Expectation on LHAASO sensitivity to decaying dark matter signatures from dwarf galaxies gamma-ray emission

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As a next-generation complex extensive air shower array with a large field of view (FOV), the Large High Altitude Air Shower Observatory (LHAASO) would be very sensitive to the 300 GeV – 1 PeV gamma rays. Dwarf spheroidal satellite galaxies (dSphs) are some of the most DM dominated objects and the ideal laboratory for dark matter (DM) indirect detection. LHAASO will become a promising project to search for the gamma-ray signatures induced by heavy DM particles in the dSphs. In this paper, we make a forecast for the LHAASO sensitivity to the gamma-ray signatures of decaying DM particles from 19 dSphs within the LHAASO FOV. We make a joint likelihood analysis for the overall 19 dSphs and also take the uncertainties of dSphs’ spatial DM distribution into consideration. We find that the LHAASO sensitivity to the DM decay lifetime will reach $O(10^{26}\text{s})$ – $O(10^{28}\text{s})$ for several decay channels at the mass scale from 1 TeV to 100 TeV.

I. INTRODUCTION

Cosmological constant $\Lambda$ plus cold dark matter (DM) paradigm has made many far-reaching predictions about the composition of Universe. Lots of compelling observational evidence has been accumulated to account for the presence of DM. DM should be neutral, non-baryonic and cold, and constitute nearly 84% of the total matter in the universe [1]. However, little is known about the DM microscopic properties as an elementary particle. In order to understand the particle nature of DM, many new physics models have been proposed in the literature [2], of which the Weakly Interacting Massive Particles (WIMPs) are the most attractive candidates.

WIMPs could either decay or self-annihilate into steady Standard Model (SM) particles through some weak interactions, such as gamma rays, neutrinos, and anti-matter particles. One kind of the DM identifications, namely indirect detection, is just to search for such high energy signals. In particular, the gamma ray signal is a powerful probe to reveal the properties of DM, because its simple propagation process with small energy loss. Among the sources with high DM densities, dwarf Spheroidal galaxies (dSphs) are the most promising targets to search for the gamma-ray signatures from DM [3–5]. These sources are relatively nearby, highly dark matter dominated with large order of magnitude of mass-to-light ratios $O(10 - 100)$, and almost free of astrophysical backgrounds [6, 7]. With these outstanding advantages, dSphs would offer the cleanest DM signals compared with other objects.

Currently, the Gamma Ray astronomy above tens of TeV remains almost completely unexplored, since the past and present telescopes are only able to record few photons in this energy range. Most of the results for the very high energy (VHE, $>100$ GeV) gamma-ray astronomy to date are mainly obtained from the observation of imaging atmospheric cherenkov telescopes. But these sensitive instruments usually have a small field-of-view (FOV) and short operation duty.

A strong interest to the VHE gamma-ray astronomy is aroused to the development of next-generation instruments, which are able to make more sensitive observations with a larger FOV in a more extended energy region. This interest brought on the ambitious under-construction project Large High Altitude Air Shower Observatory (LHAASO), which will cover the energy range from $\sim 300$ GeV to 1 PeV [8]. Remarkably, the design concept of LHAASO is to make this continuously-operated instrument extremely competitive for the gamma-ray observation in the energy range above tens of TeV. Therefore, through the VHE gamma-ray observation from dSphs by LHAASO, it is compelling to
search for the DM signatures and set strong limits on the properties of heavy DM.

In Ref. [9], we have investigated the expected sensitivity of LHAASO project to the gamma-ray signals induced by annihilating DM in 19 dSphs. Although it is natural to assume that the DM particles are absolutely stable, this assumption is not necessary. Actually, the current cosmological and astrophysical observations only require that the DM particles should be very long-lived rather than absolutely stable, with a finite lifetime much longer than the age of the Universe about $13.8 \text{ Gyr} = 4.56 \times 10^{17}$ s. This long lifetime can be achieved by some interactions at high energy scales; the relevant signatures may be detectable by indirect detection experiments (see, e.g. Refs. [10–14] and references therein). Thus, the LHAASO gamma ray observation of dSphs can also be used to impose stringent bounds on the lifetime of decaying DM.

