29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Absolute energy scale calibration of the MAGIC telescope using muon images

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The absolute overall light collection efficiency of the MAGIC telescope can be calibrated using isolated muons hitting the reflector. The geometry and the energy of the muons are reconstructed from the measured ring images and compared with Monte Carlo predictions. The amount of Cherenkov light produced by muons can be modeled with small systematic uncertainties. Muon images are recorded during normal observation with a rate of about 2 Hz. A continuous calibration can therefore be performed with no need for dedicated calibration runs. In addition the width of the muon ring images can be used to monitor the spot size of the reflector during normal data taking.

1. Introduction

The MAGIC telescope [1] for γ-ray astronomy in the energy range between 30 GeV and several TeV is situated on the Roque de los Muchachos on the Canary Island La Palma (28.8^o N, 17.8^o W) at 2200 m altitude. The 17 m diameter parabolic tessellated mirror is mounted on a light weight carbon fiber structure. The 3.5^o field of view (FOV) camera is equipped with 576 high quantum efficiency photo-multiplier tubes (PMTs). The inner area is composed of 396 PMTs of 0.10^o FOV surrounded by 180 0.20^o FOV PMTs. The analog signals are transferred via optical fibers to the trigger electronics and the 300 MHz flash analog to digital converter (FADC). The telescope has been fully operational since August, 2004.

2. Calibration Principle

The standard calibration of the MAGIC telescope [2] uses a light pulse generator which illuminates the PMT camera uniformly. This procedure provides an absolute calibration of the camera and the signal processing chain of the MAGIC telescope. In order to calibrate the overall light collection of the whole telescope including e.g. the reflectivity of the mirror dish additional information is required. A useful tool for the overall absolute calibration is provided by ring images generated by muons hitting the reflector [3, 4].

Muons hitting the reflector produce ring images on the camera plane, fully or partially contained inside the camera depending on the incident angle ξ. For muons hitting the mirror with known energy and geometry the number of photo electrons N collected per azimuth angle Φ by a mirror dish of radius R (see Fig. 1) is given by [5]:

$$\frac{dN}{d\phi} = \frac{\alpha I}{2}\sin(2\theta_c)D(\phi) \tag{1}$$

$$I \equiv \int_{\lambda 1}^{\lambda 2} \frac{\psi(\lambda)}{\lambda^2}\, d\lambda, \qquad D(\phi) = R\,\left[\sqrt{1-(\rho/R)^2\sin^2\phi} + (\rho/R)\cos\phi\right],$$

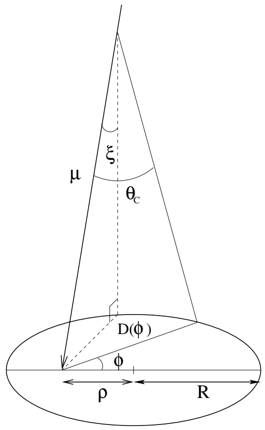

Figure 1. Geometry of Cherenkov light emitted by a muon hitting the reflector dish (R: mirror radius, ρ: impact parameter, ξ: incident angle, θ_C: Cherenkov angle

