The energy spectrum of the CR electrons at TeV energies

- The lifetime and propagation distance of Cosmic Ray electrons in the very high energy regime is strictly limited by energy losses via synchrotron radiation and inverse Compton scattering.

$$5 \times 10^5 \left(E/1\,\mathrm{TeV}\right)^{-1}\left(\left(B/5\,\mu\mathrm{G}\right)^2 + 1.6\left(w/1\mathrm{eV\,cm}^{-3}\right)\right)^{-1}$$

- Two consequences of these energy-dependent losses are:

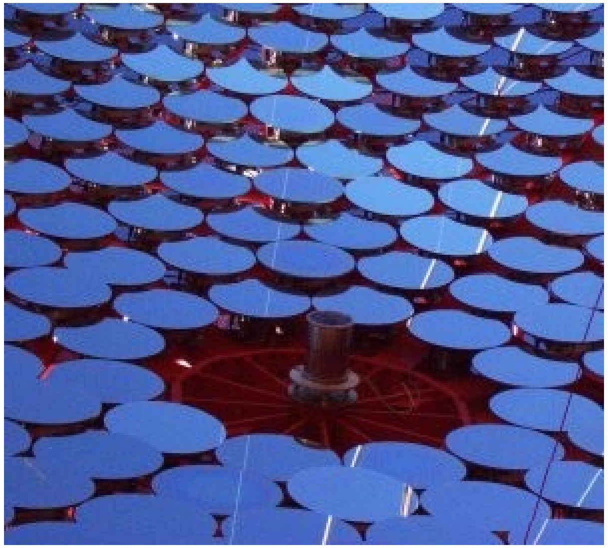
I. And according to standard diffusion-dominated models of Galactic CR transport, the sources of TeV CR electrons must be localed at distance less than < 1 kpc [1, 2].

II. The CR electron energy spectrum is steeper than energy spectrum of the hadronic Cosmic Rays ($\sim E^{-3.3}$ cf. $E^{-2.7}$).

- Almost the whole of measurements used balloon or satellite instrumentation [3]. However, there is rapidly decreasing in flux which makes such direct measurements at high energies is difficult. The very large collection arrays of ground-based IACT (Imaging Atmospheric Cherenkov Telescope) are suggested to expand CR electron energy spectrum measurements into the TeV domain [4].
- The challenge for such instruments (as indeed for all CR electron measurements) is to recognize electrons against the numerous background of hadronic CR.
- The recent improvements in hadron rejection power achieved by the High Energy Stereoscopic System (H.E.S.S.) instrument have now made such a measurement possible.

HESS instrument

- HESS II is an array of five imaging atmospheric Cherenkov telescopes located in Namibia [5].
- The array is sensitive to electrons and gamma -rays above a threshold energy of ≈ 100 GeV .
- The sensitivity of the array to expand gamma-ray emission has been proved with the mapping of supernova remnant shells [6,7], and the diffuse emission around the Galactic Center [8].
- The factor ~ 10 improvements in gamma-ray flux sensitivity of HESS over previous generation experiments that is largely based on superior rejection of the hadronic CR background.



The HESS electron analysis (1) :

