Protons Spectrum from MAGIC Telescopes data

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on behalf of the MAGIC Collaboration

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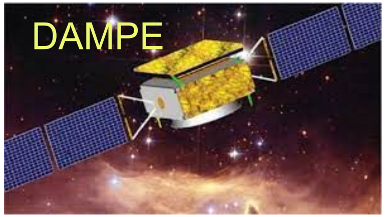
Introduction



The recent results in cosmic rays physics [1-3] demonstrate that the field is entering an era of precision experiments. The DAMPE experiment [4] with 30 months of measurements observed not trivial structure in proton spectrum. In the last two decades, Cherenkov gamma telescopes have collected vast amount of electromagnetic air showers, most of which are generated by charged cosmic rays. Single attempts to extract the proton and iron spectra have been made by IACTs → HEGRA [5], H.E.S.S. [6,7,8] and VERITAS [9,10].

The purpose of this study is to show that the background data detected by the two MAGIC telescopes can be successfully used to study the spectra of these nuclei in a wide range of energies.

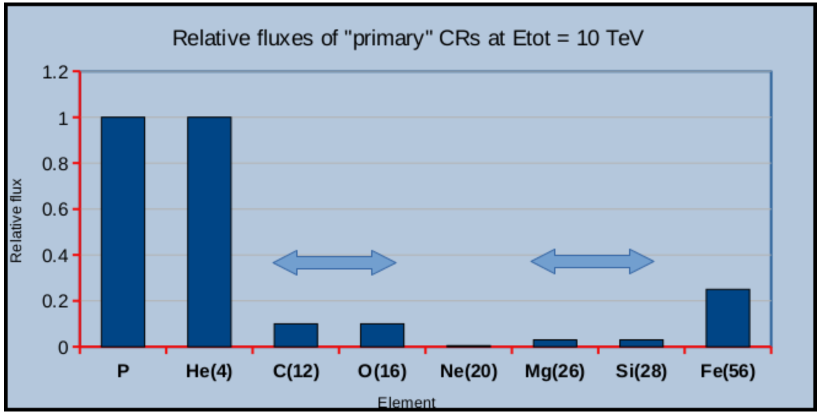
Monte Carlo simulation and real data

Air showers simulation was performed with Corsika version 6.990, adopted for MAGIC stereo telescope system.
The three most abundant cosmic rays elements were simulated: proton, helium and iron.
The atmospheric showers were simulated with the impact parameter 1500 m and the viewing angle 4 degrees in the energy range from several hundred GeV to more than 500 TeV.

For the analysis we selected only events in the energy range 700 GeV-500 TeV which passed trigger conditions and quality cuts. Finally, about simulated 80000, 56000 and 28000 events for proton, helium and iron correspondingly survived preliminary cuts. One half of these data sets were used for the networks training.

The used real data after the data quality cuts includes about 9.6 million events collected during 70 hours of observations in 2016 and 2017.

Relative fluxes of different primary nuclei at 10 TeV.

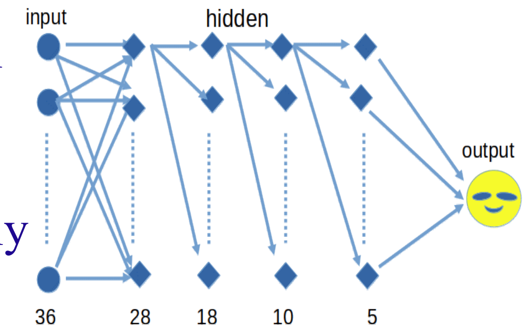


Analysis method

The method presented here needs no assumption about the estimated spectrum and thus allows detailed search of the spectral features. We use Supervised Feed-Forward Neural Networks with back propagation method for error minimization to create energy regressor and event classifier. For the input layer we use Hillas parameters and additional variables, traditional for the MAGIC experiment.

