Stato e prospettive delle analisi AD con informazioni di massa

Lorenzo Apollonio, Lorenzo Caccianiga, Geraldina Golup, Emily Martins, Max Stadelmaier, Esteban Roulet (and many more)
mail: lorenzo.apollonio@unimi.it

Introduction

Motivation
Cosmic-ray deflections scale with their rigidity, thus finding the mass (and so the charge) of the recorded event using SD information can help us in completing more significant arrival-direction analyses

Mass estimators working on SD
Currently are being developed three mass-estimators working on SD
- Universality, fit based on air-shower universality
- AixNet, deep-neural network (only up to 31/08/2018 so far)
- KANet, deep-neural network

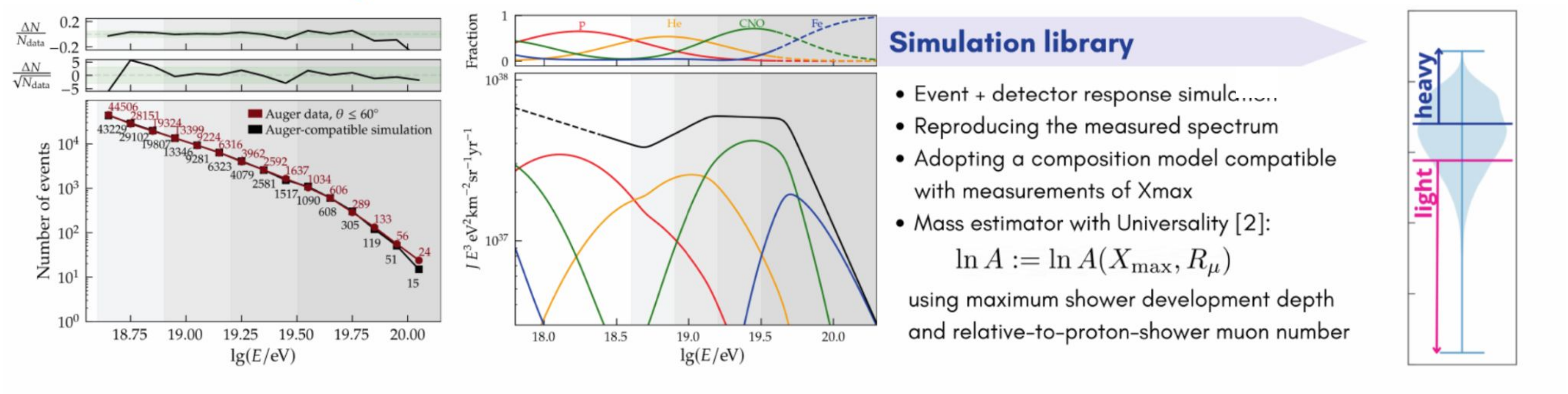
Mass-dependent observables
We focus on two main mass-dependent observable
- the depth of maximum shower (X_{max}), which scales with $\lg(E/A)$
- the muon content in the shower front (R_μ), we have very limited information on R_μ in Phase I on a event per event basis (only on Universality)

IMPORTANT: **<u>starting from mass-dependent observables we do not assign a actual mass to the event, but we focus on the mass ordering of the events</u>**

LARGE-SCALE ANISOTROPIES

Mass-dependent dipole

Work done by Emily* during her PhD



*** For a complete outlook see Emily's presentations in AD task:**
January 2023, May 2023, January 2024, February 2024, June 2024, September 2024 +
Auger Malargüe Meeting April 2024, November 2024

Mass-dependent dipole

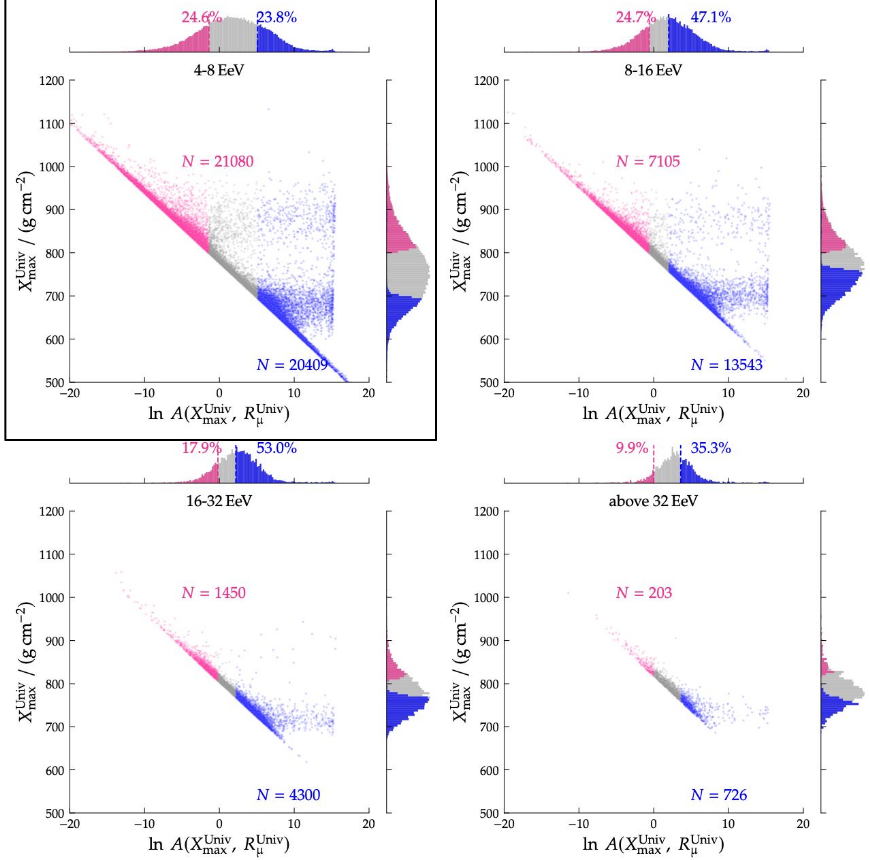
Definition of $\ln(A)$ using a combination of $X_{\max}$ and R_μ (done on **Universality**)

$$\ln A = \frac{1}{\beta(\lambda + \phi_0)} \left[\phi_0 \left(\ln R_\mu - \ln R_\mu^{\mathrm{p}}\right) - \beta \left(X_{\max} - X_{\max}^{\mathrm{p}}\right)\right]$$

Definition of **light and heavy population** for the energy bins defined to **maximize** the **significance of the dipole amplitude separation** in simulations

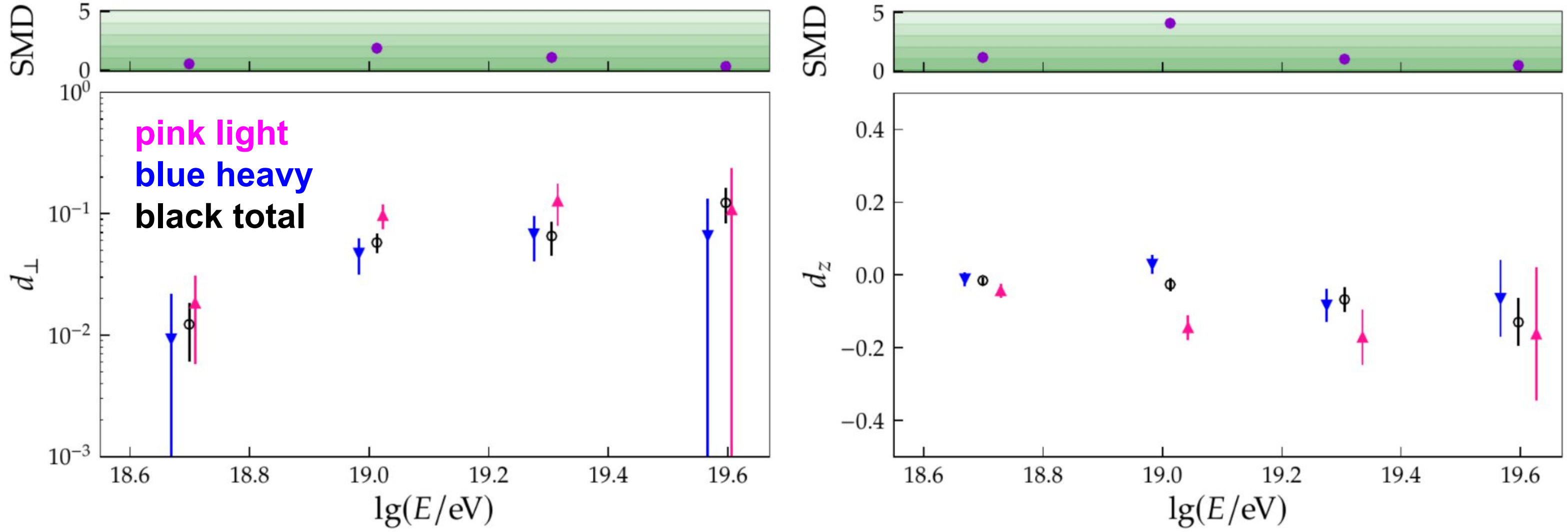
$$SMD = \frac{|d_{\text{light}} - d_{\text{heavy}}|}{\sqrt{\sigma^2_{\text{light}} + \sigma^2_{\text{heavy}}}}$$