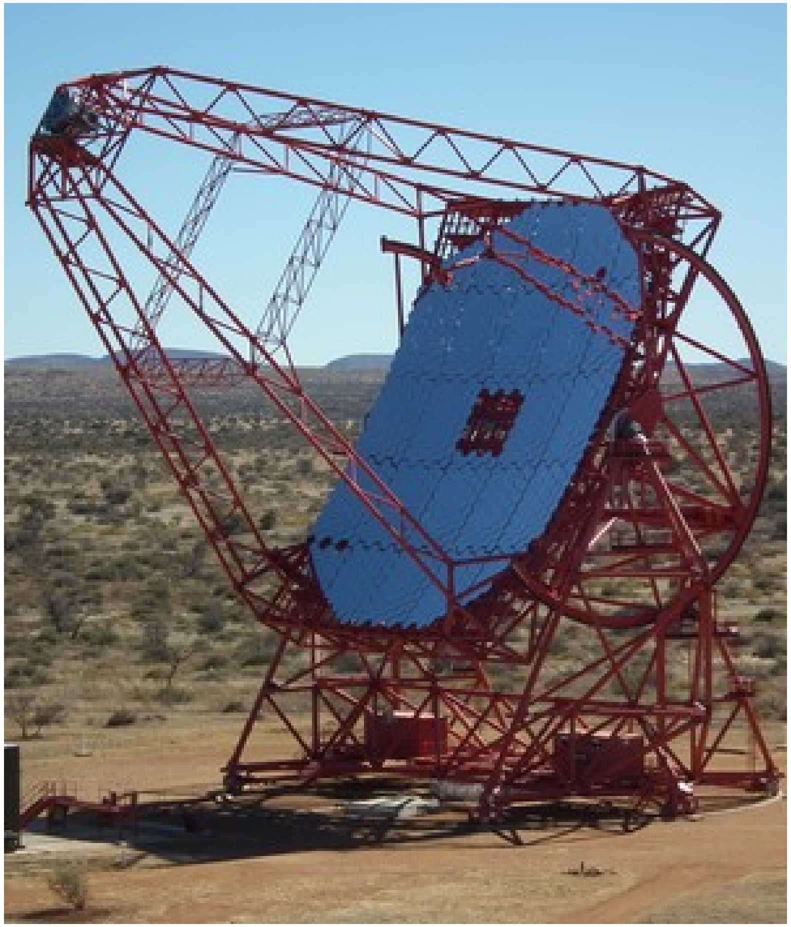
- is based on the selection of electron-like events in regions that are far from cosmic gamma-ray sources and subtraction of the remaining hadronic CR background using air-shower simulations.

- All used data in this analysis must pass selection criteria that were targeting extragalactic sources, with zenith angles smaller than 28◦. Only the central 3.0◦ of the field-of-view was used, with regions within 0.4◦ of any known or potential gamma-ray source excluded. That very hard event selection which is including the requirement that all four HESS telescopes triggered in the event leads to a high energy threshold of ≈ 600 GeV. The used data were amounting to 239 hours during 2004 to 2007.

- The effective collection area used is energy dependent and reaches ≈ $50x10^3$ m^2 at 1 TeV. The total effective exposure of this data set at 1 TeV is therefore ≈ $85x1000^3$ m^2 sr s.

The HESS electron analysis (2) :

- A Random Forest algorithm was used to convert image information from the four cameras into a single parameter zeta describing the degree to which a shower is electron-like [9,10] .
- A zeta parameter value of zero corresponds to a shower which is almost certainly background, and a value of one is assigned if the shower is almost certainly an electron.
- While a component of heavier nuclei is required to explain the distribution of zeta at values up to 0.5, the background can be considered as purely protonic at larger values of zeta parameter.



The HESS electron analysis (3) :

- The most critical aspect of CR electron analysis is the efficient rejection of the hadronic CR background.
- To subtract the hadronic CR background, the distribution of protons and nuclei must be known. For this purpose sets of $\mathbf{10^{10}}$ proton showers and heavier nuclei showers were simulated with CORSIKA [12] using both the SIBYLL [13] and QGSJET-II [14] interaction models.
- And due to the relatively high flux of CR electrons with respect to typical cosmic gamma-ray sources, tight selection cuts are made to achieve the best possible signal/background ratio.
- About $\mathbf{10^{-2}}$ of these showers trigger the array, and due to the extremely efficient background rejection, only $\mathbf{10^{-6}}$ fall into the regime zeta> 0.9.

