Three-dimensional Search for Annihilating Dark Matter in CBe dSph with the MAGIC Telescopes

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Dark matter (DM) candidates, such as Weakly Interacting Massive Particles (WIMPs), can annihilate to Standard Model particles, subsequently producing gamma rays. In this work, we search for DM-induced gamma-ray signals from Coma Berenices dwarf spheroidal galaxy (CBe dSph) using approximately 25 hours of observations carried out by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescope, located at Roque de los Muchachos Observatory, La Palma, Spain. Building upon preceding analyses in the gamma-ray regime, we extend the DM search into three dimensions by incorporating spatial information from the assumed DM-density distribution. This approach enhances sensitivity by leveraging both energy and spatial characteristics of the expected signal. The three-dimensional search for a faint signal necessitates the construction of a background model, leading to the proposal of the *exclusion-rotation* method. This method stacks all observations, excludes the source region, and corrects for the Azimuth-dependent acceptance of the telescopes by rotating the model. Furthermore, the open-source Python package TITRATE is presented, introducing *Asimov* datasets to the high-level analysis tool GAMMAPY for the approximation of the test statistic. No evidence of a DM-induced signal for annihilation to $b\bar{b}$, W^+W^-, $\mu^+\mu^-$, and $\tau^+\tau^-$ and DM masses m_χ between $0.17\,\mathrm{TeV}$ and $100\,\mathrm{TeV}$ in CBe dSph is found. Consequently, the first upper limits on the thermally averaged cross-section in energy and spatial dimensions using TITRATE are set, leading to an improvement in sensitivity over previous results by MAGIC with respect to the assumed DM density in the target halo. Moreover, the development of the Asimov datasets for DM search reduces the need for Monte Carlo simulations in estimating the mean and uncertainty bands of the sensitivity, paving the way for computationally efficient and scalable large-scale analyses across multiple targets and cosmic messengers.

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1. Introduction

Dark Matter (DM) candidates, such as the Weakly Interacting Massive Particles (WIMPs) under investigation here, include variants that are capable of annihilating into Standard Model (SM) particles [1, 2]. Despite the suppression of direct photon production [3], the subsequent production of high-energy gamma rays through alternative channels remains a possibility. For astrophysical targets the expected gamma-ray flux is determined by two factors: firstly, the astrophysical component (AP), or J-factor in case of annihilating DM, and secondly, the particle physics component (PP). The former represents the DM content within the target region along the line-of-sight, and the latter the primary interaction of DM. DM-rich targets, such as dwarf spheroidal galaxies (dSphs) offer a promising pathway for the search for DM due to their high mass-to-light ratio [4], leading to a relatively large AP contribution, and no or negligible gamma-ray background emission. [1] Consequently, the Coma Berenices (CBe) dSph is considered, due to its proximity and low astrophysical background [5, 6]. Among the instruments capable of searching for DM-induced gamma-ray signals, such as satellites as Fermi-LAT [7], Imaging Air Cherenkov Telescopes (IACTs) are capable of probing high-energy regions ($O(\text{TeV})$) of the PP contribution, by leveraging the in-air Cherenkov effect of gamma-ray-induced atmospheric showers, leading to an increased detection area over alternative telescope designs. To this end, the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescope system [8] carried out a campaign of approximately 50 h of CBe dSph observations, from which 25 h of high-quality data were selected for the analysis presented here. Previous MAGIC analyses on dSphs relied primarily on one-dimensional spectral fits [9], neglecting potential spatial information inherent in the expected DM signal distribution. Such simplified approaches may limit sensitivity, especially for faint gamma-ray signals from targets like the CBe dSph. To enhance detection capabilities, this work introduces a three-dimensional search method that integrates spatial information derived from the assumed DM density profile. However, employing spatially resolved data requires a robust method for precise background estimation.

We propose the *exclusion-rotation* (ER) method to construct an accurate and azimuthally corrected background model for stacked observations. Independent of the background method the newly developed TITRATE [10] Python package introduces Asimov datasets into the Gammapy [11] analysis framework, significantly reducing computational costs previously associated with extensive simulation of toy datasets for sensitivity estimation. This contribution presents the first results of the three-dimensional DM search in the CBe dSph using MAGIC telescope data, setting new constraints on the DM thermally averaged annihilation cross-section and comparing these new results to the one-dimensional approach.

