Introducing mass information in UHECR small-scale arrival direction studies:
a path of simulations and corrections

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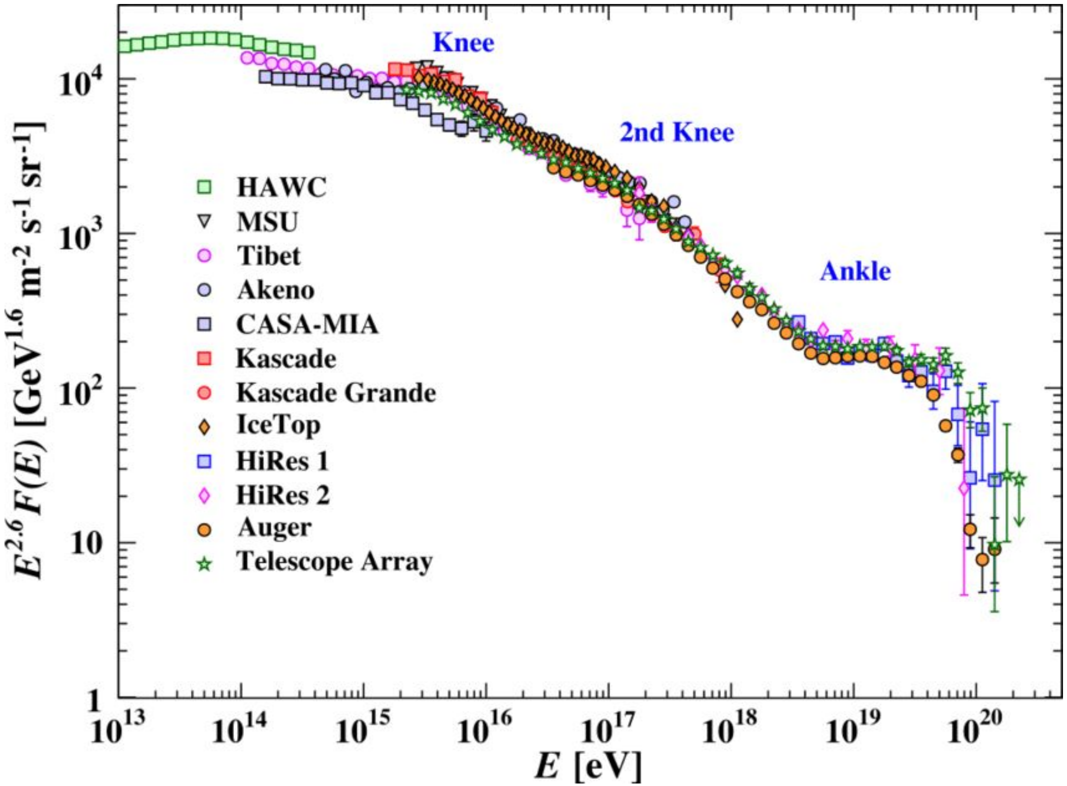
Ultra-High-Energy Cosmic Rays (UHECRs)

- Cosmic rays are particles (mainly **nuclei**) produced in the outer space entering in the atmosphere
- Ultra-High-Energy Cosmic Rays (**UHECRs**) are cosmic rays with **E ≥ 1 EeV** (1 EeV = 10^{18} eV)
- UHECR **sources** are still **unknown**



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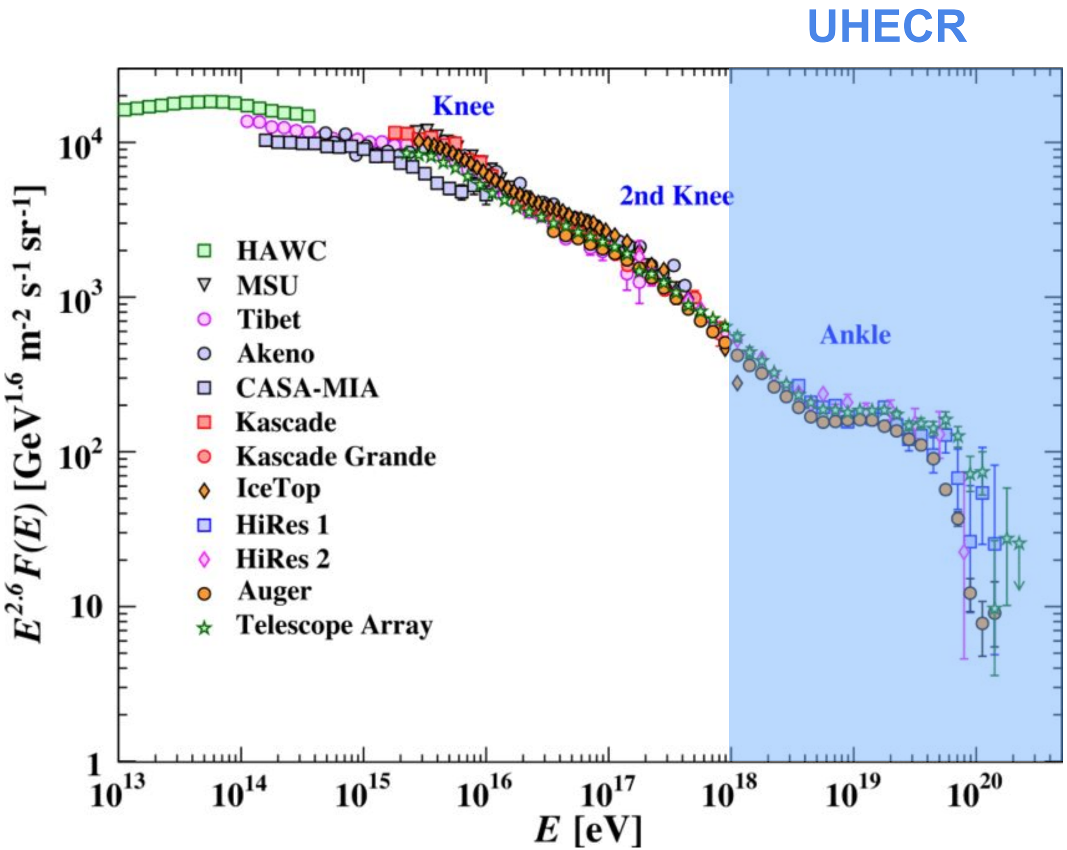
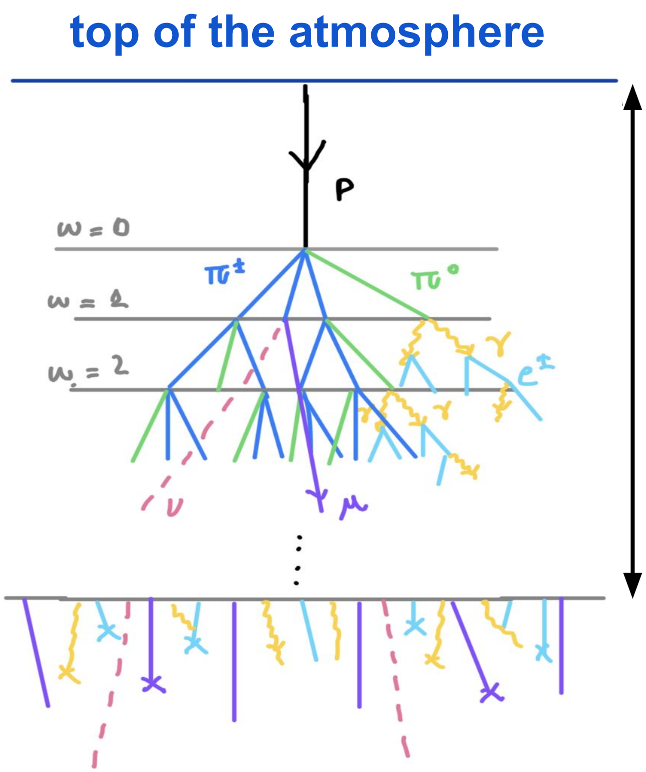


Extensive Air Showers (EASs)



$$\mathrm{p} + \mathrm{air} \rightarrow \pi^{\pm} + \pi^{0} + \ldots$$

Charged pions

they can decay

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\hookrightarrow \mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$

$$\hookrightarrow \mu^{-} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu}$$

they can interact with the atmosphere

$$\pi^{\pm} + \mathrm{air} \rightarrow \pi^{\pm} + \pi^{0} + \ldots$$

Neutral pions

$$\pi^{0} \rightarrow \gamma + \gamma$$

Extensive Air Showers (EASs)

top of the atmosphere

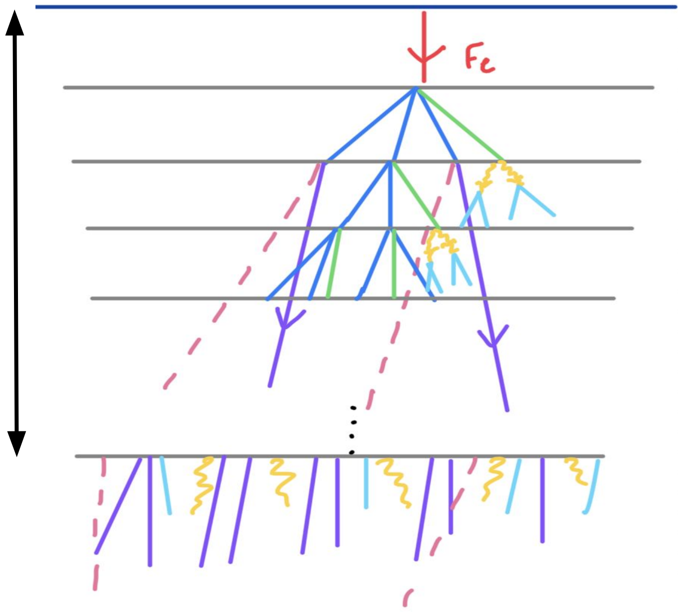
Heavy nuclei

a nucleus with A nucleons and energy E can be considered as A protons with energy E/A

$$^{56}\mathrm{Fe}(E) = 56\,\mathrm{p}(E/A)$$

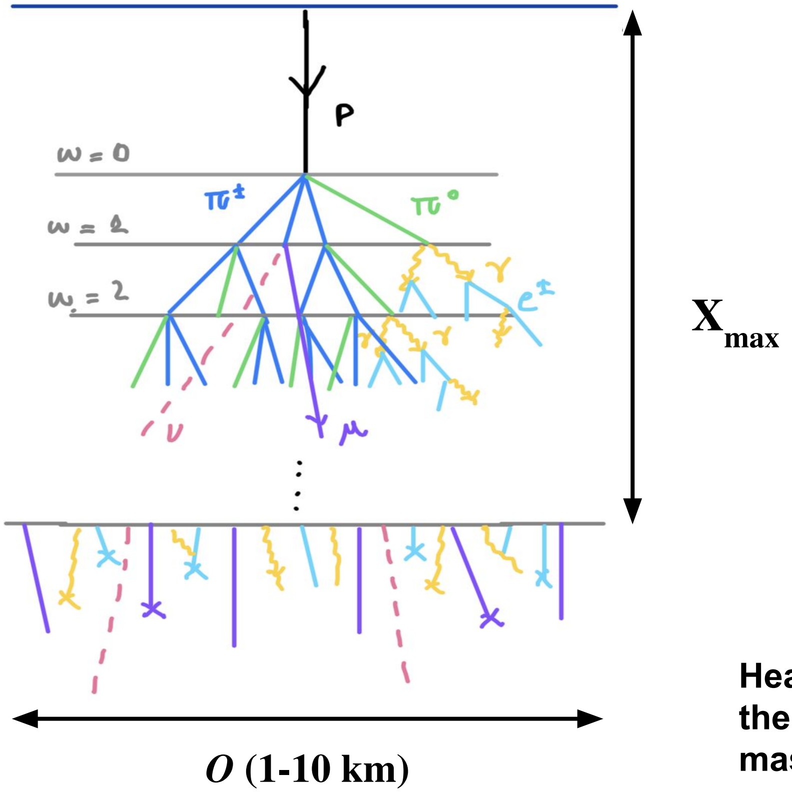
$$56\,\mathrm{p}(E/A) + \mathrm{air} \rightarrow \pi^{\pm} + \pi^{0} + \ldots$$

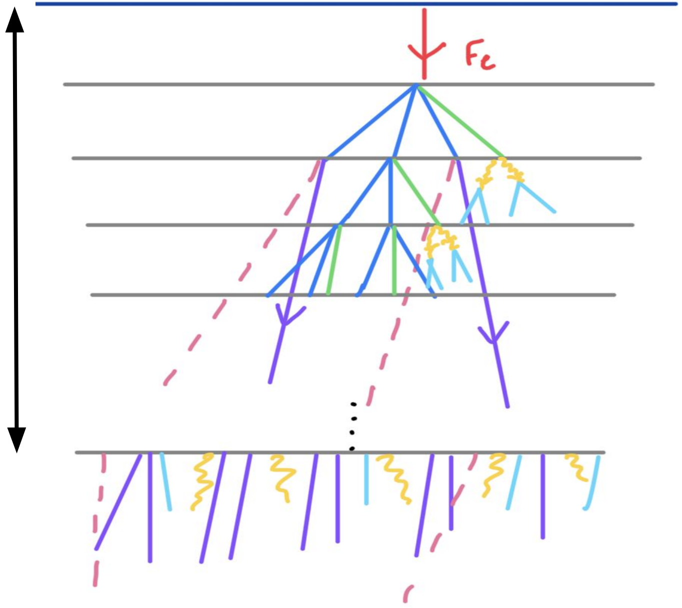
$\mathcal{O}$ (1-10 km)



Extensive Air Showers (EASs)

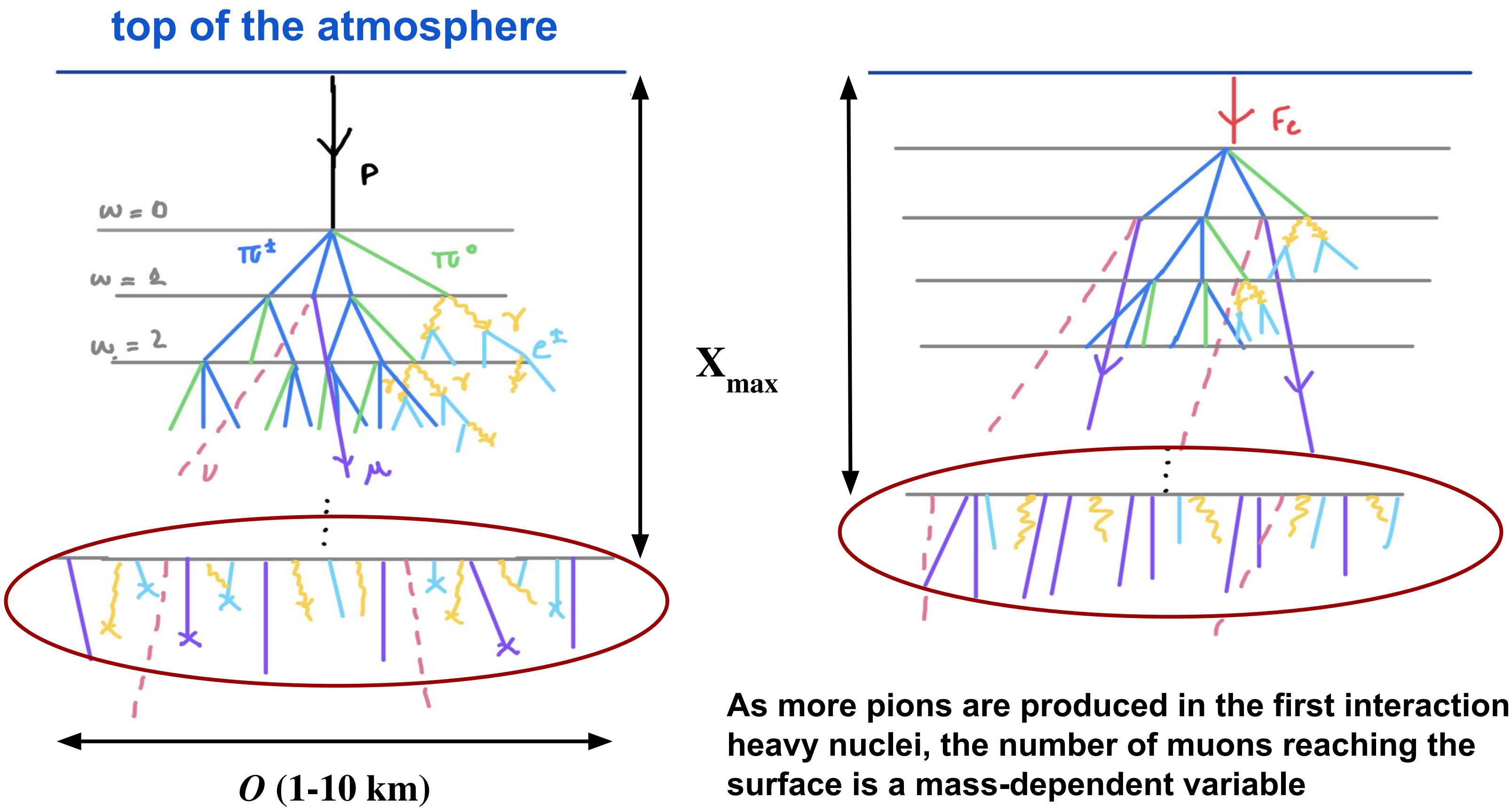
top of the atmosphere





Heavy nuclei develop earlier in the atmosphere, thus the depth of maximum number of particles (X_{max}) is a mass-dependent observables

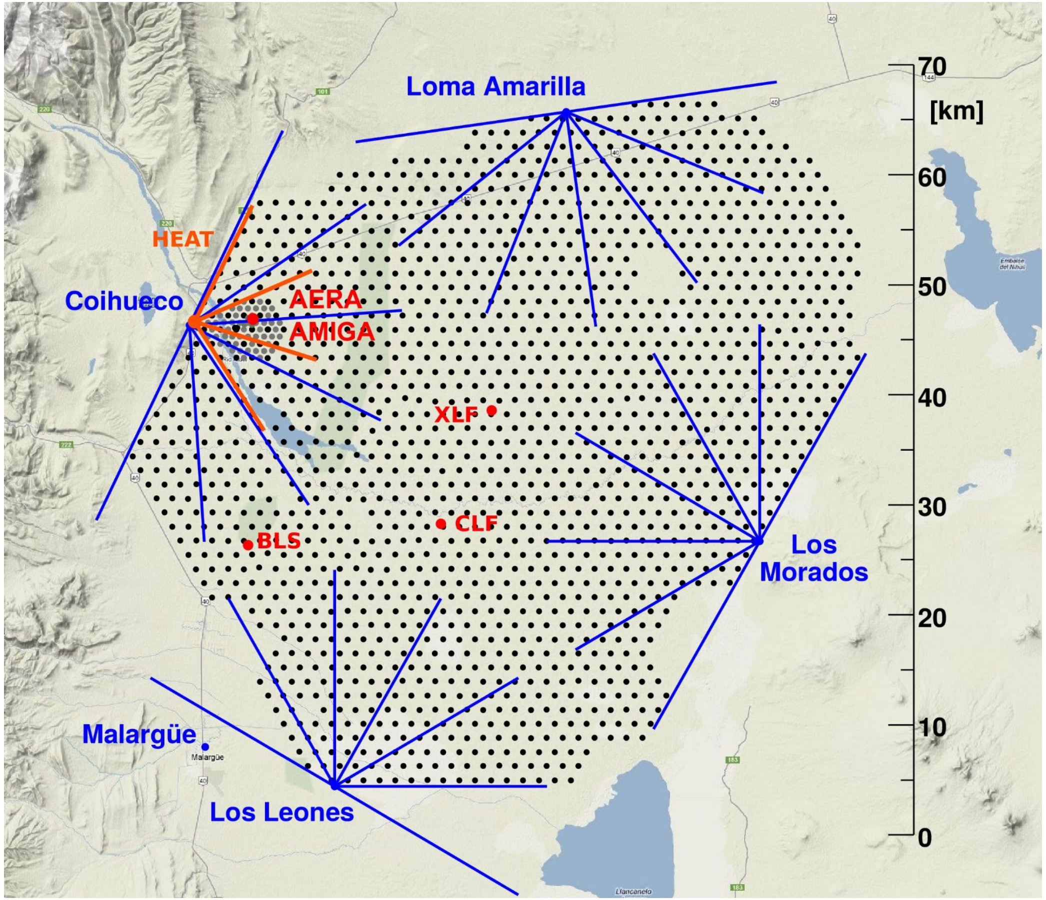
Extensive Air Showers (EASs)



As more pions are produced in the first interaction of heavy nuclei, the number of muons reaching the surface is a mass-dependent variable

The Pierre Auger Observatory

- The Pierre Auger Observatory is the **largest UHECR observatory** in the world (area of **~3000 km^2**)
- It is active since 2004
- It is located in **Argentina** near the city of Malargüe (latitude 35.6° S)
- **85% of sky coverage**, angular resolution ~1°
- At ~1400 m.a.s.l.