The distribution of the zeta parameter (1) :

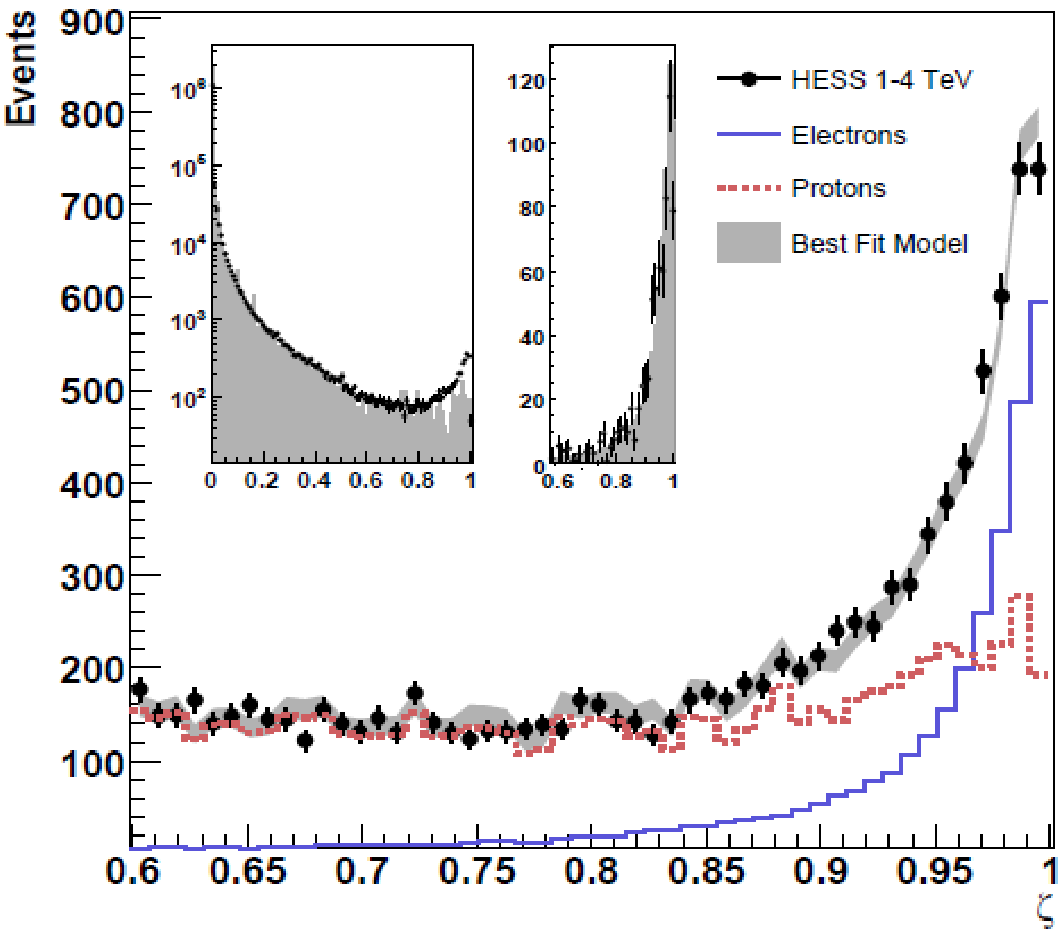


Fig. 1: shows the experimentally measured distribution (black dots) of the zeta parameter compared with the simulated distributions of electrons and protons for the reconstructed energy range 1–4 TeV.

- The shaded band represents the best fit of protons and electrons combination.
- The proton simulations are done by the SIBYLL event generator for hadronic CR interactions.
- The left inset shows the complete distribution from 0 to 1 with entries on a log scale; the data are shown as points, the filled histogram shows a mixed composition (proton, He, N, Si & Fe) cosmic-ray model .

The distribution of the zeta parameter (2) :

- To explain the match between simulated and real data in electromagnetic showers, the right inset shows gamma-ray data with subtracted background as points and gamma-ray simulations as filled histogram.

