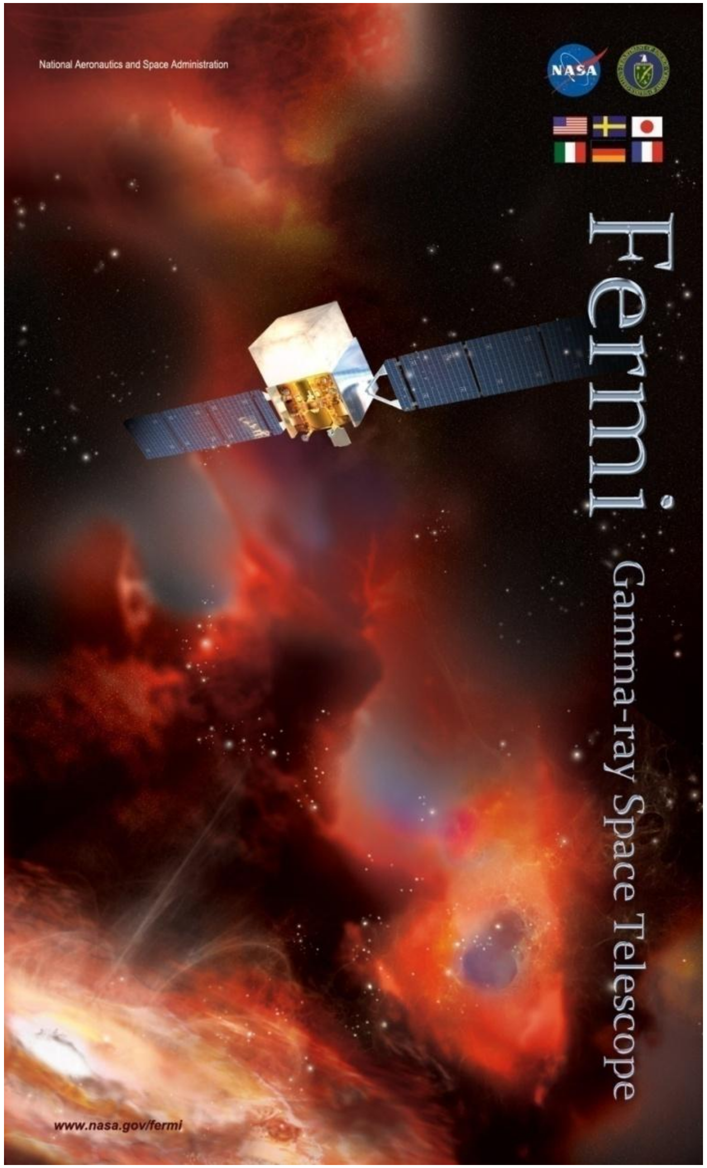

Study of Cosmic Ray Electron Anisotropies with the Fermi-LAT data

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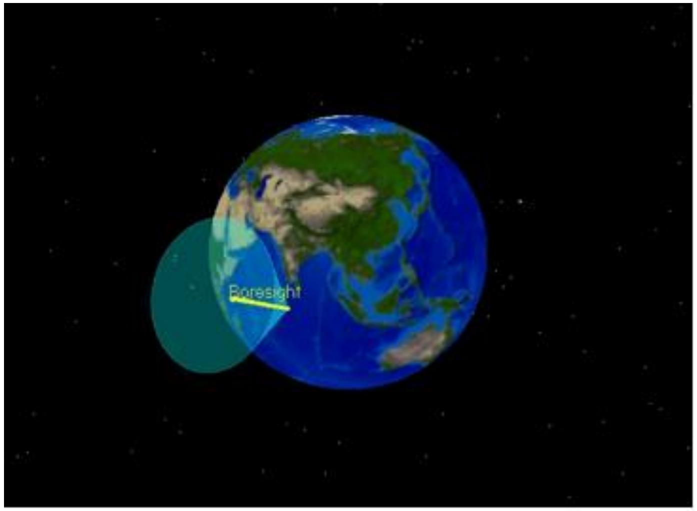
Introduction

- **High-energy charged primary cosmic rays (CRs) are known to be nearly isotropic, due to the μG Galactic magnetic fields (GMF), which randomize the directions of charged particles**
- **When traveling from their source of origin to our solar system, CRs scatter on random and irregular components of the GMF that tend to perfectly isotropize their directions**
- **One of the source of expected anisotropy is caused by the relative motion of the observer with respect to the CR plasma, known as the Compton-Getting (CG) effect**
- **Several ground experiments across a wide range of energies have found anisotropy on large angular scales**
  - **Milagro Observatory**
  - **Tibet Air Shower Arrays**
  - **Pierre Auger Observatory**
  - **…**

Introduction (cont'd)

