Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi-LAT Data

M. Ackermann, A. Albert, B. Anderson, W. B. Atwood, L. Baldini, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, E. Bissaldi, R. D. Blandford, E. D. Bloom, R. Bonino, E. Bottacini, T. J. Brandt, J. Bregeon, P. Bruel, R. Buehler, G. A. Caliandro, R. A. Cameron, R. Caputo, M. Caragiulo, P. A. Caraveo, C. Cecchi, E. Charles, A. Chekhtman, J. Chiang, G. Chiaro, S. Ciprini, R. Claus, J. Cohen-Tanugi, J. Conrad, A. Cuoco, S. Cutini, F. D’Ammando, A. de Angelis, F. de Palma, R. Desiante, S. W. Digel, D. Di Venere, P. S. Drell, A. Drlaca-Wagner, R. Essig, C. Favuzzi, S. J. Fegan, E. C. Ferrara, W. B. Focke, A. Franckowiak, Y. Fukazawa, S. Funk, P. Fusco, F. Gargano, D. Gasparini, N. Giglietto, M. Giroletti, M. Werner, R. Bellazzini, H. Tajima, M. E. Monzani, D. Gasparrini, J. F. Ormes, S. Rainò, S. Ritz, M. Mayer, A. Albert, A. Cuoco, A. Chekhtman, A. Reimer, M. Pesce-Rollins, M. Perri, F. Piron, J. S. Perkins, J. Li, M. Llena Garde, F. Longo, F. Loparco, P. Lubrano, D. Malyshev, M. Mayer, M. N. Mazziotta, J. E. McEnery, P. F. Michelson, T. Mizuno, A. A. Moiseev, M. E. Monzani, A. Morselli, S. Murgia, E. Nuss, T. Ohsugi, M. Orienti, E. Orlando, J. F. Ormes, D. Paneque, J. S. Perkins, M. Pesce-Rollins, F. Piron, G. Ivato, T. A. Porter, S. Rainò, R. Rando, M. Razzano, A. Reimer, O. Reimer, S. Ritz, M. Sánchez-Conde, S. Scholz, C. Sgrò, J. E. Siskind, F. Spada, G. Spandre, P. Spinelli, L. Strigari, H. Tajima, E. Takahashi, J. B. Thayer, L. Tibaldo, D. F. Torres, E. Troja, G. Vianello, M. Werner, B. L. Winer, K. S. Wood, M. Wood, G. Zaharijas, S. Zimmer

(The Fermi-LAT Collaboration)

1 Deutsches Elektronen Synchrotron DESY, D-15738 Zeuthen, Germany
2 W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
3 Royal Swedish Academy of Sciences Research Fellow, funded by a grant from the K. A. Wallenberg Foundation
4 Santa Cruz Institute for Particle Physics, Department of Physics and Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
5 Università di Pisa and Istituto Nazionale di Fisica Nucleare, Sezione di Pisa I-56127 Pisa, Italy
6 Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, I-34127 Trieste, Italy
7 Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
8 Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
9 Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova, I-35131 Padova, Italy
10 Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
11 Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy
12 Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy
13 Istituto Nazionale di Fisica Nucleare, Sezione di Torino, I-10125 Torino, Italy
14 Dipartimento di Fisica Generale "Amadeo Avogadro", Università degli Studi di Torino, I-10125 Torino, Italy
15 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
16 Laboratoire Univers et Particules de Montpellier, Université Montpellier 2, CNRS/IN2P3, Montpellier, France
17 Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, Palaiseau, France
18 Consorzio Interuniversitario per la Fisica Spaziale (CIFS), I-10133 Torino, Italy
19 INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, I-20133 Milano, Italy
20 Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06123 Perugia, Italy
21 Dipartimento di Fisica, Università degli Studi di Perugia, I-06123 Perugia, Italy
22 College of Science, George Mason University, Fairfax, VA 22030, resident at Naval Research Laboratory, Washington, DC 20375, USA
23 Agenzia Spaziale Italiana (ASI) Science Data Center, I-00133 Roma, Italy
24 INAF Osservatorio Astronomico di Roma, I-00040 Monte Porzio Catone (Roma), Italy
25 Department of Physics, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden
26 The Oskar Klein Centre for Cosmoparticle Physics, AlbaNova, SE-106 91 Stockholm, Sweden
27 Wallenberg Academy Fellow
28 INAF Istituto di Radioastronomia, 40129 Bologna, Italy
29 Dipartimento di Astronomia, Università di Bologna, I-40127 Bologna, Italy
The dwarf spheroidal satellite galaxies (dSphs) of the Milky Way are some of the most dark matter (DM) dominated objects known. We report on gamma-ray observations of Milky Way dSphs based on 6 years of *Fermi* Large Area Telescope data processed with the new Pass 8 event-level analysis. None of the dSphs are significantly detected in gamma rays, and we present upper limits on the DM annihilation cross section from a combined analysis of 15 dSphs. These constraints are among the strongest and most robust to date and lie below the canonical thermal relic cross section for DM of mass $\lesssim 100$ GeV annihilating via quark and $\tau$-lepton channels.

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INTRODUCTION

Approximately 26% of the energy density of the universe is composed of non-baryonic cold dark matter (DM) [1]. Weakly interacting massive particles (WIMPs) are an attractive candidate to constitute some or all of DM [2–4]. WIMPs possess the encouraging property that their current abundance, when extrapolated from an equilibrium state in the early universe, can account for all DM [5]. Self-annihilation of WIMPs would continue...
today in regions of high DM density and result in the production of energetic Standard Model particles. The large mass of the WIMP ($m_{DM}$) permits the production of gamma rays observable by the Fermi Large Area Telescope (LAT), which is sensitive to energies ranging from 20 MeV to >300 GeV.

