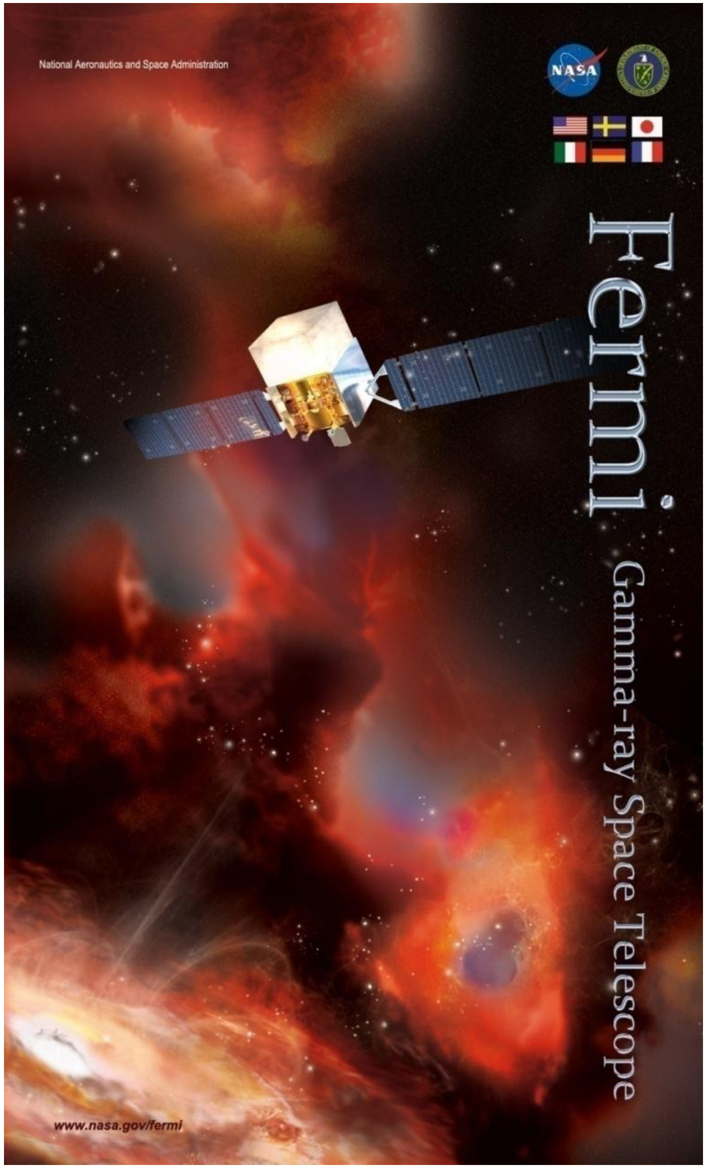

Electron/Positron Spectrum and Anisotropies search with Fermi-LAT

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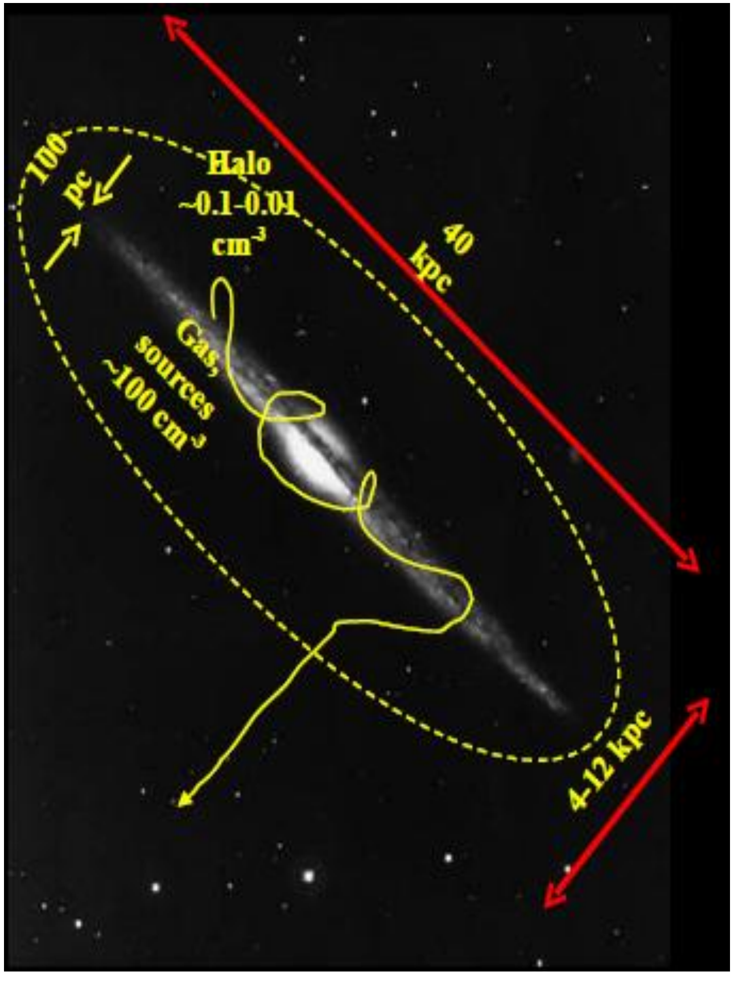
8th Workshop on Science with the New Generation of High Energy Gamma-ray Experiments
Gamma-ray Astrophysics in the Multimessenger context
Trieste, 2010, September 8 -10

Galactic cosmic rays

- High-energy (GeV–TeV) charged primary Cosmic Rays (CRs) are believed to be produced in our galaxy, most likely in Supernova Remnants (SNRs)
- CRs injected into ISM propagate for millions of years before escaping to intergalactic space
- Particle interactions with interstellar gas, radiation and magnetic fields produce EM radiation from radio to gamma rays, and other secondaries ($e^{\pm}$, nuclei, etc.)
- During the transport from their source of origin to our solar system, CRs scatter on random and irregular components of the μG Galactic Magnetic Field (GMF), which almost isotropize their directions.
- Contrary to hadronic CRs, high-energy (>GeV) Cosmic Ray Electrons and Positrons (CREs) propagating in the GMF lose their energy rapidly through synchrotron radiation and by inverse Compton collisions with low-energy photons of the interstellar radiation field.



CRE propagation equation

- For CREs the convection and reacceleration could be neglected above few GeV, so that the propagation of CREs can be expressed in terms of usual conservation equation:

$$\frac{\partial N}{\partial t} - \vec{\nabla}\cdot\left(D\vec{\nabla} N \right) - \frac{\partial}{\partial E}(bN) = q$$

  - b is the continuous energy loss rate, $b \approx 1.4 \times 10^{-16}$ GeV^{-1} s^{-1}
  - *D is the diffusion coefficient,* $D = D_0 (E/E_0)^{\delta}$
    - $D_0 \approx 5.8 \times 10^{28}$ cm^2 s^{-1}, $\delta = 1/3$ *and* $E_0 \approx 4$ GeV
- CREs lose almost all of their energy E after a time T:
  - $T = 1/bE \approx 2\times10^5$ yr$/E$(TeV)
- CREs can diffuse over a distance $R = (2DT)^{1/2}$ during the lifetime T
  - $R \approx 1.6$ (0.75) kpc for $E = 100$ GeV (1 TeV)
- Such high-energy CREs might originate from a highly anisotropic collection of a few nearby sources

