Search for gamma-ray line emission from Dark Matter annihilation in the Galactic Centre with the MAGIC telescopes

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Abstract. We present a search for dark matter spectral lines in the Galactic Centre (GC) region with the MAGIC telescopes. The MAGIC telescopes, located on the Canary island of La Palma (Spain), are sensitive to photons in the energy range from 50 GeV to 50 TeV with low zenith angle observations. MAGIC has performed indirect dark matter searches with various astrophysical targets. Since the MAGIC telescopes are located in the northern hemisphere, the GC is visible only at high zenith angles. Observations at high zenith angles significantly increase the telescopes’ effective collection area, which boosts sensitivity for gamma rays in the TeV regime. We report the results obtained with more than 200 hours of high zenith angle observations of the GC region with MAGIC.

1. Introduction

There is a wide agreement that about one fourth of mass-energy in the Universe can be explained by the existence of dark matter [1]. Dark matter motivates a new fundamental particle at energies beyond the standard model of particle physics. Weakly Interacting Massive Particles (WIMPs) are one of the most well-known candidates for dark matter. Many studies are conducted to search for dark matter such as direct detection experiments at detectors in the underground, collider experiments, and indirect dark matter searches with cosmic rays. These ways are complementary in scanning different regions of the parameter space. Despite the large effort by various experiments, no clear evidence has been found yet.
In particular, we focus on indirect dark matter searches with very high energy (VHE) gamma rays: Such gamma rays are generated by annihilation of heavy dark matter particles. In particular, indirect dark matter searches are sensitive to probe the annihilation cross-section. Searches with current-generation instruments enable us to test the thermal relic scenario, the canonic hypothesis to explain how today’s dark matter budget was produced in the early Universe. Additionally, searches for gamma rays as annihilation products provides a major advantage over searches in charged particles. Charged particles are bent by magnetic fields in the inter- and extragalactic medium, whereas gamma rays retain the information about their origin due to being a neutral particle. This is beneficial to know or constrain the dark matter spatial distribution of an astrophysical source. The expected gamma-ray flux from dark matter annihilation can be written as below [2]:

\[
\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{DM}^2} \times \frac{dN_\gamma}{dE} \times J(\Delta \Omega),
\]

where \( \langle \sigma v \rangle \) is the thermally averaged dark matter annihilation cross section, \( m_{DM} \) is an assumed WIMP mass, and \( dN_\gamma/dE \) is the photon yield per annihilation. In this study, we focus on the line emission from dark matter annihilation, which is one of the most distinctive spectral features and enables us to search for well-motivated Supersymmetric (SUSY) particles [3]. \( J(\Delta \Omega) \) is called J-factor and can be described as follows:

\[
J(\Delta \Omega) = \int_{\Delta \Omega} d\Omega' \int_{\text{l.o.s}} \rho^2(l, \Omega') \, dl.
\]

The J-factor is the integral of the squared dark matter density \( \rho \) over a solid angle \( \Delta \Omega \) and along the observed line of sight (l.o.s).

2. The Galactic Centre observation with MAGIC

The MAGIC telescopes consist of two 17 m diameter Imaging Atmospheric Cherenkov Telescopes (IACTs), which are located at the Roque de los Muchachos observatory (28°N, 18°W) on the Canary island of La Palma, Spain. The MAGIC telescopes can detect gamma rays from 50 GeV to 50 TeV from directions close to the zenith (low zenith angle observations). Low zenith angle observation is the usual observational mode. However, the Galactic Centre is visible on La Palma at zenith angles larger than 58 degrees [4]. Observing under these conditions is called large zenith angle observations. Compared to the low zenith angle condition, the Cherenkov light is absorbed more by the atmosphere under large zenith angle conditions due to the thicker atmosphere. Those effects increase the energy threshold and the energy resolution. On the other hand, the gamma-ray collection area increases proportional to approximately \( 1/\cos^2\theta \) where \( \theta \) is the zenith angle. This improves the sensitivity in energy ranges limited by the event statistics, such as the TeV regime. The MAGIC telescopes have conducted observations of the Galactic Centre for 6 years, and the total observation time reached 204 hours.
after quality cuts. The region of interests (ROIs) are described in detail in the reference [5].

3. Analysis and Results

The data was processed with the MAGIC Analysis and Reconstruction Software (MARS) and the standard analysis chain [6]. While the Galactic Centre is one of the most promising targets for indirect dark matter searches since it is believed to contain an extreme high density of dark matter, uncertainties of the dark matter profile models are predicted [7]. To deal with this problem, we adapt the sliding window method [8] for the line search analysis to maximize the sensitivity for both very cuspy and core profiles. We apply an unbinned likelihood analysis in an energy window with the following equation:

\[
\mathcal{L}_i(g_i; \nu_i, |D_i) = \mathcal{L}_i(g_i; b_i, \tau_i, \{E'_j\}_{j=1,...,N_{ON,i}}, N_{ON,i}) \times \frac{(g_i + \tau_i b_i)^{N_{ON,i}}}{N_{ON,i}!} \times \frac{1}{g_i + \tau_i b_i} \prod_{j=1}^{N_{ON,i}} (f_g(g_i f_g(E'_j) + \tau_i b_i f_b(E'_j)))
\]

where the first term is the Poisson likelihood, the second term is for an unbinned likelihood and the third term is taking care of systematic uncertainties. The index \(i\) runs over the number of observational periods of our data set, and \(N_{ON}\) is the number of events in the ROI after cuts. The parameter of interest is \(g\), which is the estimated number of signal events. The nuisance parameters are \(\nu_i\) and \(b\) are the estimated background events. \(\tau\) is the normalization factor of the background model. To take care of systematic uncertainties, the mean value \(\tau_{obs}\) and the standard deviation \(\sigma_\tau\) of an assumed Gaussian distribution of \(\tau\) are estimated with data without a dark matter target source [9, 5]. \(f_g\) is the signal p.d.f for the line spectrum, which is a \(\delta\)-function convolved with a response function of the telescope such as the energy dispersion. \(f_b\) the background p.d.f, which is estimated with a spline fitting to the energy spectra.

Finally, the analysis found no significant line-like excess inside a region of about 1° in radius around the Galactic Centre, and we set upper limits at 95 % confidence level on 15 masses from 912 GeV to 43 TeV. The sliding window technique enables us to analyze data assuming a core profile and suffers from less sensitivity degradation than an analysis relying on spatial ON/OFF regions. With a core profile [12], limits shown in Fig.1 are comparable to other results based on dwarf spheroidal galaxies. For a cuspy profile, we take parameters of the profile from [10, 11], and limits are competitive with previous results shown in Fig.1 with less observation time thanks to the large zenith angle observation technique.
4. Discussion and summary

In this study, we have reported the upper limits on the dark matter annihilation cross section $\langle \sigma v \rangle$ with 204 hours of observational data taken with the MAGIC telescopes observing the Galactic Centre. The potential for searches for a line-like gamma-ray signal with large zenith angle observations have been shown, which boost the sensitivity at high energies beyond several TeV. We have adapted the sliding window method for the line search analysis to maximize the sensitivity for both cuspy and core profiles. This result also shows that large zenith angle observations will provide an essential technique for the search of heavy dark matter signatures with the Cherenkov Telescope Array in the future.

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