Optimized analysis method for indirect dark matter searches with Imaging Air Cherenkov Telescopes

Jelena Aleksić, Javier Rico & Manel Martínez
Institut de Física d'Altes Energies (IFAE), Barcelona, Spain

Abstract

We describe a dedicated analysis approach for indirect Dark Matter searches with Imaging Air Cherenkov Telescopes. By using the full likelihood analysis, we take complete advantage of the distinct features expected in the gamma ray spectrum of Dark Matter origin, achieving better sensitivity with respect to the standard analysis chains. We describe the method and characterize its general performance. We also compare its sensitivity with that of the current standards for several Dark Matter annihilation models, obtaining gains of up to factors of order of 10. We compute the improved limits that can be reached using this new approach, taking as an example existing estimates for several benchmark models as well as the recent results from VERITAS on observations of the dwarf spheroidal galaxy Segue 1. Furthermore, we estimate the sensitivity of Cherenkov Telescopes for monochromatic line signals. Predictions are made on improvement that can be achieved for MAGIC and CTA. Lastly, we discuss how this method can be applied in a global, sensitivity-optimized indirect Dark Matter search that combines the results of all Cherenkov observatories of the present generation.

The full likelihood method

• **Conventional**: product of two Poisson for ON and OFF regions total number of events [1]:

$$\mathcal{L}(g,b\,|\,n,m) = \frac{(g+b)^n}{n!}e^{-(g+b)} \times \frac{(\tau b)^m}{m!}e^{-\tau b} \qquad (1)$$

g = estimated number of gamma-ray events
b = estimated number of background events
τ = ON/OFF normalization constant.
n = observed number of ON events
m = observed number of OFF events

• **Full likelihood**: PDF (expected measured spectral shape) times overall Poisson term [2]:

$$\mathcal{L}(N_{\mathrm{EST}}, M(\theta)\,|\,N_{\mathrm{OBS}}, E_1,\ldots,E_{N_{\mathrm{OBS}}}) = \frac{N_{\mathrm{EST}}^{N_{\mathrm{OBS}}}}{N_{\mathrm{OBS}}!}e^{-N_{\mathrm{EST}}} \times \prod_{i=1}^{N_{\mathrm{OBS}}} \mathcal{P}(E_i; M(\theta)) \qquad (2)$$

N_{OBS}, N_{EST} = Observed, estimated total number of events.

$\mathcal{P}(E_i;M(\theta))$ = PDF of a given event to be observed with *measured* energy E if dark matter model M of parameters θ is true. Obtained from normalized expected differential rate (signal+background). Contains all information from physics and instrument response.

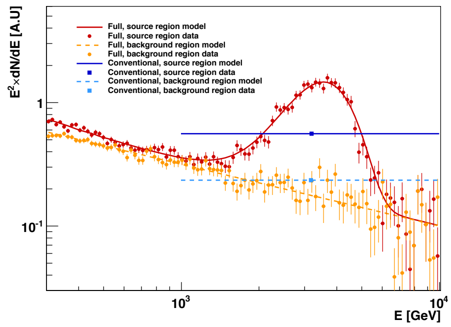

Fig 1. While the conventional analysis approach integrates out DM-induced features, the full likelihood takes maximal advantage of them. Lines show the assumed spectral energy distributions of the source and background regions, while the data points represent the measured events (fine binning is used for demonstration purposes only, the full likelihood is unbinned). The horizontal lines showto the average value within the energy range considered in the conventional method, with dots referring to the measurements.

Characterization of the method

• **Power**: we have assumed the MAGIC response function and looked for simple signal spectral features (e.g. monochromatic line or power law) in pure background simulated samples, by maximizing the likelihoods (1) and (2). Both signal estimators are unbiased (Fig. 2).

We have compared the size of confidence regions obtained by the conventional (CI_{cnvn}) and full likelihood (CI_{full}) methods.

Gain of the full likelihood is quantified by the Improvement Factor (*IF*, Fig. 3):

$$IF(M(\theta)) = \langle CI_{\mathrm{cnvn}} / CI_{\mathrm{full}} \rangle$$

• **Stability and robustness** have been satisfactorily evaluated by studying the effect on the *IF* of: different values of experimental parameters (e.g. number of events, size of the background sample, energy range); the presence of a signal in the data sample; or a non-perfectly known response function.

