Strategies for the Detection of Gamma Rays from Dark Matter Annihilation Towards the Galactic Center Region with the High Energy Stereoscopic System

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The central region of the dark matter halo of the Milky Way is a promising target for a search for a particle dark matter annihilation signal. The H.E.S.S. Collaboration has published a search for a photon flux originating from dark matter particles annihilating in the galactic center region. No significant excess was observed and upper limits on the velocity averaged dark matter self annihilation cross section were derived. The limits exclude the self annihilation of dark matter particles in the ~ 1 TeV to ~ 4 TeV mass range with a velocity averaged annihilation cross section larger than $\sim 3 \cdot 10^{-25}\,\mathrm{cm}^3/\mathrm{s}$, i.e. about one order of magnitude above the prediction for a thermal relic dark matter particle. A detailed and realistic Monte Carlo study of new strategies for the search for a particle dark matter annihilation signal from the Milky Way dark matter halo with the High Energy Stereoscopic System is presented and the sensitivity of different experimental approaches is compared.

1. Particle Dark Matter and the Milky Way Dark Matter Halo

The dynamics within the Milky Way points towards the existence of a large amount of invisible, i.e. dark, matter in the Milky Way. Many extensions of the standard model of particle physics naturally predict the existence of yet unobserved weakly interacting massive particles (WIMPs) that do not directly couple to light but only to the weak sector of the standard model. It is thus inviting to explain the failure to understand the dynamics within the Milky Way based on the visible distribution of matter by the additional abundance of WIMPs. The existence of WIMPs is also in agreement with cosmological structure formation arguments and precision measurements of the dark matter density in the universe.
In many models, WIMPs are expected to be stable on cosmological timescales but have the ability to annihilate into standard model particles. In the minimal supersymmetric extension of the standard model of particle physics with conserved R-parity, the neutralino, i.e. the superposition of supersymmetric partners to the neutral electroweak gauge bosons, is a Majorana particle dark matter candidate and is thus even able to self annihilate. Depending on the annihilation channel, the standard model annihilation products lead in part to a continuous photon spectrum. The photon energies can, depending on the particle dark matter mass, be in the Very High Energy (VHE, $E > 100$ GeV) γ-ray regime. The number of expected particle dark matter annihilation events in a given volume is proportional to the dark matter density squared. Large dark matter densities are thus promising for a search for dark matter self annihilation events. Recent large scale N-body simulations of gravitationally interacting pseudo particles predict that the dark matter density distribution at the spatial scale of galaxies can be parametrized by simple func-

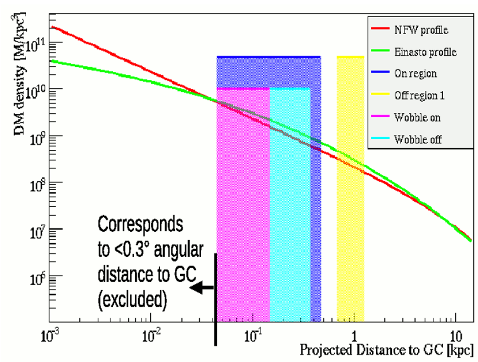

Figure 1: Two parametrizations of the dark matter density distribution as a function of the distance to the galactic center resulting from large scale N-body computer simulations. The two distributions correspond to the best fit to the dark matter distribution in two different Milky Way mass scale N-body computer simulations as obtained in Pieri et al. [2011]. The dark matter density distributions agree for distances larger than ~ 45 pc within a factor of two. Both distributions are normalized to a dark matter density of $0.3\,\mathrm{GeV/cm^3}$ at a distance of 8.5 kpc to the galactic center, i.e. the radial distance of the sun to the galactic center.

tions and few parameters (see f.i. Pieri et al. [2011]). Figure 1 shows the dark matter density distributions as recently obtained in two different Milky Way mass scale N-body computer simulations (see Pieri et al. [2011]). Both distributions are normalized such that the density at the position of the sun agrees with the value of $0.3\,\mathrm{GeV/cm^3}$ derived from different dynamical constraints. A central result of N-body simulations involving only dark matter particles is that the dark matter density is in general steeply increasing towards the center of galaxies. The agreement between the resulting dark matter density distributions of different Milky Way mass scale N-body simulations is at the level of a factor of two for distances larger than

~ 45 pc from the center of the galaxy as apparent in Fig. 1. For more information on dark matter from an astrophysical and particle physics point of view see Bertone et al. [2005] and references therein.