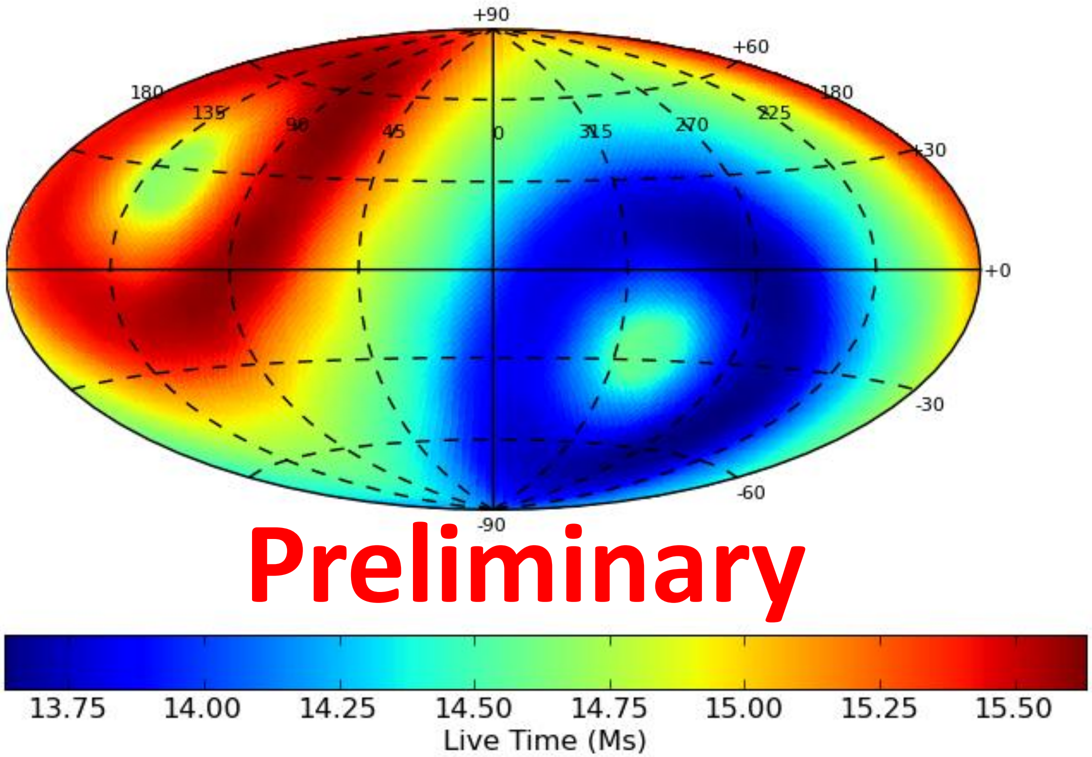
- The Large Area Telescope (LAT) on board of the Fermi satellite provides an unique high statistics sample for primary electrons/positrons components (CREs)
  - See Latronico's talk
  - The electron Point Spread Function (PSF) is of the order of 0.1 degrees or better above 20 GeV
- Contrary to hadronic CRs, CREs propagating in the GMF lose energy through synchrotron radiation and by inverse Compton collisions with low-energy photons
- CREs with energies of ~100GeV arrive at Earth from relatively nearby locations, ~ kpc away
  - This means that such high-energy CREs are originated from a highly anisotropic collection of a few nearby sources
  - Therefore, depending on the properties of the GMF, the detection of excess CREs, with energies high enough to minimize both the geomagnetic field and the heliospheric effect, might reveal the presence of such nearby CRE sources

Monitoring the Sky



- The Fermi satellite is usually operated in sky survey mode:
  - The sky is fully observed every 2 orbits (3 hours)
- This ensures a uniform exposure, with each region viewed for ~30 minutes every 2 orbits
- The rocking angle, i.e. the angle between the spacecraft Z axis and the local zenith axis, is kept at a constant value
  - the value was set to 37 degrees during the first year of operation, and was increased to 50 degrees starting from early September 2009
  - In this way the Earth albedo is kept out of the field of view (FoV) of the LAT as well
- So, an all-sky survey search without any a priori assumptions can be performed

Live time sky map



- **Integrated live time over the selected time intervals from Aug 2008 to Oct 2009 in each sky position**
  - **The map is plotted using Healpix pixelization (Nside=32, Npixels=12*Nside*Nside) in Galactic coordinates with the Galactic center (l, b) = (0, 0) in the middle**
- **For a large exposure time and for an isotropic flux, a counts map would reflect the live time map and Instrument Response Function**

Analysis methods

- The most commonly used method to search for CR anisotropies is to examine flux maps (counts/exposure maps)
  - Such a method has to use the MC simulation of the detector to calculate the exposure.
  - Any systematic of the MC's results can potentially create “features” in the flux maps.
- The starting point of an anisotropy study is the construction of a sky map corresponding to the case of no-anisotropy (null hypothesis)
  - comparison of the no-anisotropy sky map with the actual sky map can reveal the presence of any anisotropies in the data
- By assuming that the detector is responding to an isotropic particle intensity, an equivalent data set corresponding to the null hypothesis can be constructed artificially from actual data set
- Two approaches have been used:
  - Direct integration technique
  - Shuffling technique

Direct integration technique

- The number of events detected at a given direction in the detector (θ,φ) in a time interval [t,t+Δt] is:

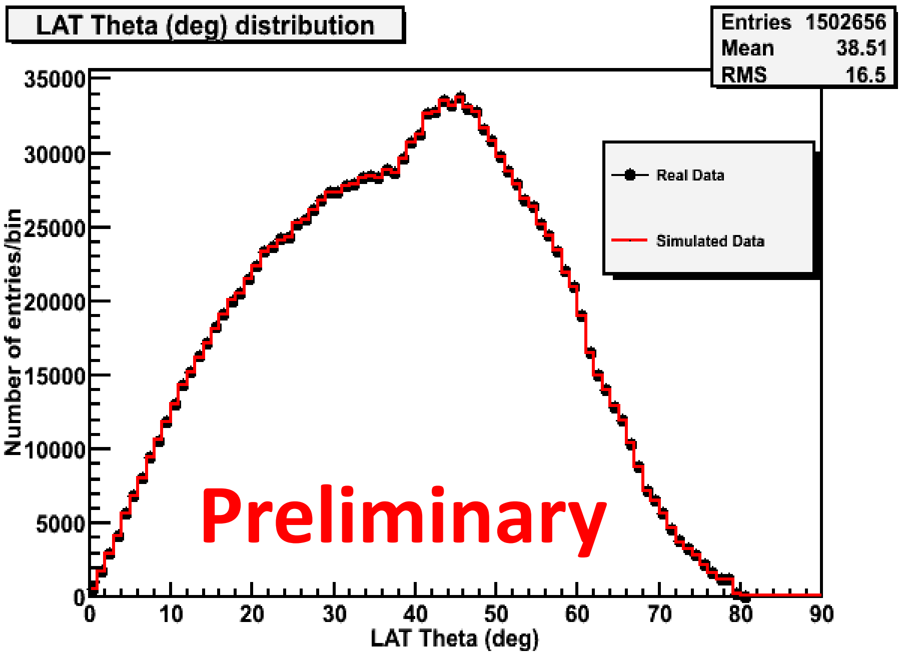
$$\Delta N\left(\vartheta,\varphi \mid t,\Delta t\right) = R_{allsky}(t)P(\vartheta,\varphi)\Delta t$$

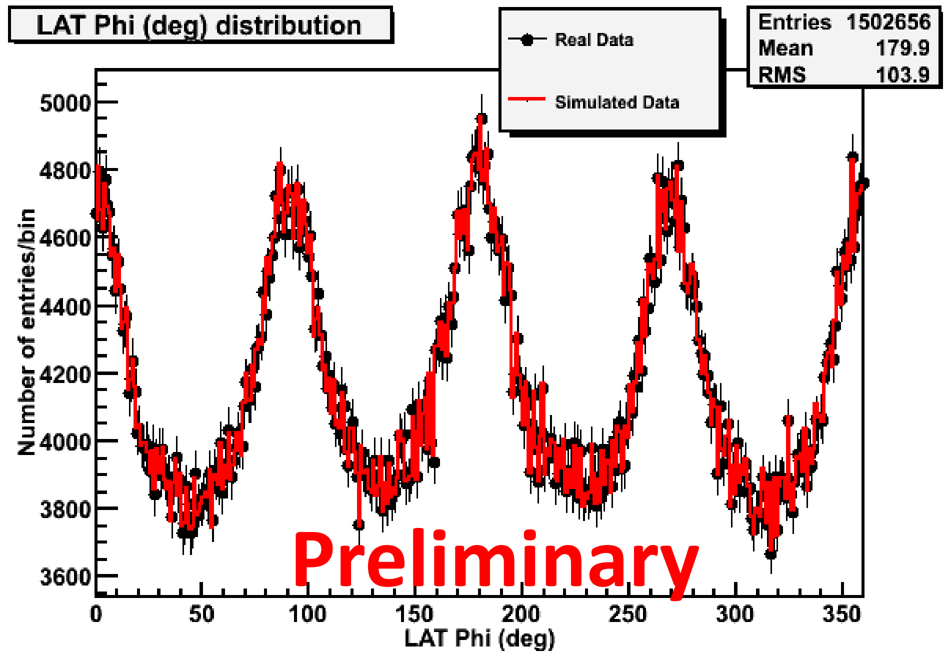
  - $R_{allsky}(t)$ = isotropic event rate from all sky at time t
  - $P(\theta,\varphi)$ = detection probability
- Any anisotropies would create fluctuations in $R_{allsky}(t)$ and $P(\theta,\varphi)$, as these anisotropies pass through the LAT's field of view
- However, in long duration observations (i.e. consisting of at least few orbits), such anisotropy effects will be averaged out and these functions will correspond to the case of no anisotropy
- For an observation of a duration short enough that the LAT's pointing can be approximated as constant, a sky map can be constructed from the averaged-over-multiple-orbits values of these functions, that corresponds to the case of no anisotropy
- Splitting the LAT dataset in such short quasi-constant pointing observations, and adding the individual sky maps of each segment, a no-anisotropy sky map for that whole dataset can be created

Shuffling technique

- An alternative way of generating a no-anisotropy map is by randomizing the reconstructed directions of the detected events
- Assuming that the arrival directions and the arrival times of detected events are uncorrelated variables, sets of simulated events can be constructed by randomly coupling the times and the directions of each event in local instrument coordinates
- This process is repeated multiple times, and at the end an averaged no-anisotropy map is produced
- The shuffling can be performed in separate energy bins or by just mixing them all
  - no significant difference between these two possibilities has been found
- By construction, this exposure preserves exactly the angular distribution of the events in the LAT reference system and accounts for the detector dead times
- However, the whole data set can be divided in segments to minimize possible effects of a varying event rate
- In this talk I will present preliminary results achieved with this technique
  - The results of both methods agree
  - The the random process is repeated 25 times