In this work, as a further step along this line, we perform a forecast of the LHAASO sensitivity to the lifetime of decaying DM using the mimic observation of VHE gamma rays for nineteen dSphs within the LHAASO FOV. In the analysis, we take the statistic uncertainties of 19 dSphs into account [15–17]. In order to derive a reasonable sensitivity, the simulated data of LHAASO considering the background rejection power are utilized.

This paper is organized as follows. In Sec. II, we introduce the calculation of the gamma-ray flux from DM decay. In Sec. III, we show the LHAASO sensitivities and make comparison with other experimental results. Finally, the conclusion is given in Sec. IV.

II. GAMMA-RAY SIGNALS FROM DM DECAY IN DSPHS

For the decaying DM particles, the expected gamma-ray integral flux arising from DM decay in a dSph (point-like source) is described by

$$\Phi = \frac{1}{4\pi} \frac{1}{m_\chi} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_{\gamma}}{dE_{\gamma}} dE_{\gamma} \times D,$$

where $m_\chi$ is the mass of DM particles, $\tau$ is the decay lifetime of DM particles, the integration is performed over each energy bin between $E_{\text{min}}$ and $E_{\text{max}}$, and $\frac{dN_{\gamma}}{dE_{\gamma}}$ stands for the gamma-ray differential energy spectrum resulting from the decay of a DM particle via a certain final state channel. In this work, we derive $\frac{dN_{\gamma}}{dE_{\gamma}}$ with the utilization of PPPC4DM package [18, 19].

In Eq. (1), the astrophysical factor “$D$-factor” is an integral of the DM density along the line of sight (l.o.s) distance $x$ in the region of interest

$$D = \int_{\text{source}} d\Omega \int_{\text{l.o.s}} dx \rho(r(\theta, x)), \quad (2)$$

where the solid angle $\Omega$ varies in the observed regions with various integration angle $\Delta\Omega = 2\pi \times [1 - \cos \alpha_{\text{int}}]$ and the $\rho(r)$ describes the DM density profile of the astrophysical system varying with the distance $r$ from its center.

In this analysis, we also take the statistical uncertainty of the $D$-factor into account using the method of Refs. [20, 21]. The likelihood in all the energy bins for one dSph is given by

$$L_j = \prod_i L_{ij}(S_{ij}, B_{ij}, N_{ij}) \times \frac{e^{-[\log_{10}(D_{ij}) - \log_{10}(D_{\text{obs}, j})]^2/2\sigma_j^2}}{\ln(10)D_{\text{obs}, j}\sqrt{2\pi}\sigma_j}, \quad (3)$$

where $L_{ij}$ is the likelihood for the $i$-th energy bin and the $j$-th dSph, which is taken to be the Poisson distribution. Here, $\log_{10}(D_{\text{obs}, j})$ and $\sigma_j$ denote the mean value and corresponding standard deviation of the $D$-factor, respectively. For given $\tau$ and $m_\chi$, $\log_{10}(D_j)$ is taken to be the value maximizing the likelihood $L_j$.

The DM density profile of dSphs can be obtained by the kinematic observation of stellar velocities through the use of the Jeans equation (see e.g. Refs. [22–24]). We take the calculated mean values of $D$-factor and their statistical uncertainties of 19 dSphs in Table I from Refs. [15–17].