- The peak close to **zeta parameter = 1** is evidence of a diffuse component of **purely electromagnetic showers at these energies.**

The distribution of the zeta parameter (3) :

- The HESS real data at zeta parameter > 0.6 can be described by a combination of simulated electrons and protons and get the most probable number of experimentally measured electron showers.

Which Model ???

The total normalized goodness-of-fit in the ζ range of 0.6–1 for reconstructed energies between 1 and 4 TeV is $\chi^2/\nu = 0.98$ for a model of simulated electrons and protons using SIBYLL (probability $p = 0.5$) and 2.15 for a model using QGSJET-II ($p = 1.7 \times 10^{-4}$), which demonstrates that the SIBYLL model provides a better description of measurable parameters of air showers initiated by protons of TeV energies.

The distribution of the zeta parameter (4) :

- Coupled with the knowledge of the energy dependence of effective collection area, which is obtained from electron simulations following a power law with a spectral index of 3.3, **the number of measured electron showers can be used to determine the primary electron energy spectrum.**

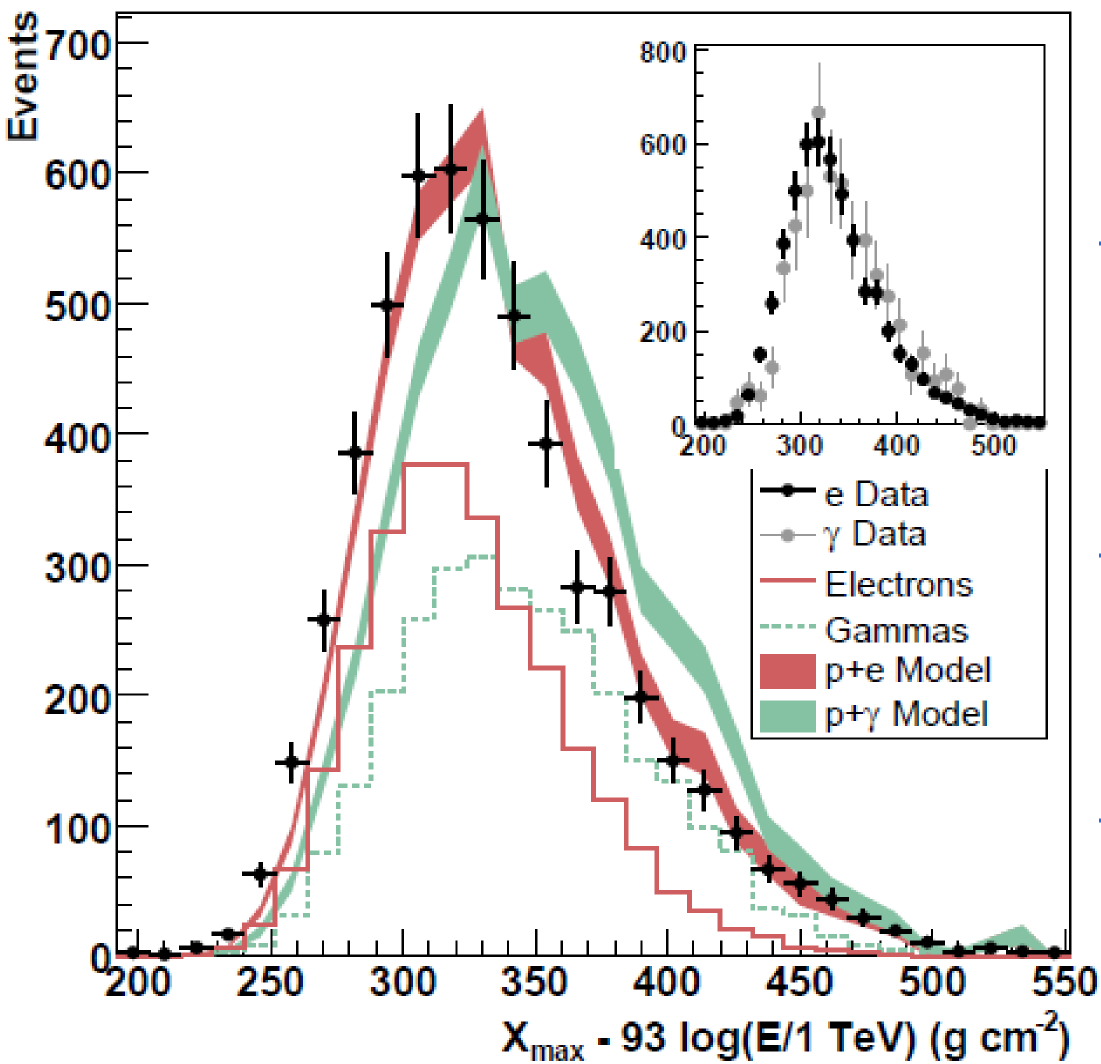
- Since the air showers initiated by electrons are in practice extremely difficult to separate from gamma-ray showers, the peak in our data at zeta = 1 may contain a contribution from Gamma-ray showers.