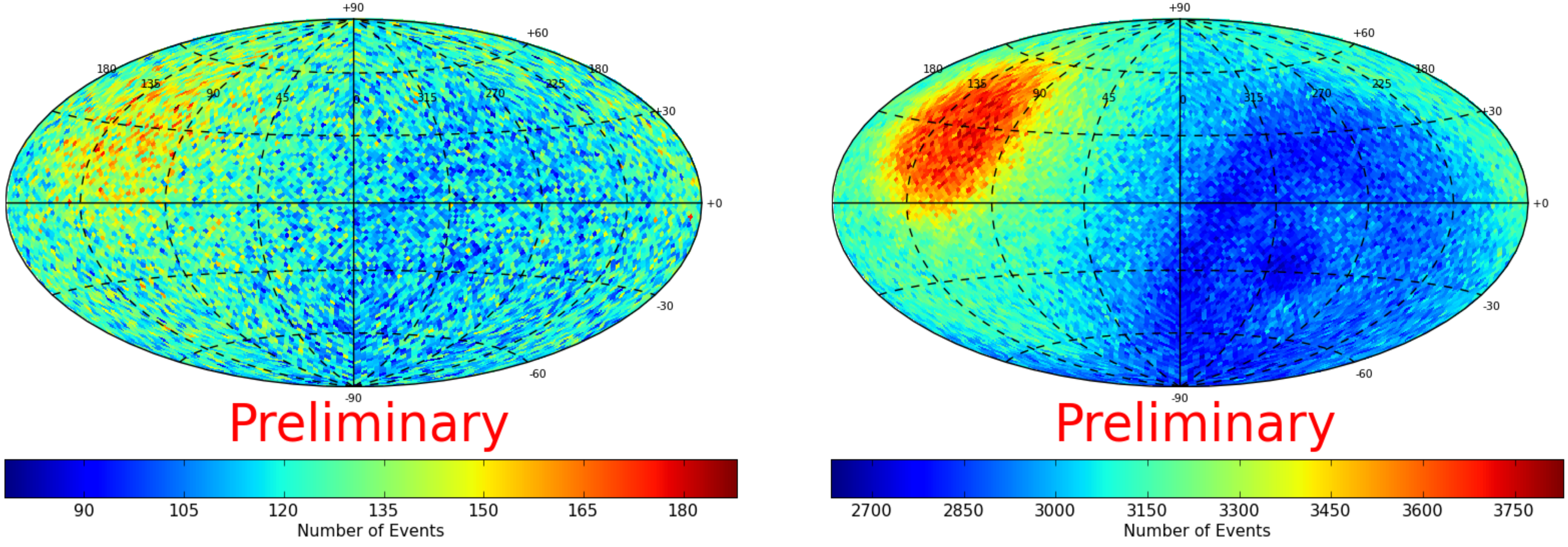
Observed/Simulated events in the LAT





- **Distribution of observed events (black line) with energy above 60 GeV as function of the zenith (left panel) and azimuth (right panel) angles in the LAT instrument reference system together with the simulated data scaled by 25 (red line)**
- **The fluctuations in the simulated distributions are small compared with those in the data**

Observed/Simulated events in the sky



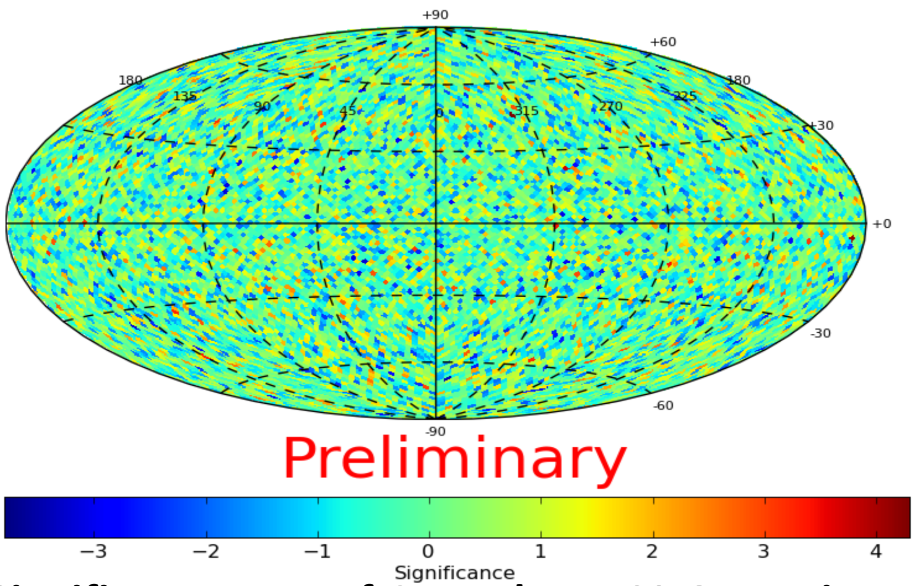
- **Left panel: sky map of real CREs above 60 GeV detected by LAT.**
- **Right Panel: sky map of simulated data above 60 GeV summing up 25 realizations by randomizing the direction of CREs included in the right panel**
- **Both maps are plotted using Healpix pixelization (Nside=32) in Galactic coordinates with the Galactic center (l, b) = (0, 0) in the middle**