Kinematic data indicate that the dwarf spheroidal satellite galaxies (dSphs) of the Milky Way contain a substantial DM component [6, 7]. The gamma-ray signal flux at the LAT, $\phi_s$ (ph cm$^{-2}$ s$^{-1}$), expected from the annihilation of DM with a density distribution $\rho_{DM}(r)$ is given by

$$\phi_s(\Delta \Omega) = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2 m_{DM}^2} \int_{E_{min}}^{E_{max}} \frac{dN}{dE_{\gamma}} dE_{\gamma} \times \left[ \int_{\Delta \Omega} \int_{\text{I.o.s.}} \rho_{DM}^2(r) d\Omega' \right]$$

(1)

Here, the first term is dependent on the particle physics properties — i.e., the thermally-averaged annihilation cross section, $\langle \sigma v \rangle$, the particle mass, $m_{DM}$, and the differential gamma-ray yield per annihilation, $dN/\gamma dE_{\gamma}$, integrated over the experimental energy range.\footnote{Strictly speaking, the differential yield per annihilation in Equation (1) is a sum of differential yields into specific final states: $dN_{\gamma}/dE_{\gamma} = \sum_f B_f \frac{dN}{dE_{\gamma}}$, where $B_f$ is the branching fraction into final state $f$. Here, we make use of Equation (1) in the context of single final states only.} The second term, known as the J-factor, is the line-of-sight (l.o.s.) integral through the DM distribution integrated over a solid angle, $\Delta \Omega$.

Milky Way dSphs can give rise to J-factors in excess of $10^{19}$ GeV$^2$ cm$^{-5}$ [8, 9], which, coupled with their lack of non-thermal astrophysical processes, makes them good targets for DM searches via gamma rays. Gamma-ray searches for dSphs yield some of the most stringent constraints on $\langle \sigma v \rangle$, particularly when multiple dSphs are analyzed together using a joint likelihood technique [10–15]. Limits on $\langle \sigma v \rangle$ derived from observations of dSphs have begun to probe the low-$m_{DM}$ parameter space for which the WIMP abundance matches the observed DM relic density.

In contrast, DM searches in the Galactic center take advantage of a J-factor that is $O(100)$ times larger, although gamma-ray emission from non-thermal processes makes a bright, structured background. Several studies of the Galactic center interpret an excess of gamma rays with respect to modeled astrophysical backgrounds as a signal of 20 to 50 GeV WIMPs annihilating via the $bb$ channel [16–19]. Coincidentally, the largest deviation from expected background in some previous studies of dSphs occurred for a similar set of WIMP characteristics; however, this deviation was not statistically significant [13].

Using a new LAT event-level analysis, known as Pass 8, we re-examine the sample of 25 Milky Way dSphs from Ackermann et al. [13] using six years of LAT data. The Pass 8 data benefits from an improved point-spread function (PSF), effective area, and energy reach. More accurate Monte Carlo simulations of the detector and the environment in low-earth orbit have reduced the systematic uncertainty in the LAT instrument response functions (IRFs) [20]. Within the standard photon classes, Pass 8 offers event types, subdivisions based on event-by-event uncertainties in the directional and energy measurements, which can increase the sensitivity of likelihood-based analyses. In this work we use a set of four PSF event-type selections that subdivide the events in our data sample according to the quality of their directional reconstruction. In addition to the improvements from Pass 8, we employ the updated third LAT source catalog (3FGL), based on four years of Pass 7 Reprocessed data, to model point-like background sources [21]. Together, these improvements, along with an additional two years of data taking, lead to a predicted increase in sensitivity of 70% relative to the four-year analysis of Ackermann et al. [13] for the $bb$ channel at 100 GeV. More details on Pass 8 and other aspects of this analysis can be found in Supplemental Material [22].

**LAT DATA SELECTION**

We examine six years of LAT data (2008-08-04 to 2014-08-05) selecting Pass 8 SOURCE-class events in the energy range between 500 MeV and 500 GeV. We selected the 500 MeV lower limit to mitigate the impact of leakage from the bright limb of the Earth because the PSF broadens considerably below that energy. To further avoid contamination from terrestrial gamma rays, events with zenith angles larger than 100$^\circ$ are rejected. We also remove time intervals around bright GRBs and solar flares following the prescription used for the 3FGL catalog. We extract from this data set $10^5 \times 10^5$ square regions of interest (ROIs) in Galactic coordinates centered at the position of each dSph specified in Table I.

At a given energy, 20%–30% of the events classified as photons in our six-year Pass 8 data set are shared with the analysis of Ackermann et al. [13]. The low fraction of shared events can be attributed to the larger time range used for the present analysis (four versus six years), the increase in gamma-ray acceptance of the PSR2_SOURCE event class relative to P7REP_CLEAN, and the migration of individual events across the class selection boundaries caused by slight changes in the reconstructed energy and direction. Due to the relatively small overlap of the
respectively event samples, the two analyses are almost statistically independent.

**J-Factors for Dwarf Spheroidal Galaxies**

The DM content of dSphs can be determined through dynamical modeling of their stellar density and velocity dispersion profiles [23–25]. Recent studies have shown that an accurate estimate of the dynamical mass of a dSph can be derived from measurements of the average stellar velocity dispersion and half-light radius alone [26, 27]. The total mass within the half-light radius and the integrated J-factor have been found to be fairly insensitive to the assumed DM density profile [13, 25, 28]. We assume that the DM distribution in dSphs follows a Navarro-Frenk-White (NFW) profile [29],

$$\rho_{DM}(r) = \frac{\rho_0 r_s^3}{r(r_s + r)^2},$$

(2)

where $r_s$ and $\rho_0$ are the NFW scale radius and characteristic density, respectively. We take J-factors and other physical properties for the Milky Way dSphs from Ackermann et al. [13] (and references therein).

**Data Analysis**

We perform a binned Poisson maximum-likelihood analysis in 24 bins of energy, log spaced from 500 MeV to 500 GeV, and an 0.1° angular pixelization. We model the performance of the LAT instrument using the Pass 7 Reprocessed Galactic diffuse model IRFs. Our diffuse background model includes a structured Galactic component and a spatially isotropic component that represents both extragalactic emission and residual particle contamination. Because the energy resolution of the LAT was not accounted for when fitting the Galactic diffuse model, differences in response (energy resolution and effective area) between IRF sets lead to different measured intensities for this component. Thus, a small energy-dependent scaling has been applied to the Pass 7 Reprocessed Galactic diffuse model. The gamma-ray characteristics of nearby point-like sources are taken from the 3FGL catalog [21].

