Response to the *Fermi* Mission Call for White Papers on Observing Strategies: A Conditional Case for Extended Observations of the Galactic Center

Large Area Telescope Collaboration

April 26, 2013

1. Executive Summary

Primarily in response to claims of detection of a 130 GeV spectral line from the region of the Galactic center (GC) using data from the *Fermi* Large Area Telescope (LAT), the *Fermi* Mission issued a call for white papers to describe the scientific benefits from alternative observing strategies for *Fermi*. The intention of the Mission is to consider adopting an alternative observing strategy starting in August 2014, i.e., after the sixth year of LAT operations is complete, and that any change in observing strategy would be for one year or longer, i.e., much longer than could be proposed to the *Fermi* Guest Investigator program. The white papers are not proposals but instead are advisory to the Mission in considering the possibilities.

The detection of an annihilation line from particle dark matter would be an enormously important discovery, and the most compelling case for adopting an observing strategy for *Fermi* different from the standard survey mode would be to deepen observations of the GC region to study the potential 130 GeV line. **The *Fermi* LAT Collaboration recommends that a strategy favoring the GC be adopted on the condition of confidence by August 2014 that the apparent signals are not systematic effects, and evidence remaining for the line based on the then-current LAT data set.** The "trigger" criteria also require that no other observations, e.g., by H.E.S.S. II, will have provided robust limits below detectability by the LAT.

This paper provides specifics of the criteria described above and a comprehensive overview of our current understanding of the potential 130 GeV line, including the physics case, reports of detections of the feature, analysis by the LAT Collaboration, studies of systematics, and the projected performance gains for Pass 8. The white paper also describes the impacts from modifying the observing strategy, both *pro* and *con*, across the broad scope of LAT science.

To make quantitative projections of impacts more feasible, the Mission has provided example pointing history files for different potential observing strategies. These strategies, denoted Option 1, Option 2, and Option 3, have different degrees of optimization of the exposure toward the GC and distribution of the remaining exposure across the rest of the sky. We present evaluations of the candidate options, and conclude that for several reasons Option 3 offers the best choice for enhancing exposure toward the GC while minimizing impacts to the rest of LAT science. We do not propose that Option 3 necessarily be the alternative observing strategy that would be adopted but we assume that the actual pointing strategy adopted would be at least as effective as Option 3 for enhanced exposure toward the GC and broad support of other LAT science.

For other LAT science the impacts from long-term adoption of Option 3 would be negative in several respects but not profoundly so, and Option 3 would provide some specific advantages, e.g., for detecting hard-spectrum γ-ray sources in the inner Galaxy and for blind-search discoveries of pulsars there. We also assume that impacts for multiwavelength observing campaigns of sources not in the inner Galaxy could be mitigated with specific intervals of pointed observations selected via peer review in the *Fermi* Guest Investigator program.

2. Dark Matter Science Case for Deep Exposure Toward the Galactic Center

2.1. Physics Case for a Line Signal

The search for evidence of particle dark matter was one of the scientific drivers for the *Fermi* mission and the γ-ray observations with the LAT have been used in many ways to make indirect searches for annihilation or decay of Weakly Interacting Massive Particles (WIMPs). A number of searches have set limits based on annihilation through $b\bar{b}$, W^+W^-, or $\tau^+\tau^-$ channels, based on calculations of the continuum γ-ray signals from secondary particles.

It has long been recognized that WIMP annihilation directly into γ rays would produce a smoking gun signature[1] but since dark matter particles are not electrically charged, the annihilation of two WIMPs will generically produce a $\gamma\gamma$ or γZ^0 final state only through higher-order loop corrections. Thus SUSY and other popular models of WIMP dark matter predict branching ratios $\ll$1 into a γ line, with the dominant branching ratio being to other Standard Model particles that produce a continuum spectrum of photons. However, the potential γ line at 130 GeV that was initially pointed out by Weniger (2012, see § 2.2) does not seem to have a large accompanying continuum spectrum (e.g., Cohen et al. 2012; Buchmüller & Garny 2012). Predicted branching ratios into a γ line as large as 1% are historically rare in the theoretical literature, though a large number of models with large branching ratios were constructed in response to the claims of a 130 GeV line, and it was shown that even in SUSY (including the MSSM) it is possible to attain the required large branching ratios (e.g., Shakya 2012; Kumar & Sandick 2013).

A large branching ratio to photons is thus possible in many models and the 130 GeV line, assuming it is from dark matter, may be indicating something very important about the properties of the dark matter particles. However, a large branching ratio to photons is theoretically less expected than a small branching ratio in a generic dark matter model. Of course, many other considerations are relevant for evaluating the significance, including the distribution of the signal on the sky (location with respect to the GC) and potential systematic effects that could make a line-like feature.

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[1] In Ackermann *et al.* (*Fermi* -LAT Collaboration) (2012) the LAT Collaboration published upper limits for such a search in the range 5–260 GeV, based on 2 years of LAT data.

2.2. Overview of Claims Based on Publicly-Available LAT Data

Several authors have reported narrow, statistically significant, features near 130 GeV in the γ-ray spectra of regions near the GC using 3−4 years of *Fermi* LAT data. Generally speaking, these signals are consistent with two-body decay or annihilation of WIMPs. Specifically, Bringmann et al. (2012) searched for WIMP annihilation including internal Bremsstrahlung in the total spectra of regions of different sizes around the GC, and found a best-fit WIMP mass of $m_\chi \sim 150$ GeV with a local significance of $s_{\rm local} = \sqrt{TS} = 4.3\sigma$ in a region centered on the GC and extending to $b \sim \pm 20°$. Weniger (2012) searched for line-like signals i.e., spectral features with the width of the LAT energy resolution, and found a signal for $m_\chi \sim 130$ GeV with $s_{local} = 4.6\sigma$ in a slightly smaller region (extending to $b \sim \pm 15°$), and with a signal-to-background ratio ($f \sim 0.37$) much larger than the expected instrumental uncertainties of $\delta f \sim 0.06$. Su & Finkbeiner (2012b) included the spatial morphology in their fitting procedure, creating a template of the astrophysical background from flight data at other energies, and found a highly significant signal ($s_{\rm local} = 6.5\sigma$) for an NFW density profile centered at $(l, b) = (1\overset{\circ}{.}5, 0\overset{\circ}{.}0)$ as well as a possible second line-like feature at $E_\gamma = 111$ GeV, potentially associated with γZ^0 final states. However, the systematic uncertainties from modeling the morphology of the astrophysical background associated with this last analysis are greater than for the first two.

