# High zenith angle observations of PKS 2155-304 with the MAGIC telescope

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***Abstract*. The high frequency peaked BL Lac PKS 2155-304 with a redshift z=0.116 was discovered 1997 in the VHE range by the University of Durham Mark 6 $\gamma$-ray telescope in Australia with a flux corresponding to ~0.2 times the Crab Nebula flux [1]. It was later observed and detected with high significance by the Southern observatories CANGAROO and H.E.S.S. establishing this source as the best studied Southern TeV blazar. Detection from the Northern hemisphere was very difficult due to challenging observation conditions under large zenith angles. In July 2006, the H.E.S.S. collaboration reported an extraordinary outburst of VHE $\gamma$-emission [2]. During the outburst, the VHE $\gamma$-ray emission was found to be variable on the time scales of minutes and at a mean flux of ~7 times the flux observed from the Crab Nebula [2]. The MAGIC collaboration operates a 17m imaging air Cherenkov Telescope at La Palma (Northern Hemisphere). Follow up observations of the extraordinary outburst have been triggered in a Target of Opportunity program by an alert from the H.E.S.S. collaboration. The measured spectrum and light curve are presented.**

***Keywords*: BL Lacertae objects: individual (PKS 2155-304) — gamma rays: observations — methods: data analysis**

## I. INTRODUCTION

The 17m diameter MAGIC telescope on the Canary Island of La Palma is the world's largest single imaging atmospheric Cherenkov telescope. One of the aims of the MAGIC collaboration is to carry out observations at large zenith angles. Under these special conditions and with a good telescope sensitivity a bigger effective area is given and sources from a large section of the Southern sky can be observed with a threshold of a few hundred GeV (≈ 100 GeV-500 GeV, zenith angle dependent).

Here we present the results of an analysis of the Crab Nebula data set taken under large zenith angles (60° to 66°). In addition to the usual image parameters [3] timing information of the recorded signals was used for reconstruction of the shower origin and for the background suppression.

Furthermore we present a reanalysis of a PKS 2155-304 data set recorded at a zenith angle range between 59° and 64°. The same analysis and cuts are used as for the Crab Nebula data set.

## II. ANALYSIS

All the data analysed in this work was taken in wobble mode, i.e. tracking a sky direction, which is 0.4° off the source position. The background is estimated from the same field-of-view, which improves the background estimation and yields a better time coverage because no extra OFF data have to be taken.

Compared to the previous analysis [4] improvements are obtained because of an updated Monte Carlo (MC) sample at high zenith angles leading to a better data-MC agreement. A further improvement is achieved in the image cleaning and in the gamma/hadron separation thanks to the usage of the timing information of the images.

In the new analysis we use the Time Image Cleaning [5]: With a sub-nsec timing resolution of the data acquisition system and thanks to the parabolic structure of the telescope mirror a smaller integration window can be chosen. This reduces the number of pixels with signals due to night sky background, which survive the image cleaning. This allows reducing the pixel threshold level (i.e. recorded charge) of the image cleaning leading to a lower analysis energy threshold.

For the analysis a robust set of dynamical cuts with a small number of free parameters is used [6]. In addition, cuts in time parameters are applied, which describe the time evolution along the major image axis and the RMS of the time spread. These two additional parameters lead to a better background suppression yielding a better sensitivity of the analysis. The energy estimation is done with the Random Forest regression method [7].

## III. RESULTS

### A. Crab Nebula

The Crab Nebula is one of the best studied celestial objects because of the strong persistent emission of the Nebula over 21 decades of frequencies. It was the first object that was detected at TeV energies by the Whipple collaboration [8] in the year 1989 and is the strongest steady source of VHE $\gamma$-rays. Due to the stability and the strength of the $\gamma$-ray emission the Crab Nebula is generally considered the standard candle of the TeV $\gamma$-ray astronomy. The measured $\gamma$-ray spectrum extends from 60 GeV [9] up to 80 TeV [10] and appears to be constant over the years (from 1990 to present).