Anisotropy

- Degree of anisotropy: $$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

  where $I_{max(min)}$ is the maximum (minimum) intensity
- In case of the dipole anisotropy: $I(\theta) = I_0 + I_1 \cos(\theta) \Rightarrow \delta = I_1/I_0$
- The anisotropy due to the pure diffusion term is given by: $$\delta = \frac{3D}{c} \frac{|\vec{\nabla} N|}{N}$$
- In case of a single source of age t_i at the position r_i (burst-like injection) the spectrum of CREs at the solar system is $\propto \exp\left(-\frac{r_i^2}{r_{diff}^2}\right)$ (Green's function)
- So that, its contribution to the anisotropy is given by:

$$\delta_i = \frac{3D}{c} \frac{2|\vec{r}_i|}{r_{diff}^2} \quad \Rightarrow \quad \delta_i = \frac{3|\vec{r}_i|}{2ct_i}$$

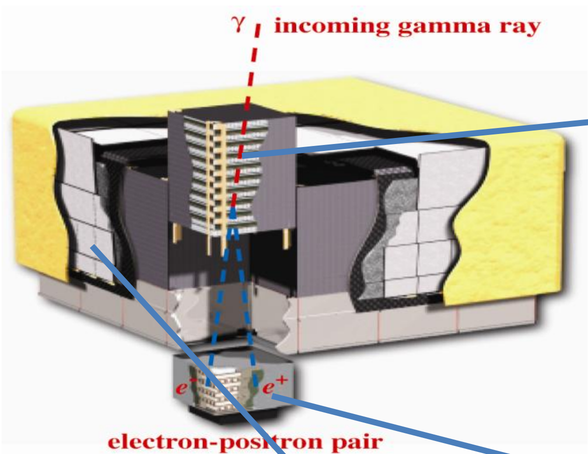
- The total anisotropy due to a distribution of point-like sources in the sky is then given by:

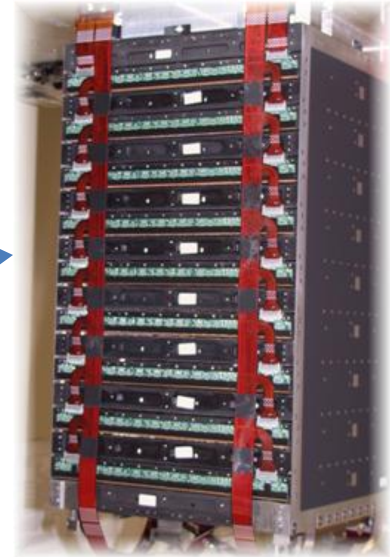
$$\delta = \frac{\sum_i N_i \, \delta_i \, \hat{r}_i \cdot \hat{n}_{max}}{\sum_i N_i}$$

  where n_{max} is the direction of maximum intensity

Overview of the Large Area Telescope (LAT)

The LAT is a γ-ray Telescope based on the conversion of gamma-rays into electron-positron pairs and is arranged in a 4×4 array of 16 identical towers.



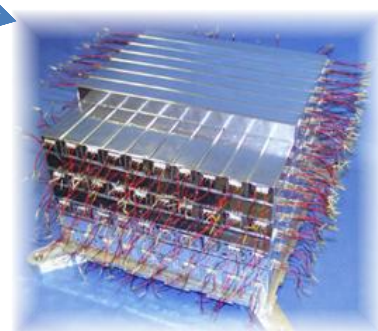


Tracker/Converter (TKR):

- Si-strip detectors
- ~ 80 m^2 of silicon
- W conversion foils
- 1.5 X_0 on-axis
- 18 X-Y planes
- ~ 10^6 channels
- Highly granular
- High precision tracking
- Average plane PHA

Anti-Coincidence (ACD):

- Segmented (89 tiles)
- Self-veto @ high energy limited
- 0.9997 detection efficiency

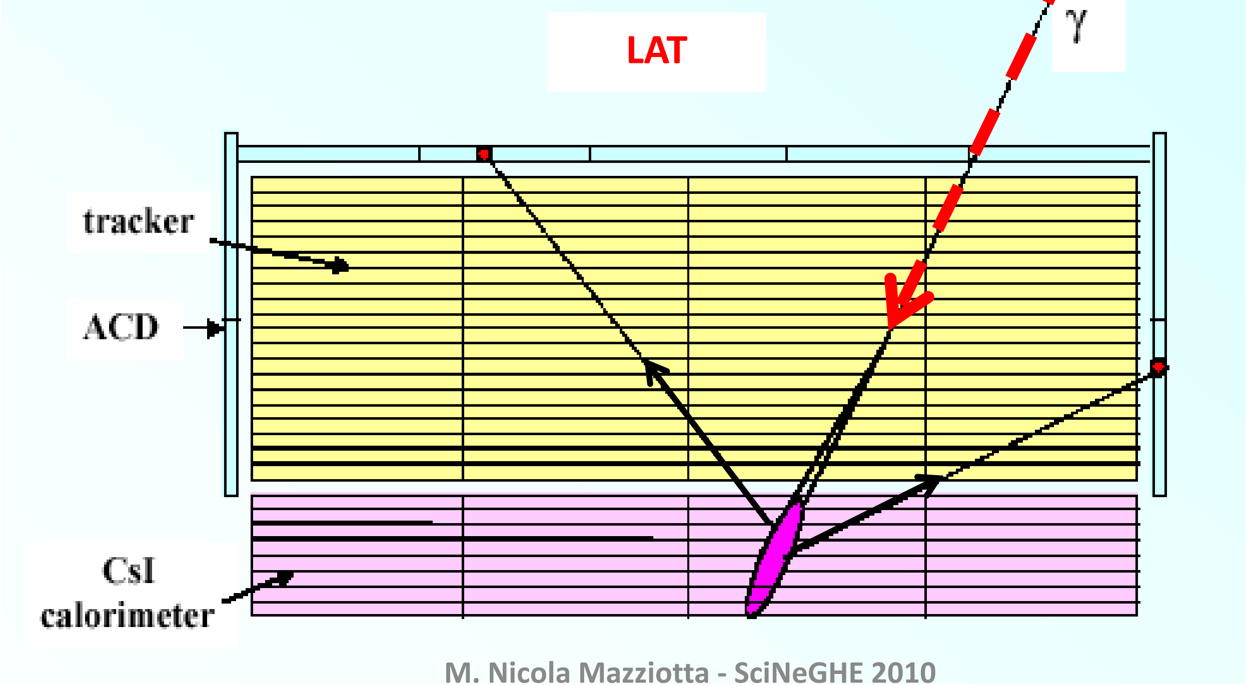


Calorimeter (CAL):

- 1536 CsI(Tl) crystals
- 8.6 X_0 on-axis
- 2 PIN-PD per Xtal end
- large dynamic range per Xtal (2MeV-60GeV)
- Hodoscopic (8 layers with 12 xtals)
- Shower profile recon
- EM vs HAD separation

The LAT is an "electron telescope" too!