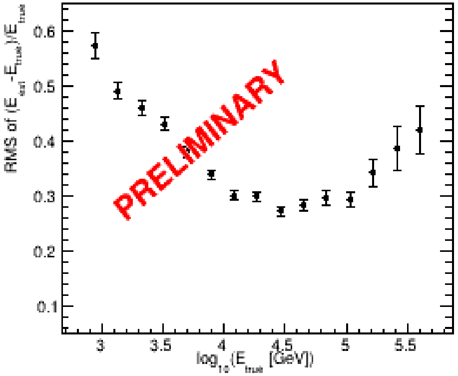
The net architecture applied for **energy reconstruction** consists of 1 input layer of 21 nodes, 3 hidden layers of 16, 8, 4 hidden nodes and output layer of 1 node. We use the network trained on MC protons to estimate the energy of He and Fe showers.

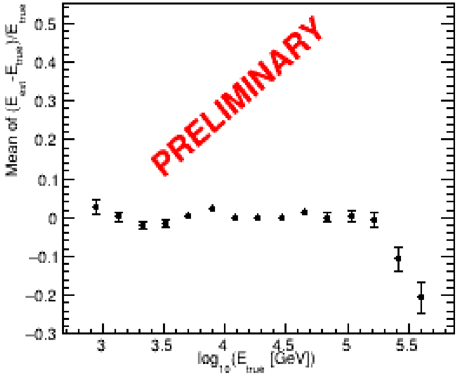
For the **discrimination of the protons from all other nuclei** we created two different networks, which discriminate the proton shower from helium and correspondingly from iron showers. Both networks have the same architecture consisting of 1 input, 4 hidden and output layer with 36, 28, 18, 10, 5, 1 nodes correspondingly. They were trained independently on a half of the corresponding MC events available. Further these two networks were applied to all real and testing MC data samples.

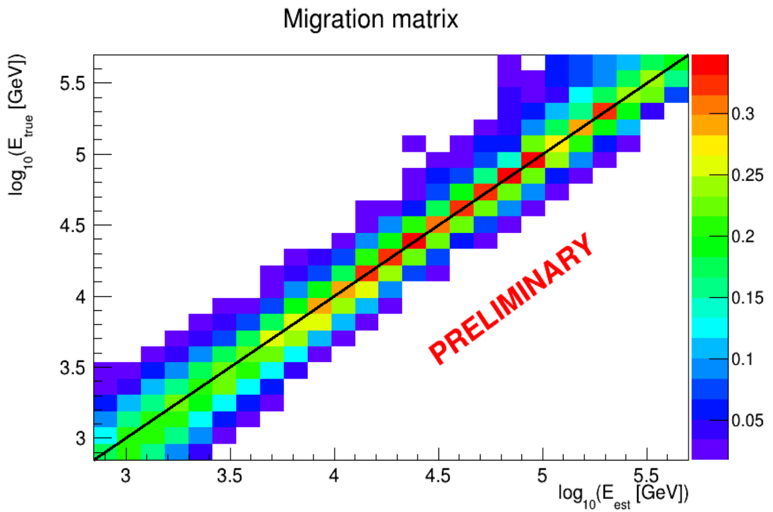


Energy estimation

The results for the MC protons obtained with the energy regressor are shown below. The energy resolution is estimated by plotting $(E_{true}-E_{estimated})/E_{true}$ in bins of E_{true} and fitting this distribution by the Gaussian function. On the left and central figures are presented the energy resolution and energy bias as functions of the simulated energy. On the right plot migration matrix between true and estimated energies is depicted. It is normalized to 1 in every row of the true energy, including overflow and underflow bins.