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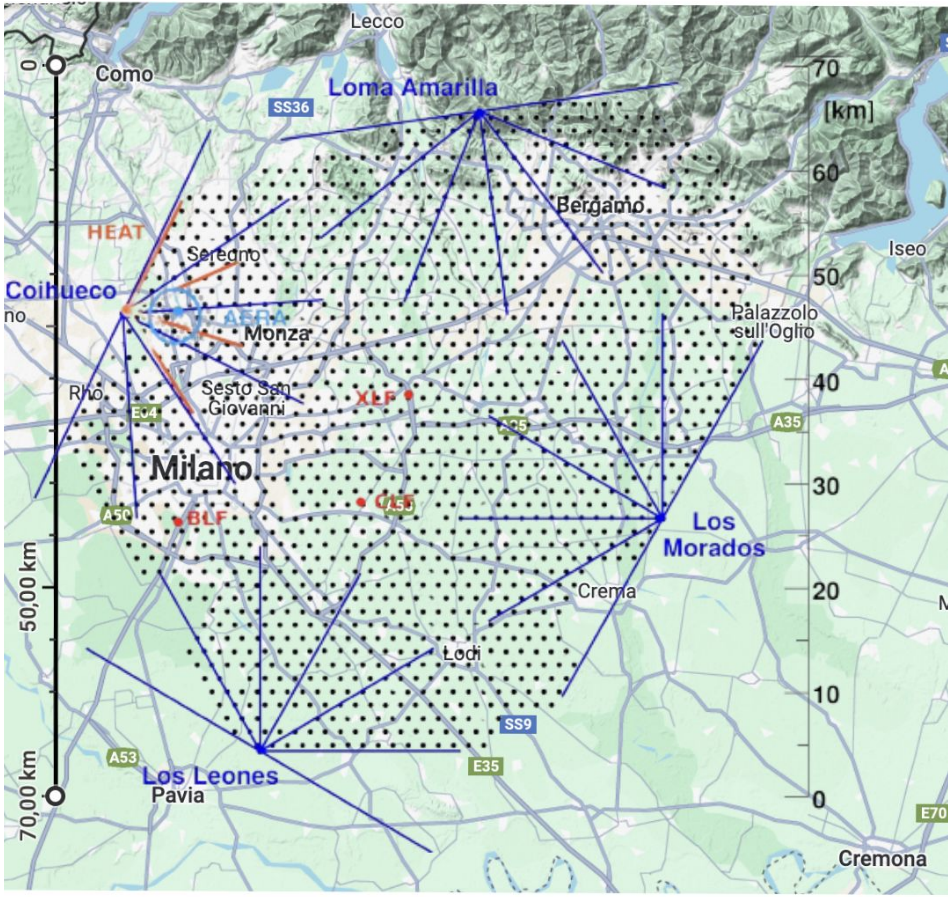

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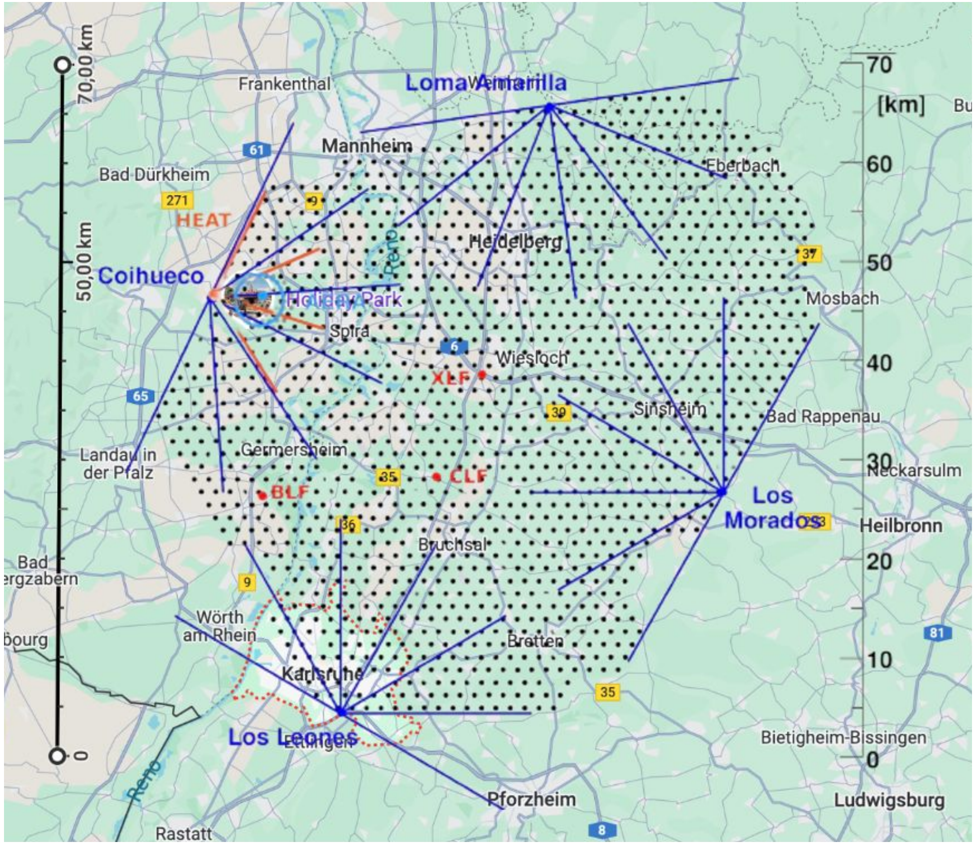
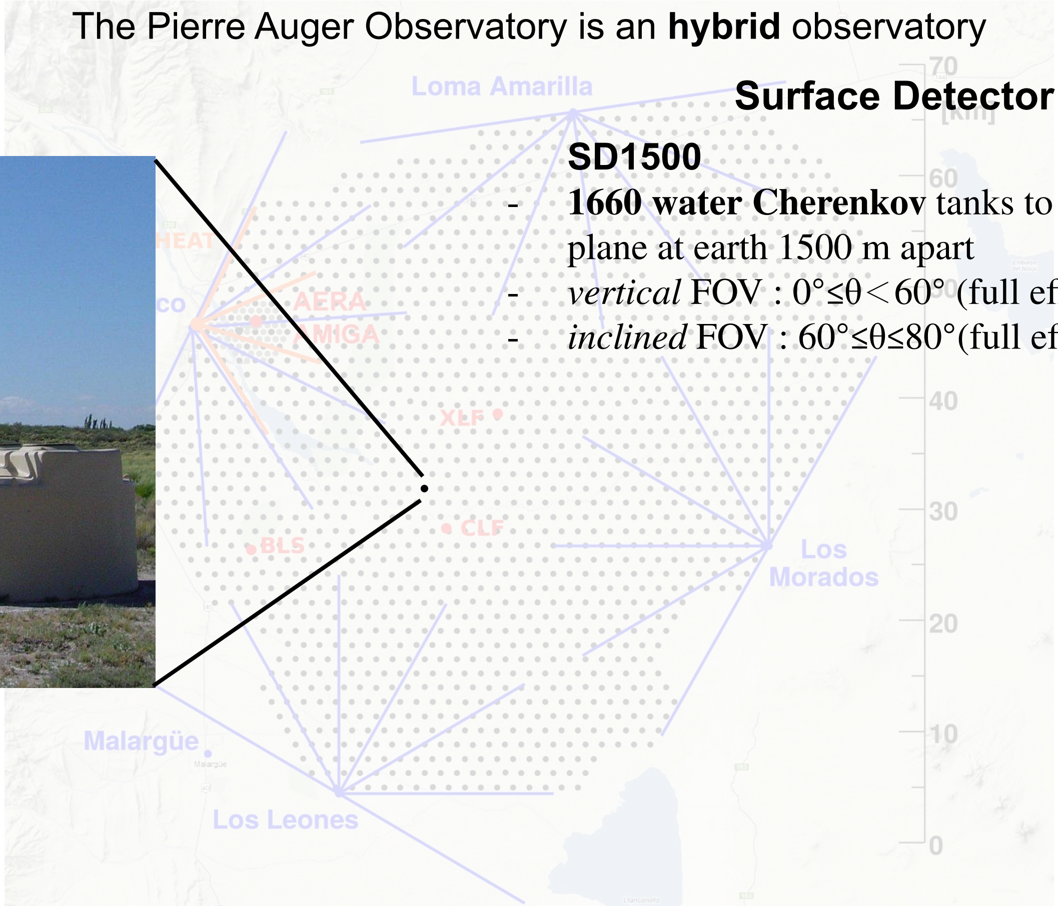


The Pierre Auger Observatory

The Pierre Auger Observatory is an **hybrid** observatory



Surface Detector (SD)

SD1500

- **1660 water Cherenkov** tanks to sample the shower plane at earth 1500 m apart
- *vertical* FOV : $0° \leq \theta < 60°$ (full efficiency above 3 EeV)
- *inclined* FOV : $60° \leq \theta \leq 80°$(full efficiency above 4 EeV)

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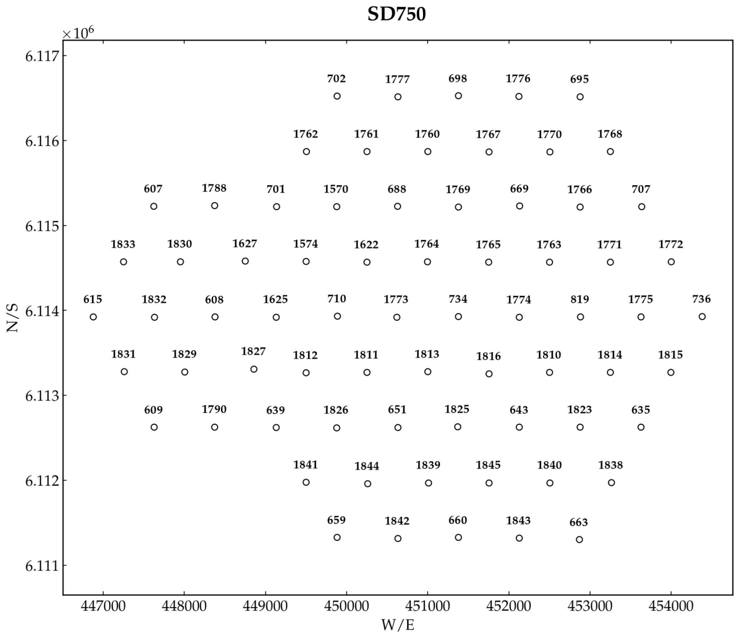

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SD750

- 60 stations, 750 m apart
- FOV : $0° \leq \theta \leq 55°$
- Full efficiency above 0.3 EeV

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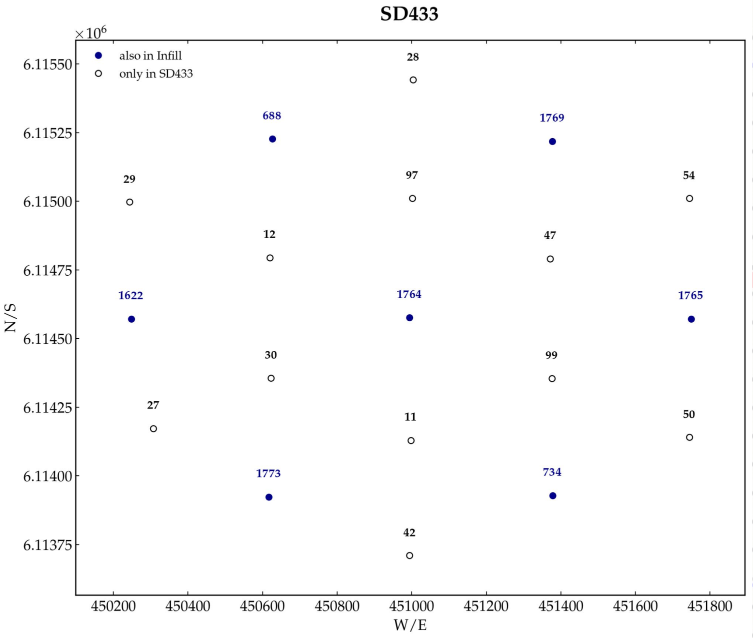

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SD433

- 19 stations, 433 m apart
- FOV : 0°≤θ≤45°
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The Pierre Auger Observatory

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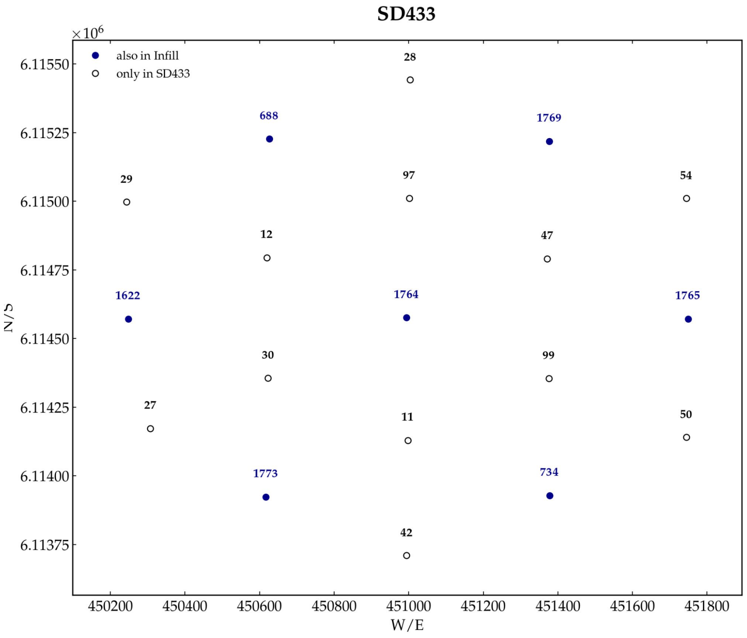

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SD750

- 60 stations, 750 m apart
- FOV : 0°≤θ≤55°
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SD433

- 19 stations, 433 m apart
- FOV : 0°≤θ≤45°
- Full efficiency above 63 PeV

duty cycle of ~100% with only information of the shower front

The Pierre Auger Observatory

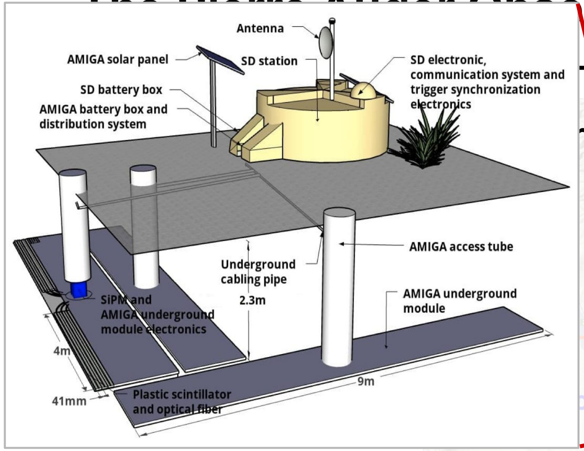
The Pierre Auger Observatory is an **hybrid** observatory

Fluorescence Detector (FD)

27 telescopes divided in four sites looking at the fluorescence light emitted by the charged particles in the shower

duty cycle of ~10% with information of the shower development in atmosphere

The Pierre Auger Observatory



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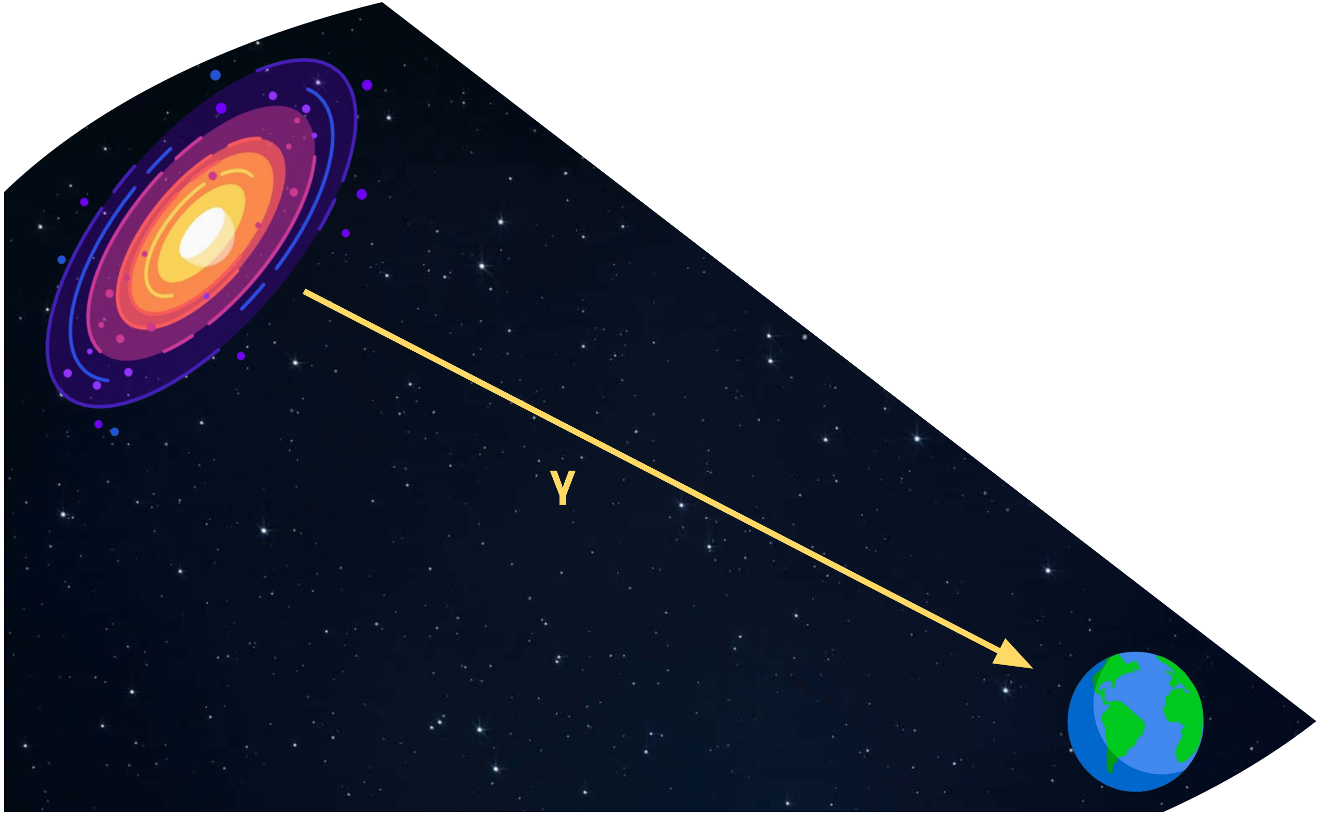
AugerPrime upgrade

The deployment of the upgrade Auger Prime ended the Phase I of the observatory: 2004-2022.

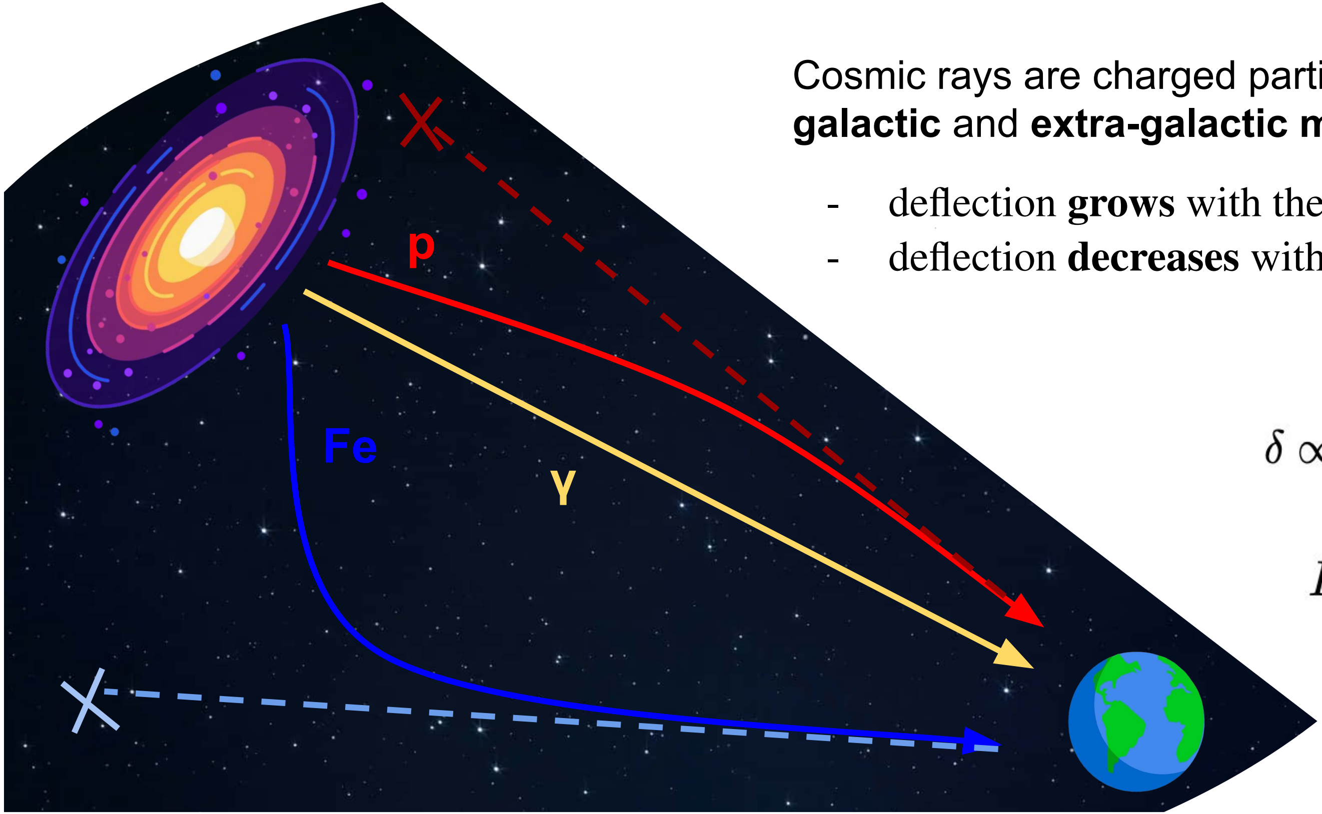
Elements of the upgrade AugerPrime are

- **plastic scintillator (SSD)** on top of each existing surface detector (SD) station
- addition of a **small photomultiplier** to the SD
- **underground scintillator muon detector** under SD433
- **radio antenna** above each SD station
- **enhanced and faster SD electronics** with an Upgraded Unified Board (UUB)

Arrival directions



Arrival directions



Cosmic rays are charged particles and deflected by the **galactic** and **extra-galactic magnetic fields**

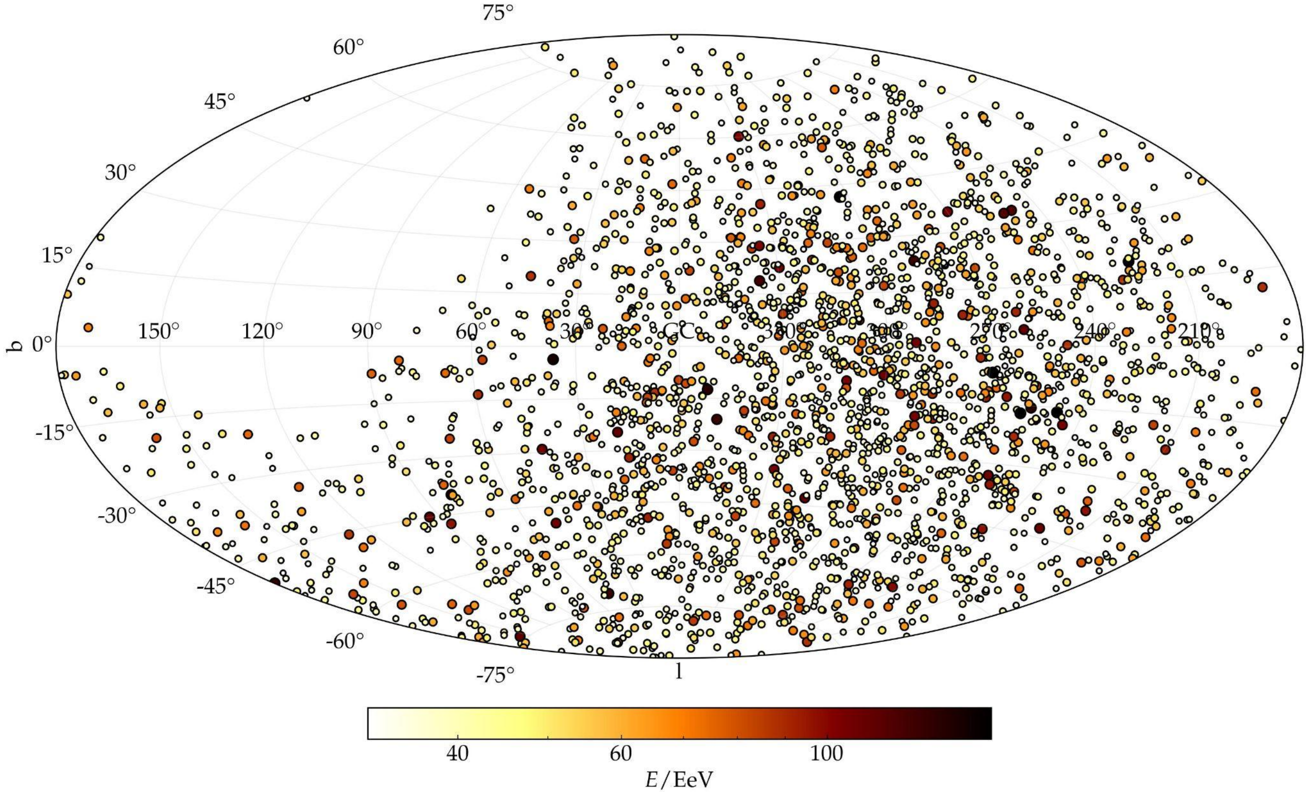
- deflection **grows** with the **charge** of the particle
- deflection **decreases** with **energy**

$$\delta \propto \frac{Z}{E} \qquad R := \frac{E}{Z}$$

$$R = \text{Rigidity}$$

Arrival directions

Events with E ≥ 32 EeV ⟶ **2636 events in ~20 yr**



The Pierre Auger Collaboration, Arrival directions of cosmic rays above 32 EeV, The Astrophysical Journal 935, 170 (2022).