Other, less statistically significant, claims have been put forward for the presence of similar signals in Galaxy clusters (Hektor et al. 2012a) and unassociated *Fermi* LAT sources (Tempel et al. 2012; Su & Finkbeiner 2012a), though the latter claims have been questioned (Hektor et al. 2012b).

Many authors have investigated the potential systematic errors associated with the line-like feature, e.g., Finkbeiner et al. (2012); Hektor et al. (2012c); Whiteson (2012). In summary, these authors report that the properties of the γ rays contributing to the feature near 130 GeV in the GC are broadly consistent with γ rays at other energies and directions, making it unlikely that the feature is being caused by misclassification of cosmic-ray (CR) background events as γ rays. However, these authors also note that a statistically significant feature appears at the same energy in a control sample of γ rays from the Earth limb, and that the distribution of the incidence angles (θ) of the γ rays contributing to signals near 130 GeV in both the GC and the Earth limb do not agree well with predictions from Monte Carlo (MC) simulations. However, these authors argue that the signal seen in the Earth limb could not explain the entirety of the signal seen in the GC.

The velocity-weighted average cross sections derived from the best-fit results are in the range of $\sim 1 \times 10^{-27} \mathrm{cm}^3\mathrm{s}^{-1}$ and depend on the region under consideration.

2.3. LAT Collaboration Line Search Studies

The LAT Collaboration has analyzed 3.7 years of data using a dataset, `P7REP_CLEAN`, that applies the same event selection criteria as the publicly available `P7SOURCE` and `P7CLEAN` event samples used in the papers mentioned in § 2.2, but was reprocessed with improved calibration constants for the Calorimeter (CAL) to correct for the gradual, expected, loss of light yield in the CAL. Applying this new calibration shifted the γ-ray energy scale upward by $\sim$3–4%, moving the apparent GC spectral feature from 130 GeV to 133 GeV. The preliminary results summarized in this section are part of paper in preparation by the Collaboration

The Collaboration considered 5 regions of interest (ROIs), which were optimized for different potential dark matter profiles, and ranged from a circle of 3° radius around the GC (R3) to the entire sky except for a mask along the Galactic plane excluding $|b| < 5^\circ$ and $|l| > 6^\circ$. The analysis also took into account an event-by-event estimator of the quality of the energy reconstruction ($P_{\rm E}$, available in the extended photon files as `CTBBestEnergyProb`) to maximize the sensitivity for line-like spectral features.

The Collaboration found positive excesses at 133 GeV in their smaller ROIs, particularly R3, and also in the R16 ROI, a 16° radius region about the GC with the Galactic plane masked for $|b| < 5^\circ$ and $|l| > 6^\circ$. However, the significances were reduced compared to the results cited in § 2.2 based on the public `P7SOURCE` and `P7CLEAN` data. Specifically, in the R3 ROI our analysis found that the significance decreased from $s_{\rm local} = 4.5\sigma$ with the `P7CLEAN` dataset to $s_{\rm local} = 3.9\sigma$ with the `P7REP_CLEAN` dataset, and to $s_{\rm local} = 3.3\sigma$ (with $f = 0.61$) when the improved energy dispersion model was used. These results are shown in Figure 1. Taking into account the large trials factor, $s_{\rm local} = 3.9\sigma$ (3.3σ) corresponds to a global significance of $s_{\rm global} \simeq 2.1\sigma$ (0.8σ).

The Collaboration also quantified the magnitudes of potential instrumental and methodological biases for line searches in terms of f and found them to be $\delta f \sim 0.035$ for most energies > 100 GeV, with the caveat that an anomalously large positive signal remained from the Earth Limb control data set at 133 GeV with $f = 0.14$ and $s_{\rm global} = s_{\rm local} = 2.0\sigma$. (No trials factor is applicable here, since the Earth Limb data set is a control sample, and the fit was made at the same energy as the GC sample.) No corresponding signal was seen in control data from locations along the Galactic plane away from the GC.

Additionally, the analysis by the LAT Collaboration confirmed that the θ-distribution of events contributing to the excess did not closely match the MC predictions. Furthermore, in the `P7REP_CLEAN` dataset, the 133 GeV feature is narrower than the LAT energy resolution; including an overall scale factor for the width in the energy dispersion model yielded a best-fit value of 0.32 (+0.30,−0.13) (95% CL).

The considerations for optimizing the observing strategy to maximize sensitivity to a line at 130 GeV depend on the nature and magnitude of the signal in question. Here we consider four scenarios based on the best-fit values we found in the R3 and R16 ROIs, with the `P7_CLEAN` and `P7REP_CLEAN` data sets. Table 1 gives the signal flux and the background flux prefactor for each of the four scenarios.