2. The High Energy Stereoscopic System

The High Energy Stereoscopic System (H.E.S.S.) is an array of Imaging Atmospheric Cherenkov Telescopes (IACTs) located in the Khomas Highland of Namibia at an altitude of ~ 1800 m above sea level. This study considers the H.E.S.S. I array of four identical ~ 100 m^2 mirror area IACTs operating in a square formation and optimized for the detection of ~ 100 GeV to ~ 100 TeV γ-rays from astrophysical sources. The instrumental field of view (FoV) of H.E.S.S. I is $\sim 5°$ in diameter. The energy and angular resolution for the reconstruction of γ-rays is $\sim 20\%$ and $\sim 0.1°$ respectivly. For more technical information on H.E.S.S. I see Aharonian et al. [2008] and references therein.

2.1. Background Subtraction and H.E.S.S. I Point Source Sensitivity

The detection of γ-rays is complicated due to the necessity to distinguish γ-ray signal events from background events from Cosmic Rays. H.E.S.S. I performs a discrimination between Cosmic Ray and γ-ray events in multiple steps at trigger (Funk et al. [2004]) and subsequent data analysis (Aharonian et al. [2008]) level. However, a perfect discrimination is not possible on an event by event basis and enforces the application of a background subtraction algorithm. Frequently used and well tested background subtraction algorithm rely on the definition of a signal and a background region in the same FoV (see Berge et al. [2007] for an overview). The background region has to be constructed such that the instrumental acceptance in the signal and background region are equal. The number of expected background events in the signal region is then measured under the assumption that the Cosmic Ray TeV flux is isotropic. This background subtraction approach is well suited for the investigation of signal regions which are much smaller than the FoV and leads typically to the ability to detect astrophysical γ-ray point sources with a photon flux of $\sim 1\%$ of the Crab nebula γ-ray flux (Aharonian et al. [2008]) at a statistical significance of 5 standard deviations within an observation time of ~ 25 h under optimal observation conditions for H.E.S.S. I. For γ-ray sources that are comparable in size or larger than the FoV of H.E.S.S. I the background region can however not be constructed in this way and alternative methods have to be applied.

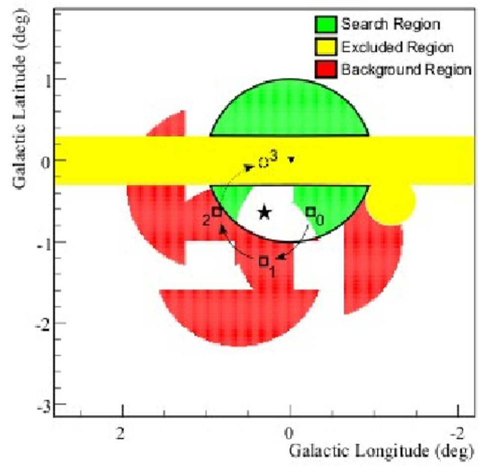

Figure 2: Signal (green) and background (red) region constructed with the rotated pixel background algorithm in galactic coordinates. Each pixel in the signal region is rotated out of the signal region at constant angular distance to the pointing direction. Known astrophysical γ-ray sources and the galactic plane are excluded (yellow).

3. The Rotated Pixel Method

The main technical problem in the search for a γ-ray signal from the galactic dark matter halo is that the halo extension is much larger than the H.E.S.S. I FoV. Traditional background subtraction algorithm that rely on the signal plus background and a background measurement in the same FoV can thus not easily be applied. The H.E.S.S. collaboration has recently published (H.E.S.S. Col. [2011]) a search for a γ-ray signal from self annihilating WIMPs in the center of the Milky Way dark matter halo which uses an adaptation of the reflected region background subtraction algorithm (see Berge et al. [2007]). The method employed relies on the steepness of the predicted dark matter density profile in the vicinity of the galactic center and the assumption of the H.E.S.S. I instrumental acceptance to be rotationally symmetric around the pointing position. A signal region of 1° angular radius around the galactic center is defined and subdivided into many pixel each of which is much smaller than the angular resolution of H.E.S.S. I. For a given observation run pointing towards a constant direction in celestial coordinates, each pixel in the overlap of the signal region and the FoV is then rotated out of the signal region at constant angular distance to the pointing position to construct the background region for a run. Known astrophysical γ-ray sources, the galactic plane ($|b| < 0.3°$) and signal pixels for which no background pixel can be constructed for geometric reasons are excluded from the analysis. Figure 1 shows the projected distances to the galactic center covered in the signal (magenta, tagged 'wobble on') and background (turquoise, tagged 'wobble off') region. The construction of the background region ensures that the signal region is always closer in angular distance to the galactic center than the background region and the predicted average dark matter density in the signal region is thus larger than in the background region. The background subtraction method relies thus not on a measurement of signal plus background and background in the same FoV but on a measurement of signal plus background and 'less signal' plus background in the same FoV. A search for a particle dark matter self annihilation signal is possible by comparing the number of events detected in the signal region with the number of events detected in the background region. The H.E.S.S. collaboration did not detect a significant signal in a rotated pixel analysis of 112 h livetime of H.E.S.S. I observations of the galactic center region. The velocity averaged self annihilation cross section $< \sigma v >$ was in consequence constrained to be smaller than $\sim 3 \cdot 10^{-25}$ cm^3/s for WIMP masses around 1 TeV (H.E.S.S. Col. [2011]). The derived limits on $< \sigma v >$ are currently the most constraining in the TeV WIMP mass range.

