Is the 130 GeV Line Real? A Search for Systematics in the Fermi-LAT Data

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Our recent claims of a Galactic center feature in Fermi-LAT data at approximately 130 GeV have prompted an avalanche of papers proposing explanations ranging from dark matter annihilation to exotic pulsar winds. Because of the importance of such interpretations for physics and astrophysics, a discovery will require not only additional data, but a thorough investigation of possible LAT systematics. While we do not have access to the details of each event reconstruction, we do have information about each event from the public event lists and spacecraft parameter files. These data allow us to search for suspicious trends that could indicate a spurious signal. We consider several hypotheses that might make an instrumental artifact more apparent at the Galactic center, and find them implausible. We also search for an instrumental signature in the Earth limb photons, which provide a smooth reference spectrum for null tests. We find no significant 130 GeV feature in the Earth limb sample. However, we do find a marginally significant 130 GeV feature in Earth limb photons with a limited range of detector incidence angles. This raises concerns about the 130 GeV Galactic center feature, even though we can think of no plausible model of instrumental behavior that connects the two. A modest amount of additional limb data would tell us if the limb feature is a statistical fluke. If the limb feature persists, it would raise doubts about the Galactic center feature, even though we can think of no plausible model of instrumental behavior.

I. INTRODUCTION

The search for non-gravitational signatures from WIMP (weakly interacting massive particle) dark matter has generally been approached from three different directions: missing energy searches at colliders, direct searches for the recoil of nuclei from underground detectors, and indirect methods including searching for dark matter signals from cosmic rays (CR) and multiwavelength astronomical observations [1–6].

For indirect detection, distinguishing the dark matter signal from conventional astrophysical backgrounds is challenging (for a recent review on indirect searches with gamma rays see [2]). Among various possible signatures, gamma-ray line emission is a long-sought “smoking gun” for dark matter annihilation [3], as no plausible astrophysical background can produce such a line signature.1 Gamma-ray line(s) could be produced by dark matter decays or annihilations into two photons, or two-body final states involving one photon plus a Higgs boson, Z boson, or other neutral non-SM particle. In most models, the branching ratio to lines is loop suppressed relative to the continuum emission, and one would have expected the branching ratio to lines is loop suppressed relative to the continuum emission. One may see the continuum first in e.g. MSSM models [e.g. 10]. Although this theoretical prejudice led most previous studies to focus on continuum searches, there are models being proposed that allow high line to continuum ratios [e.g. 2, 11–13]. However, previous searches in EGRET [10] and Fermi-LAT data [17–19] did not find any indications for a gamma-ray line signal and presented only upper limits on the line flux.

First indications for a spectral feature around 130 GeV were found by Bringmann et al. [20] in context of virtual internal Bremsstrahlung signals from annihilations. The first claim for a significant line at the Galactic center (GC) was made by Weniger [21]. Both works focused on spectral fitting to photon events in regions of interest in the inner Galaxy designed to maximize S/N. Weniger found a line structure with 4.6σ (3.2σ after the trials factor correction) at 130 GeV, and argued against an obvious instrumental cause. This claim was quickly followed up and disputed by a number of groups [22, 23].

Subsequent work by Su & Finkbeiner approached the problem with template fitting, which takes into account the spatial distribution of events along with spectral information, assuming various profiles (Einasto, NFW, Gaussian) for the DM distribution [24]. If the template is correct, this allows extraction of the DM signal with higher S/N. This work found 6.6σ (5.1σ after the trials factor correction) for an Einasto profile centered 1.5° west of the Galactic center, and also suggested that there may be two lines, at about 111 and 129 GeV. The lower

1 A narrow feature is possible in theory [see 2].
The energy line is tantalizing because it matches the expected energy of a $Z\gamma$ line if the higher energy is the $\gamma\gamma$ line. These findings have inspired a number of models and further analysis of the Fermi data [14, 15, 25–35, 35–44].

Recent evidence for lines at 111 GeV and 129 GeV with a local significance of 3.3σ from Fermi unassociated point sources suggests an annihilation signal is present [45] but see [46], as does the claim of line emission from galaxy clusters at 130 GeV [47]. Neither of these would stand on their own, but they provide support for the hypothesis that the Galactic center line signal is produced by dark matter annihilation.

The high statistical significance of the line feature motivates a search for systematic errors in the LAT data that could mimic a line in the Galactic center. Confirmation by Imaging Air Cherenkov Telescopes like HESS-II might be possible as early as next year [48], but in the meantime a thorough study of LAT systematics is urgently needed. We do not have access to the details of the reconstruction of each photon event, which would allow us to study how it developed in the tracker and calorimeter. However, we do have information about each event from the public event lists and spacecraft parameter files. We can use this information to search for any line-producing artifacts in the detector frame, and investigate if they could map onto the Galactic center.

The Earth’s atmosphere provides a convenient source of photons for systematics tests. The continual cosmic-ray cascades in the Earth’s atmosphere produce gamma rays with $dN/dE \sim E^{-2.8}$ [49]. Because these so-called ‘Earth limb photons’ result from atmospheric cascades, they are produced by interactions in a highly boosted frame, and cannot contain line emission.