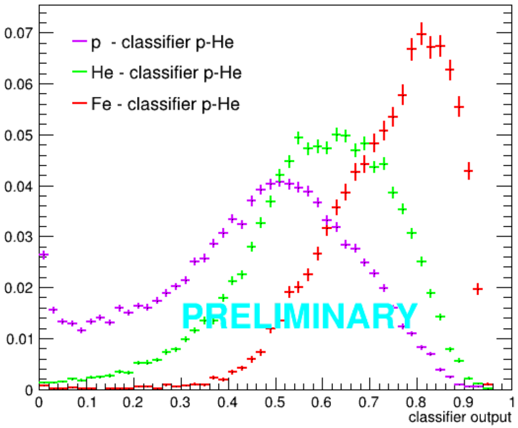


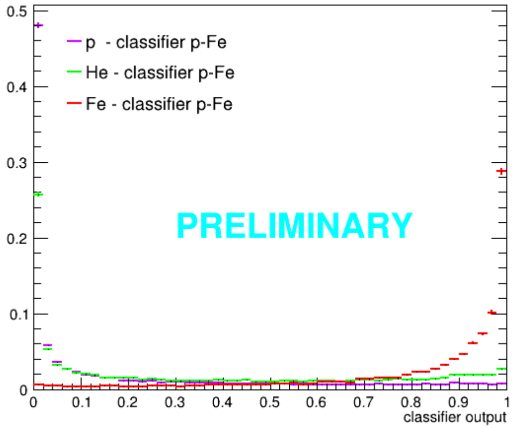


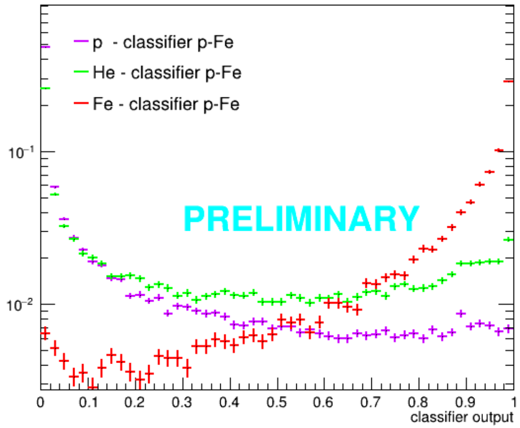


Classification

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







proton-like

proton-like

Number of protons for 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 $\mathbf{N_{protons}}$ may be estimated as:

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

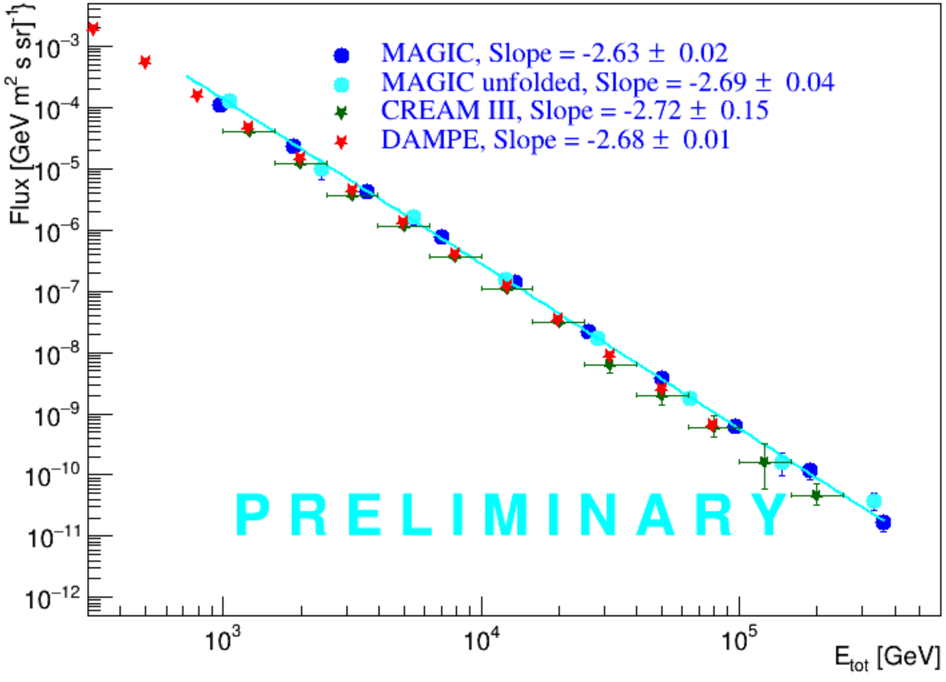
Here $\mathbf{p_{1,i}}$ and $\mathbf{p_{2,i}}$ i= p, He, Fe are the probabilities to classify a shower as proton-like in the first and second classifiers for 3 MC samples. $\boldsymbol{\varepsilon_1}$ and $\boldsymbol{\varepsilon_2}$ are the fractions of proton-like events selected from **N** real events by the first and second classifiers. $efficiency(E,\cos(\theta),zenith)=N_{selected}/N_{simulated}$ is a detection probability, calculated for the MC proton showers, where “selected" means “passed trigger and analysis cuts”, and number of simulated showers.

