A-Exam: e^+ e^- Cosmic Rays and the Fermi Large Array Telescope

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The Fermi Large Area Telescope is a particle detector in space with an effective collecting area of 9500 cm^2 meant to measure high energy cosmic ray photons and electrons. Recently the electron (e^+ and e^-) spectrum up to 1 TeV was measured using early data [1]. In this paper I will discuss the detector, the results from the electron spectrum measurements, and possible explanations for the results.

The Detector

The Large Area Telescope (LAT) is essentially a particle detector in space that consists of a 16 towers in a 4x4 geometry that contain a silicon tracker and a electromagnetic calorimeter (Figure 1).

The tracker is a silicon strip tracker interleaved with converter plates. For the electron

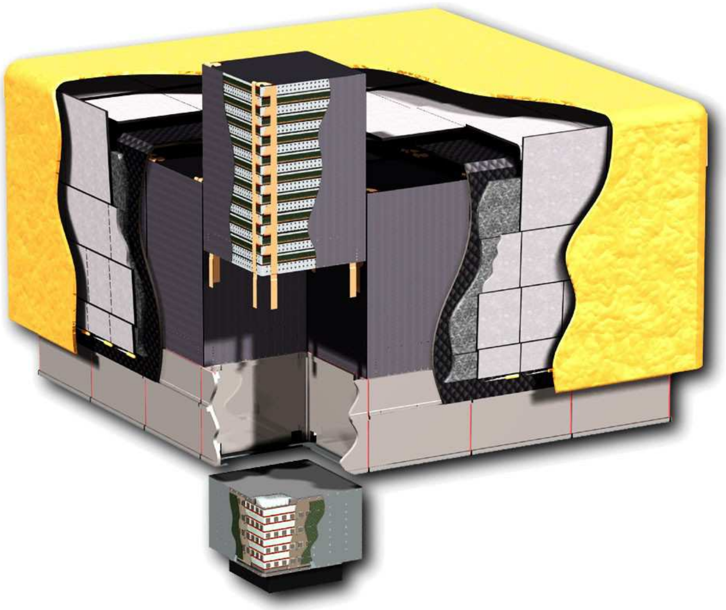

FIG. 1: The Fermi LAT

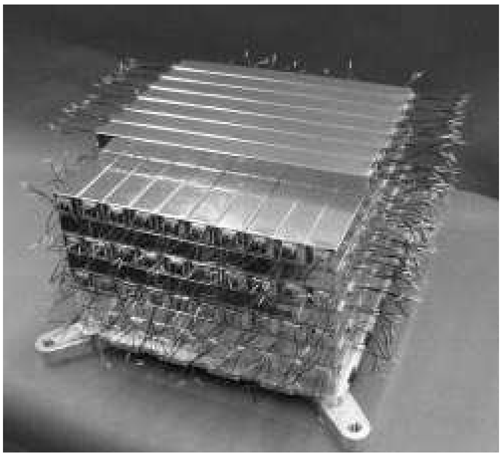

FIG. 2: Hodoscopic lay out of the CsI crystals in the LAT

spectrum measurement the converter plates aren't as essential as for the gamma ray measurements. These tungsten converter strips cause the photons to pair produce which then allows for tracking of the $e^{+}e^{-}$ pair and reconstruction of the original photon path. The layers of silicon strip modules are stacked on top of each other at a 90 degree angle to achieve x and y position measurements. There are two types of layers in the tracker, front and back. The front layers have thin converter strips to minimize multiple scattering to achieve higher resolution for low energy photons, while the back layers have thicker converter strips to have a higher conversion probability for higher energy photons.

Underneath the tracker is a hodoscopic CsI calorimeter (Figure 2) that measures the energy of the photons and electrons. This calorimeter has crystals laid out in eight layers that are at a 90 degree angle to each other. The individual crystals have an asymmetric light yield allowing a position measurement along the length of the crystal. The asymmetric light yield together with the hodoscopic layout results in a position resolution of 2.8 mm [2].

The last component of the LAT is the anti-coincidence detector (ACD) which rejects signals from charged particle cosmic rays. This subdetector is primarily used when observing gamma cosmic rays below 300 GeV. Most of these gamma's should be completely absorbed by the calorimeter, but charged particles such as protons would still be able to get past the calorimeter and be measured by the ACD which would reject the event. However in the electron spectrum measurement we want to accept charged particles so the ACD veto will not be used.