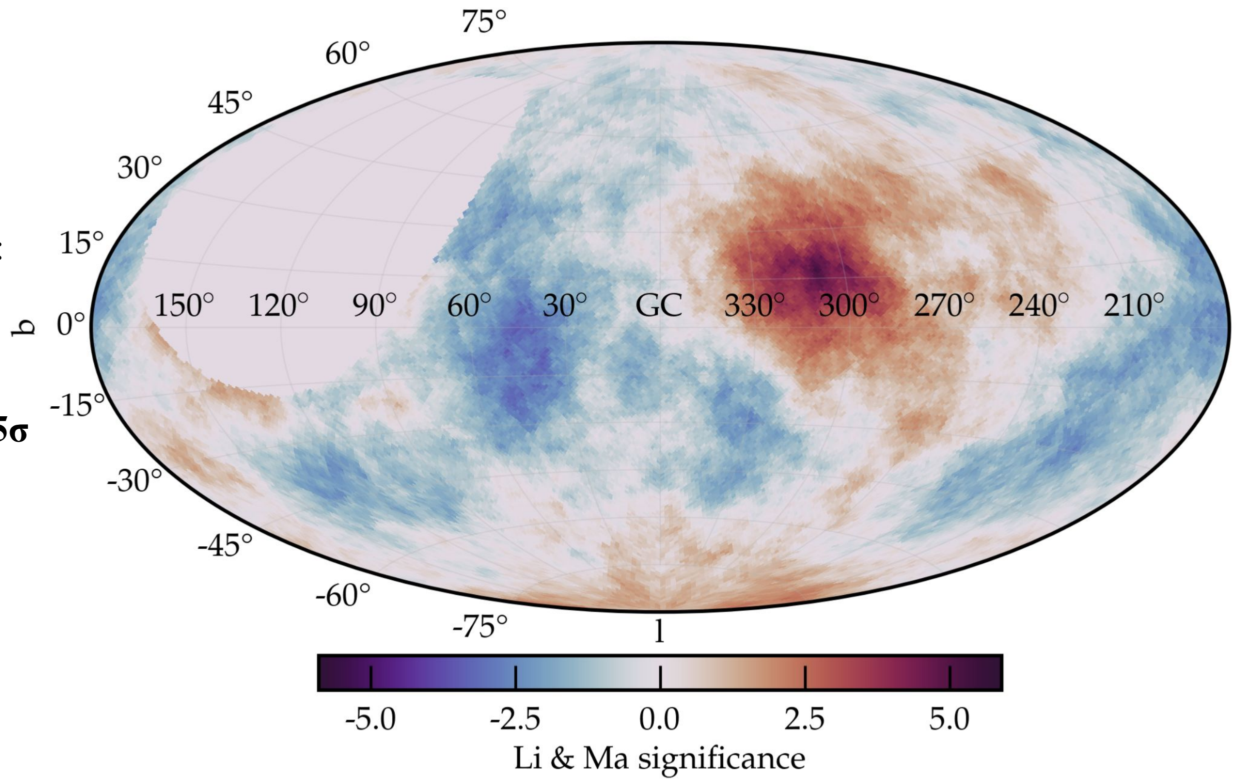
Arrival directions

Divide sky in pixels and look for **overdensities**

- **Scan in threshold energy** (E_{th}): from 32 to 80 EeV
- **Scan in top hat radius** (ψ_{th}): from 1° to 30°

pre-trial *p*-value = $3.16 \cdot 10^{-8}$ (**5.45σ one-sided**)
(R.A., dec) = (196.3°, -46.6°)
E_{th} = 40 EeV
ψ_{th} = 24°

post-trial *p*-value = 0.039 (**2.1σ one-sided**)

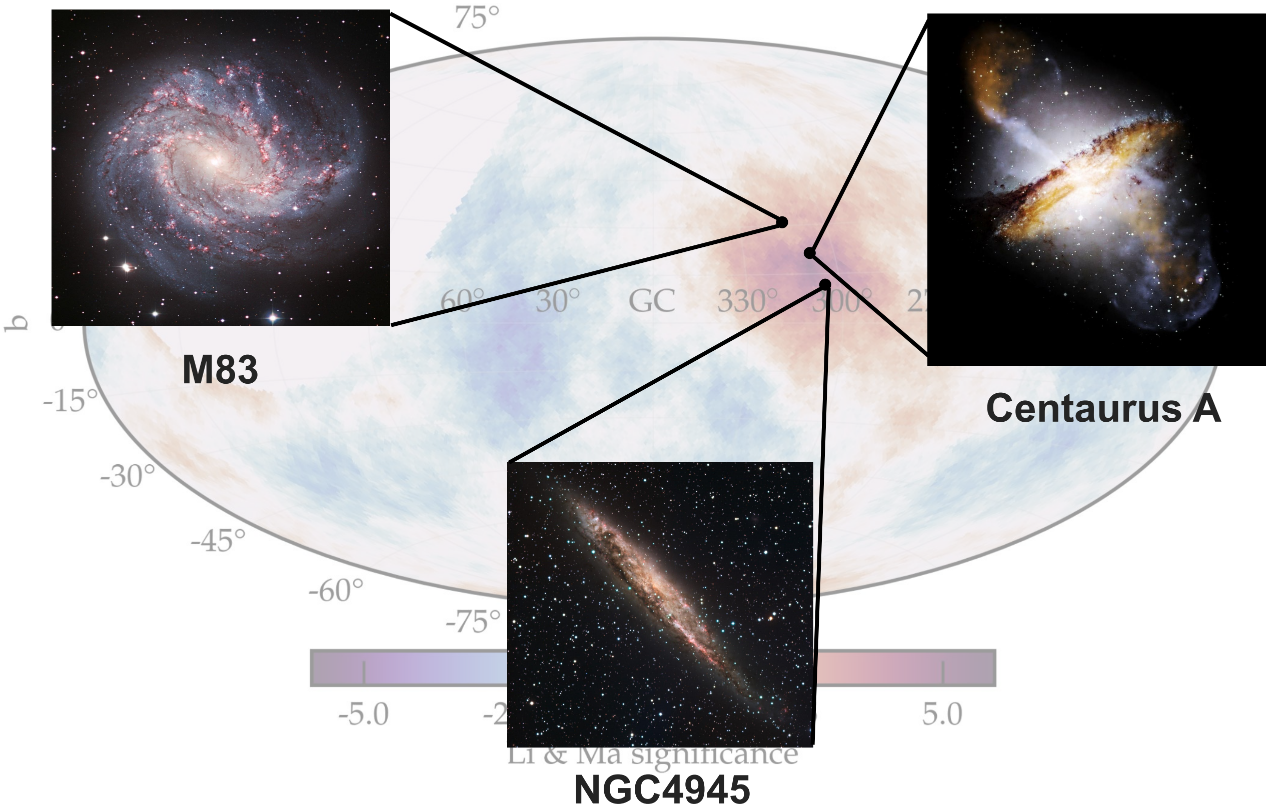


The Pierre Auger Collaboration, Arrival directions of cosmic rays above 32 EeV, The Astrophysical Journal 935, 170 (2022).

Arrival directions

Centaurus A
nearest AGN to the Earth (~3.5 Mpc)
AGNs have always been proposed as UHECR sources

2 Starburst Galaxies (SBGs)
NGC4946 (~4.5 Mpc) and M83 (~5 Mpc)
proposed UHECRs accelerators



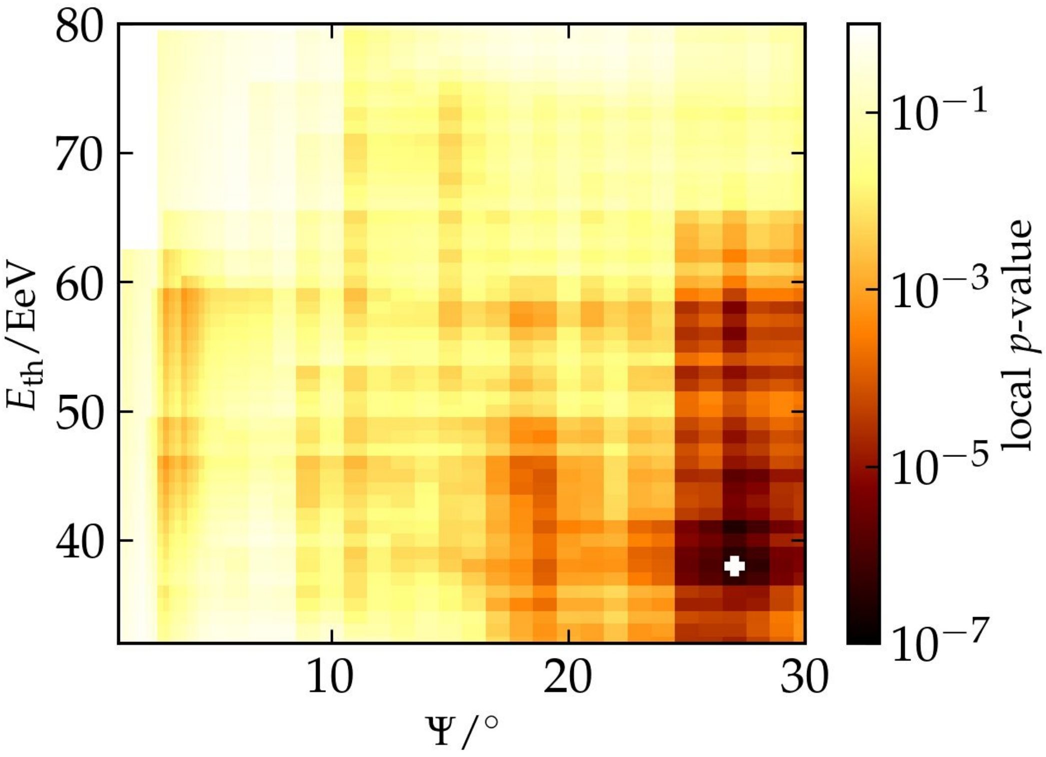
Arrival directions

Targeted analysis around **Centaurus A**

- **Scan in threshold energy** (E_{th}): from 32 to 80 EeV
- **Scan in top hat radius** (ψ_{th}): from 1° to 30°

pre-trial *p*-value = $2.16 \cdot 10^{-7}$ (**5.08σ one-sided**)
E_{th} = 38 EeV
ψ_{th} = 27°

post-trial *p*-value = $6.4 \cdot 10^{-5}$ (**4.0σ one-sided**)



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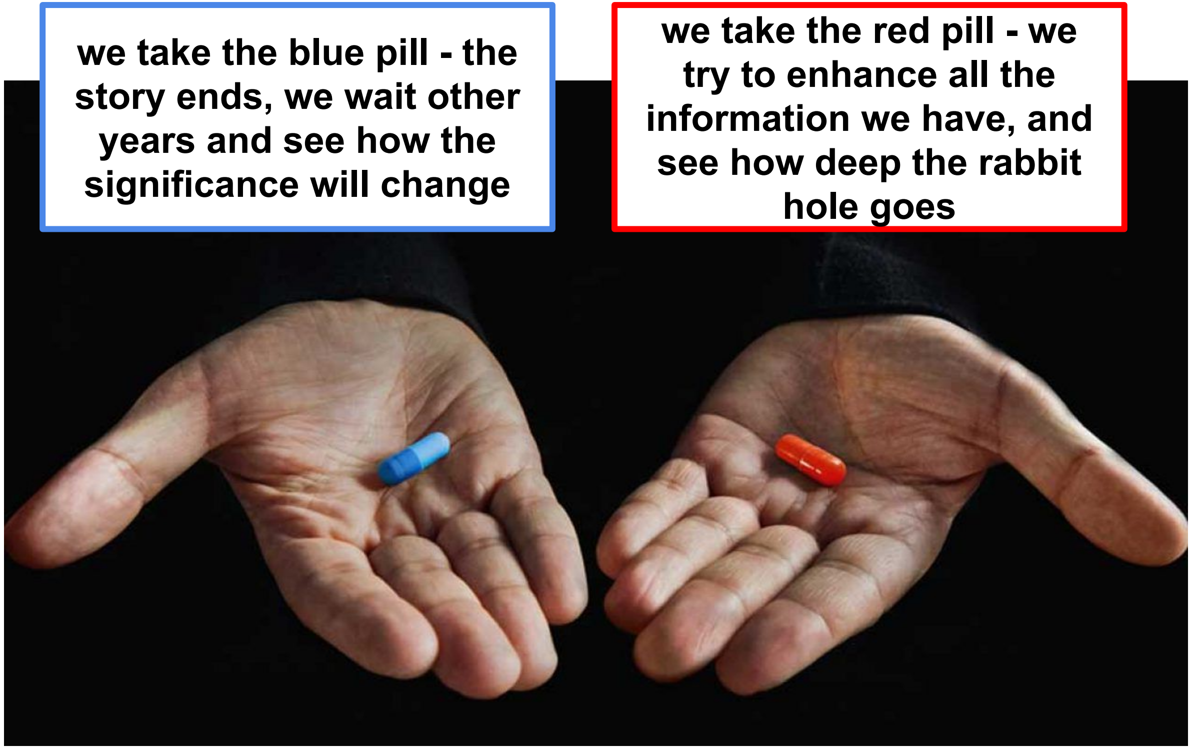
NOW WHAT???


we take the blue pill - the story ends, we wait other years and see how the significance will change
we take the red pill - we try to enhance all the information we have, and see how deep the rabbit hole goes

Enhancing information

How do we enhance information?

Enhancing information

How do we enhance information?

- UHECRs **deflections** are **determined by** their **rigidities**
- By finding the **high-rigidity events** we find the least deflected particles, that we expect to **correlate more with the sources** that emitted them
- Mass-estimators could lead to the definition of a cleaner dataset and to more significant Arrival Direction studies

Enhancing information

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- By finding the **high-rigidity events** we find the least deflected particles, that we expect to **correlate more with the sources** that emitted them
- <u>Mass-estimators could lead to the definition of a cleaner dataset and to more significant Arrival Direction studies</u>

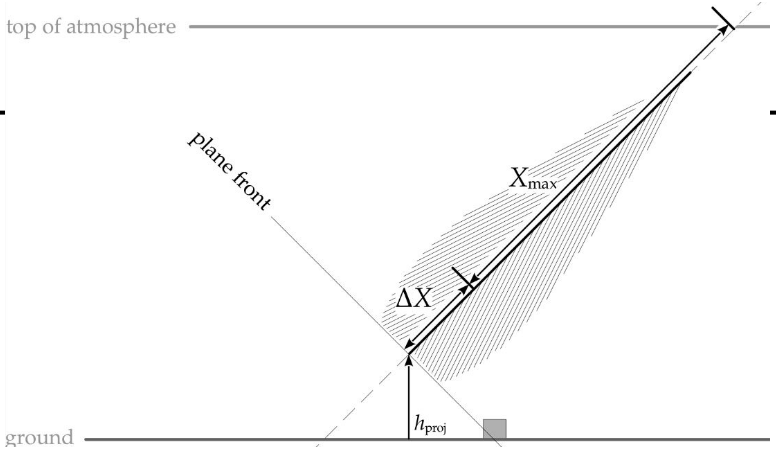
<u>As Arrival Direction studies requires all the possible statistics, we need a mass estimators able to act on SD (100% duty cycle) Phase I (from 2004 to 2022) data</u>

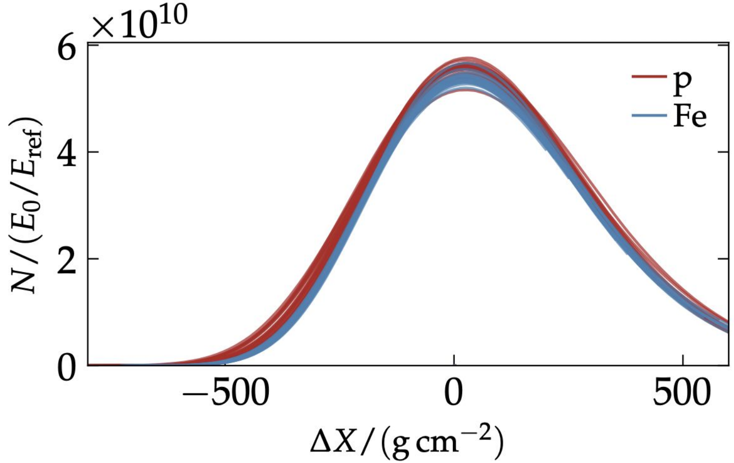
Universality

The shower component of an EAS generated by particles with energy E_0 are in good approximation **universal**, when they are considered as a function of $\Delta X = X - X_{max}$

The particle content of a shower can be divided in 4 components

- **electromagnetic component (eγ)**: electrons, positrons and photons generated in em cascades
- **muon component (μ)**: all muons and antimuons
- **electromagnetic-muon component (eγ(μ))**: electromagnetic particles generated by muon decays
- **hadronic component (eγ(π))**: electromagnetic particles generated in hadronic decays and all hadrons





M. Stadelmaier, R. Engel, M. Roth, D. Schmidt, and D. Veberic, Model of the response of surface detectors to extensive air showers based on shower universality, Phys. Rev. D 110,023030 (2024)

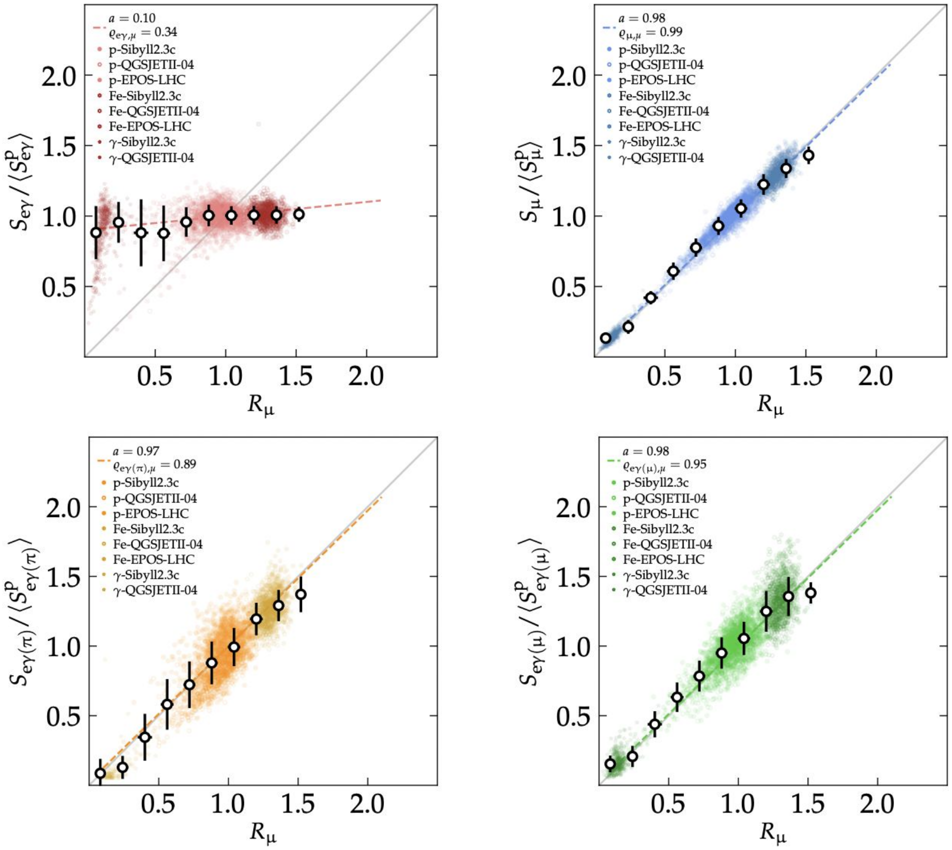
Universality

The **signal size** of the 4 components can be parameterized as a **function** of the **muon content (R_μ)**