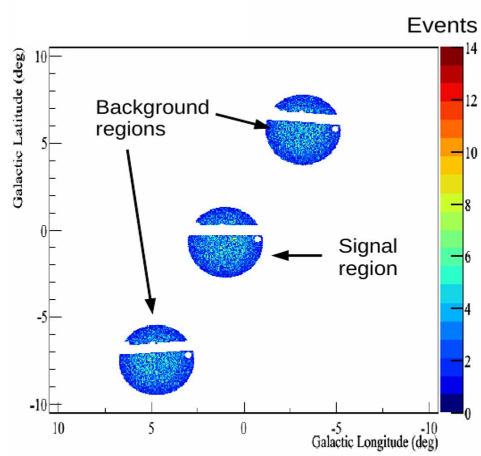

Figure 3: Simulated H.E.S.S. I events for the observation of a signal region with the full H.E.S.S. I FoV and two background regions in galactic coordinates. The pointing positions for the background regions have a symmetric offset in right ascension to the pointing position of the signal region. Known γ-ray sources and the galactic plane are excluded from the analysis and all exclusion regions are mutually applied to all observation regions in the FoV system.

3.1. Limitations

The application of the rotated pixel background subtraction algorithm limits the angular extension of the signal region by the demand to fit signal and background region into one H.E.S.S. I FoV. A larger signal region could, depending on the signal to background ratio, increase the sensitivity of H.E.S.S. I to a WIMP self annihilation γ-ray flux from the galactic dark matter halo. Without the constraint due to the rotated pixel background subtraction, the maximal signal region could be increased to be complete H.E.S.S. I FoV. The maximal distance of the background region to the galactic center is also limited by the applied background subtraction technique. If the background region can be constructed much further away from the galactic center than possible with the rotated pixel technique, the expected γ-ray flux due to WIMP self annihilation in the background region would be smaller and the sensitivity would thus improve.

In the following, two alternative background subtraction techniques that rely on special observation strategies are described and it is investigated whether an increase in sensitivity to a WIMP self annihilation γ-ray flux from the Milky Way dark matter halo is possible.

4. On/Off Background Subtraction

Figure 3 shows simulated H.E.S.S. I γ-ray events in three different FoVs. H.E.S.S. I extragalactic 'off data', i.e. observation runs with no γ-ray source in the FoV, performed at a zenith angle of $\sim 20°$ were used to obtain a realistic γ-ray candidate event rate after H.E.S.S. I standard γ-ray selection criteria (cuts). Additionally, the dependence of the γ-ray candidate event rate after cuts as a function of the offset to the observation position ('radial acceptance') and the energy dependence of the event rate after standard cuts together with the instrumental dead time as obtained from extragalactic off data are used to simulate realistic observations. Figure 3 shows in the center the simulated signal region events in the vicinity of the galactic center distributed over a complete H.E.S.S. I FoV. The observation of two background regions whose observation positions have a symmetric offset of ± 35 min in right ascension to the signal region observation position is simulated. Known γ-ray sources and the galactic plane ($|b| < 0.3°$) are excluded from the analysis and all exclusion regions are mutually applied to all observed FoVs respectively. For each simulated FoV, 50 h observation livetime were generated.