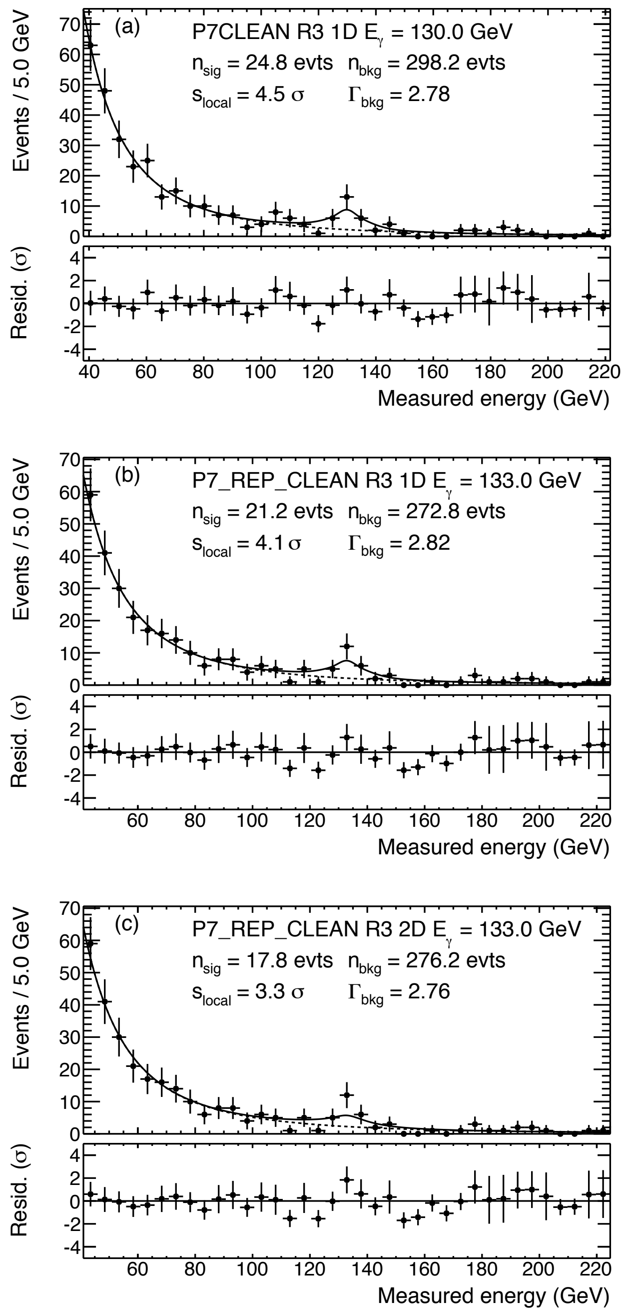

Fig. 1.— Fits for a line signal near 130 GeV for the ROI optimized for a contracted NFW profile (R3). *Top:* Fit to a γ-ray line at 130 GeV in the `P7_CLEAN` data using a 1D energy dispersion model that did not include P_{E}. *Middle:* Fit to a γ-ray line at 133 GeV in the `P7REP_CLEAN` data again using a 1D model. *Bottom:* Same as middle plot, but using a 2D energy dispersion model that included P_{E}.

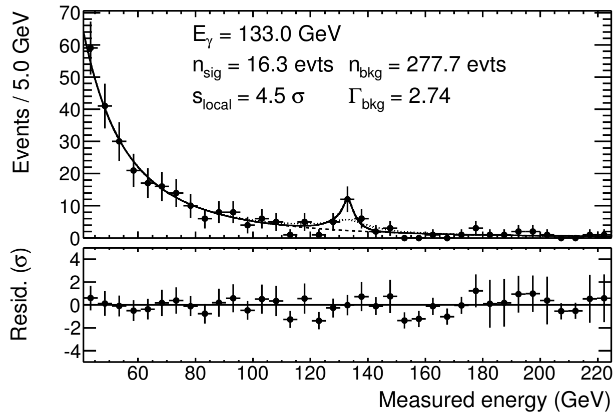

Fig. 2.— Fit to a γ-ray line at 133 GeV in the `P7REP_CLEAN` R3 data using a 2D model with a variable width.

Scenario	$\Phi_{\gamma\gamma}$ $10^{-10}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	N_0 $10^{-14}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{MeV}^{-1}$	Γ_{bkg}
P7_R3	2.4 ± 0.5	1.0	2.78
P7_R16	4.0 ± 1.0	4.1	2.68
P7REP_R3	1.7 ± 0.5	1.1	2.72
P7REP_R16	1.8 ± 1.1	4.9	2.55

Table 1: Scenarios for studies of projected sensitivity for modified observing strategies, showing the adopted signal fluxes ($\Phi_{\gamma\gamma}$) and background flux prefactors (N_0) and power law indices ($\Gamma_{\rm bkg}$) based on the best-fit results for a 130 GeV line in the R3 and R16 ROIs, with the `P7_CLEAN` and `P7REP_CLEAN` datasets. For sensitivity studies we modeled the background as a power law: $\frac{dN}{dE}(E) = N_0(\frac{E}{100\ \mathrm{GeV}})^{-\Gamma_{\rm bkg}}$.

2.4. Overview of Pass 8

The current version of the LAT Collaboration event-level analysis (Pass 7) uses reconstruction algorithms that were developed primarily based on the knowledge of the detector and its environment prior to launch. Pass 8 is a comprehensive revision of the LAT event analysis that incorporates many improvements relative to Pass 7 including algorithms to identify signal pile-up in the detector subsystems, an improved track-finding algorithm, and new reconstruction classification quantities that allow more efficient separation of γ rays from CR backgrounds. For γ rays with energies above 1 GeV, Pass 8 improves the energy reconstruction method, which fits both the longitudinal and transverse profiles of the electromagnetic shower in the CAL. The improvement in energy resolution provided by this method is expected to be greatest at energies above 100 GeV. Although the development of Pass 8 is still being finalized, the Collaboration has developed a prototype Pass 8 event class (`P8_PROTO_SOURCE`) with a residual charged particle contamination that is comparable to the

`P7SOURCE` event class. Relative to `P7SOURCE`, `P8_PROTO_SOURCE` has 25–30% greater acceptance and 10–20% better angular resolution above 1 GeV.

Pass 8 is expected to provide better sensitivity to spectral features at high energy through the improvements in acceptance and energy resolution. The energy resolution of `P8_PROTO_SOURCE` is equal to `P7SOURCE` at 100 GeV and is 10% better at 500 GeV. The final version of the Pass 8 event analysis will include an additional selection on the quality of the reconstructed energy that should further improve the energy resolution of Pass 8 relative to Pass 7. Ignoring any contribution from the improved Pass 8 energy resolution, a lower limit for the increase in sensitivity can be estimated from the projected increase in acceptance. In the limit of a background-dominated ROI the sensitivity to a line-like feature scales with the square root of the acceptance. Given the acceptance of `P8_PROTO_SOURCE`, the sensitivity of Pass 8 to a line-like feature at 130–135 GeV will increase by 12–14% for the set of ROIs used for the LAT Collaboration line analysis. Further gains in sensitivity may also be realized with the inclusion of so-called 'CalOnly' events that convert in the CAL. In a line search analysis these could increase the acceptance of the LAT by as much as 50%. However, the background contamination level for CalOnly events is expected to be significantly higher than for events converting in the tracker and their utility for analyses of high-energy diffuse emission has not yet been fully studied.