The signal deposited by a shower at a distance r from the shower core, can parameterized with three variables

- the relative depth ΔX
- the energy of the primary particle E_0
- the muon component R_μ

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



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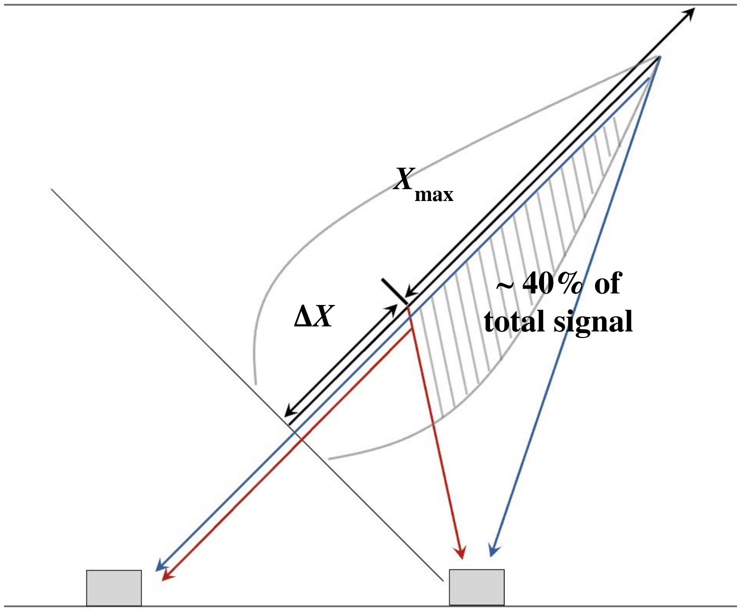
Universality

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}**



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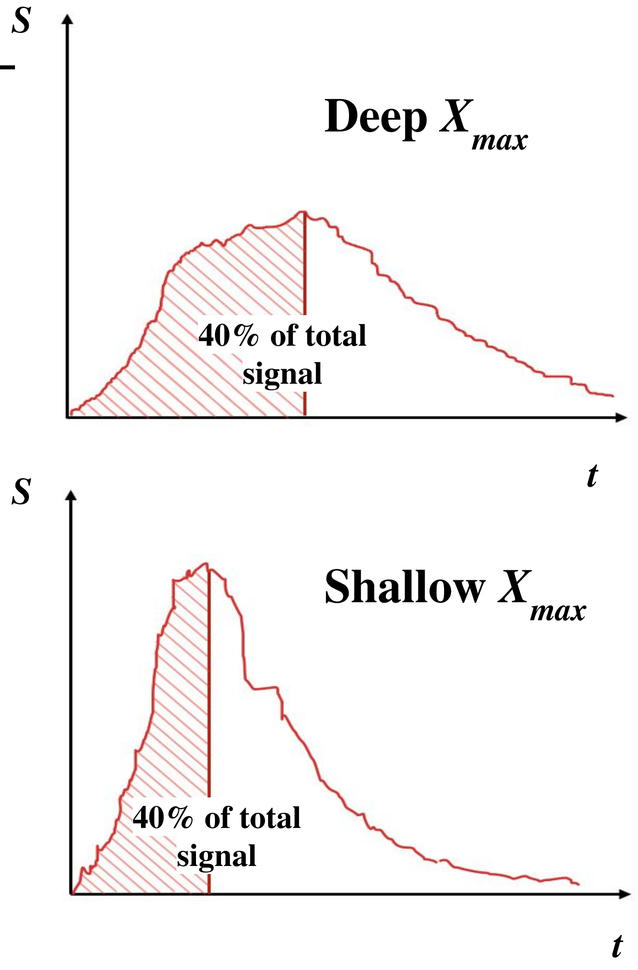


Universality

What we want to obtain

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

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

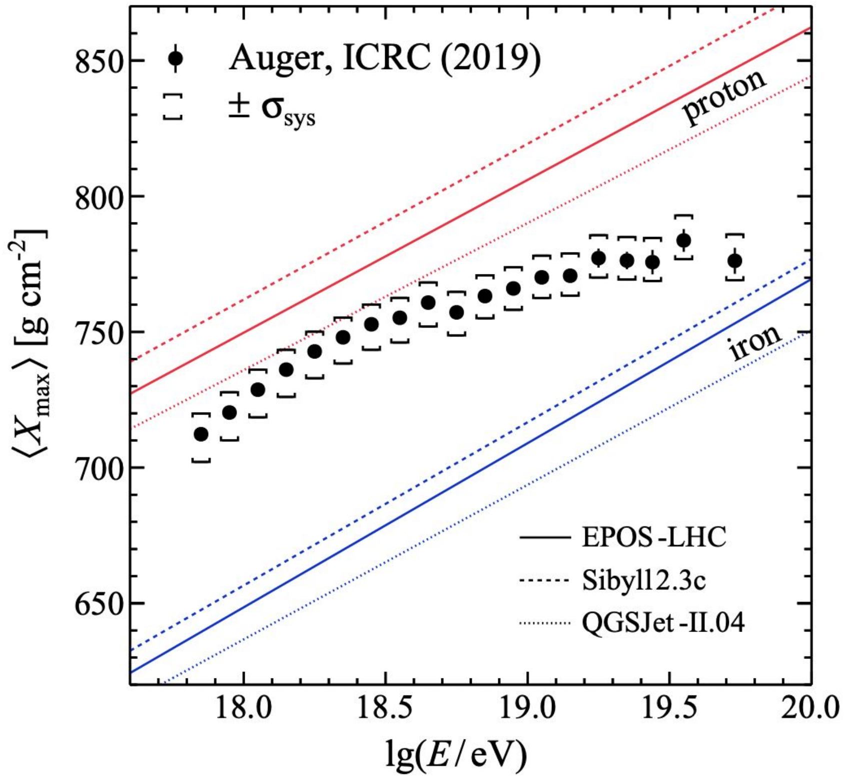
X_{max} is related to the mass of the primary particle
We can use it as mass estimators and introduce it in Arrival Direction studies

Universality

X_{max} is **not directly related to the mass** of the primary cosmic ray, but it is energy-dependent

By removing the energy dependence, we define a linear related mass-parameter

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



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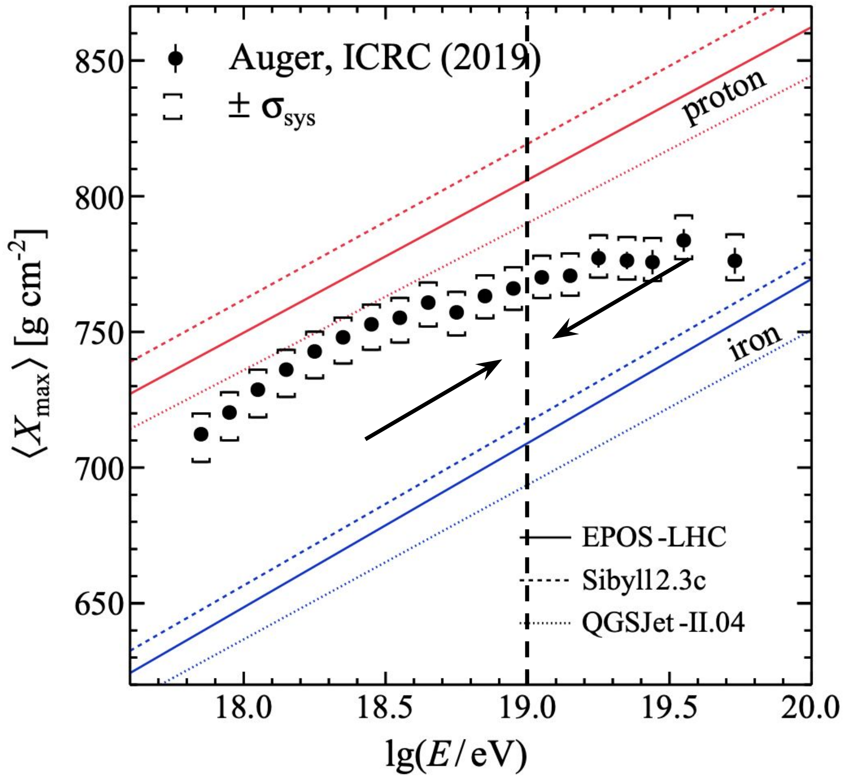

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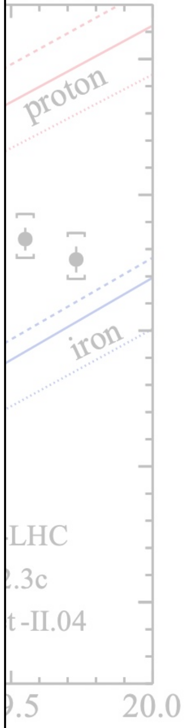

For non Auger experts

Universality is not the only method to reconstruct mass information with SD
Different DNNs have also been introduced to achieve this goal
If you are interested please look at

The Pierre Auger Collaboration, Measurement of the Depth of Maximum of Air-Shower Profiles with energies between $10^{18.5}$ and 10^{20} eV using the Surface Detector of the Pierre Auger Observatory and Deep Learning, 2024. arXiv:2406.06315.

The Pierre Auger Collaboration, Reconstruction of muon number of air showers with the surface detector of the Pierre Auger Observatory using neural networks, PoS ICRC2023, 318 (2023)

The Pierre Auger Collaboration, Deep-Learning-Based Cosmic-Ray Mass Reconstruction Using the Water-Cherenkov and Scintillation Detectors of AugerPrime, PoS ICRC2023, 371 (2023)

IS IT SAFE TO USE UNIVERSALITY FOR ARRIVAL DIRECTIONS???

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LET'S CHECK?

<u>For Auger experts</u>

All the following checks are being done in parallel both on KANet and AixNet

LET'S CHECK?

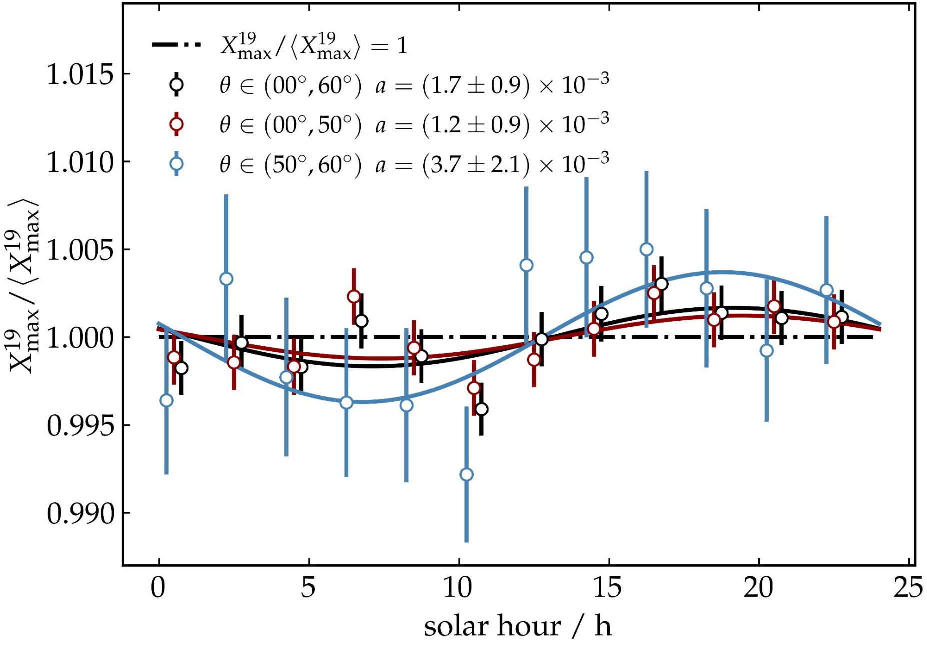
Checking for dependence: solar hour

Presence of a **modulation** as a function of the **solar hour**

A modulation in solar hour is **not physical,** as the possible arrival direction signal is dependent on the sidereal time

$$\frac{X^{19}_{\mathrm{max}}}{\langle X^{19}_{\mathrm{max}} \rangle} = a_h \cos(w_h h) + b_h \sin(w_h h)$$

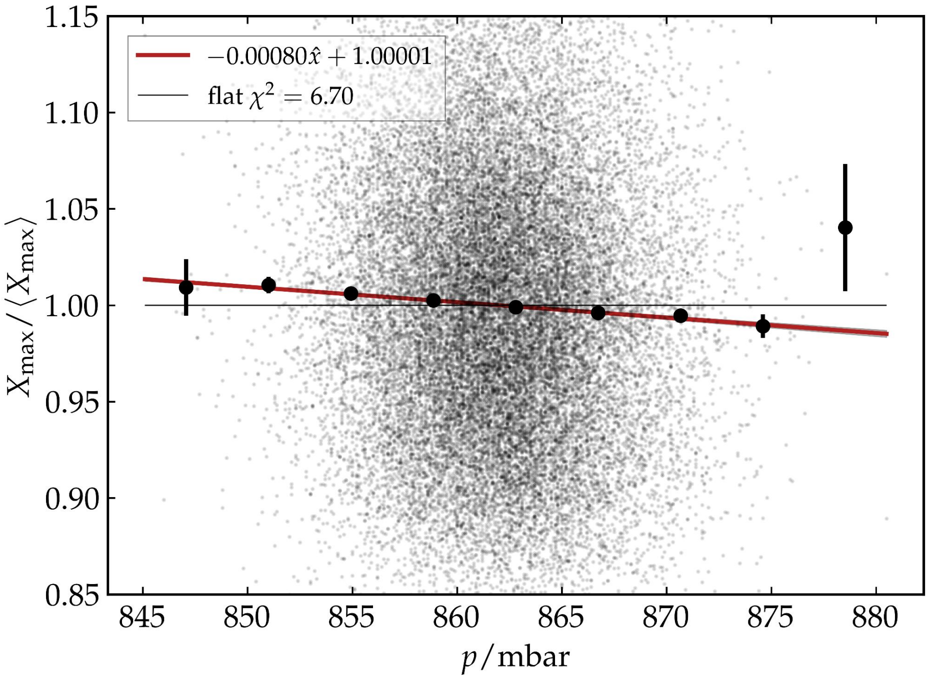
$$a = \sqrt{a_h^2 + b_h^2} \qquad w_h := \frac{2\pi}{24\,\mathrm{h}}$$



Checking for dependence: solar hour

Solution

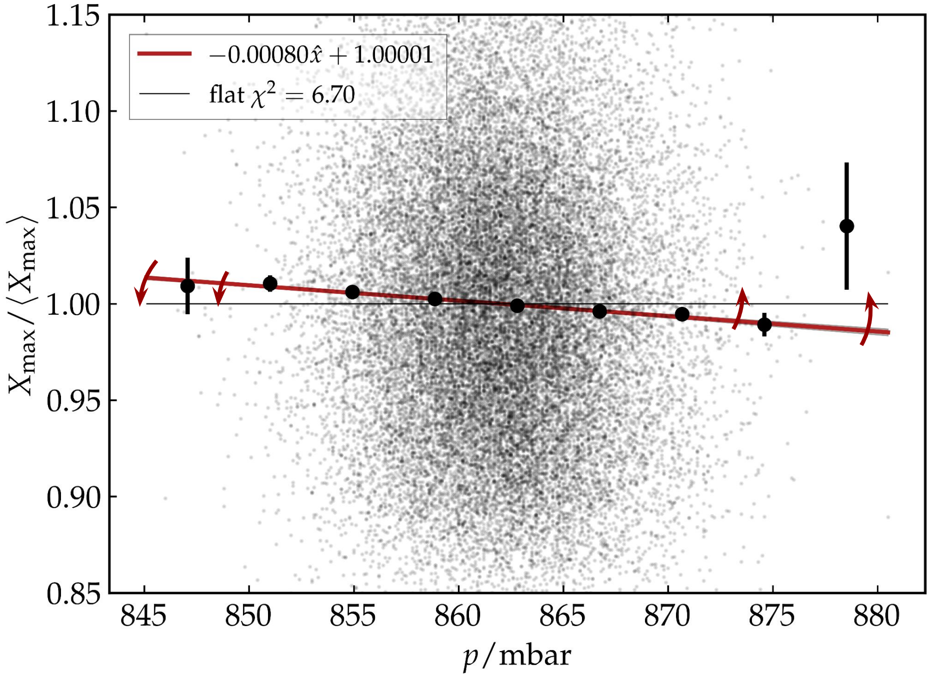
- $X_{\mathbf{max}}$ reconstruction is **dependent on the atmospheric condition** around the detectors



Checking for dependence: solar hour

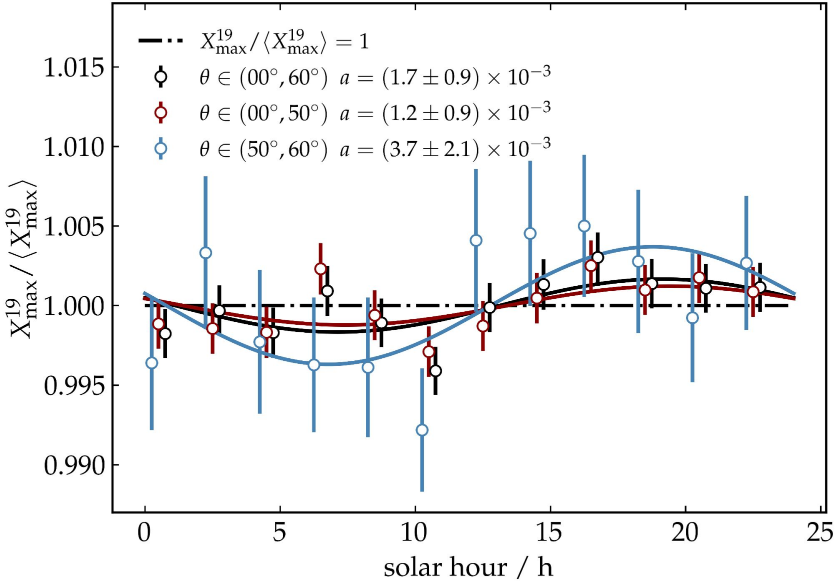
Solution

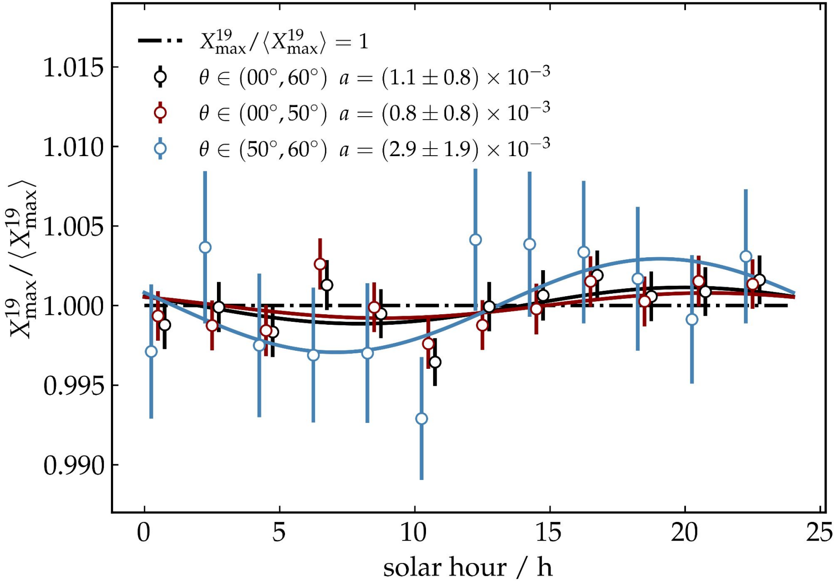
- $X_{\mathbf{max}}$ reconstruction is **dependent on the atmospheric condition** around the detectors
- We define a **correction dependent on the atmospheric pressure**
- correction leaves the **average** X_{max} value **unchanged**