The simulation models a peculiar observation strategy where always three H.E.S.S. I standard observation runs are taken consecutively such that the zenith and azimuth pointing angle range is always equal for a sequence of three runs. One observation sequence starts with the observation of a background region with -35 min offset in right ascension from the signal region pointing position and is performed with a standard length of 33 min. The array pointing moves forward by 35 min in right ascension immediately after the end of the first observation within a realistic run transition time of 2 min. The second run of the sequence observes then the signal region for 33 min. The third observation is again scheduled for 33 min immediately after the second observation by moving the array pointing again by 35 min forward in right ascension within 2 min. Finally, the number of events after the application of standard γ-ray cuts in the signal and and the corresponding number of events in background region are compared. The observation strategy ensures as stated that the zenith and azimuth pointing angle range is always the same for every run within a run sequence. The strong dependence of the H.E.S.S. I acceptance on the pointing zenith and azimuth angle does in consequence not influence the calculation of a γ-ray excess as the dependence is the same for the signal and the background region. Repeated taking of three run sequences in this observation pattern can accumulate the simulated amount of data. The advantage is that obviously the signal region can be as large as the H.E.S.S. FoV (see also the blue region in fig. 1) and the background regions (see also the yellow region in fig. 1) are further away from the signal region with the result of less expected WIMP self annihilation γ-ray flux in the background region. This leads to the expectation that the sensitivity of the On/Off observations to a WIMP self annihilation γ-ray flux in the Milky Way halo is better than for the rotated pixel background subtraction technique. On the other hand, the method needs 2/3 of the total observation time for the estimation of the expected number of background events in the signal region where the rotated pixel algorithm can use the complete observation time. It is a non trivial question which of the two competing factors is eventually dominant and therefore this realistic simulation is performed.

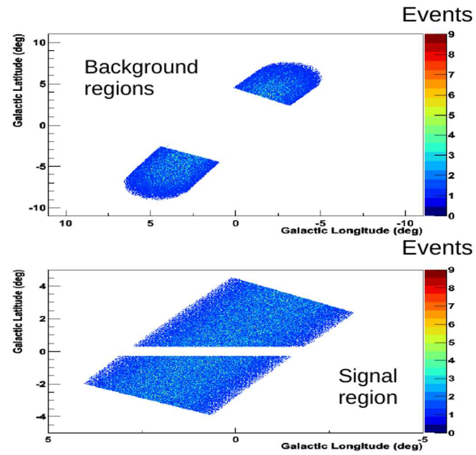

Figure 4: Simulated H.E.S.S. I events for the driftscan observation of the Milky Way dark matter halo in galactic coordinates. Simulated is the repeated taking of data at constant zenith and azimuth pointing where the galactic center region 'drifts' through the FoV after approximately half of the observation time. Each run is subsequently divided into two parts, the signal region enclosing the galactic center region in the lower panel and the background region in the upper panel. Known γ-ray sources and the galactic plane ($|b| < 0.3°$) are excluded. Exlcuded regions are treated with a special method (see text) to guarantee the same instrumental acceptance in the signal and background region.

5. Driftscan Observations

Figure 4 shows the simulation of events recorded in driftscan observations of the galactic center region. Driftscan runs are scheduled at a constant zenith and azimuth angle array pointing. The celestial pointing at the beginning of a run is chosen such that the galactic center region 'drifts through' the FoV after approximately half of the 68 min observation time. As for the simulation of On/Off events, realistic event rates for the observation at $\sim 20°$ zenith angle after standard H.E.S.S. I γ-ray cuts have been used. Also the radial acceptance as well as the energy dependence of the events after γ-ray cuts and the instrumental dead time resemble real observation conditions. A total of 150 h of observation time is simulated. The observed region is divided into many pixels each of which is much smaller than the H.E.S.S. I angular resolution. Each run is divided in time into one signal region enclosing the galactic center and one background region. The division of a driftscan run into two halves is realized such that the product of the average time a pixel stays in the H.E.S.S. I FoV with the total solid angle of the region is the same for the signal and background region. As for the rotated pixel technique and the On/Off observations all known γ-ray sources and the galactic plane ($|b| < 0.3°$) are excluded from the analysis. Excluded pixel are shifted mutually in right ascension between signal and background region at constant declination and special care is taken to guarantee that the shifting of the exclusion regions does not imbalance the instrumental acceptance of signal and background region. Every pixel excluded in the signal region is shifted along right ascension and constant declination as close as possible to the edge of the background region to minimize the expected γ-ray flux from WIMP annihilation in the background region. Similarly, every pixel excluded in the background region is shifted as close as possible to the edge of the signal region to maximize the expected γ-ray flux from WIMP annihilation in the signal region. The observation strategy and the subsequent data analysis ensure again, as for the On/Off and rotated pixel method, an equal instrumental acceptance in the signal and background region. Also similar to the On/Off method, the signal region is larger than for