2.5. Criteria for Adopting a Modified Observing Strategy

The scientific implications for a ∼130 GeV line associated with the GC region are profound and if after the Pass 8 reprocessing suggestions of a signal remain, and we are confident that it is not attributable to systematics, then clearly the motivation to obtain sufficient data to confirm the signal would be compelling. This is not to say that the corresponding modification of the observing strategy for the *Fermi* mission should be made without consideration of the impacts on other *Fermi* science. Much of the rest of this white paper explores potential observing strategies (§ 3.2) and their relative impacts on science with the LAT (§ 4.2). The objective of this subsection is to define the 'trigger' criteria for adopting a modified observing strategy. We stress that the understanding of the apparent signal and the systematics is evolving and LAT data are continuing to accumulate. The decision time frame for the Mission is currently understood to be Summer 2014.

The ingredients are as follows:

- **Other information beyond *Fermi*.** H.E.S.S. II may be able to (*a*) exclude the signal at any level that the LAT could detect, (*b*) confirm the signal at the level that the LAT could detect, or (*c*) provide hints one way or the other. In cases (*b*) and (*c*), the argument for modifying the observing plan will be at least as strong as it was without the new information, and the criteria would remain evidence for a line signal in Pass 8 that we are confident is not systematics dominated. Case (*a*) may also need to be considered carefully; H.E.S.S. II, for example, has a relatively narrow field of view (∼2° diameter) and if the signal region were extended on larger scales background subtraction in the analysis could be challenging.

- **Systematics.** Studies of potential systematic effects will continue. It is difficult to predict the outcome, but obviously finding a clear root cause in systematic effects would effectively veto the modification of the observing plan, and again decisions to trigger a modified observing strategy will require confidence that the apparent signal is above the level of systematics.

- **Pass 8.** Again the likely possibilities fall into three categories: (a) the effect persists or grows somewhat[2], (b) the effect shrinks somewhat, or (c) the effect goes away. Because the Pass 8 data will not be independent of Pass 7, both being based on the same LAT event data, changes in significances largely will be the result of analysis changes. How much more data are needed for a definitive conclusion will be driven by the results from Pass 8. The useful persistence level may be defined such that the same level of excess in additional data from a modified observing strategy would combine with earlier data to yield likelihood Test Statistic (e.g., Mattox et al. 1996) $TS \geq 25$. Given current expectation (§ 3.1), it seems likely that two years of modified observing will be needed.

The above considerations together define the trigger algorithm:

(133 GeV line NOT excluded below LAT detection limit by H.E.S.S. II) AND (TS(Pass 8, 6 years, 133 GeV, R3) $>$ 15, after accounting for systematics)

Note that the algorithm is unaffected if, e.g., $TS \geq 36$ could be reached after 10 years without modifying the survey plan. The modified observing plan would, in this case, provide the answer years earlier, and there is no guarantee the mission will continue for 10 years or longer.

3. Considerations for a Modified Observing Strategy

3.1. Considerations for Optimizing the Galactic Center Line Search

A key consideration for optimizing the observing strategy for sensitivity to a line-like feature is the 'observing profile' for the GC, i.e., the distribution of observing time as a function of the angle θ from the LAT boresight. This is because the effective area and energy resolution of the LAT vary markedly with this angle[3]. The effective area is largest on axis and decreases off axis, falling to zero at $\cos\theta \sim 0.2$. Conversely, the energy resolution is worst on-axis and improves for off-axis events, for which the CAL typically contains larger fractions of the electromagnetic showers. The sensitivity of the LAT to line-like features depends on both the effective area and the

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[2] Although not yet demonstrated to have sufficiently great background rejection, CalOnly events would provide a largely independent data sample; see § 2.4.

[3] See `http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm`.

energy resolution. However, their relative importance changes depending on whether the search is signal limited (in which case increasing the effective area to improve statistics is more important) or background limited (in which case the most important consideration is improving the energy resolution to reduce the amount of background under the signal peak).

To study the tradeoff between effective area and energy resolution, we performed a series of MC simulations of a line search. We simulated different fluxes, $\Phi_{\gamma\gamma}$, of γ-rays from a line-like signal at 130 GeV near the GC for 10^8 s observations (equivalent to the total live time that could be obtained in $\sim$4 years) for values of $\cos\theta$ from 0.25 to 0.95 in steps of 0.1, and fit the fluxes using a 1D energy dispersion model that did not include $P_{\rm E}$, (i.e., the same model that was used for the top and middle plots in Fig. 1). Figure 3 shows the projected TS values given $\Phi_{\gamma\gamma}$ corresponding to the best-fit values for the both `P7` and `P7REP` in R3 (left) and R16 (right).

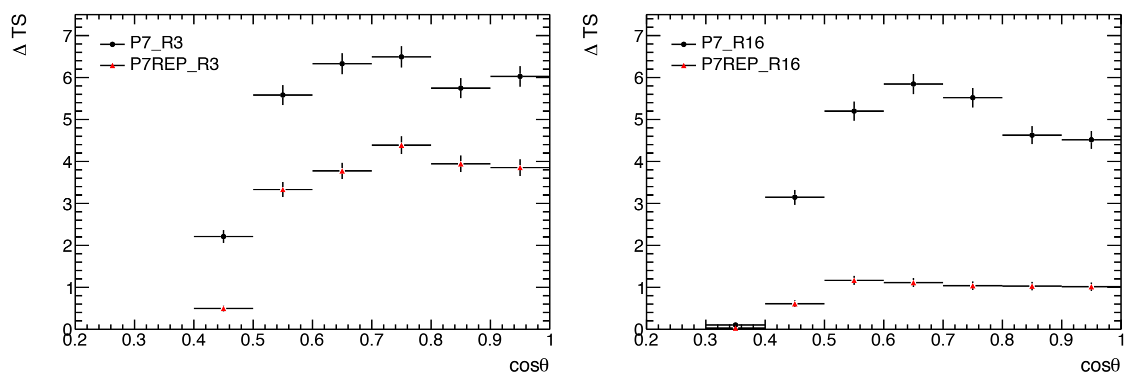

Fig. 3.— Projected TS values versus θ for 10^8 s observations for the `P7` and `P7REP` scenarios for R3 (left) and R16 (right) scenarios. The missing points at small values of $\cos\theta$ generally did not have enough statistics for fits to the line signal to converge.