Significance map

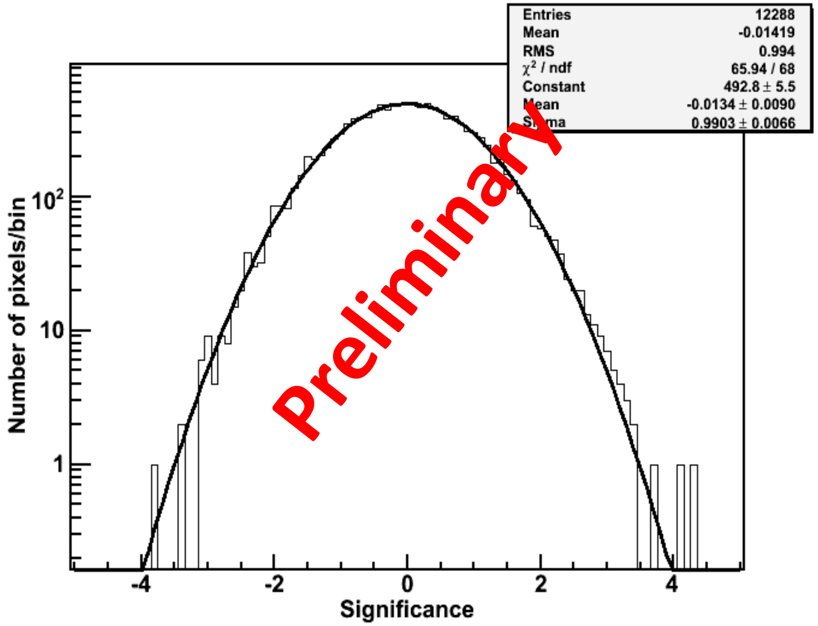
- Starting from the sky maps, a deficit/excess maps can be evaluated
- The significance maps are evaluated following the prescription of Li-Ma (ApJ 272 (1983) 31) by using the likelihood method, where the null hypothesis is the case where no signal is observed,

$$S = \sqrt{-2\ln\lambda} = \sqrt{2}\left\{N_{\rm on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2}$$

N_{on}=real events, N_{off}= simulated events, α =1/25 where 25 is the current number of random data sets



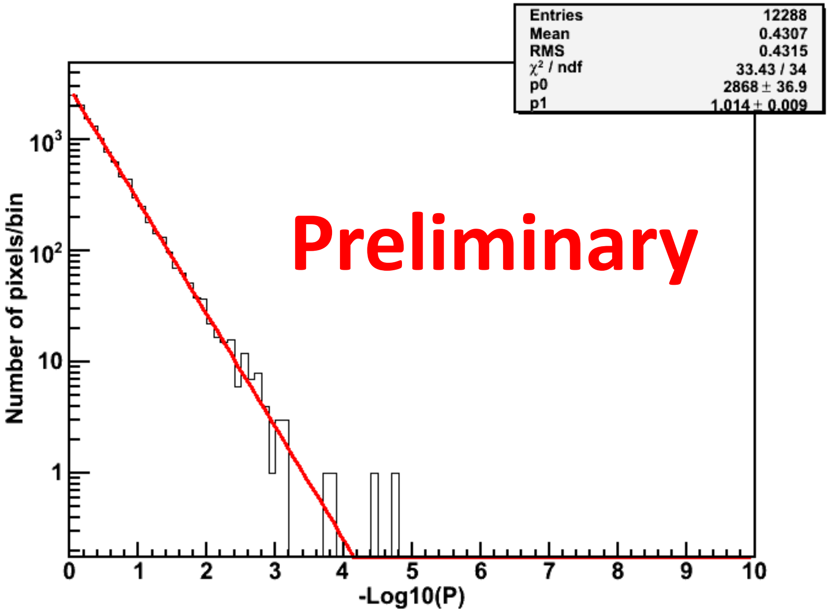
Significance map of CREs above 60 GeV using Healpix pixelization (Nside=32). For visualization purposes we assign a negative value of the significance if Nreal<αNsimu



Significance distribution of events with energy above 60 GeV together with a best fit with a gaussian function (solid line).

