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Discriminating heavy cosmic rays with the MAGIC Telescopes

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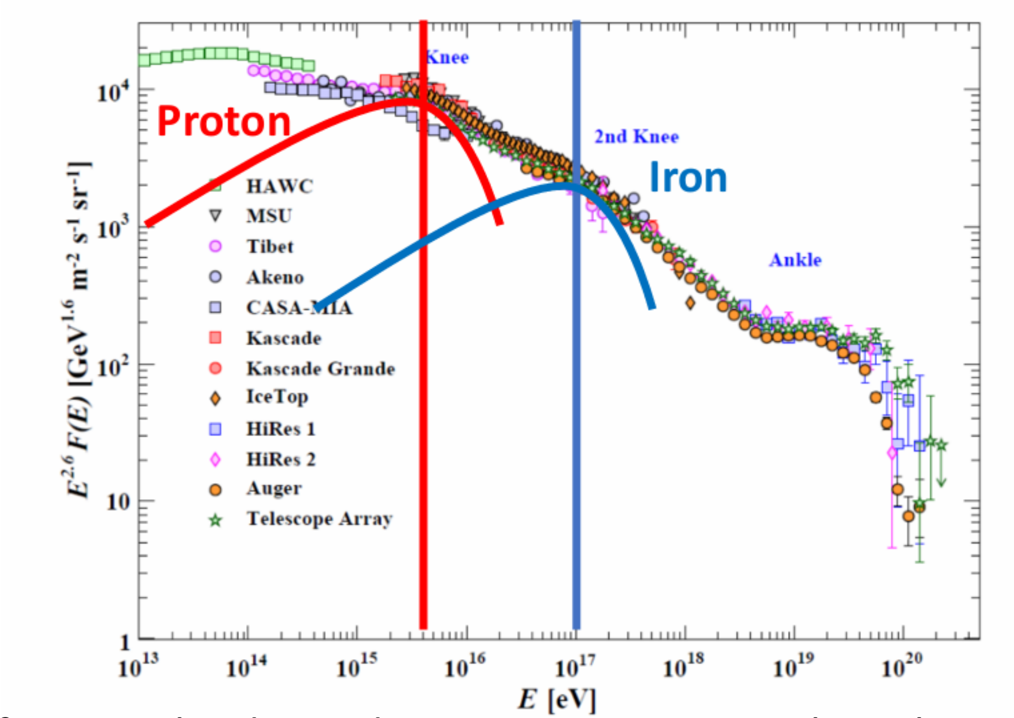
02-09-2026