In summary, the sensitivity does not change dramatically between $\cos\theta = 0.55$ ($\theta \sim 57^\circ$) and $\cos\theta = 1.0$. This allows some freedom to design an observing strategy that is both optimal for searching for a line from the GC region and mitigates the impacts on other LAT science (see Sec. 3.2).

The potential for systematic instrumental biases is also a consideration. In survey mode, the observing profile for any direction on the sky includes contributions for a range of θ, whereas for a pointed mode observation the LAT a large fraction of the observing time for the GC would accumulate in a narrow range of θ. Depending on the strategy, directions near the GC could also accumulate observing time preferentially at particular values of θ. Although this should not be a driving consideration, excluding instrument-related systematic biases is easier with an observing strategy that spreads the observation across a larger range of θ.

3.2. Observing Strategies Considered

Because the field of view of the LAT covers more than 20% of the sky, we are not faced with choosing between survey and deep stare observations. Rather, any observation with *Fermi* covers a large fraction of the sky and we can make modifications to the pointing or rocking strategy to provide enhanced coverage and exposure at selected locations of interest while still obtaining complete sky coverage. The tradeoffs are rather in uniformity and frequency of sky coverage, and to a lesser extent overall observing efficiency (average fraction of the field of view that is not blocked by the Earth).

We considered three observing strategies as alternatives to survey mode that would provide increased exposure in the GC region. These observing strategies were generated by the *Fermi* Mission using a realistic orbit and attitude simulator and made available through the *Fermi* Science Support Center[4]. We summarize them briefly here.

For each strategy, the *Fermi* observatory performs a pointed observation, transitions to survey mode when the target direction moves within 10° of the Earth limb, and returns to the pointed observation when the target emerges past 10° from the Earth limb after occultation. The strategies differ only in the choice of target directions for the pointed observations. Option 1 maximizes exposure on the GC (pointing at R.A., Dec. $261\overset{\circ}{.}4$, $-28\overset{\circ}{.}9$, J2000), Option 2 points at the celestial equator, slightly decreasing exposure at the GC relative to Option 1, but improving the uniformity of the sky coverage, and Option 3 further improves all-sky uniformity by adjusting the declination of the target direction weekly to be on the orbital equator. For all three strategies, the R.A. of the target is $261\overset{\circ}{.}4$.

Figure 4 shows how the observing time for the GC is distributed with θ for each of the options considered. The coverage is nearly uniform for Survey mode and quite nonuniform for Options 1 and 2. Option 3 is intermediate, with observing time at least as great as for Survey mode distributed out to $\cos\theta \sim 0.6$ (i.e., $>50^\circ$ off axis). This has the advantage of reducing sensitivity of the observations to any systematic effects that are strongly dependent on θ.

Figure 5 shows the distribution of exposure on daily intervals for survey mode and Option 3. Option 3 has a considerably wider range of exposure across the sky, which of course is expected, but even on daily time scales maintains complete sky coverage, an important consideration for much of LAT science. For this reason, and the enhanced exposure toward the GC with a broad range of θ, we consider Option 3 as the most suitable candidate for an alternative observing strategy that favors the GC.

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[4]See `http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html`.

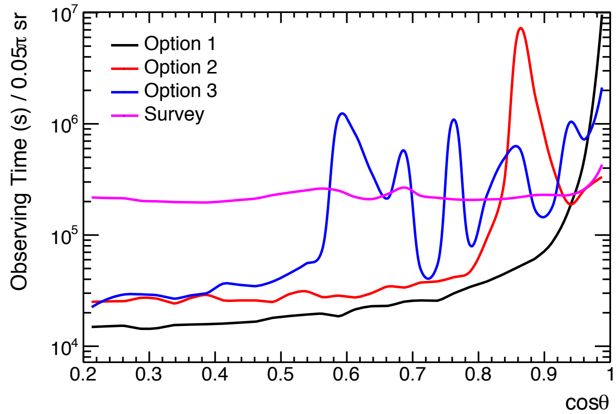

Fig. 4.— Distributions of observing time as a function of θ for the GC for a 55-day orbital precession period for the three options considered and for standard survey mode.

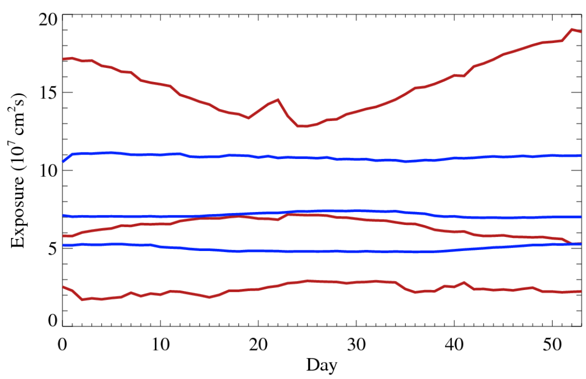

Fig. 5.— Exposure at evaluated on daily intervals for approximately precession period. The curves show the 5^{th}, 50^{th}, and 95^{th} percentile exposures (based on uniform sampling of the entire sky) at 1 GeV for survey mode (blue) and Option 3 (red). The overall average exposure for Option 3 is somewhat less than for survey mode, but the increased exposure for the GC region does not result in 'holes' in the sky coverage.

4. Impacts on LAT Science

4.1. Impacts for a Line Search in the Galactic Center

Each of the modified observing strategies considered in § 3.2 would significantly increase the exposure toward the GC, albeit with a different θ-distribution of observing time than for survey mode. To quantify the improvement in sensitivity to a line at 130 GeV, for each observing strategy we estimated the projected TS values for one-year long observations relative to the survey mode. Specifically, we simulated 100 realizations for each of the strategies and each of the scenarios listed in Table 1, fit each realization using a 1D energy dispersion model, and calculated the projected TS as: $TS_{\rm proj} = (\frac{\sum_i \sqrt{TS_i}}{100})^2$. That is, the projected rates of increase are evaluated based on the assumption that the currently-measured TS for each scenario is the same as the average TS for the actual flux of the presumed line source (Table 1). The stated uncertainties in Table 1 are just the statistical uncertainties of deriving the equivalent 1-year rates of accumulation of TS and do not reflect the considerable uncertainties in the current flux measurements.