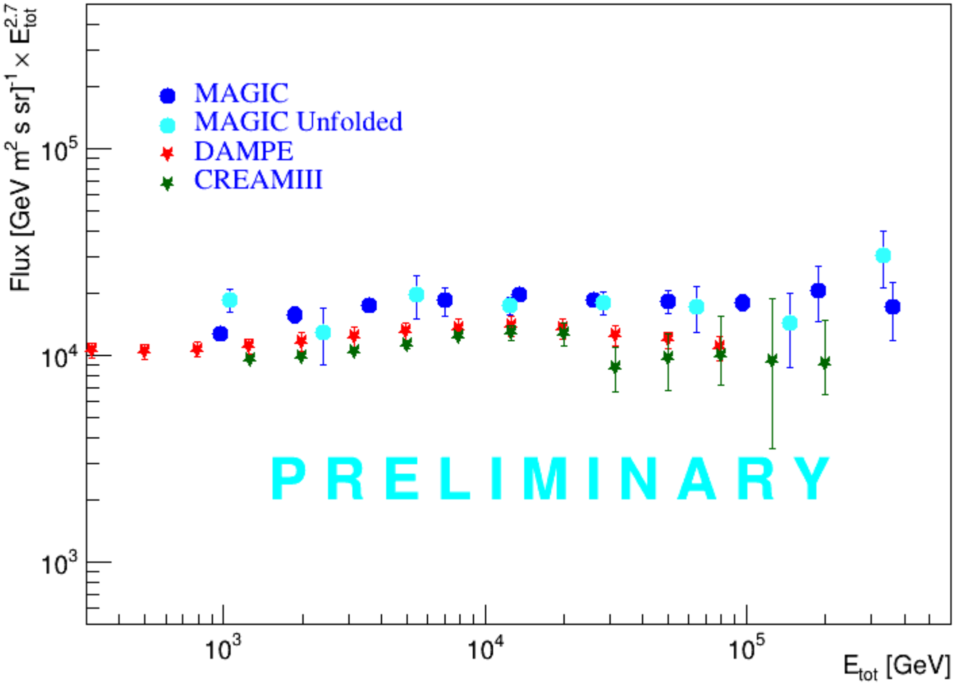
All quantities in this formula are functions of energy, cosine of proton’s arriving angle (angle between proton and telescope axis) and zenith angle of telescope pointing.

The flux per unit energy/surface/time/angle is calculated as, $F(E,\cos(\theta),zenith)=N_{protons}/(\pi\cdot I^2\cdot T\cdot\Delta E\cdot 2\cdot\pi\cdot(1-\cos(V)))$ where the **T** is the observation time, **I** is the impact factor of simulated area, **V** is the maximum angle and **ΔE** is energy bin width.

