Mass composition anisotropy with the Telescope Array Surface Detector data

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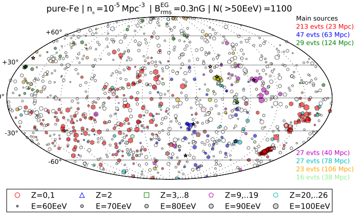
Outline

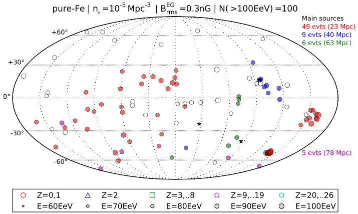
1. UHECR mass composition anisotropy: current status.
2. Telescope Array surface detector: dataset and MC.
3. TA SD mass composition BDT study.
4. Results: spatial distribution of "proton" events in the 11-year TA SD data.

- The anisotropy of cosmic ray mass composition is predicted in multiple astrophysical models (B. R. d'Orfeuil et al., Astron. Astrophys. 567, A81 (2014)).

Example (extreme): injection of purely iron nuclei at the sources, source spectral index 2.3, maximum energy $26 \times 10^{20.5}$ eV, mean extragalactic magnetic field 0.3 nG, source distribution according to 2MRS catalog.



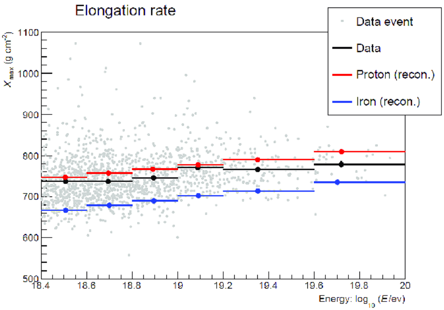
$E > 50$ EeV



$E > 100$ EeV

Introduction: mass composition anisotropy state-of-art

- The anisotropy of cosmic ray mass composition is predicted in multiple astrophysical models (B. R. d'Orfeuil et al., Astron. Astrophys. 567, A81 (2014)).
- Due to large shower to shower statistical fluctuations, primary particle type can't be assigned for each event. Mass composition obtained by averaging over large number of events.



9-year TA stereo X_{max} composition, W. Hanlon, UHECR'18

Introduction: mass composition anisotropy state-of-art

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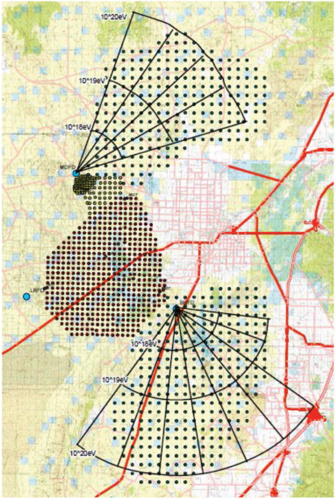
- Due to large shower to shower statistical fluctuations, primary particle type can't be assigned for each event. Mass composition obtained by averaging over large number of events.
- We are in need of mass composition indicator, as discriminating as possible, to study it's spatial distribution. Aim to benefit from SD statistics compared to FD one.
- TA SD BDT ξ parameter as a tool to study UHECR mass composition anisotropy (Y. Zhezher et al., PoS(ICRC2019)494).



The largest UHECR experiment in the Northern Hemisphere

- Utah, USA
- 507 surface detectors, $S = 3\ \mathrm{m}^2$, distance $1.2\,\mathrm{km}$
- 3 fluorescense stations
- >12 years of constant data acquisition

Data and Monte-Carlo sets

- 11-year data collected by the TA surface detector:
  2008-05-11 — 2019-05-10

  Cuts:

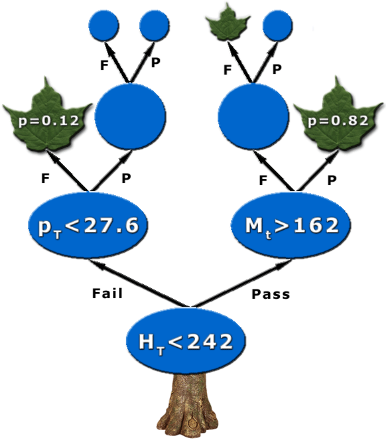
  1. Events with 7 or more triggered counters
  2. Events with zenith angle $\theta < 45°$.
  3. Events with reconstructed core position of at least 1200 m away from the edge of the array.
  4. Events with $\chi^2_G/d.o.f. < 4$ and $\chi^2_{LDF}/d.o.f. < 4$.
  5. Events with geometry reconstructed with accuracy less than 5°.
  6. Events with the fractional uncertainty of the S_{800} less than 25 %.
  7. Events with $E > 10^{18}$ eV.

  21628 events after cuts

- p and Fe 9-year Monte-Carlo sets with QGSJETII-03

Mass composition study with the TA SD

Boosted Decision Trees:
ROOT::TMVA



$$(a, AoP, \dots) \to \xi$$

SD detector array: > 90 % duty cycle, larger data statistics compared to FD

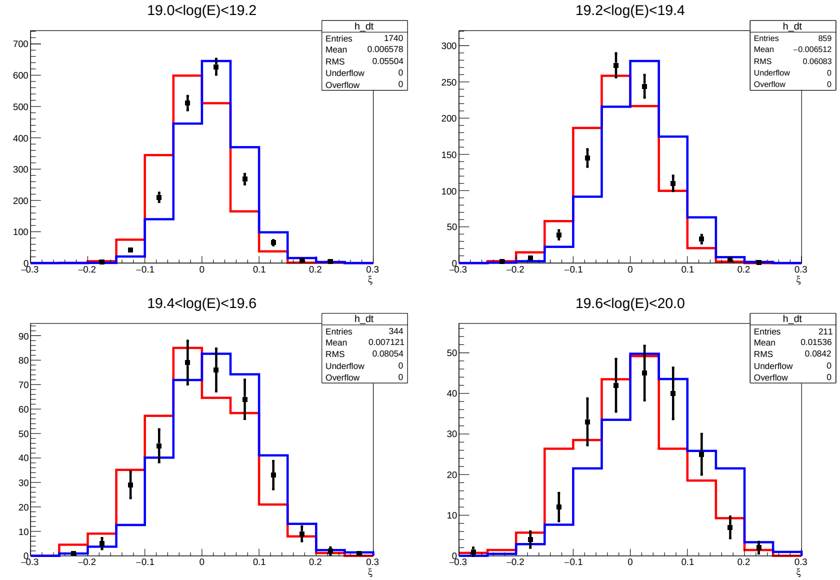
Comparison of ξ distributions for data with Monte-Carlo modelling

$\Downarrow$

Cut out "proton" events from the data.

TA, Phys. Rev. D 99, 022002 (2019)

Distribution of MVA estimator ξ, QGSJETII-03



proton, iron, data

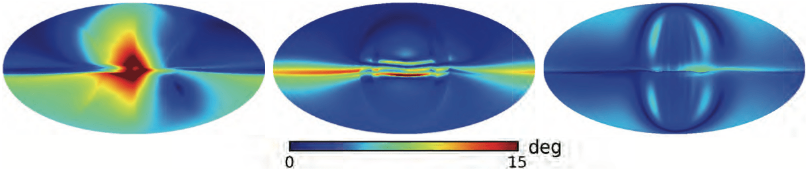
Motivation to study anisotropy of proton events

Due to deflections in magnetic fields UHECR don't point at their sources. The typical cosmic ray deflection magnitude in a turbulent extragalactic magnetic field, in the limit of many small deflections, can be estimated as:

$$\delta\theta_{EG} \approx 0.15^\circ \left(\frac{D}{3.8\ \mathrm{Mpc}} \frac{\lambda_{EG}}{100\ \mathrm{kpc}}\right)^{\frac{1}{2}} \left(\frac{B_{EG}}{1\ \mathrm{nG}}\right) \left(\frac{Z}{E_{100}}\right),$$

usually small compared to the deflections in Galactic magnetic fields.