*1) Observation and Detection:* In October 2007, the MAGIC telescope took data of the Crab Nebula with a zenith angle range of 60° up to 66°. The data was taken under dark sky conditions and in wobble mode. After quality cuts an effective on-time of 2.15 hrs is obtained. Using detection cuts (i.e. optimized on significance of a different Crab Nebula sample), a total of 247 excess events above 187 background events with a scale factor of 0.33 have been detected (see Fig. 1). According to Li&Ma formula 17 [11] the significance of this $\gamma$-ray signal is $12.8\,\sigma$. This corresponds to an analysis sensitivity of 8.7 $\frac{\sigma}{\sqrt{h}}$. Using the same set of cuts we obtain the following sensitivities for integral fluxes ($\Phi$):

$$\begin{aligned}\Phi(E > 0.4\,\mathrm{TeV}) &\Rightarrow 5.7\%\ \mathrm{Crab\ in\ 50\,hrs}\\ \Phi(E > 0.63\,\mathrm{TeV}) &\Rightarrow 5.6\%\ \mathrm{Crab\ in\ 50\,hrs}\\ \Phi(E > 1.0\,\mathrm{TeV}) &\Rightarrow 5.9\%\ \mathrm{Crab\ in\ 50\,hrs}\\ \Phi(E > 1.5\,\mathrm{TeV}) &\Rightarrow 6.8\%\ \mathrm{Crab\ in\ 50\,hrs}\end{aligned}$$

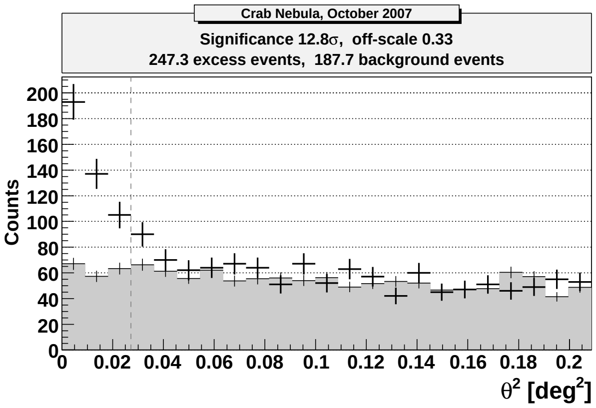

Fig. 1. The On-Source and normalized background distribution of $\Theta^2$. The On-Source is shown in the black crosses and the background is shown in the gray shaded region. 2.22 hrs of Crab data show an excess with a significance of $12.8\sigma$.

*2) Differential Energy Spectrum:* The differential energy spectrum can be described well by a power law:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (2.7 \pm 0.4) \cdot 10^{-7} \left(\frac{\mathrm{E}}{\mathrm{TeV}}\right)^{-2.46 \pm 0.13} \left(\frac{\mathrm{phe}}{\mathrm{TeV\,s\,m^2}}\right).$$

The spectrum is shown in Fig. 2. The gray band represents the range of results obtained by varying the total cut efficiency between 40% and 70%. For comparison, the Crab Nebula spectrum from data taken at low zenith angles is drawn as a dashed line [9]. A very good agreement has been found.

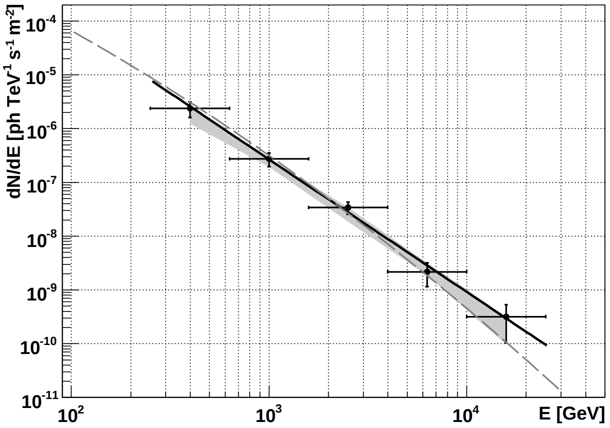

Fig. 2. Differential energy spectrum of the Crab Nebula. Black line: power law fit to the data, gray band: systematic uncertanties, dashed line: published data taken at low zenith angles [9].