The distribution of the zeta parameter (5) :

- Therefore, the signal measured by HESS close to zeta =1 is a combination of the CR electron flux (CREF) plus the extragalactic gamma-ray background (EGRB). The level of the EGRB lies many orders of magnitude below the CREF at GeV energies but a simple extrapolation of the last few data points measured by Energetic Gamma Ray Experiment Telescope (EGRET) yields an $dN/dE \propto 1/E^2$ spectrum which reaches the level of the CREF at a few TeV [15]. However, most models for the EGRB yield TeV fluxes at least one order of magnitude lower than this extrapolation [16].

- Given the uncertainty in the EGRB/CREF ratio at TeV energies, it is desirable **to separate electrons and gamma-rays in our data**. Essentially the only useful separation parameter is **the depth of shower maximum (X_{max}),** which occurs on average ≈ 20 g/cm^2 higher in the atmosphere for electrons.

The distribution of simulated shower maximum depth VS. the experimental one (1)



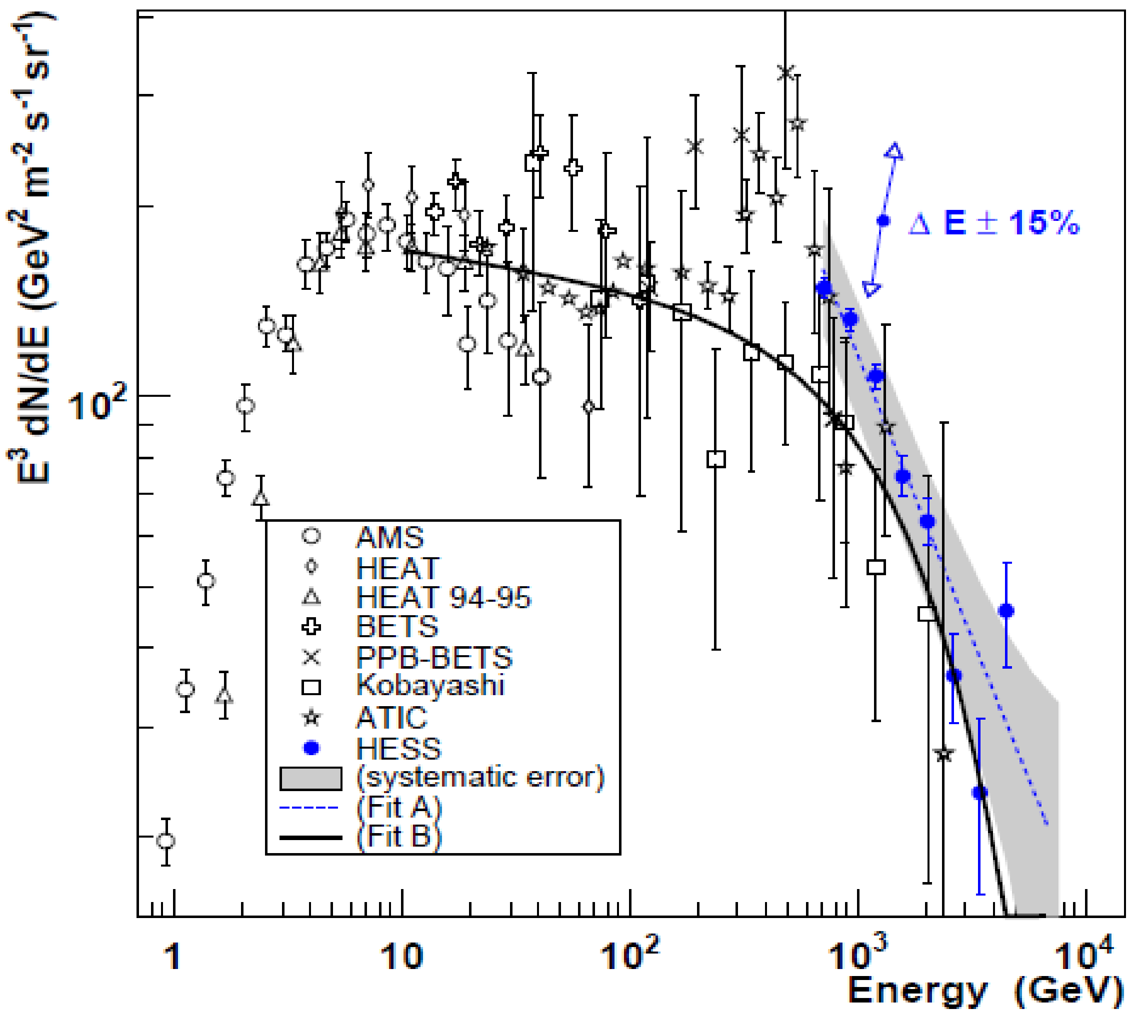
- For each shower the measured X_{max} is corrected for the energy dependent shower elongation (93 g cm^{-2}/decade is the reconstructed elongation rate expected for electron primaries).
- Fig 2 compares shower maximum depth X_{max} distributions for simulated protons, electrons and gamma-rays to the experimentally measured X_{max} distribution for electron-like events at zeta > 0.9. The events have energies between 1 and 4 TeV are included.
- The bands show the combination of electrons + protons (red) and of gamma-rays + protons (green), with a ratio determined by a fit to the distribution of the data in this energy range.