We perform a bin-by-bin likelihood analysis of the gamma-ray emission coincident with each dSph following the procedure of Ackermann et al. [13]. We first perform a broad-band fit over the entire energy range to fix the normalizations of the diffuse sources and the normalizations of point-like background sources within 5° of the dSph center. Fixing the normalizations of the background sources in the broad-band fit avoids numerical instability in the fit resulting from the fine binning in energy and the degeneracy of the diffuse background components at high Galactic latitudes. We then scan the likelihood as a function of the flux normalization of the putative DM signal independently in each energy bin (this procedure is similar to that used to evaluate the spectral energy distribution of a source). By analyzing each energy bin separately, we avoid selecting a single spectral shape to span the entire energy range at the expense of introducing additional degrees of freedom into the fit.

While the bin-by-bin likelihood function is essentially independent of spectral assumptions, it does depend on the spatial model of the DM distribution in the dSphs. We model the dSphs with spatially extended NFW DM density profiles projected along the line of sight. The angular extent of the emission profile for each dSph is set by the scale radius of its DM halo, which contains approximately 90% of the total annihilation flux. We use the set of DM halo scale radii from Ackermann et al. [13], which span a range of subtended angles between 0.1° and 0.4°.

We test a wide range of DM annihilation hypotheses by using predicted gamma-ray spectra to tie the signal normalization across the energy bins. Spectra for DM annihilation are generated with the DMFIT package based on Pythia 8.165 [13, 30, 31]. We reconstruct a broad-band likelihood function by multiplying the bin-by-bin likelihood functions evaluated at the predicted fluxes for a given DM model.

We combine the broad-band likelihood functions across 15 of the observed dSphs and include statistical uncertainties on the J-factors of each dSph by adding an additional J-factor likelihood term to the binned Poisson likelihood for the LAT data. The J-factor likelihood for target $i$ is given by

$$L_J(J_i | J_{\text{obs},i}, \sigma_i) = \frac{1}{\ln(10)J_{\text{obs},i}\sqrt{2\pi\sigma_i^2}} \times e^{-\left(\log_{10}(J_i) - \log_{10}(J_{\text{obs},i})\right)^2/2\sigma_i^2},$$

(3)

where $J_i$ is the true value of the J-factor and $J_{\text{obs},i}$ is the measured J-factor with error $\sigma_i$. This parameterization of the J-factor likelihood is obtained by fitting a log-normal function with peak value $J_{\text{obs},i}$ to the posterior distribution for each J-factor as derived by Martinez [8], providing a reasonable way to quantify the uncertainties on the J-factors. This approach is a slight modification.

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2 Constraints are insensitive to finer binning.

3 http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

4 Selected to have kinematically determined J-factors and avoid ROI overlap. The set is identical to that in Ackermann et al. [13].
of the approach in Ackermann et al. [10, 13], where an effective likelihood was derived considering a flat prior on the J-factors. We note that the J-factor correction is only intended to incorporate the statistical uncertainty in the J-factors, and not the systematic uncertainty resulting from the fitting procedure or choice of priors [22]. More details on the derivation of the J-factor likelihood and the effects of systematic uncertainties can be found in Supplemental Material [22].

Combining the broad-band gamma-ray and J-factor likelihood functions, our likelihood function for target $i$ becomes,

$$
\mathcal{L}_i(\mu, \theta_i = \{\alpha_i, J_i\} \mid D_i) = \mathcal{L}_i(\mu, \theta_i \mid D_i) \mathcal{L}_j(J_i \mid J_{\text{obs},i}, \sigma_i). 
$$

Here, $\mu$ are the parameters of the DM model, $\theta_i$ is the set of nuisance parameters that includes both nuisance parameters from the LAT analysis ($\alpha_i$) and the dSph J-factor ($J_i$), and $D_i$ is the gamma-ray data. We incorporate additional information about the event-wise quality of the angular reconstruction by forming the LAT likelihood function ($\mathcal{L}_i$) from the product of likelihood functions for four PSF event types. The four PSF event types (PSF0, PSF1, PSF2, and PSF3) subdivide the events in the SOURCE-class data set into exclusive partitions ($D_{i,j}$) in order of decreasing uncertainty on the direction measurement. The resulting joint LAT likelihood function is given by

$$
\mathcal{L}_i(\mu, \theta_i \mid D_i) = \prod_j \mathcal{L}_i(\mu, \theta_i \mid D_{i,j}). 
$$

The spectral and spatial model of gamma-ray counts for each event type partition is evaluated using a set of IRFs computed for that class and type selection.

We evaluate the significance of DM hypotheses using a test statistic (TS) defined as

$$
\text{TS} = -2 \ln \left( \frac{\mathcal{L}(\mu_0, \hat{\theta} \mid D)}{\mathcal{L}(\hat{\mu}, \hat{\theta} \mid D)} \right),
$$

where $\mu_0$ are the parameters of the null (no DM) hypothesis and $\hat{\mu}$ are the best-fit parameters under the DM hypothesis. $\mathcal{L}$ can here be either the likelihood for an individual dSph or the joint likelihood for the dSphs in our combined sample. Based on the asymptotic theorem of Chernoff [32], the TS can be converted to a significance based on a mixture of $\chi^2$ distributions. The validity of this assumption is examined further in Supplemental Material [22].