Proton spectrum

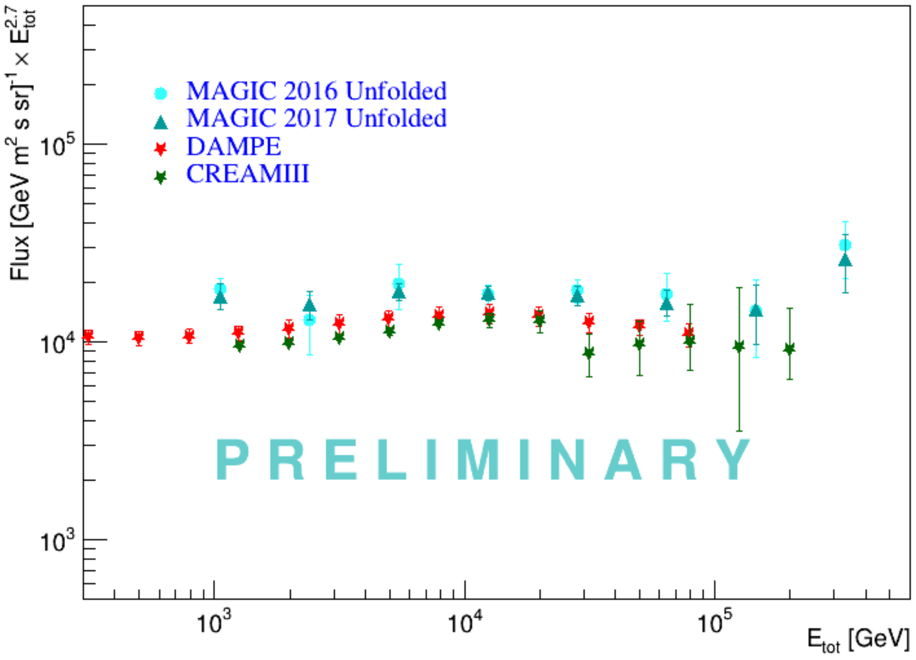
The energy spectrum was received as it was described in the previous paragraph. Unfolding of energy distribution was performed using the TUnfold software [2], which is also included in the ROOT package. The method is based on the least-square fitting and Tikhonov regularization method. The measured spectrum is plotted with blue markers. The unfolded spectrum is plotted in Cyan color and fitted by power low function $F \sim E^{Slope}$. We compare our results with the measurements from CREAM II [1] and DAMPE [4]. To improve the visibility the spectra are multiplied by the factor $E^{2.7}$ and presented on the right panel.





Proton spectrum for 2016 and 2017

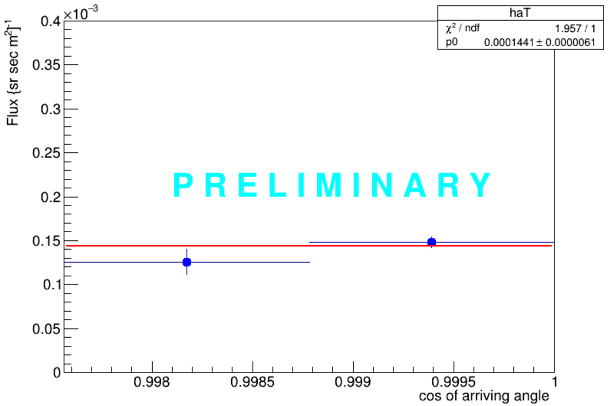
In order to demonstrate the stability of our results, we divided the data set into two sub-samples: 60 hours observations in 2016 and 10 hours in 2017. It is obvious, that the results are stable. The statistical errors are close to each other for both rather different as a size data set. It demonstrates, that our statistical uncertainty is dominated by the statistics of Monte Carlo simulations.



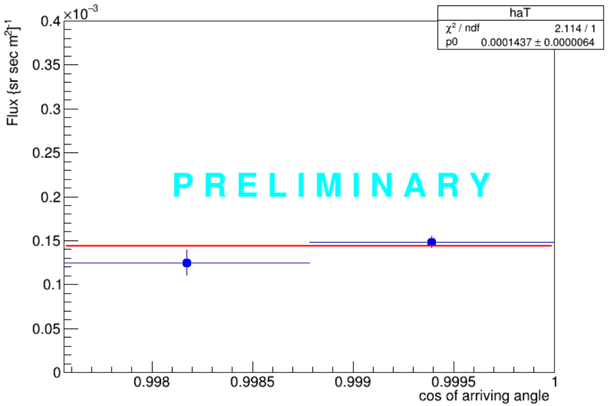
Angular distribution

Cosmic rays arrive uniformly in our energy range. We see that it is true for our analysis, and that fluxes are equal for two periods of observation.

