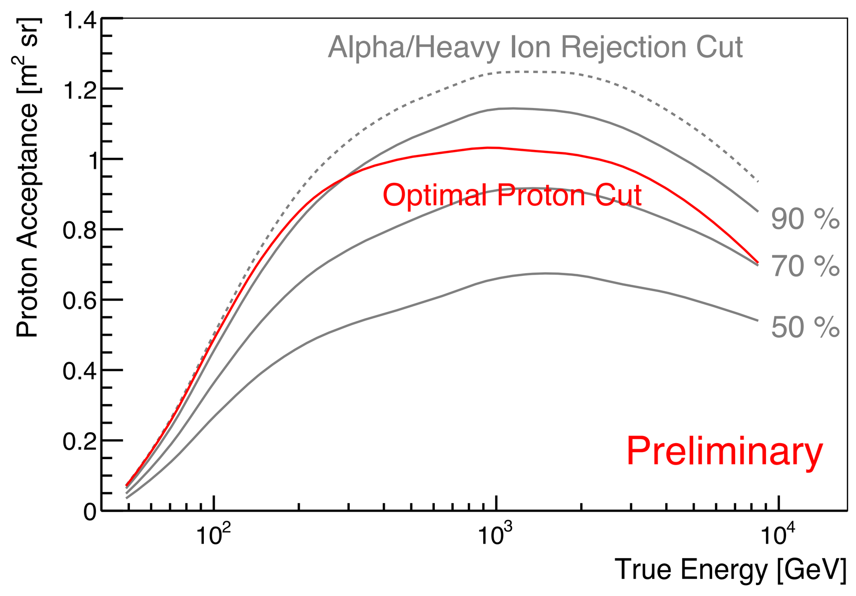

Figure 4: *Proton acceptance in m² sr*

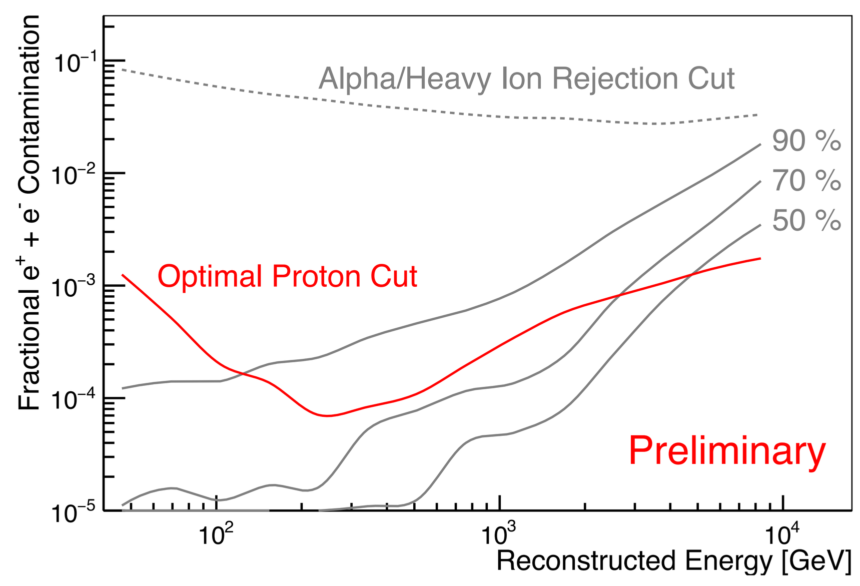

Figure 5: *Residual electron contamination*

- Dotted lines are acceptance and contamination without classifier cut
- Solid lines are the different constant scanning efficiencies
- Red lines are optimized event selection on signal vs background efficiency
- Use Tikhonov regularization to unfold true spectrum using response matrix