idea di non usare bin 4-8 EeV



Mass-dependent dipole

$$SMD = \frac{|d_\mathrm{l} - d_\mathrm{h}|}{\sqrt{\sigma_\mathrm{l}^2 + \sigma_\mathrm{h}^2}}$$



- Largest separation in dz component: scrutinized possible systematic effect fabricating amplitude but not found (after atmospheric and geomagnetic corrections)

Mass-dependent dipole

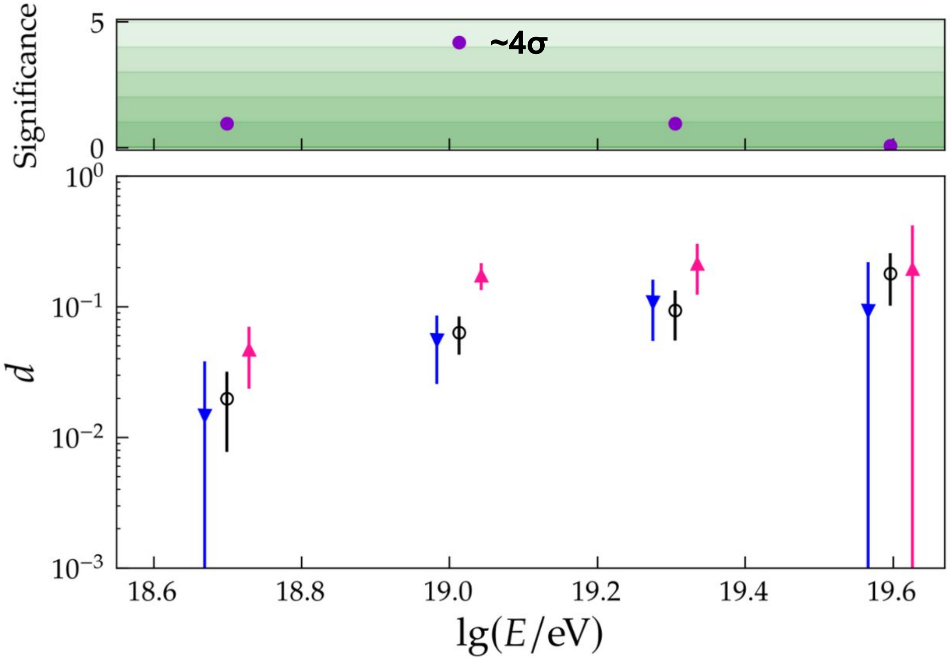
$$\text{significance} = \sqrt{2} \times \text{erfcinv}(P(\geq \bar{r}))$$

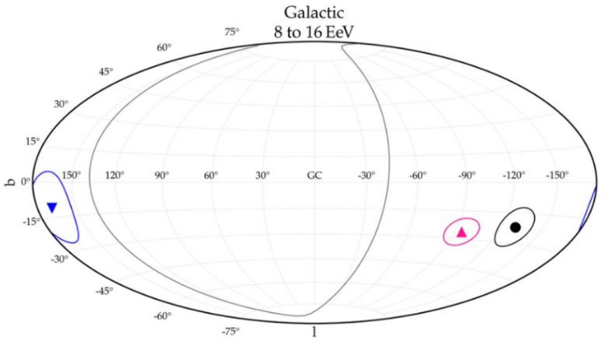
$\bar{r}$ = vec. amplitude

$$P(\geq \bar{r}) = \text{erfc}\left(\frac{\bar{r}}{\sqrt{2}\sigma_z}\right) + \frac{\sigma}{\sqrt{\sigma_z^2 - \sigma^2}}\text{erfi}\left(\frac{\bar{r}\sqrt{\sigma_z^2 - \sigma^2}}{\sqrt{2}\sigma\sigma_z}\right)\exp\left(-\frac{\bar{r}^2}{2\sigma^2}\right)$$

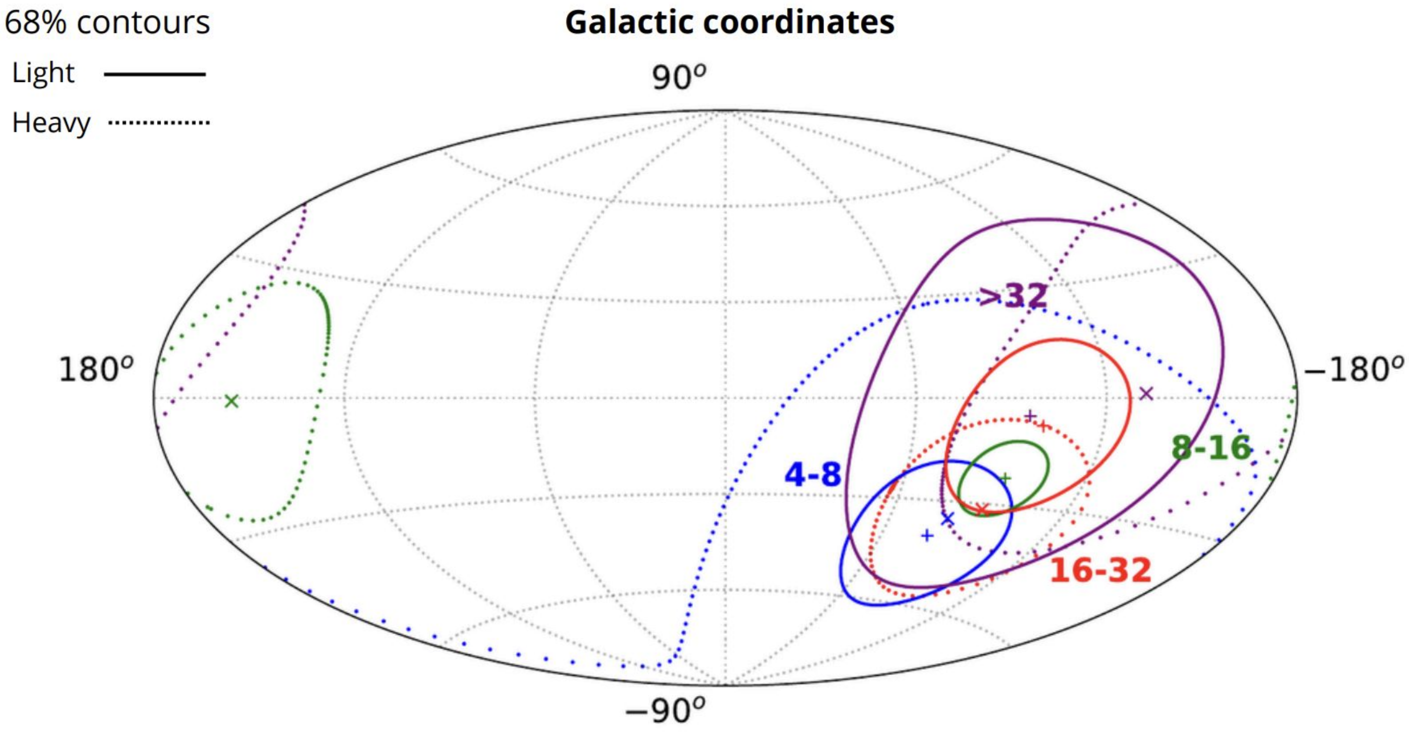
Probability of obtaining such an amplitude of separation between the two populations in the case they come from a common parent distribution.

