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# Dark Matter Searches with the Fermi-LAT in the Direction of Dwarf Spheroidals

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The dwarf spheroidal satellite galaxies of the Milky Way are some of the most dark-matter-dominated objects known. Due to their proximity, high dark matter content, and lack of astrophysical backgrounds, dwarf spheroidal galaxies are widely considered to be among the most promising targets for the indirect detection of dark matter via gamma rays. Here we report on gamma-ray observations of Milky Way dwarf spheroidal satellite galaxies based on 6 years of *Fermi* Large Area Telescope data processed with the new Pass 8 reconstruction and event-level analysis. None of the dwarf galaxies are significantly detected in gamma rays, and we present upper limits on the dark matter annihilation cross section from a combined analysis of the 15 most promising dwarf galaxies. The constraints derived are among the strongest to date using gamma rays and lie below the cannonical thermal relic cross section for WIMPs of mass $\lesssim 100\,\mathrm{GeV}$ annihilating via the $b\bar{b}$ and $\tau^+\tau^-$ channels.

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## 1. Introduction

Overwhelming evidence supports the existence of dark matter (DM) based on its gravitational influence on ordinary matter. Although the DM paradigm is well-established, the nature of the particle that may constitute DM is not yet known. One of the leading candidates for the DM particle are weakly interacting massive particles (WIMPs) that existed in thermal equilibrium with standard model particles in the early universe. The relic density of WIMPs is set by “freeze-out” when the rate of WIMP interactions drops below the expansion rate of the Universe. For particles with an annihilation cross section on the weak interaction scale such as WIMPs, this process can naturally produce a relic density equal to the density of DM observed today.

Self-annihilation of WIMPs in regions with high DM density can produce stable secondary particles detectable by ground- and space-based observatories. The gamma rays produced in these annihilations are an especially attractive target for experimental searches. Unlike charged secondaries, gamma rays can be traced back to their point of origin enabling DM signals to be more easily discriminated from astrophysical foregrounds. The Large Area Telescope onboard the Fermi gamma-ray observatory is sensitive in the energy range from 20 MeV to more than 300 GeV and is well-suited to search for the gamma-ray annihilation signature of DM. With its excellent angular resolution, the Fermi-LAT can search for signals in a variety of targets including the Galactic Center, dwarf spheroidal galaxies (dSphs), and galaxy clusters.

Milky Way (MW) dSphs are especially promising targets due to their proximity and the absence of intrinsic sources of gamma-ray emission. The MW dSphs are also predominantly found in high-latitude regions of the sky where the diffuse gamma-ray foregrounds are lower and more easily discriminated from a potential DM signal. The DM content of these objects can be robustly measured by kinematic modeling of the stellar velocities of member stars. The expected DM signal is proportional to the line-of-sight integral of the DM distribution known as the J-factor. J-factors for known dSphs generally fall in the range between $10^{17}\,\mathrm{GeV}^2\,\mathrm{cm}^{-5}$ and $10^{20}\,\mathrm{GeV}^2\,\mathrm{cm}^{-5}$. By comparison, models for the DM distribution of the Galactic Center region predict J-factors at least an order of magnitude larger. However searches for DM signals in the Galactic Center are complicated by the systematic uncertainties associated with the diffuse astrophysical foregrounds which are brightest in this region of the Galaxy. Because the astrophysical foregrounds are much lower and more easily modeled in dSphs, DM searches in dSph galaxies can offer comparable sensitivity to those in the Galactic Center.

In this paper we present an updated search for DM signals using the sample of 25 dSphs from [1] based on 6 years of LAT data processed with `Pass 8`. [1] Following the approach of previous works [3, 4, 5, 1, 6, 7], we use a joint analysis to combine the data from multiple dSphs and increase the sensitivity of our search. We discuss the implications of these measurements in the context of the Galactic center excess and other experimental constraints on the DM annihilation cross section.

## 2. Pass 8

One of the main improvements of the present analysis with respect to prior works is the use

[1]The content of this proceeding is a condensed version of [2]. See this paper and its supplementary materials for additional details.