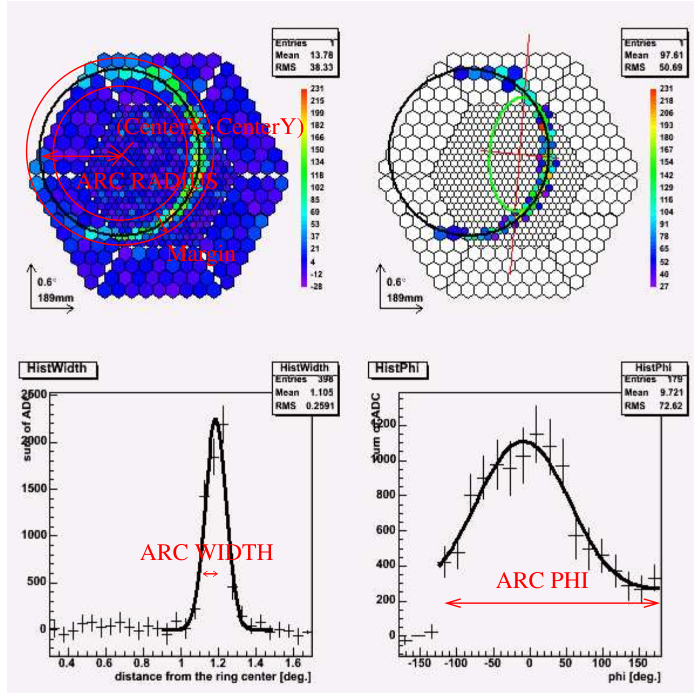

Figure 2. An example of a muon ring image in the MAGIC camera. The lower plots show the corresponding ARC WIDTH and ARC PHI distributions.

where α is the fine structure constant, $\psi(\lambda)$ is the overall photon to photo electron conversion efficiency (CE) and λ is the wavelength of the Cherenkov light. The impact parameter ρ and the energy (or $\theta_C(E)$) of the incident muon can be reconstructed from the observed muon ring radius and the Φ-distribution ($dN/d\Phi$) of the light intensity along the ring. The calibration then consists in adjusting ψ in order to match the observed and the predicted number of photo electrons.

3. Data Analysis

The reconstruction of the muon ring images starts with the standard signal reconstruction for each camera pixel. The resulting image is then fitted with a circle of radius R_{arc}. The integrated signal of all pixels inside a donut $\pm 0.2^o$ around the fitted circle ($SIZE_{muon}$) is computed. The width of the muon ring ($WIDTH_{arc}$) is determined as the σ of a Gaussian fit to the signal distribution projected onto the radial distance from the center of the circle. The signal within the $\pm 0.2^o$ donut is plotted as a function of Φ. ARC_Φ is the Φ range above a fixed threshold and the impact parameter can be estimated by fitting the Φ-distribution with eq. 1.

A clean sample of muons can then be obtained using cuts on the quality of the muon ring fit, the parameters described above and the leakage parameter which is defined as the ratio of the signal in the outer pixels of the camera to the total signal. After these cuts a muon rate of 2.3 Hz is obtained. This is enough to calibrate the energy scale every 10 minutes with an accuracy of better than 3%.

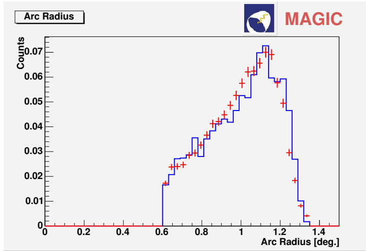

Figure 3. The distribution of the radius R_{arc} of the fitted muon rings is shown for data (red dots) and MC (blue histogram)

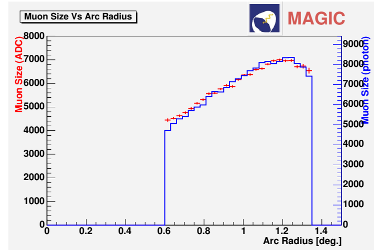

Figure 4. The dependence of $SIZE_{muon}$ on R_{arc} is shown for data (red dots) and MC (blue histogram). After overall CE calibration good agreement is achieved.

4. MC simulation

The results of the telescope data analysis are compared with MC simulations. This takes into account effects like multiple scattering of muons, the refractive index of the air as well as detector and reconstruction inefficiencies. In the first step of the simulation muons with an energy spectrum according to [6] are generated with the CORSIKA air shower program [7]. A high energy (10-1000 GeV) and a low energy (5-10 GeV) sample have been generated with different differential flux indices (-2.69 and -1.39 respectively). An impact parameter range of up to 15 m, a starting altitude of 600 g/cm^2 (corresponds to 2 km above the MAGIC site) and an opening angle of up to 1.2^o were simulated. In the second step the standard MAGIC detector simulation [8] is used.