- The distributions of electrons and gamma-rays are shown for comparison. The inset contains a comparison of this data (black) with a gamma-ray rich data set taken from regions < 0.15° from gamma-ray sources (gray).

The distribution of reconstructed simulated shower maximum VS. the experimentally measured one (2)

- A fit of the X_{max} distribution with the electron/gamma-ray fraction as a free parameter results in a maximum 10% contribution of gamma-rays to the signal (for a confidence level of 90%), which is supported by the displacement between the X_{max} distributions from real data used for this electron analysis and real data from a gamma-ray rich data set (inset of Fig. 2).

- However, taking into account a conservative systematic uncertainty in the determination of X_{max} of 5 g/cm^2 due to atmospheric uncertainties, we cannot exclude a significant contamination of ≈ 50% of our electron measurement by the diffuse extragalactic gamma-ray background. Systematic uncertainties in the hadronic modeling are not considered.

CR electron energy spectrum(1)



The data are reproduced from: AMS [18], HEAT [19],HEAT 94-95 [20], BETS [21], PPB-BETS [22], Kobayashi [2] and ATIC [23].

- Fig 3 shows the CR electron energy spectrum as measured by HESS in comparison with previous measurements. The HESS real data are shown as blue solid points with the two fit functions A and B.
- Systematic errors on the reconstructed spectrum arise from uncertainties in the simulation of hadronic interactions and the atmospheric model (The shaded band), as well as in the absolute energy scale.