In the literature, two sets of the $D$-factors depending on two choices of the integration angle are provided. One set is calculated within a constant integration angle, e.g. $\alpha_{\text{int}} = 0.5^\circ$. The other set is derived within the maximum angular radius of each source $\theta_{\text{max}} = \arcsin(r_{\text{max}}/d)$, where $r_{\text{max}}$ is an estimate of distance from the dSph’s center to the outermost member star and $d$ is the distance from the Earth to source. In general, the DM particles tend to contribute the signals from the vicinity of the source center due to the density profile, while the angle distribution of background resulting from cosmic rays is almost flat. In order to achieve a larger signal-to-background ratio, we choose the $D$-factor integrated over a smaller angle region with $\alpha_{\text{int}} = \min\{\theta_{\text{max}}, 0.5^\circ\}$. 
backgrounds and photon signals can be distinguished LHAASO and produce Cherenkov lights. The hadronic
impinge on the water Cherenkov detectors (WCDs) of Subsequently, these secondary particles from EAS would
netic and hadron cascades, collectively known as EAS. For further details about the LHAASO exper-
impulse from 19 selected dSphs with large D-factors and θmax of the dSphs are taken from Ref. [15]. However, for the four dSphs
marked with asterisks whose D-factors are not given in Ref. [15], we utilize the calculated results from Ref. [16] for Draco II, Pisces II, Willman I and from Ref. [17] for Triangulum II, respectively.

| Source        | RA       | DEC      | Distance | r_{eff} | θ_{max} | \log_{10} D_{obs} |
|---------------|----------|----------|----------|---------|---------|------------------|
| Boötes I      | 210.02   | 14.50    | 66       | 0.352   | 0.47    | 17.9 ± 0.2       |
| Canes Venatici I | 202.02   | 33.56    | 218      | 0.308   | 0.53    | 17.6 ± 0.5       |
| Canes Venatici II | 194.29   | 34.32    | 160      | 0.399   | 0.13    | 17.0 ± 0.2       |
| Coma Berenices | 180.74   | 23.90    | 4        | 0.377   | 0.31    | 18.0 ± 0.2       |
| Draco          | 260.05   | 57.92    | 76       | 0.442   | 1.30    | 18.5 ± 0.1       |
| Draco II*      | 238.20   | 64.56    | 24       | 0.451   | –       | 18.0 ± 0.9       |
| Hercules       | 247.76   | 12.79    | 132      | 0.348   | 0.28    | 16.7 ± 0.4       |
| Leo I          | 152.12   | 12.30    | 254      | 0.346   | 0.45    | 17.9 ± 0.2       |
| Leo II         | 168.37   | 22.15    | 233      | 0.372   | 0.23    | 17.2 ± 0.4       |
| Leo IV         | 173.23   | –0.54    | 154      | 0.303   | 0.16    | 16.1 ± 0.9       |
| Leo V          | 172.79   | 2.22     | 178      | 0.314   | 0.07    | 15.9 ± 0.5       |
| Pisces II*     | 344.63   | 5.95     | 182      | 0.327   | –       | 17.0 ± 0.6       |
| Segue 1        | 151.77   | 16.08    | 23       | 0.357   | 0.35    | 18.0 ± 0.3       |
| Sextans        | 153.26   | –1.61    | 86       | 0.299   | 1.70    | 17.9 ± 0.2       |
| Triangulum II* | 33.32    | 36.18    | 30       | 0.403   | –       | 18.4 ± 0.8       |
| Ursa Major I   | 158.71   | 51.92    | 97       | 0.432   | 0.43    | 17.6 ± 0.3       |
| Ursa Major II  | 132.87   | 63.13    | 32       | 0.449   | 0.53    | 18.4 ± 0.3       |
| Ursa Minor     | 227.28   | 67.23    | 76       | 0.455   | 1.37    | 18.0 ± 0.1       |
| Willman 1*     | 162.34   | 51.05    | 38       | 0.430   | –       | 18.5 ± 0.6       |

III. LHAASO SENSITIVITIES TO THE DM LIFETIME

The LHAASO experiment is is being built at HaiZi Mountain (4410 m a.s.l.) near Daoceng in Sichuan province, China. It is a complex extensive air shower (EAS) array and consists of three sub-arrays: the square kilometer particle detector array (KM2A), the Water Cherenkov Detector Array (WCDA), and the Wide Field Cherenkov Telescope Array (WFCTA). The relevant arrays for the gamma-ray detection are WCDA and KM2A, which are designed for photons with the energies approximately from 100 GeV to 20 TeV and above 20 TeV, respectively. For further details about the LHAASO experiment, we refer the reader to Refs. [25, 26].