### B. *PKS 2155-304*

Like the Crab Nebula being the so-called standard candle of $\gamma$-ray astronomy, the blazar PKS 2155-304 is the so-called lighthouse of the Southern hemisphere. The high frequency peaked BL Lac PKS 2155-304 at a redshift of z=0.116 was discovered in the VHE $\gamma$-ray range by the University of Durham Mark 6 $\gamma$-ray telescope (Australia) in 1997 with a flux corresponding to ~0.2 times the Crab Nebula flux [1]. It was later observed and detected with high significance by the Southern observatories CANGAROO [12] and H.E.S.S. [13] establishing this source as be the best studied Southern TeV blazar. Detection from the Northern hemisphere is difficult due to challenging observation conditions under large zenith angles. In July 2006, the H.E.S.S. collaboration reported an extraordinary outburst of VHE $\gamma$-emission [2]. During this outburst, the $\gamma$-ray emission was found to be variable on time scales of minutes with a mean flux of ~7 times the flux observed from the Crab Nebula. Follow up observations of the outburst by the MAGIC telescope have been triggered in a Target of Opportunity program by an alert from the H.E.S.S. collaboration [4].

*1) Observation and Detection:* The MAGIC telescope observed the blazar PKS 2155-304 from 28 July to 2 August 2006 in a zenith angle range from 59° to 64°. The data were taken under dark sky conditions and in wobble mode. After quality cuts a total effective on-time of 8.7 hrs is obtained. For the detection of PKS 2155-304, the same cuts are used as for the detection of the Crab Nebula. Three OFF regions are used and 1029 excess events above 846 background events are detected. A significance of 25.3 standard deviations is obtained. The corresponding $\Theta^2$-plot is presented in Fig. 3.

*2) Differential Energy Spectrum:* The differential energy spectrum is shown in Fig. 4 as a black line together with the measured spectrum of H.E.S.S. during the strong outburst [2] (dashed line). Note that H.E.S.S. and MAGIC data are not simultaneous. The obtained spectral points in this analysis are fitted from 400 GeV on, because at lower energies H.E.S.S. reported a change of the slope ($-3.53\pm0.05$ above 400 GeV to $-2.7\pm0.06$ below 400 GeV). The fitted MAGIC data points are consistent with a power law:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (1.8 \pm 0.2) \cdot 10^{-7} \left(\frac{\mathrm{E}}{\mathrm{TeV}}\right)^{-3.5 \pm 0.2} \left(\frac{\mathrm{phe}}{\mathrm{TeV\,s\,m^2}}\right)$$

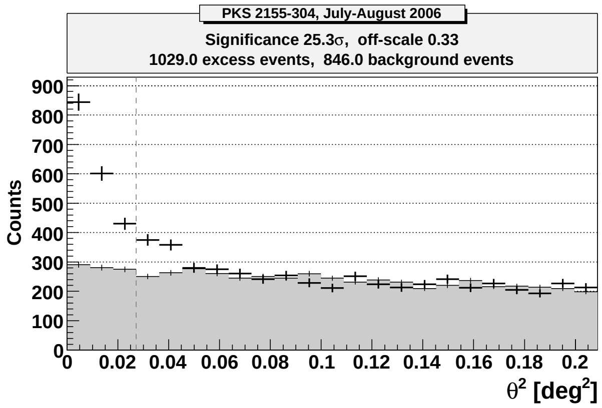

Fig. 3. The On-Source and normalized background distribution of $\Theta^2$. The denotations are the same as in figure 1. A clear excess with a significance of more than 25 standard deviations for a source at the position of PKS 2155-304 is found.

with a fit probability after the $\chi^2$-test of 81%. Above 400 GeV, the energy spectrum measured by H.E.S.S. from the preceding flare of PKS 2155-304 is one order of magnitude higher than the spectrum measured by MAGIC, but the spectral slope $(-3.53 \pm 0.05)$ is consistent within the statistical errors.