The rest of the paper is organized as follows: In Section II we briefly define key parameters of LAT photon events and describe the survey strategy. We examine peculiarities of the Galactic center observation, possible systematics of the LAT in the instrumental frame, and study whether they could fake a 130 GeV line signature. In Section III, we concentrate on a suspicious subset of Earth limb photons that shows a line-like excess at 130 GeV. We search for correlations with the GC line events, and introduce an energy remapping model as possible explanation for spurious signals. Finally in Section IV we discuss our findings and what is required to clarify the status of the 130 GeV excess.

II. THE 130 GEV EXCESS

In this section, we briefly summarize the standard survey strategy of Fermi and define the basic parameters of each event. We address the question of whether observations of the Galactic center are peculiar in a way that could enhance instrumental effects towards this direction and search for suspicious trends in other regions of the sky and the reconstruction parameters.

A. Standard survey strategy and definitions

With a field of view of $\sim 2.5 \text{ sr}$, the LAT can survey the entire sky in two orbits. In standard survey mode, the LAT points north of zenith towards the orbital pole by an angle $Z_{\text{rock}}$ on one orbit, and south of zenith by the same angle on the next orbit. In this mode, the LAT pointing is confined to the plane perpendicular to its orbital velocity. The sweeps are performed with a repeating pattern of 17 waypoints defining $Z_{\text{rock}}$ as a function of time. $Z_{\text{rock}}$ was 35° at the start of the nominal mission on August 4, 2008 until May 7th, 2009, and was changed to 50° on September 3rd, 2009 for better thermal management of the downward-facing battery radiator. This rocking-angle profile, combined with the precession of the orbit every $\sim 53.4$ days, allows the LAT to observe the whole sky with approximately uniform coverage.

Fermi spends over 95% of the mission time in standard survey mode. This is only occasionally interrupted for pointed observations of targets of opportunity (ToOs). During such times the LAT may point at larger zenith angle than usual, even at the horizon. Fermi’s survey observations are halted during passages through the South Atlantic Anomaly, resulting in an exposure differential between north and south of $\sim 15\%$. In addition, survey mode is occasionally interrupted by Autonomous Re-points of the observatory for triggered gamma-ray burst follow-up observations, and for calibration.

The reconstructed arrival direction of photons in celestial coordinates, LAT coordinates, and Earth coordinates is described by parameters in Table II. θ is the reconstructed incidence angle of the photon event with respect to the LAT boresight (defined as the +z axis). The +x axis is the line normal to the Sun-facing side of the spacecraft, i.e. the solar panels, which are parallel to the $y$ axis, face roughly the +x direction. $\phi$ is the azimuthal angle of incidence with respect to the +x axis. The Zenith angle $Z$ is the angle between the reconstructed event direction and the zenith line, which passes from the Earth center through the satellite center. All angles are in units of degrees.

Due to the increased rocking angle $Z_{\text{rock}} \approx 50°$ since September 2009, photons from the Earth limb entered the FOV of the LAT. At a spacecraft altitude $a$, the geometric (unrefracted) horizon is seen at zenith angle

$$Z_{\text{hor}} = \cos^{-1}\left(\frac{R_\oplus}{R_\oplus + a}\right) + 90°. \quad (1)$$

The Fermi orbit is nearly circular with $535 \text{ km} < a < 2500 \text{ km}$. The survey rocking angle profiles are available at [http://fermi.gsfc.nasa.gov/ssc/observations/types/allsky/](http://fermi.gsfc.nasa.gov/ssc/observations/types/allsky/). The effective dates and times for each profile are provided.

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Dispersion is about 13.6% at that energy \[21\].

129 GeV \[24\], and the FWHM of the relevant LAT energy since the dominant line at the GC is found to be around 564 km, yielding \( Z_{\text{hor}} \) in the 112.7° to 113.3° range, with the tangent point some 2400 km distant. At this distance, the \(~ 100 \) km height of the atmosphere subtends about 2°, or roughly 111° < \( Z < 113° \). Combined with the large rocking angle, the Earth limb events are dominantly seen near the incidence angle \( \theta = Z_{\text{hor}} - Z_{\text{rock}} \sim 62° \).

In Table I we define the event samples used throughout this work: ‘Standard events’ are all events with the zenith angle \( \theta > 60° \), \( \theta < 360° \), or roughly 111° < \( Z < 113° \). Combined with the large rocking angle, the Earth limb events are dominantly seen near the horizon.

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#### B. Peculiarities of the Galactic center observation

The fact that the dominant 130 GeV line signal is near the Galactic center raises a number of concerns. The gamma-ray flux at the GC is somewhat brighter and might have a harder spectrum than neighboring regions.