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of the `Pass 8` data set. `Pass 8` is a comprehensive revision to the LAT event-level analysis that reconstructs and classifies individual events from the raw data collected by the LAT subsystems. With respect to the current `Pass 7 Reprocessed` data release, `Pass 8` contains a number of improvements to the event reconstruction including algorithms to identify and remove instrumental pile-up, an improved energy reconstruction that extends the LAT energy range below 100 MeV and above 1 TeV, and a more robust pattern-recognition algorithm for track reconstruction [8].

The event classification in `Pass 8` has been fully redesigned and provides a completely new set of event classes for high-level science analysis. The `Pass 8` event class selections have been optimized using boosted decision trees to maximize the rejection power for cosmic-ray background events while maintaining a high efficiency for gamma rays. The `Pass 8` event analysis also expands the existing classification framework by adding *event types*, subdivisions of the event classes based on event-by-event uncertainties in the directional and energy measurements. The PSF event types are ordered by the quality of the angular resolution from PSF0 (worst) to PSF3 (best). At 3.16 GeV the 68% (95%) containment radii of the incidence-angle-averaged PSF for the best and worst PSF event types (PSF3 and PSF0) is $0.17^\circ$ ($0.35^\circ$) and $0.92^\circ$ ($2.3^\circ$). Our maximum likelihood analysis of the dSphs combines the four P8R2_SOURCE_V6 PSF event types in a joint likelihood function. We estimate that splitting the event sample by PSF event type improves the sensitivity of our analysis by $\sim$ 10%. Considering both the improvements in instrument performance from `Pass 8` and the expanded six-year data set, we expect an improvement of between 1.7 and 2.2 in the median sensitivity to WIMP annihilations as compared to the four-year analysis of [1] based on `Pass 7 Reprocessed` data.

## 3. Analysis

We analyzed LAT data collected during the first six years of the mission (2008-08-04 to 2014-08-05). From this data set we select events in the energy range between 500 MeV and 500 GeV in the `Pass 8` SOURCE class. We apply a zenith angle cut of $< 100^\circ$ to remove photons from the Earth Limb. Time periods around bright gamma-ray bursts and solar flares are also excised following the prescription of the *Fermi*-LAT third source catalog (3FGL) [9]. Data are binned into $10^\circ \times 10^\circ$ square regions of interest (ROIs) in Galactic coordinates centered at the position of each dSph. We use a spatial binning of $0.1^\circ$ and 24 logarithmic energy bins (8 bins per energy decade).

We perform a standard binned likelihood of the 25 dSphs in our sample using the Fermi Science Tools and the P8R2_SOURCE_V6 IRFs. We use the standard templates for isotropic and galactic diffuse emission. [2] Point-sources within each ROI are taken from the 3FGL catalog [9]. Each ROI is first fit with a baseline model in which the normalizations of the diffuse components and catalog sources within the ROI are left free to vary. For each dSph we use a spatial profile corresponding to an NFW DM density profile with halo scale radii and characteristic densities taken from [1].

After fitting the baseline model to each ROI, we derive a set of bin-by-bin likelihoods following the methodology of [1]. In each energy bin, we scan the normalization of the DM source while

[2]Specifically we use the *v06* release of the Galactic interstellar emission model and isotropic templates documented at `http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html`.



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leaving the parameters of the background model fixed. The set of bin-by-bin likelihood functions for each target is then used to reconstruct the global likelihood for a variety of DM spectral models.

Given the LAT likelihood function for a dSph, we construct a likelihood for the parameters of the DM model ($\vec{\mu}$) from the product of LAT and J-factor likelihoods. We define the likelihood function for target $i$ as

$$\tilde{\mathscr{L}}_i(\vec{\mu}, \vec{\theta}_i = \{\vec{\alpha}_i, J_i\} \,|\, \mathscr{D}_i) = \mathscr{L}_i(\vec{\mu}, \vec{\theta}_i \,|\, \mathscr{D}_i)\mathscr{L}_J(J_i \,|\, J_{\mathrm{obs,i}}, \sigma_i). \tag{3.1}$$

where $\vec{\theta}_i$ is the set of nuisance parameters that includes both parameters from the LAT analysis ($\vec{\alpha}_i$) and the dSph J-factor ($J_i$) and $\mathscr{D}_i$ is the gamma-ray data. The second term in Eq. 3.1 is the J-factor likelihood function which we use to model the uncertainty in the J-factor arising from the finite precision of the stellar kinematic analysis. We use a log-normal parameterization of the J-factor likelihood given by