Correction to Eq. (24) of ApJS 203 (2012) 34





Mass-dependent dipole



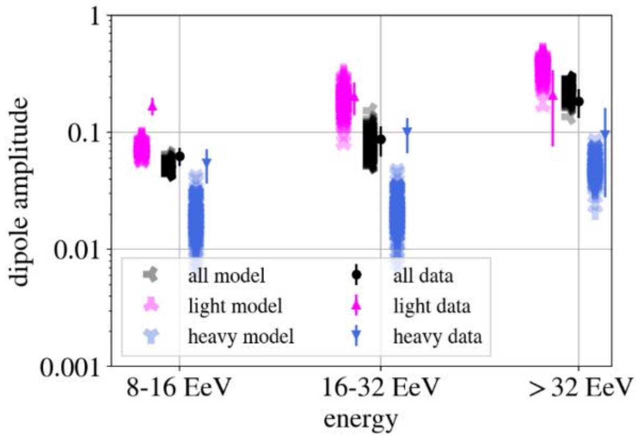
Big thanks to Geraldina for the plot

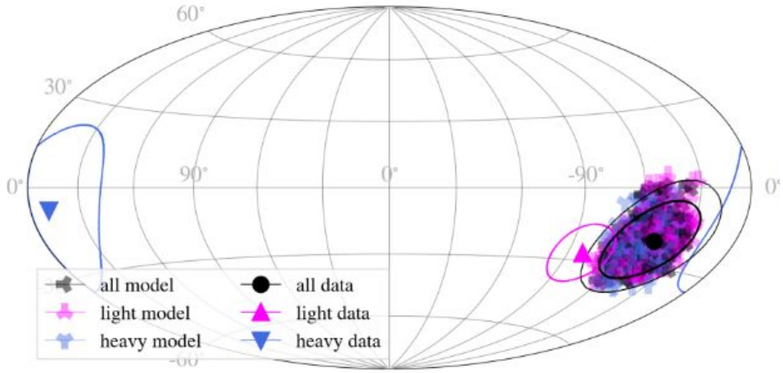
Outlook for mass-dependent dipole

Cross-check the results with DNN
- **AixNet** up to 31/08/2018
- **KANet** up to 31/12/2022

DNN do not have R_μ information

Work done by Teresa* to reproduce the dipole results considering the GMF deflections (JF12 and UF23)
- LSS model with $n_s = 10^{-3}$ Mpc^{-3}
- simulate 10 000 skies and consider the ones reproducing the total dipole
- calculate heavy and total dipole, considering universality sensitivity using a confusion matrix





* For a complete outlook see Teresa's presentations:
Pheno task Jan 2025, May 2023, AD task Sep 2024
Malargue meeting AD Nov 2024

SMALL-INTERMEDIATE-SCALE ANISOTROPIES

Mass-dependent Centaurus A

Please check-out **GAP2024-037*** & **GAP2024-053**

*updated

GAP 2024-037

PIERRE AUGER OBSERVATORY

Finding the optimal quantile of events for mass-enhanced anisotropy searches

In the near future, we aspire to analyze detector data using an SD mass-estimator based selection of events to enhance a possible signal in the sky using high-rigidity events. In this note we investigate the optimal quantile of events to be selected (or discarded) according to mass-sensitive observables. The optimal quantile of events is chosen to maximize the expected absolute significance of a possible mass-sensitive excess of ultrahigh-energy cosmic rays, and also to maximize the significance of the enhancement of a possible signal. A number of different simulation scenarios is presented, alongside with analytical considerations. We demonstrate that the optimal quantile of events to select using a mass estimator is remarkably stable in various scenarios. Furthermore, we observe that in scenarios for which no primary cosmic rays with nuclear masses $A < 5$ are present at the highest energies ($E > 38\,\mathrm{EeV}$), the mass estimators fail to enhance a possible signal. We therefore suggest to extend the energy range down to at least $E > 16\,\mathrm{EeV}$, where we expect a higher abundance of lighter primary particles.

✉ *lorenzo.apollonio@unimi.it*

https://www.auger.org/document-centre2/download/161-gap-notes-2024/5886-gap2024-037

GAP 2024-053

PIERRE AUGER OBSERVATORY

Rigidity-Parameter Sorting for Mass-Enhanced Arrival Direction Studies

We investigate the best fraction of events to discard using SD mass-estimators to possibly enhance small-scale anisotropies from the arrival direction data at energies above $32\,\mathrm{EeV}$. We define a rigidity parameter to sort events, using only a minimal set of model-dependent parameters, and investigate the potential significance with which a signal can be detected, if there is a high-rigidity population of cosmic rays in the region of Centaurus A. This note is an follow-up to GAP 2024-037.

✉ *lorenzo.apollonio@unimi.it*

https://www.auger.org/document-centre2/download/161-gap-notes-2024/5926-gap2024-053

Method

only X_{max} information

Thanks to Esteban for the proposal!

how to sort?

decadal elongation rate

$$X_{max}^{19} := X_{max}(E) - D \lg\left(\frac{E}{10^{19}\,\mathrm{eV}}\right)$$

the only inserted model parameters are those that are approximately constant for all hadronic interaction models!

charge-like parameter, but real number (not integer)! NOT ABSOLUTE VALUE OF THE CHARGE!

$$1/\widetilde{Z} := 2\exp\left((X_{max}^{19} - X_{ref})/\lambda\right)$$

hadron multiplicity parameter from Heitler-Matthews model

$$D = 58\,\mathrm{g/cm^2}$$

$$\widetilde{R} := E_0/\widetilde{Z}$$

$$\lambda = 22.3\,\mathrm{g/cm^2}$$

$$X_{ref} = 742\,\mathrm{g/cm^2}$$

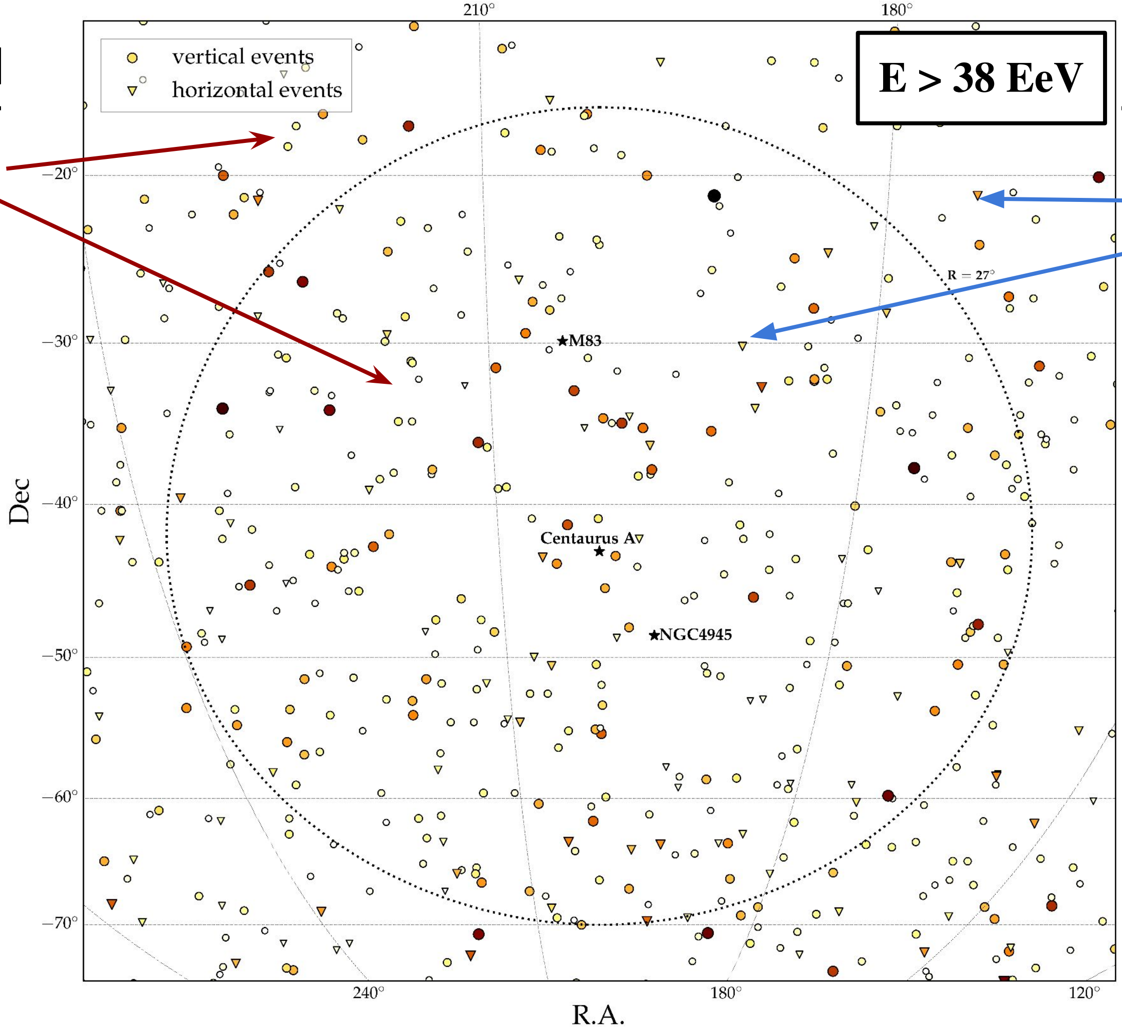
Average X_{max}^{19} reconstructed with Universality of the events with E ≥ 32 EeV