Table I: Event parameter definitions. The Cartesian coordinates \((x, y, z)\) are defined such that the \(z\)-axis corresponds to the LAT boresight, and the \(y\)-axis is parallel to the solar panels.

| Parameter name | Range | Description |
|----------------|-------|-------------|
| \( \theta \) | \( 0 \sim 80 \) | Polar coordinate (instrument frame) |
| \( \phi \) | \( 0 \sim 360 \) | Azimuthal coordinate wrt \(+x\) (instrument frame) |
| \((x, y, z)\) | \(-1 \sim 1 \) | Cartesian coordinates; \( \propto (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \) |
| \( Z \) | \( 0 \sim 113 \) | Zenith angle (horizon at \( Z = 113° \)) |
| \( \ell \) | \(-180 \sim 180 \) | Galactic longitude |
| \( b \) | \(-90 \sim 90 \) | Galactic latitude |
| \( \psi \) | \( 0 \sim 180 \) | Angle to Galactic center; \( \cos \psi \equiv \cos \ell \cos b \) |
| \( Z_{\text{rock}} \) | \(-110 \sim 110 \) | Rocking angle (boresight angle N of zenith) |

Also, the GC is near the ecliptic \( (\beta \sim -5°) \) and is observed in a restricted range of angles in instrument coordinates \((\theta, \phi)\) when the Sun passes near it. We consider whether these facts could exacerbate any systematic errors in the LAT data to produce a spurious signal.

1. **Hypothesis:** The Galactic center is bright, so instrumental artifacts are more significant there.

The hardware trigger rate of the LAT is typically about \( 10^3 \sim 10^4 \) Hz, with the rate of accepted \( \text{SOURCE} \) and \( \text{CLEAN} \) class events below 3 Hz \[51\], and the rate of \( E > 100 \) GeV events orders of magnitude lower. In light of these low trigger rates (and assuming steady sources and CR background fluxes) the LAT instrumental response cannot depend on the brightness of an observed region. Further-
more, at \(E > 100\) GeV, the Galactic center is only modestly brighter than the surrounding regions, so that related effects should also appear away from the GC. Otherwise, fake 130 GeV events would have to be mistakenly mapped from either lower energy (\(E \leq 10\) GeV) gammas or much lower energy photons (e.g. X-rays from the 1E 1740.7-2942 microquasar \([51]\) or 511 keV photons \([52]\)) in which the Galactic center is much brighter. It is difficult to see how this could happen.

Bright regions provide samples with a high gamma-ray-to-CR ratio, which are used for calibration purposes by the LAT team \([50]\). Besides that, their main virtue is that they feature a large number of events so that the impact of an instrumental effect, like e.g. energy reconstruction or acceptance anomalies that affect the reconstruction of gamma-ray events, can be statistically more significant there. We check as a warm-up whether we find indications for suspicious features at 130 GeV. Besides the Galactic center (with an intensity of \(\sim 8 \times 10^{-8}\) ph cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) above 100 GeV), we consider the Earth limb (with all incidence angles and an intensity of \(\sim 3 \times 10^{-7}\) ph cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) above 100 GeV \([49]\)) and the inner Galactic plane (\(\sim 9 \times 10^{-8}\) ph cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)), see Table \(\text{II}\). The sample with the highest number of celestial photons (but a smaller intensity, \(\sim 5 \times 10^{-9}\) ph cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\), and hence a higher CR contamination) is simply the whole sample of standard events excluding the region around the GC (\(\psi > 10^\circ\)). For these samples, we show the corresponding energy distributions in Fig. \(\text{II}\). None of the samples exhibit an \(O(1)\) excess at 130 GeV as observed in the Galactic center. Note that in the vicinity of the bright point sources Vela and Geminga (within 0.8° radius, corresponding to the 95% containment angle) only four \(E > 100\) GeV events were measured, at 102.5, 111.5, 123.8 and 205.5 GeV.

In Fig. \(\text{III}\) we show fits to the energy spectra of the GC, inner Galactic plane, and Earth limb. The model fits a line on a power-law background, convolved with the instrumental response, as in \([21]\). The \(TS\) value is defined as \(TS = -2 \ln L_{\text{null}}/L_{\text{alt}}\), where \(L_{\text{null(alt)}}\) is the likelihood of a fit without(with) a line. The line normalization is constrained to be non-negative. While the \(TS\) value of 18.8 in the GC is relatively large, there is no indication for line contributions in the Inner Galactic plane or Earth limb samples.

We emphasize that signal significances calculated from the GC region as defined in this paper do not represent the full significance of the putative signal, which is higher in regions with optimized signal-to-noise ratio \([20, 21]\) or when extracted by a template analysis \([24]\). We use the GC region as defined here since it should be dominated by line events, making it a good starting point to look for suspicious trends in the data.