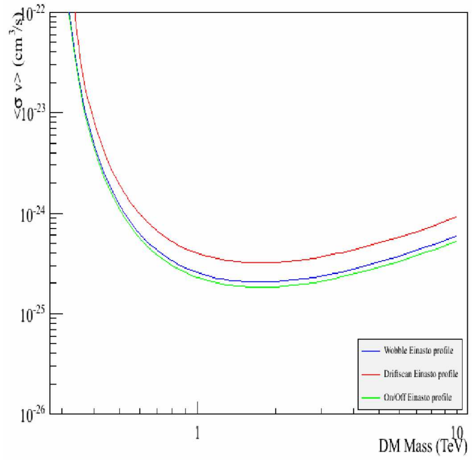

Figure 5: Sensitivity comparison between the rotated pixel method (blue), the On/Off method (green) and the driftscan method (red). Shown is the sensitivity (average 95% C.L. upper limit) to the velocity averaged self annihilation cross section $< \sigma v >$ as a function of the assumed WIMP mass in case that no signal can be detected.

the rotated pixel method and the background region is further away from the galactic center than possible for the rotated pixel method. These effects should increase the sensitivity to a WIMP annihilation γ-ray flux from the galactic halo. On the other hand, the increase in sensitivity competes with the decrease in sensitivity due to observation time only used for background observations and the average expected signal flux per signal pixel is smaller than for the On/Off method because the signal FoV is larger. Again, it is non trivial to estimate which effect dominates and a realistic simulation that compares all three discussed methods under equal conditions is necessary.

6. Sensitivity Comparison

Figure 5 shows the sensitivity of the rotated pixel, the On/Off and the driftscan method to the velocity averaged self annihilation cross section $< \sigma v >$ as a function of the WIMP mass. The Einasto parametrization for the dark matter density distribution of the Milky Way is assumed, parameters are taken from Pieri et al. [2011]. The continuous γ-ray spectrum expected from the WIMP self annihilation is adopted from Tasitsiomi and Olinto [2002]. For each investigated method, the On/Off, the driftscan and the rotated pixel method a total of 150 h of observation time is simulated. No WIMP annihilation γ-ray signal is simulated but only background events such that no significant γ-ray excess is resulting in all cases and an upper limit on $< \sigma v >$ can be derived which serves as a sensitivity estimation for the method under consideration. The upper limit on $< \sigma v >$ itself is calculated at 95% confidence level using H.E.S.S. I effective areas and energy threshold lookups for standard Hillas cuts (Aharonian et al. [2008]) and with a method that leads to results that are compatible with the method employed in H.E.S.S. Col. [2011] under equal conditions.

Figure 5 shows that the sensitivity to $< \sigma v >$ of each method investigated is comparable in the order of magnitude. The On/Off method is slightly more sensitive ($\sim$ 20% at 1 TeV WIMP mass) than the rotated pixel method. The driftscan method is less sensitive ($\sim$ a factor of 2 at 1 TeV WIMP mass) than the rotated pixel method and the On/Off method. However, the sensitivity of the driftscan method can be increased compared to the result shown in Fig. 5 when the size of the driftscan background region is increased at the cost of the size of the signal region. In an optimized signal to background region size case the sensitivity of the driftscan method agrees with the sensitivity of the On/Off and rotated pixel method within $\sim$ 30%.

Overall it can be stated that the increase in sensitivity of background subtraction methods alternative to the rotated pixel method is not as large as could be expected. The reason for this is the large amount of observation time that the alternative background subtraction methods need only for background observations. On the other hand, it is obvious that the alternative background subtraction methods can be sensitive to a WIMP annihilation γ-ray flux even in the case when the dark matter density profile is for some reason nearly constant in the vicinity of the Milky Way halo center but only decreasing at large distances to the galactic center. Additionally, the sensitivity of the driftscan and On/Off method is larger than the sensitivity of the rotated pixel method if the center of the Milky Way dark matter halo is not spatially coincident with the galactic center but offset by $\sim 1° - 2°$ as possibly indicated in Kuhlen et al. [2012]. In conclusion it is (despite of the sensitivity to the discussed benchmark model with an Einasto dark matter density profile being comparable to the rotated pixel technique) of interest to record at least a limited amount of observational data with the discussed observation strategies.

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