rigidity-like parameter maintaining the rigidity-order NOT ABSOLUTE VALUE OF THE RIGIDITY!

Centaurus reg

6T5+5T5 vertical events

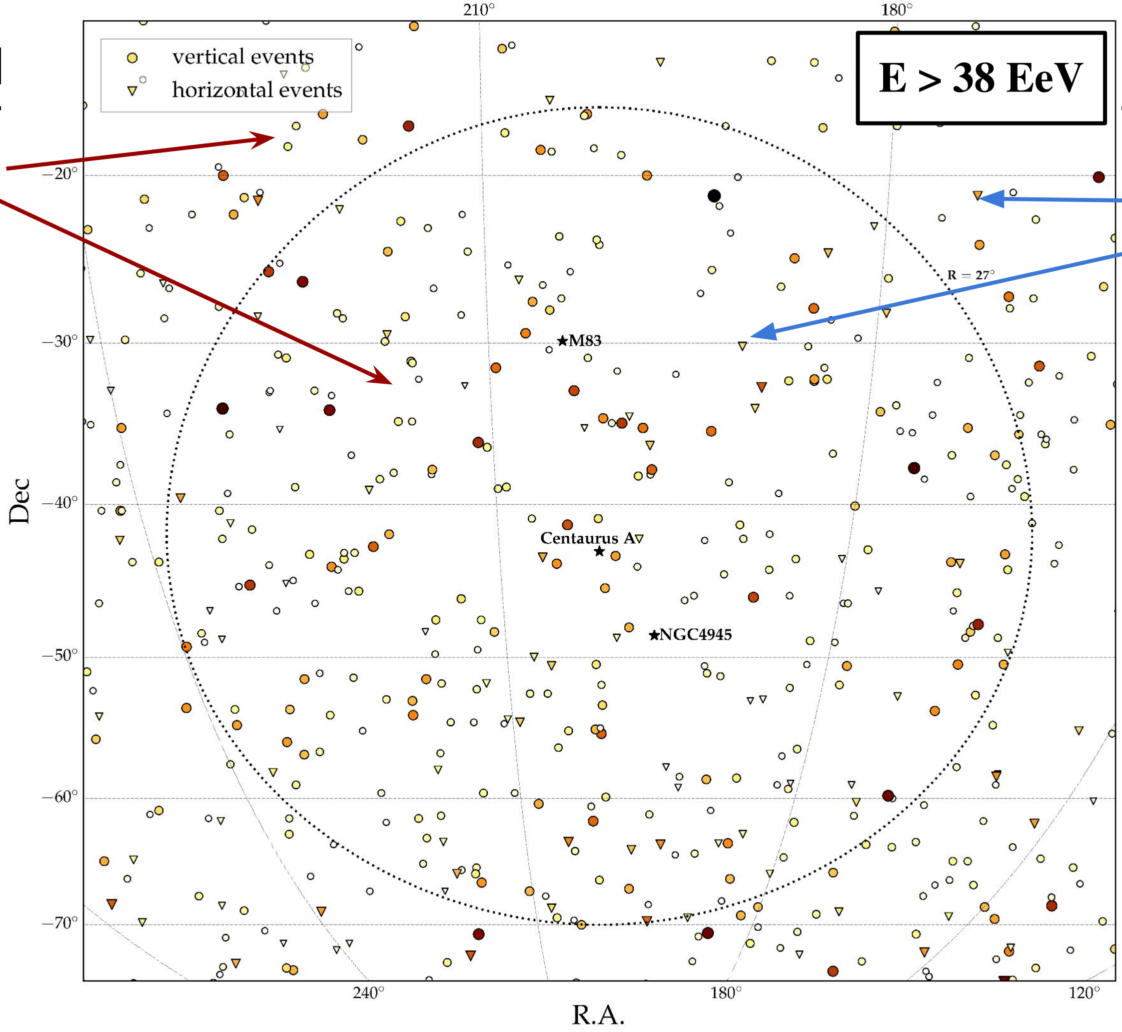
- Reconstruct X_{max} with **universality**
- Assign a rigidity-like value
- Order them and discard the **fraction** f_{rej} **of the lowest-rigidity ones**



horizontal events

- **mass estimators** do **not** reconstruct mass-dependent parameters for **horizontal events**
- they are **not discarded**, they are all kept for each f_{rej}

Centaurus reg



6T5+5T5 vertical events

- Reconstruct X_{max} with **universality**
- Assign a rigidity-like value
- Order them and discard the **fraction** f_{rej} **of the lowest-rigidity ones**

4T5 vertical events

- X_{max} is **not reconstructed for 4T5 vertical events**
- we decided to **treat these events in the same way as the horizontal** events and not discard them at any f_{rej}

horizontal events

- **mass estimators** do **not** reconstruct mass-dependent parameters for **horizontal events**
- they are **not discarded**, they are all kept for each f_{rej}