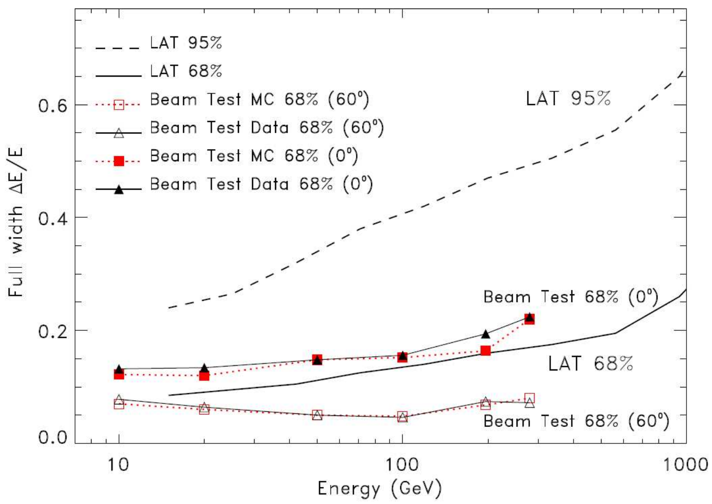

FIG. 3: Energy Resolution for electrons up to 1 TeV

These three subsystems together achieve an energy resolution of less than 20% up to 1 TeV of energy (Figure 3) and an angular resolution of 0.15 degrees at 10 GeV.

Results from the electron cosmic ray spectrum measurement

The electron flux (J_E) was measured after collecting 4 million electron events after approximately six months of data taking. Figure 4 shows the distribution of $E^3 J_E$ from the LAT results for energies ranging between 20 GeV and 1 TeV. The figure also shows the results from other experiments as well as the expected results from the conventional theoretical model (black line). This theoretical model is known as the Diffusive Galactic Continuum Gamma Rays model and attempts to predict all the previous experimental results from many different experiments (from proton flux, to gas density/geometry measurements) with one model [3]. The GeV excess (from EGRET, a previous gamma ray experiment) was not taken into consideration because the LAT did not observe the excess. However at even higher energies this model fails to predict the excess of high energy electrons as measured by the Fermi LAT. The model gives the number of electrons depending on their energy by approximately (the actual model takes source distribution into account and many more factors)

$$N_e(E) \propto E^{-(\gamma_0+\delta_0/2+1/2)} \tag{1}$$

Here γ_0 is a function of the source and is known as the injection spectrum index, while

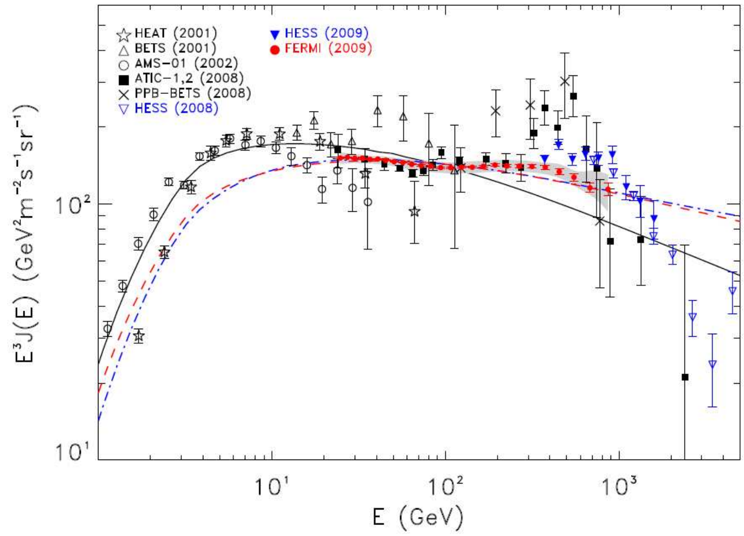

FIG. 4: Modified Conventional Models: The red line has $\gamma_0 = 2.42$ and $\delta = 0.33$ while the blue has $\gamma_0 = 2.33$ and $\delta = 0.6$. Several experimental results are shown including the Fermi LAT data.