When VHE gamma rays and cosmic ray nuclei enter the atmosphere, they interact with the atmospheric nuclei and then separately bring about the electromagnetic and hadron cascades, collectively known as EAS. Subsequently, these secondary particles from EAS would impinge on the water Cherenkov detectors (WCDs) of LHAASO and produce Cherenkov lights. The hadronic backgrounds and photon signals can be distinguished in light of their different energy distributions deposited across the WCDs. An electromagnetic cascade shower typically has a smoother distribution across WCDs whereas a hadronic cascade shower has a clumped distribution. In addition, for the gamma rays above 10 TeV, the measurement of muon component in the showers by the muon detectors of KM2A can further allow a more efficient hadronic background rejection.

We investigate the LHAASO sensitivity to the DM decay signals from 19 selected dSphs with large D factors as shown in Table I. In comparison with the research of HAWC [3], in this analysis we consider four more dSphs due to the larger FOV of LHAASO (defined in the declination range −11° < δ < 69°), including Draco II, Leo V, Pisces II, and Willman 1. For each dSph, we perform a series of simulated observations under the null hypothesis and then calculate the likelihood described in Eq. 3. The further details of the analysis are provided in Appendix. A, which are similar to our previous work [9]. Subsequently, we can derive the 95% sensitivity to the DM lifetime τ by decreasing the likelihood by 2.71/2 from its maximum for the given DM mass in each mimetic observation, assuming a χ²-distributed test statistic [27].

In Fig. 1, we show the LHAASO sensitivities to the DM decay lifetime τ for the individual dSph in a ran-
FIG. 1. The projected sensitivities to the DM lifetime $\tau$ at 95% confidence level for nineteen dSphs within the LHAASO FOV of one year for the $b\bar{b}$, $t\bar{t}$, $\mu^+\mu^-$, $\tau^+\tau^-$, $W^+W^-$ decay channels. The solid red line represents the combined sensitivity resulting from a joint likelihood analysis, considering the observations of all dSphs.
FIG. 2. The LHAASO expected median combined sensitivities (red solid lines), and related two-sided 68% (yellow bands) and 95% (green bands) containment bands of one year for the $b\bar{b}$, $t\bar{t}$, $\mu^+\mu^-$, $\tau^+\tau^-$, and $W^+W^-$ decay channels. The HAWC combined dSph limit [3], Fermi-LAT combined dSph limit [4] and VERITAS Segue 1 limit [5] are also shown for comparison.
domly selected mimic observation. Here, we consider five typical DM decay channels, including $b\bar{b}$, $t\bar{t}$, $\mu^+\mu^-$, $\tau^+\tau^-$, and $W^+W^-$. In this figure, we also show the LHAASO sensitivities from a combined analysis for all the selected dSphs using a joint likelihood $L_{\text{tot}} = \prod_j L_j$. We find that the combined sensitivity is dominated by the influence of two dSphs with large $D$-factors and favorable locations inside the LHAASO FOV, namely Draco and Ursa Major II. Although Triangulum II and Willman 1 have almost the largest $D$-factors among all the selected dSphs and Triangulum II is also close to the center of LHAASO FOV, they are not utterly dominant over the combined sensitivity. The reason is that the statistical uncertainty of the $D$-factors of these two dSphs are considerably large owing to the lack of kinematic observational data. Containing the uncertainty of the $D$-factor into the likelihood stacked analysis would largely loosen the sensitivity to the gamma-ray signals from dSphs. On the other hand, although some dSphs have relatively large $D$-factors with small uncertainties, they are close to the edge of LHAASO FOV. Consequently, LHAASO is not sensitive enough to detect the signals from these dSphs.

