Using gamma-ray observation of dwarf spheroidal galaxy to test a dark matter model that can interpret the W-boson mass anomaly

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A recent result from Fermilab suggests that the measured W-boson mass deviates from the prediction of the Standard Model with a significance of > 7σ, and there may exist new physics beyond the SM. It is proposed that the inert two Higgs doublet model (i2HDM) can well explain the new W-boson mass. The preferred dark matter mass is between 54 and 74 GeV. More interestingly, it is found that part of the parameter space of this model can explain both the Galactic center GeV gamma-ray excess detected by Fermi-LAT and the GeV antiproton excess detected by AMS-02 through a $SS \rightarrow WW^*$ annihilation. In this paper, we aim to test this model using the Fermi-LAT observation of Milky Way dwarf spheroidal (dSph) galaxy. We mainly focus on the four nearest confirmed dSphs, which are among the dSphs with the largest J-factors. We find that our constraints are above the favored parameters and can not exclude such a model, suggesting i2HDM is a promising model that can interpret the W-boson mass anomaly, GeV excess, and antiproton excess.

I. INTRODUCTION

The presence of dark matter (DM) particles in the universe is supported by many astrophysical observations. Latest observation results show that non-baryonic cold DM contributes ~ 84% of the matter density of the Universe [1]. However, the particle nature of the DM is still unknown. The most promising DM candidate models are weakly interacting massive particles (WIMPs). WIMPs can produce γ-ray or cosmic-ray signals through annihilating or decaying into Standard Model (SM) particles [2–6], which provide a possible approach for probing DM particles. With the astrophysical instruments such as the Fermi Large Area Telescope (Fermi-LAT [7]) and the Dark Matter Particle Explorer (DAMPE [8, 9]), a lot of efforts have been made to search for WIMP DM.

The CDF collaboration recently reported an exciting progress in physics, providing an informative hint for the study of DM. They reported their newly measured W-boson mass $m_W = 80.4335 \pm 0.0094$ GeV [10], which deviates from the prediction of the standard model (SM) by 7σ. Such a large discrepancy provides strong evidence of the presence of new physics. Ref. [11] proposed that the inert two Higgs doublet model (i2HDM) can interpret the new W-boson mass without violating other astrophysical/experimental constraints. More intriguingly, in this model the DM annihilation through $SS \rightarrow b\bar{b}$ and $SS \rightarrow WW^*$ channel will produce antiprotons and gamma rays [11, 12], and can simultaneously explain the Galactic center (GC) GeV excess [13–19] and antiproton excess signals [20, 21]. The consistency of the DM particle properties required to account for the three anomaly signals suggest a common origin of them.

The kinematic observations show that the dSph is a DM-dominated system. Besides the GC, the dSph is another most promising target for indirect detection of DM due to their vicinity and low gamma-ray background[22–24]. Previously, based on the non-detection of robust gamma-ray signal in the direction of dSphs, people have set very strong constraints on the mass $m_\chi$ and the annihilation cross section $\langle\sigma v \rangle$ of the particle DM [25–32]. In this work, we aims to test the i2HDM model with the Fermi-LAT observation of the Galactic dwarf spheroidal (dSph) galaxies. We only consider the dSphs at distances ≤ 50 kpc. To reduce the uncertainty, we also limit our sample to include those sources having kinematic measurements. The 4 dSphs used for analysis are listed in Table I.

II. SEARCHING FOR DARK MATTER EMISSION FROM THE DSHPS

We use thirteen years (i.e. from 2008 October 27 to 2021 October 27) of Fermi-LAT Pass 8 data in 500 MeV to 300 GeV. To remove the Earth’s limb emission, we use only the γ events with zenith angle < 100°. Meanwhile, the quality-filter cuts (DATA_QUAL==1 & LAT_CONFIG==1) are applied to ensure the data valid for scientific analysis. We take $5^\circ \times 5^\circ$ region of interest (ROI) for each target to perform a binned analysis. The latest version of Fermitools is used to analyze the Fermi-LAT data. To model the background, we consider

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all 4FGL-DR3 sources \(^1\) within 10° circle region centered on each target and two diffuse models (the Galactic diffuse gamma-ray emission \texttt{gll_iem_v07.fits} and the isotropic component \texttt{iso_P8R3_SOURCE_V3_v1.txt}). We model all 4 dSphs as point-like sources.

We first perform a standard binned likelihood analysis \(^2\) to obtain the best-fit background model. During the fit, the parameters of all 4FGL-DR3 sources within ROI, together with the re-scale factor of the two diffuse components are set free. Based on the best-fit background, we search for gamma-ray emission from the dSphs and derive the TS values and flux upper limits of the targets. The test statistic (TS) is defined as

\[ TS = -2 \ln \left( \frac{L_{\text{bkg}}}{L_{\text{dsph}}} \right) \]  

where \(L_{\text{bkg}}\) and \(L_{\text{dsph}}\) are the best-fit likelihood values for the background-only model and the model containing a putative dSph, respectively. The significance is roughly \(\sqrt{TS}\). To obtain energy-dependent flux upper limits, we divide the whole energy range of 500 MeV – 300 GeV into 20 logarithmically-spaced energy bins. For each energy bin, the background sources are fixed and a power-law spectral model \(\frac{dN}{dE} \propto E^{-\Gamma}\) with \(\Gamma = 2\) \(^3\) is used to model the putative dSph source. The energy-dependent flux upper limits are shown in Figure 1.