2. Hypothesis: The Galactic center has a hard spectrum, making energy mapping errors more significant.

The Galactic center black hole (Sgr A\(^{+}\)) is visible up to 20 TeV, and other sources in the GC may be unusually hard. If these high energy photons are occasionally reconstructed with energies close to 130 GeV, this could produce a line feature in the data that would appear preferentially at the Galactic center. In Table \(\text{II}\) we list the ratio of \(E > 300\) GeV events to \(E > 100\) GeV events and of \(E > 100\) GeV to \(E > 30\) GeV events for our samples. The GC spectrum is not much harder than the rest of the Inner Galactic plane, but the latter shows no sign of a feature at 130 GeV (Fig. \(\text{I}\)). Note that about \(\sim 20\) events contribute to the central part of the line feature seen at the GC \([24]\). Assuming that the GC spectrum is not harder than \(dN/dE \propto E^{-2.0}\) (normalized to the number of events above 150 GeV), the GC events

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**TABLE II:** Definition of six samples of events used throughout this work. The number with \(E > 100\) GeV is given for each sample, along with the indicated ratios. All samples have \(10 \leq E \leq 500\) GeV.

| Sample                         | Cuts                          | \(N(>100\text{ GeV})\) | \(N(>100\text{ GeV})/N(>30\text{ GeV})\) | \(N(>100\text{ GeV})/N(>300\text{ GeV})\) |
|-------------------------------|-------------------------------|--------------------------|------------------------------------------|------------------------------------------|
| Standard events               | \(Z < 100^\circ\)             | 5093                     | 13.4%                                    | 9.6%                                     |
| Inner Galactic plane          | \(Z < 100^\circ, 3^\circ < |\ell| < 30^\circ, |b| < 2^\circ\) | 703                                      | 16.9%                                    | 9.8%                                    |
| Galactic center               | \(Z < 100^\circ, \psi < 3^\circ\) | 82                       | 17.4%                                    | 9.8%                                     |
| Galactic center line         | \(Z < 100^\circ, \psi < 3^\circ, 120\text{ GeV} < E < 138\text{ GeV}\) | 26                        | 82                                       | 17.4%                                    | 9.8%                                     |
| Earth limb                    | \(Z > 110^\circ\)             | 3120                     | 10.2%                                    | 9.2%                                     |
| Earth limb line               | \(Z > 110^\circ, 30^\circ < \theta < 45^\circ, 120\text{ GeV} < E < 138\text{ GeV}\) | 45                        | 82                                       | 17.4%                                    | 9.8%                                     |

FIG. 2: Energy distribution in various event samples as discussed in the text. None of them show the excess events around 130 GeV seen in the Galactic center. The red dotted lines indicate 111 and 129 GeV.
3. Hypothesis: the GC observations have a restricted range of incidence angles on the instrument.

If the Galactic center were predominantly observed at specific angles in LAT instrumental coordinates, associated instrumental problems could be projected onto the Galactic center simply for geometric reasons. In late December (June), the Sun crosses the Galactic disk, and the angular distance between the Sun and the Galactic center (anti-center) decreases to \( \sim 5^\circ \). Since \textit{Fermi} keeps the solar panels aligned to the Sun (the Sun is in the \( x-z \) plane), this leads to an increase of Galactic center events at instrument azimuth angles of \( \phi \approx 0^\circ \) (\( \phi \approx 180^\circ \)). This behaviour is clearly visible in the upper left panel of Fig. 4, where we show the \( \phi \) distribution of \( > 10 \text{ GeV} \) events from the Galactic center as a function of time of year. The \( \phi \) distribution in the upper right panel reflects the precession pattern with a \( \sim 53.4 \) day period. Integrated over time, the \( \phi \) and \( \theta \) distributions look like in the lower panels of Fig. 4, where they are shown as a function of the Galactic longitude. Close to the GC, the \( \phi \) distribution becomes significantly bimodal. Note that this effect occurs along the full ecliptic, but the intersection with the Galactic disk close to the center is accompanied by the largest number of events.

It is tempting to relate the location of the 130 GeV excess in the Galactic plane to this inhomogeneous \( \phi \) distribution. As a test, we select standard events from the full sky (excluding \( \psi < 10^\circ \)) in the range \( \phi = -20 \ldots 20^\circ \) mod 180\(^\circ \). The total number of these events is \( \sim 10 \) times larger than the number of Galactic center events; an anomaly in the event reconstruction near these \( \phi \) angles would appear in this data sample with high significance. However, the energy distribution shown in Fig. 5 shows no significant feature at 111 or 129 GeV.

C. Peculiarities of the instrument

Instrumental effects are likely to be correlated with specific instrumental coordinates rather than sky coordinates. In this subsection we search for suspicious trends at 130 GeV as a function of the event incidence angles, quality parameters, and arrival times. We also search for the possibility of ‘hotspots’ at other regions of the sky; they could indicate instrumental effects or an exotic source population.

An error in the LAT effective area (e.g. various cuts at \( \sim 130 \text{ GeV} \) are less/more restrictive for some reason) could in principle explain the GC line, but would also produce a line in the other samples listed in Tab. 1. Exactly this already happened in the past at energies close to 10 GeV [19]. However, no 130 GeV feature is seen in the main test samples outside of the GC (though in a small subsample that we will discuss below). The LAT team estimated the point-to-point correlation of the effective area on scales relevant for line searches to be on...
FIG. 4: Upper panels: \( \phi \) (left panel) and \( \theta \) (right panel) distributions of standard events close to the Galactic center, as a function of time modulo one year (with Jan 1st at the origin). In Dec (Jun) the Sun passes near the Galactic center (anti-center). In these periods, most GC events are observed at \( \phi \approx 0^\circ \) (\( \phi \approx 180^\circ \)), since the LAT \( x-z \) plane is determined by the Sun to keep the solar panels oriented. Lower panels: \( \phi \) (left panel) and \( \theta \) (right panel) distribution of standard events along the Galactic disk. Close to the GC, the distribution becomes significantly bimodal. The red and blue dots are as in Fig. 1.

