Very high energy observations of the Galactic Centre with H.E.S.S.

L. Rolland, for the H.E.S.S. collaboration
Laboratoire de Physique Nucléaire et des Hautes Energies, IN2P3/CNRS, Universités Paris VI & VII
4 place Jussieu, F-75252 Paris Cedex 05, France
http://www.mpi-hd.mpg.de/hfm/HESS/public/hn_hesscollab.html

First results of the Galactic Centre (GC) observations with the H.E.S.S. array of Cherenkov telescopes in 2004 are presented, as well as preliminary interpretation of the very high energy (VHE) γ-ray signal in the framework of dark matter (DM) annihilation.

1 Introduction

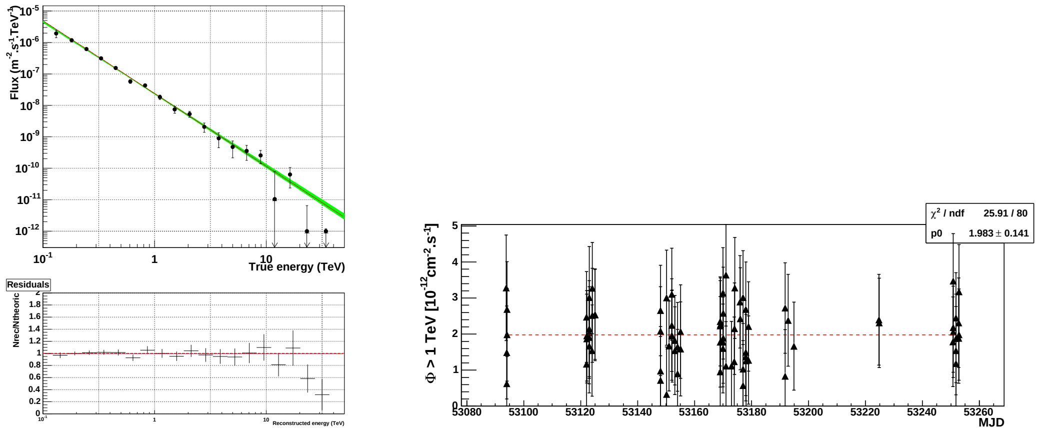
H.E.S.S. (High Energy Stereoscopic System) is an array of four Imaging Atmospheric Cherenkov Telescopes located in Namibia and dedicated to the detection of VHE γ-rays with energies above 100 GeV. Each telescope has a mirror with an area of 107 m^2 and a camera consisting of 960 photomultiplier tubes. With its angular resolution of better than $0.1°$ per event and its large field of view ($5°$), it is able to study the γ-ray morphology of extended sources.

Observations of the GC with two telescopes of H.E.S.S. in 2003 has revealed a signal [1,2]. The source lies within 1' of the black hole Sgr A* and exhibits a power-law energy spectrum with photon index of $2.21 \pm 0.09 \pm 0.15$.

Further 35.5 hours of observations have been collected with the full four-telescope system between April and September 2004. Independent techniques were employed to calibrate the detector [3], to reconstruct the air showers [4,5] and to derive the energy spectra [6,7] and angular distributions. Both yield consistent results. Preliminary analysis of the 2004 data are presented and possible interpretations are discussed.

2 H.E.S.S. observations and results

The data show a clear excess at the $32\,\sigma$ level within $0.14°$ around Sgr A*. Assuming a point-like source at the GC, the γ-ray excess is located at $l = 359°56'38''\pm10''\pm20''$, $b = 0°02'42''\pm8''\pm20''$,



(a) Energy spectrum

(b) Light curve

Figure 1: (a)Energy spectrum dN/dE of γ-rays from the GC. In the top panel, the line indicates the best fit spectrum. The colored area gives the $1\,\sigma$ confidence level (statistics) on the flux. The residuals are drawn in the lower panel: the ratio of the measured to fitted numbers of γ-rays in every energy bin shows the goodness of fit. (b) Run per run (28 minutes) light curve of the H.E.S.S. GC source in 2004. Systematics of 20% on the flux are included. The dashed line indicates the average integrated flux above 1 TeV.

within $4'' \pm 41''$ from the position of Sgr A*. Systematic errors dominate the uncertainties and are under study in order to be reduced.