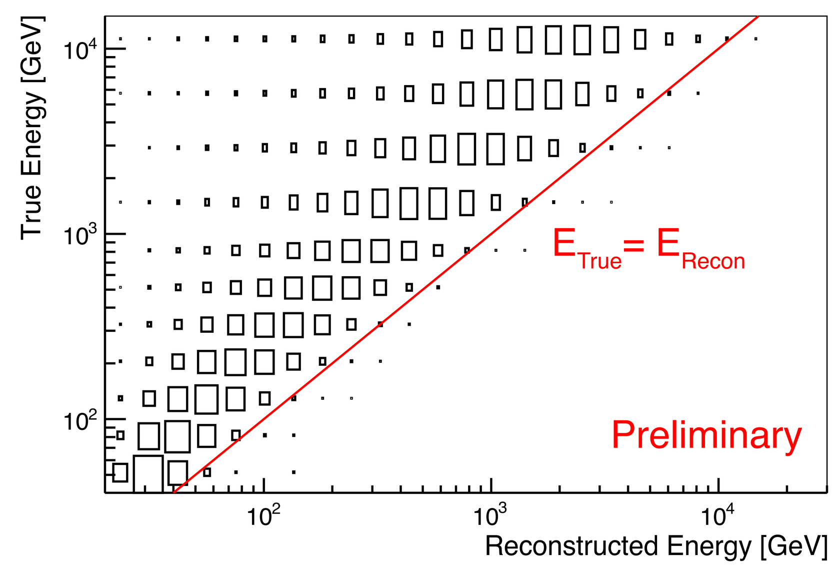

Figure 6: *Energy response matrix for LAT Protons*

Results - Preliminary Proton Spectrum

- 3 Months of data (live-time: 6 Ms)
- Shaded region is the maximum variation in the spectrum from efficiency scans
  - 2σ shaded error includes error from unfolding and statistical error
- Red markers are from 'optimized' efficiency
- Number of energy bins limited by energy resolution of LAT for protons (~30 %)

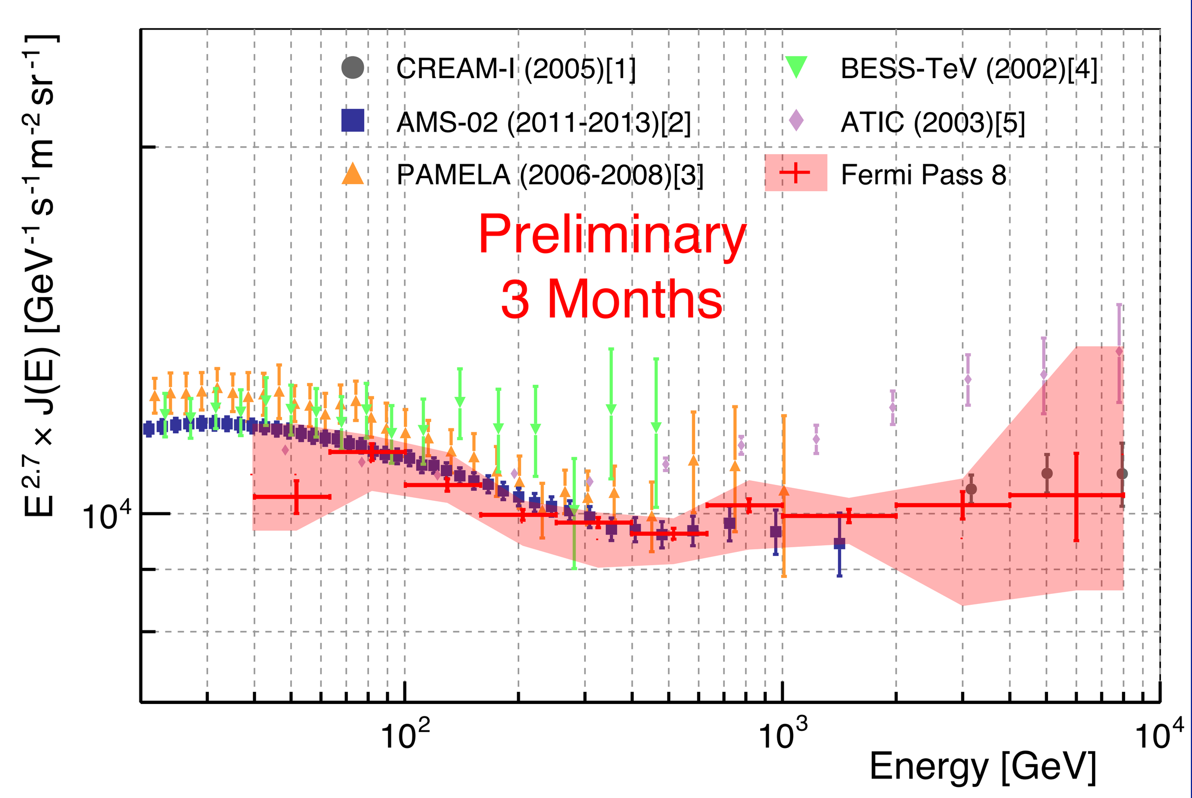

Figure 7: *Preliminary proton spectrum from 40 GeV to 8 TeV*

References

[1] Yoon et al., CREAM, ApJ 728, 122 (2011)
[2] Aguilar et al., AMS-02, PRL 114, 171103 (2015)
[3] Adriani et al., PAMELA, Science 132, 69 (2011)
[4] Shikaze et al., BESS-TeV, APh 28, 154 (2007)
[5] Panov et al., ATIC, Bull. Russian Acad. Sci. 73, 564 (2009)

Conclusions and Future

- Pass 8 allows for the measurement of the cosmic-ray proton spectrum using the Fermi LAT
- We can improve energy resolution through selection on proton population with well reconstructed energy
  - An improved energy resolution will hopefully improve systematic errors
- Systematic errors relevant for the spectral measurement and need further evaluation