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

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

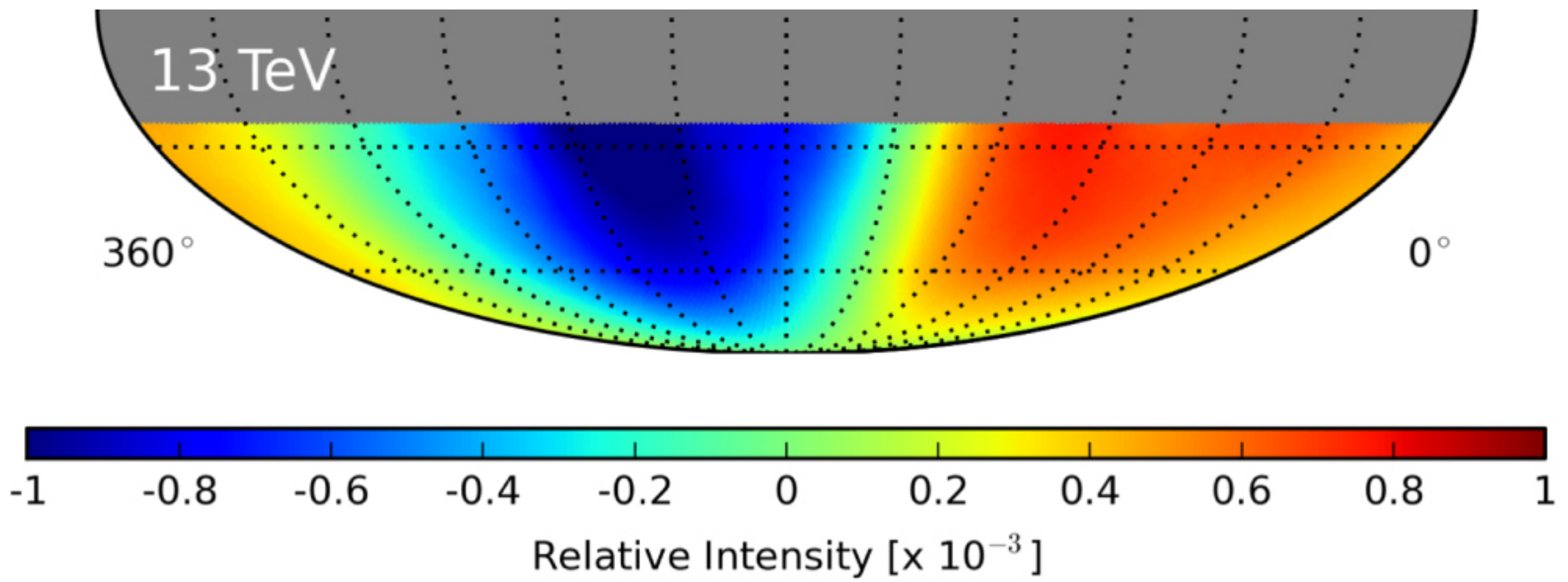
Outline

- Motivation
- Fermi Large Area Telescope
- Event selection
- Anisotropy analysis methods
- Results

Motivation

IceCube

Large-scale (Equatorial)



Aartsen, M. G. et al. 2016, ApJ, 826, 220

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 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

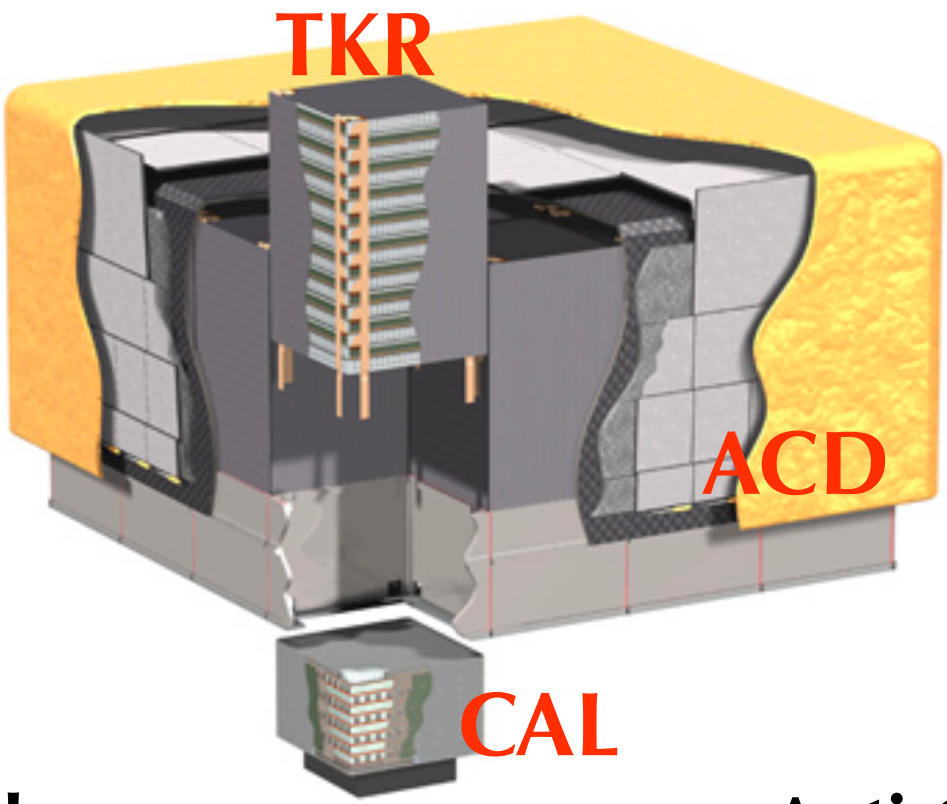
Survey instrument

- 2.4 sr instantaneous field of view (20% 4π)
- 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)

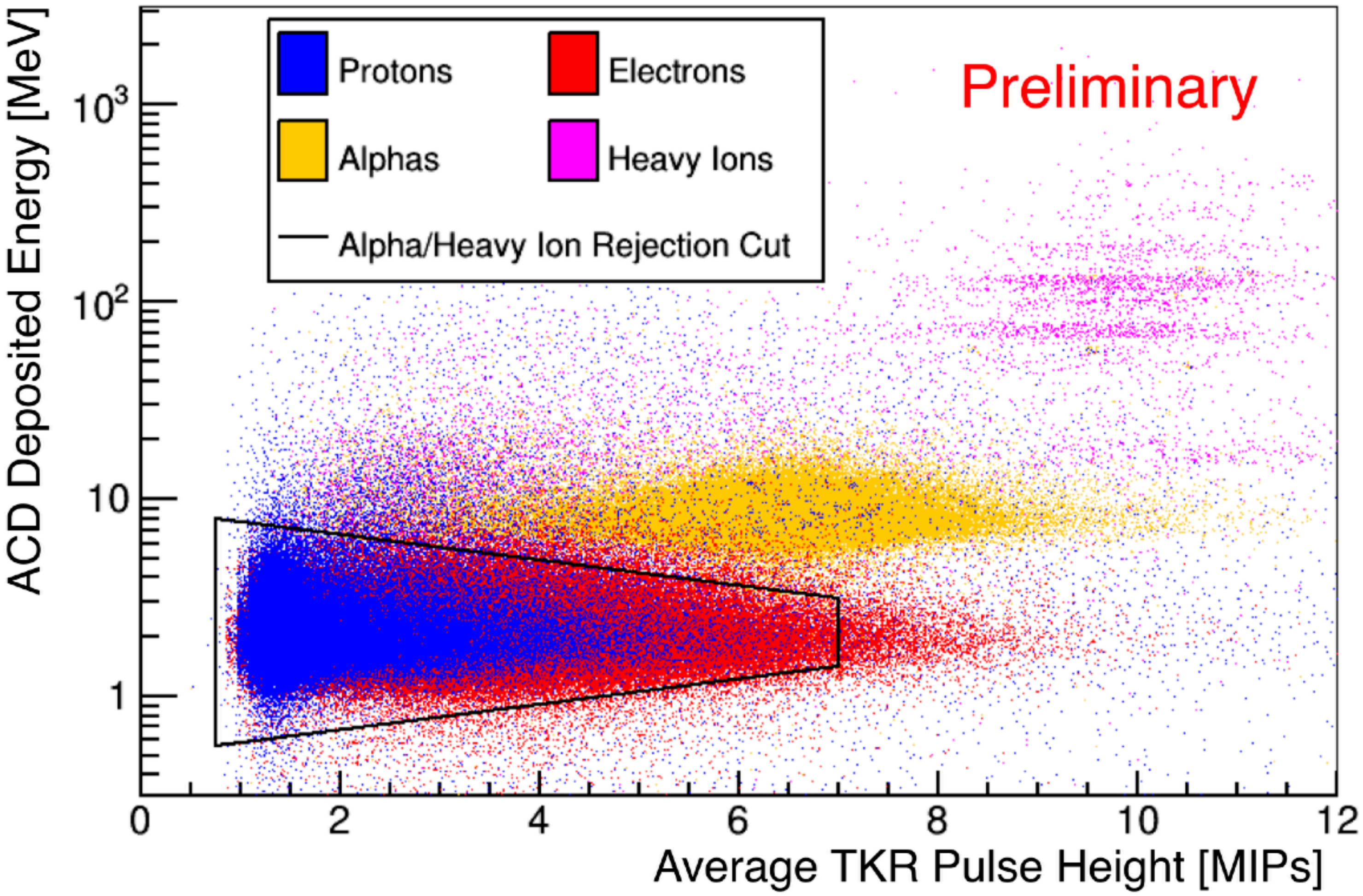
- 8 layers of CsI crystals
- 3D shower structure
- Energy measurement
- Lepton/hadron separation

Anti-Coincidence Detector (ACD)