TeV Particle Astrophysics TeVPA 2026 Tendo Japan August 30 - September 4, 2026

MAGIC

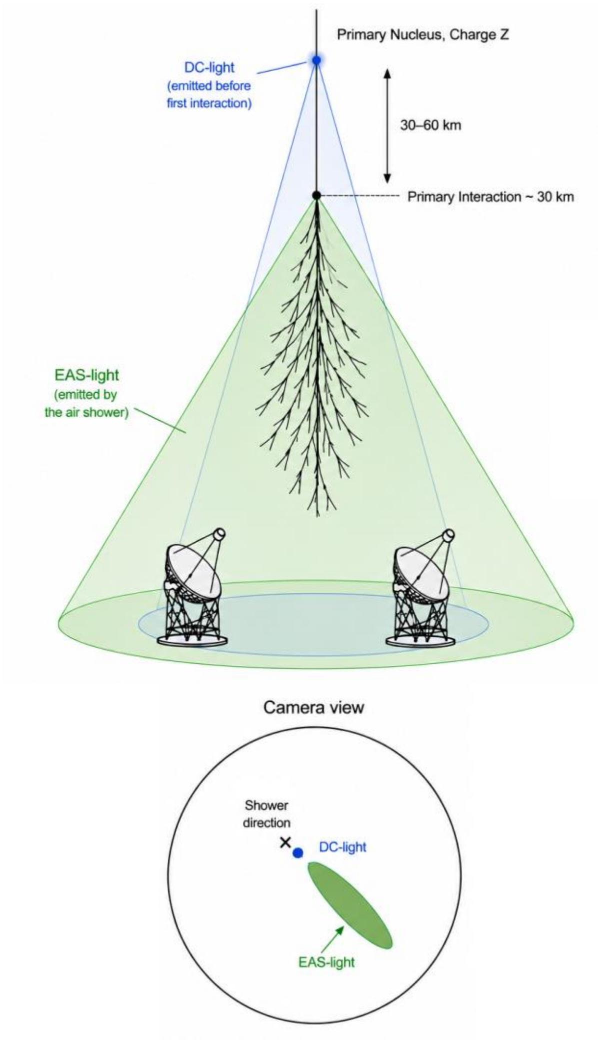
Introduction

- The measurement of the Iron spectrum is of particular interest to understand if the features in the all-particle spectrum are proportional to the elemental charge
- Iron is one of the most abundant elements in cosmic rays at TeV energies



- Above few TeV the direct detection experiments have low statistics due to the small collection areas
- Ground-based experiments, such as IACTs, can profit from their large collection areas to measure cosmic rays with the appropiated techniques

Introduction



- In contrast to photons, cosmic rays with sufficient energy emit Cherenkov light themselves prior to interacting with air nuclei

- The Direct Cherenkov (DC) light intensity is $\propto Z^2$

- The presence of DC-light is a signature of showers induced by heavy elements, of which iron is the most abundant

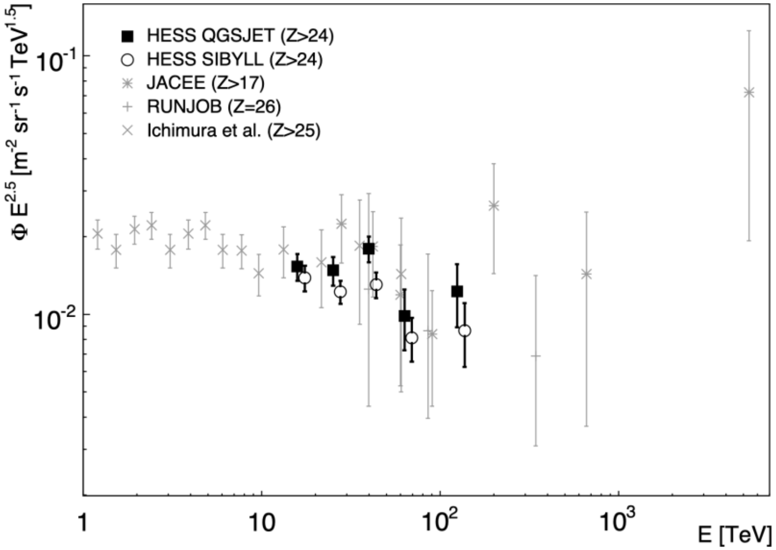
- At $\sim 30\ km$ the particle interacts creating an Extensive Air Shower (EAS)$\Rightarrow$ Wider EAS light cone

- The challenge is to distinguish DC from the much brighter EAS light

Introduction

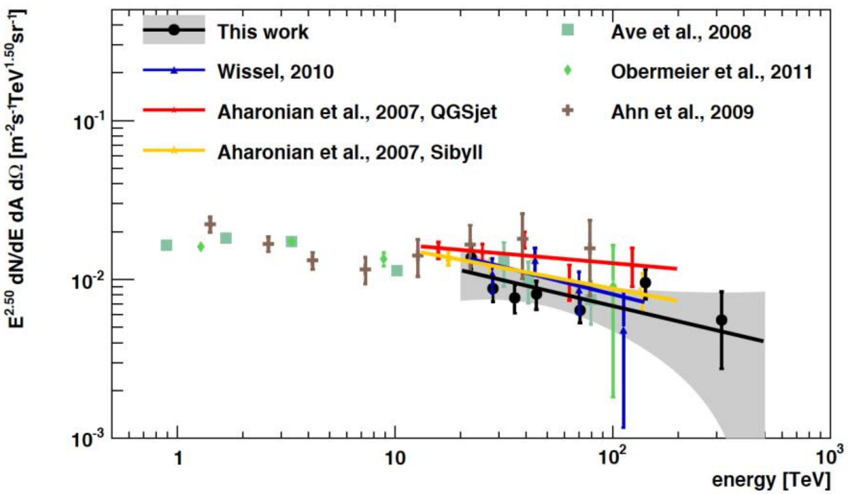
H.E.S.S.