Assuming a rotation invariant Gaussian shape of the source brightness, $\rho \propto \exp[-\theta^2/(2\sigma^2_{source})]$, a slight extension is found, at the level of $\sigma_{source} = 1.7' \pm 0.4'$ (statistical errors). It corresponds to 4 pc $\pm$ 1 pc at the distance of the GC (8.5 kpc). This is lower than the H.E.S.S. angular resolution of ∼6' per event and systematic errors have still to be estimated properly: as a first check, the strong signal from the point-like blazar PKS 2155-304 matches the point spread function.

The γ-ray spectrum of the GC source is shown in figure 1(a). It is consistent with a power-law, $\Phi(E) \propto E^{-\Gamma}$, with photon index $\Gamma = 2.29 \pm 0.05 \pm 0.10$ above the post-cuts energy threshold of 125 GeV. The derived integrated flux above 1 TeV is $\Phi(E > 1\,TeV) = (0.18 \pm 0.01 \pm 0.04) \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The spectrum shape and the flux of the source are consistent with the 2003 parameters and there is no indication for time variability of the flux as seen in figure 1(b), which shows the 28-minute average integrated flux above 1 TeV. An exponential cut-off $\Phi(E) \propto E^{-\Gamma} e^{-E/E_{cut}}$ has been searched for in the data. There is no indication for such a cut-off and a lower limit of $E_{cut} > 6$ TeV can be derived at 95% CL.

3 Constraints on dark matter

The γ-ray flux $\Phi(E)$ from annihilation of DM particles of mass m_{DM} located in a spherical halo of mass density profil $\rho(r)$ depends on the velocity-weighted annihilation cross-section $< \sigma v >$ and on the number of photons per annihilation event dN_γ/dE. It is usually factored into a term depending on the particle physics model and a term $\bar{J}$ depending on the halo parameters:

$$\Phi(E) = F_0 \times \frac{dN_\gamma}{dE} \times \frac{< \sigma v >}{3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}} \times \left(\frac{1\,\mathrm{TeV}}{m_{DM}}\right)^2 \times \bar{J} \times \Delta\Omega$$

where $F_0 = 2.8 \times 10^{-12}\,\mathrm{cm^2 s^{-1}}$. $\bar{J}$ is the average of the line-of-sight integrated squared particle density over the solid angle $\Delta\Omega$ of the observations (2×10^{-5} sr in this analysis):

$$\bar{J} = \frac{1}{8.5\,\mathrm{kpc}} \times \left(\frac{1}{0.3\,\mathrm{GeV\,cm^{-3}}}\right)^2 \times \frac{1}{\Delta\Omega} \times \int_{\Delta\Omega} d\Omega \int_{\ell=0}^{\infty} d\ell\, \rho^2(\ell)$$

From such an equation, one can derive the shape of the DM halo from the angular distribution of the annihilation signal, and constrain the particle physics model from the shape of the observed annihilation γ-ray spectrum. For the interpretation of the signal, we will assume that DM is formed of neutralinos, which are natural DM candidates in the minimal supersymmetric models (MSSM). Concerning the shape of the halo, N-body simulations of large scale structure formation predict that halo density profiles follow a power-law $\rho(r) \propto^{-\gamma}$ with γ between 1 (Navarro-Frenk-White NFW[8]) and 1.5 (Moore[9]). However, such simulations are valid for radius larger than ~1 kpc and extrapolations of the profiles down to subparsec scales result in huge uncertainties concerning their shape and density [10] (more than 6 orders of magnitude uncertainties).