RESULTS

We find no significant gamma-ray excess associated with the Milky Way dSphs when analyzed individually or as a population. In the combined analysis of 15 dSphs, the largest deviation from the background-only hypothesis has $\text{TS} = 1.3$ occurring for $m_{DM} = 2$ GeV annihilating through the $e^+ e^-$ channel. Among the dSphs in our combined analysis, the dSph with the largest individual significance is Sculptor with $\text{TS} = 4.3$ for $m_{DM} = 5$ GeV annihilating through the $\mu^+ \mu^-$ channel. The maximum TS of our combined analysis is well below the threshold set for gamma-ray source detection and is completely consistent with a background fluctuation [21]. We set upper limits on $\langle \sigma v \rangle$ at 95% confidence level (CL) for WIMPs with $m_{DM}$ between 2 GeV and 10 TeV annihilating into six different standard model channels ($b\bar{b}$, $\tau^+ \tau^-$, $\mu^+ \mu^-$, $e^+ e^-$, $W^+ W^-$, $u\bar{u}$). Figure 1 shows the comparison of the limits for the $b\bar{b}$ and $\tau^+ \tau^-$ channels with expectation bands derived from the analysis of 300 randomly selected sets of blank fields. Sets of blank fields are generated by choosing random sky positions with $|b| > 30^\circ$ that are centered at least 0.5° from 3FGL catalog sources. We additionally require fields within each set to be separated by at least 7°. Our expected limit bands are evaluated with the 3FGL source catalog based on four years of Pass 7 Reprocessed data and account for the influence of new sources present in the six-year Pass 8 data set.

Comparing with the results of Ackermann et al. [13], we find a factor of 3–5 improvement in the limits for all channels using six years of Pass 8 data and the same sample of 15 dSphs. The larger data set as well as the gains in the LAT instrument performance enabled by Pass 8 both contribute to the increased sensitivity of the present analysis. An additional 30–40% improvement in the limit can be attributed to the modified functional form chosen for the J-factor likelihood (Equation 3). Statistical fluctuations in the Pass 8 data set also play a substantial role. Because the Pass 8 six-year and Pass 7 Reprocessed four-year event samples have a shared fraction of only 20–30%, the two analyses are nearly statistically independent. For masses below 100 GeV, the upper limits of Ackermann et al. [13] 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.

Uncertainties in the LAT IRFs, modeling of the diffuse background, and estimation of J-factors all contribute systematic errors to this analysis. By examining maximal variations of each contributor, we find that at 100 GeV they lead to ±9%, ±8%, and ±33% shifts in our limits, respectively (see Supplemental Material [22]).

Our results begin to constrain some of the preferred parameter space for a DM interpretation of a gamma-ray excess in the Galactic center region [16–19]. As shown in Figure 2, for interpretations assuming a $b\bar{b}$ final state, the best-fit models lie in a region of parameter space slightly above the 95% CL upper limit from this analysis, with an annihilation cross section in the range of $(1–3) \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ and $m_{DM}$ between 25 and 50 GeV. However, uncertainties in the structure of the Galactic
FIG. 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 [13]. The dashed gray curve in this and subsequent figures corresponds to the thermal relic cross section from Steigman et al. [5].

FIG. 2. Comparison of constraints on the DM annihilation cross section for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels derived from work with previously published constraints from LAT analysis of the Milky Way halo (3$\sigma$ limit) [33], 112 hours of observations of the Galactic Center with H.E.S.S. [34], and 157.9 hours of observations of Segue 1 with MAGIC [35]. Closed contours and the marker with error bars show the best-fit cross section and mass from several interpretations of the Galactic center excess [16–19].

DM distribution can significantly enlarge the best-fit regions of $\langle \sigma v \rangle$, channel, and $m_{DM}$ [36].

In conclusion, we present a combined analysis of 15 Milky Way dSphs using a new and improved LAT data set processed with the Pass 8 event-level analysis. We exclude the thermal relic annihilation cross section ($\sim 2.2 \times 10^{-26}$ cm$^3$ s$^{-1}$) for WIMPs with $m_{DM} \lesssim 100$ GeV annihilating through the quark and $\tau$-lepton channels. Our results also constrain DM particles with $m_{DM}$ above 100 GeV surpassing the best limits from Imaging Atmospheric Cherenkov Telescopes for masses up to 1 TeV. These constraints include the statistical uncertainty on the DM content of the dSphs. The future sensitivity to DM annihilation in dSphs will benefit from additional LAT data taking and the discovery of new dSphs with upcoming optical surveys such as the Dark Energy Survey [37] and the Large Synoptic Survey Telescope [38].

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| Name                  | \(\ell^a\) | \(\delta^a\) | Distance (kpc) | \(\log_{10}(J_{100})^b\) | Ref. |
|-----------------------|------------|--------------|----------------|---------------------------|-----|
| Bootes I              | 358.1      | 69.6         | 66             | 18.8 ± 0.22              | [39]|
| Canes Venatici II     | 113.6      | 82.7         | 160            | 17.9 ± 0.25              | [40]|
| Carina                | 260.1      | −22.2        | 105            | 18.1 ± 0.23              | [41]|
| Coma Berenices        | 241.9      | 83.6         | 44             | 19.0 ± 0.25              | [40]|
| Draco                 | 86.4       | 34.7         | 76             | 18.8 ± 0.16              | [42]|
| Fornax                | 237.1      | −65.7        | 147            | 18.2 ± 0.21              | [41]|
| Hercules               | 28.7       | 36.9         | 132            | 18.1 ± 0.25              | [40]|
| Leo II                | 220.2      | 67.2         | 233            | 17.6 ± 0.18              | [43]|
| Leo IV                | 265.4      | 56.5         | 154            | 17.9 ± 0.28              | [40]|
| Sculptor              | 287.5      | −83.2        | 86             | 18.6 ± 0.18              | [41]|
| Segue 1               | 220.5      | 50.4         | 23             | 19.5 ± 0.29              | [44]|
| Sextans               | 243.5      | 42.3         | 86             | 18.4 ± 0.27              | [41]|
| Ursa Major II         | 152.5      | 37.4         | 32             | 19.8 ± 0.28              | [40]|
| Ursa Minor            | 105.0      | 44.8         | 76             | 18.8 ± 0.19              | [42]|
| Willman I             | 158.6      | 56.8         | 38             | 19.1 ± 0.31              | [45]|

\(\ell^a\) Galactic longitude and latitude.  
\(\delta^a\) J-factors are calculated assuming an NFW density profile and integrated over a circular region with a solid angle of \(\Delta \Omega \sim 2.4 \times 10^{-4}\) sr (angular radius of 0.5\(^\circ\)).

dsphs below the horizontal line are not included in the combined analysis.

