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Protons Spectrum from the MAGIC Telescopes data

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Imaging Atmospheric Cherenkov telescopes (IACTs) are designed to detect cosmic gamma rays. As a by-product, IACTs detect Cherenkov flashes generated by millions of hadronic air showers every night. We present the proton energy spectrum from several hundred GeV to several hundred TeV, retrieved from the hadron induced showers detected by the MAGIC telescopes. The protons are discriminated from He and other heavy nuclei by means of using machine learning classification. The energy estimation is based on a specially developed deep neural network regressor. In the last decade, Deep Learning methods gained much interest in the scientific community for their ability to extract complex relations in data and process large datasets in a short time. The proton energy spectrum obtained in this work is compared to the spectra obtained by dedicated cosmic ray experiments.

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1 Introduction

The recent results in cosmic ray physics demonstrate that we are entering an era of precision experiments. The experiments CREAM [1], NUCLEON [2] and CALET [3] found evidence for some structure above 10 TeV in the proton spectra. The DAMPE experiment with 2½ years of selected measurements published precise spectra of cosmic nuclei that show not trivial structure [4].

Over the last two decades, imaging air Cherenkov telescopes (IACT) have collected huge amounts of air shower data, most of which are generated by charged nuclei. It is generally believed that data from IACTs, which are designed to preferentially detect gamma induced showers, are not well-suited for studying charged cosmic-ray particles. However, there have been few attempts to extract the proton spectrum from such data. For example, the experiment HEGRA successfully extracted the proton spectrum, but in a narrow range of energies [5]. Later independent researches of the proton spectrum were conducted on the basis of H.E.S.S. measurements [6,7]. Measurements of the cosmic iron spectrum were performed by the experiments H.E.S.S. and VERITAS [9,10,11], for events selection using the direct Cherenkov radiation of the heavy nuclei before the start of induced atmospheric showers; these based on the method proposed by Kieda et al. [8].

The purpose of this study is to show that the background data detected by the two MAGIC telescopes, which are generated in the atmosphere mainly by charged cosmic particles, can be successfully used to study the spectra of these nuclei in a wide range of energies. The method presented here needs no assumption about the estimated spectrum and thus allowed us to perform a detailed search of the spectral features. The proton spectrum obtained in the region 700 GeV-500 TeV is well-compatible with the precision of DAMPE and CREAM-III proton spectrum measurements.

2 Data and Simulations Sets

For this study we have used about 70 hours of observational data taken in 2016 and 2017. The Monte Carlo (MC) simulations were done for the 3 most abundant components of charged cosmic rays: protons, helium and iron. At energy 10 TeV their ratio is about 1:1:0.2. In future we plan to use Monte Carlo simulation of C and O nuclei.

The showers were simulated within the impact parameter range of up to 1500 m and the viewing angle of 4 degrees in the following energy ranges and statistics in the Corsika code (version 6.990) :

- Protons: 70 GeV – 500 TeV – about $2.5 \cdot 10^8$ events.
- He: 140 GeV – 2000 TeV – about $1.2 \cdot 10^8$ events
- Fe: 400 GeV – 6000 TeV – about $5 \cdot 10^7$ events

For the analysis we selected only events that have passed trigger conditions in the energy range 700 GeV-5000 TeV. Finally, about 80000, 56000 and 28000 simulated events for proton, helium and iron correspondingly survived for the analysis. The used real data after data quality cuts includes about 9.6 million events collected during 70 hours of observations in 2016 and 2017.

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3 Analysis method

We use Supervised Feed-forward Neural Networks with Back Propagation method for error minimization to create the energy regressor and event classifier. As input variables we used Hillas parameters and additional variables, traditional for the MAGIC experiment. We don't use the convolution layers method, because it is too sensitive to small differences between simulation and real data.