- Segmented scintillator tiles
- Charged particle ID

Event selection

- 8 years of Pass 8 data
  - Dec. 2008 - Dec. 2016
- 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°



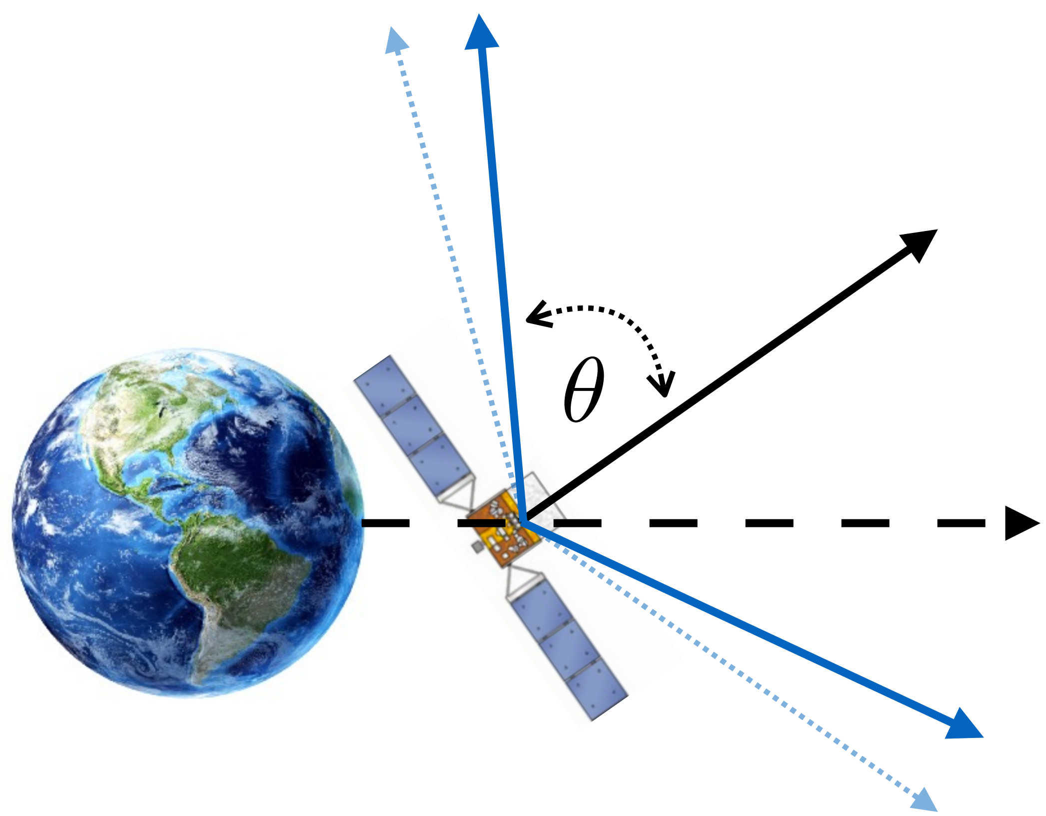
Geomagnetic systematics

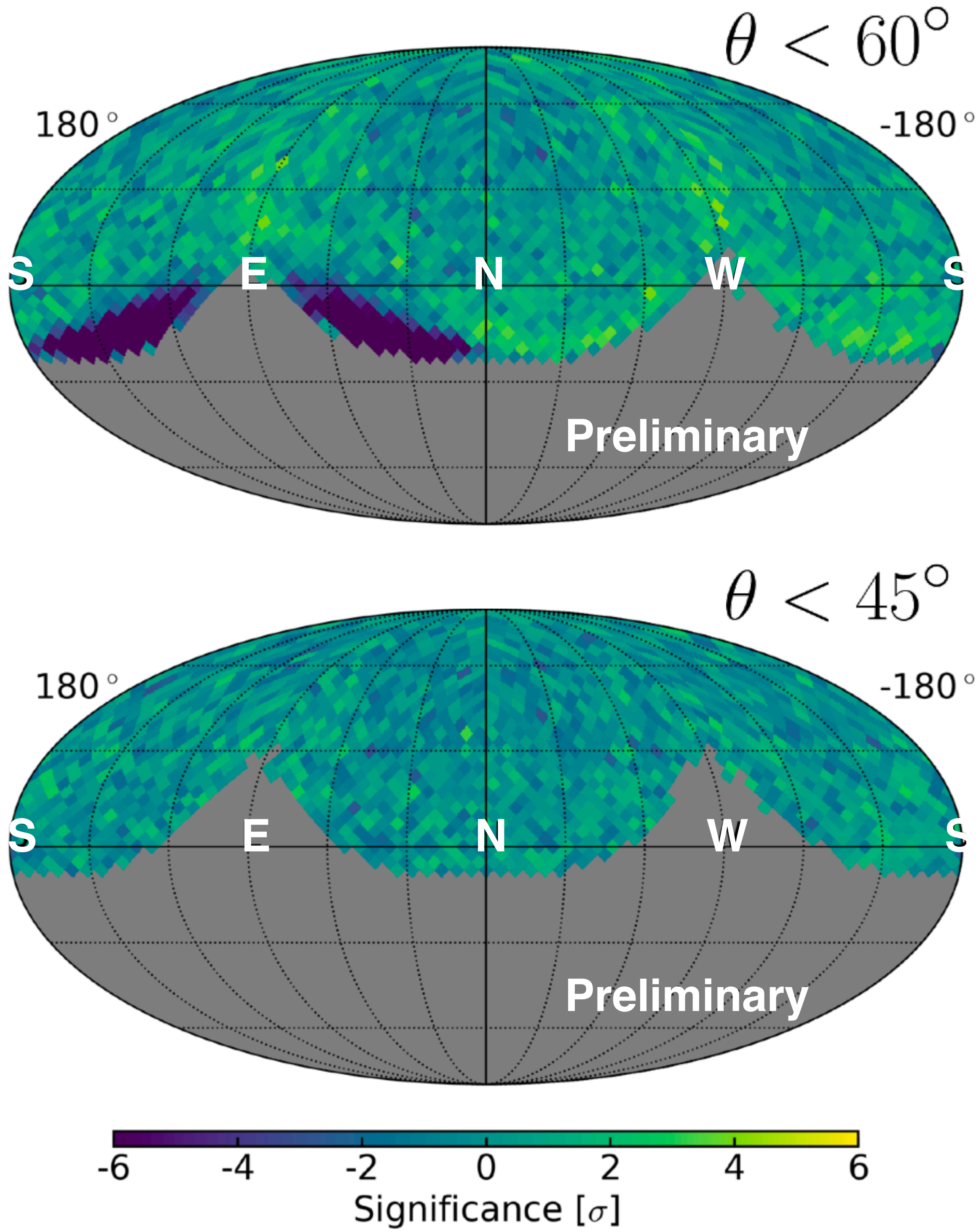
Wide field of view -> LAT sees near Earth's horizon

- East-West effect visible in Altitude-Azimuth coordinates

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

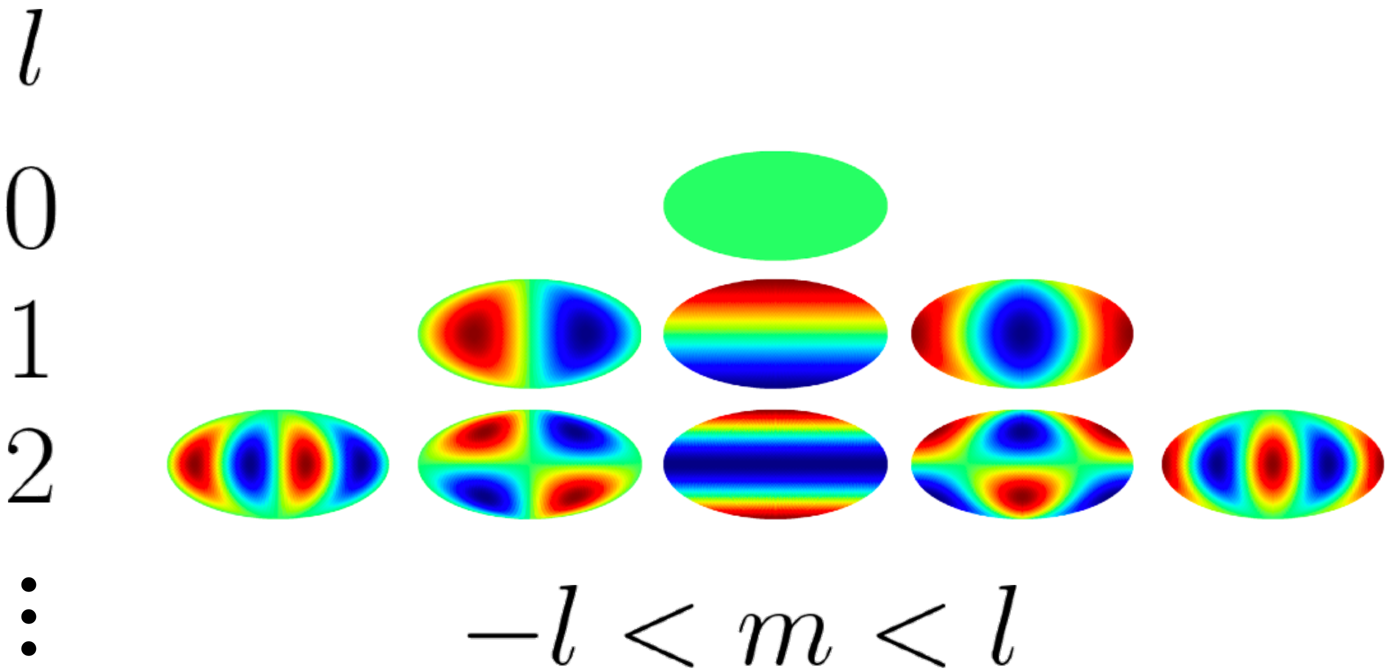
- 78 GeV < E_{reco} < 139 GeV: θ<45°
- E_{reco} > 139 GeV: θ<50°