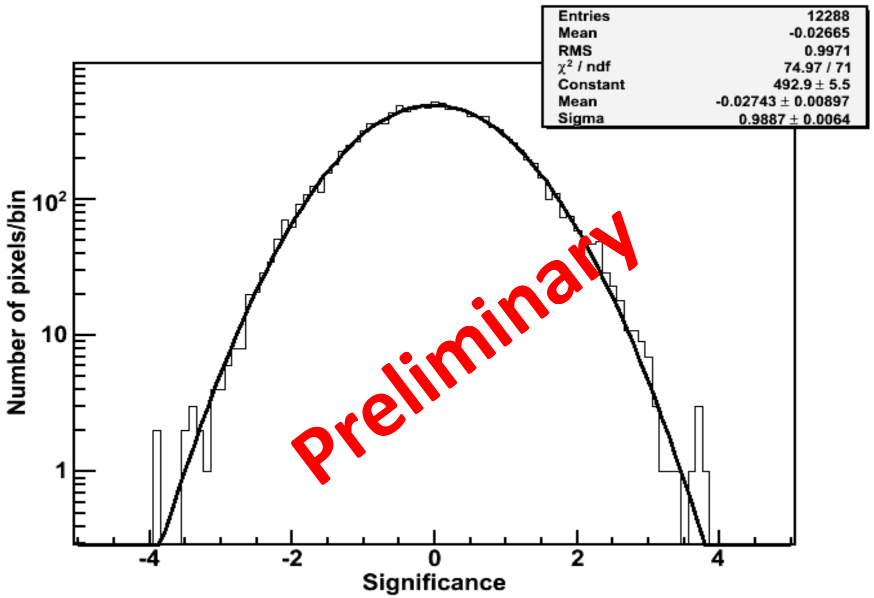
Confidence likelihood of S

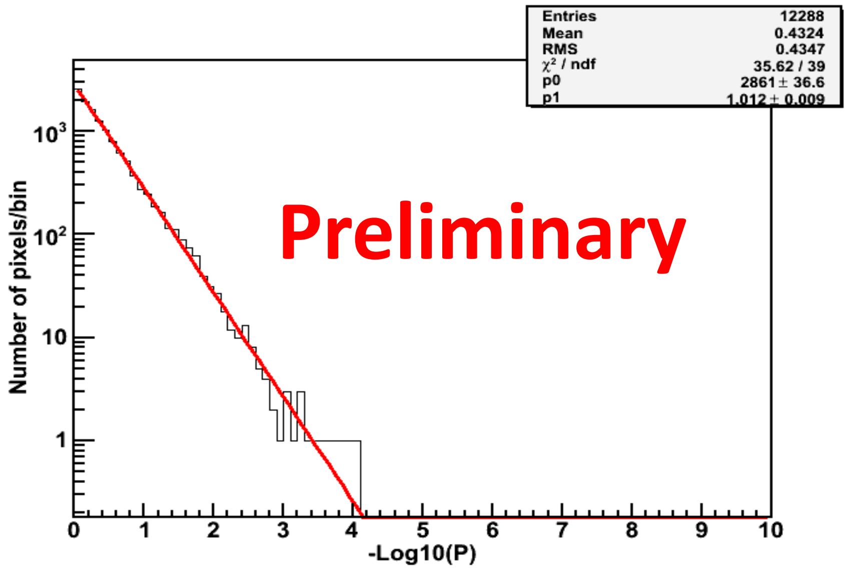
- The probability that a pixel with a significance larger than S is consistent with the null hypothesis can be evaluated from a Gaussian distribution with null mean and unit variance.
- Then the probability P that a real source exists, i.e. the confidence level, can be evaluated.
- This can be obtained using the cumulative distribution function for the χ^2 distribution with 1 degree of freedom
- For uncorrelated pixels (independent) the cumulative frequency distribution of P is expected to follow a power law with index -1.



- Distribution of the values of $-Log_{10}(P)$ evaluated from the significances S shown in the previous slide
- If 5 sigma is set as attention level that a real excess exists, it corresponds to a probability of about 5.73 10^{-7}
- No pixels above this value are observed

Significance for CREs above 120 GeV





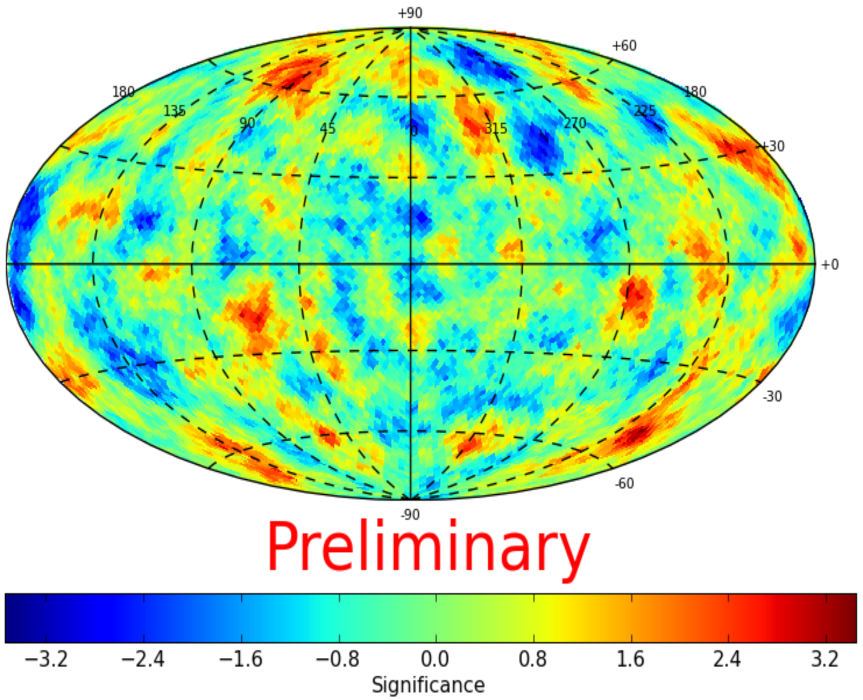
- Left panel: Significance distribution together with a best fit with a gaussian function (solid line) for events above 120 GeV
- Right panel: Distribution of –Log10(P) of observed events in individual pixels with a significance larger than S in the null hypothesis (black line), together with a best fit with an exponential function (red line)
- These distributions have been evaluated starting from a sky maps using Healpix pixelization with Nside=32 in Galactic coordinates with events above 120 GeV
- Again, no pixels above 5 sigmas are observed

Searches for large structure anisotropies

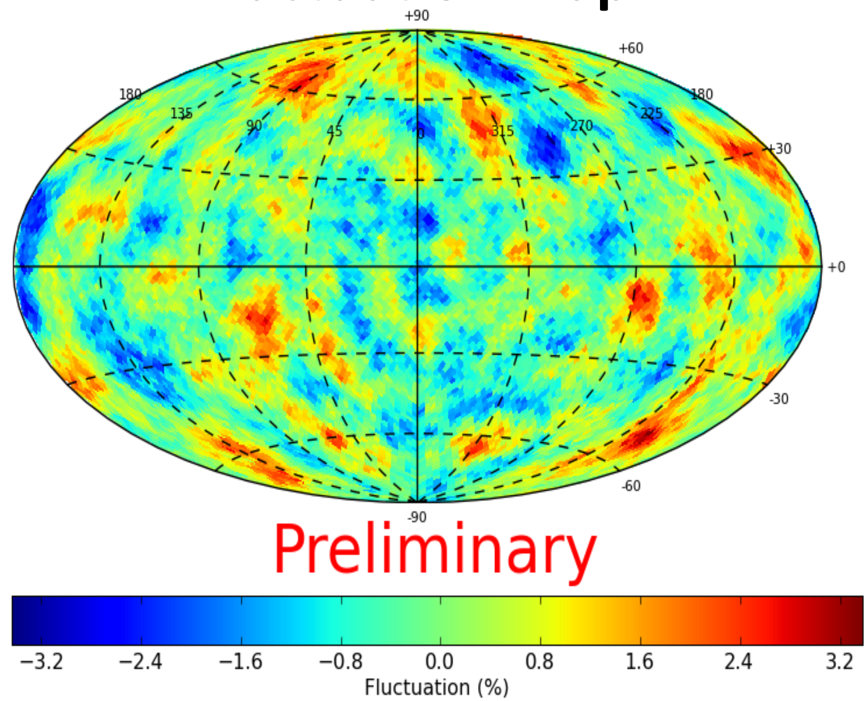
- A large scale anisotropy is also expected
- A smoothed sky map can be built in a way that the content of each pixel becomes the integrated number of events detected within a given angular radius (Region of Interest, RoI) from the bin center
  - The RoI is chosen to be equal to the size of the anisotropy under investigation
- An anisotropy with an angular size close to the RoI will be contained in at least one bin of such a smoothed map
  - This will make any spillover effects more tolerable (such as in the case of independent bins) and will maximize the sensitivity.