Scenario	Option 1	Option 2	Option 3	Survey
P7_R3	7.3 ± 0.3	6.5 ± 0.3	6.3 ± 0.3	3.3 ± 0.2
P7_R16	5.5 ± 0.2	5.2 ± 0.2	4.9 ± 0.2	3.0 ± 0.2
P7REP_R3	4.5 ± 0.2	4.3 ± 0.2	4.0 ± 0.2	1.6 ± 0.1
P7REP_R16	1.0 ± 0.1	0.9 ± 0.1	0.9 ± 0.1	0.6 ± 0.1

Table 2: Projected TS increase per year for each of the observing strategies considered, for each of four different scenarios for the signal and background fluxes. The quoted error is the uncertatiny of $TS_{\rm proj}$ only, and does not include expected statistical variations, or the uncertainties in the signal and background flux models.

In summary, Option 1 gives the largest increase in sensitivity to a line, with TS increase relative to survey mode in the range $[1.8, 2.8]$, depending on the scenario. Options 2 and 3 provide somewhat less of an increase, with TS improvement factors in the ranges $[1.7, 2.7]$ and $[1.6, 2.5]$ respectively. For Option 3, the TS for the `P7REP_R3` scenario would be projected to be ∼8 (currently) + 2×1.6 (through year 6 in survey mode) + $2 \times 4.0 \approx 19$ after 2 years. This total TS would increase by about 25% with Pass 8 (§ 2.4). The projection has a large statistical uncertainty, of course.

4.2. Impacts on Other LAT Science

Here we consider the impacts, *pro* and *con*, for other LAT science if the observing strategy is modified to favor the GC. For some topics, quantitative statements are made based on the Option 3 observing strategies discussed in § 3.2.

4.2.1. Active Galactic Nuclei

An important strength of the *Fermi* mission has been the all-sky monitoring provided by the LAT. Blazars are characteristically quite variable on a wide range of time scales. Survey mode observations have provided complete, moderately uniform sky coverage every 2 orbits (∼3 hr). The exposure is even more uniform when integrated over time periods of the order of the 53-day precession period of the orbit. The sensitivity is of course not uniform, owing to the wide range of brightness of the Galactic diffuse emission across the sky, but for bright transient sources detectable on time scales of orbits or longer, survey mode has proven to be very effective.

Con: A modified observing strategy favoring the GC would decrease the effectiveness of the LAT as a (fairly uniform) sky monitor. The impacts of, e.g., Option 3, are considerably less than for a standard pointed observation, but still not negligible. Figure 6 illustrates how the exposures for Option 3 would compare to survey mode for blazars already detected by the LAT. We assume that a long-term modification to the observing strategy would not preclude Targets of Opportunity and would also admit the possibility of proposing coordinated multiwavelength campaigns during which the *Fermi* observing strategy would revert to standard survey mode or perhaps to pointed observations favoring a proposed target.

Pro: Figure 6 also shows that more than 100 blazars associated with LAT sources would be more deeply observed with Option 3. This is a minority of the LAT blazars but for many the rate of exposure increase would more than double, allowing more sensitive monitoring and spectral studies.

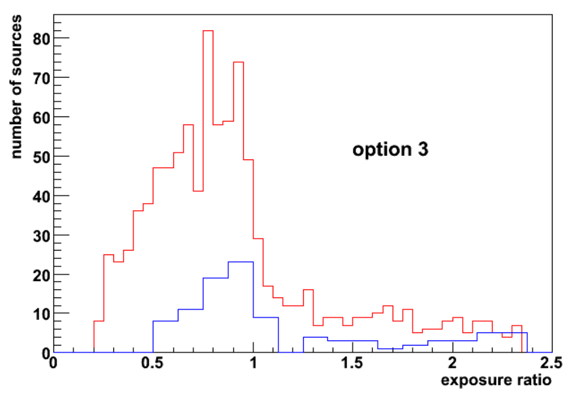

Fig. 6.— Relative exposures at 1 GeV for all 2LAC AGNs (Ackermann et al. 2011, red) and AGNs with $|b| < 10°$ (from associations in Nolan et al. 2012, blue), comparing Option 3 to standard survey mode.

4.2.2. Catalogs/Source Populations

Pro: Above 10 GeV the spatial resolution of the LAT becomes good enough and the Galactic diffuse emission faint enough that source detection is limited by statistics and an observing strategy that favors the GC region would detect more hard sources and localize them better. Identification will remain a challenge because of the large density of potential counterparts in that region of the sky.

Con: LAT catalogs published to date have included systematic evaluations of light curves on ∼1-month time scales. Favoring the GC would necessarily result in greater unevenness in sensitivity (see Sec. 4.2.1).

Con: The distribution of blazars with flux $N(S)$ has been studied in detail with the LAT data and supporting simulations to derive the detection efficiencies (Abdo et al. 2010; Ajello et al. 2012). The deepening exposure with time has allowed these studies to probe fainter fluxes, and effectively to resolve greater fractions of the extragalactic γ-ray background. Extended observations of the GC region would not prevent further deepening of the measurement of $N(S)$ but because the sensitivity of the LAT is less in regions with bright Galactic diffuse emission, the gains would be less.

4.2.3. Galactic Diffuse Gamma-ray Emission

Pro: The increased exposure toward the GC would increase the sensitivity for point sources in the inner Galaxy, and aid resolving them from diffuse separation. We note, however, that the model for Galactic diffuse emission has substantial systematic uncertainties in this region in any case, and the current γ-ray statistics in the GeV range are not particularly limited. The increased exposure is may help for reducing the systematics of the model.

Pro: Increased statistics for the Galactic diffuse emission would be obtained at energies close to what can be reached by ground-based atmospheric Cherenkov telescopes; H.E.S.S. reported a measurement of diffuse γ-ray emission above 300 GeV in the GC region (Aharonian et al. 2006), and H.E.S.S. II should lower the threshold below 100 GeV.

Con: Local Group and starburst galaxies that the LAT has detected would generally accumulate exposure less rapidly than they would in survey mode. For the former, spatially-resolved follow-up studies of the LMC and M31 galaxies would achieve somewhat less detail than they would have with survey mode.