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Supplemental Material: Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi-LAT Data

Pass 8 Event-Level Analysis

Pass 8 is a new event-level analysis for the LAT instrument and is the successor to the Pass 7 event-level analysis [20, 47, 48]. Some of the key features of Pass 8 are new algorithms to identify out-of-time signals, a new tree-based pattern recognition for the tracker subsystem, and an improved energy reconstruction that extends the LAT energy range below 100 MeV and above 1 TeV. Pass 8 implements a new classification analysis based on boosted decision trees (BDTs), which provides enhanced background rejection power relative to Pass 7 [20]. The Pass 8 event-level analysis enhances the capabilities of the LAT in all metrics relevant for high-level science analysis. In the energy range between 1 GeV and 10 GeV, the new P8R2_SOURCE event class has a 30–40% better point-source sensitivity than the P7REP_CLEAN event class.

Pass 8 introduces an event type classification scheme that partitions events within a class according to their reconstruction quality. The event type classification is a generalization of the existing conversion type designation that identifies events converting in the Front or Back section of the tracker [49, 50]. Pass 8 defines eight new event type selections based on a sequence of energy-dependent cuts on the BDT variables that categorize the quality of the direction and energy reconstruction. Four event types categorize the quality of the directional reconstruction (PSF0 to PSF3), and another four do so for the energy reconstruction (EDISP0 to EDISP3). By construction, these selections partition the gamma-ray acceptance at each energy such that an event class will have approximately the same number of events belonging to the best PSF event types.

Our maximum likelihood analysis of the dSphs combines the four P8R2_SOURCE_V6 PSF event type partitions in a joint likelihood function. Although each partition contains approximately the same fraction of the total instrument acceptance, the angular resolution as measured by the 68% and 95% containment radii of the PSF is significantly better for events belonging to the best PSF event types. At 3.16 GeV the 68% (95%) containment radii of the inclination-angle-averaged PSF for the best and worst PSF event types (PSF3 and PSF0) is 0.17° (0.35°) and 0.92° (2.3°). By combining the event types in a joint likelihood function, we weight the contribution of events within a class by their reconstruction quality, e.g., events with the least well-characterized direction (PSF0) are assigned the lowest weight when testing the hypothesis of a putative DM source. We estimate that splitting the event sample by event type improves the sensitivity to an isolated point source by 10%. We expect that larger sensitivity gains will occur in regions where the gamma-ray intensity is strongly non-uniform.

Given these improvements, along with two additional years of data, our flux constraints are expected to improve by a factor of ∼1.7 below 10 GeV and ∼2.2 above 100 GeV relative to the analysis of Ackermann et al. [13]. Although both the Pass 7 and Pass 8 analyses yield limits on the DM annihilation cross section within their respective 95% sensitivity bands, their constraints differ by a factor that is appreciably larger than expected from the median experimental sensitivities. For the bb channel, the Pass 8 constraints are ∼5 times lower at 100 GeV. For two independent data sets, statistical fluctuations can easily account for the difference in limit realizations.

We find that, at a given energy, only 20–30% of events in the six-year Pass 8 SOURCE-class data set are shared with the four-year Pass 7 Reprocessed CLEAN-class data set. Figure 3 shows this fraction of shared events as a function of energy. This relatively small event overlap comes from both the increased number of events in the Pass 8 data set, and the fact that the reconstructed characteristics of individual events have changed. Many events that were in the Pass 7 data set now lie outside the ROIs, below the energy threshold, or no longer pass our photon event selection. Changes in the reconstructed energy and direction of shared events also contribute to the statistical independence of the two analyses.

Using the fractional overlap, we can estimate the evolution of a background fluctuation between analyses. For example, the largest Pass 7 excess occurred for the bb channel at masses between 10 and 25 GeV, and had a local significance of ~3σ. If we assume this excess resulted from an upward fluctuation of the background, the addition of new data is likely to reduce its significance. Quantitatively, we expect the significance to drop by a factor that depends only on the intrinsic fraction of shared events, $f_e$, and the ratio of observation times $t_1/t_2$.

$$f_\sigma \approx f_e \sqrt{t_1/t_2}. \tag{1}$$

where the intrinsic fraction is related to the observed fraction ($f_{obs}$) by $f_e \approx f_{obs}(t_2/t_1)$. In the energy range between 1 and 10 GeV, the Pass 8 analysis shares ~30% of its events with Pass 7 and has a 50% longer observation period corresponding to an intrinsic shared fraction of ~45%. In that case, a 3σ background fluctuation should drop to ~1.1σ, which is consistent with our observations.
FIG. 3. Fraction of events in the 6 yr. Pass 8 SOURCE data set that are also in the 4 yr. Pass 7 CLEAN data set. Each set is comprised of events within the $10^6 \times 10^6$ ROIs surrounding the same 15 dSphs.

**Statistical Methodology**

We use a maximum likelihood-based statistical formalism [51] to test the DM signal hypothesis and derive confidence intervals on $\langle \sigma v \rangle$. Our global likelihood function for $\langle \sigma v \rangle$ is constructed from the product of likelihood functions for individual dSphs in our sample. We compute the profile likelihood function for $\langle \sigma v \rangle$ by maximizing the global likelihood function with respect to the nuisance parameters for each dSph ($\theta_i = \{\alpha_i, J_i\}$):

$$
\lambda(\langle \sigma v \rangle, m_{DM}) = \prod_i \tilde{L}_i(\langle \sigma v \rangle, m_{DM}, \hat{\theta}_i(\langle \sigma v \rangle, m_{DM}) | D_i).
$$

(2)

Confidence intervals on $\langle \sigma v \rangle$ are calculated 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 [52].

Among the nuisance parameters in Equation (2), we distinguish between parameters constrained by the gamma-ray data ($\alpha$) and the J-factors ($J$), which are constrained by an independent analysis of stellar kinematics. We use J-factors derived from a two-level Bayesian hierarchical modeling analysis that incorporates information on both stellar kinematics and priors on the distribution of global dSph properties [8]. For each dSph the Bayesian analysis provides a posterior distribution function, $P(J_i)$, which we approximate with a log-normal distribution with central value, $J_{\text{obs},i}$, and uncertainty, $\sigma_i$.

