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Sensitivity of CTA to dark matter annihilations in the Galactic Centre

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We investigate that prospects for dark matter detection of the Cherenkov Telescope Array (CTA). We derive a realistic assessment of the sensitivity of CTA to photon fluxes from dark matter annihilation by means of a binned likelihood analysis for the Einasto and Navarro-Frenk-White halo profiles. We use the most up to date instrument response functions and background simulation model provided by the CTA Collaboration. We find that, with 500 hours of observation, under the Einasto profile CTA is bound to exclude at the 95% C.L. the majority of realistic models for heavy supersymmetric dark matter. CTA will be able to probe many cases corresponding to a spin-independent scattering cross section below the reach of 1-tonne underground detector searches for dark matter, in fact even well below the irreducible neutrino background for direct detection. On the other hand, many points lying beyond the sensitivity of CTA will be within the reach of 1-tonne detectors, and some within collider reach. Altogether, CTA will provide a highly sensitive way of searching for dark matter that will be partially overlapping and partially complementary with 1-tonne detector and collider searches, thus being instrumental to effectively explore the nearly full parameter space of many models of SUSY dark matter.

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1. Introduction

The search for particles that comprise the dark matter (DM) in the Universe has in recent years made much progress. Alternative and complementary experimental strategies are employed ranging from direct detection of DM-nucleon scattering in underground laboratories, to indirect detection of DM through observation of the Standard Model products of annihilation in astrophysical phenomena, to DM direct production at colliders.

In this proceedings, we report on our recent paper [1] in which we calculated the sensitivity of the upcoming Cherenkov Telescope Array (CTA) to DM annihilations in the Galactic Centre (GC), and used the results to determine the prospects for detection of supersymmetric (SUSY) models with neutralino DM.

2. Derivation of the CTA reach

We present here the calculation of CTA's sensitivity to the DM annihilation cross section. Some other recent work on the subject can be found in [2, 3, 4, 5].

We use the *Ring Method*. Two regions are identified in the plane of the galactic coordinates l and b, as shown in Fig. 1. The "signal", or ON, region is based on a circle of angular radius $\Delta_{\rm cut} = 1.36^\circ$ around the GC. The "background", or OFF, region is based on a ring centred at the offset coordinate $b_{\rm off} = 1.42^\circ$, with an inner angular radius of $r_1 = 0.55^\circ$ and an outer radius of $r_2 = 2.88^\circ$, from which the ON region is subtracted. The strip of sky characterised by $|b| < 0.3^\circ$ about the GC and the region of the sky within the inner radius r_1 do not belong to either the ON or OFF regions.

We proceed to create a binned likelihood function. For each energy bin, i, the expected number of counts from DM annihilation is calculated:

$$N_i^{\rm ann} = t_{\rm obs} \cdot J \cdot \frac{\sigma v}{8\pi m_\chi^2} \int_{\Delta E_i} dE \left(\frac{1}{\sqrt{2\pi\delta(E)^2}} \int_{26\,{\rm GeV}}^{m_\chi} d\bar{E} \frac{dN_\gamma(\bar{E})}{d\bar{E}} A_{\rm eff}(\bar{E}) e^{-\frac{(E-\bar{E})^2}{2\delta(E)^2}} \right), \tag{2.1}$$

where $A_{\rm eff}$ is the effective area of the detector, $\delta(E)$ is the energy resolution, dN_γ/dE is the annihilation spectrum, and J is the J-factor for either the ON or OFF region. For $A_{\rm eff}$ and $\delta(E)$ we use the most up to date instrument response functions provided by the CTA Collaboration. We take an observation time $t_{\rm obs} = 500$ h .

As is well known, the J-factor is defined by integration along the line of sight of the DM halo profile squared, $\rho^2(r)$. Using the Einasto DM density profile [6], we obtain $J_{\rm ON}^{\rm Ein} = 7.44 \times 10^{21}\,{\rm GeV}^2/{\rm cm}^5$ and $J_{\rm OFF}^{\rm Ein} = 1.21 \times 10^{22}\,{\rm GeV}^2/{\rm cm}^5$ for the J-factors of the ON and OFF regions, respectively. The corresponding values for the NFW [7] profile are $J_{\rm ON}^{\rm NFW} = 3.89 \times 10^{21}\,{\rm GeV}^2/{\rm cm}^5$ and $J_{\rm OFF}^{\rm NFW} = 5.78 \times 10^{21}\,{\rm GeV}^2/{\rm cm}^5$.