δ_0 depends on the diffusion of the light emitted from the source. The black line shown in figure 4 has $\gamma_0 = 2.54$ and $\delta_0 = 0.33$.

Possible causes of the excess

There are a few explanations of such an excess in the higher energy electron spectrum. Dark matter annihilation, neutron stars and other local sources could cause such an excess. The conventional model can also explain the excess if their is a harder electron injection spectrum due to re-acceleration from super novae remnants and other astrophysical sources.

Refitting the conventional model

The parameters of the diffusive galactic spectrum used to fit pre-Ferm LAT data may need to change to fit for a higher energy spectrum. Figure 4 shows two new models with the new injection and diffusion indeces. The new models fit the Fermi LAT data better but no longer fit low energy data from previous experiments. This could be solved with further tweaking of parameters. Another problem with these modified models is that they can't explain the positron excess measured by the PAMELA experiment.

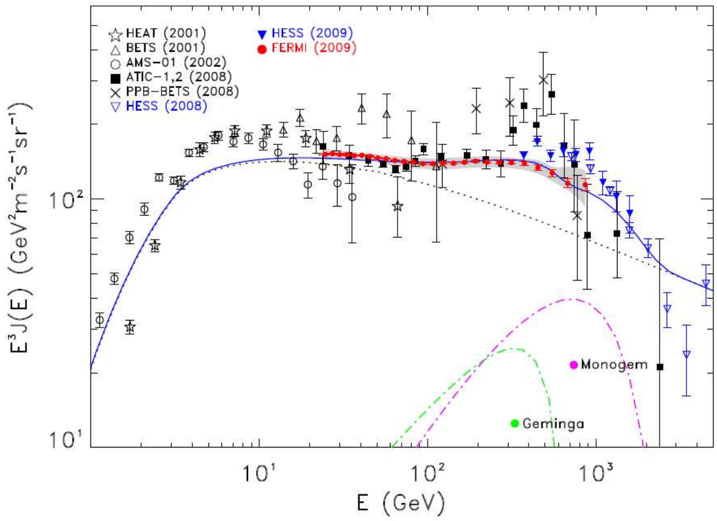

FIG. 5: The blue line shows the predictions of the conventional model with the added contribution of nearby pulsars. The two largest pulsar contributions are also shown: Geminga and Monogem.

Pulsars

Pulsars are a known source of electron-positron pairs which are produced when high energy electrons, that are accelerated by large electric fields in the pulsar's magnetosphere, synchrotron radiate photons which in turn can pair produce high energy e^+e^- pairs by interacting with the pulsar's magnetic field or with the photons produced by the pulsar. These acceleration energy can be up to 10^3 TeV for young pulsars and fall with the age of the pulsar but are expected to still be in the TeV range for mature pulsars [4]. However the resulting e^+e^- pairs will be trapped in the pulsar's wind nebula or the supernova remnant that surrounds it if the pulsar is young ($10^4 - 10^5$ years [5]). Thus, only mature pulsars can be considered as local sources of electron cosmic rays. When the contributions of local known pulsars is added to the conventional model, the resulting prediction fit the Fermi LAT data (Figure 5) and the PAMELA data well.

Dark matter annihilation

Another possible explanation for the excess in the electron spectrum is dark matter annihilation to e^+e^- pairs. The most probable model has two heavy (with m>100 GeV) dark matter particles annihilate into two scalars ($\chi\chi \rightarrow \phi\phi$) which in turn decay into two muons or electrons. The scalar would have it's mass constraint by experimental measurements that constrain the number of anti-protons and gamma ray spectrum, which the π^0 decay would contribute to. Thus the mass of ϕ must be less than the π^0 mass [6]. Since most of the dark matter in the galaxy should be localized to the center of the galaxy (to explain velocity curves) there should be a higher electron flux coming from the galactic center. This would not be caused by pulsars since they are assumed to have an uniform spacial distribution withing the galaxy. There is evidence for an excess of gamma rays in the 10-100 GeV range near the galactic center. These gamma rays could come from inverse Compton scattering from the e^+e^- pairs produced by dark matter annihilation. Dark matter as a possible source for an excess of electrons could not only explain the measurements of the Fermi LAT but could also explain an excess in positron fraction measured by the PAMELA experiment.

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