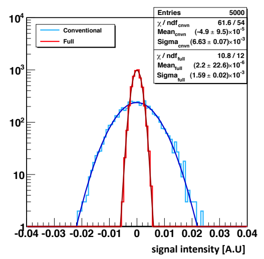

Fig 2. Distribution of the free parameter (signal intensity) estimated by the conventional and full likelihood methods, when searching for a power-law signal in 5000 simulated background experiments.

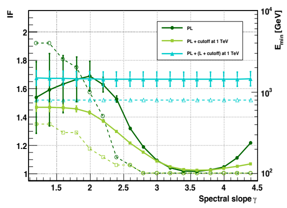

Fig 3. Improvement Factor as a function of spectral slope for pure power law (PL), PL with cutoff and PL with cutoff and monochromatic line. Also shown are the optimal values of the lower energy bound of the integration range for the conventional approach.

Sensitivity for dark matter searches

• **Benchmark models**. We have computed the Improvement Factors for DM benchmark models studied in [3] expected for MAGIC and CTA. They range between 1.2 (1.6) for MAGIC (CTA) searches of model *K'*, and 2.1 (3.8) for model *BM4*.

• **Secondary γ-rays from annihilation into SM particles**. We have considered annihilation into $b\bar{b}$, $\tau^+\tau^-$ and W^+W^- and computed how the latest DM results by VERITAS [4] could have been improved by using the full likelihood method (Fig. 4a). We have also computed the limits expected for the same channels with observations with MAGIC and CTA (Fig 4b). We obtain Improvement Factors, increasing with the DM particle mass (m_χ), and implying sensitivity improvements of up to one order of magnitude.

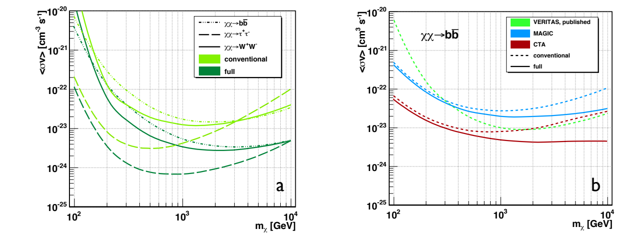

Fig 4. Comparison of the 95% confidence level upper limits on $\langle\sigma v\rangle$ as a function of m_χ, obtained with the conventional and full likelihood analyses and 50 h of observations of the Segue 1 galaxy. (a) Results for VERITAS for different final state channels. (b) Results for MAGIC, CTA and VERITAS for $b\bar{b}$ final state.

• **Monochromatic line**. Finally, we have considered DM annihilations into 2γ for MAGIC and CTA (Fig. 5).

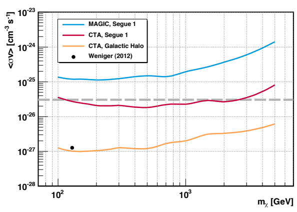

Fig 5. MAGIC and CTA 5σ sensitivity to $\langle\sigma v\rangle$ as a function of m_χ, for 50 hours of observations of Segue I and the Galactic Halo (CTA only), together with the value of $\langle\sigma v\rangle$ for the signal hint at m_χ=129 GeV, claimed in [5].

Towards a global result of indirect DM searches

The use of likelihood allows for a trivial merge of results though a global likelihood:

$$\mathcal{L}_T(M(\theta)) = \prod_{i=1}^{N_{\mathrm{inst}}} \mathcal{L}_i(M(\theta)),$$

where the index i can run over targets and/or observatories.

Therefore, merging results from e.g. MAGIC, HESS and VERITAS would benefit from a ~70% extra improvement in sensitivity, hence producing the most sensitive possible global DM search before CTA.

References

1. Rolke et al., *Nucl. Instrum. Meth.* A 551 (2005) 493
2. Aleksić, Rico & Martínez, JCAP 10 (2012) 032
3. Bringmann, Doro & Fornasa, JCAP 01 (2009) 016
4. Aliu et al., Phys. Rev. D 85 (2012) 062001
5. Weniger, JCAP 08 (2012) 007