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# Measurement of the Proton Spectrum with the MAGIC Telescopes

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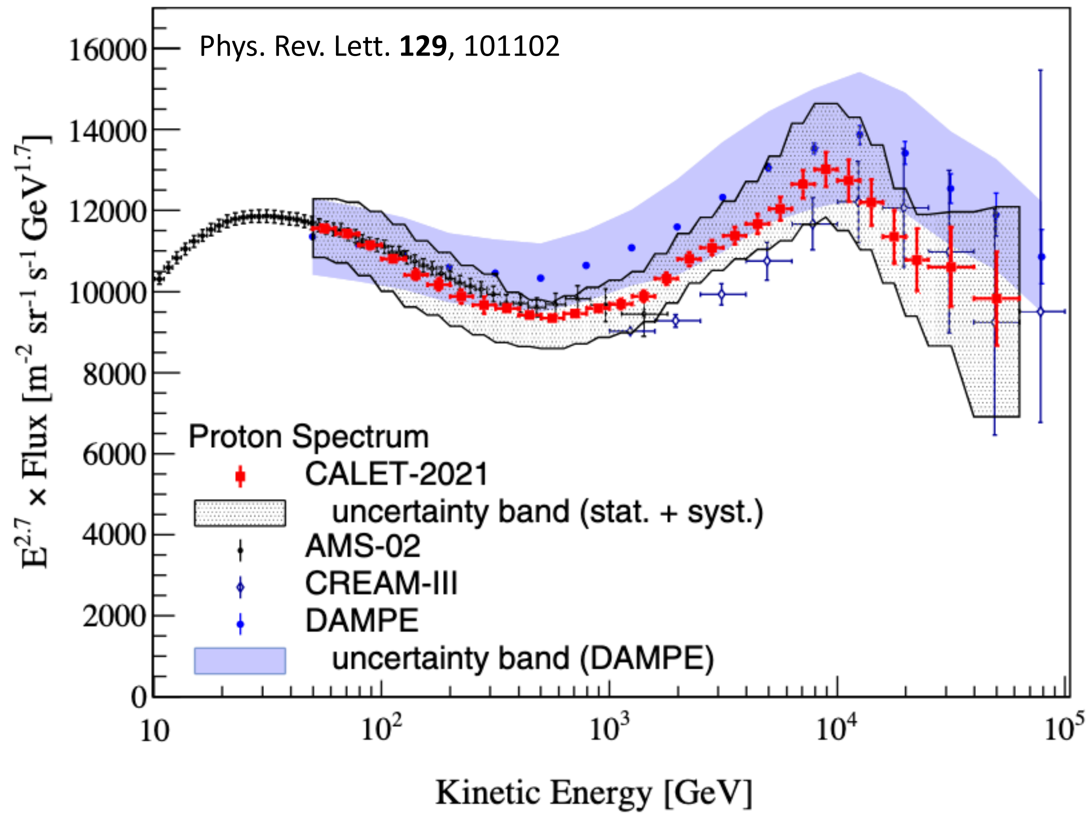
MAGIC

# Introduction

Recent measurements of the proton spectrum from dedicated cosmic ray experiments have found structures at about 10 TeV




The purpose of this work (firstly presented at ICRC 2021) is to show that the background data in gamma-ray observations with IACTs can be used for cosmic ray studies

# MAGIC Telescopes

- Two 17 m diameter f/1 Cherenkov Telescopes at the Roque de los Muchachos Observatory
- Energy range: > 20 GeV
- Field of view: 3.5 deg, 1039 PMT-based pixels
- Primarily designed for VHE gamma-ray detection
- Cosmic rays constitute the main source of background for gamma-ray observations. However, with dedicated analysis, these species can be studied.

Performance details: Aleksić et al., AP (2016) 72, 76-94

# Data and MC simulations

- Data:
  - Zenith Range: 5-35°
  - Good atmospheric conditions
  - Total effective exposure time amounts to 434 hours
- MC:
  - Similar zenith conditions
  - Energy range from 500 GeV to 2 PeV
  - Several species were produced for this analysis

**MC simulations**

| Particle | Z | Gen. Events [$\times 10^7$] |
|---|---|---|
| Proton | 1 | 27.5 |
| Helium | 2 | 15.4 |
| Carbon | 6 | 9.9 |
| Oxygen | 8 | 5.6 |
| Magnesium | 12 | 2.8 |
| Silicon | 14 | 2.1 |
| Iron | 26 | 22.6 |