78 GeV < E_{reco} < 139 GeV

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

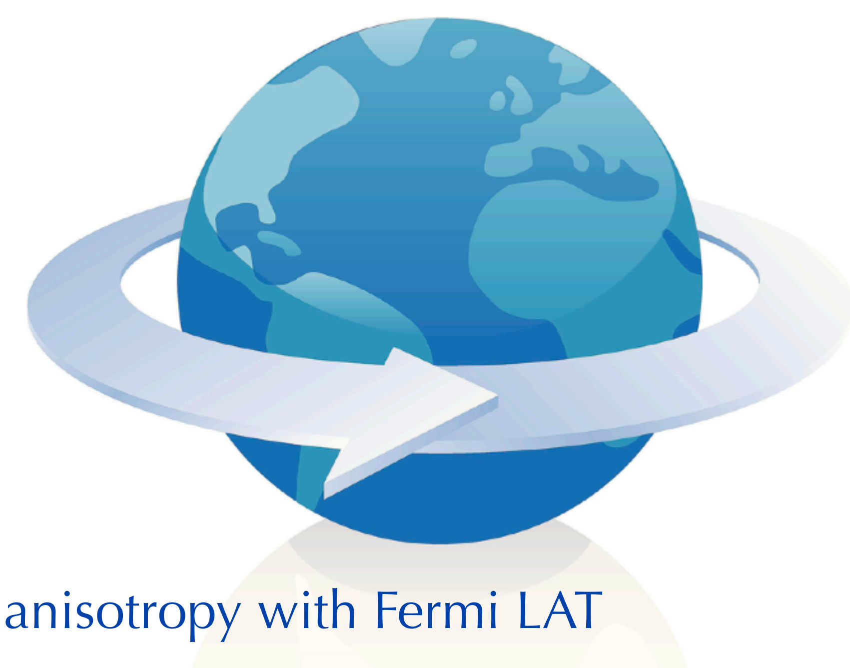
Ground-based

- Loss of sensitivity in declination

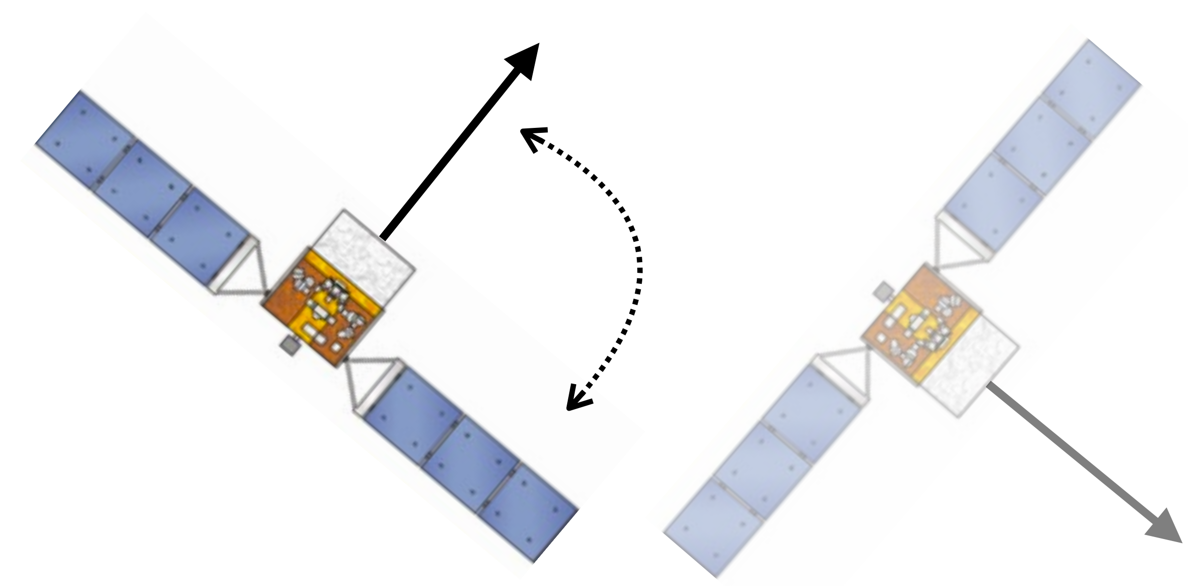
Fermi LAT

- Spacecraft slewing -> extra degree of freedom
- 2D sensitivity

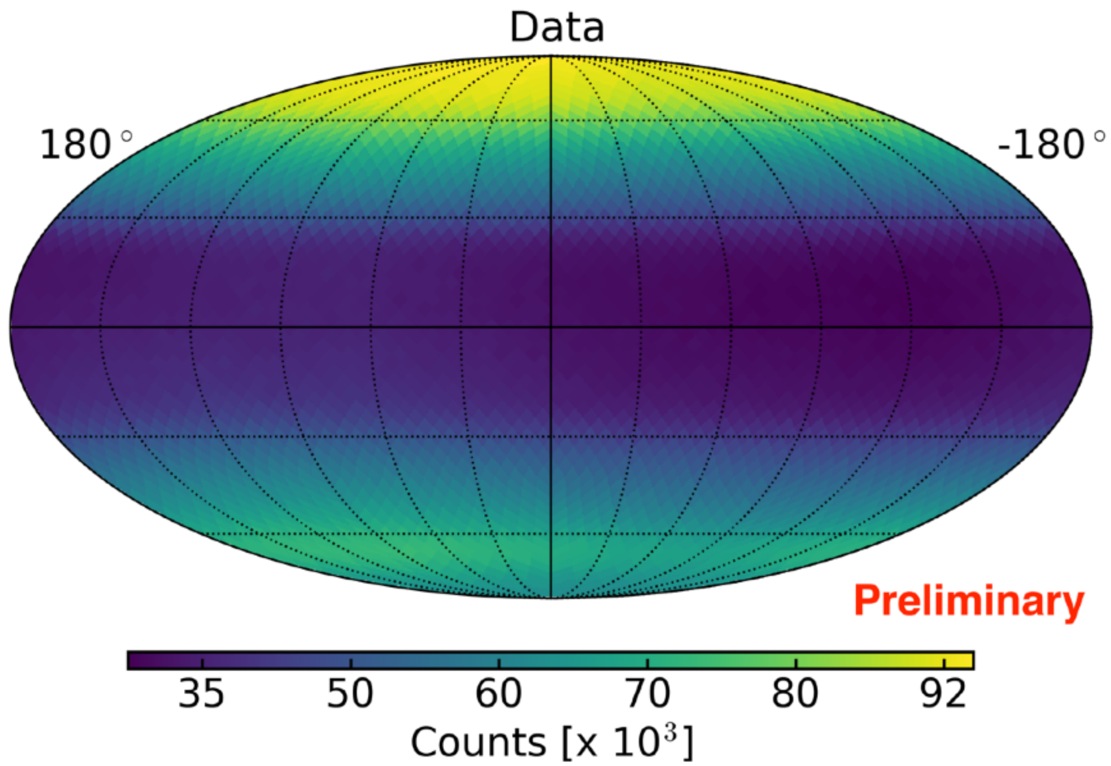
Average in right ascension

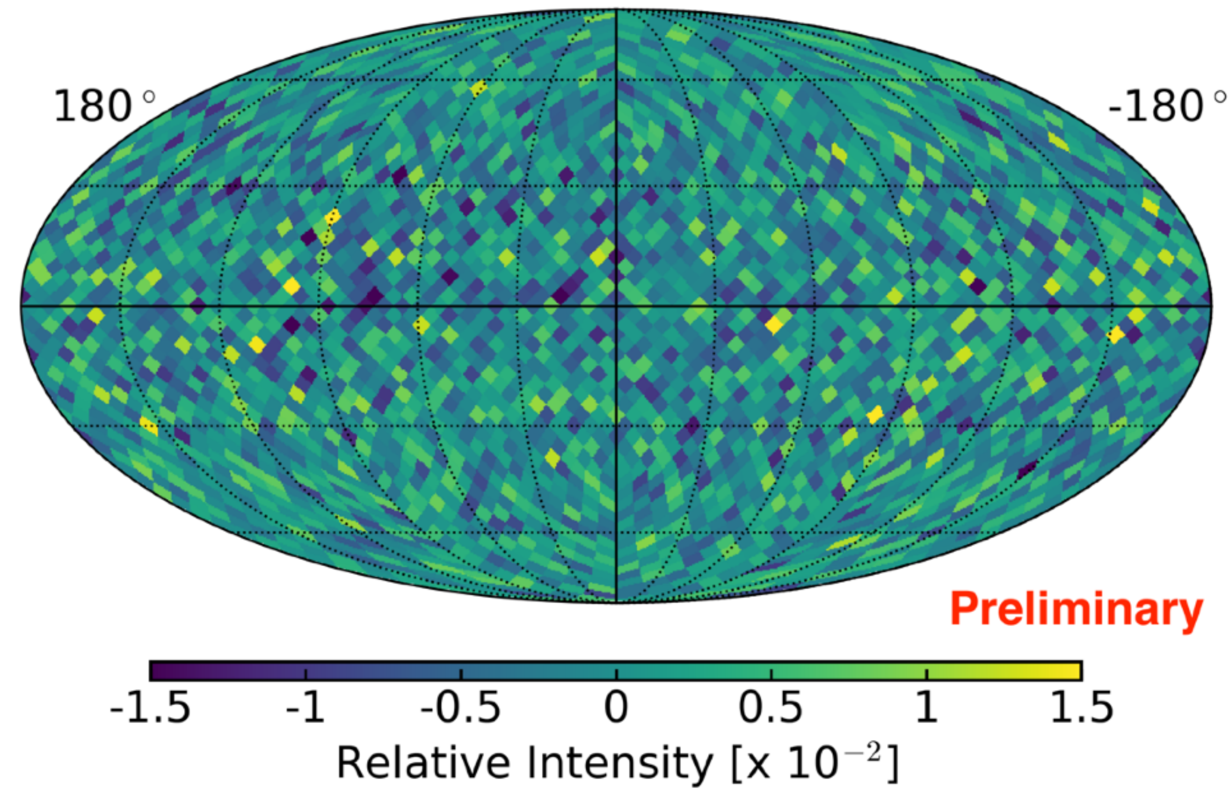