2. Background Modelling

The ER method estimates the background, defined as the observed events falsely classified as gamma rays, directly from the data. A three-dimensional histogram, in general referred to as a *cube*, with the axes $\mathcal{A} = (\hat{E}, \text{FoV}_{\text{Az}}, \text{FoV}_{\text{Alt}})$ is defined as the background model. Here, $\hat{E}$ denotes the recon-

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structed energy and $\hat{FoV}_{Az}$, $\hat{FoV}_{Alt}$ the reconstructed direction in the Field-of-View (FoV) Alt-Az frame for the observed events. The *exclusion-only* method to populate the histogram is as follows: Create three empty cubes N_{eff}, T_{eff}, T_{tot} each with axes $\mathcal{A}$. Iterate over all observations and populate the N_{eff} with the events of the observation while excluding all events within a circular region of radius $r = 0.4\,$deg[2] centered on the observation target. T_{eff} and T_{tot} are filled simultaneously with the exposure time, with *eff* denoting the cube with the source region excluded and *tot* with it included. In practice, the exclusion region can be created in the average Alt-Az frame of each observation. However, as Figure 1 illustrates, the rotation of the source in the FoV during an observation is not negligible. To mitigate the impact of a falsely located exclusion region, the observations are divided into sub-observations with reduced live time. The final background model is defined as

$$\frac{\mathrm{d}N}{\mathrm{d}t\mathrm{d}E\mathrm{d}\Omega} = \frac{N_{eff}}{(T_{eff}/T_{tot})\Delta\Omega\Delta E T_{obs}}, \tag{1}$$

where $\Delta\Omega$ and ΔE define the solid angle and energy width of each bin in the cube, while T_{obs} represents the total time of all observations.

According to Mender et al. [12], the MAGIC telescopes exhibit a highly asymmetric *stereo blob*[3]. The empirical law between the orientation of the stereo blob, given by the rotation angle γ_{theory}, and the Az alignment of the MAGIC view cones has been established as

$$\gamma_{theory} = Az - \Delta\gamma, \tag{2}$$

with the offset of $\Delta\gamma = 34.23°$. Although a division of the background model in multiple Az bins is possible to compensate for the rotation of the acceptance among the observations, doing so leads to a decrease in statistics proportional to the number of bins, which therefore leads to a decrease of sensitivity.

We propose the novel ER method[4] based on the preceding exclusion method, which de-rotates the events within one sub-observation according to the angle γ_{PCA} from the first component of the Principal Component Analysis (PCA) [14] applied to the spatial event distribution in every energy bin. The de-rotated events are re-rotated according to Equation 2 for the Az pointing of the observation. This procedure allows the use of all de-rotated events of all observations to construct one background model per Az pointing (one per observation). To avoid the influence of secondary effects of the zenith distance (Zd) on the background, the method is implemented in three Zd bins: 5-15, 15-25, and 25-35 deg. The background models are created in 30 bins in the range $-3°$ to $3°$ for the Alt-Az and 8 bins per decade in the range 0.05 TeV to 5 TeV for the energy axes. Figure 2 displays the model of an arbitrary observation of the CBe dSph constructed with the ER method for four of sixteen energy bins. For low energies, the background is concentrated in the center of the FoV showing the characteristic stereo blob. For increased energy, the background model exhibits a distinctive "donut"-like shape emerging from the incapability of IACTs reconstructing showers with large Cherenkov footprints not fitting within the telescope camera. Reconstructable fully-enclosed shower images originate outside the central area of the FoV.

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[2]$r = 0.4$ deg is equal to the MAGIC wobble distance [8]

[3]The stereo blob arises from the viewcone overlap of both telescopes.