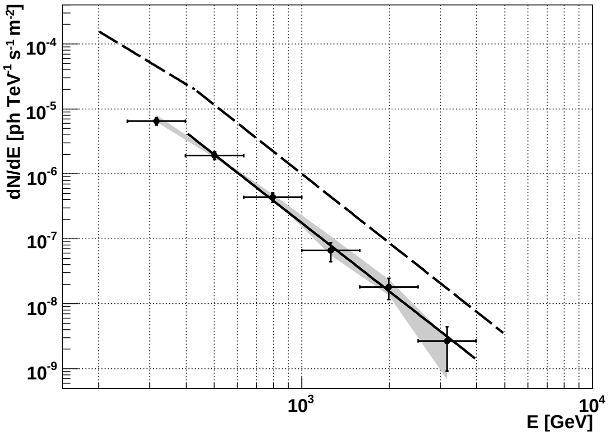

Fig. 4. Differential energy spectrum (black line) together with systematic errors due to varying cuts efficiencies (gray band). The black dashed line corresponds to the H.E.S.S. measurement during the flare.

*3) Intrinsic Energy Spectrum:* The VHE photons of PKS 2155-304 interact with the low-energy photons of the extragalactic background light ([14], [15]). The predominant reaction $\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+e^-$ leads to an attenuation of the intrinsic spectrum $\mathrm{d}N/\mathrm{d}E_{intr}$ that can be described by

$$\mathrm{d}N/\mathrm{d}E_{obs} = \mathrm{d}N/\mathrm{d}E_{intr} \cdot \exp[-\tau_{\gamma\gamma}(E,z)]$$

with the observed spectrum $\mathrm{d}N/\mathrm{d}E_{obs}$, and the energy dependent optical depth $\tau_{\gamma\gamma}(E,z)$. Here we use the recent model of Kneiske et al. that has been adopted by MAGIC [16], [17]. The measured spectrum and the reconstructed deabsorbed spectrum are shown in Fig. 5. For comparison the Crab Nebula spectrum is also shown. A power law fit to the deabsorbed spectrum results in a spectral index of $2.4 \pm 0.1$. However, the fit probability is rather low (4%) which motivates a higher order fit function. We have chosen a curved power-law fit (a parabolic shape in log-log representation) of the following form: $\mathrm{d}N/\mathrm{d}E = N_0(E/1\mathrm{TeV})^{-\alpha+\beta\cdot\ln(E/1\mathrm{TeV})}$. The best fit parameters are: $N_0 = (9.7 \pm 0.9)\cdot 10^{-11}\,\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, $\alpha = 2.4 \pm 0.2$, $\beta = -0.5 \pm 0.2$ (solid line in Fig. 5) and the fit probability is 77%. The observed curvature is indicative of a maximum in the energy density and is usually interpreted as due to inverse Compton (IC) scattering. The fitted peak position is determined to be at $E_{peak} = (672^{+104}_{-157})$ GeV.

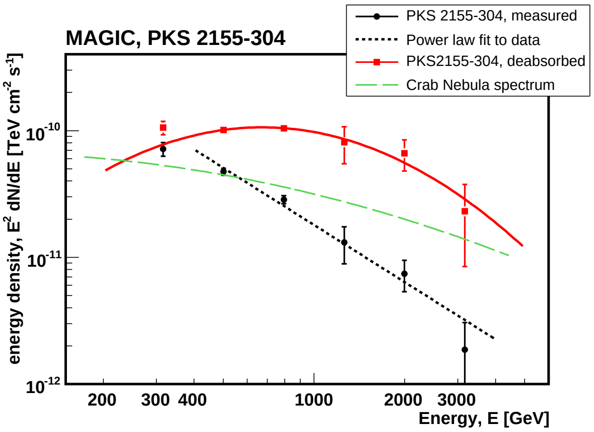

Fig. 5. Measured and intrinsic differential energy density of PKS 2155-304. The effect of the EBL is taken into account by using the recent model of Kneiske adopted by MAGIC [17]. The power law fit to the observed spectrum is given by the dotted line, while the curved fit to the intrinsic spectrum is shown by the solid line. The fitted peak position is located at $E_{peak} = (672^{+104}_{-157})$ GeV. For comparison the Crab Nebula spectrum is shown as the dashed line.

