Search for relic neutralinos with Milagro

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Abstract. The neutralino, the lightest stable supersymmetric particle, is a strong theoretical candidate for the missing astronomical "dark matter". Depending on their annihilation cross section, relic neutralinos from early formation of the Universe trapped in orbits around the Sun may currently be annihilating at measurable rates. The Minimal Supersymmetric extensions of the Standard Model predict that such annihilations should produce gamma rays with energies above 100 GeV.

Milagro is an air shower array which uses the water Cherenkov technique and is capable of detecting TeV gamma rays from the direction of the Sun with an angular resolution of 0.75 degrees. Analysis of Milagro data with an exposure to the Sun of 1165 hours shows no statistically significant signal. Resulting limits that can be set on the gamma-ray flux due to near-Solar neutralino annihilations and on neutralino cross-section are presented.

INTRODUCTION

There is very strong evidence that the Universe, and galaxies in particular, are full of non-baryonic “dark matter” (see, for example, [1, 2, 3]). One candidate for this dark matter is the neutralino (χ), a weakly interacting massive particle (WIMP) predicted by super-symmetric theories [4, 5].

One possible method for detecting dark matter particles is from their annihilation into gamma rays. The Minimal Supersymmetric extension of the Standard Model (MSSM) predicts that the gamma rays emerging from $\chi\chi \to \gamma\gamma$ and $\chi\chi \to Z\gamma$ neutralino annihilation modes will give distinct monochromatic signals in the energy range between 100 GeV and 10 TeV, depending on the neutralino mass. An additional “continuum” spectrum signal of photons will be produced by the decay of secondaries produced in the non-photonic annihilation modes.

The Milagro γ-ray observatory, which has been taking data since 1999, is sensitive to cosmic gamma rays at energies around 1 TeV and is capable of continuously monitoring the overhead sky with an angular resolution of 0.75°. In this paper, we present the results of a search for a TeV gamma-ray signal from the vicinity of the Sun (1-2 solar radii) with Milagro. For a more detailed description of the detector itself and reconstruction techniques used, see references [6, 7].

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[1] R. Atkins, W. Benbow, D. Berley, E. Blaufuss, J. Bussons, D. G. Coyne, T. DeYoung, B. L. Dingus, D. E. Dorfan, R. W. Ellsworth, L. Fleysher, R. Fleysher, G. Gisler, M. M. Gonzalez, J. A. Goodman, T. J. Haines, E. Hays, C. M. Hoffman, L. A. Kelley, C. P. Lansdell, J. T. Linnemann, J. E. McEnery, R. S. Miller, A. I. Mincer, M. F. Morales, P. Nemethy, D. Noyes, J. M. Ryan, F. W. Samuelson, A. Shoup, G. Sinnis, A. J. Smith, G. W. Sullivan, D. A. Williams, S. Westerhoff, M. E. Wilson, X. W. Xu, G. B. Yodh