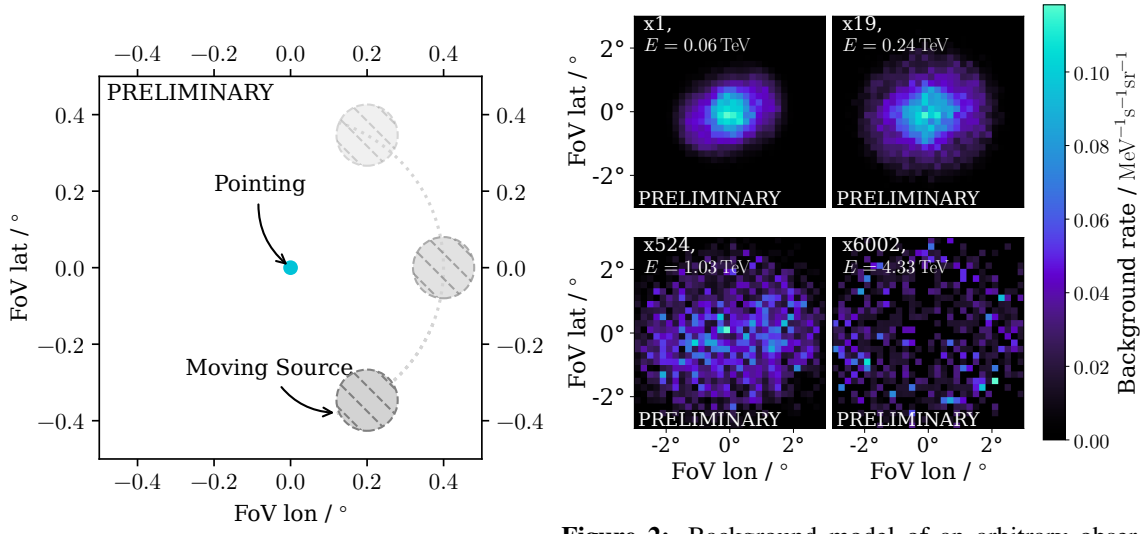[4]An implementation of this method within the BAccMod [13] Python package can be found on GitHub https://github.com/mdebony/BAccMod/pull/40

Figure 1: Schematic of the source rotation relative to the pointing position within the Alt-Az FoV during the observation.

Figure 2: Background model of an arbitrary observation created with the novel *exclusion-rotation* (ER) method. Each background map is multiplied by the factor denoted in the sub-figures to match the rate of the first energy bin.

3. Asimov Datasets

The calculation of the detection significance or upper limits of a DM model parameter on the observed data necessitates the computation of the p-value of the distribution $f(q_\mu|\mu, \vec{\theta})$ of the test statistic (TS) q_μ, defined as the profiled log-likelihood ratio (pLLR). Here, μ denotes the strength parameter of the signal and $\vec{\theta}$ the nuisance parameters. A common approximation for $f(q_\mu|\mu, \vec{\theta})$ is a χ^2 distribution, according to Wilks' theorem [15]. However, two main problems arise from using the Wilks approximation: firstly, if the estimator $\hat{\mu}$ [5] is smaller than zero after calculating the pLLR, the statistical test loses physical meaning and secondly, a vast amount of computationally costly toy Monte Carlo (MC) datasets is necessary to compute the background-only expectation (sensitivity). We propose the usage of the *Asimov datasets* published by Cowan et al. [16] to approximate the TS distribution without relying on extensive MC simulations. The Asimov datasets are constructed such that the estimators fulfill $\hat{\mu} = \mu'$ and $\hat{\vec{\theta}} = \vec{\theta}'$, representing the expected outcome under the hypothesis $(\mu', \vec{\theta}')$.

To ensure valid statistical inference for the unphysical case, $\hat{\mu} < 0$, we employ the *modified test statistic* $\tilde{q}_\mu$, which remains well-defined at the boundary. The approximation of the TS distribution as a non-central χ^2 allows for the use of the CL_s [6] method [17] for the first time in a MAGIC analysis, yielding the computation of upper limits and expected sensitivity bands $\pm N\sigma$ [18]:

$$p_\mu \overset{!}{=} \frac{1 - \Phi(\sqrt{\tilde{q}_\mu})}{\Phi(\sqrt{\tilde{q}_{\mu,A}} - \sqrt{\tilde{q}_\mu})}, \tag{3}$$

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[5]From here on all quantities denoted as $\hat{\ }$ represent estimators on the respective quantity.