The location of the TeV signal within errors at Sgr A* is consistent with a DM origin of the signal from the galactic DM halo which is now discussed.

3.1 Dark matter annihilation signal

As a first hypothesis, one assumes that the VHE signal observed by H.E.S.S. comes from DM annihilation only. It is then possible to constrain both the shape of the DM halo and the particle physics models. Assuming a DM halo with a spherical density profile $\rho(r) \propto r^{-\gamma}$, the shape of the signal is consistent with DM predictions for $0.95 < \gamma < 1.15$ ($2\,\sigma$ statistical errors only).

The energy spectrum provides the second test for a possible DM origin. The lower limit of 6 TeV of any exponential cut-off requires masses of DM particles that are unconfortably large for particle physics models. In the case of phenomenological MSSM models (described in the code DarkSusy[12]), the average γ-ray annihilation spectrum of heavy neutralinos of mass m_χ is approximated by [11]:

$$\frac{dN}{dE} = \begin{cases} \frac{0.73}{m_\chi} \times \frac{e^{-7.8\,E/m_\chi}}{(E/m_\chi)^{1.5}} & \text{if } E < m_\chi \\ 0 & \text{otherwise} \end{cases}$$

Such a shape is inconsistent with the data: compared to the fitted power law spectrum using a likelihood ratio, the neutralino annihilation spectrum is excluded with a confidence level of more than $6\,\sigma$.

In summary, the angular distribution is close to expectations for a NFW profile but the spectrum shape allows to exclude a neutralino annihilation origin for the signal.

3.2 Dark matter annihilation and background

The spectrum constraint can be relaxed assuming that only a fraction of the VHE γ-ray signal originates from DM annihilation. For the dominant non-dark-matter part, one assumes a power-law spectrum as generally observed. Constraints on the DM cross-sections are obtained assuming the shape and density of the halo. The upper limits derived in the case of a NFW profile are shown in the figure 2. They are easily normalised for other halo assumptions, e.g. they are reduced by a factor 500 in the case of the Moore profile ($\gamma = 1.5$), then excluding most of the pMSSM models. However, uncertainties on the shape of the halo do not allow to conclude.

4 Conclusion

Using the observations of the GC in 2004 with H.E.S.S., a VHE γ-ray source was confirmed within 1' of the central black hole Sgr A*. The measured spectrum has photon index of 2.29 ±

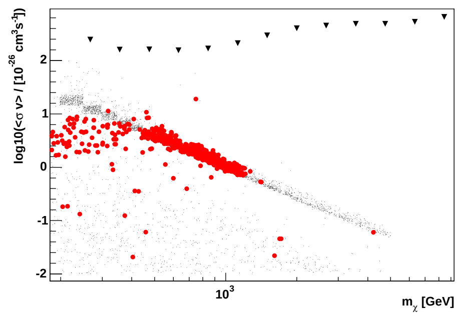


Figure 2: $3\,\sigma$ upper limits on the velocity average cross-sections as function of the neutralino mass (triangles) in the case of a NFW profile. Points are predictions of pMSSM models obtained from a scan using the DarkSusy package. Circles highlight the models whose DM relic density is compatible with the cosmological constraints ($0.094 < \Omega_{DM} h^2 < 0.129$).

0.05 ± 0.10 and the integrated flux above 1 TeV is $(0.18 \pm 0.01 \pm 0.04) \times 10^{-11}$ cm^{-2}s^{-1}. No time variability was seen between April and September 2004.

The position and extension of the VHE signal as seen by H.E.S.S. are compatible with astrophysical γ-ray emission originating from the black hole Sgr A*[13] or from the supernova remnant Sgr A East[14]. Concentrating ourselved into DM analysis in the framework of pMSSM models, the observed signal can not be interpreted as neutralino annihilations. If a DM component is superimposed onto a non-DM power law spectrum, loose constraints on the cross sections are obtained due to the huge halo uncertainties. Further studies on DM interpretation of the GC signal are under analysis[15].

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