Phys. Rev. D 75, 042004 (2007)



VERITAS

Phys. Rev. D 98, 022009 (2018)



HESS and VERITAS were able to measure the iron flux using the DC-light detection technique

MAGIC Telescopes

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

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

Data and MC simulations

- Data:
  - Pixel-wise information (intensity and arrival time) is preserved
  - Zenith Range: 5-35 ° (no DC-light intensity is lost)
  - Good atmospheric conditions
  - Total effective exposure time amounts to 494 hours

Source	Exposure Time [h]
M15	54.5
M87	60.3
Cyg-X3	36.7
Draco	34.1
Crab Nebula	72.3
Mrk421	47.1
Mrk501	46.9
Geminga	27.7
TriangulumII	59.9
PG1553+113	54.5

Data and MC simulations

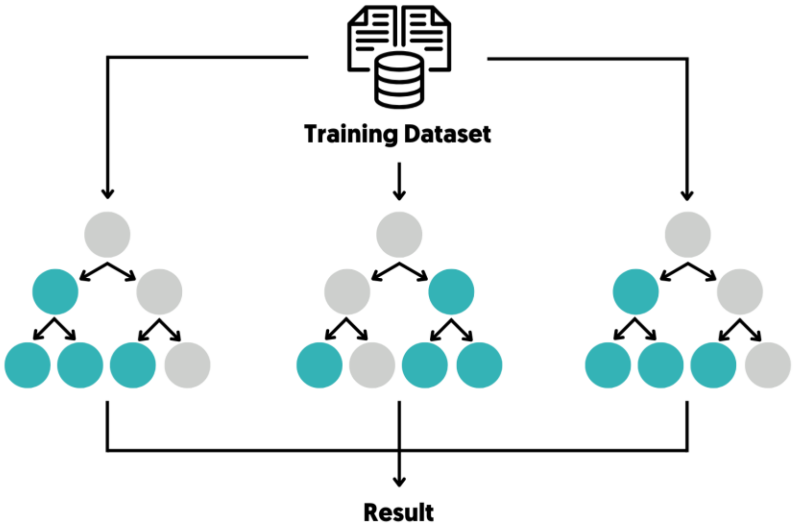
- MC:
  - Similar conditions as the data (preserve pixel-wise information, and zenith range)
  - Several species were simulated to account for the signal and background with common parameters:
    - Impact Point: 200 m
    - View Cone Angle: 1.5 °
    - Energe Range: 10 to 150 TeV

Particle	Z	Gen. Events [$\times 10^6$]
Proton	1	1.5
Helium	2	1.2
Oxygen	8	0.7
Magnesium	12	0.7
Silicon	14	2
Iron	26	10

Energy Reconstruction

The energy reconstruction process relies on the novel technique developed for the MAGIC telescopes based Random Forest algorithm

K. Ishio and D. Paneque, Atroparticle Physics, 158, 102937, 2024.



- The method uses as inputs image parameters from the standard Hillas parametrization as well as optimized parameters for the DC-light detection
- Iron MC is used to train and test the RF

Data Selection

1 **Quality Cuts**

- Minimum Hillas Size, Width and Length
- C.o.g far from the edge of the camera
- Brightest pixel far from the edge of the camera
- Width/Length < 0.9