[6]Although this denotes the name of the method, it is notable that CL is short for confidence level. See [17] for more details.
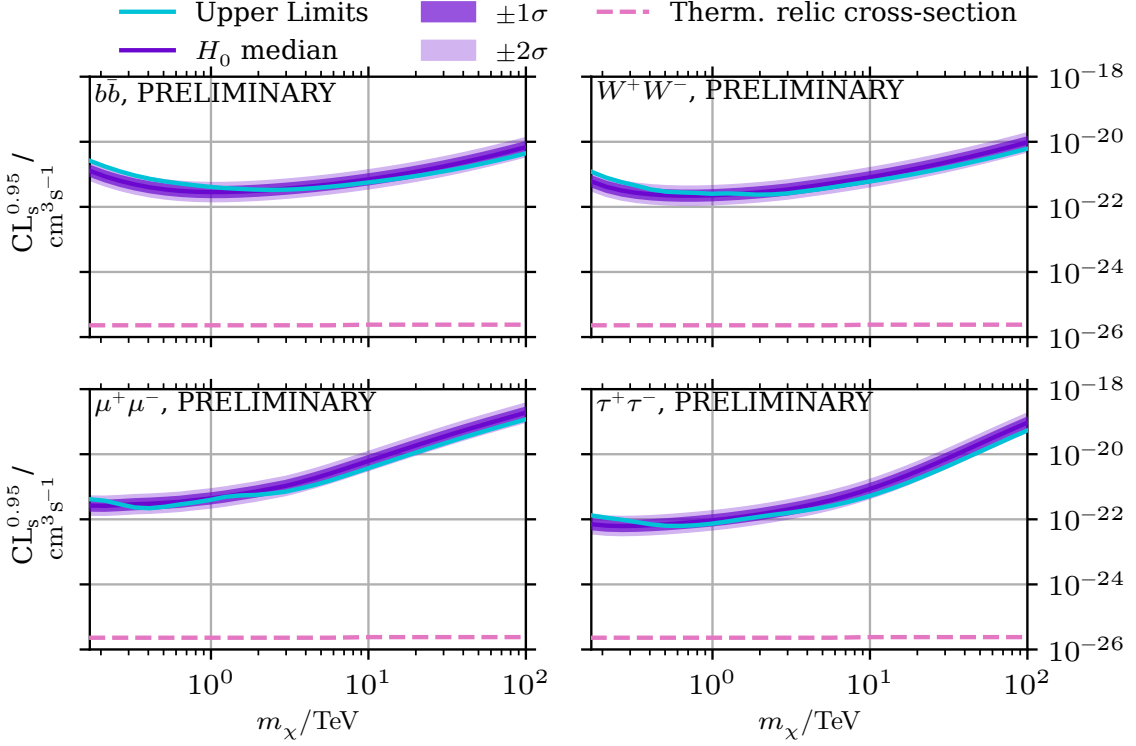
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Figure 3: Upper limits and sensitivity bands on the thermally averaged cross-section for the 3D analysis. Thermal relic cross-section taken from [19].

$$\mu_{\exp} = \sigma\left(\Phi^{-1}(1 - \alpha\Phi(N)) \pm N\right),\tag{4}$$

at confidence level $1 - \alpha$, while $\Phi(.)$ denotes the cumulative density function (CDF) of the standard normal distribution and index "A" denotes the evaluation of the TS on the Asimov dataset. We provide an implementation of the Asimov-based computations through the newly developed Python package TITRATE[7].

4. Results

No significant excess was observed in approximately 25 h of MAGIC observations of the CBe dSph. We compute 95% CL_s upper limits on the thermally averaged annihilation cross-section as a function of DM mass $m_\chi \in [0.17, 100]$ TeV for four annihilation channels: $b\bar{b}$, W^+W^-, $\mu^+\mu^-$, and $\tau^+\tau^-$. The empirical modeling of the AP contribution is taken from Geringer-Sameth et al. [6].