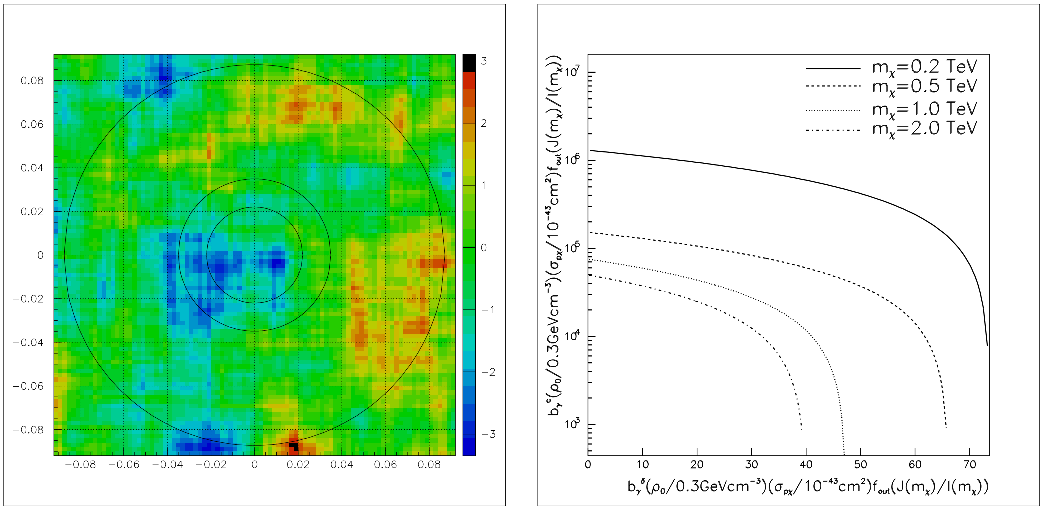

FIGURE 1. **Left:** The map of statistical significance (z-score) of the number of excess events from the region of the sky around the Sun. The map is made using azimuthal equal-area projection in polar case centered on the Sun. Contours represent loci of distance 1.26°, 2.0° and 5.0° from the Celestial object. **Right:** The values of $\left(\rho_0\sigma_{p\chi}b_\gamma^\delta f_{out}J(m_\chi)/I(m_\chi),\, \rho_0\sigma_{p\chi}b_\gamma^c f_{out}J(m_\chi)/I(m_\chi)\right)$ below the lines are allowed based the constructed limit for corresponding neutralino masses. As one progresses from low to high m_χ, the detector effective area goes up while the flux of incoming neutralinos goes down as $1/m_\chi$ for fixed dark matter density ρ_0. In addition, the capture probability is also decreasing as $1/m_\chi$ for elastic scattering on a fixed mass target. This explains qualitative behavior of these lines.

OUTCOME OF THE OBSERVATION

The data used in this work was chosen to satisfy the following conditions: online reconstruction between the 19th of July 2000 and the 10th of September 2001, the number of PMTs required for a shower to trigger the detector greater than 60, the number of PMTs used in the angular reconstruction greater than 20, zenith angles smaller than 45 degrees, and passing the gamma/hadron separation cut [7]. The start and end dates correspond respectively to introduction of the hadron separation parameter into the online reconstruction code and detector turn-off for scheduled repairs. Several data runs were removed from the dataset which included calibration runs and the data recorded when there were online DAQ problems.

For each position of the Sun the number of expected background events is found using event rates from the same local region of the sky at a time when the Sun is not present using the technique described in [8]. The method is based on isotropy of the cosmic-ray background and the assumption of short time scale detector stability. It allows exclusion of known sources from background estimation and correct restoration of the number of excess events to be used for flux measurement. Hence, $\pm 5°$ regions around the Moon and the Crab Nebula were vetoed from the data set as they present known sources of anisotropy to the cosmic-ray background.

For the current search we define at the outset the critical value of the z-score (number of sigmas) at 5σ (which approximately corresponds to the level of significance of $2.9 \cdot 10^{-7}$). If no excess from the vicinity of the Sun is found, we construct a limit