2 **Heavy Nuclei Identification**

2.1 Direct Cherenkov Identification

2.2 Intermediate Charge Background rejection

Data Selection

2.1 Direct Cherenkov Identification

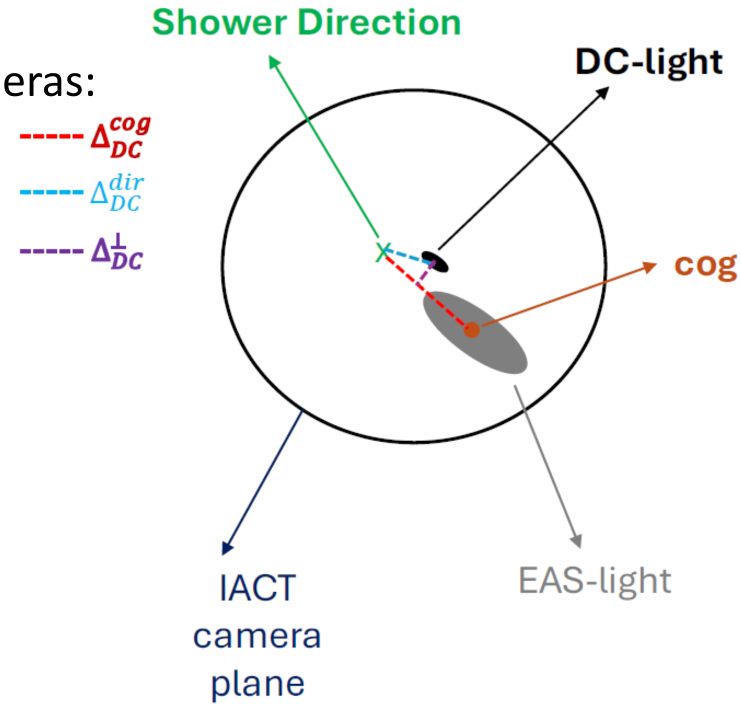
We first identify the DC-light in the MAGIC cameras:

- DC ratio:

$$Q_{DC} = \frac{< I_{neigh} >}{I_{pixel}}$$

- Geometry:

$$\Delta_{DC}^{ShD}, \Delta_{DC}^{cog}, \Delta_{DC}^{\perp}$$



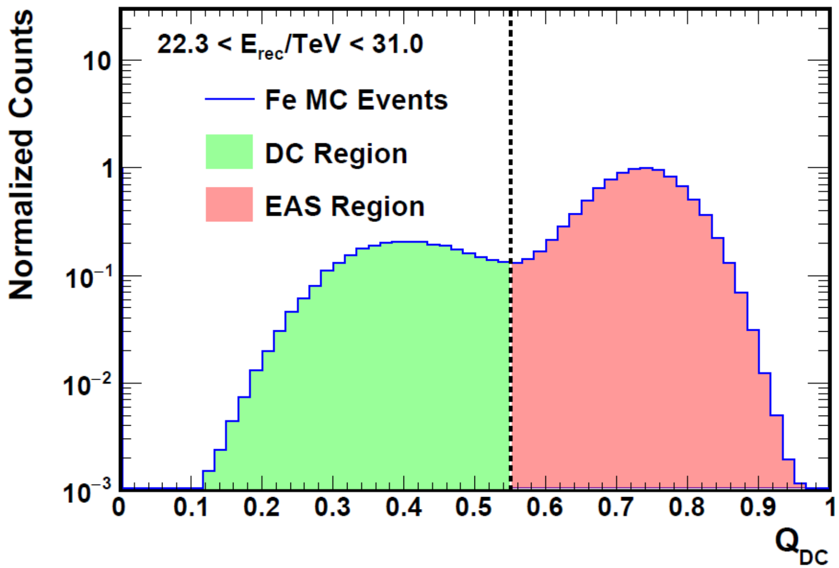
Data Selection

2.1 Direct Cherenkov Identification

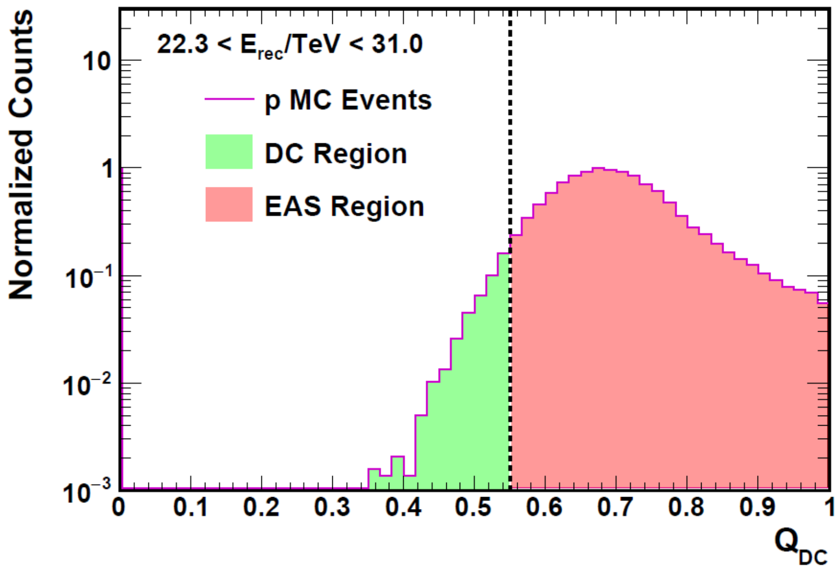
Fixed cut in Q_{dc} is performed for M1 and M2 to identify direct Cherenkov light

Example M1

Iron



Proton



As expected protons do not produce a significant amount of DC-light

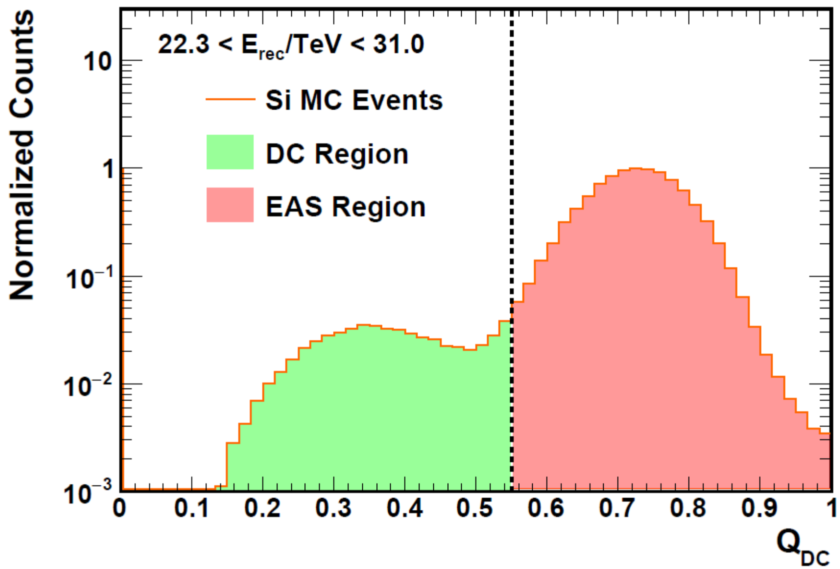
Data Selection

2.1 Direct Cherenkov Identification

Si produces a non-negligible amount of DC-light

Example M1

Silicon



The Q_{dc} cut allows to identify DC-light and reject proton and helium events from heavy nuclei. However, it is not able to completely reject the intermediate Z nuclei