The level of 2\% [5], which is not enough to explain the O(1) GC or Earth limb features.

If the GC line is due to non-rejected CRs, it is hard to understand how mono-energetic particles could be present in the CR spectrum. What is more, a bright region like the Galactic center has a large gamma-ray-to-CR ratio, such that a CR contamination would affect it last, not first.

1. **Hypothesis: A 130 GeV features is visible at specific incidence angles on the instrument.**

One concern is that a 130 GeV feature in the reconstructed events is visible only for events with certain incidence angles \((\theta, \phi)\) in instrumental coordinates. The 130 GeV excess would be then imprinted on regions of the sky that are predominantly observed at these problematic angles.\(^4\)

To study line-like features at different incidence angles, we split up the \((\theta, \phi)\) plane in different regions as shown in the left panels of Fig. 6. We then analyse the spectrum of all events that hit the detector at these incidence angle patches separately and search for lines. The fits are performed as in Ref. [21], but the energy window is fixed to 80 to 200 GeV, we assume a flat acceptance and for a line we take a simple Gaussian with a standard deviation of 6\% (to approximate the central part of the non-Gaussian LAT energy dispersion).

The left panels of Fig. 6 show from top to bottom the results obtained (1) using all events, (2) using Earth limb events only, and (3) using standard events only; the latter two are disjoint subsets of the former one. For each \((\theta, \phi)\)

\(^4\) A study of the \(x-y\) positions of the events inside the tracker and calorimeter is not possible using public data only. It is however difficult to conceive how these parameters could be correlated with certain regions of the sky.
range we quote three numbers: the significance of a 129 GeV line-feature in terms of the TS value, the signal-to-background ratio of the putative line signal, and the number of events above 80 GeV that contribute to this region. The TS values are also indicated by color for better visibility.

We also compute the TS as a function of energy in each region of (θ, φ) to check whether there is anything unusual about 130 GeV (Fig. 4, right panels). In particular the lower two plots which correspond to independent data sets show clearly that the enhanced TS values at different energies in different panels are not correlated. Lastly, we note that the significance of the largest TS value, TS ≃ 11 (at 115 GeV), has a p-value of about 0.3 when taking into account ~ 2 × 23 × 2 trials over a $\chi^2_{k=2}$ distribution (two Z ranges, 23 incidence angle panels, ~ 2 independent search regions [5,6]).

Fig. 4 suggests that the TS values observed in some panels in case of Earth limb ($Z > 110^\circ$) events are well within the statistical expectations once the large number of associated trials is taken into account. However, it cannot be excluded that the 130 GeV excess in these parts of the Earth limb indicates a real instrumental effect. Then the energy reconstruction at different incidence angles would have to somehow additionally depend on the zenith angle Z of the events (e.g. via a subtle correlation with the rocking angle). We postpone an in-depth discussion of this possibility to section III in any case more Earth limb data will help to verify or falsify this possibility.

2. **Hypothesis:** The Galactic center events are flagged as badly reconstructed.

   Although we do not have access to all details of the event reconstruction, the extended LAT event files contain a few figure-of-merit quantities from the first step of the event-level analysis, which inform about the quality of calorimeter and tracker event reconstruction. CTBCore describes the probability that the direction estimate is good (roughly the probability that the reconstructed direction falls within the nominal 68% containment angle), CTBBestEnergyProb the probability that the reconstructed energy falls into the core of the energy dispersion [54]. We show these parameters for the GC line events in the upper panel of Fig. 4. The background histogram shows the distribution of these parameters in standard events above 100 GeV. No significant bias in the distribution appears.

   The red bars in the lower panel of Fig. 4 indicate the first tracker layer that shows evidence of a particle hit for the best track reconstruction (Tkr1FirstLayer) in case of the GC line events. Tracker layers are 0–17, where 0 is closest to the calorimeter and 6–17 (2–5) corresponds to FRONT- (BACK-)converting events (tracker layers 0 and 1 do not have conversion foils due to requirements of the three-in-a-row trigger primitive). The dark gray bars show the distribution averaged over all > 100 GeV standard events. The light gray bars show for comparison the distribution of a ‘dirty’ > 100 GeV event sample. It is defined as all SOURCE-CLEAN events with $|b| > 5^\circ$, and hence has a high CR contamination. The distribution of the latter is significantly biased towards the first and last tracker layers, whereas the distribution of GC line events is compatible with the expectations for standard events.

3. **Hypothesis:** There are ‘hotspots’ with line-like features in other sky regions.