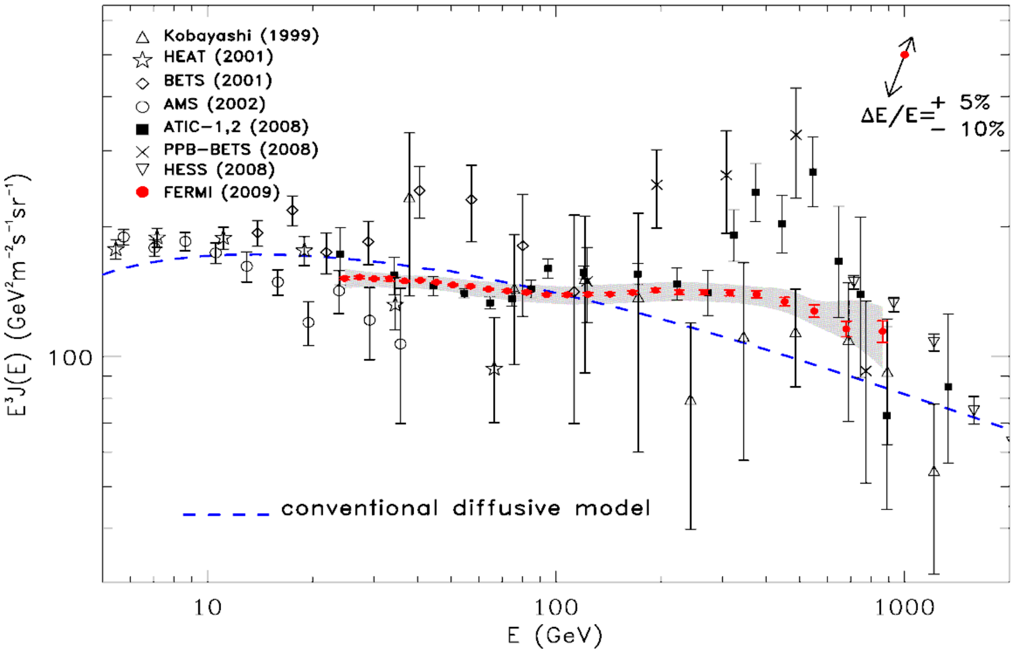
- **Gamma-ray detection:**
  - Look for an electromagnetic cascade
  - Reject charged particles
- **Electron detection:**
  - Also an electromagnetic cascade!
    - Removed charge veto, tighten the other cuts
  - Fermi-LAT does not distinguish between e^- and e^+, we use the word "electrons" to refer to both



Event selection

- All the three LAT subsystems contribute to the rejection of the hadronic (mainly protons) background
  - The shower development in the calorimeter plays a prominent role
- Peak effective geometry factor of almost 3 m^2 sr around 50 GeV
  - Given the large statistics, the knowledge of the effective geometry factor dominates the systematic uncertainties
  - Evaluated by means of extensive analysis of data/Monte Carlo discrepancies using both flight and beam test data
- The estimated hadronic contamination is below 20%
  - Statistically subtracted from the candidate electron sample
- The photon contamination is negligible (< 0.1%)

Phys. Rev. Lett. 102, 181101 (2009)



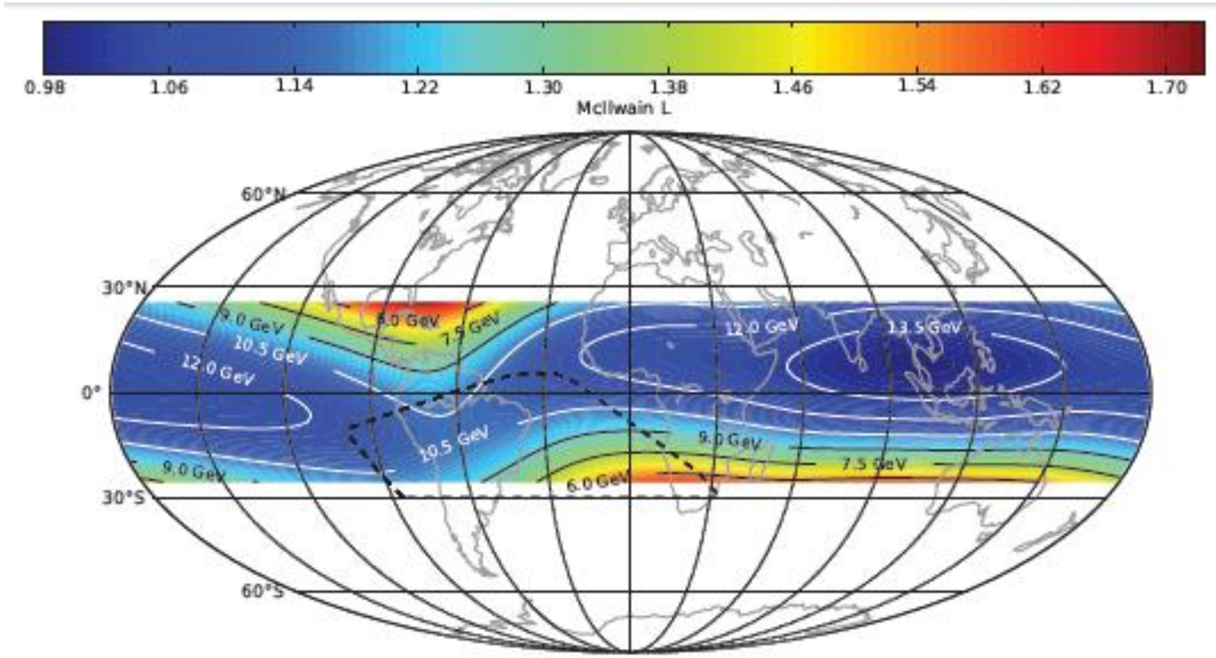
Cited 340 times from May. 2009 to Aug. 2010

- **Data collected in the first six months of operation**
- **4 M candidate electron events above 20 GeV**

What's new since then?

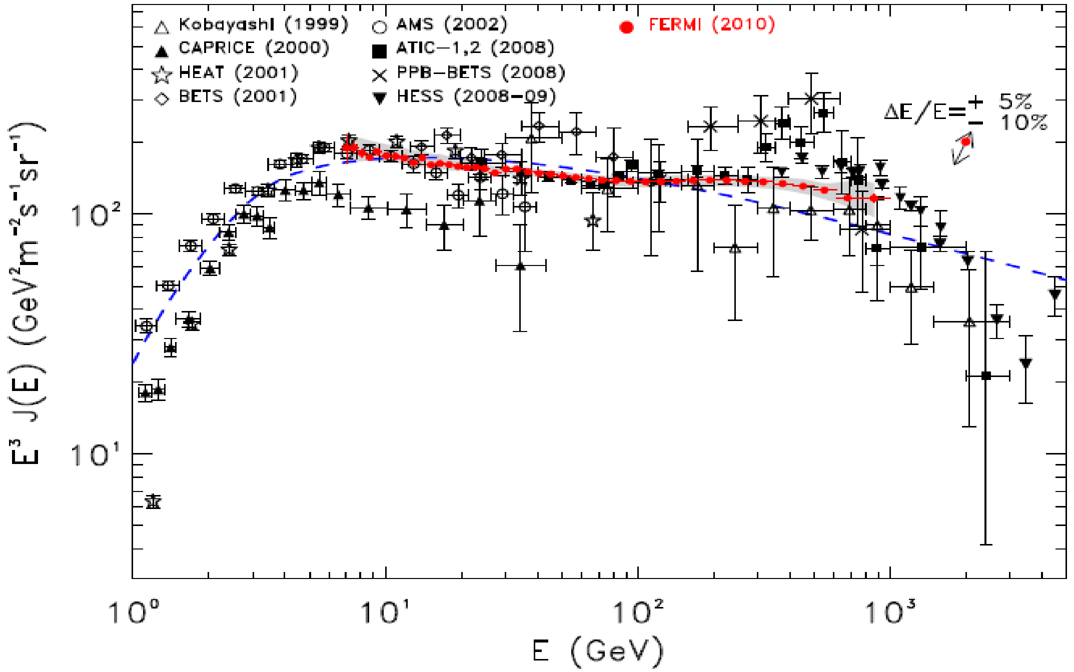
- **CRE analysis paper accepted by Physical Review D (arXiv:1008.3999)**
  - **Detailed description of the electron analysis, spectrum extension down to 7 GeV**
  - **Events with long path (13 X_0 min, 16 X_0 average) have been used to cross check the results**
    - **Selection optimized for energy resolution (better than 5% at 1σ up to 1 TeV)**
- **CRE anisotropy paper accepted by Physical Review D (arXiv:1008.5119)**