4.2.4. Extragalactic Diffuse Gamma-ray Emission

Con: An observing strategy that favors the GC would have decreased exposure for the high-latitude regions used to perform measurements of the extragalactic diffuse γ-ray background and its anisotropy. For measurements of the extragalactic diffuse spectrum, the principal issue is reduced statistics at the highest energies. For anisotropy studies, over most of the energy range of interest ($\gtrsim$ 1 GeV), the uncertainty on the measured angular power spectrum is dominated by shot noise, and hence scales roughly inversely to the number of observed γ-rays in the region used for the analysis. Due to contamination from Galactic diffuse emission, only latitudes $|b| > 30^\circ$ are suitable for an anisotropy analysis. The expected improvement in the precision of an anisotropy measurement obtainable with a specified observing strategy is given by the increase in exposure in this region.

However, the decrease of exposure at high latitudes for the options considered here would not be dramatic. For Option 3, the decrease is only 20% at 10 GeV, for the half of the sky at $|b| > 30^\circ$.

Hence the negative impact on high-energy spectral studies or future anisotropy measurements from adopting an alternate observing strategies favoring the GC would be small.

4.2.5. Gamma-Ray Bursts and Short Duration Transients

Pro: The overall rates of detections of GRBs, and of short-duration transient sources generally, depend primarily on fluence and not on the observing strategy. However, for an observing strategy favoring the GC, the rates of detection of transient sources in the inner Galaxy would be much greater than for survey mode observation. Part of the gain would come from increased exposure, and the rest from longer intervals of continuous coverage. The signal-to-noise ratio for a given fluence would increase, in particular increasing the detectability of transient sources with durations greater than $\sim$2 ks; see Figure 7.

Con: For follow-up observations of LAT-detected GRBs and other extragalactic transients at other wavelengths, the inner Galaxy is less desirable than most other directions on the sky because of optical and X-ray obscuration by interstellar dust and gas, and because of the high density of stars.

4.2.6. Other Dark Matter & New Physics

Pro: If observations of the GC region allow the systematic uncertainty of the Galactic diffuse emission model to be reduced at energies >10 GeV (§ 4.2.3), then several open questions potentially could be addressed, including dark matter detection claims in the few-GeV range (e.g., Hooper & Goodenough 2011) and the presence of possible *Fermi* Bubble-related substructures. In addition, improved constraints could be obtained on the continuum emission from dark matter annihilation that should be coincident with the line signal.

Con: With observations favoring the GC, dwarf spheroidal and Galaxy clusters typically would be less deeply exposed than in survey mode, and the regions that do receive greater exposure would be toward the relatively bright diffuse foreground of the inner Galaxy. So for a modified observing strategy favoring the GC, the sensitivity of dwarf spheroidal and Galaxy cluster searches for WIMP signals would increase more slowly than for survey mode observations.

4.2.7. Pulsars & Other Galactic Sources

Pro: The modified observing strategy would provide increased sensitivity for pulsars (radio loud and radio quiet) in the central part of the Milky Way. A number of unassociated LAT sources with pulsar-like spectral characteristics are in the vicinities of the tangents of the Scutum arm (in the north) and the Norma arm (in the south), i.e., within about 30° of the GC and probably much

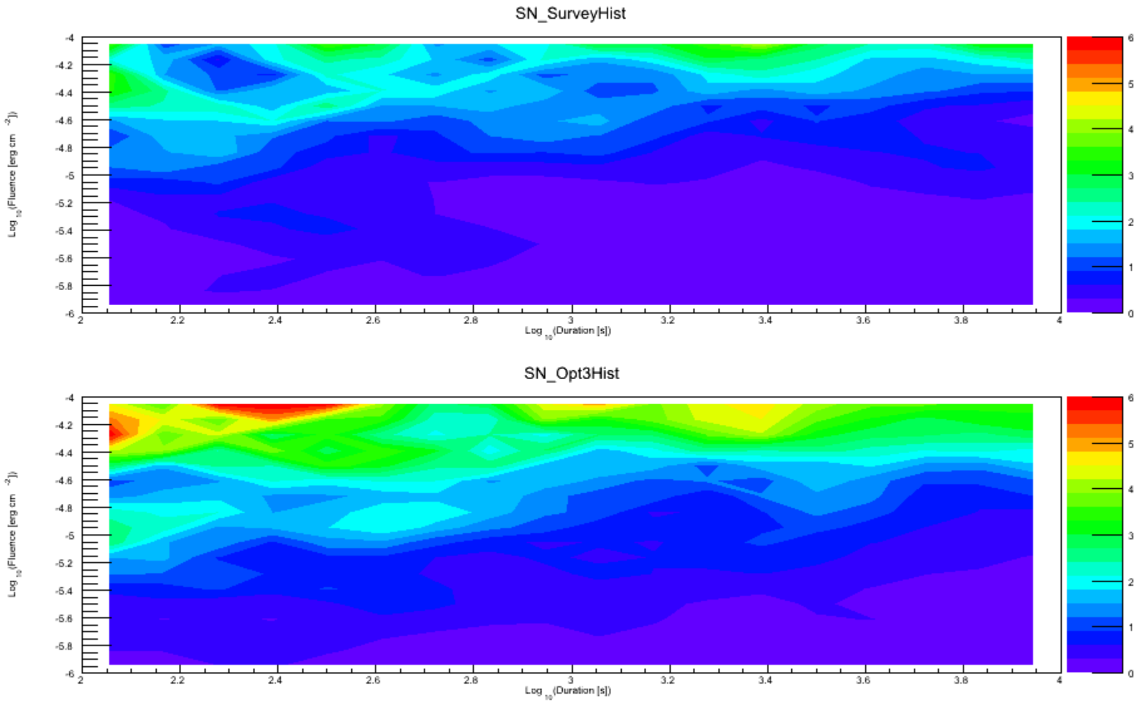

Fig. 7.— Dependence of the average signal-to-noise ratios on duration and fluence for observations of transient sources in survey mode (upper panel) and Option 3 (lower panel). The simulated transient sources are within 40° of the GC and have constant emission while they are on, with photon spectral index 2.05. The background model includes the Galactic diffuse, isotropic, and Earth limb emission, and all point sources in the 2FGL catalog.

closer than the GC. Relative to known radio pulsars, the fraction of LAT pulsars in the inner Galaxy is smaller. To some extent this may represent the flux limit of the LAT for pulsar detection but clearly many undetected γ-ray pulsars lie toward the inner Galaxy. A modified observing strategy that favors the GC would markedly increase the sensitivity for blind searches for pulsations[5]. The unassociated source close to the GC, 2FGL J1745.6−2858, has a pulsar-like spectrum. In the close vicinity of Sgr A*, pulsation searches would have to take into account accelerations due to orbital motions; with obtainable data and a time-differencing analysis approach, orbital periods as short as 300 days could be found with a modified observing strategy lasting one year or longer.