Checking for dependence: solar hour

Before pressure correction → **After pressure correction**

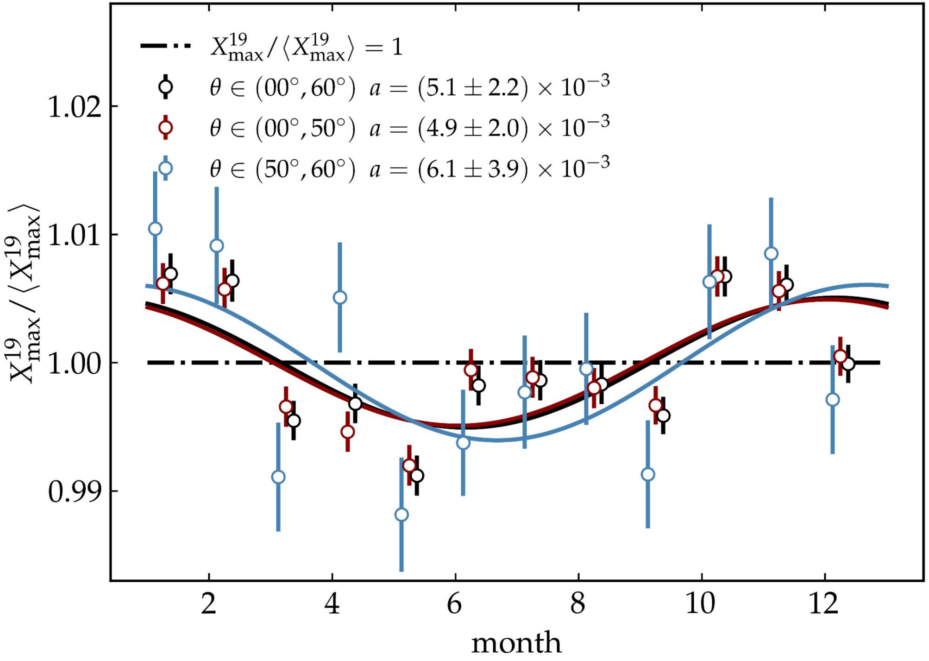




Checking for dependence: season

Presence of a **modulation** as a function of the **time of the year**

All the **seasonal dependences** should **average out**



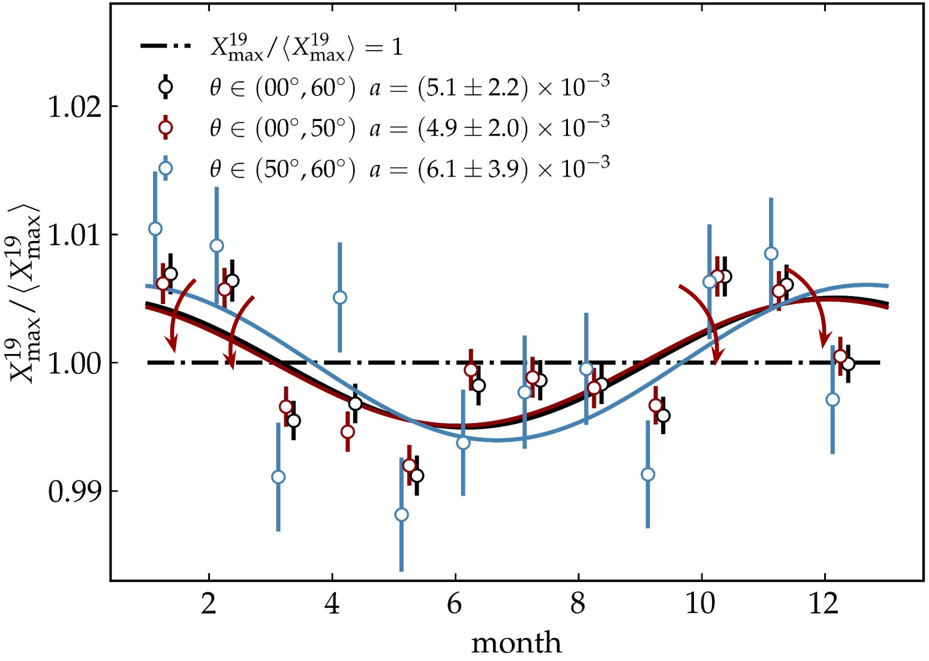
Checking for dependence: season

Presence of a **modulation** as a function of the **time of the year**

All the **seasonal dependences** should **average out**

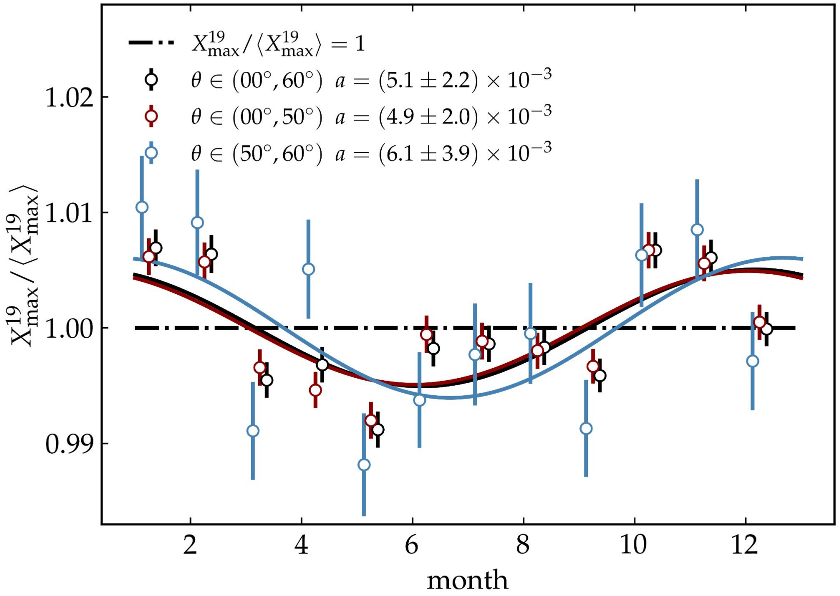
Solution

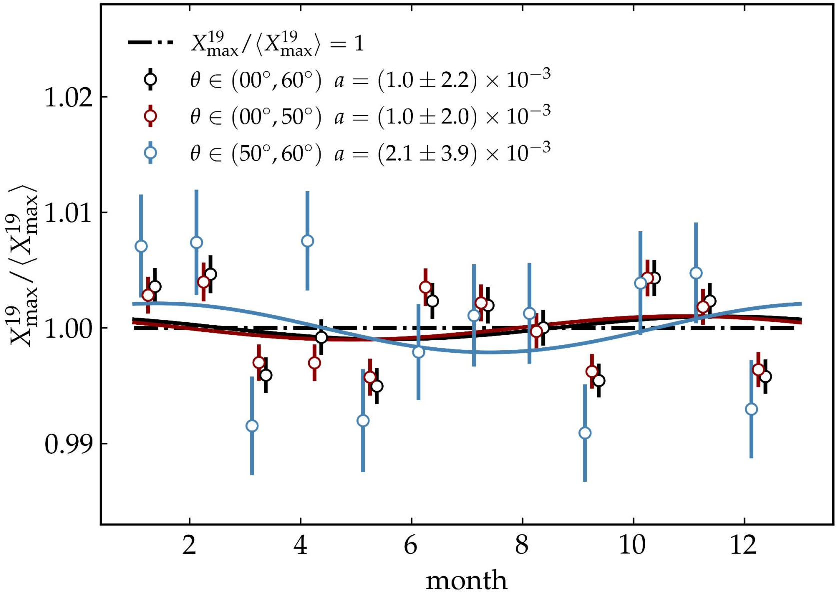
- We define a **deleting the seasonal modulation**
- correction leaves the **average X_{max} value unchanged**



Checking for dependence: season

Before seasonal correction → **After seasonal correction**





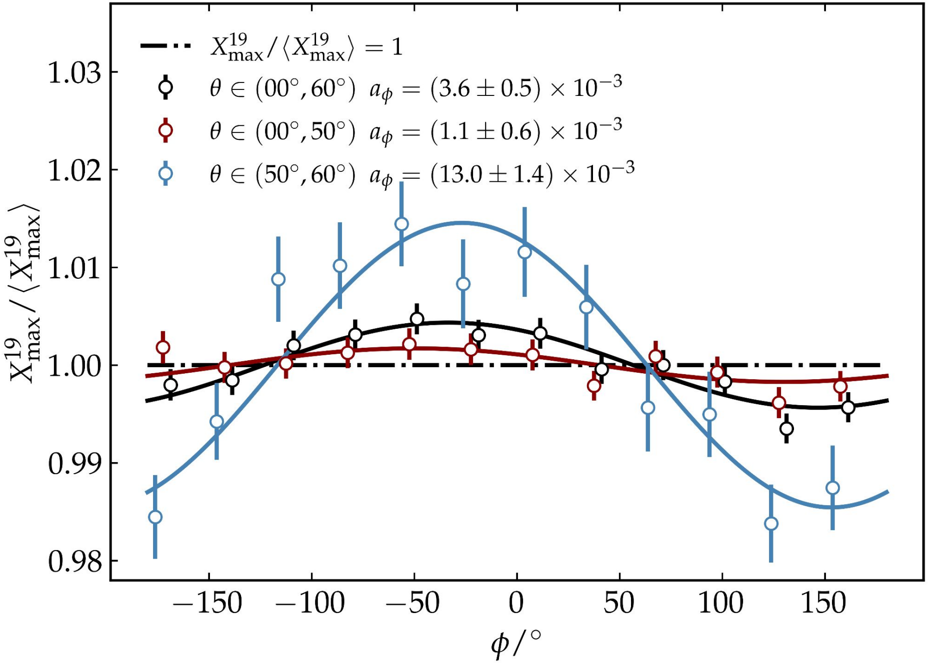
Checking for dependence: azimuth angle

Presence of a **modulation** as a function of the **azimuth angle**

non negligible contribution in the **East-West** direction

Due to the Earth rotation all the **physical dependence** in this direction should **average out**

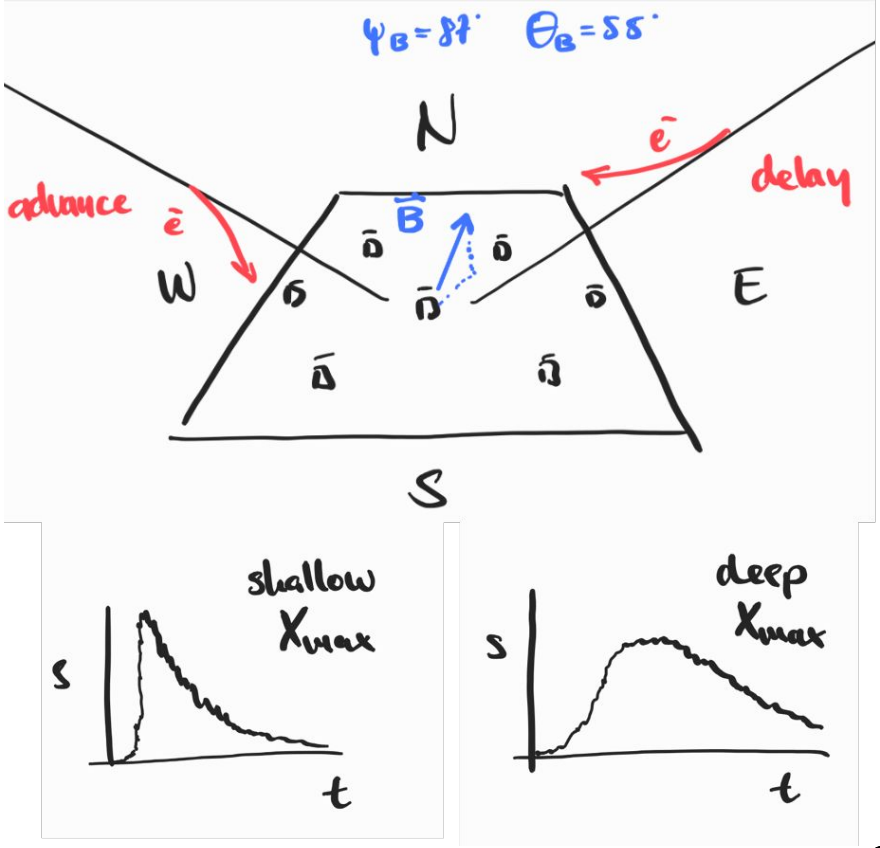
$$\frac{X_{\mathrm{max}}^{19}}{\langle X_{\mathrm{max}}^{19} \rangle} = a_\phi \cos(\phi) + b_\phi \sin(\phi)$$



Checking for dependence: azimuth angle

Solution

- Modulation due to the **displacement of the electrons** in the shower front due to the Earth magnetic field
- Extensive Air Showers have a **larger amount of electrons**, due to the positron annihilation with atomic electrons
- Electrons arriving in **delay** (advance) produce a **deeper** (shallower) X_{max}



Checking for dependence: azimuth angle

Solution

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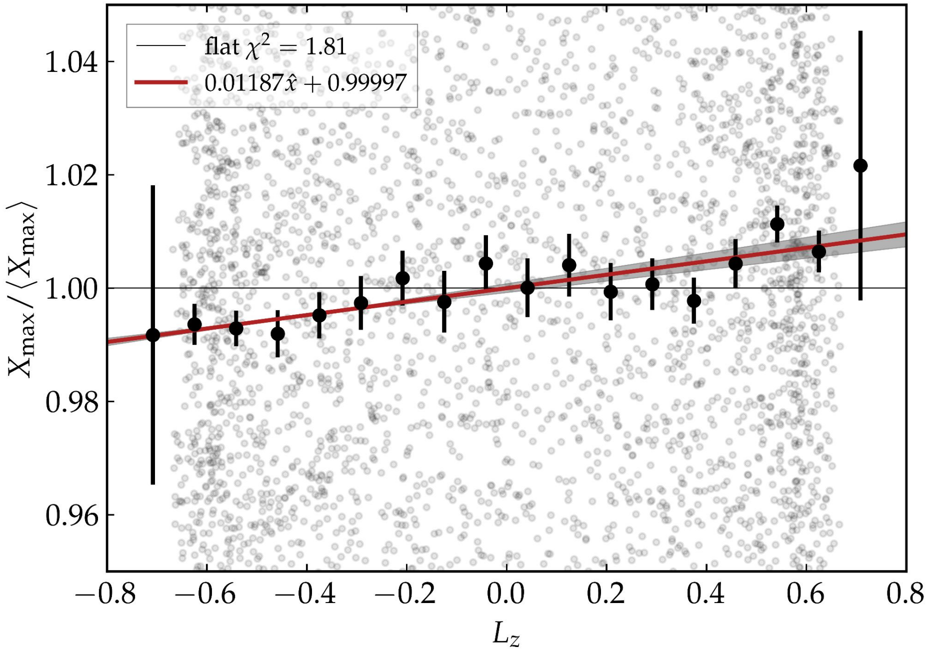
- Extensive Air Showers have a **larger amount of electrons**, due to the positron annihilation with atomic electrons
- Electrons arriving in **delay** (advance) produce a **deeper** (shallower) X_{max}
- **Dependence** of X_{max} on the **vertical component of the Lorentz vector** to be corrected



Checking for dependence: azimuth angle

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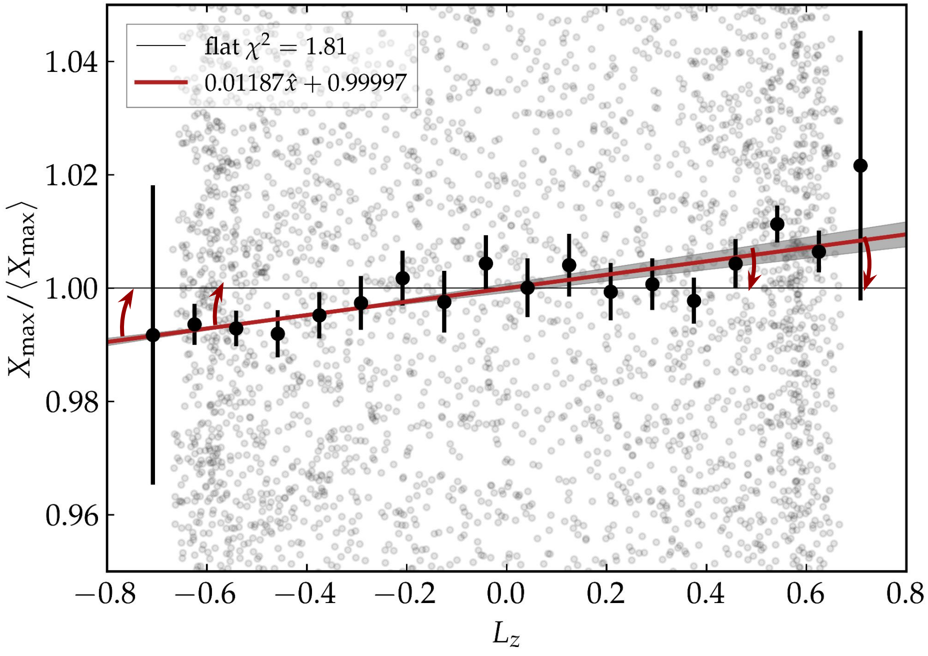
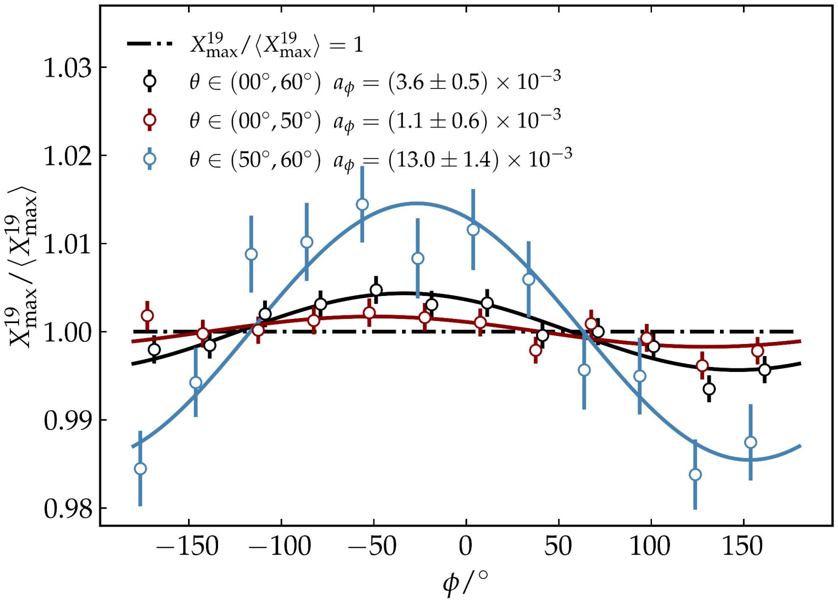
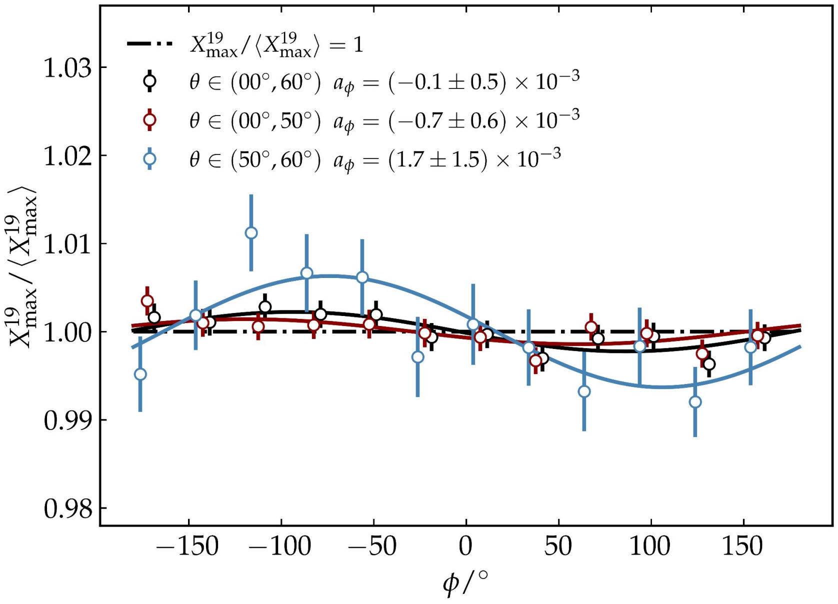


Checking for dependence: azimuth angle

Before geomagnetic correction → **After geomagnetic correction**



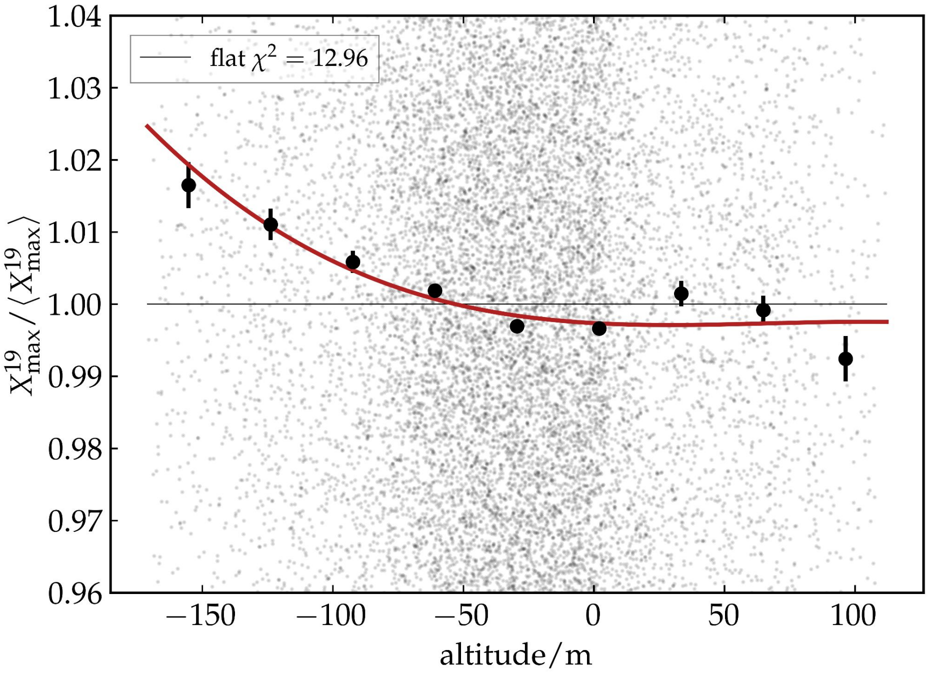


Checking for dependence: altitude

The Pierre Auger Observatory **area is not completely flat**, the minimum altitude is ~ 1330 m.a.s.l, while the maximum is ~ 1620 m.a.s.l.