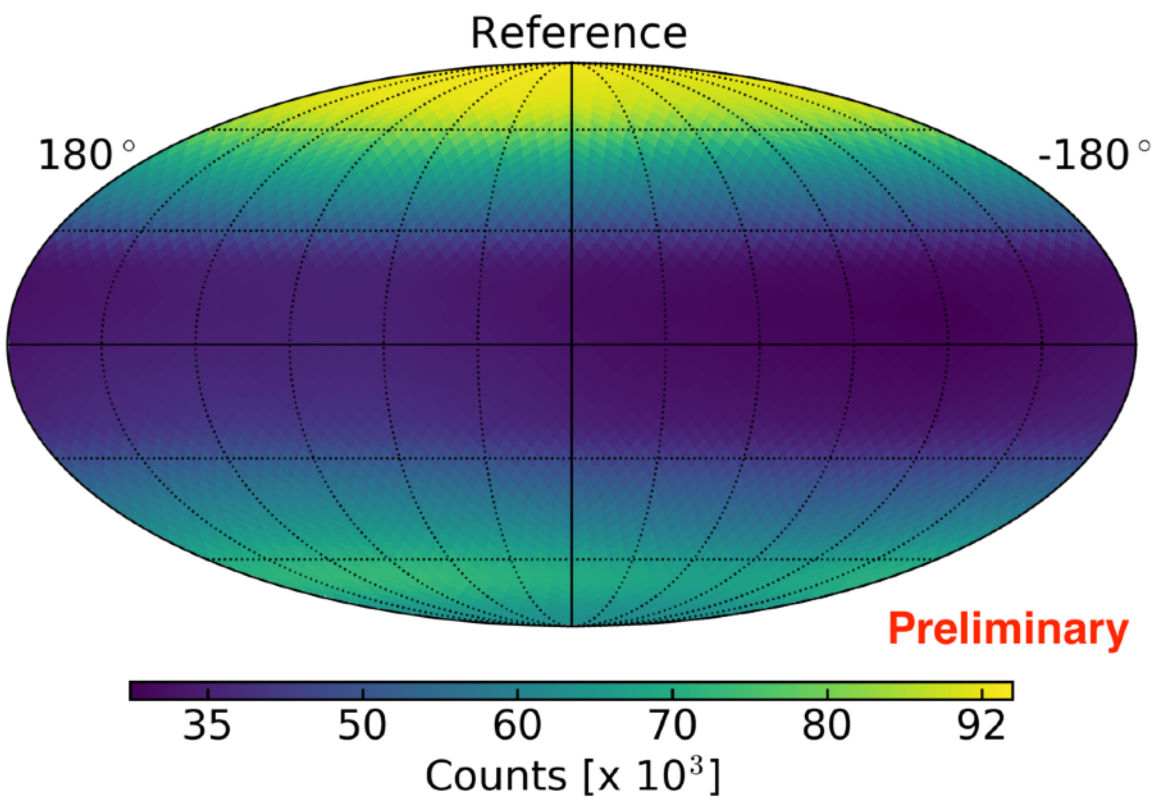
Average in RA and Dec



Equatorial sky maps







Data map — Reference Map

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

E_{reco} > 78 GeV

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

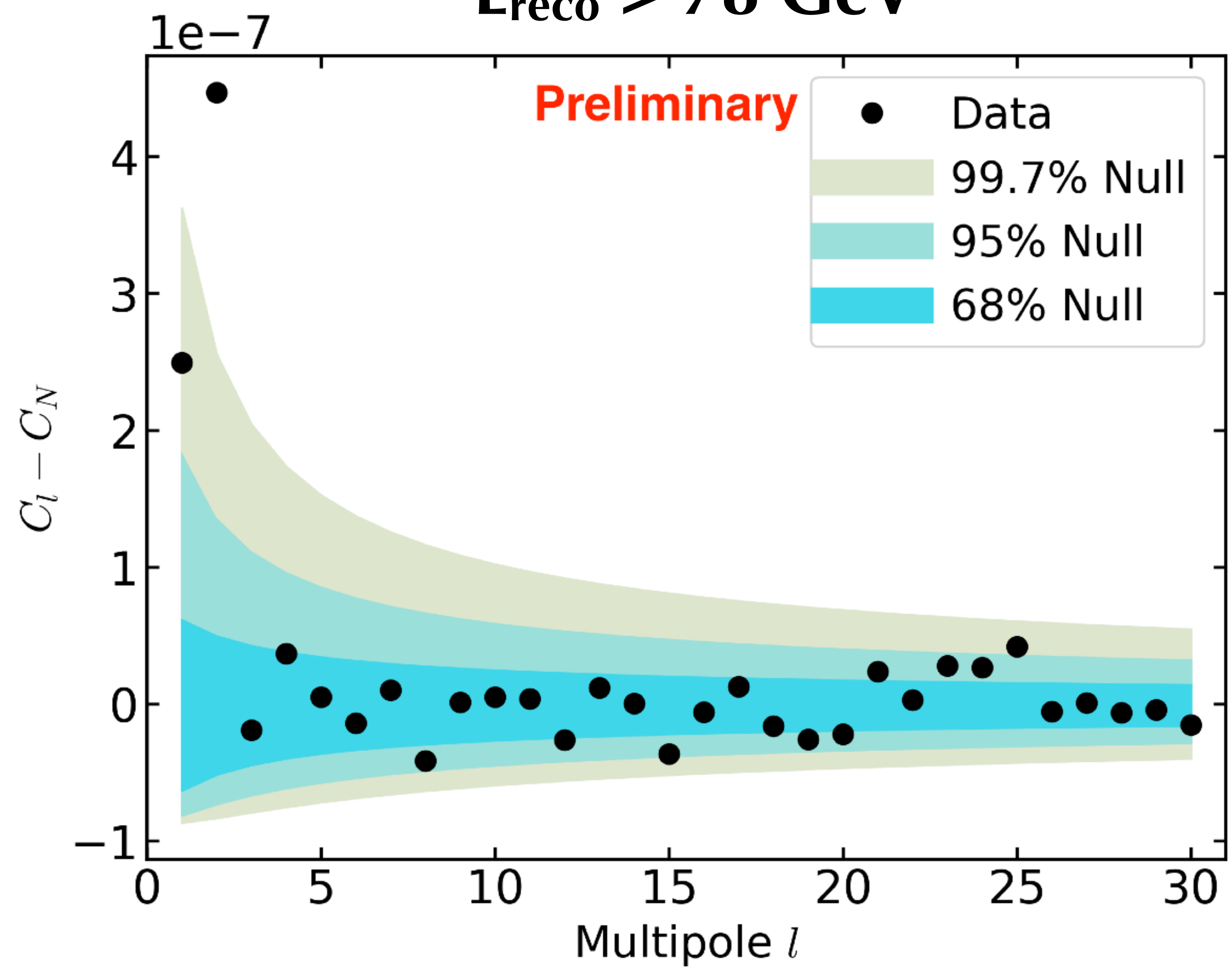
Angular power spectrum

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

E_{reco} > 78 GeV

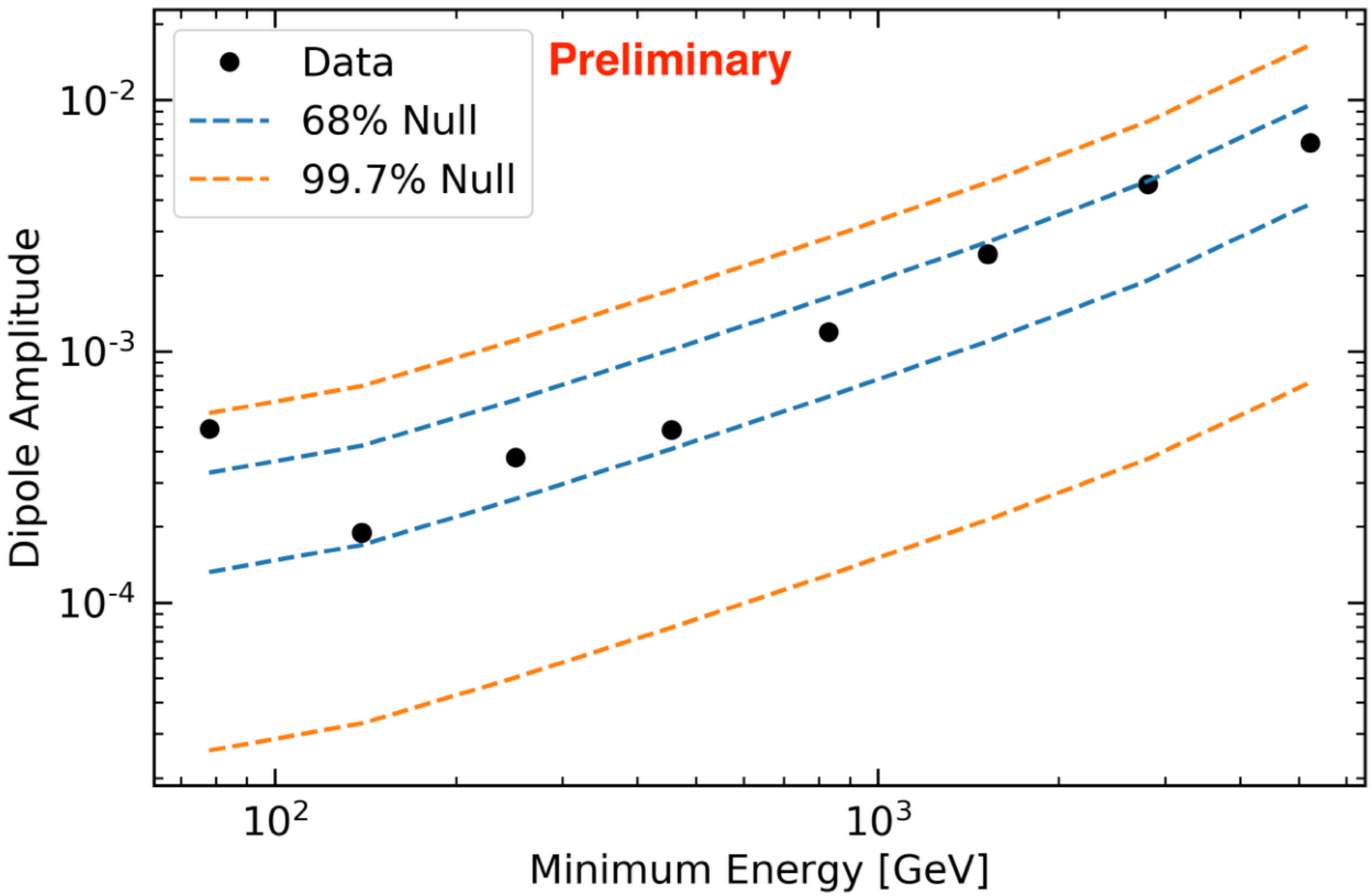