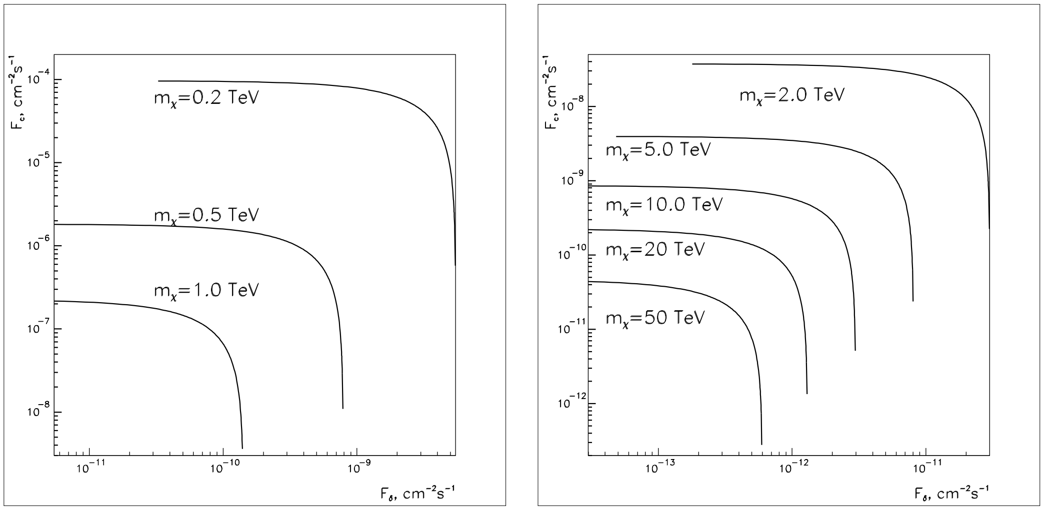

FIGURE 2. The values of (F_δ,F_c) below the lines are allowed for corresponding neutralino masses.

on the source strength as a strength which, if present, would have given us a detectable signal ($> 5\sigma$) with 97.7% (2σ) probability [9]. In addition, following the more standard procedure [10], assuming that the source exists, a 90% one-sided confidence interval on its strength is also calculated.

Photons produced in the Sun will be absorbed, whereas the distribution of neutralino annihilations outside is a rapidly falling function of distance from the Sun. Therefore, we believe that the gamma-ray signal is produced mostly between 1 and 2 solar radii and treat the gamma-ray source as circle of 0.5° radius. It has been shown [11] that the optimal bin size is a slow function of the source size and for estimated 0.75° angular resolution of the detector, the optimal "on-source" bin is a circular one with the radius of 1.26° centered on the Sun.

Overall, 1164.7 hours of exposure to the Sun is obtained in the data set. The total number of events observed in the "on-source" bin is $N_{on} = 137211$ while $N_{on}^b = 137728$ events is expected based on the "off-source" exposure, leading to the z-score value of -1.35σ (see figure 1(left)). Therefore, the null hypothesis of the absence of gamma-ray emission from the Sun can not be rejected and a limit on the possible γ-ray flux from the solar region is obtained. For details of the proformed analysis please see [11, 12]

LIMIT ON THE PHOTON FLUX DUE TO NEUTRALINO ANNIHILATIONS

Because the two close direct-production spectral lines can not be resolved by the Milagro detector, the differential photon flux due to neutralino annihilations is assumed to have the form (see [13]):

$$\frac{dF(E_\gamma)}{dE_\gamma} = F_\delta \delta(E_\gamma - m_\chi) + \frac{F_c}{m_\chi} \cdot \frac{\left(\frac{E_\gamma}{m_\chi}\right)^{-3/2} e^{-7.8E/m_\chi}}{\int_{0.01}^{1} x^{-3/2} e^{-7.8x} dx} \tag{1}$$