The **depth of the atmosphere** above the Observatory **changes with the altitude**

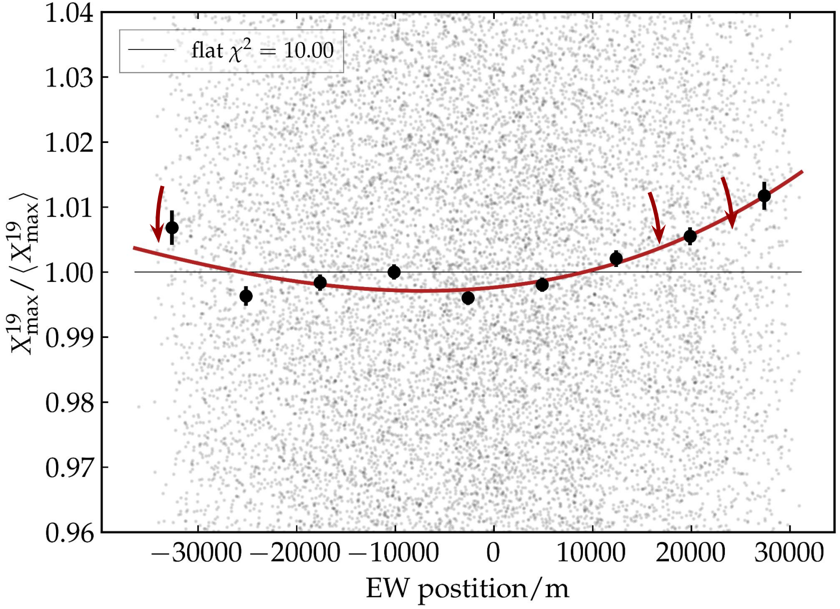
The reconstructed $X_{\mathbf{max}}$ **has to be corrected** to ensure that there is **not a dependence on the position**

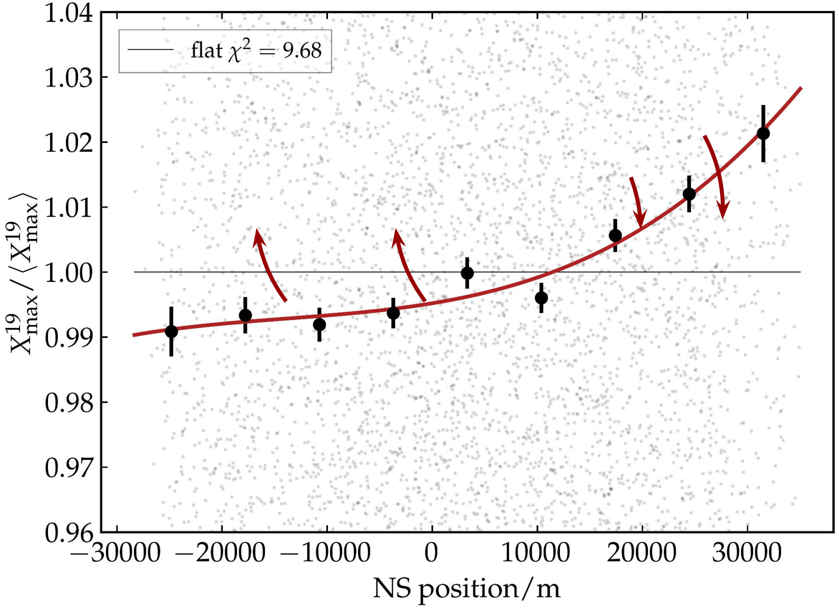


Checking for dependence: altitude

Solution

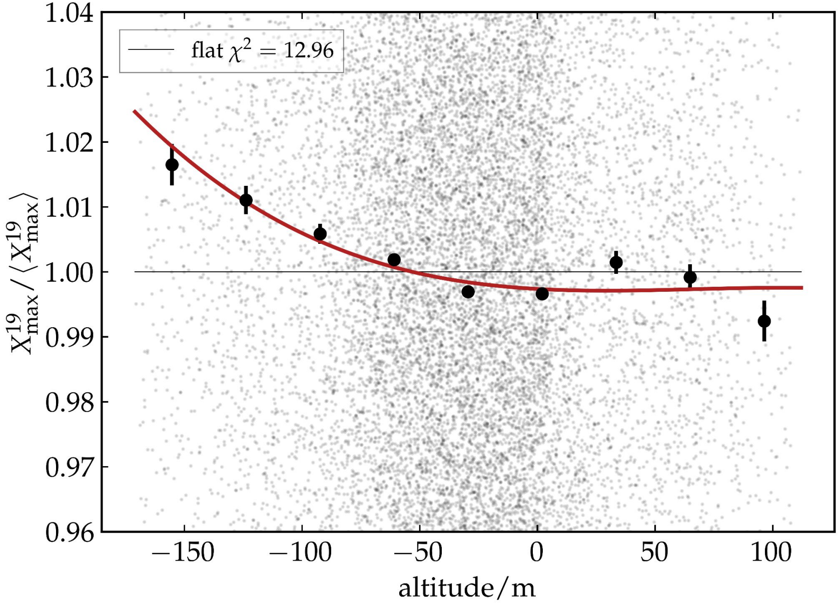
- As the **height** of the event core is **determined by its position in the array**
- we assure a **flatness in the position** dependence of X_{max}

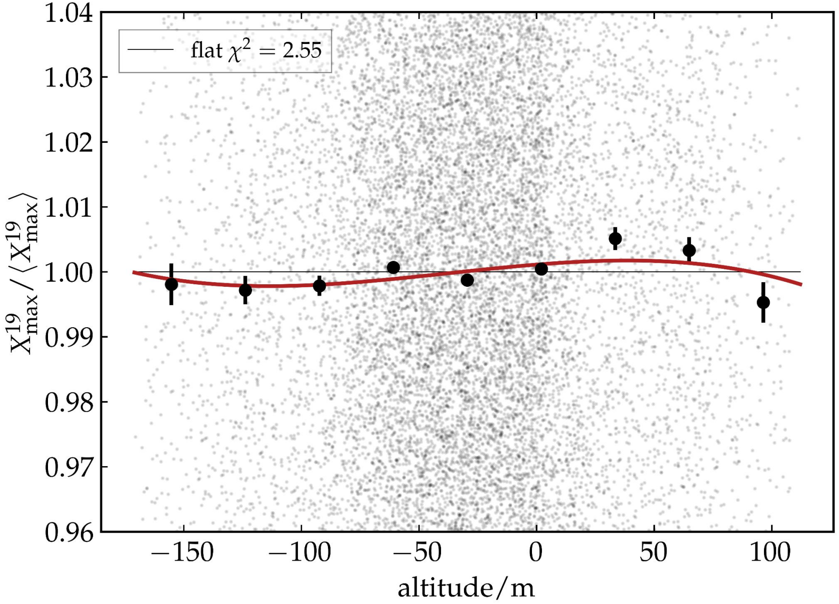




Checking for dependence: altitude

Before position correction → **After position correction**

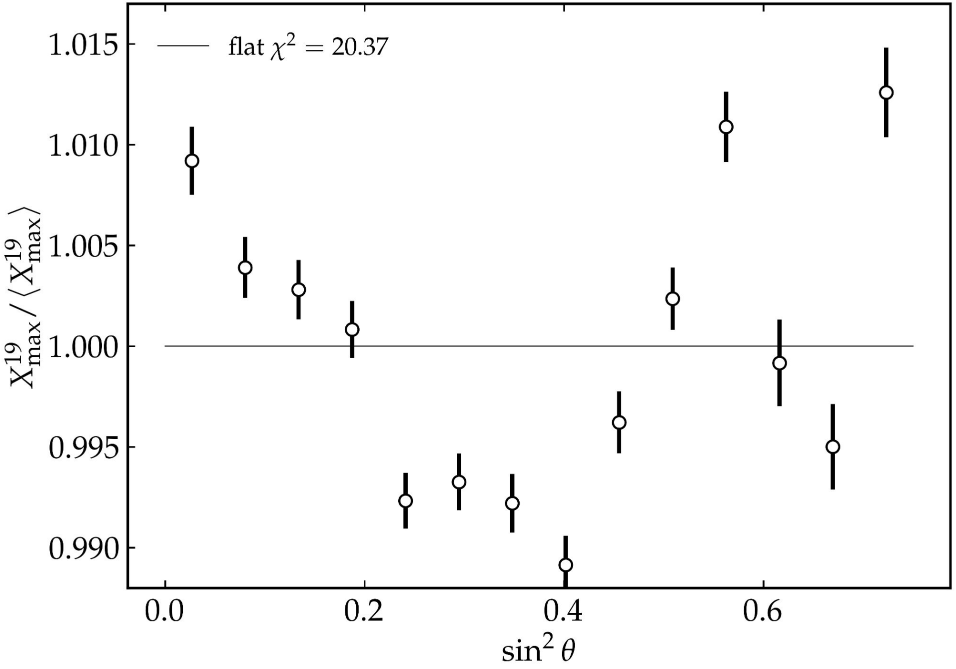




Checking for dependence: zenith angle

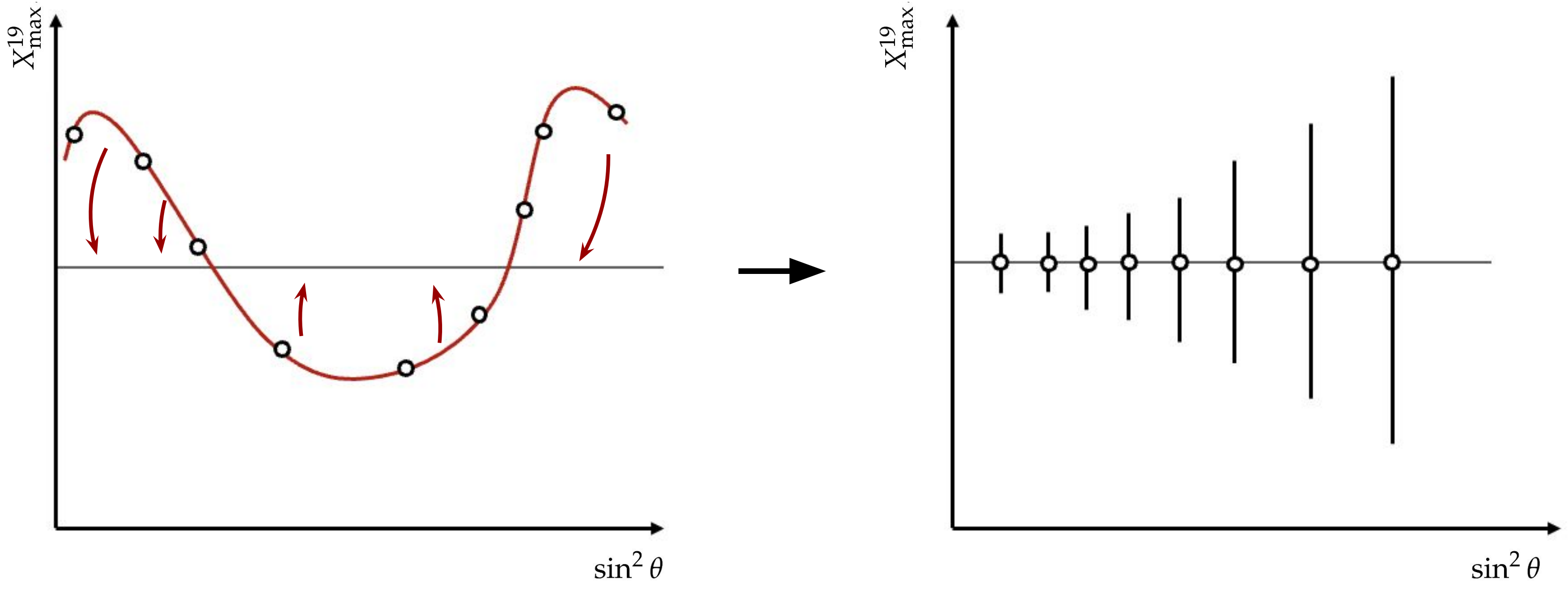
The reconstructed X_{max} has a **dependence on the zenith angle**

As the **arrival directions** are d**ependent on zenith angle**, we have to ensure that both the **average** and the **width** of the distribution of X_{max} are approximately **flat in sin²(θ)**



Checking for dependence: zenith angle

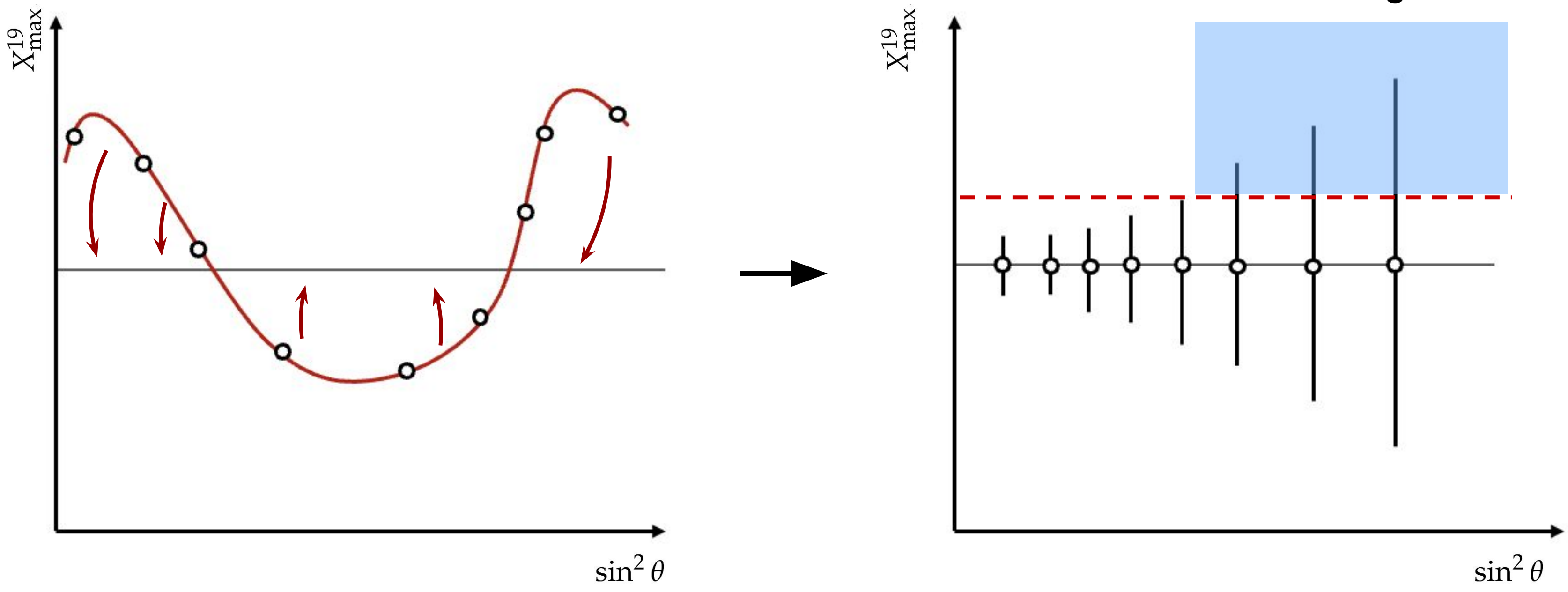
Solution



Checking for dependence: zenith angle

Solution

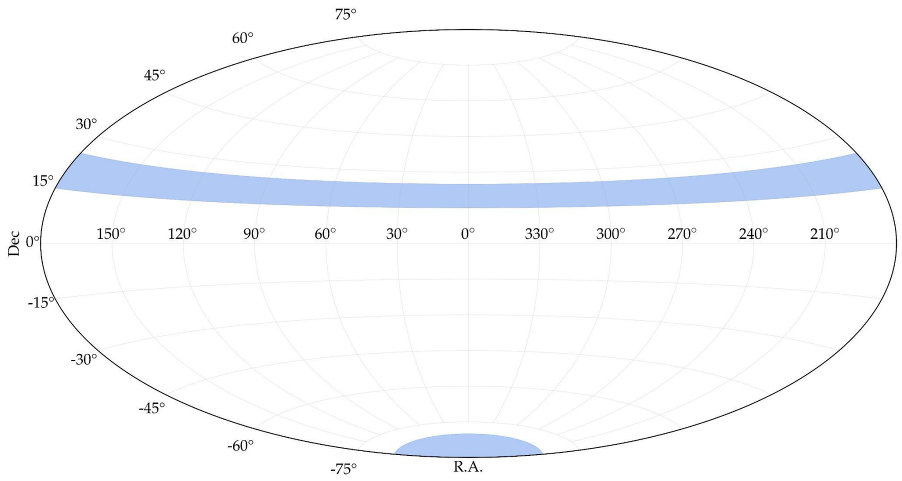
more events selected at larger zenith angles



Checking for dependence: zenith angle

Solution

regions where AD are generated only by the over selected zenith angles will be more populated



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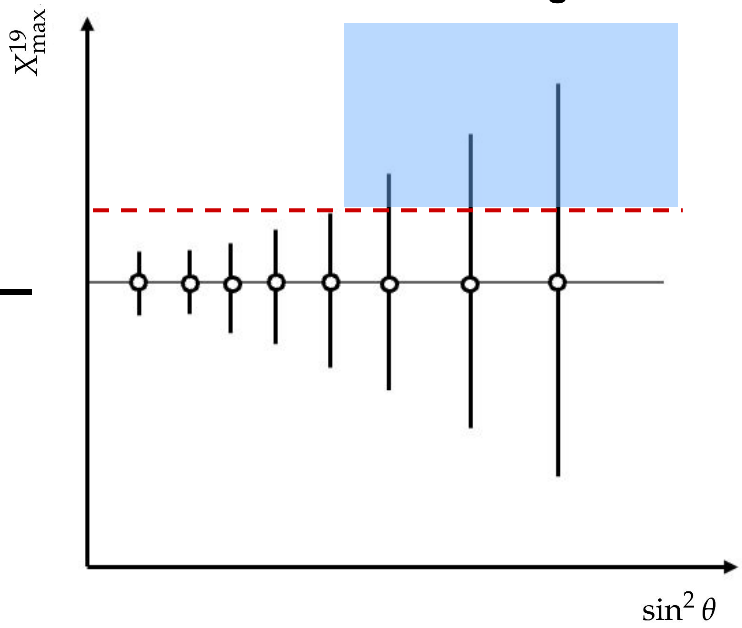

Checking for dependence: zenith angle

Solution

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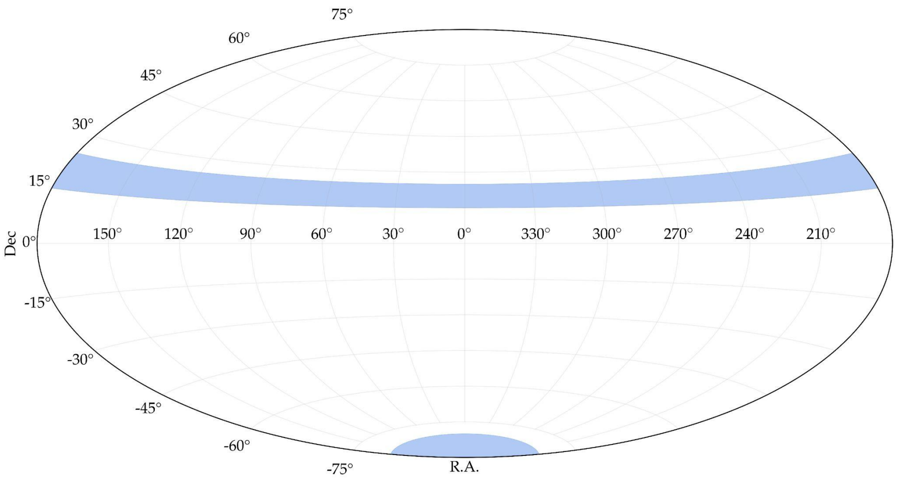

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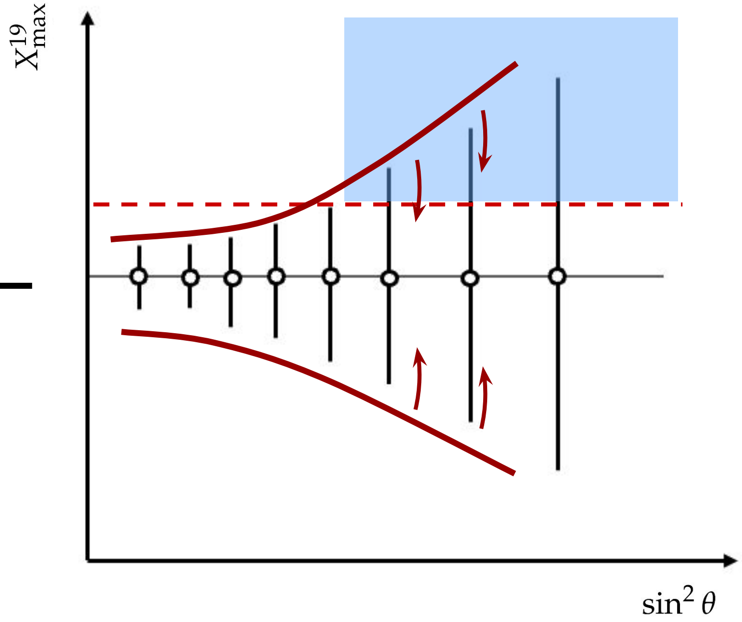
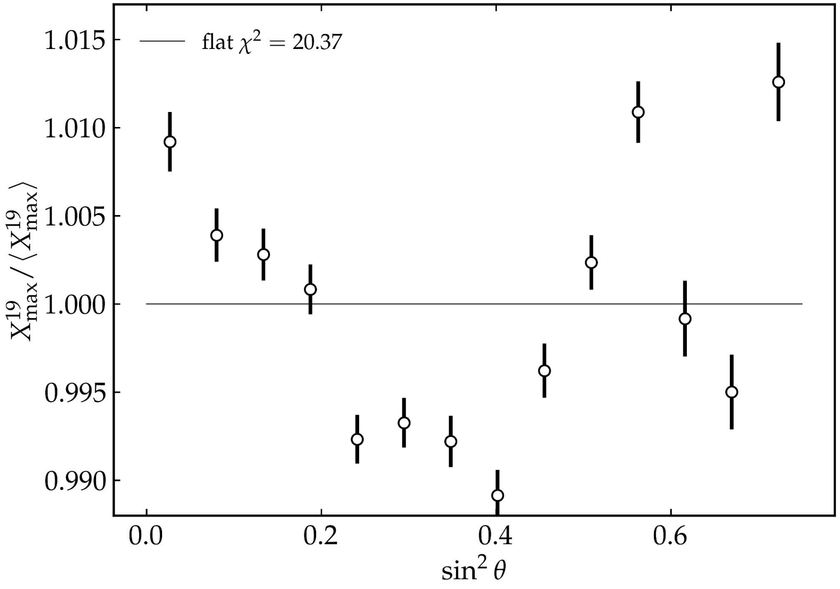
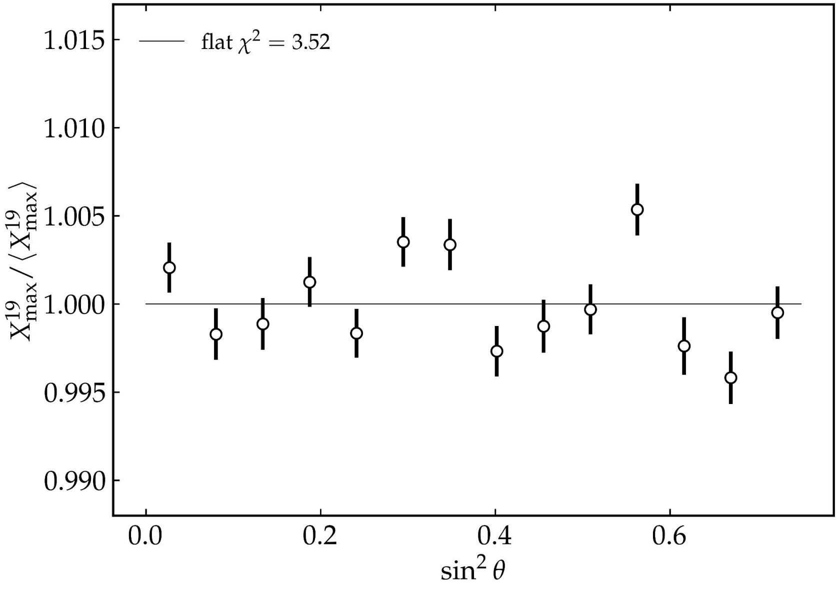


Checking for dependence: zenith angle

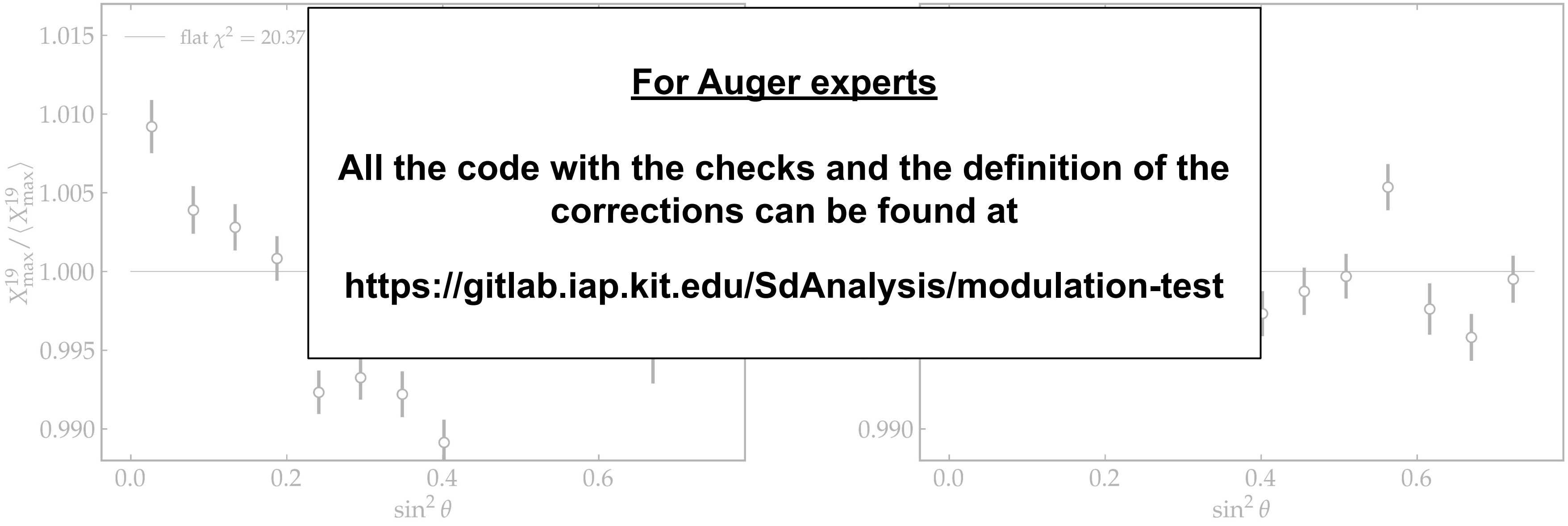
Before zenith correction → **After zenith correction**





Checking for dependence: zenith angle

Before zenith correction → After zenith correction



For Auger experts

All the code with the checks and the definition of the corrections can be found at

https://gitlab.iap.kit.edu/SdAnalysis/modulation-test

CAN WE GO TO DATA NOW???