Final dataset and analysis

Energy of events above 32 EeV

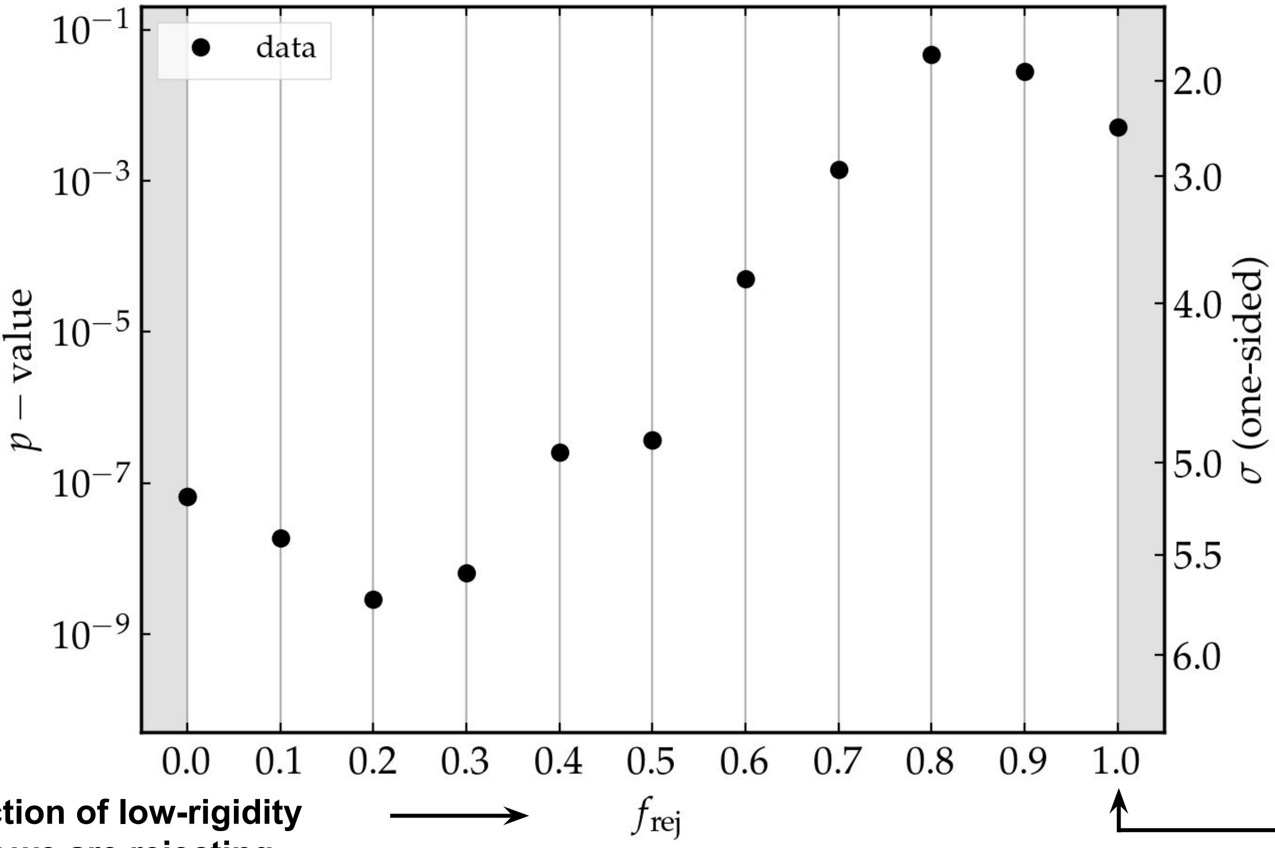
- number of 5T5+6T5 vertical events with mass information = 2112
- number of horizontal events = 664
- number of 4T5 vertical events = 138

Energy and **AD** reconstructed with **Herald**
$X_{\mathbf{max}}$ reconstructed with **Universality**

ANALYSIS

Do a scan rejecting fractions of low-rigidity events, in 10% step, from 0% (no events rejected) to 100% (all vertical 5T5+6T5 events rejected).
We perform the scan in rigidity only for the optimized values of the Centaurus A analysis (E_{th} = 38 EeV, ψ = 27°), to not enhance the penalization factor strongly.

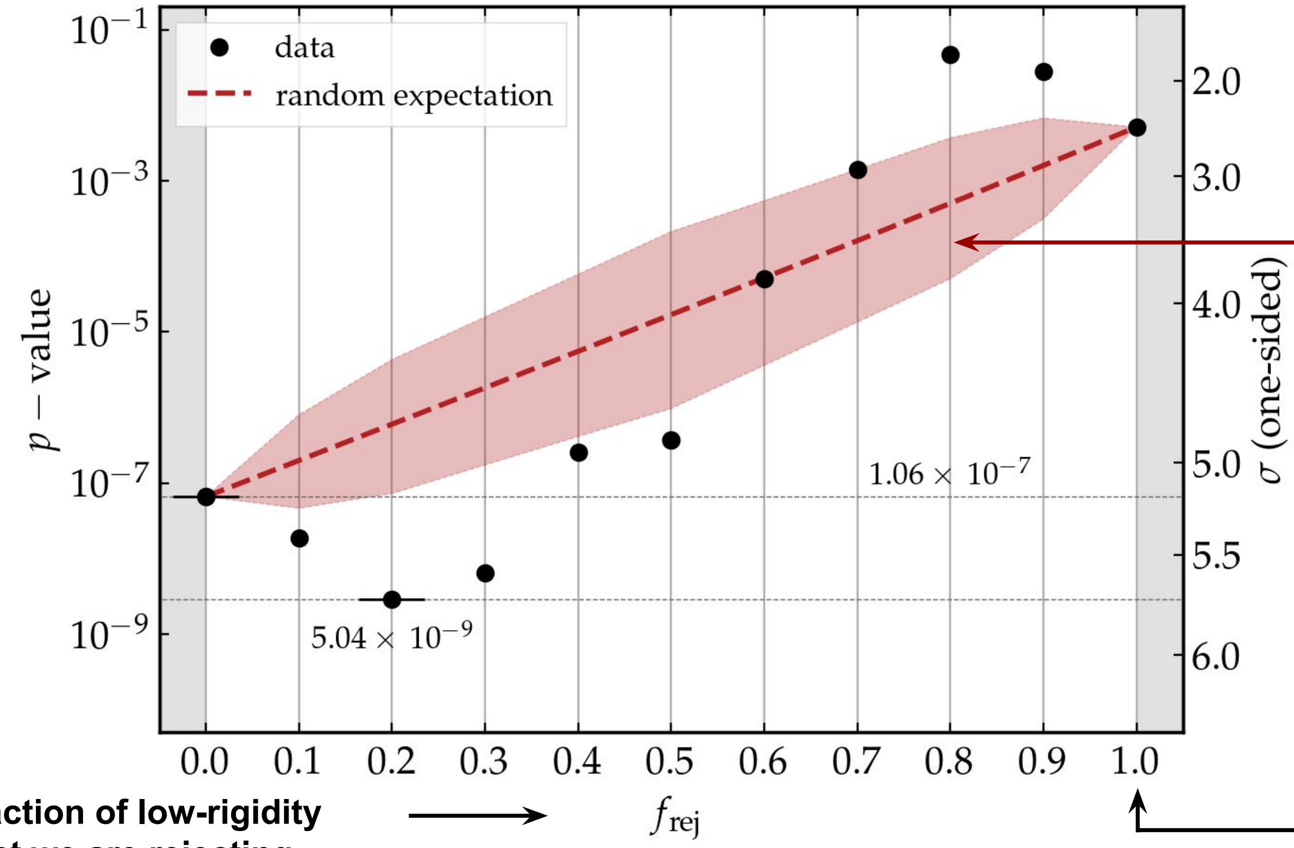
Final dataset



all events rejected only inclined and 4T5 left

f_{rej} **is the fraction of low-rigidity events that we are rejecting**

Final dataset



shaded area contains 1σ deviations from random expectations

all events rejected only inclined and 4T5 left

f_{rej} is the fraction of low-rigidity events that we are rejecting

Final results

Penalization against isotropy

- generate **10^8 simulated isotropic skies** and evaluate how many times we get a smaller p-value than what has been obtained

post trial p-value = 1.59 x 10^{-6} (4.66 σ one-side)

- we evaluated the probability of obtaining a lower p-value than what has been found at $f_{\mathrm{rej}} = 0.2$ by randomly selecting events in the dataset

p-value of random choice = 0.008 (2.4 σ one-side)

Outlook for small-intermediate scale anisotropies

Cross-check the results with DNN

- **AixNet** up to 31/08/2018
- **KANet** up to 31/12/2022

Three proposed following analyses

- **Catalog likelihood at same energy threshold** with fixed parameters
- **Centaurus A targeted at lower energy** ($E > 16$ EeV) with scan in rigidity and angular radius (only on vertical)
- **Catalog likelihood at lower energy** ($E > 16$ EeV) introducing a parameter in the likelihood that consider the absorption and evolution of the events

Rigidity-based backtracking of UHECRs

- **Motivation:**
  - Taking into account the GMF
  - Heavier composition at the high energies -> lower rigidities
  - Ballistic propagation for $R > 6\,\mathrm{EV}$
- **Method:**
  - X_{max} prediction with DNN
  - Rigidity determination - probability distribution for each event
  - Check the method sensitivity: simulate different excess scenarios
  - Backtracking through the GMF
  - Data: assign each event a probability region on the sky

BACKUP

Catalog likelihood

Issue:

- $a(d)$ takes in account the **absorption** of CRs emitted, assuming a mixed compositions, as a function of the luminosity distance (d) of the source
- If we want to compare directly if the TS improves we have to use the same parameter $a(d)$, but if we **discard events** according rigidity we are **changing the composition**