Low-energy extension



- ❑ Need to take into account the effect of the Geomagnetic field
- ❑ Rigidity cutoff depends on the detector geomagnetic position
  - ❑ ≈ 7 GeV is the minimum energy accessible in the Fermi orbit
- ❑ Data are divided in 10 independent McIlwain L bins
  - ❑ For each energy bin only the McIlwain bins for which the measured cutoff is significantly below the low edge are used

1 year full energy spectrum



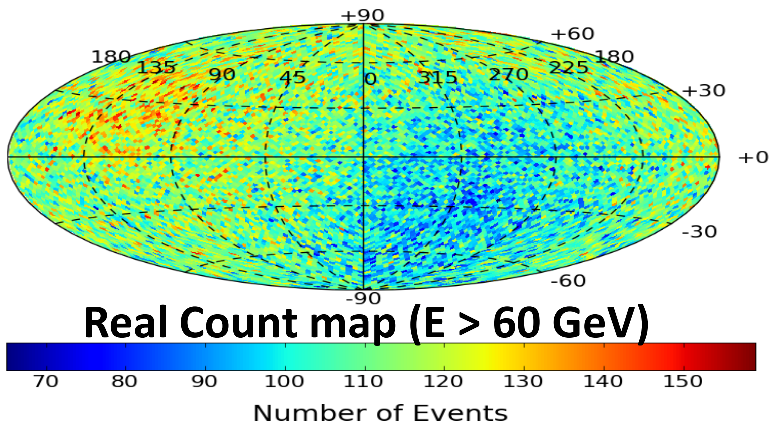
- Almost 8M electron candidates collected in the first year of operations
  - More than 1000 in the highest-energy bin (772-1000 GeV)
- No evidence of a prominent spectral feature
- Within the systematic errors (shown by the grey band) the entire spectrum from 7 GeV to 1 TeV can be fitted by a power law with spectral index in the interval 3.03 – 3.13 (best fit 3.08)

Anisotropy search methods

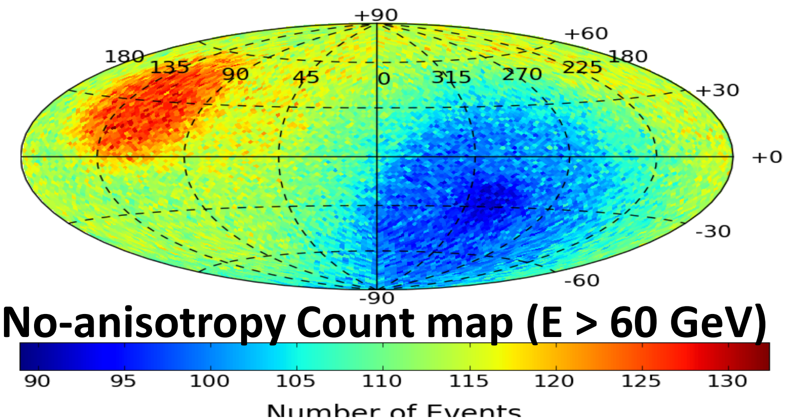
- Fermi offers a unique opportunity for the measurement of possible CRE anisotropies
  - Large exposure factor and uniform exposure of the sky
- More than 1.6M candidate electrons above 60 GeV collected in the first year of operation
  - 60 GeV is the minimum energy to avoid any geomagnetic effects at the LAT latitudes
- The starting point of an anisotropy study is the construction of a sky map corresponding to the case of no-anisotropy (null hypothesis - case of a perfectly isotropic distribution)
  - No flux maps (counts/exposure maps) method is used to prevent systematic effects when evaluating the exposure
  - 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 the actual data set
- Two approaches have been used to build the no-anisotropy sky map:
  - Direct integration technique
  - Shuffling technique

Search for CRE anisotropy

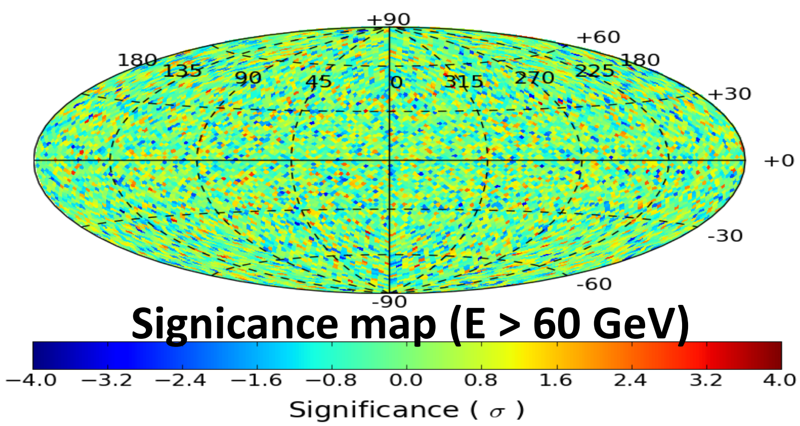
- **The arrival directions of events from the whole sky were searched for anisotropies in Galactic coordinates**
  - **Healpix pixelization scheme (12288 pixels, ≈3deg^2) used for the skymaps**



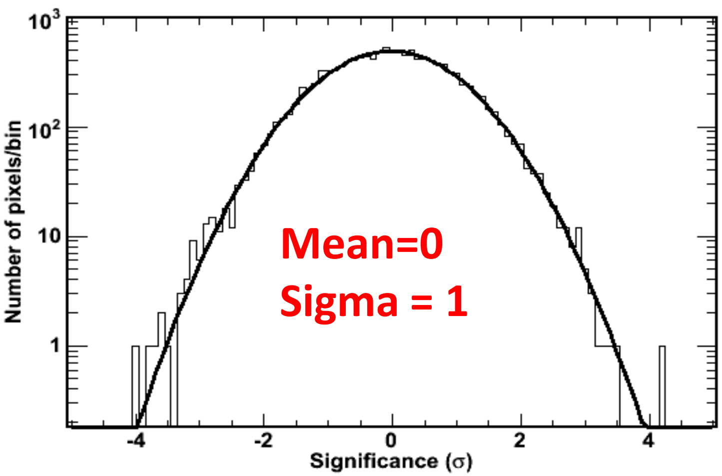
Real Count map (E > 60 GeV)



No-anisotropy Count map (E > 60 GeV)



Signicance map (E > 60 GeV)