Following the approach developed in Ackermann et al. [10, 13], we account for statistical uncertainty on the J-factor by multiplying the LAT likelihood function with a J-factor likelihood function, $L_J(J_i | J_{\text{obs},i}, \sigma_i)$. We construct an ansatz for the J-factor likelihood function by equating the sampling distribution of $J_{\text{obs},i}$ with $P(J_i)$. With this underlying assumption, the likelihood function is given by a log-normal distribution with central value $J_{\text{obs},i}$ and width $\sigma_i$,

$$
L_J(J_i | J_{\text{obs},i}, \sigma_i) = \frac{1}{\ln(10)J_{\text{obs},i} \sqrt{2\pi\sigma_i}} e^{-\left(\log_{10}(J_i) - \log_{10}(J_{\text{obs},i})\right)^2/2\sigma_i^2}.
$$

(3)

We note that Ackermann et al. [10, 13] used a different form for the J-factor likelihood function with $L_J(J_i | J_{\text{obs},i}, \sigma_i) = P(J_i)$. The J-factor likelihood function used in this work differs in the substitution of nominal J-factor ($J_{\text{obs},i}$) for the true J-factor ($J_i$) in the denominator of Equation (3). The log-normal likelihood formulation has several advantages over the log-normal posterior used in Ackermann et al. [10, 13]. When interpreted as a sampling distribution for $J_{\text{obs},i}$, it is properly normalized for all values of $J_i$. The maximum likelihood estimator $\hat{J}_i$ for the J-factor also coincides with its nominal value $J_{\text{obs},i}$ from the stellar kinematic analysis.
To confirm that our upper limits have the correct frequentist statistical coverage we have performed a series of independent Monte Carlo realizations of our analysis in which we include a DM signal. In these simulations the true J-factors are fixed to their nominal values while the measured J-factors are randomized by sampling from a log-normal approximation to the J-factor posterior of each dSph. Figure 4 shows the upper limits on $\langle \sigma v \rangle$ from one set of realizations simulated with a $b\bar{b}$ annihilation spectrum and $m_{\text{DM}} = 25$ GeV. Under the assumption that the J-factor posterior is a good representation of the sampling distribution for J-factor measurements, we find that our statistical methodology produces the correct statistical coverage for a 95% CL upper limit.

**Hybrid Bayesian Analysis**

The main results of this work are evaluated with the delta-log-likelihood method, a fully frequentist statistical approach. In constructing the likelihood function of the delta-log-likelihood analysis, a central assumption is that the posterior distribution function is a good approximation to the J-factor sampling distribution. If this assumption holds, then our limits have the correct frequentist statistical coverage. To determine the robustness of our results to the choice of statistical methodology, we have performed an alternative analysis based on a Bayesian statistical approach in which we marginalize over the posterior distributions of the J-factors. For each target we use the same LAT likelihood function as for the primary analysis but set $L_J = P(J_i)$. We then eliminate the nuisance parameters in the gamma-ray analysis ($\alpha_i$) by profiling, and marginalize to eliminate the J-factors. The resulting one-dimensional
marginal posterior density is given by

$$\mathcal{P}(\langle \sigma v \rangle) = \frac{\int \prod_i \lambda_i(\langle \sigma v \rangle, m_{\text{DM}}, J_i) \pi(\langle \sigma v \rangle) d\sigma v}{\int \prod_i \lambda_i(\langle \sigma v \rangle, m_{\text{DM}}, J_i) \pi(\langle \sigma v \rangle) d\sigma v}$$

(4)

where $\pi(\langle \sigma v \rangle)$ is the prior for $\langle \sigma v \rangle$ and

$$\lambda_i(\langle \sigma v \rangle, m_{\text{DM}}, J_i) = \mathcal{L}_i(\langle \sigma v \rangle, m_{\text{DM}}, J_i, \hat{\alpha}_i(\langle \sigma v \rangle, m_{\text{DM}}, J_i)) \times \mathcal{P}(J_i)$$

(5)

is the profile likelihood for target $i$ maximized with respect to the ROI nuisance parameters ($\alpha_i$). Given the marginal posterior density of Equation (4), we derive an upper limit by finding the value $\langle \sigma v \rangle_{0}$ that satisfies

$$\int_{\langle \sigma v \rangle_{0}}^{\infty} \mathcal{P}(\langle \sigma v \rangle) d\sigma v = p$$

where we use $p = 0.05$ to define a Bayesian equivalent to the frequentist 95% CL upper limit.

An important consideration for the Bayesian analysis is the choice of the prior distribution, $\pi(\langle \sigma v \rangle)$, which is needed to evaluate the posterior density in Equation (4). In order to choose a prior that minimally influences our inference on $\langle \sigma v \rangle$, we consider the class of non-informative priors derived according to Jeffreys’ rule [53]. As two approximations to the Jeffreys’ prior for our likelihood, we take the Jeffreys’ prior for the mean of a Gaussian distribution of known width, the uniform prior with $\pi(\mu) = 1$, and the Jeffreys prior for a Poisson distribution, $\pi(\mu) = \mu^{-1/2}$, which we refer to here as the Poisson prior. The uniform prior should be applicable when the expected background is large relative to the signal and the LAT sensitivity is background-limited. In this regime the likelihood function of the LAT data given the model asymptotically approaches a Gaussian distribution. On the other hand, the Poisson prior is applicable when the expected background is negligible and the likelihood is well approximated by a Poisson distribution. For spectral models of WIMP annihilation through quark or lepton channels, the background- and signal-limited sensitivity regimes correspond to models of low and high mass, respectively.