CAN WE GO TO DATA NOW???

NOT YET!

Centaurus A

Targeted analysis around **Centaurus A**

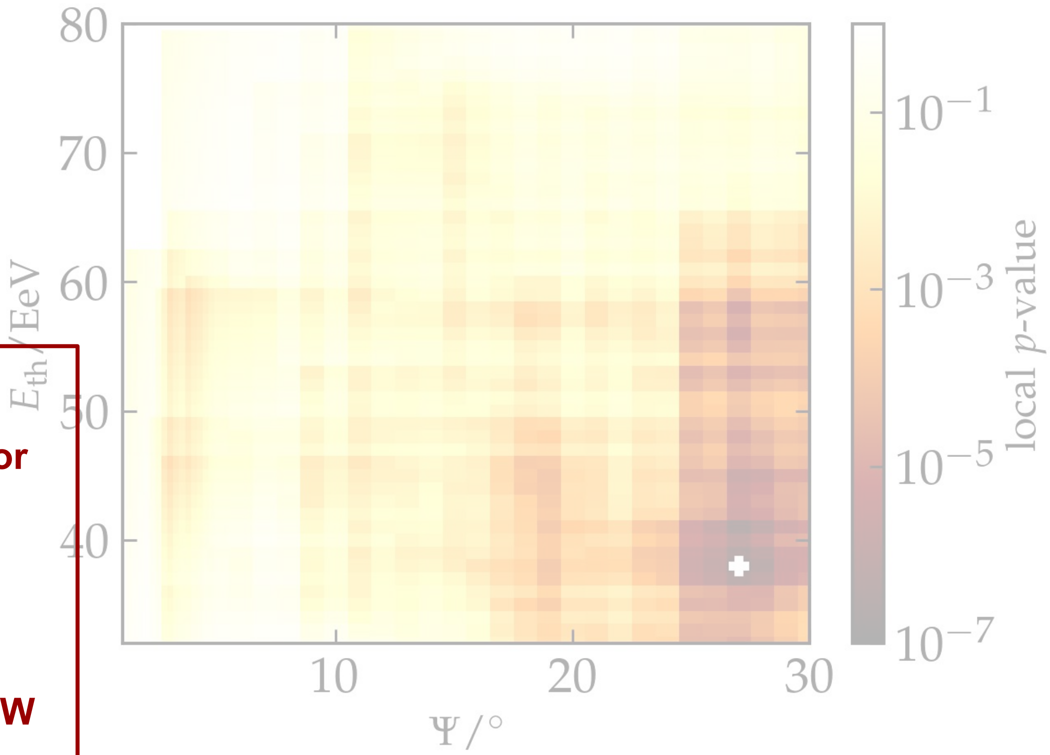
- **Scan in threshold energy** (E_{th}): from 32 to 80 EeV
- Scan in top hat radius (ψ_{th}): from 1° to 30°

pre-trial *p*-value = $2.16 \cdot 10^{-7}$ (**5.08σ one-sided**)
E_{th} = 38 EeV
ψ_{th} = 27°

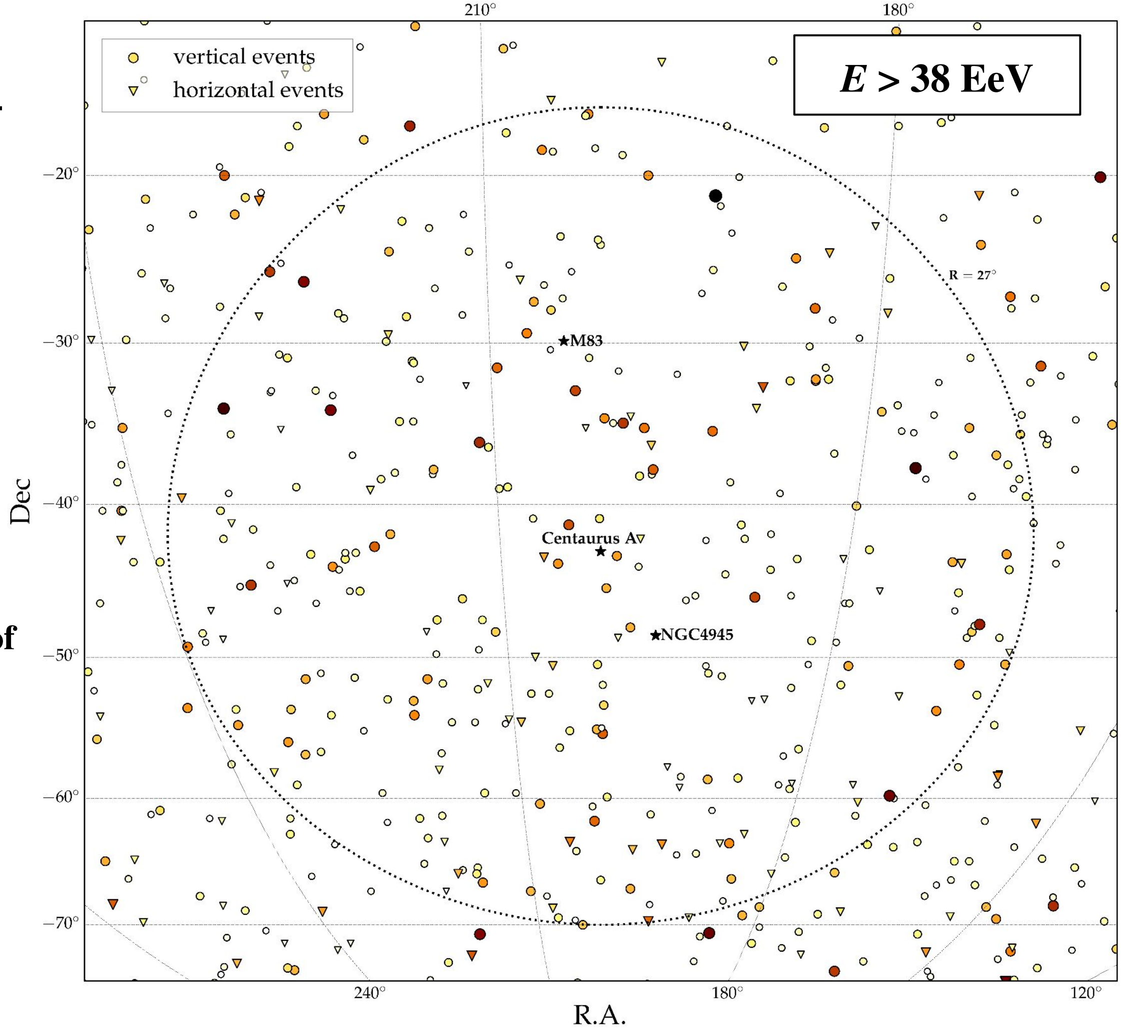
huge penalization factor we have to try to not enhance it anymore

post-trial *p*-value = $6.4 \cdot 10^{-5}$ (**4.0σ one-sided**)

DEFINE A WORKFLOW STRATEGY!



Centaurus A



vertical events

- zenith angle < 60°
- Reconstruct X_{max} with **universality**

discard a fraction (δ) of low-rigidity vertical events and see if they correlate more with Centaurus A

inclined events

- zenith angle > 60°
- **universality** does **not** reconstruct mass-dependent parameters for **horizontal events**

do not discard any horizontal event

how to discard?

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!

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

hadron multiplicity parameter from Heitler-Matthews model

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

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

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

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

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!

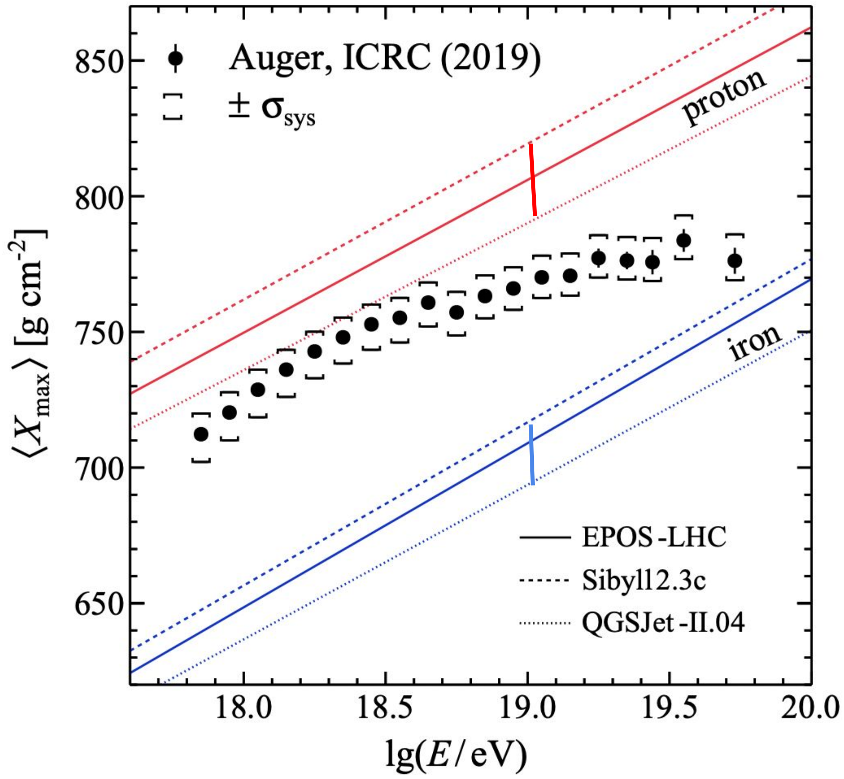
Proton scale

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

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

The charge-like parameter is obtained converting Xmax to a mass-scale, and then to a charge-scale

$$X_{\max}^{19} \longrightarrow A \longrightarrow Z$$



Proton scale

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

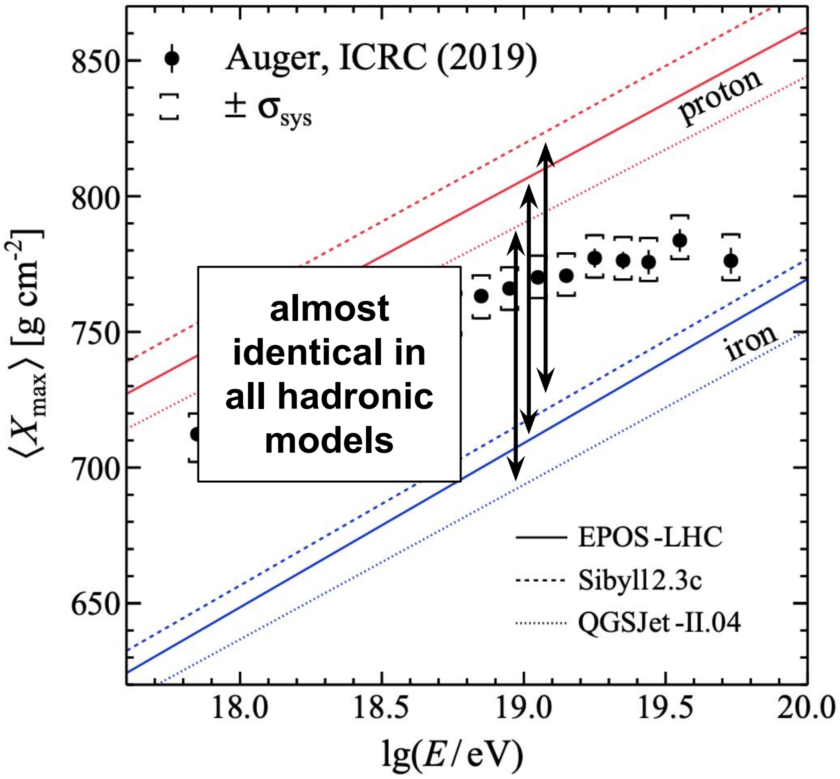
$$\widetilde{R} := E_0/\widetilde{Z}$$

The charge-like parameter is obtained converting Xmax to a mass-scale, and then to a charge-scale

$$X_{\max}^{19} \longrightarrow A \longrightarrow Z$$

$$X_{\max}^{19} \longrightarrow \widetilde{A} = \alpha A \longrightarrow \widetilde{Z} = \frac{\widetilde{A}}{2}$$

As we are interested only in the ordering, we move from a $X_{\max}$ scale to a charge scale without assuming any hadronic interaction model



Proton scale

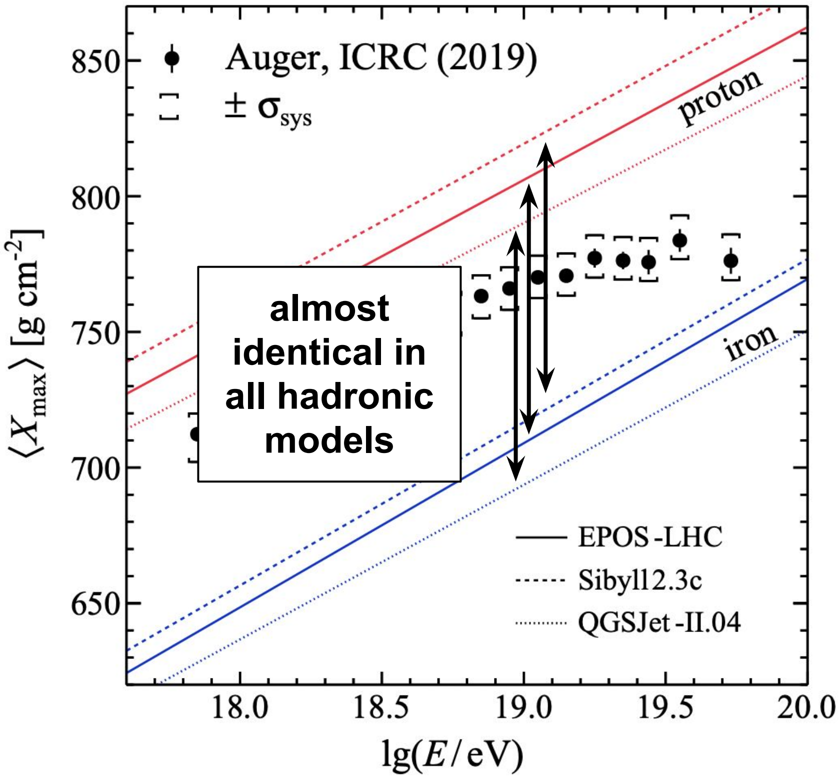
$$1/\widetilde{Z} := 2\exp\left((X^{19}_{\max} - X_{\mathrm{ref}})/\lambda\right)$$

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

$$\boxed{X^{19}_{\max} \qquad \widetilde{A} = \alpha A \qquad \widetilde{Z} = \frac{\widetilde{A}}{2}}$$

- Z = A/2 is not true for protons
- to not assign a specific value of A to the events we are forced to allow protons half their real charge

- **<u>imposing a threshold value to A, over which we impose Z = A = 1 would be assigning mass to the particles, thus imposing an hadronic interaction model</u>**



IS $\tilde{R}$ A GOOD PARAMETER FOR OUR PURPOSE???

Does it have some dependences?

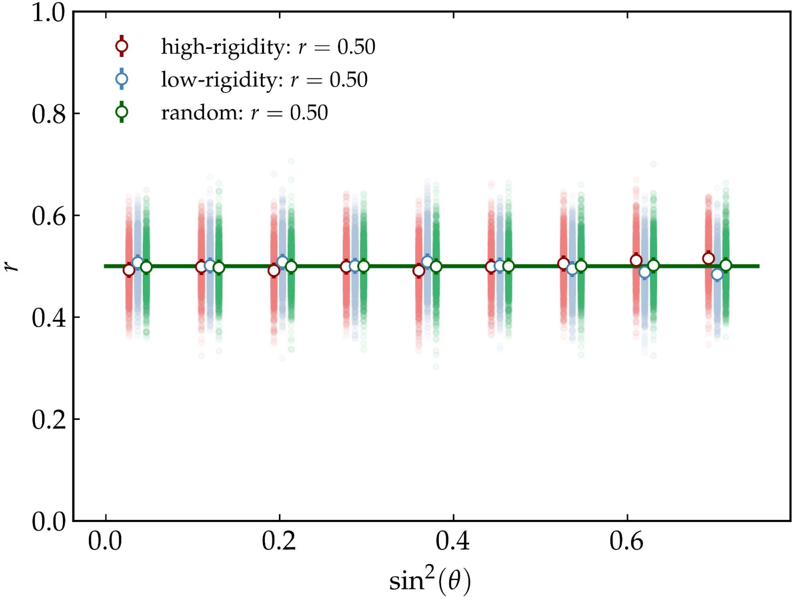
To check if there are possible dependences we performed a set of isotropic simulations of mixed-compositions

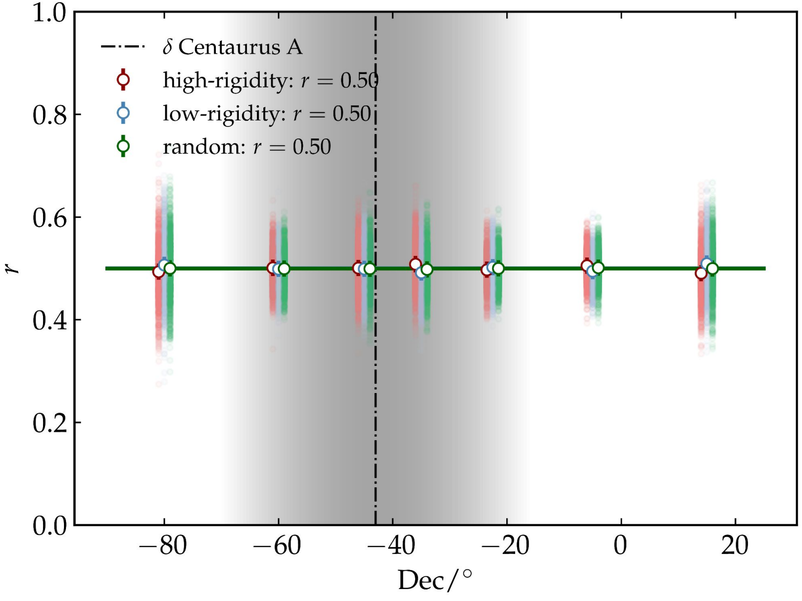
- simulations have 1000 events, roughly the **same number of vertical events** as the one observed **above 38 EeV** (energy threshold of the Centaurus excess)
- simulations have **mixed composition** (25% p, 25% He, 25% O, 25% Fe)
- simulations are **flat in $\sin^2(\theta)$**
- X_{max} are selected from a library of events reconstructed with universality, with energy above 38 EeV, **according to mass and zenith angle**
- a **random utc time**, between the beginning and the end of Phase I, and a r**andom azimuth angle**, between 0° and 360°, are selected for each event, assuring the generation of a **isotropic skies**

Does it have some dependences?