Search for CRE anisotropy

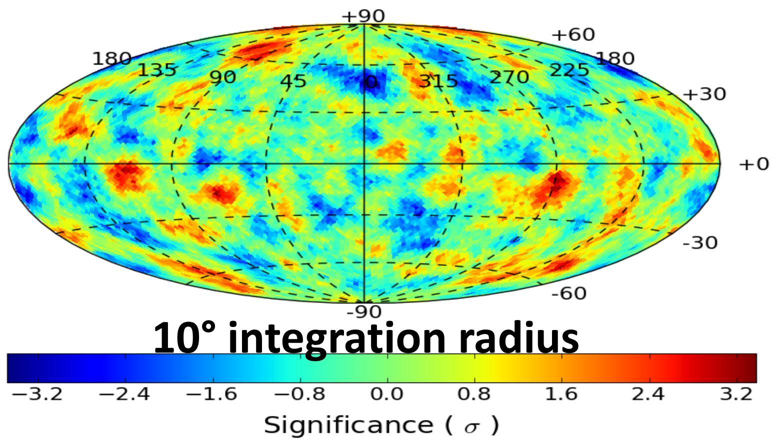
Search for possible anisotropies with different energy thresholds (> 60 GeV) and on different angular scales

- **Direct bin-to-bin comparison**
  - By construction, started with ~1° *independent-bins skymaps*
  - Can't search for tens-of-degs anisotropies with such skymaps (spillover effects reduce sensitivity)
  - Produced several *integrated skymaps, each with a different integration radius: 10°, 30°, 45°, 60°, 90°*
  - Then, a bin-to-bin comparison between the actual data and the predicted for the case of no anisotropy was performed
    - The effective number of trials involved in evaluating all possible directions in an angular integrated skymaps need to be taken into account
- **Spherical harmonic analysis**
  - Spherical harmonic analysis of a fluctuation map produced by dividing the signal with the no-anisotropy skymap
  - The fluctuation map was first expanded in the basis of spherical harmonics
  - The average variance of these coefficients (Cl) was used to construct an angular power spectrum
  - The power spectrum was compared to the expected spectrum of a white-noise data set (applicable for an isotropic sky)

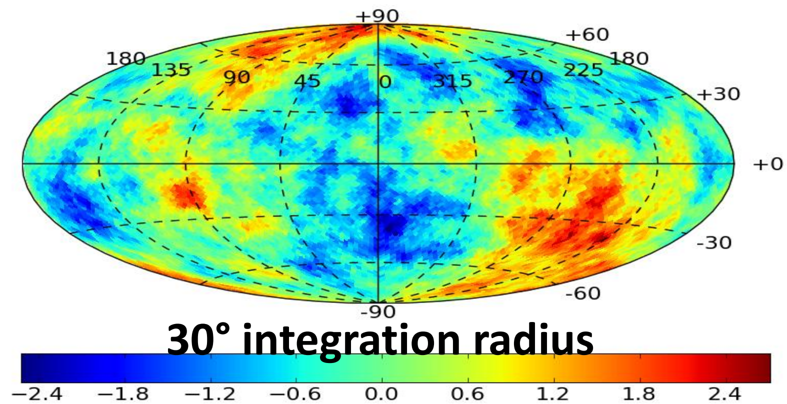
Significance skymaps

A pre-trials significance map produced by a bin to bin comparison of the no-CRE-anisotropy to the actual skymap:

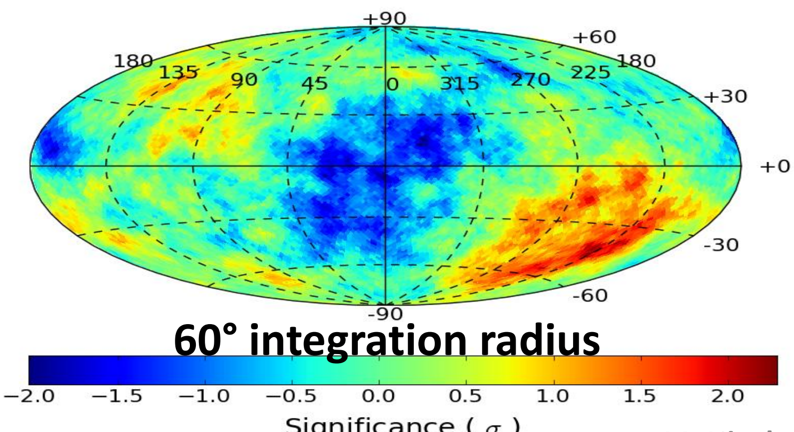
- **Integration radius 10°, 30°, 60° and 90° and Energy>60GeV**
- **Because of the large number of trials (from ≈100 trials at 90° up to ≈ 5000 at 10° integration angular radius) all the observed fluctuations are *post-trials insignificant***