Figure 3 shows the limits derived from the 3D analysis using TITRATE and Asimov datasets. The median expected limits (H_0) and $\pm 1\sigma$, $\pm 2\sigma$ containment bands are computed with Equation 4. The observed limits lie within the bands, consistent with background-only expectation. Additionally, the thermal relic cross-section taken from Steigman et al. [19] is displayed. To evaluate the performance of the new analysis method, the expected limits are obtained with the Gammapy [11] MapDataset
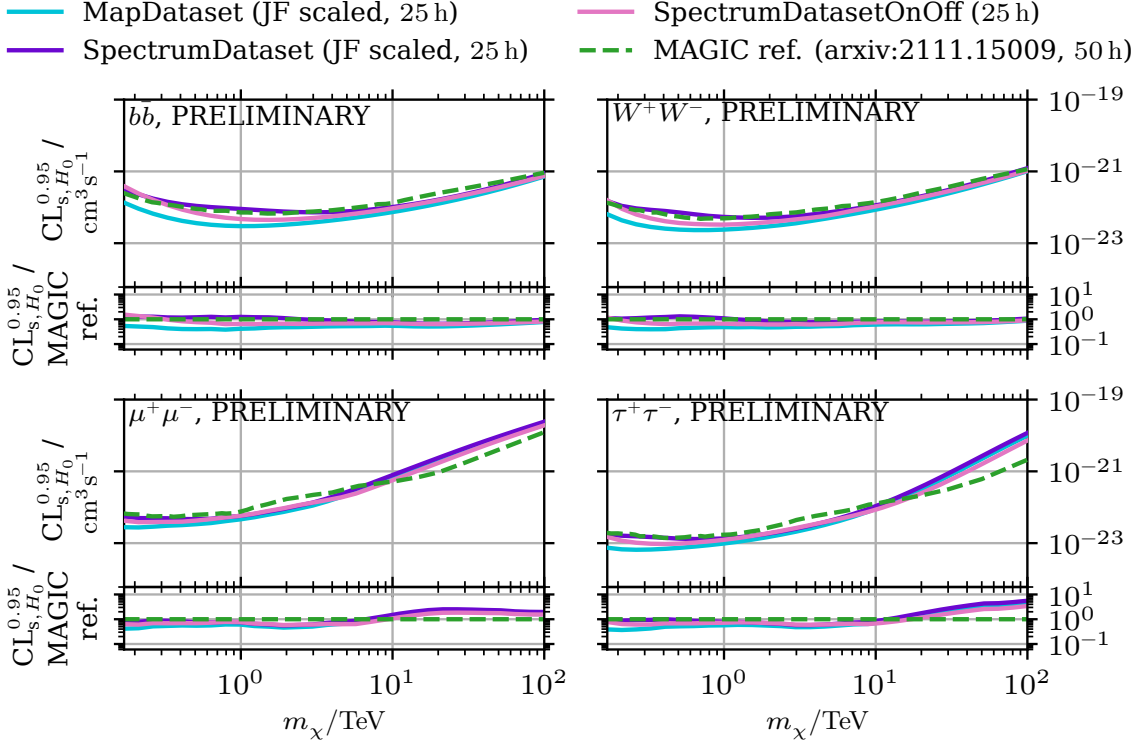
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[7]https://github.com/StFroese/TITRATE

Figure 4: Median expected limits on the thermally averaged cross-section for the Gammapy datasets and the preceding MAGIC analysis [9], as well as their ratios.

(3D, spatial+energy), SpectrumDataset (1D, energy-only), and SpectrumDatasetOnOff (1D, energy-only). While the SpectrumDataset is constructed via integration of the spatial axes of the MapDataset in a region of $\theta^2 = 0.03 \, \text{deg}^2$[8] around the source position, the SpectrumDatasetOnOff does not rely on the ER method presented, but rather constructs the background from Off-regions. Figure 4 displays a comparison of the sensitivities to the preceding MAGIC publication on the CBe dSph found in [9]. It is notable, that the previously published limits rely on full observation time of the CBe dSph campaign, while this analysis relies on the high-quality 25 h set. The 3D analysis exhibits an increase in sensitivity compared to the SpectrumDataset-based analysis in all channels and DM masses. While the 3D analysis shows the most sensitive limits for the non-leptonic channels and up to $\approx 4 \, \text{TeV}$ and $\approx 7 \, \text{TeV}$ for the leptonic channels among the Gammapy datasets, the SpectrumDatasetOnOff-based analysis is the most sensitive approach at higher mass ranges for the leptonic channels. Overall, the 3D analysis illustrates improved limits for the non-leptonic channels and the leptonic channels up to $\approx 10 \, \text{TeV}$ with half the amount of exposure time in comparison to the previously published MAGIC results.

5. Summary

In this work, we have presented a three-dimensional search for gamma rays from DM annihilation in the CBe dSph dwarf spheroidal galaxy using approximately 25 h of data from the MAGIC telescopes. We have introduce the ER method for background estimation and modelling. This approach

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[8]This size is given by the ON-region size of the preceding MAGIC publication [9]

corrects for azimuth-dependent acceptance variations without relying on external simulations. To estimate sensitivities without MC trials, we provide TITRATE, a Python package that integrates Asimov dataset generation into Gammapy. This enables fast computation of the TS distribution and associated upper limits, as well as the introduction of the CL_s method for gamma-ray analyses within Gammapy. TITRATE further allows reproducible and scalable analysis across targets, making it suitable for future multi-messenger DM searches. No excess consistent with DM annihilation into SM products was observed. We have set upper limits on the thermally averaged cross-section for annihilation channels into $b\bar{b}$, W^+W^-, $\mu^+\mu^-$, and $\tau^+\tau^-$ in the mass range from 0.17 TeV to 100 TeV. By incorporating spatial information from the assumed DM distribution, the analysis gains a mass- and channel-dependent sensitivity improvement over traditional spectral-only approaches with half the amount of exposure time.

Acknowledgments

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