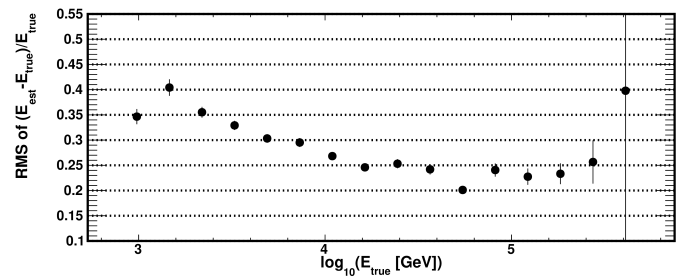
# Energy Reconstruction

We use the supervised feedforward neural networks with back propagation method for the energy regressor and event classifier

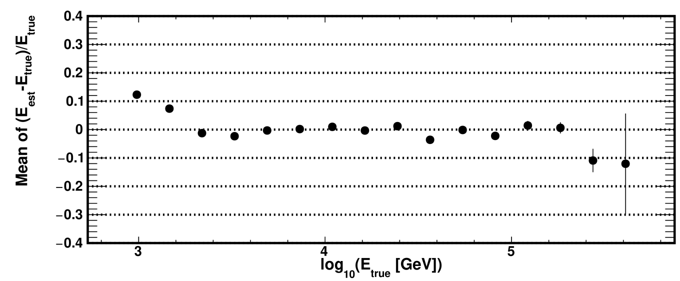
## Architecture Energy Regressor

| Layers | 1 input | 3 hidden | 1 output |
|---|---|---|---|
| Nodes | 21 | 16, 8, 4 | 1 |

**Energy Resolution**




**Energy Bias**



# Proton Classifier

- Create MC Proton classifier with every of the other six elements: p-He, p-C, p-O, p-Mg, p-Si and p-Fe $\Longrightarrow$ We get 6 neural networks
- This approach provides better rejection power than a single combined model

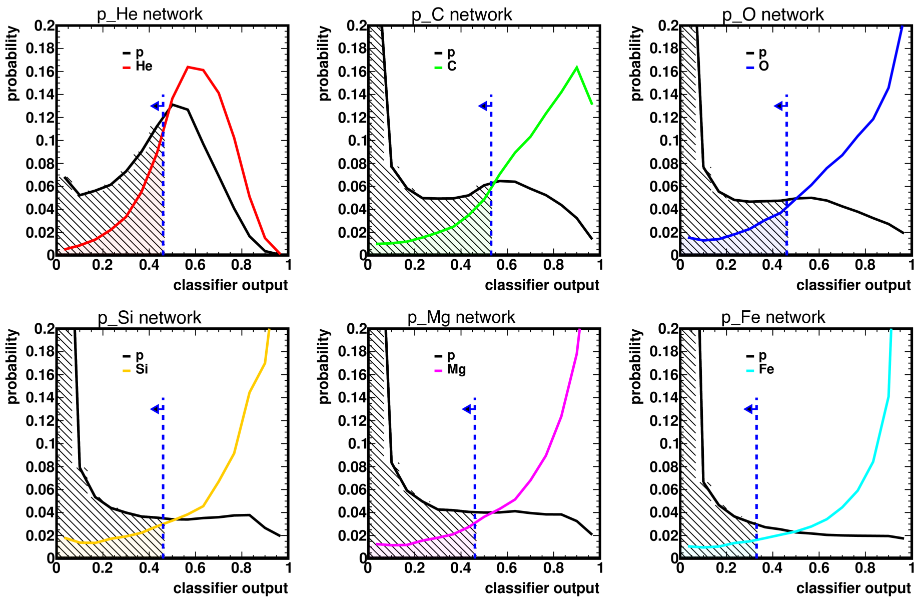
Architecture Classifier

| | | | |
|---|---|---|---|
| Layers | 1 input | 4 hidden | 1 output |
| Nodes | 36 | 28, 18, 10, 5 | 1 |

- Every MC is run through each neural network
- Data is run through each neural network

# Proton Classifier

Define selection region for proton-like events independently for each neural network




- The classifiers provide the probabilities $Prob_i(plike_i|j) = p_{ij}$ of given a nucleus (j= p, He, C, O, Mg, Si and Fe) to be selected as proton-like event for each classifier (i)
- Obtain the proton-like probability $\epsilon_i$ of an event in real data being classified as proton-like by the j-th classifier

# System of linear equations

With the $p_{ij}$ and $\epsilon_i$ probabilities we can define a system of linear equations

$$\sum_{j=1}^{7} p_{ij}\, N_j = \epsilon_i N \quad ; \quad i = (1,6)$$

$$\sum_{j=1}^{7} N_j = N$$

$N_j$ unknown number of type j particle
*N* total number of selected events in the data