Angular scale ~ 180°/l

C_l = measured power

C_N = power due to Poisson noise

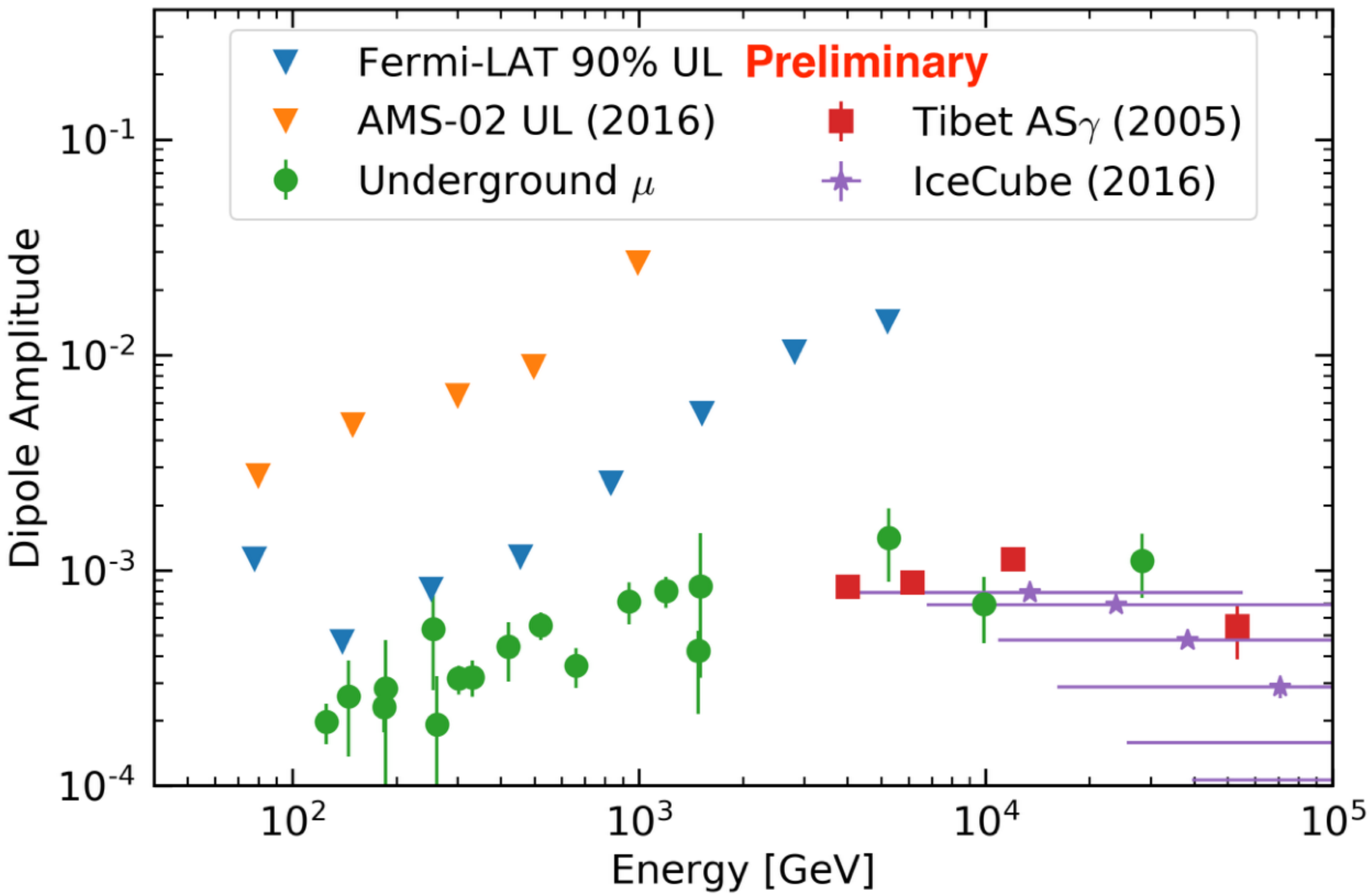
$$\delta = 3\sqrt{\frac{\hat{C}_1}{4\pi}}$$



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

Dipole upper limits



Fermi LAT 90% CL and AMS-02 95% CL

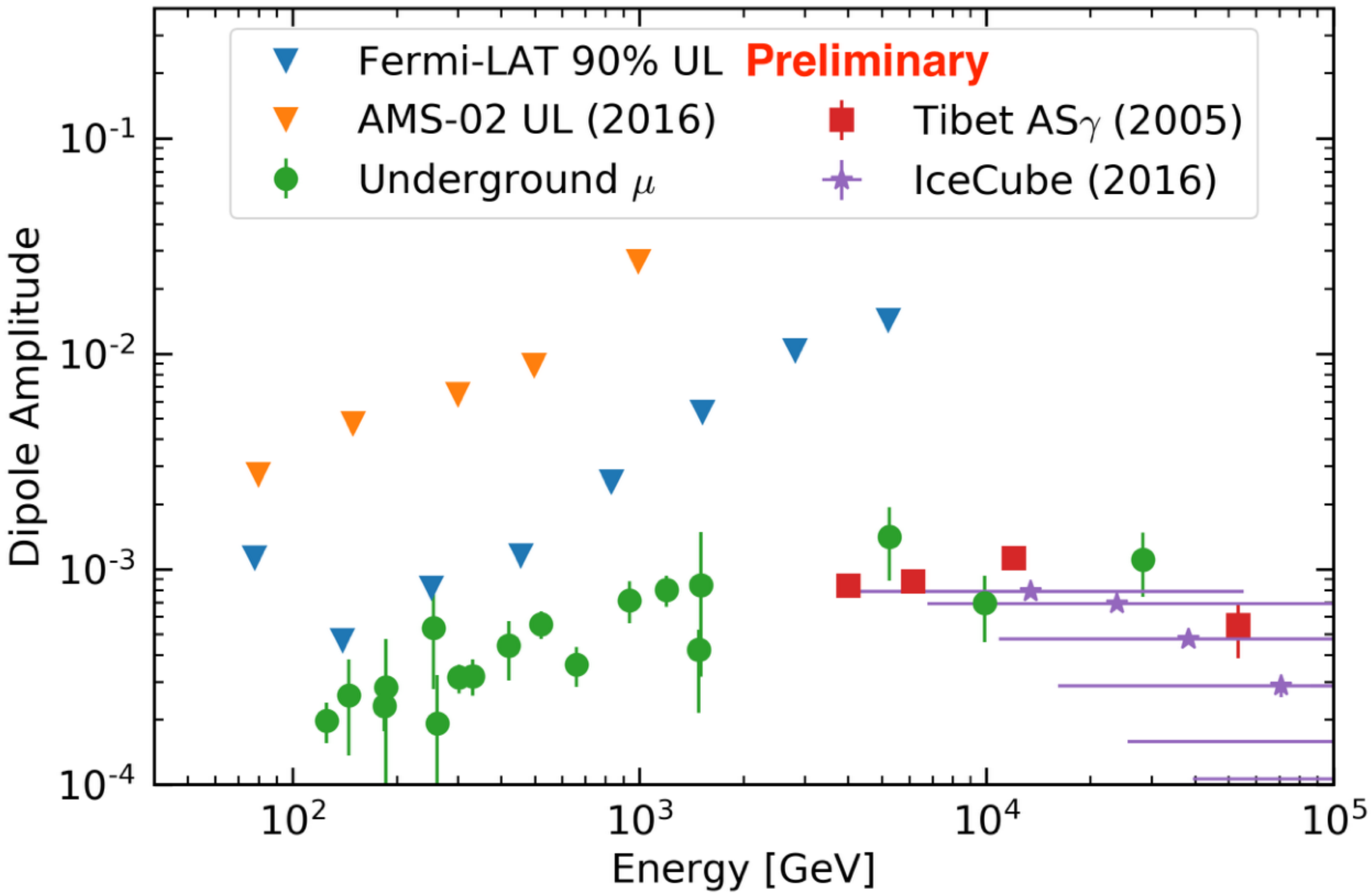
- Cumulative energy bins
- AMS-02 not absolute measurement (uses low-energy protons as reference)