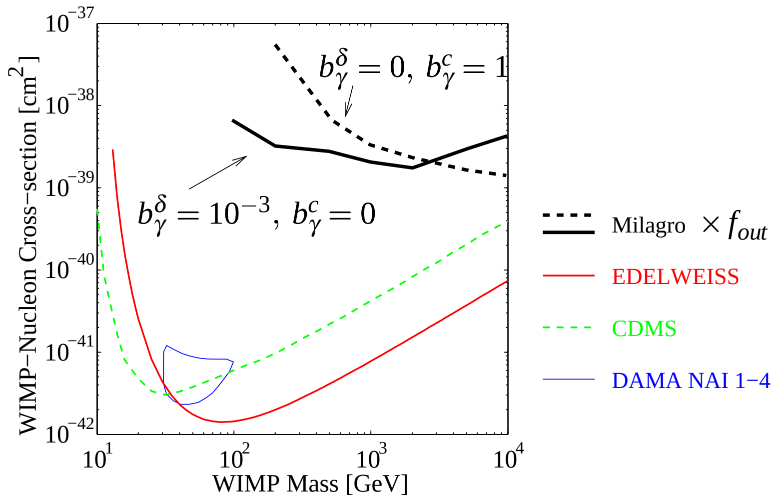

FIGURE 3. Upper boundary of a 90% one-sided confidence interval on neutralino-nucleon cross-sections obtained from different direct-search experiments. The closed contour is the allowed region at 3σ confidence level from the DAMA experiment. The plot is adopted from [14]. The two Milagro curves plotted assume an equilibrium situation where the annihilation rate $J(m_{\chi})$ equals the capture rate $I(m_{\chi})$, and consider the direct and nondirect annihilation modes for preset values of b_{γ} [15, 16]. The Milagro limit is obtained by dividing the plotted values by the fraction of annihilations that occur outside the Sun, f_{out}, for which calculations vary from 10^{-1} to 10^{-16} [17, 18, 11].

where F_{δ} is the integral flux due to a δ-function-like photon annihilation channel and F_c is the integral flux of photons with energies greater than $0.01 \cdot m_{\chi}$ due to continuum photon spectrum annihilation channel of neutralinos with mass m_{χ}. Here, the normalization of the continuum photon spectrum has been written out explicitly.

Figure 2 presents the curves demarcating the allowed and excluded regions in the photon flux parameter space (F_{δ}, F_c) corresponding to the significance $2.9 \cdot 10^{-7}$ and the power of the test of 97.7% which have a form of straight lines in the (F_{δ}, F_c) plane. For the depiction of the one-sided 90% confidence interval in the (F_{δ}, F_c) plane, both axes in the figure 2 should be rescaled by 0.4344.

Figure 2 is the derived limit on the values of the parameters of the gamma-ray emission model (equation (1)) due to near solar WIMP annihilation and is independent of the models of their distribution in the Milky Way galaxy and the Solar system.

NEUTRALINO LIMITS

The interpretation of the constructed limit on the gamma-ray flux is highly model dependent. It is based, for instance, on assumptions regarding the shape of the velocity distribution of the dark matter in the galactic halo and its density profile in the Solar System. Therefore, several assumptions are made to construct limits on physically interesting quantities.

We assume Maxwellian velocity distribution of the neutralinos in the Solar system with mean velocity $V_0 = 220\ km/s$ and width $2V_0^2$. The photon flux of equation (1) at the Earth due to neutralino annihilations can be computed as:

$$dF_\chi(E_\gamma) = f_{out}(m_\chi) \cdot f_e \cdot b_\gamma(E_\gamma, m_\chi) \cdot \frac{J(m_\chi)}{4\pi L_\oplus^2}\, dE_\gamma \tag{2}$$

where $b_\gamma(E_\gamma, m_\chi)$ is differential photon yield per neutralino for producing a photon with energy E_γ in neutralino-neutralino annihilation, $f_{out}(m_\chi)$ is the fraction of neutralinos annihilating outside the Sun, f_e is the fraction of produced photons which escape from the Sun and is of the order of $1/2$, $J(m_\chi)$ is the total neutralino annihilation rate in the Solar system and $L_\oplus = 1.5 \cdot 10^{11}\ m$ is the mean Sun-Earth distance.

Given the functional form of the flux from equation (1), the photon yield $b_\gamma(E_\gamma, m_\chi)$ is:

$$b_\gamma(E_\gamma, m_\chi) = b_\gamma^\delta(m_\chi)\delta\left(E_\gamma - m_\chi\right) + \frac{b_\gamma^c(m_\chi)}{m_\chi} \cdot \frac{\left(\frac{E_\gamma}{m_\chi}\right)^{-3/2} e^{-7.8E/m_\chi}}{\int_{0.01}^{1} x^{-3/2} e^{-7.8x} dx} \tag{3}$$

where b_γ^δ (b_γ^c) is the number of photons produced per annihilation directly (indirectly).