Figure 5 compares limits for the $b\bar{b}$ channel calculated with the delta-log-likelihood and Bayesian analyses. In this comparison we calculate two sets of Bayesian upper limits using the $\langle \sigma v \rangle$ marginal posterior (Equation 4) and substituting the uniform and Poisson priors for $\pi(\langle \sigma v \rangle)$. We find that the Bayesian upper limits are in good agreement with the limits of the delta-log-likelihood analysis when the appropriate prior is chosen for the form of the likelihood on $\langle \sigma v \rangle$. For DM masses below 100 GeV where the likelihood is well approximated by a Gaussian, the limits from the Bayesian analysis with a uniform prior lie within 10% of those from the delta-log-likelihood analysis. At higher DM masses, a similar level of agreement (10–20%) is observed when comparing the delta-log-likelihood limits to the limits evaluated with the Poisson prior. We note that these changes are comparable to or smaller than the effect of the systematic uncertainties considered in the following sections. We conclude that our upper limits are robust to the choice of statistical methodology used to model the J-factor uncertainties.

**Systematic Uncertainties**

The dominant systematic uncertainties of this analysis arise from incomplete knowledge in three areas: the LAT instrument response, the Galactic diffuse gamma-ray background, and the distribution of DM in the dSphs. To estimate the impact of these uncertainties, we repeat our DM search using varying assumptions intended to encompass the range of possibilities in each of these areas. Below we address systematics associated with the IRFs and diffuse background model, which both affect constraints at the 10% level, with the latter becoming less relevant for hard DM spectra ($m_{\text{DM}} > 100\text{ GeV}$). Systematics associated with the J-factors are addressed in the following section, while here we quote the maximum deviation from our fiducial NFW model, which occurs when assuming a cored Burkert density profile [54],

$$\rho_{\text{DM}}(r) = \frac{\rho_{\text{NFW}}}{(r_s + r)(r_s + r)^2},$$

(6)

The J-factor systematic uncertainty has a greater impact than that of the IRF or diffuse models, approximately 35% at 100 GeV. We provide a summary of the systematic uncertainty as a function of DM mass and annihilation channel in Table II.

In addition to the standard model of interstellar gamma-ray emission for the LAT, we consider eight alternative models to sample a fairly wide range of possibilities for the diffuse gamma-ray background [55]. Although we can vary parameters within our background models, there are no doubt sources of gamma-ray emission that remain unmodeled. It was observed by Ackermann et al. [13] that the TS distribution from random blank sky locations
FIG. 5. Comparison of upper limits (b\bar{b} channel) for the combined analysis of 15 dSphs as derived with the delta-log-likelihood analysis (solid line) and the Bayesian analysis performed with a uniform (dashed line) and Poisson (dot-dashed line) prior. The lower panel shows the ratio of these curves to the limits for the delta-log-likelihood analysis.

deviated from statistical expectations, suggesting an incomplete background model. This indicated that a rescaling was necessary when converting from TS to significance, effectively lowering the sensitivity of the study. One large class of objects known to be unmodeled are sub-threshold point sources, i.e., those which contribute gamma rays but are not significant enough individually to be included in a catalog. It has been speculated that these give rise to the larger than expected rate of type I errors (false positives) that skew the TS distribution relative to the expectation from Poisson statistics [13, 56].

Figure 6 shows the distribution of TS obtained from the analysis of randomized ROIs when the data are analyzed using the 2FGL and 3FGL catalogs. We additionally analyze simulated ROIs with the 3FGL catalog using an input model for the simulations that includes 3FGL sources and our templates for the Galactic and isotropic diffuse backgrounds. Using the 3FGL, which roughly doubles the number of modeled sources, brings the TS distribution closer to the asymptotic expectation. However, a significant deviation with respect to the asymptotic expectation from Chernoff’s theorem is still observed, indicating that additional unmodeled components may still be present in the data.

The uncertainty in the LAT response is bracketed by using IRFs that are maximally and minimally sensitive to our signal. The maximally sensitive set has a greater effective area, narrower PSF, and accounts for dispersion in the reconstructed energy. The minimally sensitive IRFs are the opposite. The effective area is set at the boundaries of the envelope described in Ackermann et al. [47], while the energy dispersion and PSF width are scaled by ±5% and ±15%, respectively.

**J-factor Uncertainties**

We have described a statistical methodology to account for uncertainties on the J-factors when deriving limits on the DM annihilation cross section. This procedure captures statistical uncertainties on the J-factor arising from the analysis of stellar velocity dispersion data. As implemented in the likelihood, it is not intended to account for
TABLE II. Effect of systematic uncertainties for various WIMP masses and channels reported as a symmetrical relative deviation from the combined 95% CL upper limits.

| Channel | 10 GeV | 100 GeV | 1 TeV | 10 TeV |
|---------|--------|---------|-------|--------|
| $e^+e^-$ | IRFs 6% 10% 11% 11% | IRFs 6% 10% 11% 11% | IRFs 6% 10% 11% 11% |  |
|         | Diffuse 12% 6% 3% 2% | Diffuse 13% 6% 3% 2% | Diffuse 29% 32% 18% 16% |  |
|         | J-factor 29% 31% 17% 16% | J-factor 29% 31% 17% 16% | J-factor 29% 31% 17% 16% |  |
| $\mu^+\mu^-$ | IRFs 7% 9% 11% 11% | IRFs 7% 9% 11% 11% | IRFs 7% 9% 11% 11% |  |
|         | Diffuse 15% 6% 1% 1% | Diffuse 15% 6% 1% 1% | Diffuse 15% 6% 1% 1% |  |
|         | J-factor 24% 35% 15% 14% | J-factor 24% 35% 15% 14% | J-factor 24% 35% 15% 14% |  |
| $\tau^+\tau^-$ | IRFs 6% 7% 9% 10% | IRFs 6% 7% 9% 10% | IRFs 6% 7% 9% 10% |  |
|         | Diffuse 23% 12% 7% 4% | Diffuse 23% 12% 7% 4% | Diffuse 23% 12% 7% 4% |  |
|         | J-factor 16% 34% 31% 24% | J-factor 16% 34% 31% 24% | J-factor 16% 34% 31% 24% |  |
| $u\bar{u}$ | IRFs 6% 7% 9% 10% | IRFs 6% 7% 9% 10% | IRFs 6% 7% 9% 10% |  |
|         | Diffuse 23% 12% 7% 4% | Diffuse 23% 12% 7% 4% | Diffuse 23% 12% 7% 4% |  |
|         | J-factor 16% 34% 31% 24% | J-factor 16% 34% 31% 24% | J-factor 16% 34% 31% 24% |  |
| $b\bar{b}$ | IRFs 6% 7% 9% 11% | IRFs 6% 7% 9% 11% | IRFs 6% 7% 9% 11% |  |
|         | Diffuse 23% 12% 7% 4% | Diffuse 23% 12% 7% 4% | Diffuse 23% 12% 7% 4% |  |
|         | J-factor 16% 34% 31% 24% | J-factor 16% 34% 31% 24% | J-factor 16% 34% 31% 24% |  |
| $W^+W^-$ | IRFs 7% 10% 11% | IRFs 7% 10% 11% | IRFs 7% 10% 11% |  |
|         | Diffuse 13% 6% 2% | Diffuse 13% 6% 2% | Diffuse 13% 6% 2% |  |
|         | J-factor 32% 31% 17% | J-factor 32% 31% 17% | J-factor 32% 31% 17% |  |