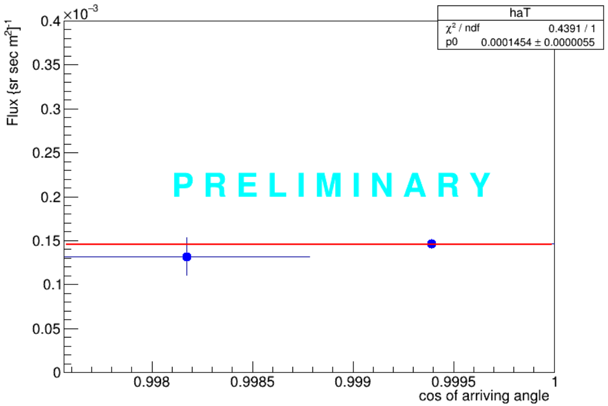
$1.441 \pm 0.006 \cdot 10^{-3}$ | $1.437 \pm 0.006 \cdot 10^{-3}$ | $1.454 \pm 0.005 \cdot 10^{-3}$



2016-2017, 70 hours



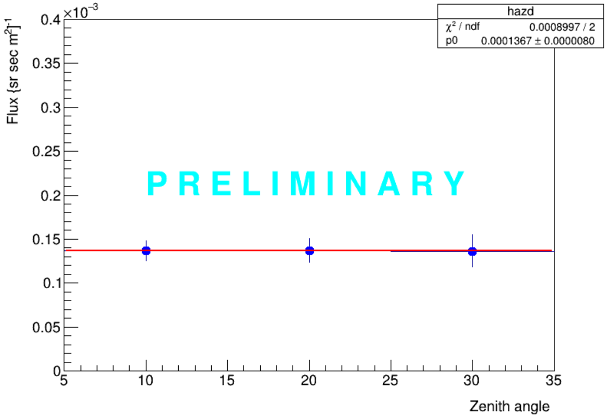
Year 2016, 60 hours

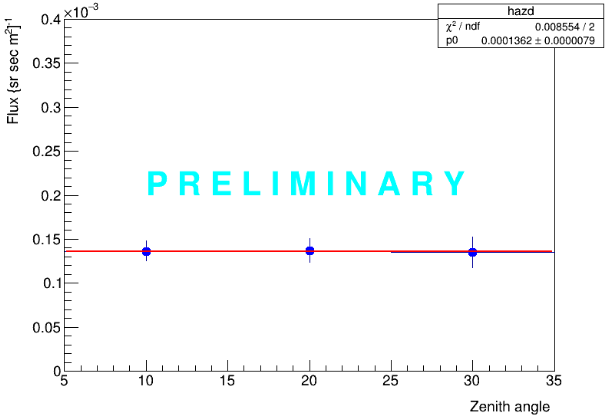


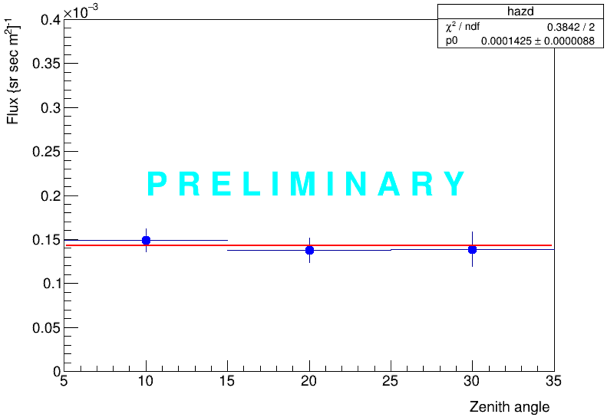
Year 2017, 10 hours

Consistency check

If the flux calculation and detecting efficiency corrections are done properly, the flux values must be independent from the pointing telescope direction. It is seen that the integrated flux for all data and for sub-samples from 2016 and 2017 are constant as a function of zenith angle and are equal for 3 different cases: $1.347 \pm 0.008 \cdot 10^{-3}$, $1.362 \pm 0.008 \cdot 10^{-3}$ and $1.143 \pm 0.009 \cdot 10^{-3}$







Systematic uncertainties

There are 3 main sources of systematic uncertainties:

- Influence of C and O nuclei which are not taken into account. It could contribute up to 10 % of the proton flux
- Inaccuracy of hadronic model used in Corsika simulation. According to R. D. Parsons and H. Schoorlemmer [13] it could be less than 10 % in energy range 1-100 TeV
- Different reasons due to the detector and the analysis chain. From typical Magic systematic effects [14] and from flatness of zenith and arriving angles we estimate these effects as 30 %.

If we add them quadratically, the total systematic error will be about 33 %.

Conclusions and plans

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

Acknowledgments

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

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