   The 130 GeV excess is located in a narrow range of about $\sim 5^\circ$ around the Galactic center. The existence of other significant ‘hotspots’ (localized regions with a significant line-like emission at or around 130 GeV) in the sky could indicate an unexpected instrumental effect, or point to a new exotic source class. In absence of knowledge about the distribution of such possible sources, we adopt the following strategy. We select partially overlapping regions of $6^\circ \times 6^\circ$ size, centered along the Galactic disk at $b = 0^\circ$, $|\ell| = 13.5^\circ, 16.5^\circ \ldots 178.5^\circ$. The size of the region is chosen to include roughly 50–100 events above 80 GeV (like in our ‘GC region’); regions close to the GC are excluded to avoid contamination with the 130 GeV excess. In each region we calculate the TS value for the presence of a line at various energies. The details of the fit are the same as above for Fig. 4 (in particular the energy window is always fixed to 80–210 GeV). The distribution of TS values obtained in this way is shown in Fig. 8 by the dotted colored lines for different line energies; a combination of TS values for all line energies is shown by the solid black line. Its tail...

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5 [http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/](http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/)
FIG. 6: Left panels: Significance for a $\sim 130$ GeV line-like excess in different parts of the $\theta$-$\phi$ plane (for $\theta = 0$–$80^\circ$). From top to bottom, the results are derived from all events, from the Earth limb events, and from standard events. The three numbers show the TS value for the presence of a 129 GeV line, the signal-to-background ratio and the number of events above 80 GeV inside the considered $\theta$-$\phi$ region. $\theta$-cuts are made at $15^\circ$, $30^\circ$, $45^\circ$ and $60^\circ$. Right panels: The significance for a line-like excess as a function of $E_\gamma$ for the same $\theta$-$\phi$ regions. Solid (dashed, dotted, dash-dotted) lines correspond to panels at different $\phi$, starting counterclockwise from $\phi = 0^\circ$. 
FIG. 7: Upper panel: Distribution of CTBCORE (the probability that the direction estimate is good) and CTBBestEnergyProb (the probability that the best energy chosen from the two energy estimators is correct) for Galactic center line events (in red), compared to the distribution of > 100 GeV standard events. Lower panel: First tracker layer to show evidence of a particle hit for the best track reconstruction. Tracker layers are 0-17 where 0 is closest to the calorimeter, and 6-17 (2-5) corresponds to FRONT-(BACK-)converting events (tracker layers 0 and 1 have no conversion foils). The dark (light) gray bars show the average over all > 100 GeV standard events (‘dirty’ sample defined as SOURCE-CLEAN events with $|\theta| > 5\,^\circ$); the red bars show the distribution for the GC line.

distribution is in excellent agreement with the statistical expectations (shown by the black dotted line) within the ±1σ error bars, showing no indication for the presence of ‘hotspots’. We obtain the same result when reducing the size of the regions, shifting them by a common offset, or selecting random circular regions all over the sky with the requirement that ~100 events are included.

4. Hypothesis: The observed signal is variable.

An interpretation of the 130 GeV excess in terms of dark matter annihilation requires steadiness of the source; a strong variability could indicate (time-dependent) instrumental effects. In Fig. 9 we plot how the TS value of the GC signal evolved over time (assuming $E_\gamma = 129.8$ GeV [21]). The dark red line corresponds to the GC region from Tab. III, the light red line shows the results for region Reg4 from Ref. [24]. We compare them to the time-evolution of the suspicious Earth limb line (blue) and the time evolution of the TS value obtained from the Inner Galactic plane (gray). The ‘GC region’ curve appears to have grown most strongly between March 2011 and February 2012, and falling during last few months; on the other hand, the signal observed in the larger Reg4 does not show the same behaviour and appears more steady. In all cases, the open circles indicate an event between 120 and 138 GeV. The curves show no strong sign for a variability of the line features. Note
that the number of GC region line events in the first and second half of the observational period are respectively 12 and 14.

### III. EARTH LIMB PHOTONS

In this section, we follow up the weak excess at $\sim 130$ GeV in the limb photons (Fig. 6) and characterize the nature of the apparent excess more precisely. We show that the critical incidence angles are not (solely) responsible for the GC excess. We then consider the possibility that an energy mapping error could redistribute events in energy, thus making a spectral feature, and explore the various parameters of the GC line events and the limb bump events.

In Fig. 10 we plot incidence angle $\theta$ versus energy for limb events ($Z > 110^\circ$). For $125 \text{ GeV} < E < 135 \text{ GeV}$, we find an excess of events with $30^\circ < \theta < 45^\circ$, as already indicated in Fig. 6. This $\theta$ range contains 6% of the limb events for $E > 100 \text{ GeV}$. The 129 GeV bump is clearly visible in the spectrum plotted in the bottom panel of Fig. 11, and decreases for larger ranges of $\theta$ (other panels). The bump appears equally in FRONT and BACK converting events.

