

Dark Matter annihilation lines with the Fermi-LAT

**Tomi Ylinen^{*}, Yvonne Edmonds[†], Elliott D. Bloom[†] and Jan Conrad[‡],
on behalf of the Fermi-LAT collaboration**

^{}Department of Physics, Royal Institute of Technology (KTH),
AlbaNova, SE-106 91 Stockholm, Sweden &
School of Pure and Applied Natural Sciences,
University of Kalmar, SE-391 82 Kalmar, Sweden &
The Oskar Klein Centre for Cosmo Particle Physics,
AlbaNova, SE-106 91 Stockholm, Sweden*

*[†]Kavli Institute for Particle Astrophysics and Cosmology,
SLAC National Accelerator Laboratory,
Stanford University, Menlo Park, California 94025, USA*

*[‡]Department of Physics, Stockholm University,
AlbaNova, SE-106 91 Stockholm, Sweden &
The Oskar Klein Centre for Cosmo Particle Physics,
AlbaNova, SE-106 91 Stockholm, Sweden*

Abstract. Dark matter constitutes one of the most intriguing but so far unresolved issues in physics today. In many extensions of the Standard Model the existence of a stable Weakly Interacting Massive Particle (WIMP) is predicted. The WIMP is an excellent dark matter particle candidate and one of the most interesting scenarios include an annihilation of two WIMPs into two gamma-rays. If the WIMPs are assumed to be non-relativistic, the resulting photons will both have an energy equal to the mass of the WIMP and manifest themselves as a monochromatic spectral line in the energy spectrum, smeared only by the energy resolution of the detector. This type of signal would represent a "smoking gun" for dark matter, since no other known astrophysical process should be able to produce it. The Fermi Gamma-ray Space Telescope (FGST) has been successfully launched on June 11, 2008, and is currently performing a one-year all sky survey. We report here on the search for dark matter line signals with Fermi Large Area Telescope (LAT), a pair conversion detector designed to study the gamma-ray sky in the energy range from 20 MeV to more than 300 GeV with unprecedented sensitivity and resolution.

Keywords: dark matter, lines, Fermi-LAT

I. INTRODUCTION

The evidence for the existence of cold Dark Matter (DM) is today convincing and range from measurements of galaxy clusters [1], galactic rotation curves [2], gravitational lensing [3], colliding galaxy clusters such as the Bullet cluster [5] and the cosmic microwave background [4].

In many theoretical models of DM a particle nature is proposed and many of the DM particle candidates have annihilation channels directly into two gamma-rays.

This means that if the DM particles are non-relativistic, the resulting gamma-rays will have an energy that is equal to the mass of the DM particle. The resulting energy spectrum will therefore have a spectral line with a shape given by the energy dispersion of the detector. The supersymmetric so-called Weakly Interacting Massive Particle (WIMP) and the inert Higgs particle [6] are two examples of promising DM candidates with this type of signal. If such a signal can be found it would represent the "smoking gun" of DM, since no other astrophysical source should be able to produce it.

Unfortunately, some of the promising models also predict low branching fractions for the 2γ channel, since tree-level Feynman diagrams are forbidden for the process. This is for example the case for the supersymmetric WIMP [7]. It is, however, possible that this can be compensated by a boost of the annihilation rate due to e.g. substructures in DM halos, steep DM halo profiles or the Sommerfeld enhancement [8].

Also other theoretical models exist, where the resulting spectrum is similar to an annihilation line and can therefore be searched for in a similar manner. These include e.g. gravitino decay [9] and radiative corrections to internal bremsstrahlung [10].

II. FERMI LARGE AREA TELESCOPE

The Fermi Gamma-ray Space Telescope (FGST) was launched successfully from the Kennedy Space Center in Florida on June 11, 2008, and is now orbiting the Earth at an altitude of 565 km and an inclination of 25.6° .

The main instrument onboard the FGST is the Fermi Large Area Telescope (LAT), which is a pair conversion detector designed to measure gamma-rays in the sky in the energy range from 20 MeV to more than 300 GeV [11]. It consists of a 4×4 array of 16 identical towers, where each tower is composed of a tracker

module and a calorimeter module. Each tracker module is made up of planes of multilayer silicon-strip detectors, interleaved by tungsten converter foils whereas each calorimeter module is based on hodoscopically arranged CsI(Tl) crystals. The tracker part of the Fermi-LAT is covered by an anti-coincidence shield of plastic scintillators which is used to distinguish the gamma-rays from the charged particle background. The instrument has an unprecedented sensitivity and resolution compared to its predecessor the Energetic Gamma-Ray Experiment Telescope (EGRET) [12] and one of the main science goals of the Fermi-LAT is to probe the nature of DM.