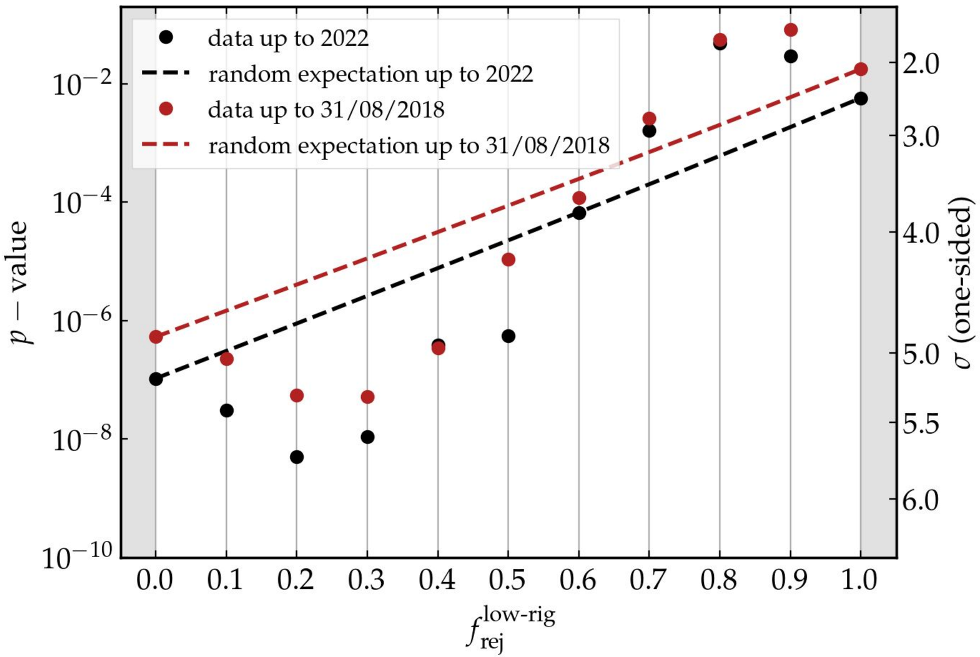
$$n^{H_1}(\mathbf{u}) = (1-\alpha) \times n^{H_0}(\mathbf{u}) + \alpha \times \frac{\sum_j s_j(\mathbf{u};\Theta)}{\sum_i \sum_j s_j(\mathbf{u_i};\Theta)}$$

$$s_j(\mathbf{u};\Theta) = \omega(\mathbf{u}) \times \phi_j \boxed{a(d_j)} \times \exp\left(\frac{\mathbf{u}\cdot\mathbf{u}_j}{2(1-\cos\Theta)}\right)$$