One can also make an assumption that an equilibrium situation has been reached and that the annihilation rate $J(m_\chi)$ and the capture rate $I(m_\chi)$ are identical. (We use this in figure 3 below.)

A 3-D calculation has been performed [11] to determine the rate $I(m_\chi)$ of WIMP capture by the Sun as a function of the neutralino mass. For given local galactic dark matter density ρ_0, a structure-less $\chi - p$ elastic cross-section $\sigma_{p\chi}$ determines how often a neutralino passing through the Sun scatters and loses enough energy to get gravitationally captured.

A limit on $\sigma_{p\chi} b_\gamma$ would provide constraints on parameters of Super Symmetric models. Using the formulae (1,2,3), however, one obtains neutralino-mass-dependent limits on the product of $\rho_0 \sigma_{p\chi} b_\gamma f_{out}(J/I)$ as presented in figure 1(right). While the value of the local dark matter density ρ_0 is known relatively well, there are substantial disagreements on the fraction of neutralino annihilations near the Sun f_{out}.

The problem of WIMP capture on bound near-solar orbits was considered in [19, 20]. To our knowledge, the first one-dimensional computer simulation of the distribution of the annihilation points near the Sun was treated by Strausz [17]. There, it was assumed that the Solar system consists of a uniform density Sun only and that the capture of a particle happens in its first scattering inside the Sun with an additional assumption that the Solar system has reached a dynamic equilibrium and that the capture rate $I(m_\chi)$ is equal to the annihilation one $J(m_\chi)$. Strausz [17] concluded that the fraction of all annihilations happening outside the Sun is $f_{out} \sim 10^{-5} - 10^{-7}$. Under essentially the same assumptions, a simulation done by [18] provided a drastically different prediction of $f_{out} \sim 10^{-14} - 10^{-16}$. However, a 3-D computer simulation of the neutralino annihilation distribution [11] provides an estimate $f_{out} \sim 10^{-1}$.

Therefore, in figure 3 we illustrate 90% one-sided confidence intervals on $f_{out}\sigma_{p\chi}$ for two different simplified cases: first $b_\gamma^\delta = 0.001$ and $b_\gamma^c = 0$, and second $b_\gamma^\delta = 0$ and $b_\gamma^c = 1$. In both cases we take $\rho_0 = 0.3\ GeV/cm^3$, $J(m_\chi) = I(m_\chi)$, and $f_{out} = 1$. It should be noted that while b_γ^δ is always less than unity [15], b_γ^c can be as high as 10 for some Super Symmetric models [16].

CONCLUSION

Analysis of the Milagro data set collected during 2000-2001 shows no evidence for a gamma-ray signal due to such a process. The limit on the possible gamma-ray flux due to such a process with significance $2.9 \cdot 10^{-7}$ and the power 97.7% has been set (see figure 2). Even in the absence of a clear signal the constructed exclusion limit may constrain the values of free parameters of supersymmetric models (see figure 1(right)). In addition, a standard 90% one-sided confidence interval on the magnitude of the photon flux due to near-Solar neutralino annihilations has been constructed.

The interpretation of the constructed limit on the gamma-ray flux is highly model dependent. Conversion of the flux measurement to a cross section limit requires knowledge of the annihilation rate, $J(m_\chi)$, the fraction of annihilations outside the Sun, f_{out}, and photon yield per annihilation, b_γ. These, in turn, depend on parameters of astrophysical and Super Symmetric models. Therefore, the results are presented with all these parameters written out explicitly.

ACKNOWLEDGMENTS

We acknowledge Scott Delay and Michael Schneider for their dedicated efforts in the construction and maintenance of the Milagro experiment. This work has been supported by the National Science Foundation (under grants PHY-0070933, -0075326, -0096256, -0097315, -0206656, -0245143, -0302000, and ATM-0002744) the US Department of Energy (Office of High-Energy Physics and Office of Nuclear Physics), Los Alamos National Laboratory, the University of California, and the Institute of Geophysics and Planetary Physics.

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