E>60 GeV and RoI=10°

Significance map



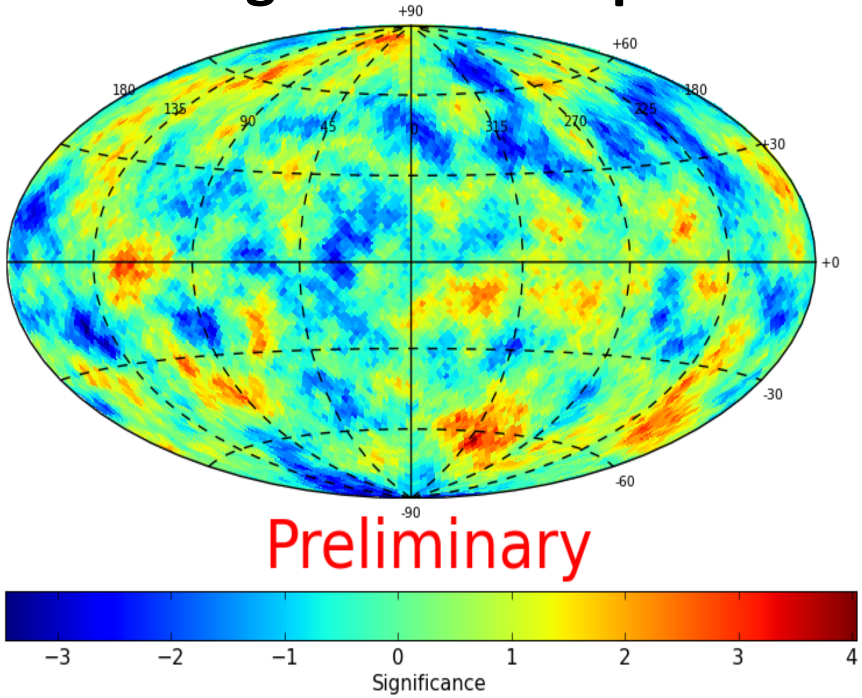
Fluctuation map



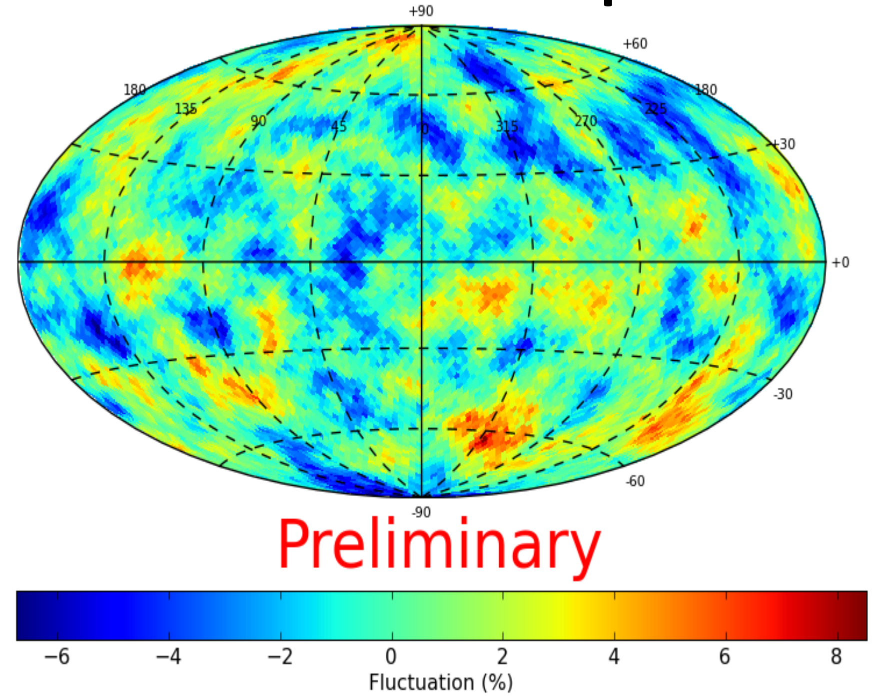
- **Significance (left panel) and Fluctuation, i.e. (Real-Back)/Back, (right panel) maps including all events with energy above 60GeV within 10° of radius cone**
- **The maps are plotted using Healpix pixelization with Nside=32 in Galactic coordinates with the Galactic center (l, b) = (0, 0) in the middle**
- **The color scale is coded with a asymmetric range from Min to Max**