We also perform a stacking analysis of the 4 dSphs. The stacking analysis can give a better sensitivity of the analysis by merging the observations of multiple sources. We sum the data (i.e. the count cubes in the analysis) of 4 sources together. The likelihood is evaluated by

\[ \ln L = \sum_i N_i \ln M_i - M_i - \ln N_i! \]  

(1)

where \(M_i\) and \(N_i\) is the model-expected counts and observed counts in each pixel, respectively; and the index \(i\) runs over all energy and spatial bins. The \(M_i\) is obtained using \texttt{gtmodel} in \texttt{Fermitool} software. For our stacking analysis, \(M_i = \sum_k m_{i,k}\) and \(N_i = \sum_k n_{i,k}\) with index \(k\) summing over 4 sources. We get the upper limits at 95% confidence level of flux when \(\ln L\) changing by 1.35. Note that the method used here is not the

\(^1\) \url{https://fermi.gsfc.nasa.gov/ssc/data/access/lat/10yr_catalog/}

\(^2\) \url{https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/likelihood_tutorial.html}

\(^3\) J-factors derived through stellar kinematics. For Reticulum II, it is taken from [35], others are from [36].

| Name                  | \(l, b\) [deg] | Distance [kpc] | \(\log_{10}(J)\) [\(\text{GeV}^2\text{cm}^{-5}\)] |
|-----------------------|----------------|----------------|-----------------------------------------------|
| Coma Berenices        | (241.89, 83.61) | 44             | 19.0±0.4                                     |
| Reticulum II          | (266.30, -49.74)| 32             | 18.9±0.6                                     |
| Segue 1               | (220.48, 50.43) | 23             | 19.4±0.3                                     |
| Ursa Major II         | (152.46, 37.44)| 32             | 19.4±0.4                                     |

TABLE I: The information of the 4 considered dSphs.
same as the commonly used combined likelihood analysis [25, 28, 29]. The advantage of our method is that it can effectively avoid the loss of sensitivity due to the uncertainty of J-factor.

We use the above method to scan a serious of DM masses. Since we are focusing on the i2HDM model that can commonly interpret the W-boson mass anomaly in the i2HDM model are around the star symbol [11].

FIG. 2: The favored DM parameters of \( SS \to WW^* \) via fitting to the antiproton and GC excess data (1\( \sigma \) and 2\( \sigma \) from inside to outside, extracted from [12]). The parameters that can simultaneously interpret the W-boson mass anomaly in the i2HDM model are around the star symbol [11].

reads

\[
\Phi(E_\gamma) = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \times J,
\]

where \( m_\chi \) and \( \langle \sigma v \rangle \) are the DM particle mass and the velocity-averaged DM annihilation cross section. The term

\[
J = \int r^2(r) dld\Omega
\]

is the so-called J-factor, which can be determined through stellar kinematics. The J-factors of the 4 sources are listed in Table I. The \( dN_\gamma/dE_\gamma \) is the differential \( \gamma \)-ray yield per annihilation. For the \( SS \to WW^* \) channel and when the DM mass is \( m_S < m_W \), the off-shell annihilation into \( WW^* \) is considered. We use the spectra the same as those in [12], which is simulated with MadGraph5_aMC@NLO [42] and PYTHIA8 [43]. For the DM mass \( m_S > m_W \), the DM spectra are obtained from PPP4DMID [44].

The results are shown in Figure 2. The i2HDM parameters that can simultaneously interpret the W-boson mass anomaly, the GC GeV excess and the GeV antiproton excess are within a very small region around the star symbol. We find that the upper limits are well above the favored parameters, thus the dSphs observation can not exclude such a model. Although we only consider 4 dSphs, including other sources are not expected to give constraints tighter too much due to their much longer distance and smaller J-factors.

IV. SUMMARY

The new measurement of W-boson mass by the CDF collaboration [10] shows that the mass deviates from the standard model prediction with a significance of 7\( \sigma \). This result indicates there may exist new physics beyond the SM. Ref. [11, 12] proposed that the inert two Higgs doublet model (i2HDM) can well explain the new W-boson mass. More encouragingly, they found that this model can also explain both the GC GeV gamma-ray excess in the GC and the GeV antiproton excess with common parameters. The gamma-ray and cosmic-ray are produced through a \( SS \to WW^* \) annihilation.

In this paper, we have tested this model using the Fermi-LAT observation of the 4 nearest confirmed dSphs of Milky Way. These dSphs have almost the largest J-factors and the observation of them is appropriate to search for the gamma-ray signal from the \( SS \to WW^* \) annihilation and test the i2HDM model. We do not find any significant signal in both the single-source analysis and the stacking analysis. Based on the null results, we place constraints on the cross section. We find that our constraints can not exclude the favored parameters reported in [12], suggesting i2HDM is a promising model that can simultaneously interpret the W-boson mass anomaly, GeV excess and antiproton excess. Since the favored parameters are not too far below the constraints, the future larger
γ-ray telescopes [45, 46] may probe these parameters with dSph observations in the near future.

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