$$\mathscr{L}_J(J_i \,|\, J_{\mathrm{obs,i}}, \sigma_i) = \frac{1}{\ln(10) J_{\mathrm{obs,i}} \sqrt{2\pi}\sigma_i} \times e^{-\left(\log_{10}(J_i) - \log_{10}(J_{\mathrm{obs,i}})\right)^2 / 2\sigma_i^2}, \tag{3.2}$$

where $J_i$ is the true value of the J-factor and $J_{\mathrm{obs,i}}$ is the measured J-factor with error $\sigma_i$. We obtain the J-factor likelihood parameterization by fitting a log-normal function with peak value $J_{\mathrm{obs,i}}$ to the posterior distribution for each J-factor as derived by [10].

We perform a combined analysis for DM signals in our dSph sample by forming a joint likelihood from the individual dSph likelihoods. Our combined sample consists of 15 dSphs that have kinematically determined J-factors and avoid ROI overlap and corresponds to the same set that was used in [1]. The combined likelihood function is given by the product of the individual dSph likelihoods,

$$\tilde{\mathscr{L}}(\vec{\mu}, \{\vec{\theta}_i\} \,|\, \mathscr{D}) = \prod_i \tilde{\mathscr{L}}_i(\vec{\mu}, \vec{\theta}_i \,|\, \mathscr{D}_i), \tag{3.3}$$

where the index $i$ runs over the 15 dSphs in our combined sample. With the combined dSph likelihood, we test the hypothesis of a DM signal in the entire sample where the expected signal in each dSph is weighted in proportion to its J-factor. For a given mass and annihilation channel, upper limits on the annihilation cross section are evaluated with the delta-log-likelihood technique, requiring a change in the profile log-likelihood of 2.71/2 from its maximum for a 95% CL upper limit [11].

## 4. Results

We find no evidence for significant gamma-ray emission from any of the individual dSphs or in the combined sample. Using the joint likelihood for the 15 dSphs in the combined sample, we derive limits on the WIMP annihilation cross section as a function of WIMP mass. Figure 1 shows the combined limits evaluated for the $b\bar{b}$ and $\tau^+\tau^-$ annihilation channels. The expectation bands show the expected range for these limits based on an analysis of 300 sets of randomly selected blank fields with $|b| > 30°$. We find that the limits from the six-year `Pass 8` analysis improve on the limits of [1] by a factor between 3 and 5. This improvement can be attributed to a number of factors including the improved sensitivity of the `Pass 8` data set and the different statistical realizations of the two data sets. Because the `Pass 8` six-year and `Pass 7 Reprocessed` four-year event samples have a shared fraction of only 20–40%, the two analyses are nearly statistically independent. For masses below 100 GeV, the upper limits of [1] were near the 95% upper bound of the expected sensitivity band while the limits in the present analysis are within one standard deviation of the median expectation value.