Since there are statistic fluctuations in each particular mimic observation, we perform 500 mimic observations under the null hypothesis to include this containment in the final results. We show the median combined sensitivities of LHAASO and the related two-sided 68% and 95% containment bands for five decay channels in Fig. 2. For comparison, the lower limits on the DM lifetime from other three gamma-ray observations, including the HAWC combined dSphs limit [3], Fermi-LAT combined dSphs limit [4], and VERITAS Segue 1 limit [5], are also shown.

In Fig. 2, we can clearly see that the LHAASO sensitivities are better than the current experimental limits for the DM masses $m_\chi$ approximately larger than 10 TeV and can reach $\tau \sim \mathcal{O}(10^{27})$ s for almost all the channels. For the hadronic channels, such as the $b\bar{b}$ channel, the initial photon spectra are soft. Thus, the Fermi-LAT dSph observations place the most stringent limits up to $m_\chi \approx 10$ TeV, due to their pretty good sensitivities to low-energy gamma rays. For the DM masses below 10 TeV, since we impose a cut on the observed photon energies $E > 0.7$ TeV that is in consistent with the public LHAASO simulation results, the expected LHAASO sensitivities in this energy region are not good enough compared with the current limits. Nevertheless, for the masses above 10 TeV, LHAASO could become more sensitive for these channels through the excellent observation of VHE photons. What’s more, for the $W^+W^-$ channel, LHAASO behaves as the most sensitive experiment compared with the limits set by other experiments at the masses above approximately 3 TeV. With regard to the $\mu^+\mu^-$ and $\tau^+\tau^-$ channels, LHAASO has the great sensitivities for almost all the DM masses above $\sim 1$ TeV. Therefore, we can conclude that LHAASO will become a powerful tool to study the property of the decaying heavy DM particles at the mass scale above $\mathcal{O}$(TeV).

We also find that, although including the statistical uncertainties of $D$ factors in our analysis would loosen the LHAASO sensitivity, the expected combined sensitivities are still better than the limits set by HAWC by a factor of $8 \sim 10$. As shown in Ref. [9], however, the LHAASO sensitivities to the DM annihilation cross section are only stronger than the HAWC limits by a factor of $2 \sim 5$. Obviously, the improvement for DM decay is even much more significant than the case of DM annihilation.

Next, we shall discuss the potential reasons for this issue. In Fig. 1, we can clearly see that the combined sensitivity is in particular dominated by the high-latitude sources, such as Draco and Ursa Major II. For these sources, the LHAASO sensitivities would be significantly stronger than HAWC by 1 $\sim$ 2 orders of magnitude. This is due to the fact that LHAASO is located at a higher latitude of $\sim 29^\circ$ in comparison with HAWC which is located at the latitude of $\sim 19^\circ$. The dSphs at high-latitudes such as Draco and Ursa Major II are located near the edge of the HAWC FOV so that HAWC is sensitive to them. However, these sources could still contribute significant signals in the LHAASO FOV. In addition, LHAASO has a larger effective area and a better ability of gamma-proton discrimination in comparison with HAWC. Taking all these issues into consideration, the LHAASO sensitivities to the DM decay lifetime are conceivable to be higher than the constraints from HAWC by a factor of $8 \sim 10$.

IV. CONCLUSION

In this paper, we investigate the LHAASO sensitivity to the lifetime of the decaying DM particles for five decay channels through the gamma-ray observation of 19 dSphs. We calculate the individual sensitivities for each dSph within the LHAASO FOV using a likelihood ratio analysis method. The statistical uncertainties of the
$D$-factor are also incorporated as a nuisance parameter in the likelihood formulation in order to make the analysis more comprehensive and reliable. In addition, we also calculate the LHAASO combined sensitivity from a stacked likelihood analysis for all the dSphs so as to enhance the statistical power in the calculation, which is the first simulated sensitivity to the decay lifetime of heavy DM particles.