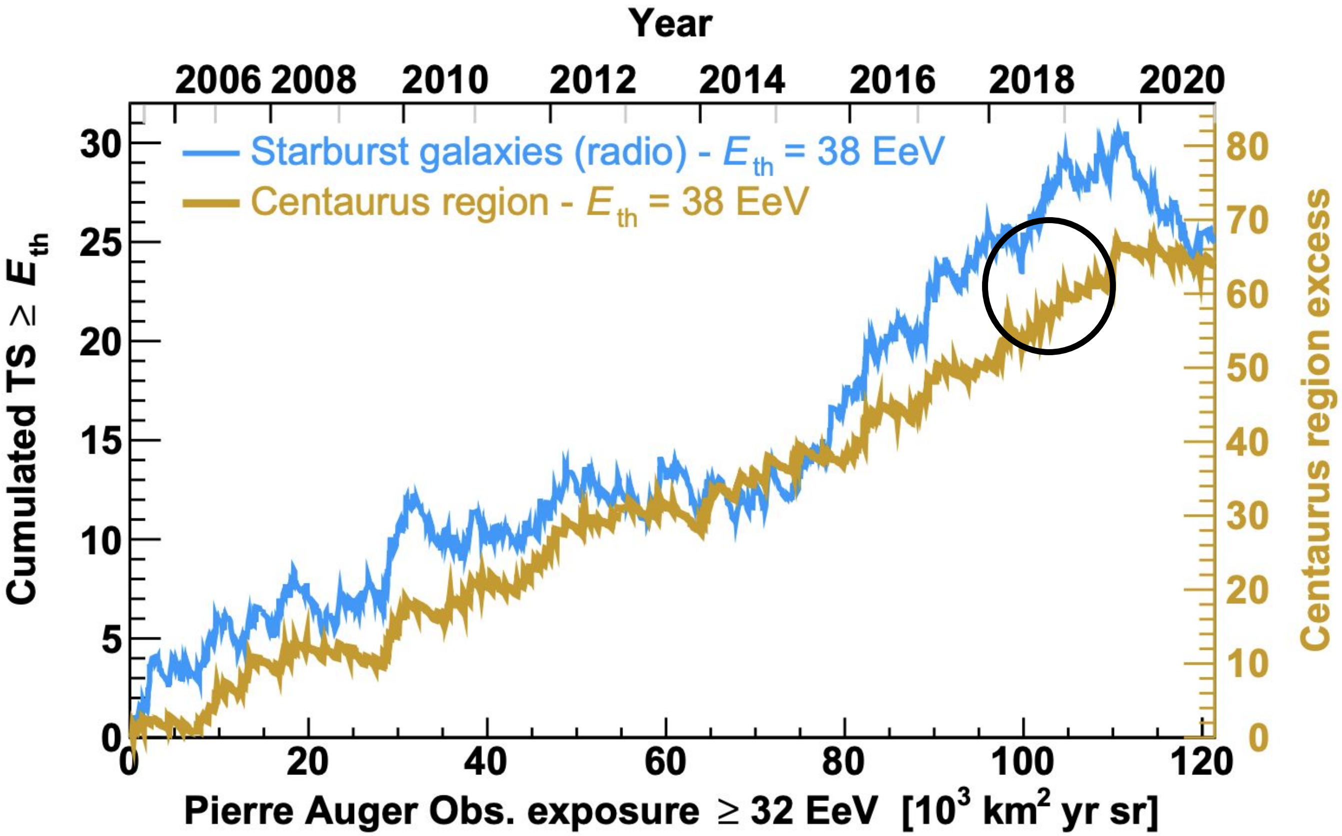
Expectation universality up to 2018

What now?
Cross-check with AixNet with data up to 31/08/2018

Universality data

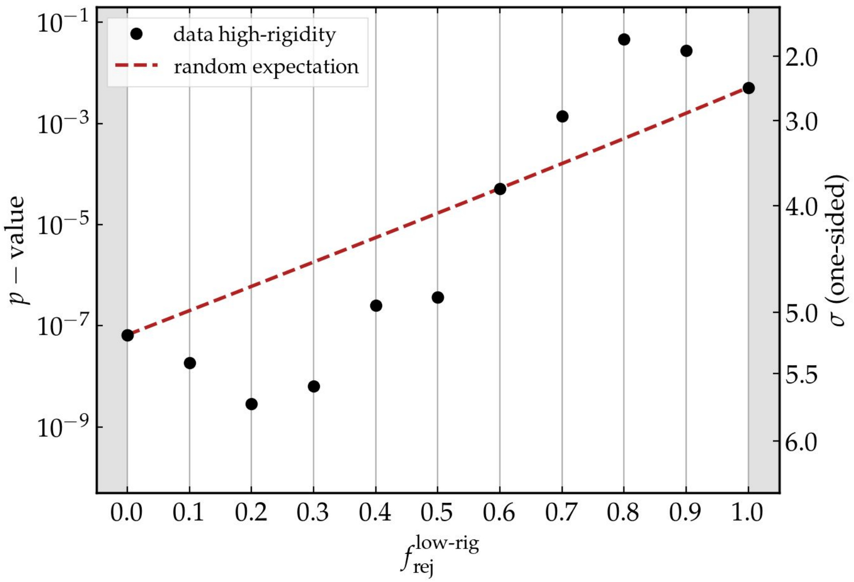


Data up to 2018

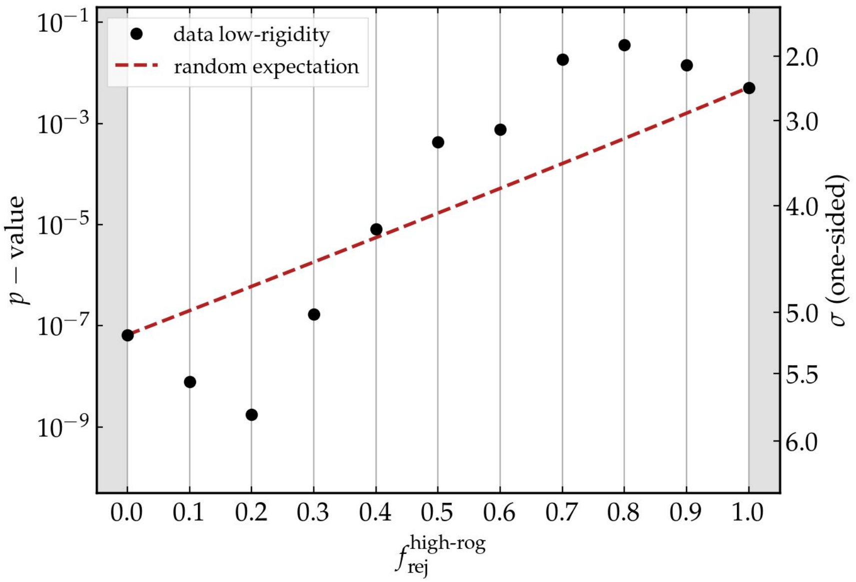


Low-rigidity and high-rigidity comparison

discarding low-rigidity events



discarding high-rigidity events



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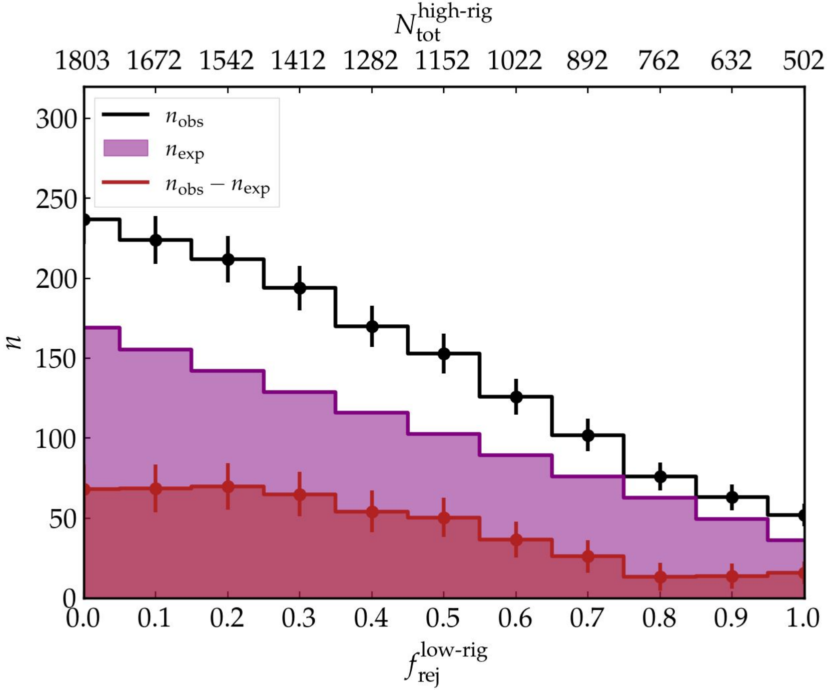

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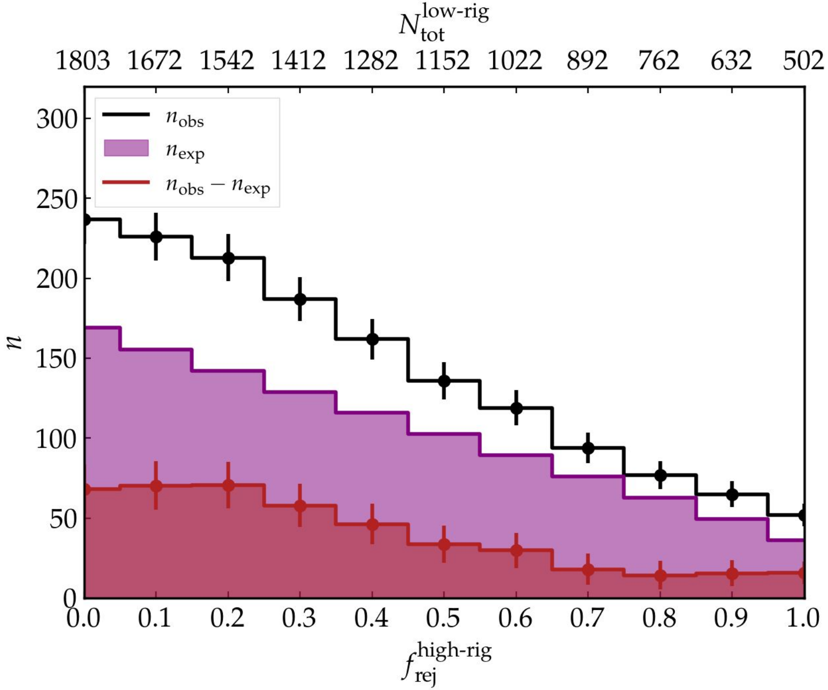