The binned Poisson likelihood is defined by

$$\mathcal{L} = \prod_{i,j} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} . \tag{2.2}$$

In Eq. (2.2) μ_{ij} is the expected number of photons in bin ij, with the index i running over the energy bins and $j = 1,2$ for the ON and OFF region, respectively. It is given by the sum of the background

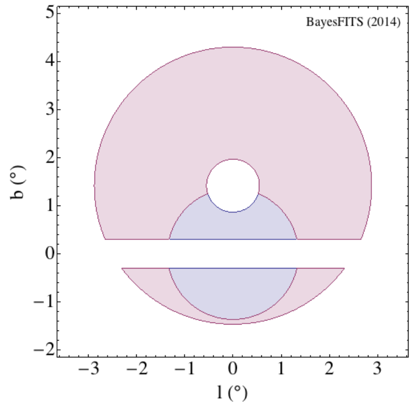

Figure 1: In blue, the **ON** region: the angular radius is $\Delta_{\rm cut} = 1.36°$. In pink, the **OFF** region: the offset from the GC is $b_{\rm off} = 1.42°$; the inner radius is $r_1 = 0.55°$ and the outer radius is $r_2 = 2.88°$. The strip of sky at $|b| < 0.3°$ is subtracted from the ON and OFF regions.

and the expected count from DM annihilation, Eq. (2.1). n_{ij} is the number of photons counted in bin ij.

We find the 95% C.L. limit by setting n_{ij} equal to the number of background-only photons and calculating $\mathscr{L}$ by increasing the annihilation cross section from the best fit value (σv= 0) until the difference in $-2\ln\mathscr{L}$ from the best fit value is 2.71 (one-sided 95% C.L.). We use an updated [8] background estimate provided by the CTA Collaboration [9].

It should be noted that we have not included uncertainties in the DM distribution, systematic uncertainties in the detector response, or included the diffuse γ-ray background. The uncertainty in the DM distribution enters into the calculation of the limits through the J-factors in Eq. (2.1). We account for this by presenting limits for two different realisations of the DM distribution, the NFW and Einasto profiles. The systematic uncertainty due to the finite energy resolution of the experiment already appears in Eq. (2.1). However further systematic effects can be present such as varying acceptance across the field of view or uncertainties in the effective area. Finally, the diffuse astrophysical γ-ray background around the GC measured by H.E.S.S. [10] and Fermi-LAT [11] presents a challenge to this type of ON/OFF analysis since this background will be larger in the ON (signal) region than the OFF (background) region mimicking the searched for signal. Thus the sensitivity presented here is somewhat optimistic and would be reduced due to the diffuse background and systematic uncertainties, however the treatment of Ref. [5] suggests that a morphological analysis could partially mitigate these effects.

Figure 2 shows the derived 95% C.L. limits for some specific final states including the most common primary annihilation channels found in the Minimal Supersymmetric Standard Model (MSSM) using the binned likelihood of Eq. (2.2). The limits obtained can probe values of σv below the "canonical" thermal relic value for all of the final states.

3. Application to the parameter space of the pMSSM

We apply the results of Sec. 2 to a scan of the phenomenological MSSM (pMSSM), whose parameters and ranges are given in Ref. [1]. The scan is bound by set of constraints, which are also

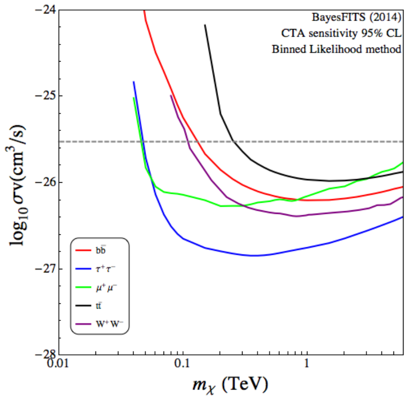

Figure 2: 95% C.L. CTA projected limits derived for the specific final states most commonly found in the MSSM with the binned likelihood of Eq. (2.2) for the Einasto profile. The limits for the W^+W^- and $b\bar{b}$ final states are compared to realistic MSSM models in Fig. 3.

described in detail in [1]. These include, most importantly, the measured values of the relic DM density [12], the mass of the Higgs boson [13], and several constraints from rare b decays.