Con: Many LAT-detected pulsars are now timed exclusively or primarily from LAT data[6]. The ephemerides are valuable for studies of these sources at any wavelength. Biasing the survey

[5]Some details are presented in this poster by Saz Parkinson, Belfiore, & Razzano for the 2012 *Fermi* Symposium, `https://confluence.slac.stanford.edu/display/LATTalks/Enhancing+Searches+for+Gamma-ray+Pulsars+around+the+Galactic+Center+with+Fermi-LAT+PublicTalkID+14947`.

[6]See `https://confluence.slac.stanford.edu/display/GLAMCOG/LAT+Gamma-ray+Pulsar+Timing+Models`

toward to GC will reduce the sensitivity to short-term timing variations (glitches) for pulsars not in the inner Galaxy. However, the impacts are not projected to be deleterious, and for some pulsars a modified observing strategy would greatly increase the exposure (Fig. 8).

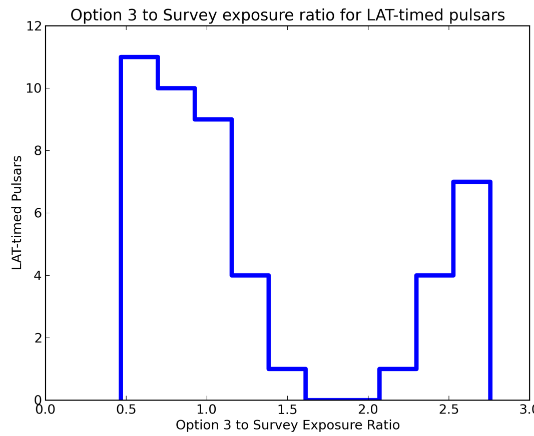

Fig. 8.— Exposures for Option 3 relative to survey mode for the 47 pulsars that are being timed exclusively or primarily by the LAT. The median ratio is 0.95. The pulsars toward the inner Galaxy would receive more than 2.5 times greater exposure with Option 3, and no pulsar loses more than about half of the exposure relative to survey mode. For this comparison the exposures were evaluated at 10 GeV.

4.2.8. Solar System

This topic includes the Sun and Moon as well as the Earth limb.

Con: Except when they are passing through the vicinity of the GC, the Sun and Moon would be (somewhat) less routinely observed. For the Sun in particular this is a consideration because of the impulsive nature of γ-ray emission associated with solar flares.

Pro: A modified observing strategy tracking any particular direction on the sky would include data with larger rocking angles than for standard survey mode observations, and notably the largest rocking angles would be toward the east and west (in orbital coordinates). So the exposure of the Earth limb would increase and in particular it will greatly increase in the directions that matter for studies of positron/electron separation in the geomagnetic field (Fig. 9). The increased exposure of the limb would also increase the statistics of Earth limb gamma rays useful for control studies of systematics (§ 2.3).

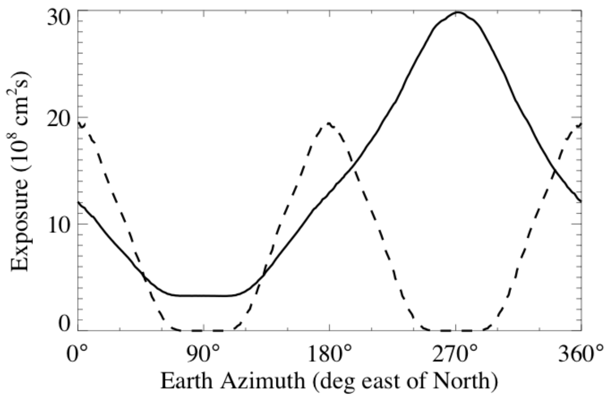

Fig. 9.— Variation of exposure at 1.1 GeV (Clean class) with Earth azimuth for nadir angle 65° for Option 3 (solid) and survey mode (dashed). Both are considered for one precession period, ∼54 days. North has Earth azimuth 0° and east is 90°. Option 3 provides much more exposure in the east and west for this nadir angle, which is just below the horizon and in the range used for studies of positron/electron separation in the geomagnetic field.

4.3. Summary of Science Impacts

Modifying the observing strategy to favor the GC region after 6 years of sky survey observations would unavoidably have negative impacts on some LAT science, particularly monitoring the sky on time scales of hours to days. The negative impacts for sky monitoring on this time scale are lessened for observing strategies like Option 3 that trade off increased exposure at the GC for more uniform coverage of the sky and increased overall average exposure. Also, during a long-term modified observing strategy, Autonomous Repoint Requests and Targets of Opportunity will still be possible for high-priority pointed observations, and proposals for specific pointed observations, such as for coordinated multiwavelength campaigns, should be considered for up to several weeks per year.

Most of the other negative impacts relate to the decreased rate of exposure accumulation away from the GC. At high latitudes, the average rate would decrease by about 20% for Option 3. For studies that depend on the average brightness of the sky or the average fluxes of point sources, such as of the extragalactic diffuse background or the luminosity function of blazars, the impact would be small, as the exposure would be accumulating in addition to 6 years of data primarily in survey mode.

Some impacts on other LAT science would be positive. In particular, pointed observations (in any direction) would increase the sensitivity to fainter and longer (> 1 ks) transient sources. For an observing strategy favoring the GC, the rate of pulsar discovery in the inner Galaxy would be increased. In addition more exposure toward the Earth limb in the east and west would be obtained, data that are uniquely useful for studies of cosmic-ray electrons and positrons and may also be useful for investigating systematics of the 130 GeV feature in the Earth limb.

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