The latter strongly depends on the employed GMF model:



Deflections of 60 EeV proton. From left to right: the Jansson and Farrar, the Sun and Reich and the Pshirkov, Tinyakov and Kronberg models.

How to cut out “proton” events?

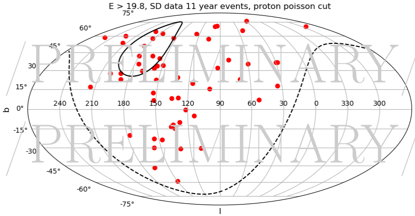
- Use of ξ parameter distribution as a function of energy.
- Separation is not perfect, impossible to cut out “100 % proton” events.
- Statistical significance of “signal” (protons) in the presence of “background” (iron nuclei):

$$S = \frac{signal}{\sqrt{background}}$$

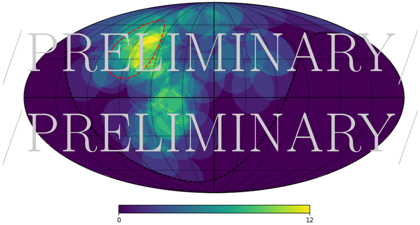
- Find ξ_{cut} value which maximizes S as a function of energy.

“Proton” data events distribution, $\log E > 19.8$

Event distribution



20° oversampling



57 events

Excesses are observed in the hotspot and Galactic plane area.

———— - - - - - - - - - – hotspot area

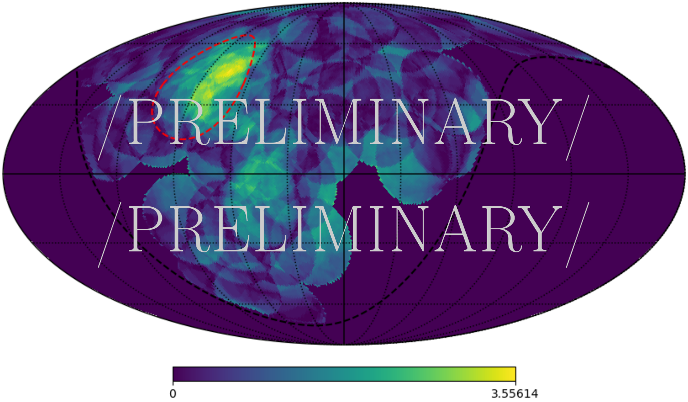
Pre-trial significance estimation for "proton" data events with $\log E > 19.8$:

- Create isotropic MC set with data composition (TA, Phys. Rev. D 99, 022002 (2019)) based on proton and iron MC sets.
- Choose "proton" events with the same ξ_{cut} as used for the data.
- Compare two distributions with the use of Li-Ma statistics (T.-P. Li & Y.-Q. Ma, ApJ, 1983):

$$S_{\mathrm{LM}} = \sqrt{2}\left[N_{\mathrm{on}}\ln\left(\frac{(1+\eta)N_{\mathrm{on}}}{\eta(N_{\mathrm{on}}+N_{\mathrm{off}})}\right) + N_{\mathrm{off}}\ln\left(\frac{(1+\eta)N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]^{1/2}$$

N_{on} – number of "proton" events in the dataset in the specific direction, N_{off} – number of background "proton" events from the MC, η – ratio of events in "on" and "off" datasets.

$\log E > 19.8$, pre-trial significance



Pre-trial significance of the excess: $3.56\ \sigma$ (post-trial $1.7\ \sigma$).
Compatible with the position of hotspot (TA, ApJ 790 L21 (2014)).

- - - - - - - - - – hotspot area

Summary

1. Mass composition anisotropy studies based solely on SD data which allows to benefit it's higher statistics compared to FD.
2. BDT ξ parameter allows to study the mass composition anisotropy based on the TA SD data.
3. It is possible to cut out "proton" events from the data which are supposed to be less deflected by Galactic magnetic fields.
4. Observed "proton" excess at the position of the hotspot with pre-trial significance 3.56 σ (post-trial 1.7 σ).