CR electron energy spectrum(2)

- The double arrow indicates the effect of an energy scale uncertainty ~ 15%, the systematic uncertainty on the HESS points which is generated from the subtraction of the hadronic background. The energy scale uncertainty has been estimated by comparison of the spectra obtained using the SIBYLL and QGSJET-II models.
- The zeta parameter distributions,Fig. 1, for protons show a slight rise toward zeta = 1, presumably reflecting events where a large fraction of proton energy is transformed to a single π°. The rise is somewhat more pronounced for SIBYLL as compared to QGSJET-II, giving rise to the model dependence. Artificially doubling the gamma-ray like component in SIBYLL reduces the electron flux by ~ 20%, without significant change in spectral shape.

CR electron energy spectrum (3)

The data are well described by a power-law, : $dN/dE = k\,(E/1\mathrm{TeV})^{-\Gamma}$ with $k = (1.17 \pm 0.02) \times 10^{-4}\ \mathrm{TeV}^{-1}\,\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$ and $\Gamma = 3.9 \pm 0.1\ (\mathrm{stat})\ (\chi^2/\nu = 3.6,\ p = 10^{-3},\ \mathrm{Fit\ A})$,

- Which implies a steepening of the spectrum compared to GeV energies. The spectral index shows little model and sample dependence, resulting in small uncertainty in $\Gamma \leq 0.3$. At lower energies the flux reported here is somewhat higher than previous results, but fully consistent within the 15% scale error.

- Leaving the scale factor free, HESS data combined with earlier electron data are well reproduced by an exponentially cutoff power law with an index of − 3.05±0.02 and a cutoff at 2.1±0.3 TeV, combined with a scale adjustment of − 11% (Fit B).

- HESS data are also compatible with very recent data by Advanced Thin Ionization Calorimeter ATIC [23]. In addition to the detailed tests of the analysis using different zenith angle ranges, different analysis cuts , different regions in the sky, different seasons and years as well as another fitting algorithm all yield consistent results.

Summary

- The very large collection area of ground-based gamma-ray telescopes gives them an important advantage over balloon/satellite based instruments in the detection of cosmic-ray electrons at very high energy (> 600 GeV) regions.
- The energy spectrum of CR electrons derived from real data taken by HESS is presented.
- The evidence is found for an essential steepening in the energy spectrum above 600 GeV compared to lower energies. That implies the existence of at least one source of CR electrons in the local Galaxy (within distance ~ 1 kpc).
- This measurement is the first ground-based measurement of CR electrons. In this measurement, the electron energy spectrum is extended beyond the range of direct measurements. Future IACT arrays with effective areas beyond 1000000 m^2 should be able to expand the CR electron energy spectrum to about 10 TeV using this technique.

References

[1] F. A. Aharonian, A. M. Atoyan, H. J. V¨olk, Astron. & Astrophys., 294, L41 (1995).

[2] T. Kobayashi et al., Astrophys. J., 601, 340 (2004).

[3] D. M¨uller, Adv. Space Res., 27, 659 (2001).

[4] J. Nishimura, Proc. Towards a Major Cherenkov Detector III, Universal Academy Press, Tokyo, page 1 (1994).

[5] J. A. Hinton (H.E.S.S. Collaboration), New Astron. Rev. 48, 331 (2004).

[6] F. A. Aharonian et al., Nature 432, 75 (2004).

[7] F. A. Aharonian et al., Astron. & Astrophys. 437, L7 (2005).

[8] F. A. Aharonian et al., Nature 439, 695 (2006).

[9] L. Breiman & A. Cutler, http://www.stat.berkeley.edu/users/breiman/RandomForests/

[10] R. K. Bock et al., Nuclear Instruments and Methods in Physical Research A516, 511 (2004).

[11] A. Hillas, Proceedings 19th International Cosmic Ray Conference, La Jolla, F. C. Jones, 3, 445 (1985).