E>120 GeV and RoI=10°

Significance map

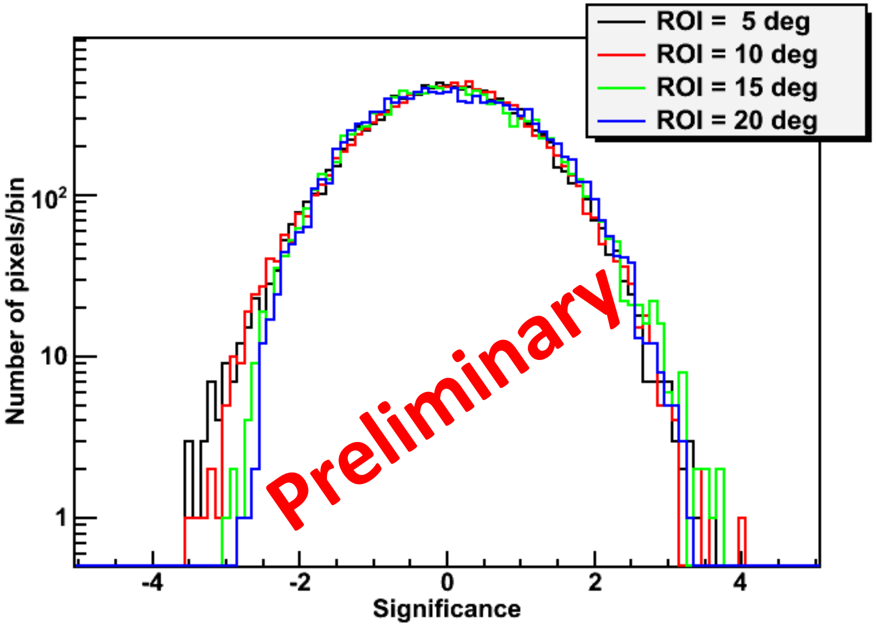


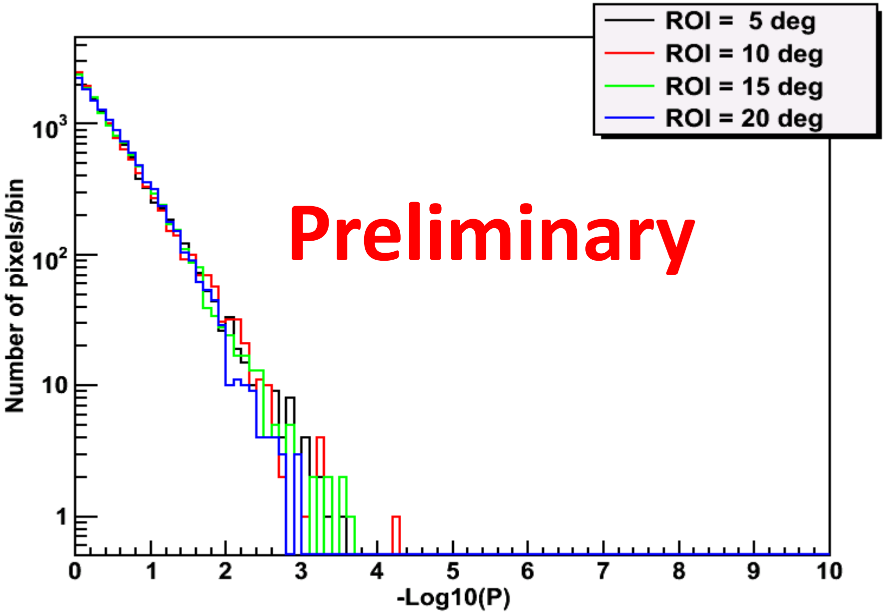
Fluctuation map



- **Significance (left panel) and Fluctuation, i.e. (Real-Back)/Back, (right panel) maps including all events with energy above 120GeV within 10° of radius cone**
- **The maps are plotted using Healpix pixelization with Nside=32 in Galactic coordinates with the Galactic center (l, b) = (0, 0) in the middle**
- **The color scale is coded with a asymmetric range from Min to Max**

Significance distribution E>120 GeV





- Left panel: Distribution of significance S for different RoIs, i.e. 5, 10, 15 and 20 deg
- Right panel: Distribution of –Log10(P) for observed number of events in individual pixels with a significance larger than S in the null hypothesis
- These distribution have been evaluated starting from a sky maps using Healpix pixelization with Nside=32 in Galactic coordinates with events above 120 GeV
- The significance distributions are not expected to follow a Normal distribution since the events are involved many times (correlation between adjacent pixels)
- Searches for excess correlated with emission on angular scales from 5° to 20° are also proved negative

Conclusions

- The methods used to search for anisotropies with the Fermi-LAT data have been presented
- Preliminary results have been also presented using CREs of energies of ~100GeV by means of the shuffling method
  - No significant evidence of anisotropies for steady excesses/deficits from any sky location
  - In addition, searches for excess correlated with emission on angular scales from 5° to 20° are also proved negative
- Systematic uncertainties are mainly due to hadron contamination sample that ranges from 4% at 20GeV to 20% at 1 TeV
  - Anisotropies for hadrons have been detected at 10^{-3} level by other experiments, so the induced effect on CRE anisotropies due to hadron contamination should be of order of 10^{-4} or less, which is less than the current sensitivity
- Improvements in the analysis ongoing
  - The Compton-Getting effect will also be taken into account