We focus here in particular on Fig. 3(a), where we show on the plane of the annihilation cross section, σv, versus the neutralino mass, m_χ, the distribution of the pMSSM points with largest branching ratio to W^+W^-. The colour code shows the actual value of the branching ratio for each point. The distribution of the points predominantly annihilating to $b\bar{b}$ is shown in Fig. 3(b). In the panels of Fig. 3 we indicate with a dashed black line the expected reach of CTA in the relative final state. We also mark with orange stars the positions of a few benchmark points for indirect detection, which are tabulated in [1].

In Fig. 3(a) one can see a large region of points characterized by $m_\chi \sim 1\,\mathrm{TeV}$ and $\sigma v \sim 10^{-26}\,\mathrm{cm}^3/s$. That is the well known $\sim 1\,\mathrm{TeV}$ higgsino region, which is overwhelmingly favoured after the discovery of the Higgs boson at $\sim 125\,\mathrm{GeV}$ in many constrained SUSY models (see, e.g., [14]). One can also notice an Eiffel-tower shaped region for $m_\chi \approx 1.5-3.5\,\mathrm{TeV}$ characterized by an almost pure wino-like neutralino, for which σv is enhanced thanks to the Sommerfeld enhancement [15]. Both the 1 TeV higgsino and the $2-3\,\mathrm{TeV}$ wino solutions for heavy DM are well inside the sensitivity of CTA under the Einasto profile assumption.

Figure 3(b) shows that, under the same assumption, CTA will be sensitive to models featuring $b\bar{b}$ annihilation final states.

4. Complementarity of CTA with other experiments

In Fig. 4(a) we show the projected reach of CTA in the (m_χ, σ_p^{SI}) plane to compare it with direct detection experiments, which are sensitive to the spin-independent neutralino-proton cross section, σ_p^{SI}. The projected sensitivity of XENON-1T [16], is shown as a dashed grey line. The dot-dashed magenta line shows the onset of the irreducible background due to atmospheric and diffuse supernova neutrinos [17].

Figure 4(a) shows that over most of the pMSSM parameter space the reach of CTA is orthogonal to that of detectors directly measuring σ_p^{SI}. CTA will be able to probe the vast majority of

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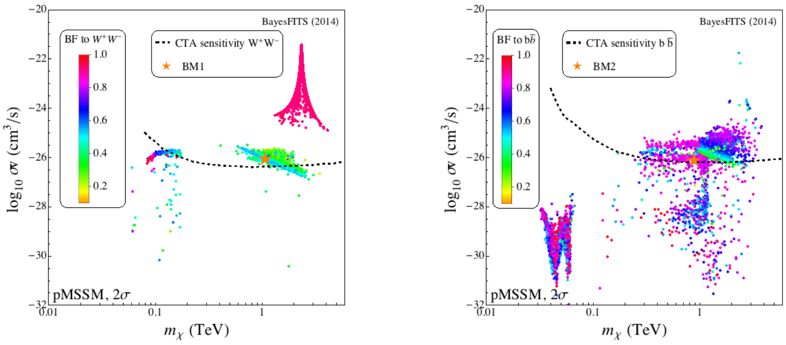


(a) (b)

Figure 3: (a) Distribution in the (m_χ, σv) plane of the points of our scan annihilating primarily into W^+W^-. The colour code shows the value of the W^+W^- branching fraction for each point. The dashed black line shows the projected sensitivity of CTA to points with BR($\chi\chi \to W^+W^-$) $= 100\%$, under the Einasto halo profile assumption. (b) Same as (a) but for $b\bar{b}$.

the points that lie well beyond the reach of 1-tonne detectors and even reach the region where the irreducible neutrino background will strongly curb sensitivity advances for direct detection experiments.