This equation can be written in a matrix form A$\vec{x} = \vec{b}$, with A and $\vec{b}$ known quantities, and $\vec{x}$ the unknowns

$$A = \begin{pmatrix} p_{11} & \cdots & p_{17} \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 1 \end{pmatrix} \qquad \vec{x} = \begin{pmatrix} N_1 \\ \vdots \\ N_7 \end{pmatrix} \qquad \vec{b} = \begin{pmatrix} \epsilon_1 N \\ \vdots \\ \epsilon_7 N \end{pmatrix}$$

We solve the system with MINUIT to obtain $N_1$

# Flux Computation

When we solve the system we obtain $N_1$ and then we can compute the flux as

$$\Phi(E, \cos(\theta), Z) = \frac{N_1(E, \cos(\theta), Z)}{A_{eff}(E, \cos(\theta), Z) T \Delta E}$$

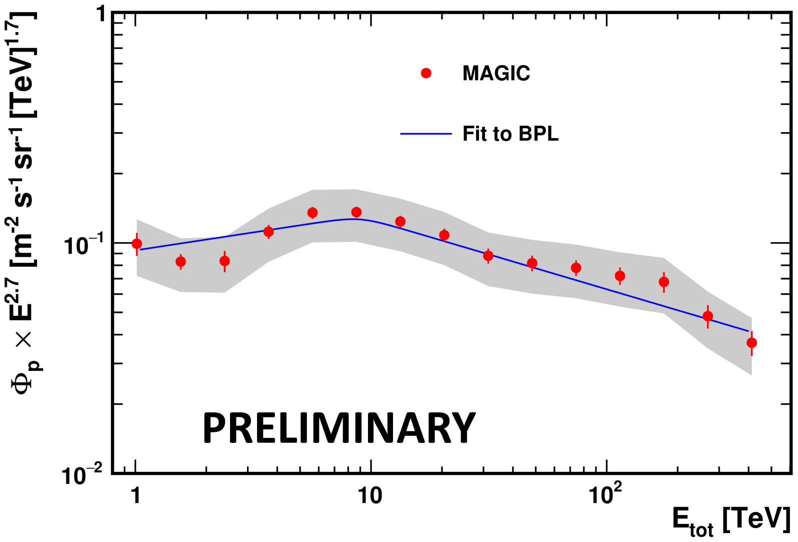
$A_{eff}(E, \cos(\theta), Z)$: effective acceptance

$T$: Exposure Time

$\Delta E$: Energy bin

# Proton Flux: Spectral Behavior

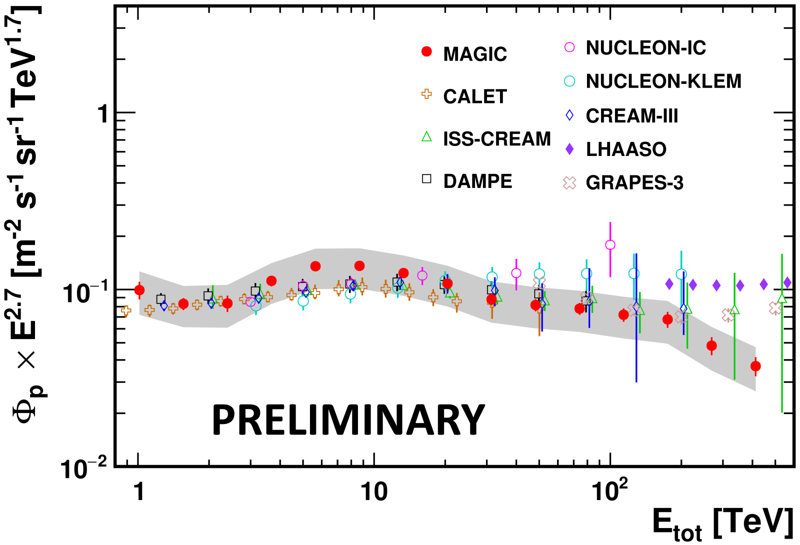
The MAGIC proton flux from 0.8 to 500 TeV is presented




The flux is fitted with a broken power law (BPL) and the data suggest a spectrum break at ∼9 TeV

# Proton Flux: Comparison

The MAGIC data is compared with the measurements from other experiments



# Conclusions

- The methodology to compute the proton spectrum with the MAGIC telescopes from the cosmic-ray background data was presented
- Several MC species were produced for this analysis: p, He, C, O, Mg, Si and Fe
- The analysis method is based on neural networks to obtain the number of proton events
- The MAGIC proton spectrum from 0.8 to 500 TeV was presented
- Results are compatible with other experiments and suggest an energy break around $\sim 9$ TeV
- These methodology could be used to compute other nuclei fluxes with the MAGIC telescopes