Ground-based

- Right ascension sensitivity only

Strongest limits on declination component of dipole at any energy

Conclusion

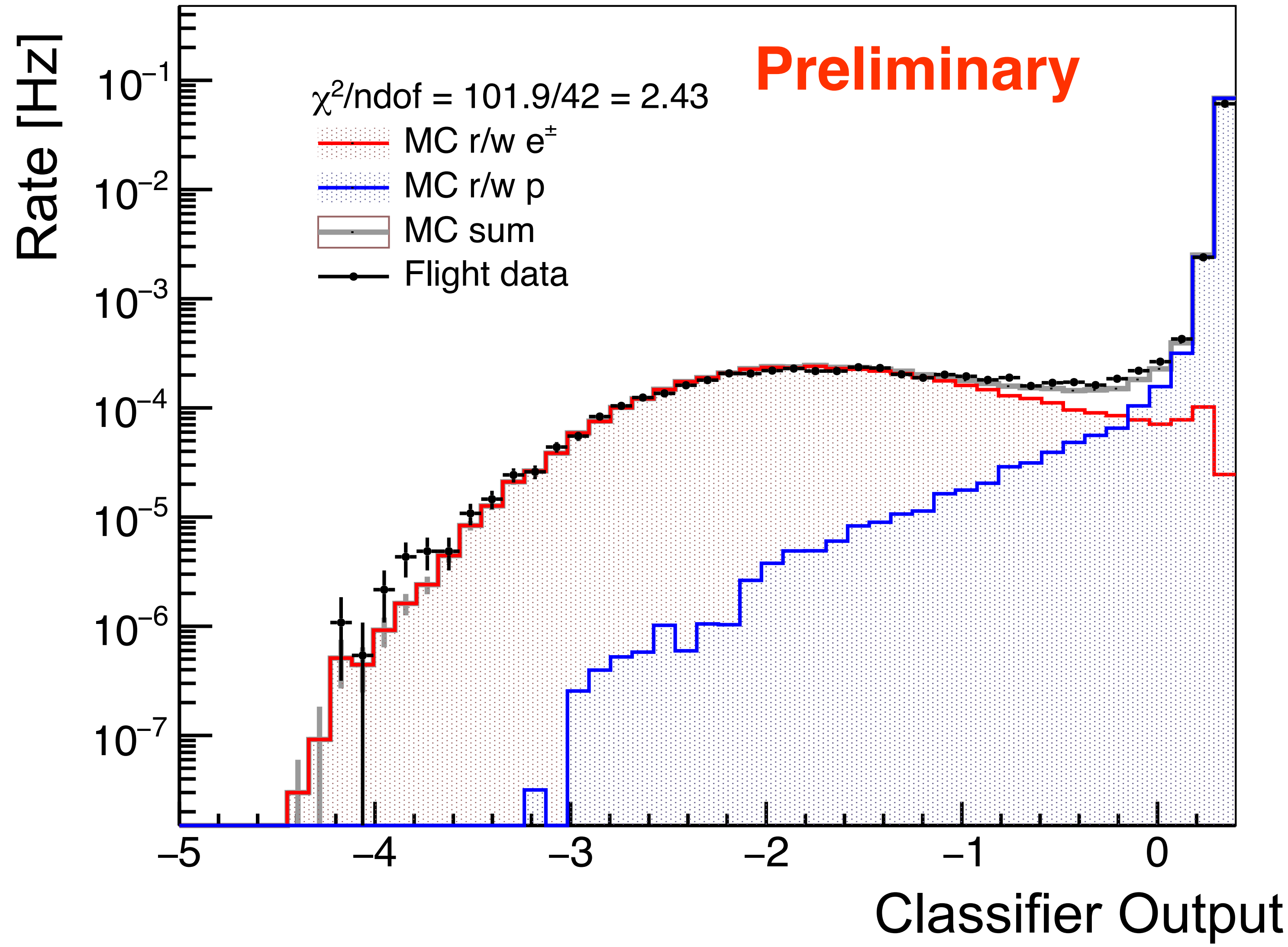


- **Searched for anisotropy in 160 million events in 8 years of Fermi-LAT data**
- **No significant dipole**
- **Significant quadrupole is under investigation**
- **Strongest limits to date on the declination component of the dipole amplitude (for any energy range)**

Backup

e+/e- classifier

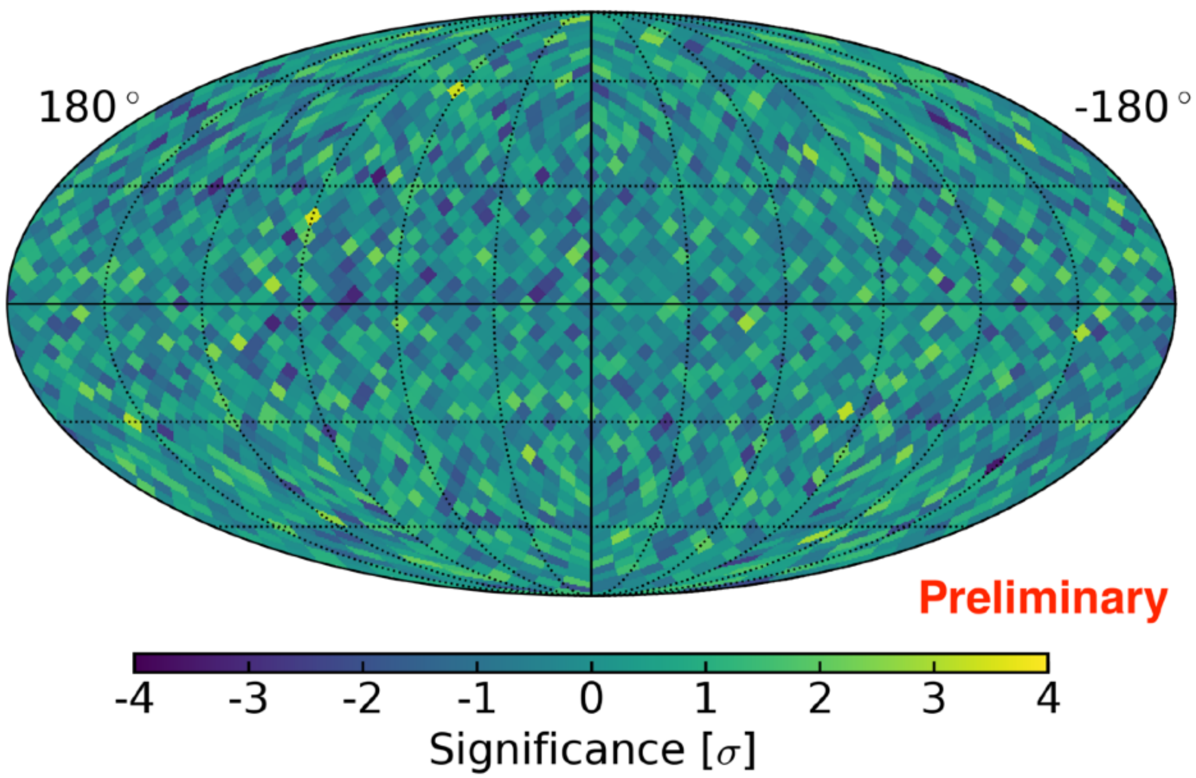
- **Dedicated classifier developed for Fermi LAT e+/e- analyses**
- **Uses differences in leptonic vs. hadronic showers**
- **8 energy bins**
- **Residual lepton contamination < 1%**