*4) Light curve:* The integral light curves above 400 GeV shown in Fig. 6 have a binning of one flux point per night (bottom panel) and a binning in two runs which corresponds to about 10 minutes per bin (top panel). Significant detections in most of the time bins are obtained. A significant intranight variability is found for the second night MJD 53945 (29 July 2006) giving a probability for a constant flux of less than $5 \cdot 10^{-9}$. For the other nights, no significant intranight variability is found. In the lower panel of Fig. 6, a night-by-night light curve is shown. A fit by a constant to the run-by-run light curve results in a chance probability of less than $10^{-12}$. However, a fit by a constant to the night-by-night light curve results in a chance probability of $7 \times 10^{-2}$. We, therefore, conclude that there is a significant variability on the time scales reaching from days (largest scale we probed) down to 20 minutes (shortest scale we probed).

## IV. CONCLUSION

A study of high zenith angles (60° - 66°) observations with the MAGIC telescope was performed. A new Time

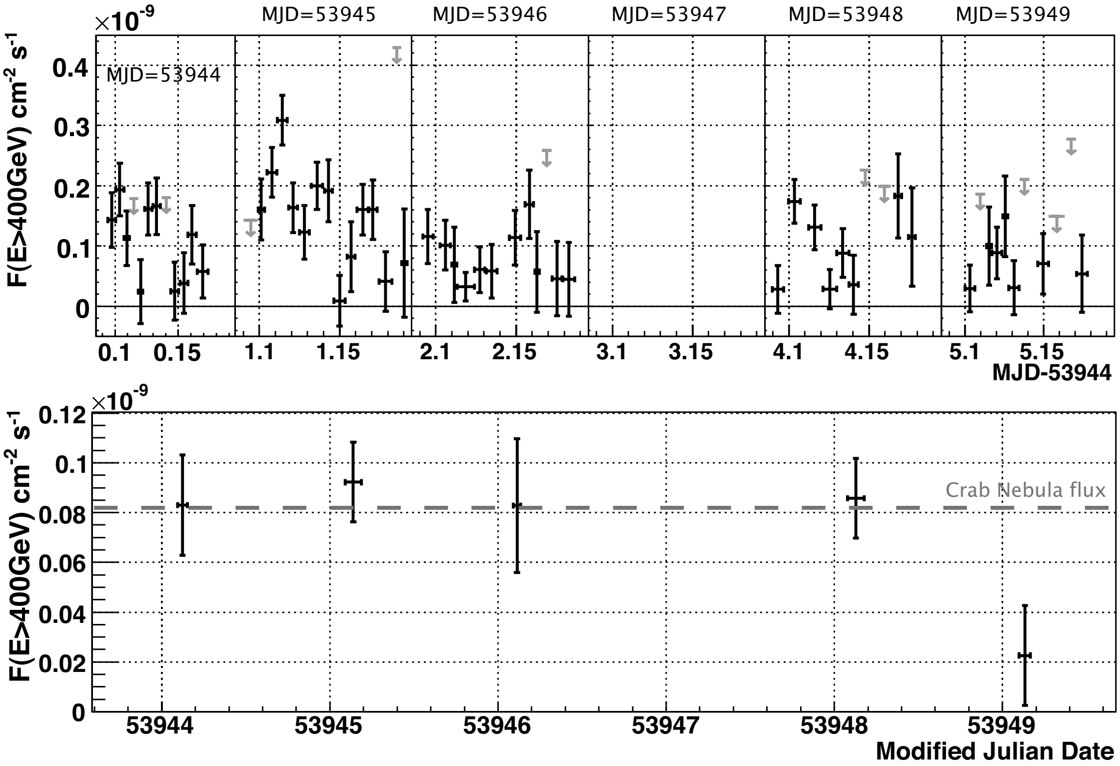

Fig. 6. *Top:* Light curve for individual nights for E>400 GeV of PKS 2155-304. Only the second night (MJD 53945) shows significant variability. Vertical arrows represent flux upper limits. *Bottom:* Light curve for the total data set for E>400 GeV with one flux point per night. The error bars in x-direction represent the observation time. The Crab Nebula flux is shown for comparison. For more information see text.