III. ANALYSIS

The limits we will present at the conference are determined with an unbinned likelihood method, in which a composite model given by Eq. 1 is minimised with MINOS, inherent in the ROOT class RooMinuit.

$$L(\bar{x}|f, \gamma) = \prod_{i=0}^{n_{tot}} f \cdot S(x_i) + (1 - f) \cdot B(x_i, \gamma) \quad (1)$$

Here, f and γ are free parameters and represent the signal fraction and the index of the power-law function used to model the background, respectively. The normalised signal and background models are constructed to a composite model within the RooFit framework in ROOT [13].

When the likelihood has been minimised, both upper limits and detections can be determined from the shape of the \ln -likelihood function as a function of the signal fraction, as shown in Fig. 1. The $i\sigma$ confidence interval on f is determined by stepping up from the minimum of the \ln -likelihood by an amount given by $i^2 \cdot 0.5$ and finding the corresponding values of f . The inclusion of zero in the confidence interval for f corresponds to an upper limit whereas an exclusion marks a detection at the specified confidence level $i\sigma$.

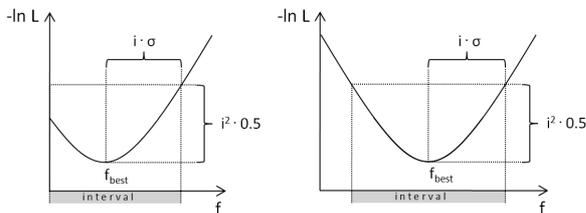


Fig. 1: An illustration of how an upper limit (*left*) or a detection (*right*) can be determined from the shape of the \ln -likelihood function. The number of sigmas of the confidence level is represented by i and f is the signal fraction.

In order to localise the background estimate as much as possible, a sliding window in energy is used. Due to the steeply falling spectrum and the resulting low statistics at higher energies, a larger window is used at the high end of the spectrum to better constrain the background.

The properties of a statistical method can be measured in terms of its power and coverage. In terms of confidence intervals, coverage is the probability to include the true parameter value in the confidence interval, i.e. $P(f \in [f_1, f_2]) = 1 - \alpha$. Power is the probability to reject the null hypothesis when the alternative hypothesis is true. If the null hypothesis is the alternative hypothesis, power reduces to $1 - \text{coverage}$.

We have tested the power and coverage of the unbinned likelihood at 95% confidence level with simulations and found them to be satisfactory. The simulations show that at a given mass the coverage is close to nominal across a wide range of true signal fractions, i.e. the probability of success (the exclusion of the true parameter value in the interval), p , is roughly α . The limits are, however, determined at n different masses, corresponding to n close to independent trials, so the probability of at least one success in a given experiment will be more than α . This leads to a loss of coverage as shown in Fig. 2, where the number of trials is $n = 15$. As can be seen in the figure, $p = 5\%$ does not give the nominal coverage of 95%.

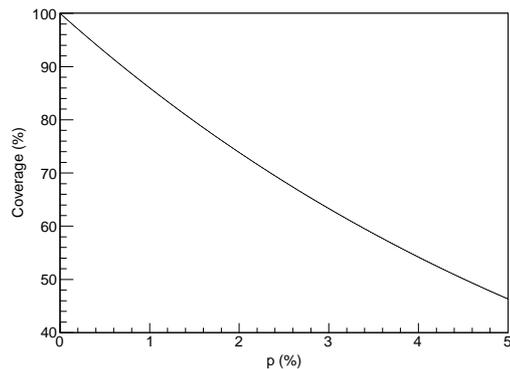


Fig. 2: The true coverage as a function of the probability for success for $n = 15$. For a p -value of 5%, the nominal coverage is less than 95%.

The nominal coverage can be achieved via a “trial factor” corrected α . The trial factor corrected $p = \alpha$ can be deduced from Eq. 2, which represents the binomial probability of zero successes, $k = 0$, in n trials if the probability of success in each trial is p .

$$P(K = 0) = (1 - p)^n, \quad (2)$$

where the random variable $K \sim B(n, p)$.