additional systematic uncertainties. Such systematic uncertainties on the J-factor include parameterization of the DM profile and the choice of priors for the profile parameters. While previous studies have shown that the derived J-factors are robust against these systematic uncertainties for dSphs with large stellar data sets [57], it is nonetheless important to quantify their impact. To assess the impact of systematic uncertainties in the J-factor derivations, we examine a set of four alternative J-factors derived by various fitting methods.

The first set of alternative J-factors comes from the recent analysis of Geringer-Sameth et al. [9] assuming a generalized NFW profile with non-informative priors on its parameters. We also examine the J-factors derived by Charbonnier et al. [58] assuming a generalized Hernquist profile with uniform priors. Additionally, we perform our own alternative analysis following the procedure of Essig et al. [59] assuming a simple NFW profile with non-informative priors on the scale radius and scale density, and a velocity anisotropy parameter that is assumed to be constant with radius. Lastly, we show results derived from the multi-level modeling approach of Martinez [8] assuming a cored Burkert profile as presented in Ackermann et al. [13].

For each of these alternative sets of J-factors, we re-derive the limit on the DM annihilation cross section in the context of the LAT data. For cuspy spatial profiles, the spatial template of the DM distribution has little impact on the LAT analysis. Thus, for the first three sets of alternative J-factors we only alter the nominal J-factor and associated uncertainty. When assuming a Burkert profile, we use the full spatial profile of the assumed DM distribution (the change in spatial profile affects the limits by <5%). Since the analyses of Charbonnier et al. [58] and Geringer-Sameth et al. [9] do not include all of the dwarfs used in our analysis, when a dSph is missing from one of these data sets we assign it the nominal J-factor and uncertainty from Table I in the main text. When asymmetric errors are given for the best-fit J-factor, we use the geometric mean to set the width of the log-normal J-factor likelihood.

The resulting change in the upper limit on the DM cross section is shown in Figure 7. The mass dependence of the curves in Figure 7 reflects the fact that by changing the J-factors we change the relative importance of each dSph, leading to an interplay between the LAT data and the assumed J-factors. Unsurprisingly, the largest change in the upper limit comes from requiring a cored Burkert profile. This increases the upper limit by a factor of 20–40% with respect to the nominal limit (this is slightly larger than was observed by Ackermann et al. [13]) and is what we quote in Table II as the overall J-factor systematic uncertainty. The J-factors derived by Charbonnier et al. [58] and the alternative analysis with non-informative priors both yield slightly smaller changes in the limit. Finally, we observe that the J-factors from Geringer-Sameth et al. [9] are most similar to the nominal J-factors and result in differences of 5–10%.

The combined limits presented here include both classical and ultra-faint dSphs. Bayesian hierarchical modeling sets rather tight constraints on the J-factors of the ultra-faint dSphs as members of the dSph population; however, stellar kinematic data yield larger uncertainties on ultra-faint dSphs when analyzed individually. To assess the maximum impact of mis-modeling the ultra-faint dSphs, we split the dSph population into ultra-faint (Bootes I,
Canes Venatici II, Coma Berenices, Hercules, Leo IV, Segue 1, Ursa Major II, Willman 1) and classical (Carina, Draco, Fornax, Leo II, Sculptor, Sextans, Ursa Minor) galaxies. For soft annihilation spectra (e.g., the $b \bar{b}$ channel for DM with mass $< 100 \text{ GeV}$), the classical and ultra-faint populations yield comparable limits, each $\sim 40\%$ worse than the combined limit. For harder annihilation spectra with spectral energy distributions that peak above $10 \text{ GeV}$, the limits from the ultra-faint population are roughly comparable to the combined limits, while the classical dSphs yield limits up to five times weaker. Considering only the classical dSphs, models with the thermal relic cross section are excluded for slightly lower masses ($\lesssim 80 \text{ GeV}$).

### Annihilation Channels

WIMPs may annihilate through a variety of Standard Model channels. For the quark and boson channels, the resulting gamma-ray spectra are all similar and largely depend on $m_\text{DM}$. The three leptonic channels have harder spectral energy distributions with a peak in energy flux that is closer to $m_\text{DM}$. We perform our analysis for six representative annihilation channels ($b \bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $e^+e^-$, $W^+W^-$, and $u\bar{u}$) and for each we assume a 100% branching fraction. The resulting constraints, shown in Figure 8, are similar to the $b \bar{b}$ and $\tau^+\tau^-$ channels depicted in the main body of this work, except for the $e^+e^-$ and $\mu^+\mu^-$ channels which are somewhat higher.
FIG. 7. Change in the limits derived for the DM annihilation cross section under the assumption of alternative sets of J-factors. Alternative J-factors are taken from Geringer-Sameth et al. [9] and Charbonnier et al. [58]. Non-informative priors are used to derive J-factors following the procedure of Essig et al. [59]. Burkert J-factors are derived using the multi-level modeling approach of Martinez [8] and are taken from Ackermann et al. [13].
FIG. 8. DM annihilation cross-section constraints derived from the combined 15-dSph analysis for various channels.