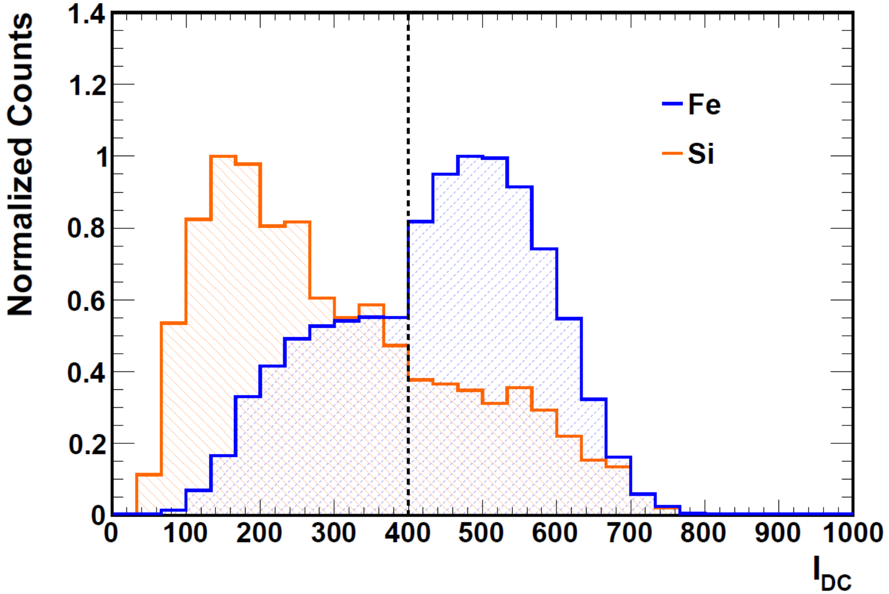
Data Selection

2.2 Intermediate Charge Background rejection

We separate heavy from intermediate Z nuclei using DC-light intensity

$$I_{DC} = I_{pixel} - < I_{neigh} >$$

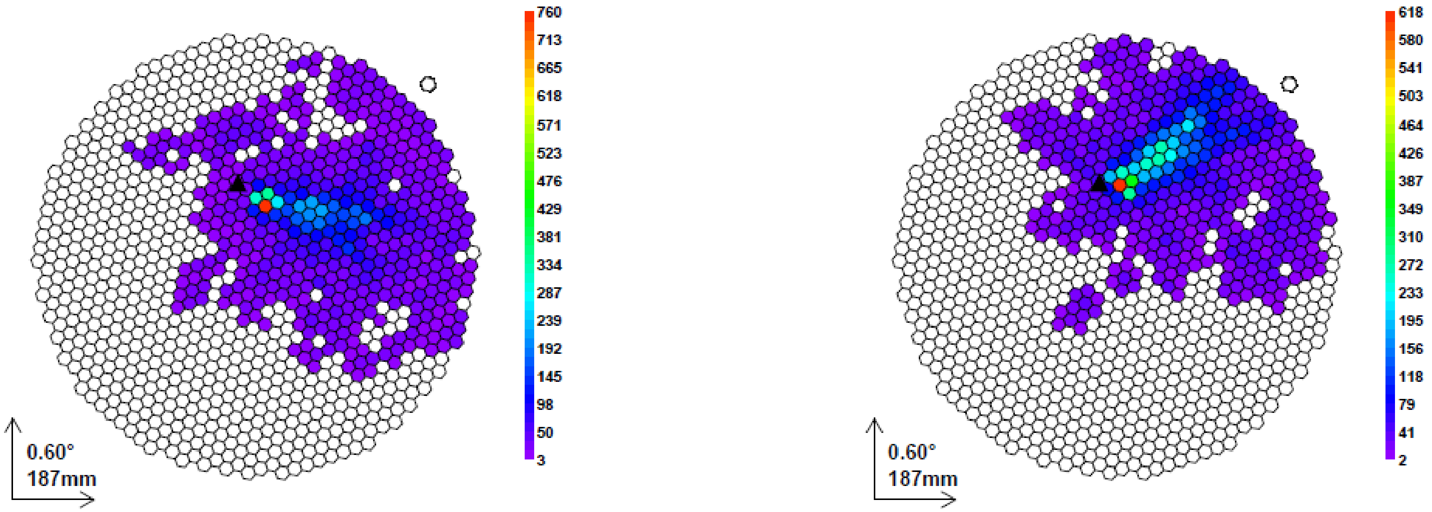
Example M1



The combined cuts of Q_{dc}, I_{dc} and the rest of selection cuts provide a background rejection to $Z \leq 14$ nuclei better than 95%

Selected Events

Recorded event of 28 TeV in the data sample



A total of 293 events are observed in ~ 494h

Systematic Uncertainties

Study of the systematic uncertainties has been performed:

- Energy reconstruction + typical MAGIC systematic effects
- Inaccuracy of hadronic model used in CORSIKA
- Influence of nuclei with $Z \leq 14$
- Analysis method