5. Light collection efficiency

The R_{arc} distribution shown in Fig. 3 shows good agreement between data and MC. Since R_{arc} is related to the muon energy, this indicates that the energy distribution of the muons is sufficiently well simulated. Also the shapes of the $SIZE_{muon}$ distributions as a function of R_{arc} agree well between data and MC. The conversion factor from ADC counts to photons hitting the reflector can thus be extracted by normalizing the distributions. A value of Conv$_{ADC\rightarrow photon}$ = $1.38 \pm 0.01(stat.)$ has been obtained. Using Conv$_{ADC\rightarrow phe}$ = $0.149 \pm 0.005(stat.) \pm 0.017(sys.)$ as obtained from the standard MAGIC light calibration [2], one obtains the photon to photo electron conversion efficiency: Conv$_{photons\rightarrow phe}$ = $0.108 \pm 0.003(stat.) \pm 0.012(sys.)$.

The Cherenkov light from the muons in this analysis is produced very near to the telescope. The light from muons is therefore less affected by Rayleigh scattering than the light from typical γ-ray showers. This leads to a small difference in the spectral distribution of the Cherenkov light. Since also the photon collection efficiency is wavelength dependent, a small correction of 3% has to be applied to the conversion factor for γ-ray showers. The resulting conversion factor is:

$$Conv_{photons\rightarrow phe} = 0.105 \pm 0.003(stat.) \pm 0.012(sys.)$$

The above results have been obtained using a 2 hours data sample of September '04. The analysis has been automatized and applied during the standard data reconstruction [9]. In Table 1 the the average CE per month is shown for 3 selected months. A small degradation of $\sim 2\%$ has been observed for January '05 which is compatible with the number of mirror panels excluded from the AMC (see next section) due to faulty connectors during that time.

Table 1. The CE and the PSF for September '04, January '05 amd May '05 are shown. The CE is given in % of the value implemented in the MC used for this analysis and the PSF is given in degree FOV.

Month	CE ratio [%]	PSF [deg]
Sept '04	101.2±1.3	0.037±0.006
Jan '05	99.5±1.7	0.046±0.003
May '05	102.5±2.0	0.035±0.003

6. Point Spread Function

The MAGIC telescope uses an active mirror control (AMC) which adjusts the orientation of each of the 247 mirror panels in order to optimize the mirror focusing for every position of the telescope. Muon rings provide a powerful tool to measure the point spread function (PSF) of the reflector continuously during data taking.

The PSF can be estimated from the $WIDTH_{arc}$ distribution of the muon rings. Several effects contribute to the broadening of the muon ring such as multiple scattering of the muons, mirror aberrations and the effect that the telescope focuses at 10 km for best imaging of γ-ray showers (the muon rings are smallest when focusing to infinity). The $WIDTH_{arc}$ distribution in data is thus compared to the corresponding distribution obtained from MC with different PSFs. For the September '04 data set best agreement has been achieved for PSF = 0.037^o (σ of Gaussian fit). This is a satisfactory value when compared to the 0.1^o inner pixel diameter. For January '05 a slightly worse PSF has been found (see table 1) which is consistent with a known temporary degradation of the AMC accuracy during winter '05.

7. Conclusions

Ring images of muons hitting the telescope reflector have been used to calibrate the overall light collection efficiency. A conversion factor of $Conv_{photons \rightarrow phe} = 0.105 \pm 0.003(stat.) \pm 0.012(sys.)$ has been obtained. The width of the muon rings is used to monitor the PSF of the mirror of the MAGIC telescope.

8. Acknowledgments

We would like to thank the IAC for excellent working conditions. The support of the Italian INFN, German BMBF and MPG, Spanish CICYT and Japanese JSPS is gratefully acknowledged.

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