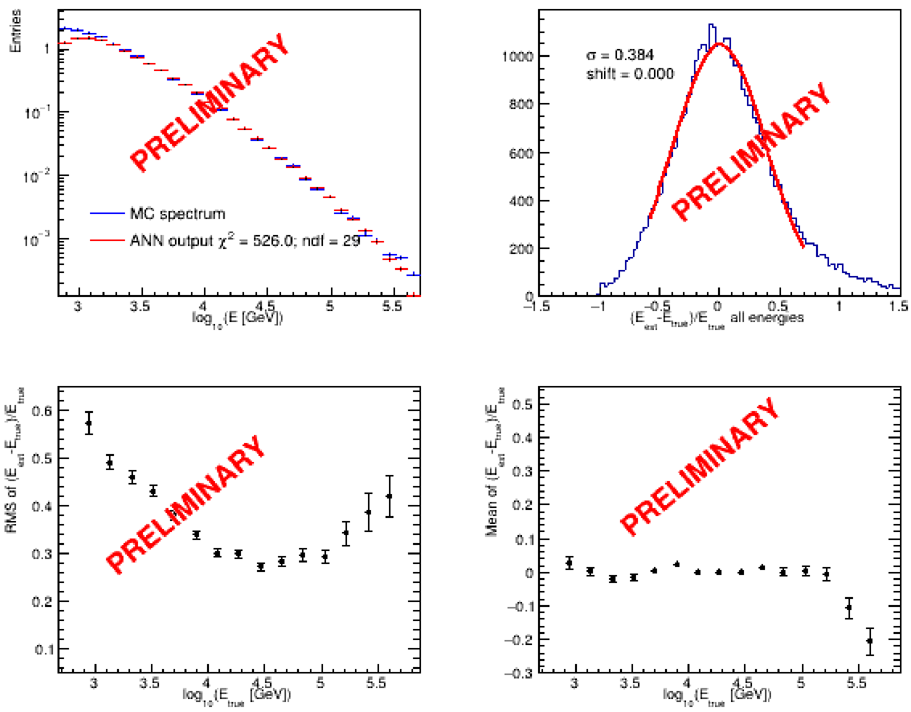
The network architecture applied for the energy reconstruction consists of 1 input layer of 21 nodes, 3 hidden layers of 16, 8, 4 hidden nodes and 1 output layer of 1 node. Although corresponding networks were created, trained and validated for any of the three mentioned above types of nuclei, in the proton flux determination for He and Fe we used energy obtained with the network, trained to reconstruct the proton energy.

For the separation of the protons from all the other nuclei we created two completely different networks, aiming at the discrimination of the proton induced shower against helium and against iron induced showers. Both networks have the same architecture consisting of 1 input, 4 hidden and 1 output layers with 36, 28, 18, 10, 5, 1 nodes correspondingly. These were trained independently on one half of the corresponding MC events and validated on the other half of the MC events, not used in the training procedure. These two networks were applied to all the real data samples.

3.1 Energy reconstruction

The results obtained for the MC protons from the described above energy regressor are shown in the figures below. The energy resolution is estimated by plotting $(E_{true}-E_{estimated})/E_{true}$ in bins of E_{true} and fitting this distribution by a Gaussian function.

On the below figure the top left panel presents the simulated and reconstructed spectra. On the top right panel the energy resolution, integrated for all energies is presented. The bottom left and right panels are for energy resolution and energy bias as functions of the simulated energy.



On the next figure the migration matrix between true and estimated energies is presented. It is normalized to 1 in every row of true energy, including overflow and underflow bins. Only bins with contents > 0.003 are plotted.