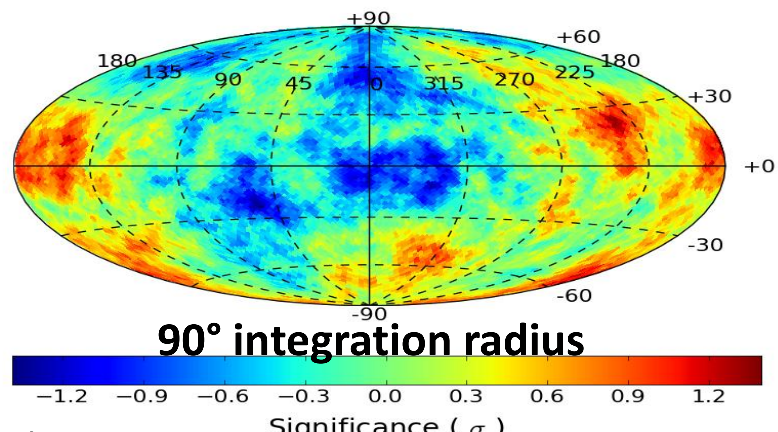
10° integration radius



30° integration radius



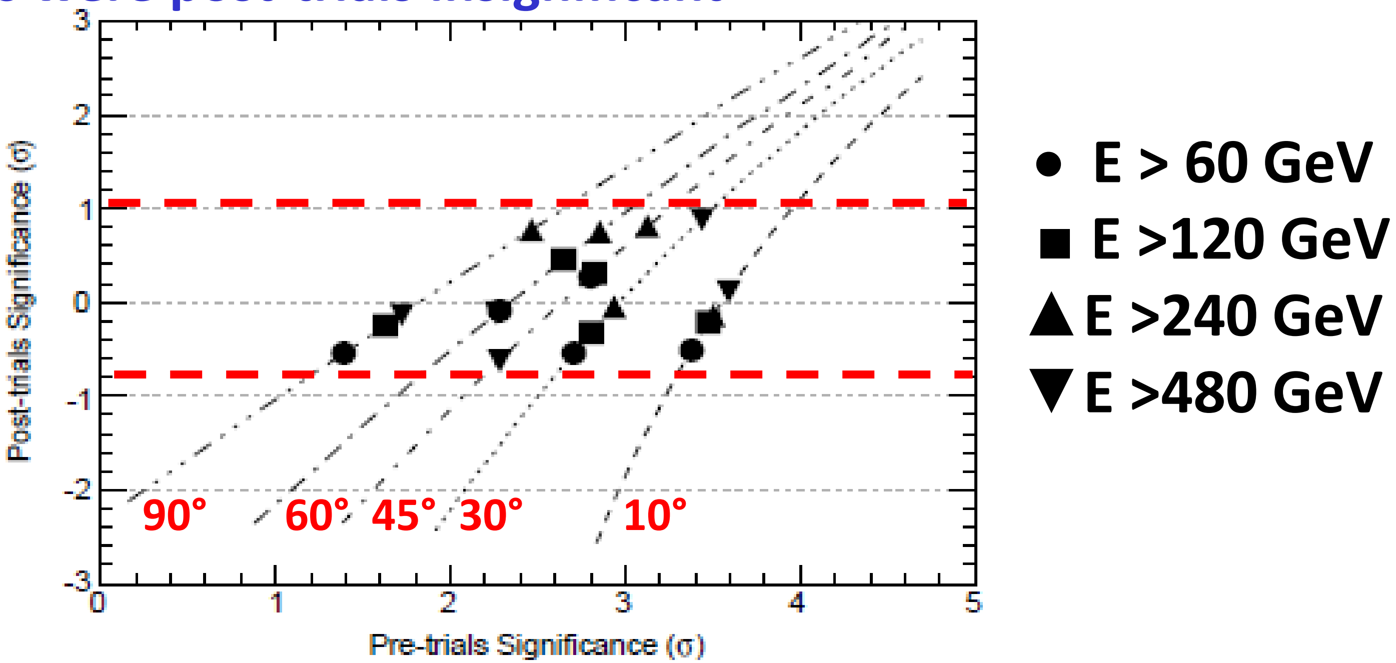
60° integration radius



90° integration radius

Results of the bin-to-bin comparison

- Curves: Correspondence between a pre and a post-trials significance
  - Left to right 90°, 60°, 45°, 30°, 10° integration radius
- Markers: highest significance for different minimum energies and integration radius
- All the results were post-trials insignificant

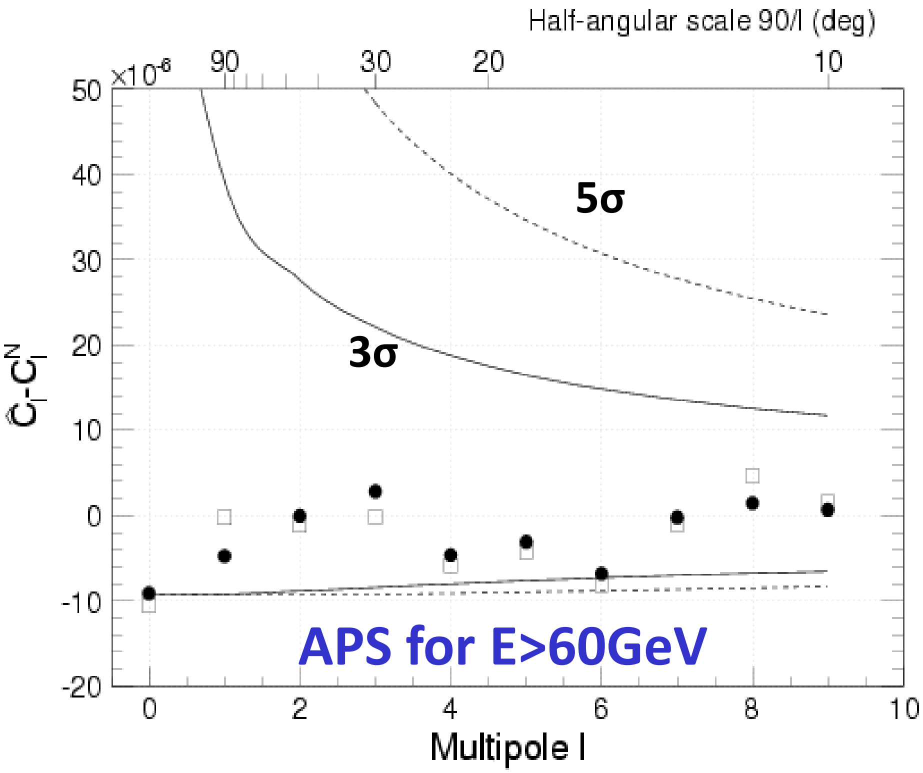


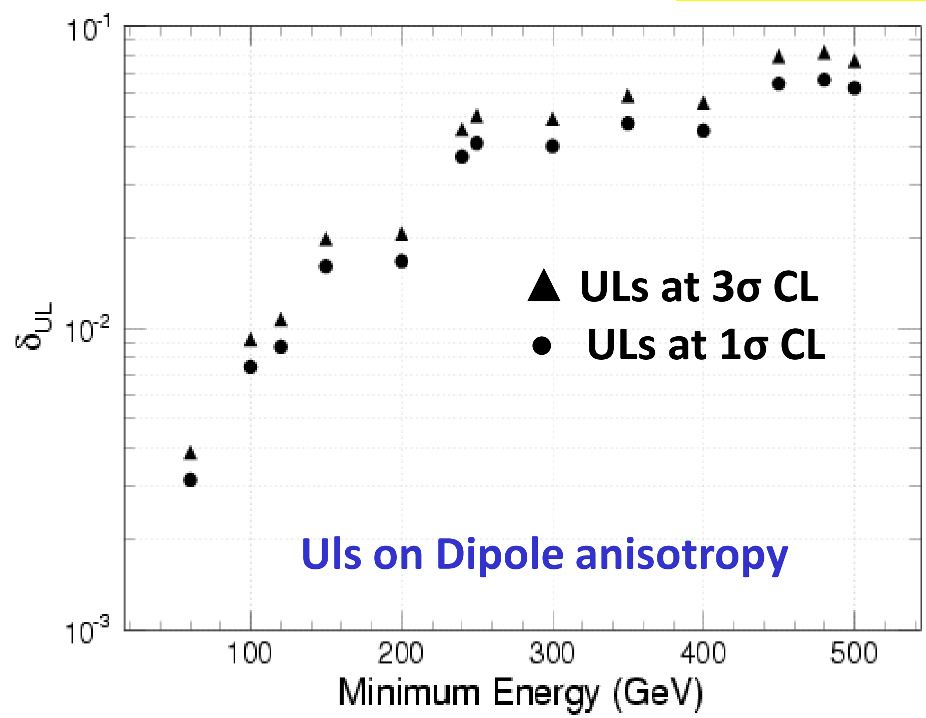
- An evaluation of the maps towards interesting locations (Geminga, Vela, Monogem pulsars, and the Galactic and anti-galactic centers) also yielded null results

Angular Power Spectra (APS)

- **All the spectra were consistent with being mere statistical fluctuations of an isotropic signal**
- **C_1 set the Upper Limits (ULs) on Dipole anisotropy δ**