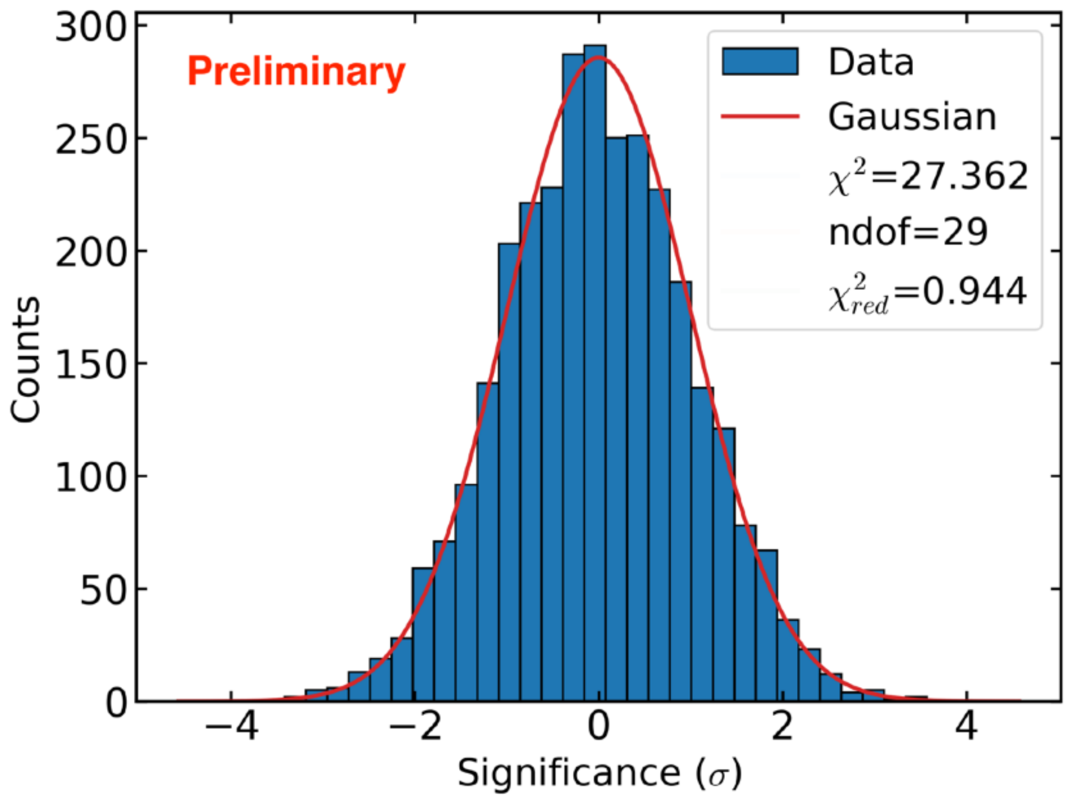


Reference map algorithm

- 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

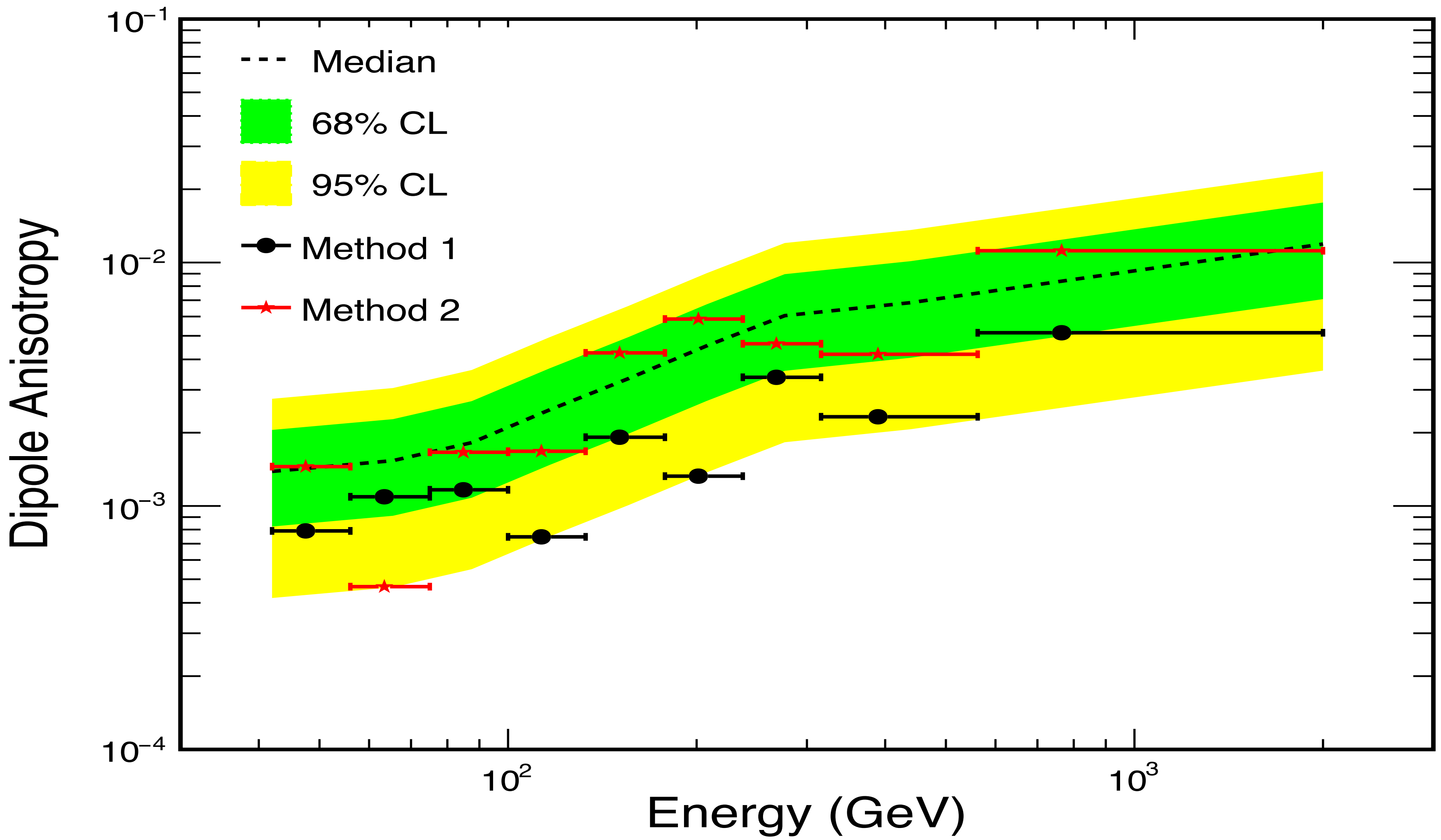




E_{reco} > 78 GeV

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

Fermi LAT e+/e- anisotropy

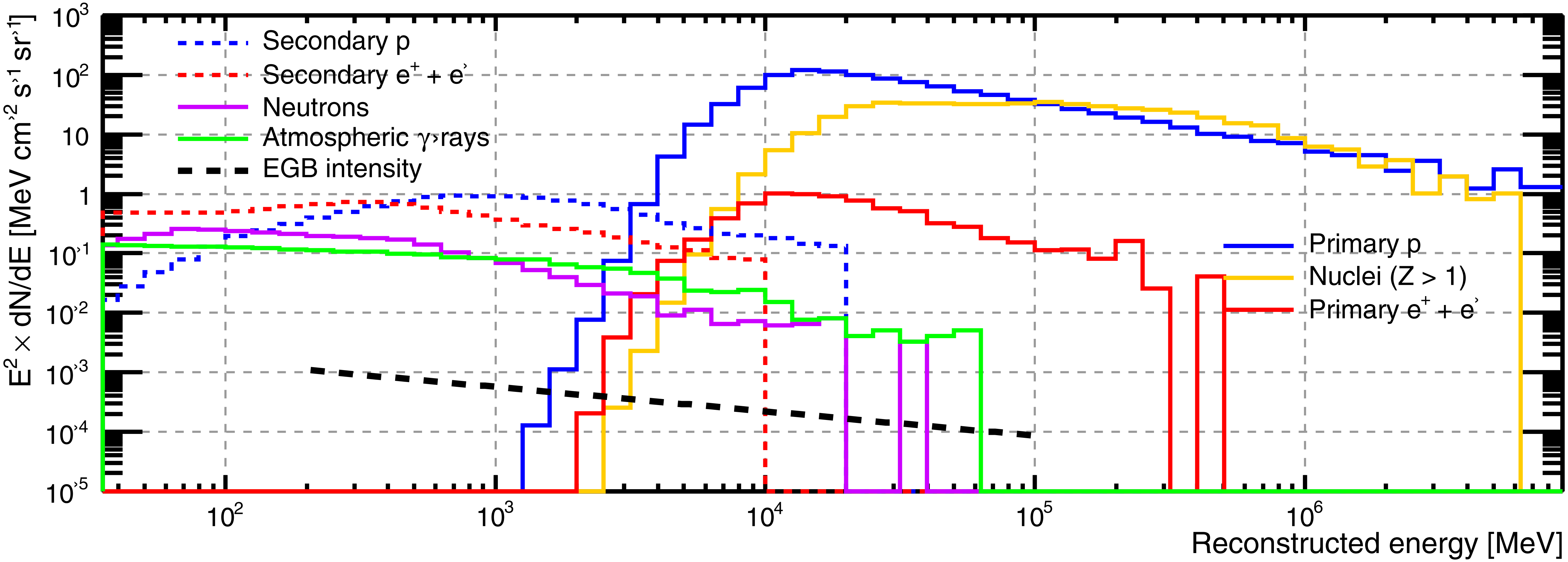


Fermi-LAT Collaboration, S. Abdollahi et al., *Phys. Rev. Lett.* **118** (2017) 091103.

- **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 x 10^{-3} - 3 x 10^{-2}**