References

[12] D. Heck et al., Forschungszentrum Karlsruhe Report FZKA 6019 (1998).

[13] R. S. Fletcher, T. K. Gaisser, P. Lipari, & T. Stanev, Phys. Rev. D 50, 5710 (1994).

[14] S. Ostapchenko et al., Proceedings 29th International Cosmic Ray Conference, Pune, Tata Institute of Fundamental Research, 7, 135 (2005).

[15] A. W. Strong, I. V. Moskalenko & O. Reimer, Astrophys. J., 613, 956 (2004).

[16] P.S. Coppi & F. A. Aharonian, Astrophys. J., 487, L9 (1997).

[17] I. V. Moskalenko, T. A. Porter, S. W. Digel, Astrophys. J., 652, L65 (2006).

[18] M. Aguilar et al., Physics Reports 366, 331 (2002).

[19] S. W. Barwick et al., Astrophys. J., 498, 779 (1998).

[20] M. A. DuVernois et al., Astrophys. J., 559, 296 (2001).

[21] S. Torii et al., Astrophys. J., 559, 973 (2001).

[22] S. Torii et al., arXiv:0809.0760 (2008).

[23] J. Chang et al., Nature, 456, 362-365 (2008).


شكراً
بارك الله فيك
thank you

Back_up

- Only the central 3.0◦ of the field-of-view was used, with regions within 0.4◦ of any known or potential gamma-ray source excluded.
- Random Forests algorithms were trained in five energy bands using simulated electron showers and real data taken from empty regions.
- Some scenarios of a strong local source [2] are excluded.
- The primary input parameters to the Random Forest algorithm are the Hillas moments of the images recorded in each telescope [11].
- The goodness of fit in the zeta range of 0.6–1 for reconstructed energies between 1 and 4 TeV for SIBYLL model of simulated electrons and protons provides a better description of measurable parameters of air showers. initiated by protons of TeV energies.

The HESS electron analysis (2) :

- The most critical aspect of CR electron analysis is the efficient rejection of the hadronic CR background.

- Given the relatively high flux of CR electrons with respect to typical CR gamma-ray sources, it is appropriate to make tight selection cuts to achieve the best possible signal/background ratio.

- Very hard event selection, including the requirement that all four H.E.S.S. telescopes triggered in the event, leads to a greatly increased energy threshold of ≈ 600 GeV.

- To subtract the hadronic CR background, the distribution of protons and nuclei must be known. For this purpose sets of 10^{10} proton showers and showers of heavier nuclei were simulated with CORSIKA [12] using both the SIBYLL [13] and QGSJET-II [14] interaction models.

- About 10^{-2} of these showers trigger the array, and due to the extremely efficient background rejection, only 10^{-6} fall into the regime (zeta> 0.9). While a component of heavier nuclei is required to explain the distribution of zeta at values up to 0.5, the background can be considered as purely protonic at larger values of zeta parameter.

CR electron energy spectrum(3)

Which implies a steepening of the spectrum compared to GeV energies. The spectral index shows little model and sample dependence, resulting in small uncertainty in $\Gamma \leq 0.3$. At lower energies the flux reported here is somewhat higher than previous results, but fully consistent within the 15% scale error.

Leaving the scale factor free, HESS data combined with earlier electron data are well reproduced by an exponentially cutoff power law with an index of -3.05 ± 0.02 and a cutoff at 2.1 ± 0.3 TeV, combined with a scale adjustment of − 11% (Fit B).

HESS data are also compatible with very recent data by Advanced Thin Ionization Calorimeter ATIC [23]. Detailed tests of the analysis using different zenith angle ranges, different analysis cuts , different regions in the sky, different seasons and years as well as another fitting algorithm all yield consistent results.

The energy spectrum of cosmic-ray electrons at TeV energies

Constants:

- Introduction
- HESS
- HESS electron analysis
- Results
- Summary