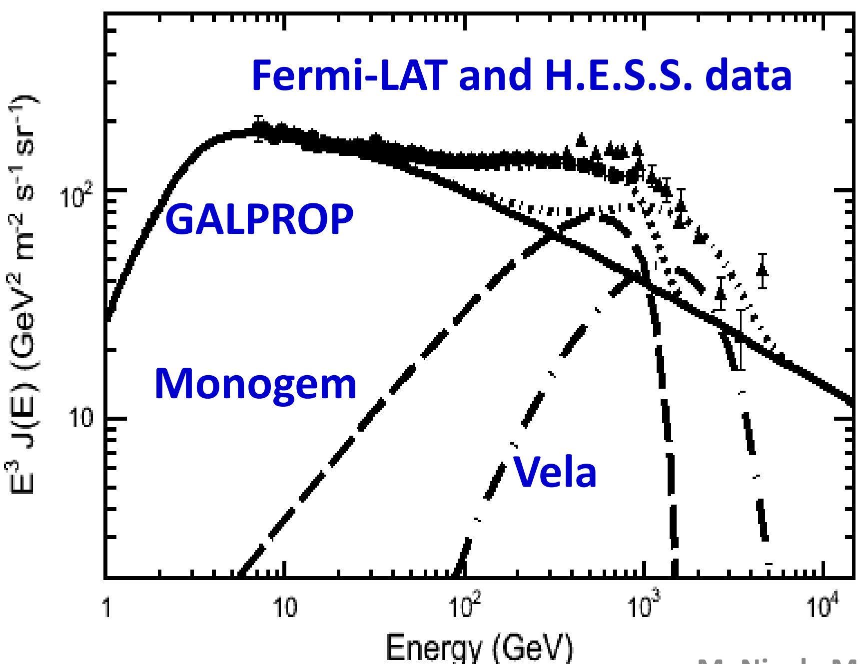
$$\delta = 3\sqrt{\frac{C_1}{4\pi}}$$

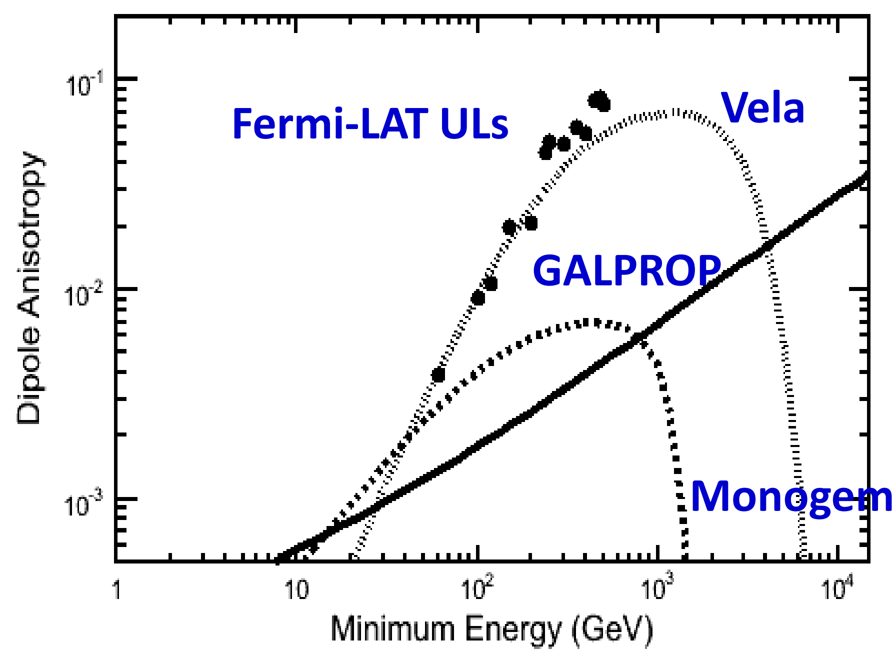




Some interpretations …

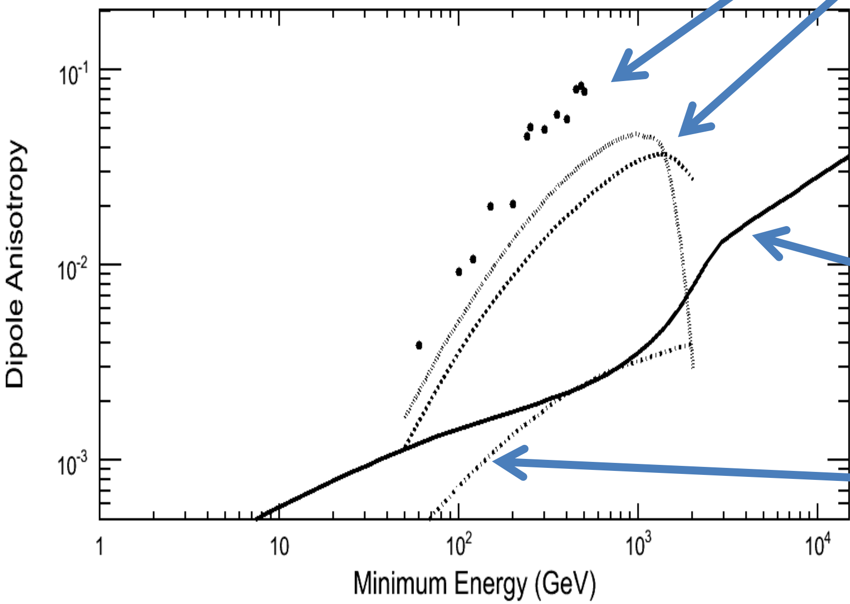
- Hard to fit the CRE spectrum with a single-component diffusive model
- Good fit possible with an additional high-energy component
  - If it's an e^+/e^- source (e. g. nearby pulsars or dark matter), the Fermi spectrum and Pamela positron fraction can be simultaneously fitted
- For single sources (e.g. Vela-like and Monogem-like) the value of the injected luminosity is such that the total flux is not higher than the one measured by the Fermi-LAT and H.E.S.S.
- For each source, the anisotropy has been evaluated assuming that the contributions to the anisotropy from all remaining sources are negligible





… and DM scenario

The positron excess detected by PAMELA can be ascribed not only to astrophysical sources such as pulsars, but also to the annihilation or decay of Galactic dark matter



- Markers: 3 sigma ULs data
- Dashed (dotted) lines: single nearby dark matter clump with a speed of 300km s^{-1} perpendicular to the Galactic plane, with DM particle mass of 5 TeV that is departing at 1.54 kpc (mass of 5 TeV that is approaching at 1.43 kpc) (for more details see M. Regis and P. Ullio, arXiv:0907.5093)
- Solid line: DM distributed in the Milky Way Halo according to a Navarro, Frenk and White (NFW) profile, with a 3 TeV mass candidate that annihilates into $\tau^+\tau^-$
- Dot-dashed line: DM from the population of Galactic substructures of dark matter clumps in the halo following a NFW profile , with DM particle mass of 3.6 TeV that annihilates into τ leptons (for more details see I. Cernuda, arXiv:0905.1653)

Conclusions

- Fermi has published the first extensive measurement of the Cosmic-Ray Electron spectrum up to 1 TeV
- Now extended down to the lowest energy accessible by the Fermi-LAT, given its orbit
  - Covering almost 2.5 decades in energy
- No evidence for anisotropies in the arrival directions of CREs above 60 GeV
  - Upper limits (a fraction of % to a few %, depending on the energy threshold/angular scale) are already interesting in terms of modeling
    - Some test case of single nearby sources dominating the high-energy electron spectrum could approach the measured Uls

BACKUP SLIDES

Propagation Equation

N = CR density

$$\frac{\partial N(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ sources (SNR, nuclear reactions…)

Diffusion $$+\vec{\nabla}\cdot[D_{xx}\vec{\nabla}N - \vec{V}N]$$

Diffusive reacceleration
(diffusion in the momentum space)
$$+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{N}{p^2}\right]$$

convection
(Galactic wind)