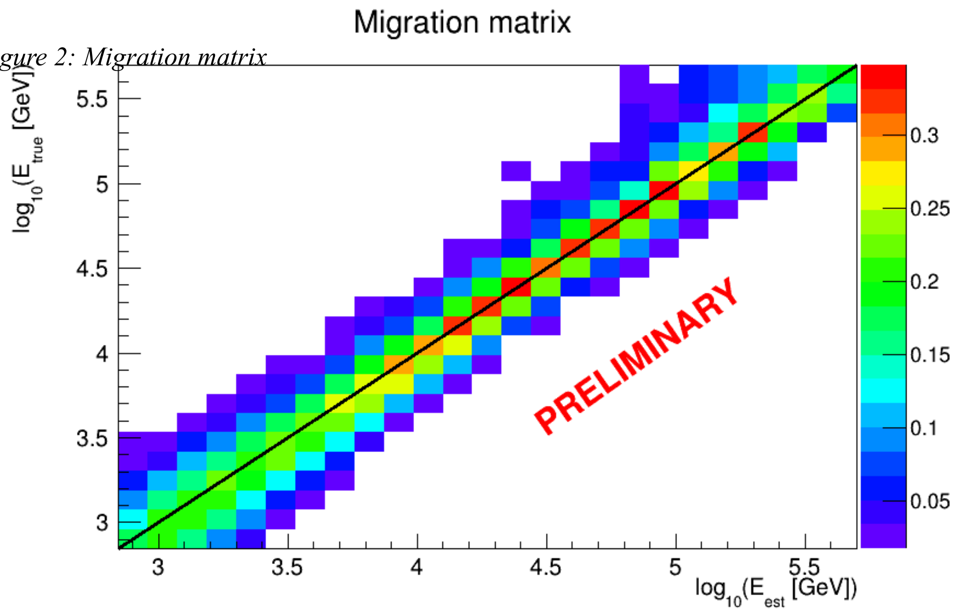


Figure 2: Migration matrix

3.2 Classification

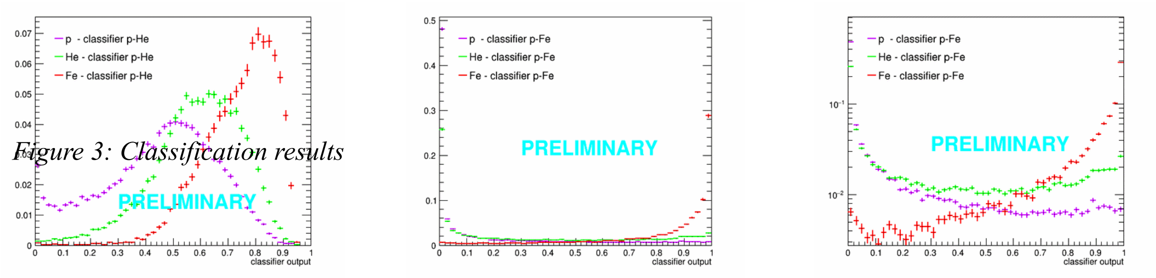


Figure 3: Classification results

On the figures below the outputs of 2 classification networks (p-He and p-Fe) for 3 elements (p, He and Fe) are shown. For the p-Fe classifier we present the graphs also in logarithmic scale for better visibility.

3.3 Flux calculation

In the case of 3 components (proton, He, Fe) and two neural networks for classification (p-He and p-Fe) the number of protons $N_{protons}$ may be estimated as:

$$N_{protons} = \frac{\varepsilon_1 \cdot (p_{2,He} - p_{2,Fe}) - \varepsilon_2 \cdot (p_{1,He} - p_{1,Fe}) + p_{1,He} \cdot p_{2,Fe} - p_{2,He} \cdot p_{1,Fe}}{p_{1,p} \cdot (p_{2,He} - p_{2,Fe}) - p_{2,p} \cdot (p_{1,He} - p_{1,Fe}) + p_{1,He} \cdot p_{2,Fe} - p_{2,He} \cdot p_{1,Fe}} \frac{N}{Efficiency}$$

Here $\mathbf{p_{1,i}}$ and $\mathbf{p_{2,i}}$ i=p,He,Fe are the probabilities to classify a shower as proton-like in the first and second binary classifiers for 3 the MC samples i. $\boldsymbol{\varepsilon_1}$ and $\boldsymbol{\varepsilon_2}$ are the fractions of proton-like events selected from **N** real events by the first and second classifiers. The efficiency:

$$Efficiency(E, \cos(\theta), Zenith) = N_{selected} / N_{simulated}$$

is a detection probability, calculated for MC proton showers, where $N_{selected}$ represents the number of events that passed the trigger and analysis cuts, and $N_{simulated}$ is the number of simulated showers.

All quantities in this formula are functions of energy, cosine of proton's arriving angle (angle between proton and telescope axis) and zenith angle of telescope pointing.

Statistical errors for probabilities p and fractions ε are calculated from the corresponding binomial distributions. The statistical error of $\mathbf{N_{protons}}$ is estimated using the approximate error propagation formula keeping only the first two terms of the Taylor series. Due to the limited statistics of MC (specially for Fe) the main contributions to the total error are due to uncertainties of quantities $\mathbf{p_{i,j}}$ (determined from simulated events). There exist statistical correlations between random variables corresponding to events of one type classified in both networks, i.e. for $\mathbf{p_{1,i}}$ and $\mathbf{p_{2,i}}$ for equal i = p,He,Fe and between $\boldsymbol{\varepsilon_1}$ and $\boldsymbol{\varepsilon_2}$**.** These correlations were taken into account by calculating the final value of the statistical error of the estimated number of protons $\mathbf{N_{protons}}$.

The flux per unit energy/surface/time/angle is calculated as

$$F(E, \cos(\theta), Zenith) = N_{protons} / (\pi \cdot I^2 \cdot T \cdot dE \cdot 2 \cdot \pi \cdot (1 - \cos(V)))$$

where T is the observation time, I is the radius of the simulated area, V is the maximum simulated angle and ΔE is the energy bin width.

4 Results

4.1 Energy spectrum

The energy spectrum was estimated as it was described in the previous paragraph. It is important to perform an unfolding of the energy distribution, especially because the energy resolution in our case is about 30%. We used the TUnfold software [12], which is included in the ROOT package. The method is based on the least-square fitting and the Tikhonov regularization method. The preliminary measured and unfolded spectra are presented in the slides for the talk at this conference. The value of the measured flux changes by 7 orders of magnitude and is in good agreement with the fluxes published by the experiments CREAM [1] and DAMPE [4].