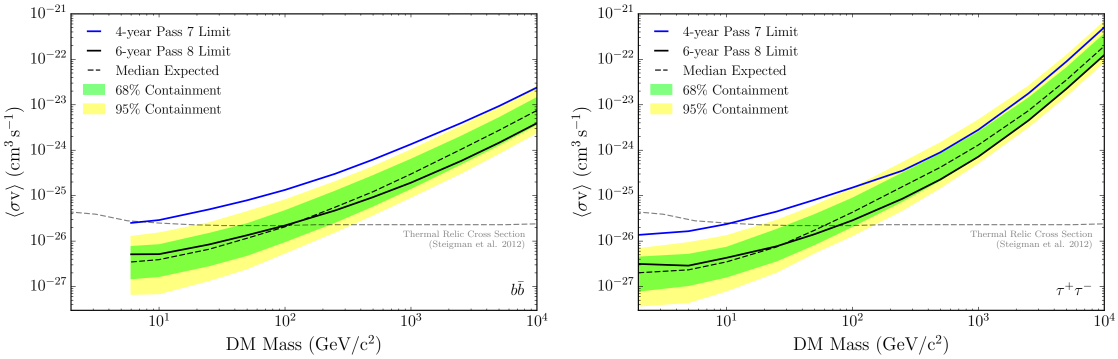


**Figure 1:** Constraints on the DM annihilation cross section at 95% CL for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels derived from a combined analysis of 15 dSphs. Bands for the expected sensitivity are calculated by repeating the same analysis on 300 randomly selected sets of high-Galactic-latitude blank fields in the LAT data. The dashed line shows the median expected sensitivity while the bands represent the 68% and 95% quantiles. For each set of random locations, nominal J-factors are randomized in accord with their measurement uncertainties. The solid blue curve shows the limits derived from a previous analysis of four years of `Pass 7 Reprocessed` data and the same sample of 15 dSphs [1]. The dashed gray curve corresponds to the thermal relic cross section from [12].

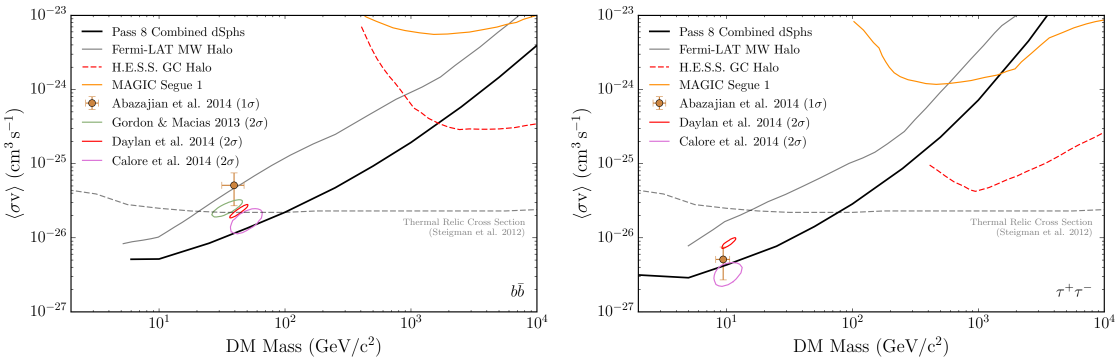


**Figure 2:** Constraints on the DM annihilation cross at 95% CL section for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels derived from the combined analysis of 15 dSphs with 6 years of Pass 8 data. For comparison limits from previously published searches are shown from LAT analysis of the Milky Way halo ($3\sigma$ limit) [13], 112 hours of observations of the Galactic Center with H.E.S.S. [14], and 157.9 hours of observations of Segue 1 with MAGIC [15]. Pure annihilation channel limits for the Galactic Center H.E.S.S. observations are taken from [16] and assume an Einasto Milky Way density profile with $\rho_\odot = 0.389\,\mathrm{GeV\,cm^{-3}}$. Closed contours and the marker with error bars show the best-fit cross section and mass from several interpretations of the Galactic center excess [17, 18, 19, 20].

Figure 2 shows the comparison of the limits from this work with other published limits on the DM annihilation cross section. The `Pass 8` combined dSph limits are currently among the strongest experimental constraints on the WIMP annihilation cross section and exclude WIMPs with the thermal relic cross section for $m_{\rm DM} \lesssim 100\,\rm GeV$. Our results also constrain DM particles with $m_{\rm DM}$ above $100\,\rm GeV$ surpassing the best limits from Imaging Atmospheric Cherenkov Telescopes for masses up to $\sim 1\,\rm TeV$ for quark channels and $\sim 300\,\rm GeV$ for the $\tau$-lepton channel.

These limits also begin to constrain the preferred region of parameter space for DM interpretations of the Galactic Center excess [19, 17, 20, 18]. However, uncertainties in the Galactic DM distribution can significantly enlarge the best-fit regions of $\langle \sigma v \rangle$, channel, and $m_{\rm DM}$ [21].

The future sensitivity to DM annihilation in dSphs will benefit from additional LAT data taking and the discovery of new dSphs with current and upcoming optical surveys such as the Dark Energy Survey [22] and the Large Synoptic Survey Telescope [23]. The recent discovery of new dSph candidates in the first year of the DES survey [24, 25] suggests that the sample of dSphs that can be targeted for gamma-ray searches will continue to grow over the next 5–10 years. Future analyses incorporating these new dSph galaxies will improve the sensitivity of the LAT to a DM signal and allow the DM annihilation parameter space to be probed to even lower cross sections.

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