Flux Computation

The heavy nuclei flux is computed as follows:

$$\Phi_{Fe}(E) = \frac{N(E)}{\Delta E A_{eff}(E) T \Omega}$$

$N(E)$: Number of events

ΔE: Energy bin

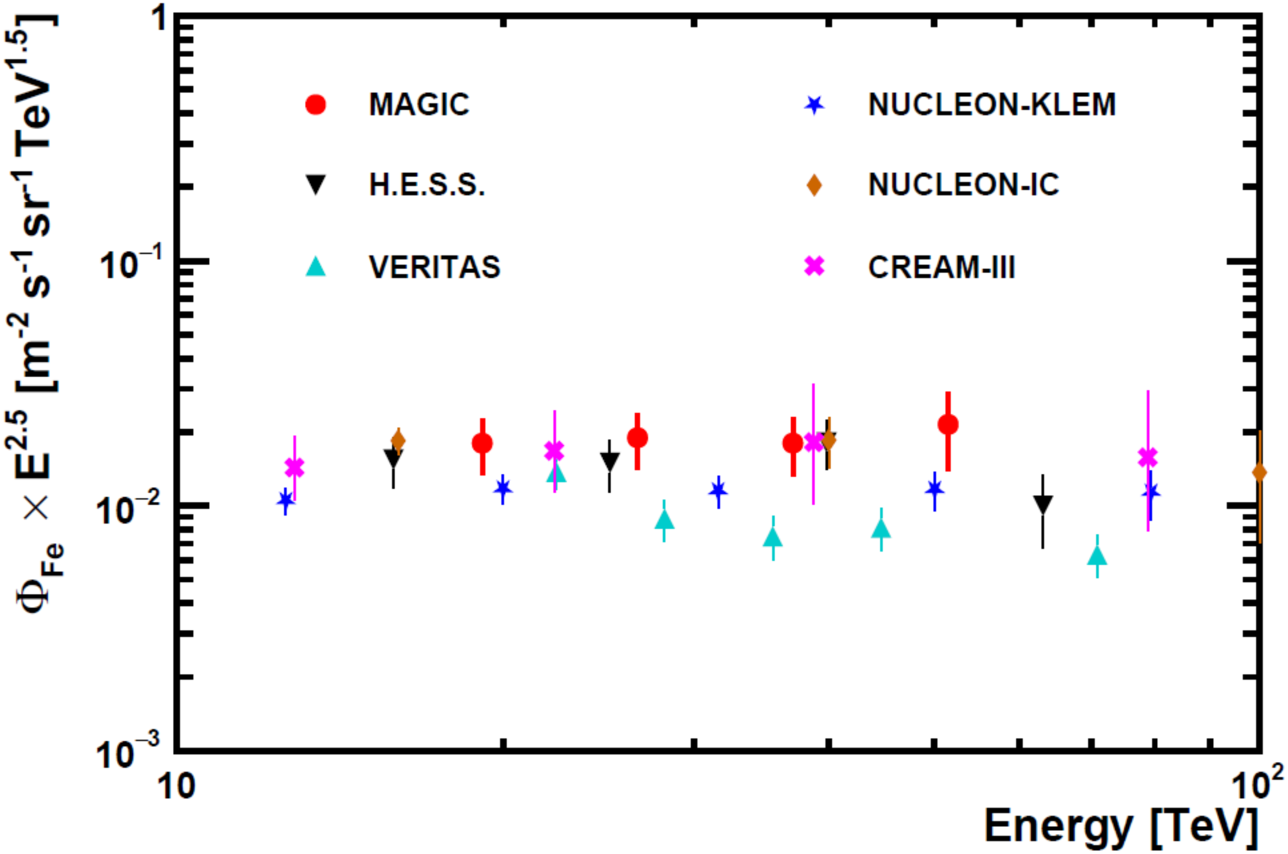
$A_{eff}(E)$: Effective acceptance

T: Exposure Time

Ω: Solid Angle

Heavy Nuclei Flux

The heavy nuclei flux from 16 to 60 TeV is presented



Results are in agreement with previous measurements and with other IACTs studies

Conclusions

- Specific MCs have been produced for DC-light detection
- Around 500 h of data with pixel information have been produced and analyzed
- A data selection study to identify heavy nuclei using dedicated MC simulations has been performed:
  - Light Z (proton and helium) are efficiently rejected
  - Intermediate Z (Z<=14) are rejected in more than 95%
- Study of the systematics has been computed
- Flux obtained with DC-light technique is consistent with other experiments