A search for cosmic-ray proton anisotropy with the Fermi Large Area Telescope

Justin Vandenbroucke
Matthew Meehan
on behalf of the Fermi-LAT Collaboration

TeVPA 2017
Columbus, OH
August 10, 2017
Outline

• Motivation
• Fermi Large Area Telescope
• Event selection
• Anisotropy analysis methods
• Results
**Motivation**

**IceCube**

Large-scale
(Equatorial)

Known TeV-PeV anisotropy
- Dipole amplitude $O(10^{-4} - 10^{-3})$
- Small-scale structure $O(10^{-5} - 10^{-4})$

Still unknown
- Full-sky orientation (missing declination component)
- Composition dependence

Fermi LAT $O(100 \text{ GeV})$ data set tests complementary energy range and sensitive to full sky (inc. declination)

Fermi Large Area Telescope

Fermi Gamma-ray Space Telescope launched in June 2008
- Equatorial orbit (25.6° inclination)

Large Area Telescope (LAT)
- Pair conversion gamma-ray telescope

Survey instrument
- 2.4 sr instantaneous field of view (20% 4\pi)
- Full-sky coverage every ~3 hrs (2 orbits)
- Slews N/S from zenith to survey entire sky
Fermi LAT subsystems

Tracker (TKR)
- 18 layers X and Y Si strips
- Tungsten to promote pair conversion
- Direction reconstruction

Calorimeter (CAL)
- 8 layers of CsI crystals
- 3D shower structure
- Energy measurement
- Lepton/hadron separation

Anti-Coincidence Detector (ACD)
- Segmented scintillator tiles
- Charged particle ID

Proton anisotropy with Fermi LAT  Justin Vandenbroucke
Event selection

- 8 years of Pass 8 data
- 78 GeV - 9.8 TeV
- Use ACD and TKR to measure charge
  - Residual nuclei contamination < 1%
- Classifier to separate protons from e+/e-
  - Residual lepton contamination < 1%
- Classifier and ACD cuts reject photons
- Proton angular resolution ~0.02°
Geomagnetic systematics

Wide field of view -> LAT sees near Earth’s horizon

- East-West effect visible in Altitude-Azimuth coordinates

Energy-dependent theta (angle between event and LAT axis) cuts

- \(78 \text{ GeV} < E_{\text{reco}} < 139 \text{ GeV}: \theta < 45^\circ\)
- \(E_{\text{reco}} > 139 \text{ GeV}: \theta < 50^\circ\)
Analysis methods

Angular power

$$\hat{C}_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |\hat{a}_{lm}|^2$$

Dipole amplitude

$$\delta = 3\sqrt{\frac{\hat{C}_1}{4\pi}}$$

Sensitivity < 0.1%

- Cannot estimate exposure using simulation

Data-driven approach: Reference map

- Detector response to an isotropic sky

Spherical harmonic analysis of relative intensity

- Full-sky exposure -> unbiased estimate of multipole coefficients
Reference maps

Data-driven method
  – Average out anisotropy in the data while maintaining exposure

Ground-based
  – Loss of sensitivity in declination

Fermi LAT
  – Spacecraft slewing -> extra degree of freedom
  – 2D sensitivity

Average in right ascension

Average in RA and Dec
Equatorial sky maps

Data map
- 160 million events (3072 pixels)
- Reference map = average of 25 independent realizations

$$\delta I_i(\alpha_i, \delta_i) = \frac{n_i(\alpha_i, \delta_i) - \mu_i(\alpha_i, \delta_i)}{\mu_i(\alpha_i, \delta_i)}$$

$E_{\text{reco}} > 78$ GeV

Proton anisotropy with Fermi LAT

Justin Vandenbroucke
Angular power spectrum

Significant power in the quadrupole
  – Preliminary!
  – Working to understand this anisotropy
  – Systematics in l=2 due to equatorial orbit

Consistent with isotropic sky at all other angular scales

Angular scale \( \sim 180^\circ/l \)

\[ C_l = \text{measured power} \]

\[ C_N = \text{power due to Poisson noise} \]
Energy-integrated dipole amplitude

- Calculate angular power spectrum for subsets of data with increasing minimum energy
- Calculate dipole amplitude directly from power at $l=1$
Fermi LAT 90% CL and AMS-02 95% CL

- Cumulative energy bins
- AMS-02 not absolute measurement (uses low-energy protons as reference)

Ground-based

- Right ascension sensitivity only

Strongest limits on declination component of dipole at any energy
Conclusion

• Searched for anisotropy in 160 million events in 8 years of Fermi-LAT data
• No significant dipole
• Significant quadrupole is under investigation
• Strongest limits to date on the declination component of the dipole amplitude (for any energy range)
• Dedicated classifier developed for Fermi LAT e+/e- analyses
• Uses differences in leptonic vs. hadronic showers
• 8 energy bins
• Residual lepton contamination < 1%
Reference map algorithm

- Bin data in time (bin size is one year)
- Calculate average rate and $P(\theta, \phi)$ from distribution of detected events in the detector frame
- Given these quantities, calculate expected $N$ events for each second of live time
- Draw direction from $P(\theta, \phi)$
- Calculate sky direction from drawn direction and spacecraft pointing
- Repeat 25x and average realizations to beat down statistical fluctuations
Significance map

• No features present in Li & Ma significance Map
• Significance distribution consistent with standard normal

$E_{\text{reco}} > 78$ GeV
Fermi LAT e+/e- anisotropy

- Fermi LAT e+/e- anisotropy search in 7 years of Pass 8 data
- Consistent with isotropy across all energy bins
- Dipole UL range from $3 \times 10^{-3} - 3 \times 10^{-2}$

LAT particle spectra

Model of the cosmic-ray particles fluxes from background simulation. Note that particle energy is reconstructed under the gamma-ray hypothesis and does not necessarily represent actual energy for hadrons.
Fermi LAT exposure


Full-sky exposure

– Full-sky coverage every 3 hours or 2 orbits
– Spacecraft rocks N/S on successive orbits

Proton anisotropy with Fermi LAT

Justin Vandenbroucke
Anisotropy search method

1 - Relative intensity

\[ \delta I_i(\alpha_i, \delta_i) = \frac{n_i(\alpha_i, \delta_i) - \mu_i(\alpha_i, \delta_i)}{\mu_i(\alpha_i, \delta_i)} \]

Data map

Reference Map

2 - Spherical harmonic decomposition

\[ \hat{a}_{lm} = \frac{4\pi}{N_{pix}} \sum_{i=1}^{N_{pix}} Y^*_{lm}(\pi - \delta_i, \alpha_i) \delta I_i(\alpha_i, \delta_i) \]

3 - Angular power spectrum

\[ \hat{C}_l = \frac{1}{2l + 1} \sum_{m=-l}^{l} |\hat{a}_{lm}|^2 \]

4 - Dipole amplitude

\[ \delta = 3\sqrt{\frac{\hat{C}_1}{4\pi}} \]
Instrument response to protons

Angular separation between true track direction and reconstructed track direction (from simulation)

68% containment: 0.02°

Energy response matrix comparing reconstructed energy to true energy (from simulation)