#### A. Energy mapping error: a model for the limb bump

As we discussed above in Sec. II, it is very unlikely for the GC line to be caused by extra events (from either photons with much higher energies or CR background); the same is true for the line feature in the low incidence Earth limb events. Given these difficulties, we consider the possibility that the Earth limb bump results from an energy mapping error, and assume that for some unknown reason it only affects low incidence Earth limb events (and potentially the GC).

We propose a simple model, in which the mapping from true energy to reported energy, $E(E_t)$, is linear except for a bump near some reference energy. Smooth low-level perturbations over large energy scales are not relevant here, and could be absorbed in the effective area calibration. In order to include a small-scale bump in the response, we introduce a local compact perturbation in the form of a Gaussian. It is convenient to work in logarithmic quantities, so we take $x = \log E_t$, $y = \log E$, and

$$y = x - A \sigma \exp \left( \frac{1}{2} - \frac{(x - x_0)^2}{2\sigma^2} \right), \quad (2)$$

Similar to anomalies in the effective area, one would expect that such an error should affect all regions of the sky, in contradiction to the observations.
We find a 4.7σ excess of 30° – 45° limb photons at 129 GeV, with no significant excess at 0° – 30° or 45° – 60°.

where $A$ is a dimensionless amplitude of the bump ($-1 < A < 1$ is required for monotonicity of $y(x)$), $x_0$ is a reference log energy, and $\sigma$ is the width of the bump (see Fig. 12). The effect of the distortion is to change the true spectrum $dN/dx = dN/d\log(E_t)$ into an observed spectrum

$$
\frac{dN}{dy} = \frac{dN}{dx} \left(\frac{dy}{dx}\right)^{-1},
$$

with

$$
\frac{dy}{dx} = 1 + A\sigma \exp\left(\frac{1}{2} - \frac{(x - x_0)^2}{2\sigma^2}\right) \frac{x - x_0}{\sigma^2}.
$$

Note that that the extreme values of $dy/dx = 1 \pm A$ occur at $x - x_0 = \pm\sigma$ and at $y = x_0(1 - A)\sigma$. Assuming the true limb spectrum is a power law, we may apply this factor to obtain a model spectrum, and maximize the Poisson likelihood of observing the data given the model.

In Fig. 13 we fit the energy mapping model to the Earth limb data for various ranges of inclination angle. We find a 4.7σ excess of 30° – 45° limb photons at 129 GeV, with no significant excess at 0° – 30° or 45° – 60°.

B. The Earth limb line and correlations with the GC signal

As shown in the top panel of Fig. 13, fitting the Earth limb events at incidence angles 30° < $\theta$ < 45° with a monochromatic line at 129 GeV instead of an energy remapping model yields a local significance of only 2.9σ (adopting an energy range from 80 to 210 GeV like above in Fig. 3). However, a further tuning of the $\theta$-range yields significances up to 4.1σ (for 25° < $\theta$ < 53°; central panel of Fig. 14), but this comes with an additional number of trials. In any case, the overall statistical significance for a line in the $\theta < 60°$ Earth limb data is above 3σ. For comparison, the bottom panel of Fig. 14 shows a fit to the Galactic center energy spectrum without incidence angles 30° < $\theta$ < 45°. The GC excess is not removed by this cut, which would have indicated a spurious signal. Even when removing all events with 25° < $\theta$ < 53° from the GC region (from region Reg4 [21]), we obtain $TS = 5.1$ (TS = 10.1) for the Galactic center signal, whereas the
Earth limb line completely disappears.

The Earth limb line events are distributed all over the sky, as expected (Fig. 15). The arrival time of these events is concentrated during periods of high rocking angle, because it is geometrically impossible to see limb events at $\theta < 45^\circ$ in normal survey mode (Fig. 16). As already mentioned in Section II, the distribution of $(\theta, \phi)$ vs. each other and vs. time and longitude are as expected (Figs. 1 and 4). In short, none of these tests reveals suspicious trends or correlations, or indicates in any way that a systematic error in detector coordinates could map events specifically onto the Galactic center.
IV. DISCUSSION AND CONCLUSION

In this paper, we search the publicly available LAT data for any trends or correlations that might indicate an instrumental origin for the spectral feature at $\sim 130$ GeV towards the GC [20,21,24]. After addressing the following concerns, we find no evidence that the 130 GeV feature is spurious.

The Galactic center is bright and has a hard spectrum. On degree scales, the GC surface brightness is less than a factor of 2 brighter than the inner Galactic plane. The inner plane provides an order of magnitude more photons, and shows no sign of a 130 GeV bump. Even larger samples (all limb photons, all non-limb non-GC photons) also show no significant signal. The GC has a hard spectrum, and at TeV energies the GC is brighter than the surrounding plane, but even if all events above 300 GeV (assuming a hard spectrum $dN/dE \sim E^{-2}$) were incorrectly remapped to 130 GeV, there would not be enough photons to explain the GC signal.