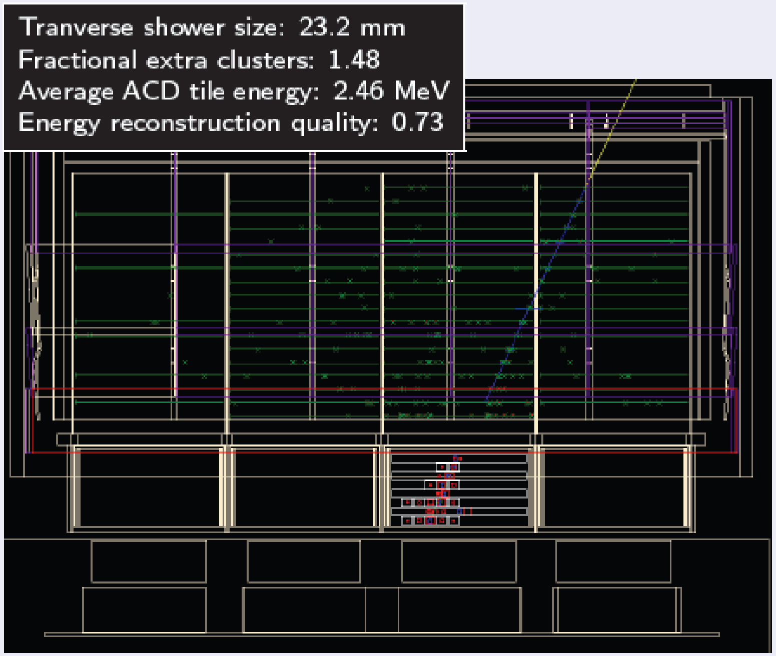
E-loss $$-\frac{\partial}{\partial p}\left[\frac{dp}{dt}N - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}N\right]$$

fragmentation $$-\frac{N}{\tau_f} - \frac{N}{\tau_d}$$ radioactive decay

+ boundary conditions

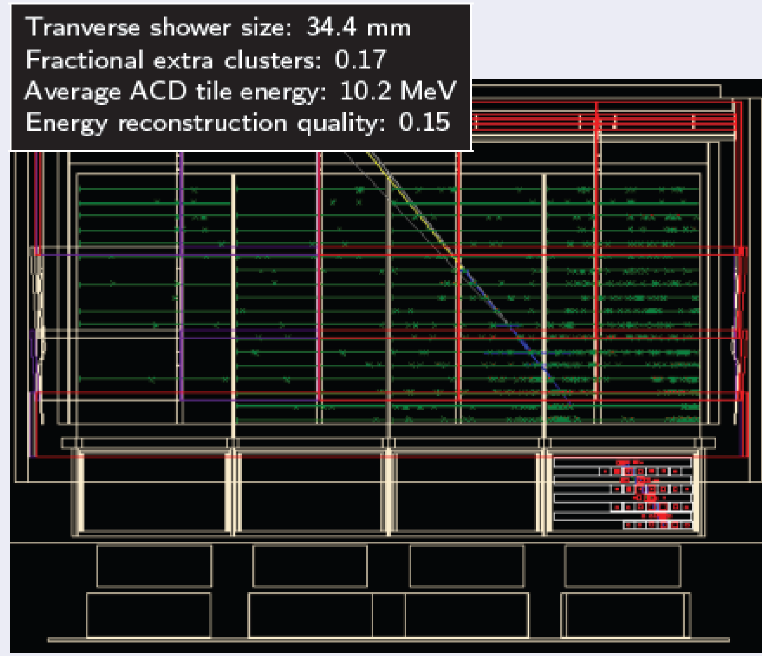
Event topology

Candidate electron
475 GeV raw energy, 834 GeV reconstructed



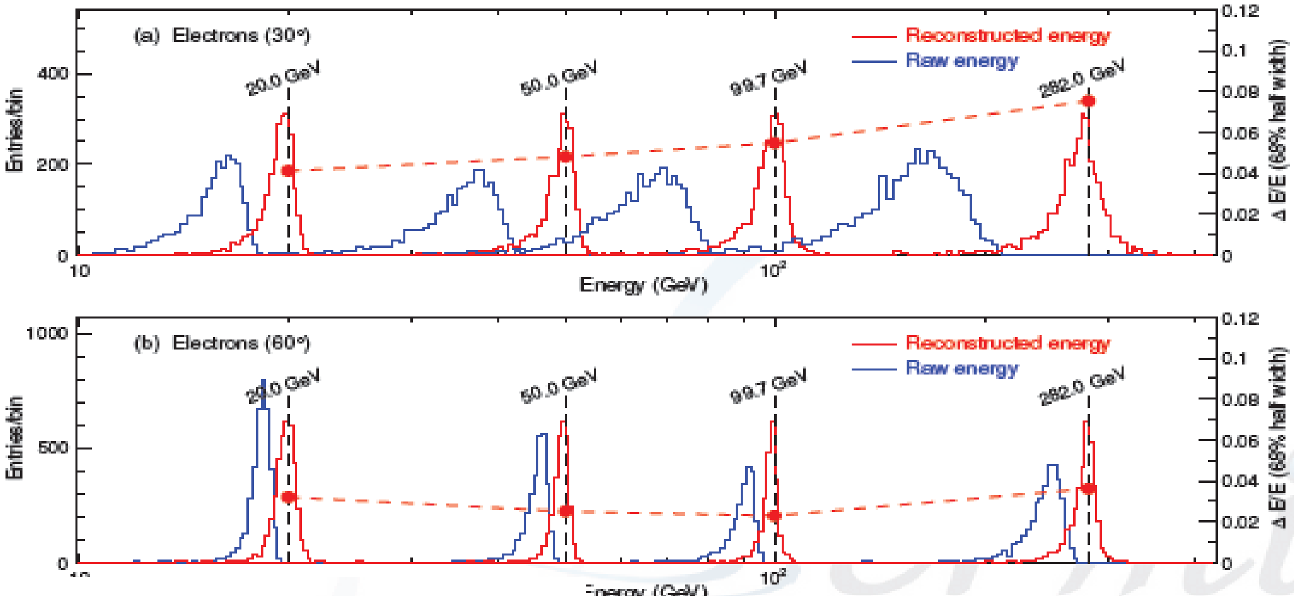
- Well defined (not fully contained) symmetric shower in the calorimeter.
- Clean main track with extra clusters close to the track (note backsplash from the calorimeter).
- Relatively few ACD tile hits, mainly in conjunction with the track.

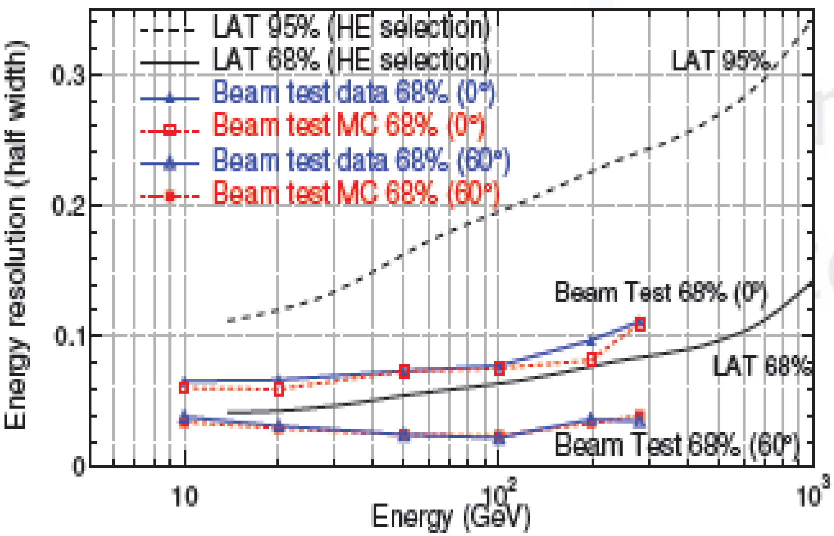
Candidate hadron
823 GeV raw energy, 1 TeV reconstructed



- Large and asymmetric shower profile in the calorimeter.
- Small number of extra clusters around main track, many clusters away from the track.
- Different backsplash topology, large energy deposit per ACD tile.

Energy reconstruction





- Same algorithms used for the analysis.
- Validated with electron beams at CERN.
- The excellent data/MC agreement gives us solid ground in extrapolating to 1 TeV.
- 5-15% (20 GeV- 1 TeV) for an isotropic flux, after the electron cuts.