Image Cleaning and also time parameters were used for the background suppression, which leads to a significant improvement of the sensitivity.

From Crab Nebula observations a sensitivity of 5.7% of the Crab Nebula flux for 50 hrs of observations above 0.4 TeV has been determined. The differential energy spectrum of the Crab Nebula is in excellent agreement with the published data at lower zenith angles. This improved analysis is used to reanalyze data of PKS 2155-304 taken with MAGIC in 2006.

The energy spectrum from 400 GeV up to 4 TeV has a spectral index of $(-3.5 \pm 0.2)$ and shows no change of spectral slope with flux state. It agrees well with the results of H.E.S.S. [2] and CANGAROO [12]. Furthermore we corrected the measured spectrum for the effect of the EBL absorption using the recent model of Kneiske et al. The resulting intrinsic spectrum shows a clear curvature. A fitted peak position in the energy density distribution is at $E_{peak} = (672^{+104}_{-157})$ GeV.

The light curves show a significant variability on daily as well as on intra-night time scales. Finally we conclude that high zenith angle observations with the MAGIC telescope have proven to yield high quality spectra and light curve at a low energy threshold.

## ACKNOWLEDGEMENTS

We would like to thank the Instituto de Astrofisica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN and Spanish MICINN is gratefully acknowledged. This work was also supported by ETH Research Grant TH 34/043, by the Polish MNiSzW Grant N N203 390834, and by the YIP of the Helmholtz Gemeinschaft. D.M's research is supported by a Marie Curie Intra European Fellowship within the 7th European Community Framework Programme.

## REFERENCES

[1] P. M. Chadwick et al., *ApJ* 513:161-167, 1999.
[2] F. A. Aharonian et al. (H.E.S.S. Coll.), *ApJ* 664:L71-L74, 2007.
[3] A. M. Hillas, In Proc. 19th Int. Cosm. Ray Conf., La Jolla, USA, 3:445-448, 1985.
[4] D. Mazin and E. Lindfors for the MAGIC Coll., In Proc 29th Int. Cosm. Ray Conf., Merida, Mexico, 3:1033-1036, 2008.
[5] E. Aliu et al., *Astropart. Phys.*, 30:293, 2009.
[6] B. Riegel and T. Bretz, In Proc 29th Int. Cosm. Ray Conf., Pune, India, 4:315, 2005.
[7] J. Albert et al. (MAGIC Coll.), *NIMA* 588:424-432, 2008.
[8] T. Weekes et al., *ApJ*, 342:379-395, 1998.
[9] J. Albert et al. (MAGIC Coll.), *ApJ*, 674:1037-1055, 2008.
[10] F. A. Aharonian et al. (HEGRA Coll.), *ApJ*, 539:317-324, 2000.
[11] T. P. Li and Y. Q. Ma, *ApJ*, 272:317-324, 1983.
[12] Sakamoto et al. (CANGAROO Coll.), *ApJ*, 676:113-120, 2008.
[13] F. A. Aharonian et al. (H.E.S.S. Coll.), *A&A*, 430:865-875, 2005.
[14] R. J. Gould & Schreder, *Phys.Rev. Lett.*, 16:252, 1966.
[15] M. G. Hauser & E. Dwek, *ARA&A*, 39:249, 2001.
[16] T. Kneiske, K. Mannheim and D. Hartmann, *A&A*, 386:1, 2002.
[17] E. Aliu et al. (MAGIC Coll.), *Science*, 320:1752, 2008.