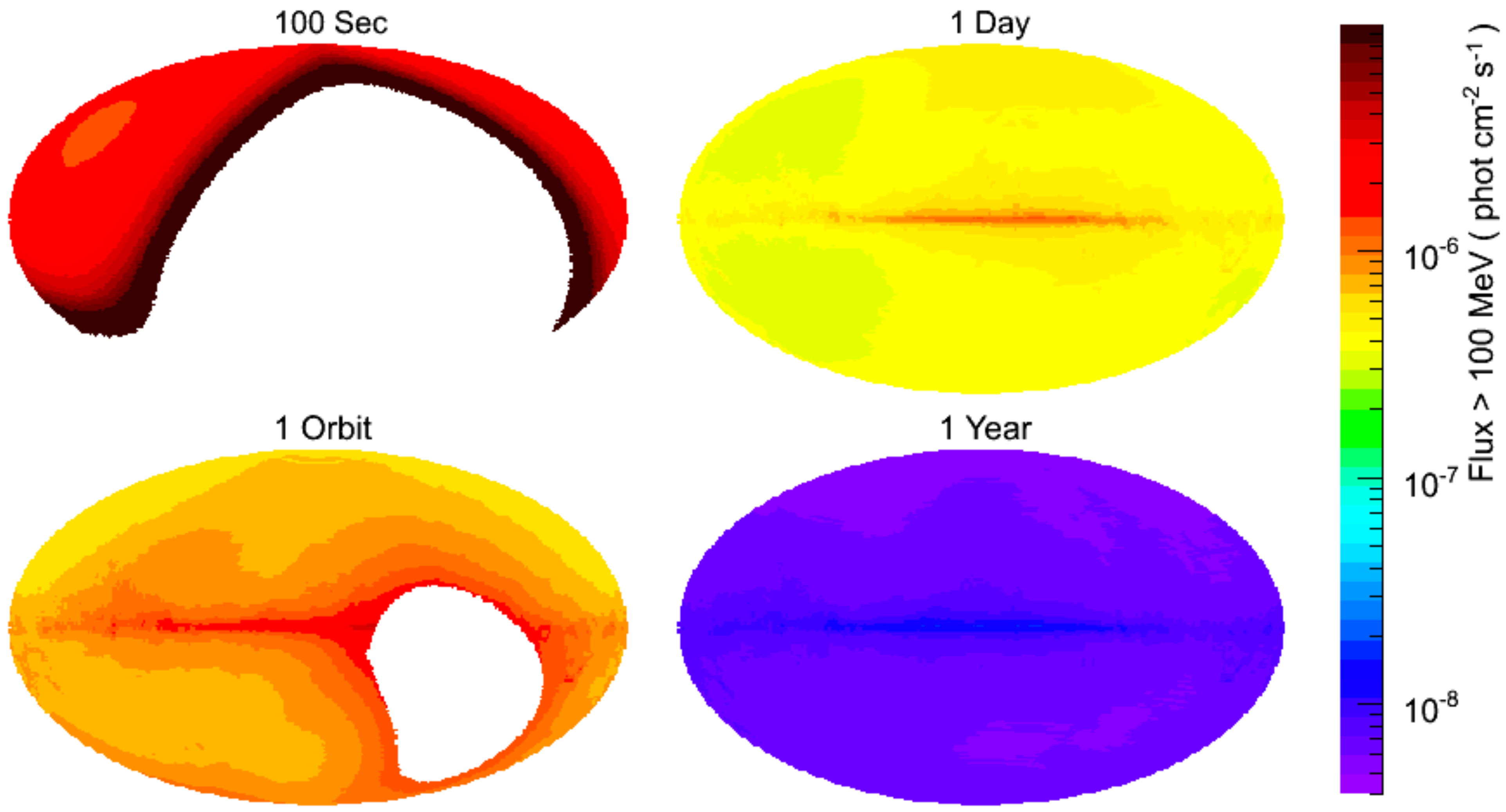
LAT particle spectra

Ackermann, M. et al. 2012. ApJS, 203, 4



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



Atwood et al, ApJ 697, 1071 (2009)

Full-sky exposure

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

Anisotropy search method

1 - Relative intensity

Data map

Reference Map

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

2 - Spherical harmonic decomposition

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

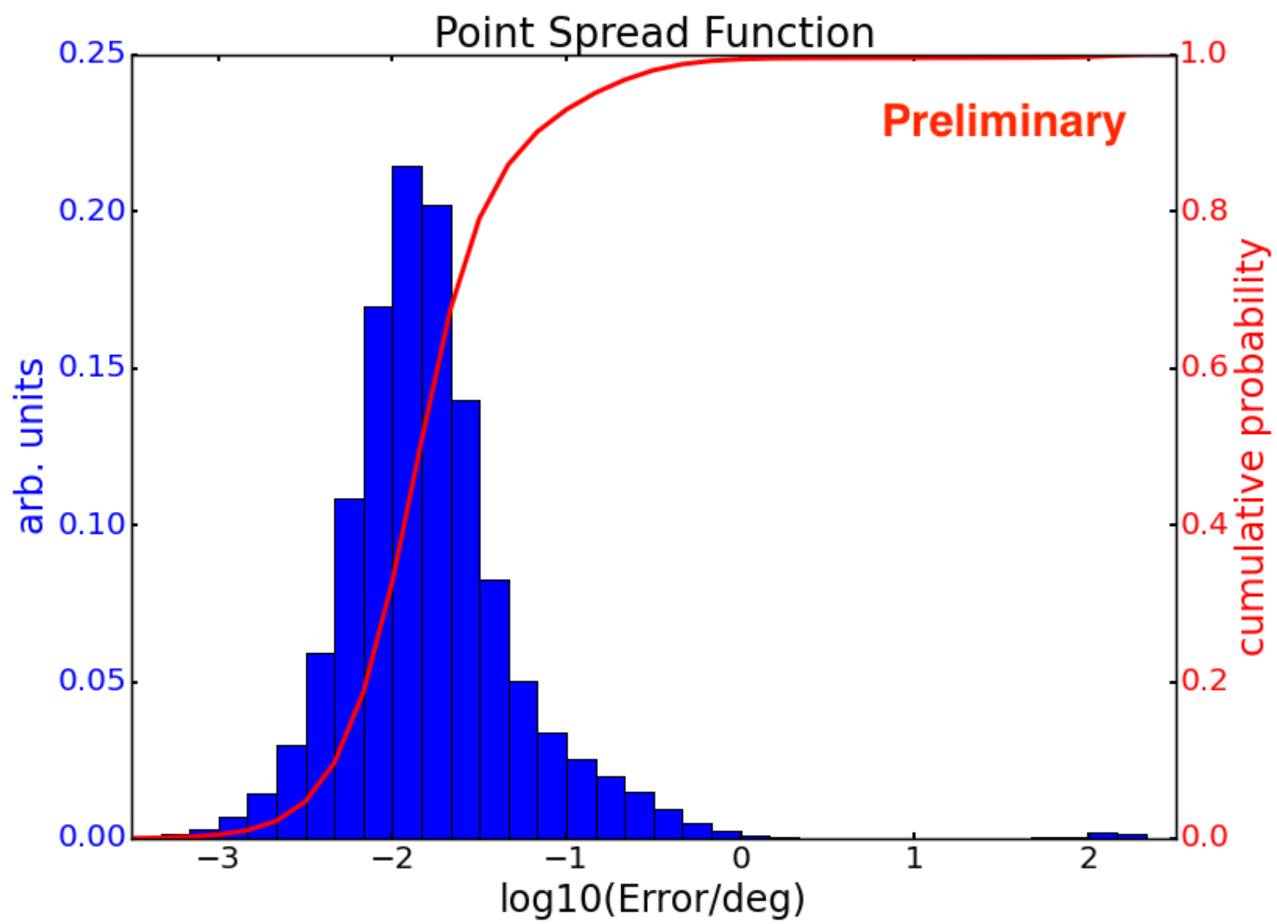
3 - Angular power spectrum

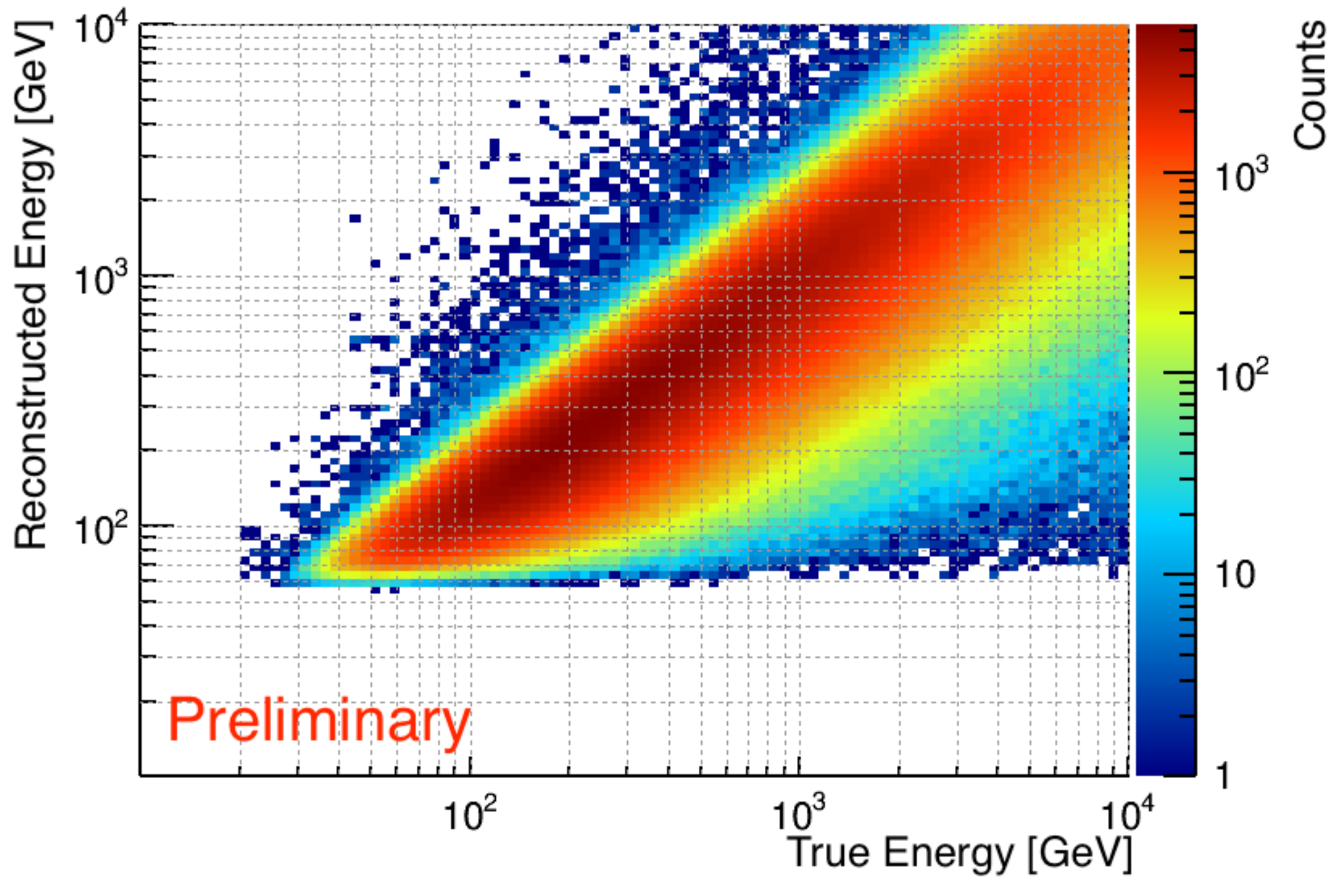
$$\hat{C}_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |\hat{a}_{lm}|^2$$

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)