A potential spectral line from DM annihilations will be smeared out by the energy dispersion of the detector. The signal model used in the unbinned likelihood must therefore reflect the line response of the detector. For this analysis the line shape has been parametrised with the sum of two Gaussian functions, whose parameters have been determined with GLEAM, a GEANT 4-based Fermi-LAT detector simulation package.

An illustration of the resulting parametrised line shape over the analysed energy range can be seen in Fig. 3.

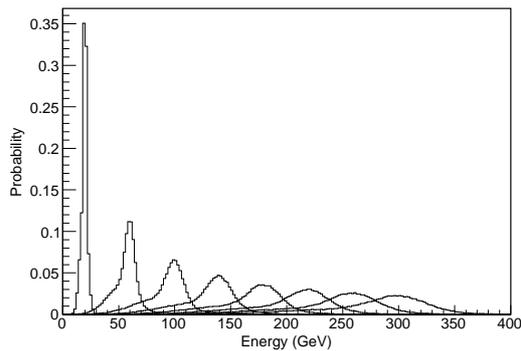


Fig. 3: The evolution of the probability distribution function for the line with energy.

In the event reconstruction of the Fermi-LAT, three different energy reconstruction algorithms are used. One of them is based on determining the energy of the incoming gamma-ray from its longitudinal electromagnetic shower profile. For this analysis, we use this “profile energy” instead of the standard energy, which is a composition of all three energy reconstruction algorithms.

IV. DATA SELECTION

For the analysis, Fermi-LAT data is used. The region-of-interest has been chosen to be the full sky but excluding galactic latitudes of $|b| < 10^\circ$ and a circular region around all point sources specified in the Fermi-LAT source catalogue.

The energy dependent exposure is determined with ScienceTools [15], a software framework developed by the Fermi-LAT collaboration. ScienceTools takes an event file (FT1) and a spacecraft file (FT2) as input, both in fits-format, and calculates the exposure in units of cm^2s , taking into account both the movement of the satellite in its orbit as specified in the FT2 file and the instrument response function. Events outside the field of view of the Fermi-LAT have also been removed from the FT1 file.

The solid angle of the region-of-interest is calculated via “sphere point-picking”, i.e. by uniformly generating points on a unit sphere and then determining which fraction of the points lie within the specified region-of-interest.

V. RESULTS

The confidence level at which detection can be claimed is set to 5σ , corresponding to a probability given by five standard deviations from the mean of a Gaussian distribution. The resulting 5σ limits in the case of detection and the trial factor corrected 2σ limits in the case of a non-detection from the unbinned likelihood method will be shown at the conference.

We are currently preparing a paper, where a large data set of almost one full year of Fermi-LAT data is analysed.

ACKNOWLEDGEMENTS

The Fermi-LAT collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy for science analysis during the operations phase is also gratefully acknowledged.

REFERENCES

- [1] F. Zwicky, *Helvetica Physica Acta*, 6 (1933) 110.
- [2] W.J.G. de Blok & S.S. McGaugh, *MNRAS*, 290 (1997) 533.
- [3] J.A. Tyson, G.P. Kochanski & I.P. DellAntonio, *ApJ*, 498 (1998) L107.
- [4] D.N. Spergel, et al., *ApJS*, 170 (2007) 377.
- [5] M. Markevitch, et al., *ApJ*, 606 (2004) 819.
- [6] M. Gustafsson, et al., *Phys. Rev. Lett.*, 99 (2007) 041301.
- [7] L. Bergström & P. Ullio, *Nucl. Phys. B*, 504 (1997) 27.
- [8] J. Bovy, *Phys. Rev. D*, 79 (2009) 083539, arXiv:0903.0413v2 [astro-ph.HE].
- [9] A. Ibarra & D. Tran, [astro-ph/0709.4593v1] (2007).
- [10] T. Bringmann, et al., *JHEP*, 01 (2008) 049.
- [11] W.B. Atwood, et al., arXiv:0902.1089v1 [astro-ph.IM] (2009).
- [12] G. Kanbach, et al., *Space Sci. Rev.* 49 (1988) 69.
- [13] W. Verkerke & D. Kirkby, arXiv:physics/0306116v1 [physics.data-an] (2003).
- [14] W. Rolke, A.M. López & J. Conrad, et al., *NIM A*, 551 (2005) 493.
- [15] <http://glast.gsfc.nasa.gov/ssc/data/>