In order to demonstrate the stability of our results, we divided the data set into two sub-samples measured in different years: 60 hours of observations in 2016 and 10 hours in 2017. The two spectra coincide with each other taking into account the statistical errors. The statistical uncertainties are comparable for both data sets which have rather different sizes. It demonstrates that our statistical uncertainty is dominated by the statistics of the MC simulations.

4.1.1 Flux vs Arriving angle

Cosmic rays arrive uniformly in the considered energy range. Below the angular distributions are presented. In the left panel the distribution for the whole data set is shown, in the central and right panels the distributions for 2016 and 2017 are plotted. It is seen that the angular distribution is uniform and there is no significant difference between the estimated fluxes for the two different periods of observations.

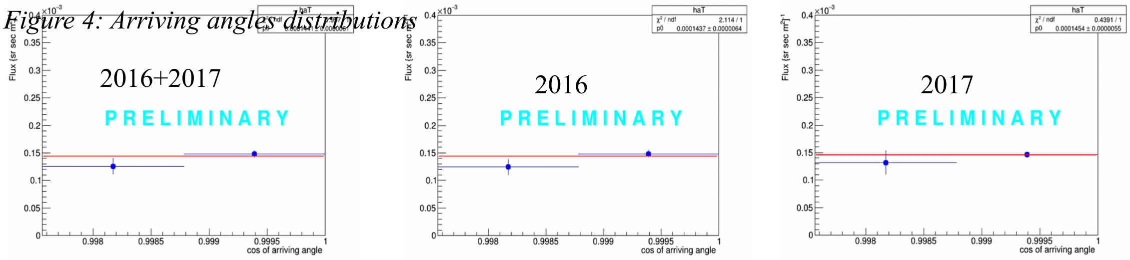


Figure 4: Arriving angles distributions

5 Consistency check

If the flux calculation and the detection efficiency corrections are done properly, the flux values must be independent from the pointing telescope direction. Indeed, in our case the integrated flux for all the data and for the sub-samples from 2016 and 2017 are constant as a function of the zenith angle and are in good concordance for different cases: $1.345 \pm 0.008 \cdot 10^{-3}$, $1.356 \pm 0.008 \cdot 10^{-3}$ and $1.365 \pm 0.008 \cdot 10^{-3}$.

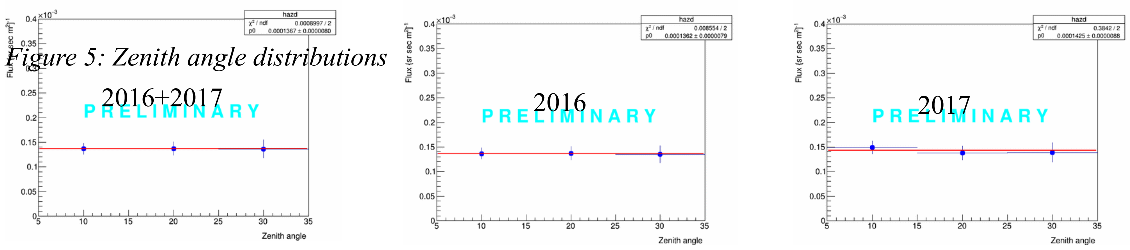


Figure 5: Zenith angle distributions

6 Systematic uncertainties

There are 3 main sources of systematic uncertainties:

- One is the influence of C and O nuclei which are not yet taken into account. Their contribution could be less than 10% to the proton flux
- Inaccuracy of hadronic model used in Corsika simulation code. According to R. D. Parsons and H. Schoorlemmer [13] it is estimated to be less than 10% in energy range 1-100 TeV
- Diverse uncertainties of the detector. From the typical MAGIC systematic effects [14] and from the flatness of the zenith and the arriving angles we estimate these effects as ≤ 30%.

When we add these quadratically, the total systematic error turns out to be about 33%.

7 Conclusions

We demonstrated the practical feasibility of measuring the proton spectrum with high statistical accuracy in the energy range 1-500 TeV using a small fraction of data collected by the MAGIC telescopes system. The analysis method produces stable results. The next step could be the application of this method to the study of the spectra of different cosmic nuclei. Such study will permit high accuracy measurements of the energy spectra and elemental composition of cosmic nuclei by using the background data of IACT experiments.

8 Acknowledgements

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`https://magic.mpp.mpg.de/acknowledgments_ICRC2021`

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