In Fig. 4(b) we show the reach of CTA in the ($m_{\tilde{g}}$, m_χ) plane. The solid black line shows the 95% C.L. bound obtained at ATLAS for the simplified model of [18]. With the exception of the coannihilation band, shown in Fig. 4(b) as a region of mass degeneracy, the reach of CTA is largely independent of the sparticle spectrum.

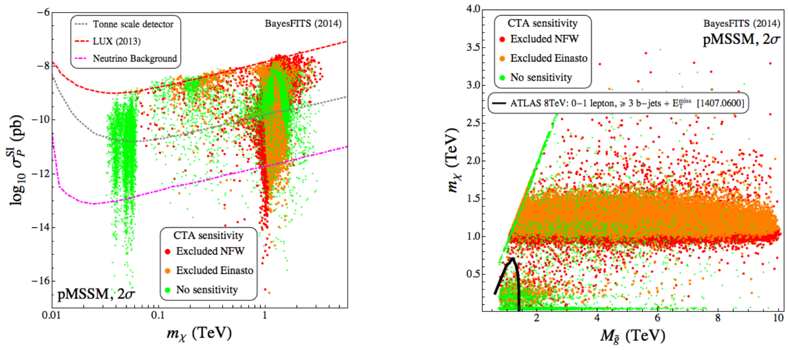
5. Impact of CTA sensitivity in the CMSSM

In Fig. 5 we show the constraining power of a combination of future upcoming experiments for the special case of the CMSSM [14]. These include: CMS and ATLAS direct SUSY searches at the LHC Run II; precise measurement of BR($B_s \to \mu^+\mu^-$) at LHCb in Run II; direct searches for dark matter at XENON-1T and other tonne-scale experiments; and indirect detection of dark matter at CTA through γ rays from the GC.

We want to point out that there is no single unconstrained point left in the figure. Figure 5 highlights the considerable amount of overlapping between the parameter space probed by CTA and that of other experiments, so that for most of the parameter space detection/exclusion will not rely on a single measurement.

6. Conclusions

We have shown in these proceedings that CTA will provide a highly sensitive way of searching for DM that will be partially overlapping and partially complementary with 1-tonne detector and collider searches, thus being instrumental to effectively explore the nearly full parameter space of the pMSSM.



(a) (b)

Figure 4: (a) The sensitivity of CTA to the pMSSM in the (m_χ, $\sigma_p^{\rm SI}$) plane. Red points are within reach of CTA assuming an NFW profile, orange points assuming an Einasto profile, green points are beyond the sensitivity of CTA. The LUX 90% C.L. bound is shown a dashed red line. The projected sensitivity of 1-tonne detectors is shown as a dotted grey line. The onset of the atmospheric and diffuse supernova neutrino background is shown with a dot-dashed magenta line. (b) Sensitivity of CTA in the ($m_{\tilde{g}}$, m_χ) plane, the thick black line shows the current ATLAS limit in the simplified model of Ref. [18].

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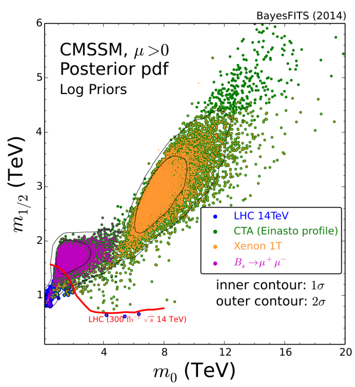

Figure 5: Marginalized 2D posterior pdf in the (m_0, $m_{1/2}$) plane of the CMSSM with $\mu > 0$. 68% and 95% credible regions are shown by the inner and outer contours, respectively. Points are distributed according to the posterior probability. The projected LHC Run II 95% C.L. exclusion line is shown in red solid for reference. Coloured points show the future sensitivity to direct SUSY searches in blue, measurement of BR $\left(B_s \to \mu^+\mu^-\right)$ in magenta, tonne-scale underground detectors in orange, and CTA in green.

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