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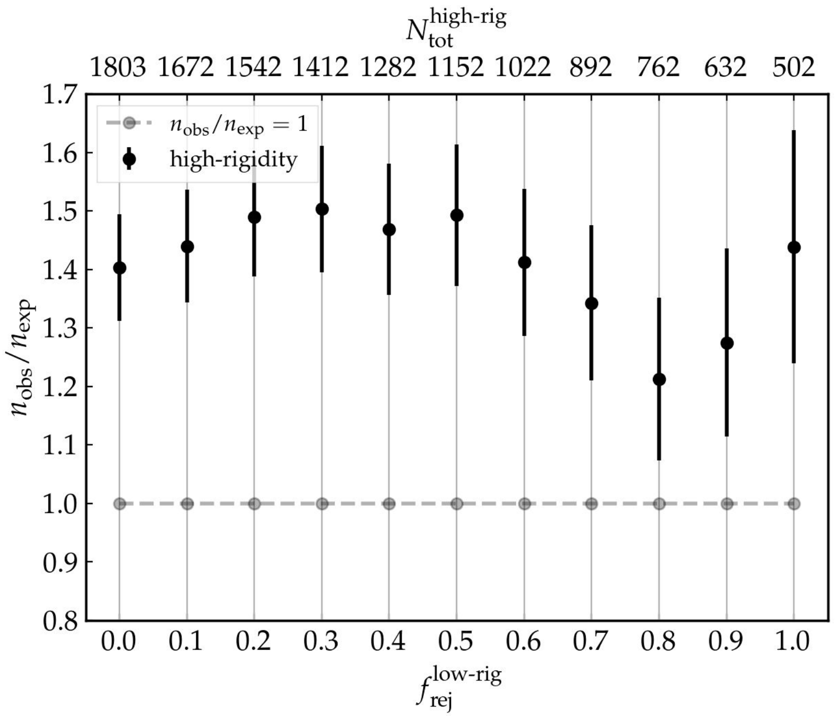
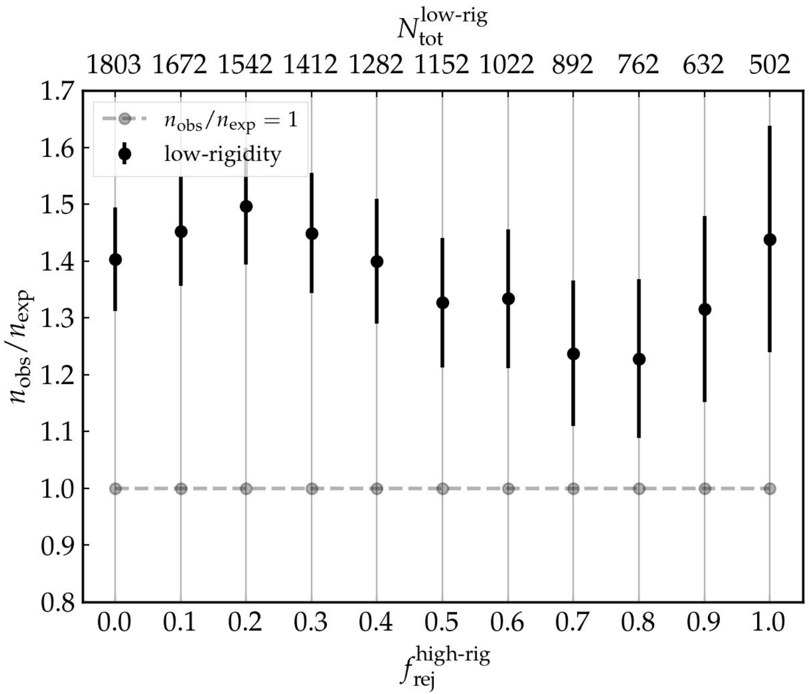
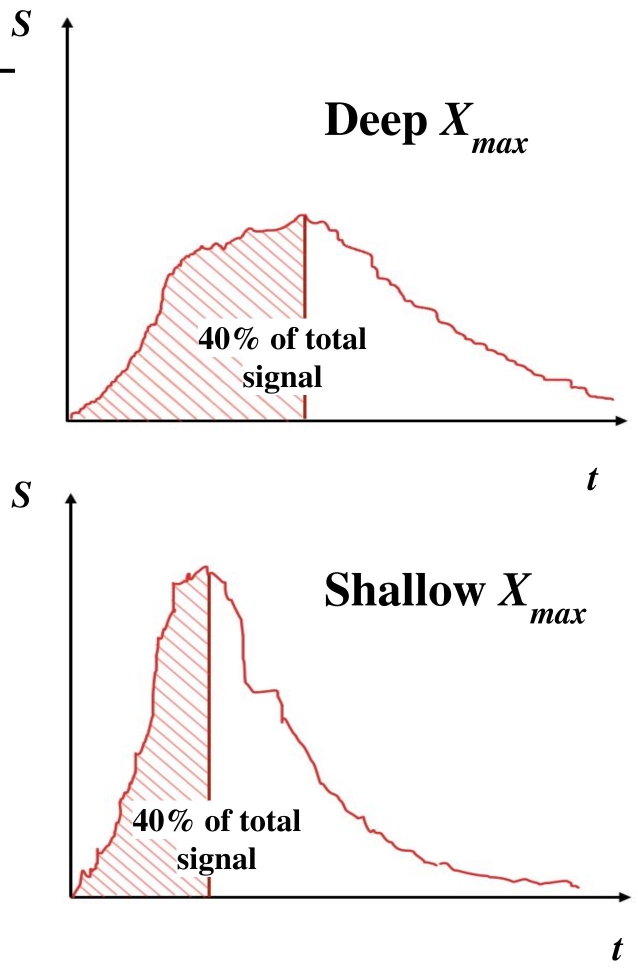


discarding high-rigidity events



X_{max} estimation

- Particles are **mostly produced near the shower core**
- The **deeper in the atmosphere** the particles are produced, the **later** they arrive to the stations
- As ~40% of the particles are produced before X_{max}, the **time** in which **40% of the signal is deposited** in the stations is **dependent on** X_{max}



Universality

What we want to obtain

$$\rho = \left(a\left(R_{\mu} - 1\right) + 1\right) \left(\frac{E_0}{E_{\text{ref}}}\right)^{\gamma} g(\Delta X)\, f(r)\, u(\psi)$$

Signal released in the WCDs

Energy obtained from the selected estimator (FD, WCDs, …)

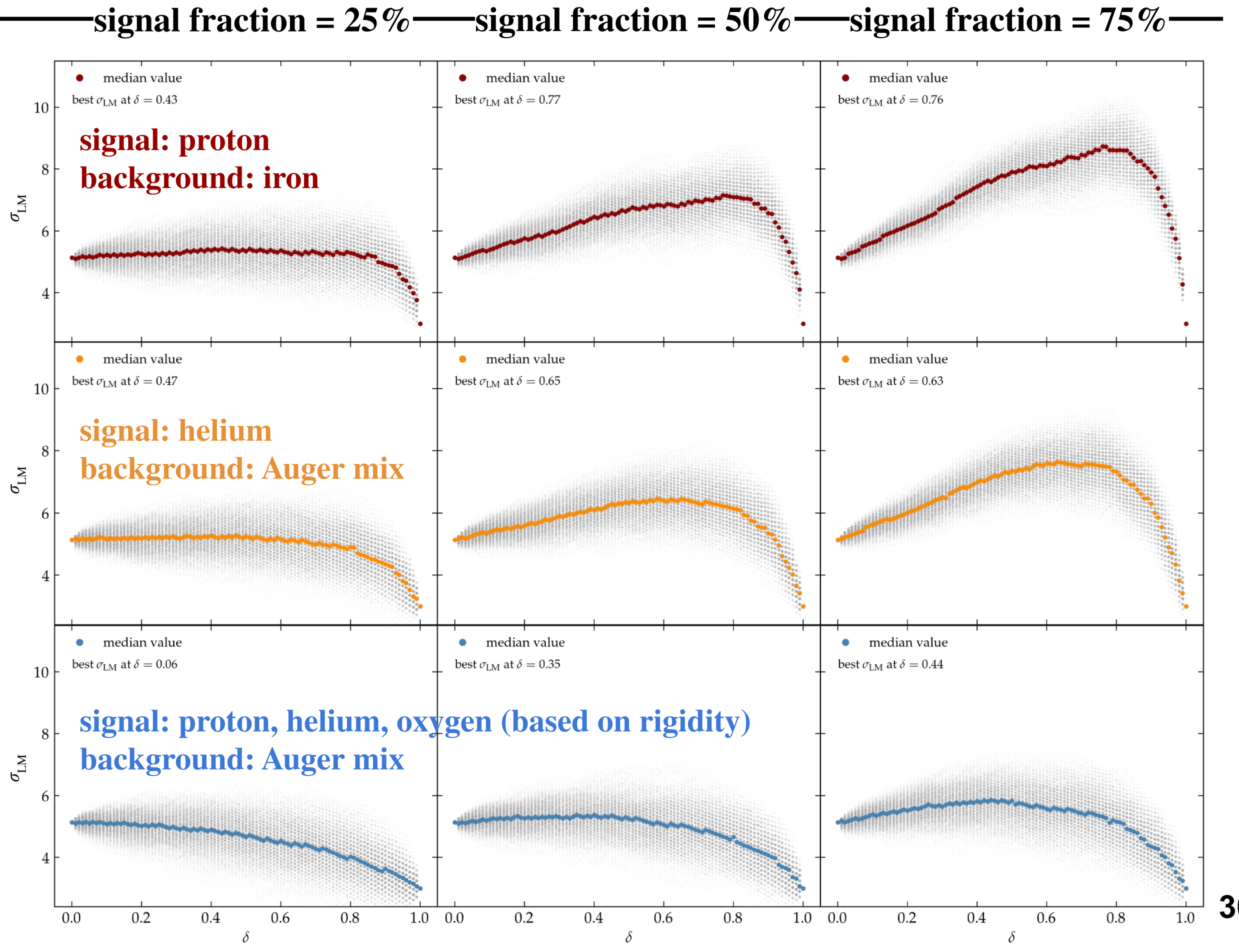
Obtained from arrival time in SD stations

If the energy is obtained from WCDs we can not use ρ to obtain R_{μ}
In Phase I of Pierre Auger Observatory we can obtain only a limited information on R_{μ}

X_{max} is related to the mass of the primary particle
We can use it as mass estimators and introduce it in Arrival Direction studies

Signal enhancing

- we consider the **hypothesis** that the **excess** in the Centaurus region is formed by **high-rigidity particles**
- we **assign** a mass and a **simulated X_{max}** to all the particles
- we **order** according **rigidity**
- we see how the **significance of the excess** changes when **discarding** more **events**



Rigidity vs mass selection