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Calibration of the Cherenkov telescope array using cosmic ray electrons

R.D. Parsons*, J.A. Hinton, H. Schoorlemmer

Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029, Heidelberg, Germany

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ABSTRACT

Cosmic ray electrons represent a background for gamma-ray observations with Cherenkov telescopes, initiating air-showers which are difficult to distinguish from photon-initiated showers. This similarity, however, and the presence of cosmic ray electrons in every field observed, makes them potentially very useful for calibration purposes. Here we study the precision with which the relative energy scale and collection area/efficiency for photons can be established using electrons for a major next generation instrument such as CTA. We find that variations in collection efficiency on hour timescales can be corrected to better than 1%. Furthermore, the break in the electron spectrum at ∼ 0.9 TeV can be used to calibrate the energy scale at the 3% level on the same timescale. For observations on the order of hours, statistical errors become negligible below a few TeV and allow for an energy scale cross-check with instruments such as CALET and AMS. Cosmic ray electrons therefore provide a powerful calibration tool, either as an alternative to intensive atmospheric monitoring and modelling efforts, or for independent verification of such procedures.

1. Introduction

Electrons (and positrons) represent $< 1\%$ of the cosmic ray flux at 100 GeV energy. However, after the hadron-rejection cuts typically applied to date taken by Cherenkov telescope arrays, they represent a dominant background over a wide energy range, with improving hadron rejection compensating for the steeper electron spectrum ($\sim E^{-3}$ versus $\sim E^{-2.7}$) up to the break in the electron spectrum at 900 GeV [1]. The electron background is uniform on the sky at the $< 5\%$ level below 100 GeV [2], while at higher energies the anisotropy is unknown (although anisotropy is expected to increase with energy). Electrons are therefore present in every field observed by Cherenkov telescope arrays, with close to isotropic flux, and separable from protons and nuclei using modern background-rejection methods [1,3–6]. Once the electron spectrum is known, the rate and spectrum measured in a given observation can be used to correct for atmospheric and instrumental deviations from the ideal case, or to check that atmospheric and instrumental corrections have been successfully applied. The advantages over cosmic ray protons and nuclei for this purpose (see for example [7]) are the close similarity of gamma and electron initiated air showers in terms of morphology and atmospheric depth at which the maximum number of particles is reached, albeit with a half radiation length shift, and the presence of a distinct feature in the CR electron spectrum: the 0.9 TeV break. This feature raises the prospect of independently establishing collection area and energy scale changes, something which is impossible using single power-law spectra. The spectral break position and level of high energy anisotropy in electrons will be established independently by future ground-based Cherenkov telescope arrays and by space-based instruments such as CALET [8] and perhaps AMS [9], providing a means for cross-calibration of the instrument based on a independent energy scale.

Measuring the cosmic ray electron spectrum with an array of Imaging Atmospheric Cherenkov Telescopes (IACTs) is, however, a significant challenge. The H.E.S.S. collaboration was the first to demonstrate that this is at all possible, by applying hard selection cuts (four telescope multiplicity and a random forest approach) [1]. Subsequently, these measurements were extended to lower energies for H.E.S.S. [10] and now confirmed by MAGIC [11] and VERITAS [12]. For current-generation instruments these measurements require long exposures: typically many hundreds of hours. Spectral measurements for gamma-ray sources make use of background estimates established using regions in the field of view thought to be empty of gamma-ray emission. This approach is clearly not possible for electrons, which are close to isotropic. Instead a model of the background in terms of some separation parameter (for example the output of a neural network classifier)

* Corresponding author.
E-mail address: daniel.parsons@mpi-hd.mpg.de (R.D. Parsons).

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must be established. This requires a detailed understanding of the development of hadronic cascades in the Earth's atmosphere. Significant differences exist (at the ∼ 10% level) between hadronic interaction models (or Monte–Carlo event/interaction generators) due to underlying physical uncertainties, particularly in the production of pions with a large forward momentum in the energy range of interest [13,14]. Dedicated instruments at the LHC, such as LHCf and TOTEM, as well as the general purpose ATLAS and CMS detectors, have now significantly reduced the uncertainties in this energy range and models such as EPOS LHC and QGSJETII are currently being refined to reflect these developments [15,16]. The systematic uncertainties on electron spectrum extraction will therefore be much smaller in the near future than those presented in the existing IACT publications.

The next generation facility CTA (the Cherenkov Telescope Array [17]) will employ over 100 telescopes at two sites (CTA-North and CTA-South), dramatically improving on the performance of current generation IACTs. The wider field of view of CTA telescopes (∼8° diameter), lower energy threshold (∼20 GeV), and very large collection area of the instrument (typically an order of magnitude larger than current instruments for gamma ray analyses, and even more for electron analyses due to the hard cuts often used, at all energies) [18] combine to produce an electron rate after quality selection cuts that is two or more orders of magnitude larger than that measured by current arrays [19] at ∼0.9 TeV. Furthermore, the background rejection power of CTA will be superior to that of current generation instruments, allowing the extraction of the cosmic ray electron spectrum over a wide energy range in a short time, with modest systematic uncertainties [19].