Observations of the GC have a restricted range of instrumental incidence angles. It is true that the survey strategy, orbital precession, and solar panel alignment cause a non-trivial mapping of GC events onto $(\theta, \phi)$ as a function of time of year. Specifically, they occur near the $x-z$ plane ($\phi = 0$ or 180) when the Sun is near the GC or anti-center. However, the GC line events are drawn from the full range of $\theta$, $\phi$, and $\ell$. The limb line events are broadly distributed in $\theta$, $\phi$, and $\ell$, with times corresponding to pointed observations at large zenith angle. There is no evidence that the distribution of line events deviates from expectations.

There are excess line events in the limb data for some incidence angles. For a small subset of the limb data with large rocking angle (when the limb may be seen at small incidence angles) and a particular incidence angle range around 30$^\circ$ to 45$^\circ$, we find a marginally significant 130 GeV feature (above 3$\sigma$). The majority of events with incidence angle 30$^\circ$ to 45$^\circ$ are not from the Earth limb, and we find no 130 GeV feature in this much larger sample of events at these incidence angles. If the limb line events are an artifact, they must conspire to only appear when the LAT is positioned at high rocking angle.

The bump in the limb data might result from an energy mapping error. We propose a simple model for an error in the mapping from true photon energy to reported energy. This model reproduces the shape of the limb line feature at 130 GeV and the dip at slightly higher energy, and has a local significance of 4.7$\sigma$. A modest amount of additional limb data would tell us if the limb feature is a statistical fluke. If the limb feature persists, it raises serious concerns about the Pass 7 processing of $E > 100$ GeV events.

Additional limb data are available from the commissioning period. The Launch & Early Operations (LEO) data were taken during the first 60 days of the mission. Combined with a dedicated Earth-limb observation in September 2008, this provides $\sim 250$ hours total livetime on the Earth limb [49].

With Pass 6 diffuse class events, [49] has analyzed the spatial morphology and the energy spectrum of the Earth limb sample, which contains 218 photons above 100 GeV and 16 photons above 500 GeV. The energy spectrum is a power-law with spectral index 2.79 $\pm$ 0.06 for 3-500 GeV photons (Fig. 2 of [49]), which is consistent with the primary cosmic-ray spectral index 2.75 $\pm$ 0.03.7

The spectrum of the Earth limb photons provided by [49] does not show any significant feature at 130 GeV. If improved processing of the limb photons does not replicate the line or the “energy mapping error” we found for a subsample of the limb photons during the normal survey mode, it can be dismissed as a statistical fluke. If it reappears, a deeper investigation into its cause will be necessary.

Even then, it is a challenge to understand how such an instrumental feature could be mapped so precisely onto a localized region within 5 – 10$^\circ$ of the GC. The GC is not near the path of the orbital pole, nor its axis of precession. The orbital phase, precession, Earth’s orbit, and time of year are all well mixed by the few $\times 10^4$ orbits and 25 precession cycles over 1500 days. We have shown that the events in question are drawn from every part of event and spacecraft parameter space available in the public files.

In summary, we find no significant instrumental systematics that could plausibly explain the excess Galactic center emission observed at 130 GeV.

Note added: During the final stages of this work we became aware of another group discussing instrumental indications in the Earth limb data [55].

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7 The Earth limb photon above 10 GeV from CR interactions in the upper atmospheric layers do not suffer large energy losses and the cosmic-ray primaries at this energy are unaffected by the Earth’s magnetic fields. The Earth limb photons should have a spectral index close to that of the primary cosmic rays [55].
FIG. 17: Distribution of events in Earth longitude and latitude (upper panel) and satellite zenith RA,dec (lower panel). In this and following figures, Galactic center line photons (red), Earth limb line photons (blue) and Earth limb photons for all incidence angles (black) are shown. The avoidance of the SAA leaves a hole in the upper panel.

http://idlastro.gsfc.nasa.gov).

V. APPENDIX

In this Appendix, we compare the distribution of the Galactic center line events with the Earth limb photons in various projections of the event parameter space, and search for any unexpected behavior. As above, red points represent the Galactic center line photons and the blue points represent Earth limb line events. Earth limb photons with $135 \text{ GeV} > E > 125 \text{ GeV}$ at all incidence angles are shown in black. None of the Figures (Figs. 17-22) show any sign of unexpected behavior.

FIG. 18: RA and Dec of spacecraft Z axis (boresight direction) and X axis (Solar panel direction).

FIG. 19: Zenith angle vs. Earth azimuth angle for limb photons. As expected, the $\theta > 60^\circ$ limb photons observed in survey mode are seen predominantly to the north and south azimuth directions, i.e approximately perpendicular to the orbit direction. The blue points are the Earth limb line events.
FIG. 20: Events as a function of orbital precession phase (upper panel) and time of year (lower panel). Note that there are only about 6 months of the year during which the 38 Earth limb line events (blue) are seen.

FIG. 21: The rocking angle of the Galactic center line events (positive values indicate a rock angle toward the north from zenith).

FIG. 22: All events as function of zenith angle $Z$ and incidence angle $\theta$. The change of the rocking angle from $35^\circ$ to $50^\circ$ in 2009 is clearly visible. None of the GC line events is observed near the horizon.