Our results manifest that the combined sensitivity is mainly dominated by the influence of two dSphs with large $D$-factors and high latitudes, namely the Draco and the Ursa Major II. Moreover, we also make a comparison for the LHAASO sensitivities with the results from other current experimental observations (i.e., Fermi-LAT, HAWC, and VERITAS). We find that the LHAASO sensitivities are better than the current limits for the DM masses above approximately 3, and 10 TeV for the $W^+W^-$ and $b\bar{b}$ channels, respectively. For the $t\bar{t}$, $\mu^+\mu^-$ and $\tau^+\tau^-$ channels, LHAASO has great sensitivities in the large mass range from 1 TeV to 100 TeV. All in all, we can conclude that the gamma-ray researches from the observation of dSphs by LHAASO would be a compelling and promising approach for probing the physics of dark matter decay.

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Appendix A: Expected event counts at LHAASO

We perform a series of mimic observations so as to derive the expected LHAASO sensitivities to the DM decaying signals. First, we estimate the expected background counts $B$ induced by cosmic ray nuclei. Second, we perform a Gaussian sampling around $B$ to obtain the observational event counts $N$ in each mimic observation.

As the energy resolution of WCDA varies from 30% to 100% with the decreasing energy, for the sake of alleviating the systematic errors induced by the reconstructed energy dispersion, in this work we adopt some wide energy bins with $E_{\text{max}}/E_{\text{min}} = 3$. The background counts $B$ in one energy bin can be estimated by

$$B = \zeta_{cr} \int_{E_{\text{min}}}^{E_{\text{max}}} \int_0^T \Phi_p(E) \cdot A_{\text{eff}}^p(E, \theta_{\text{zen}}(t)) \cdot \varepsilon_p(E) \, dt \, d\Omega \, dE,$$

where $\Phi_p(E)$ is the primary proton flux in cosmic rays, which is described by a single power-law and best-fitted by the observational datasets of the experiments ATIC [28], CREAM [29], and RUNJOB [30]. The integration is performed within a cone of $\Delta \Omega = 2\pi \times [1 - \cos(\max\{\alpha_{\text{int}}, \theta_c\})]$, in which $\theta_c$ is the energy dependent angular resolution of LHAASO, varying from 2° to 0.1° with the increased photon energy [8]. Here, we also introduce a scale factor $\zeta_{cr} = 1.1$ to include the contributions of the rest nuclei in the primary cosmic rays.

The expected signal event counts $S$ in one energy bin is calculated by

$$S = \epsilon_{\Delta \Omega} \int_{E_{\text{min}}}^{E_{\text{max}}} \int_0^T \Phi_\gamma(E) \cdot A_{\text{eff}}^\gamma(E, \theta_{\text{zen}}(t)) \cdot \varepsilon_{\gamma}(E) \, dt \, d\Omega \, dE,$$

where $\epsilon_{\Delta \Omega} = 0.68$ is the fraction of observed photons within the experimental angular resolution.

The effective area $A_{\text{eff}}^\gamma$ of LHAASO is obtained by an interpolation calculation in the LHAASO Science White Paper [8], which is the function of energy and zenith angle. Moreover, the zenith angle $\theta_{\text{zen}}$ is also a function of the observation time $t$. DsPhs at different declinations are expected to accompany with different $\theta_{\text{zen}}(t)$ functions, which would lead to different visibilities. The total observational time of LHAASO is taken to be one year. In order to briefly reflect the visibility, we show the effective time ratio $r_{\text{eff}}$ in Table I, which is indicated by the proportion of effective observation time during which the corresponding zenith angle $\theta_{\text{zen}}$ is smaller than 60°.

With regard to the survival ratios $\varepsilon$ for various kind of particles after the selection, Ref. [31] has provided a detailed analysis for the working efficiencies of WCDA in discriminating the gamma signals from the hadronic background. They found that for the energies above 0.6 TeV, the survival rate of the proton $\varepsilon_p$ can be suppressed from 0.03% to 0.11% with the increasing energy, while the survival rate of the gamma $\varepsilon_\gamma$ is approximately to be 50%. In this paper, we adopt a more conservative gamma-proton discrimination as $\varepsilon_p \sim 0.28\%$ with $\varepsilon_\gamma \sim 40.13\%$. 


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