CTA will employ LIDAR-based atmospheric monitoring systems to measure variation in light propagation through the atmosphere ([20], and references therein). Whilst these measurements will be used to ensure realistic atmospheric treatment in the Monte Carlo simulation of the detector response, it is highly desirable to have a procedure for continuous confirmation that such measurement procedures have been successful, and as an independent means of deriving correction factors. In addition, instrumental effects may change the efficiency with which gamma-like showers trigger the array and pass selection cuts, and/or lead to systematic under or over estimation of photon energy. Again, CTA will make use of multiple methods to characterise such effects, but the approach of deriving the cosmic ray electron spectrum in a routine way for all observations without a significant diffuse gamma-ray component promises a convenient end-to-end method to establish correct performance or to derive correction factors. Due to the lack of bright diffuse gamma-ray emission in the relevant energy range and the small angular size of point-like sources compared to the instrument field-of-view, the electron spectrum can be extracted from almost all potential CTA extragalactic observations without the addition of an gamma-ray electron separation, simply by the removal of significant point sources from a given observation set (typically 1 source per field in the current generation of telescopes).

Here, we propose a method for a CTA electron spectrum measurement and assess the timescales on which the flux normalisation and break energy can be found. We go on to discuss the systematic uncertainties associated with this approach and its merits for the array-level calibration of CTA.

2. Approach

To test the feasibility of using the electron spectrum as a means of high level calibration, electron spectral measurements were simulated using the CTA-South “Production-2” Monte Carlo dataset [18]. Array layout “2Q” was used, which contains 4 large sized telescopes (23 m diameter), 24 medium sized telescopes (12 m) and 72 small sized telescopes (4 m). Direction and energy reconstruction were performed using the CTA baseline analysis,[1] under the assumption that the events are diffuse electrons. To ensure the quality of the images that are used in the reconstruction, we apply cuts on the number of pixels and number of photo-electrons (p.e.), these selection criteria were optimised for the nominal night-sky background rate (extrapolated from measurements at the H.E.S.S. site) and are summarised in Table 1 for each telescope type. To improve the quality of the reconstructed air shower parameters we require that the reconstructed shower direction lies within 4° of the telescope pointing direction and that a minimum of four telescopes participated in the reconstruction.

Table 1
Image cuts for the different type of telescopes.

Type	Amplitude (p.e.)	N_{pix}
Large (4)	>92.7	≥5
Medium (24)	>90.6	≥4
Small (72)	>29.5	≥4

An artificial neural network was created using the TMVA package [22] to perform classification of electrons from protons. The neural network was trained in five energy bins covering the full energy range of the CTA instrument (0.02–100 TeV), using the following discriminating variables:

- Mean scaled event width/length (see e.g. [23])
- Root mean square of scaled event width/length between telescopes
- Root mean square of event energy estimates between telescopes
- Reconstructed depth of shower maximum (X_{max})
- Spread of X_{max} estimates between telescopes
- Mean time gradient across an image [24]

Once trained, an independent sample of simulated data was passed through the network to produce the expected classifier (ζ) distributions of electrons and protons. Combining these distributions with the correct normalisations to provide the expected distribution of events when observing a gamma-ray free region of the sky requires assumptions on the spectra of protons and electrons, for which we adopt the following functional form for protons (based on data from [25]):

$$F_p = \phi_{0,\mathrm{p}}\left(\frac{E}{1\,\mathrm{TeV}}\right)^{\Gamma} \tag{1}$$

with $\phi_{0,\mathrm{p}} = 9.6\times10^{-2}\,\mathrm{m^{-2}s^{-1}TeV^{-1}sr^{-1}}$ and $\Gamma = -2.7$. For electrons we have

$$F_e = \phi_{0,\mathrm{e}}\left(\frac{E}{1\,\mathrm{TeV}}\right)^{\Gamma_1}\left[1+\left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right]^{(\Gamma_2-\Gamma_1)\alpha} \tag{2}$$

with $\phi_{0,\mathrm{e}} = 1.5\times10^{-4}\,\mathrm{m^{-2}s^{-1}TeV^{-1}sr^{-1}}$, $\Gamma_1 = -3.0$, $\Gamma_2 = -4.1$, $E_b = 0.9\,\mathrm{TeV}$, and $\alpha = 0.2$ (the H.E.S.S. measurement gives a limit of $\alpha < 0.3$), consistent with measurements using Fermi-LAT [2], AMS [9] and H.E.S.S. [10] respectively. The contribution of heavier cosmic-ray nuclei can be safely ignored, due to their lower expected fluxes and the extremely powerful background rejection for such events. This “data” distribution can then be scaled and Poisson fluctuations added to represent any length of observation time. Once this simulated observation expectation has been created, we use a component fitting technique similar to that used in [1], using the aforementioned particle classifier distributions to estimate

[1] Consisting of Hillas parameterisation of images and a weighted combination of the intersection of image axes for direction reconstruction, and energy estimation using look-up tables [21].