Dependences on rate

- complete **simulations on mixed composition** (p, He, O, Fe), select 50% high-rigidity (low-rigidity) events and compare them with random selections
- check if the **rate** of selected events (r) has some **dependences** on **zenith angle or declination**

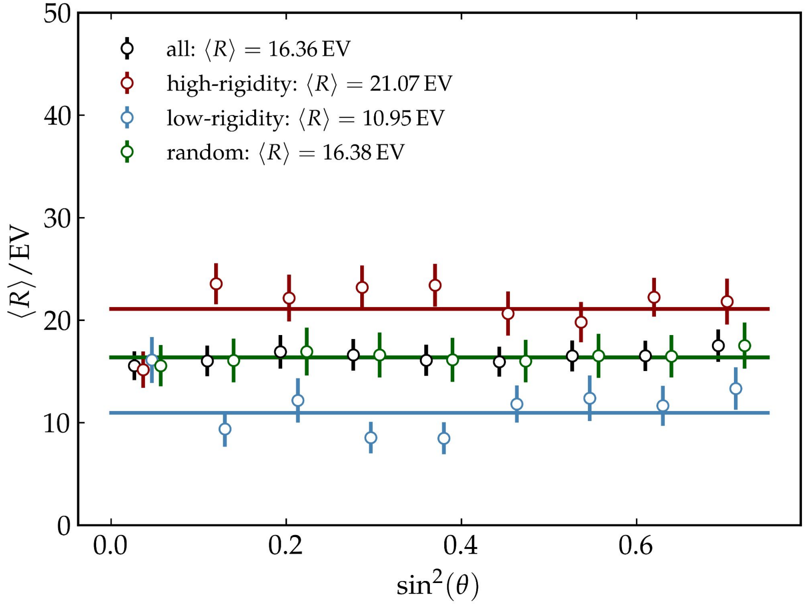


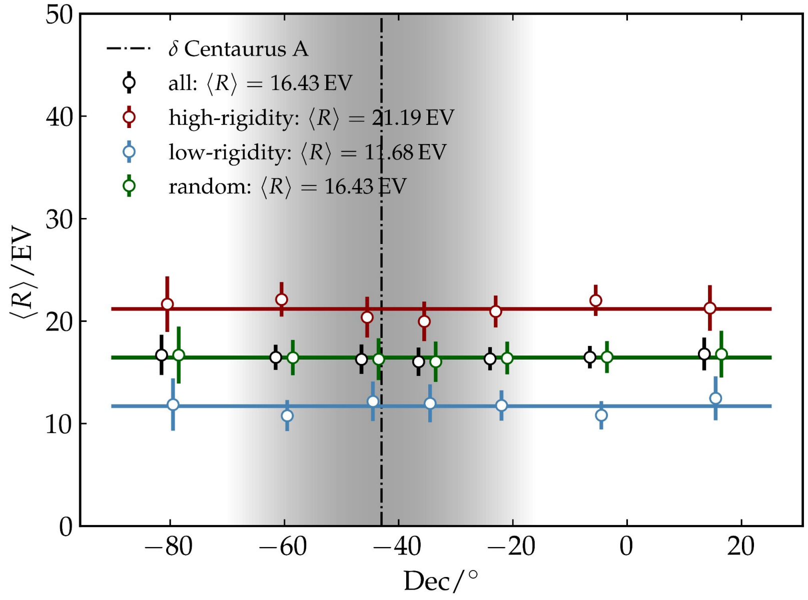


Is it good at recovering the rigidity?

Rigidity recovery

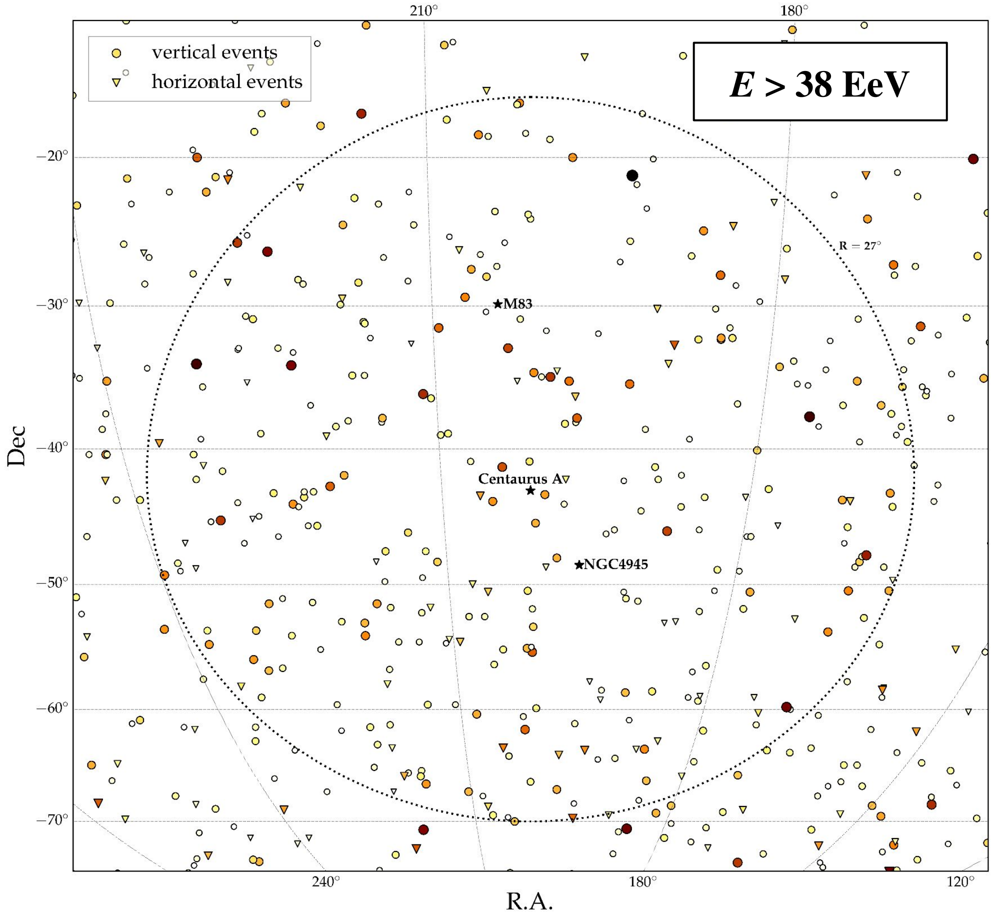
- complete **simulations on mixed composition** (p, He, O, Fe), select 50% high-rigidity (low-rigidity) events and compare them with random selections
- check if the **rigidity of selected events** (R) has some **dependences** on **zenith angle or declination**





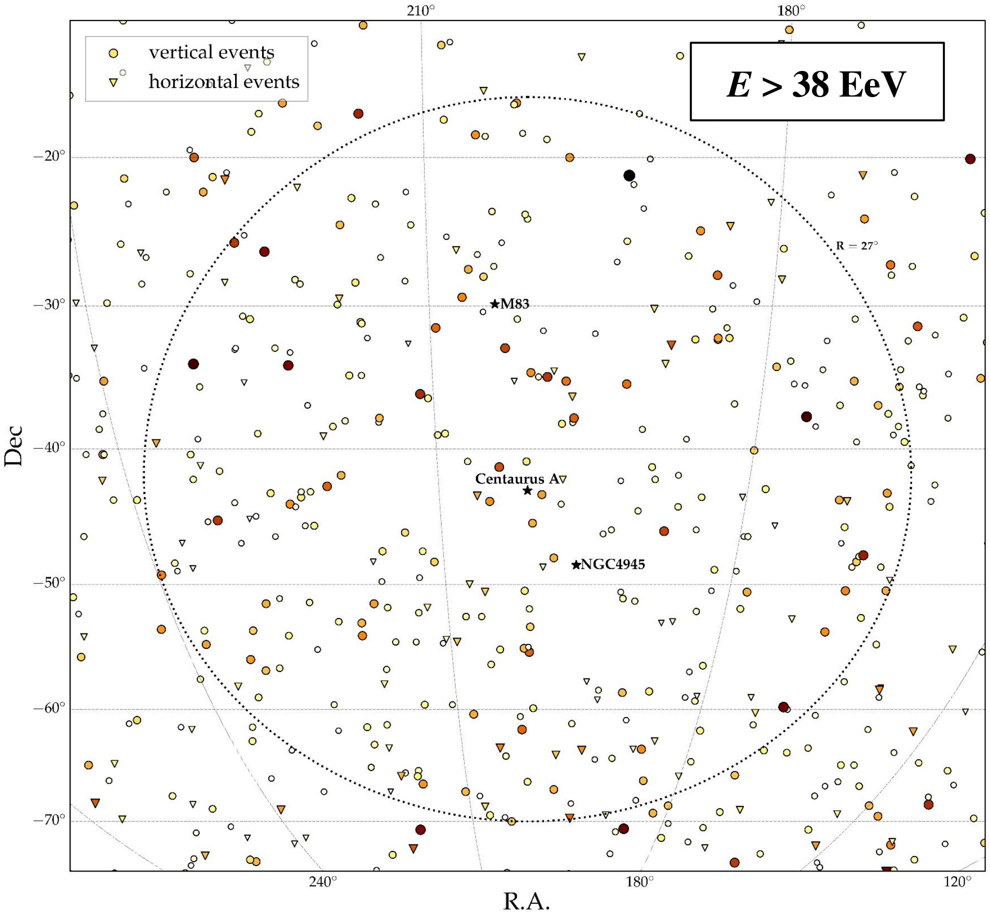
Can we enhance a signal by using it?

Can we enhance a signal by using it?



hypothesis: excess in Centaurus region is formed by high-rigidity events

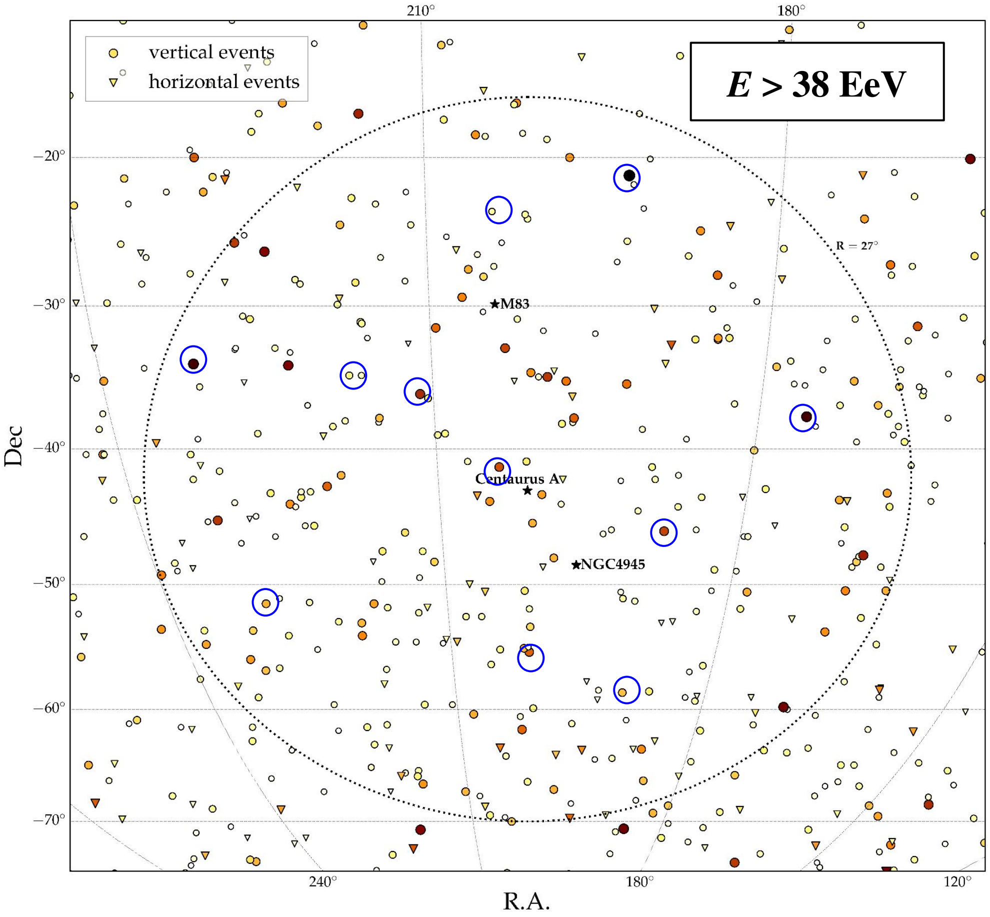
Can we enhance a signal by using it?



hypothesis: excess in Centaurus region is formed by high-rigidity events

- suppose a **signal** (high-rigidity) and **background** (low-rigidity) population

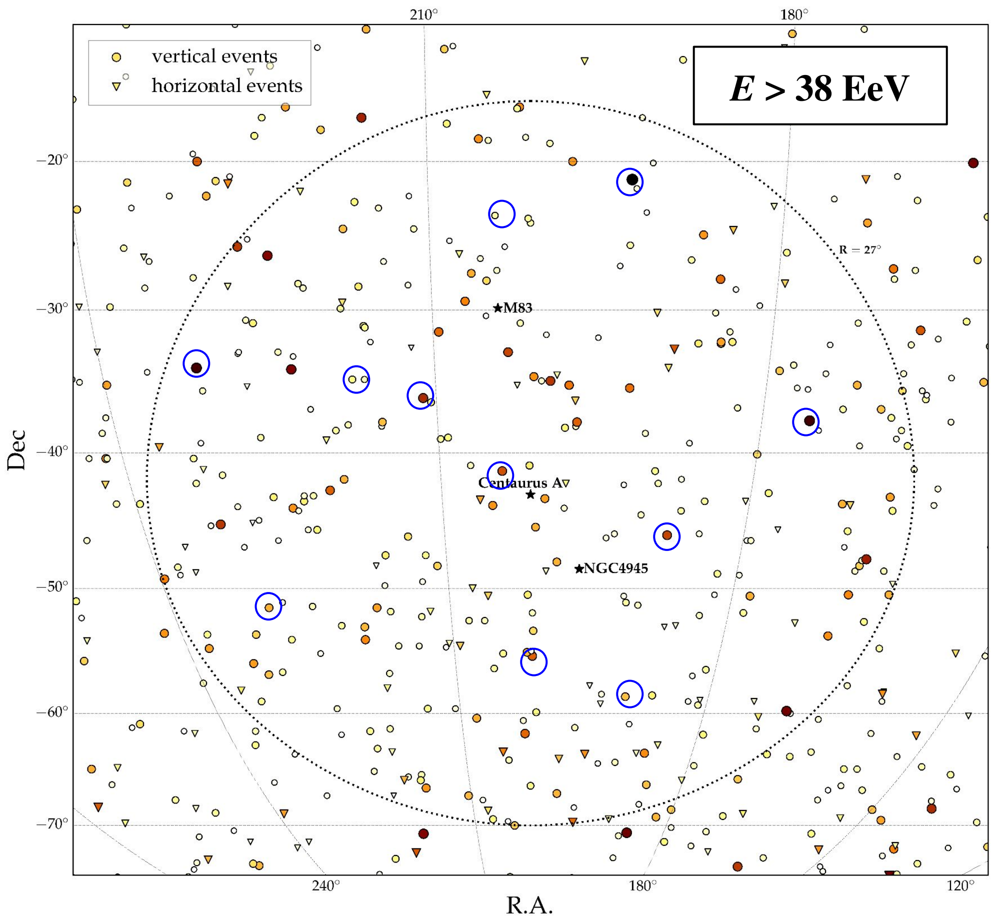
Can we enhance a signal by using it?



hypothesis: <u>excess in Centaurus region is formed by high-rigidity events</u>

- suppose a **signal** (high-rigidity) and **background** (low-rigidity) population
- select a **fraction of signal events** among all the vertical events in Centaurus region, and **randomly select vertical events to be signal** assigning a mass accordingly

Can we enhance a signal by using it?



hypothesis: <u>excess in Centaurus region is formed by high-rigidity events</u>

- suppose a **signal** (high-rigidity) and **background** (low-rigidity) population
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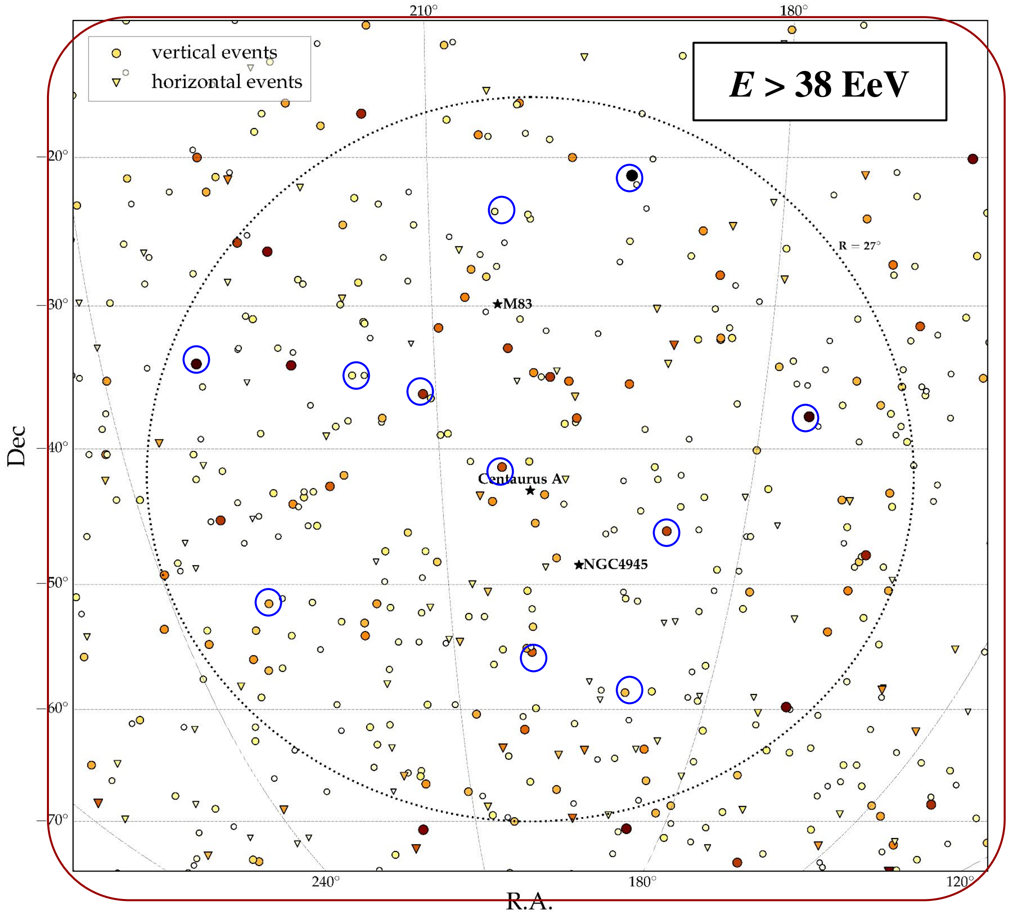
- assign a **reconstructed $X_{\mathbf{max}}$** from a Universality simulated library according to the selected mass

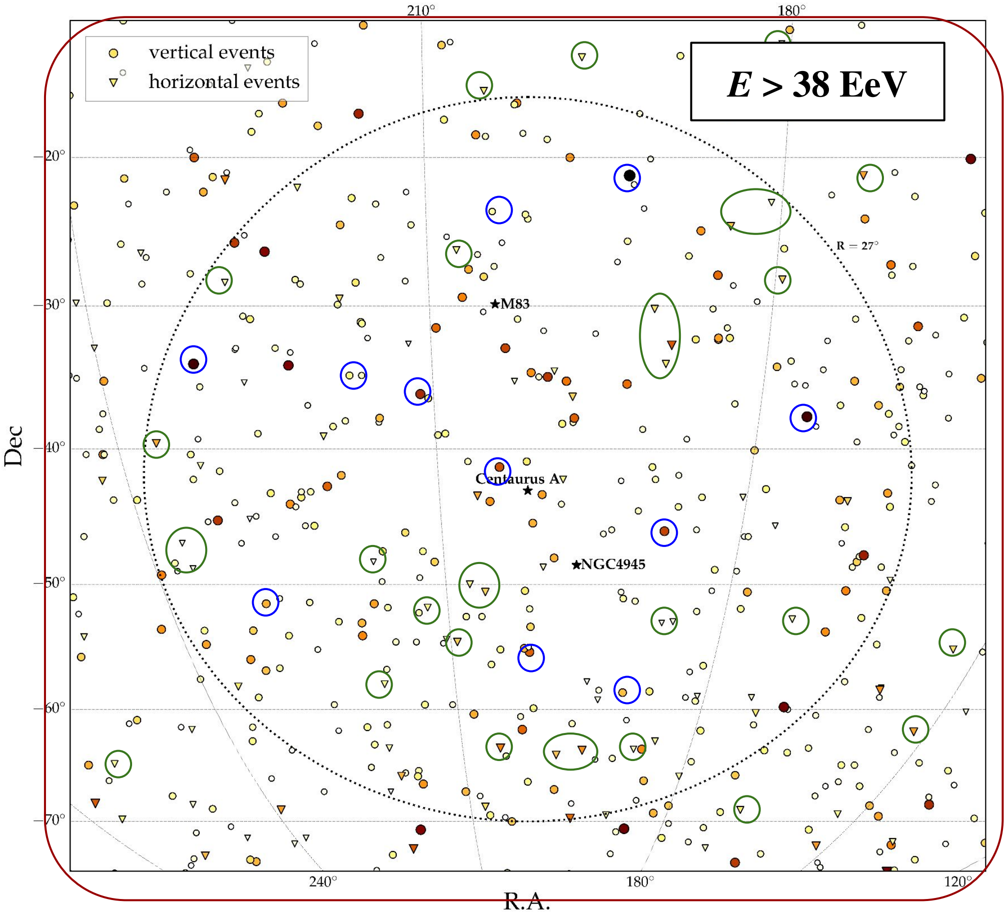
Can we enhance a signal by using it?



hypothesis: excess in Centaurus region is formed by high-rigidity events

- suppose a **signal** (high-rigidity) and **background** (low-rigidity) population
- select a **fraction of signal events** among all the vertical events in Centaurus region, and **randomly select vertical events to be signal** assigning a mass accordingly
- assign a **reconstructed $X_{\mathbf{max}}$** from a Universality simulated library according to the selected mass
- assign a **simulated mass** and a **reconstructed $X_{\mathbf{max}}$** to all the **other vertical events** (both inside and outside the Centaurus region) according to the **background** population

Can we enhance a signal by using it?



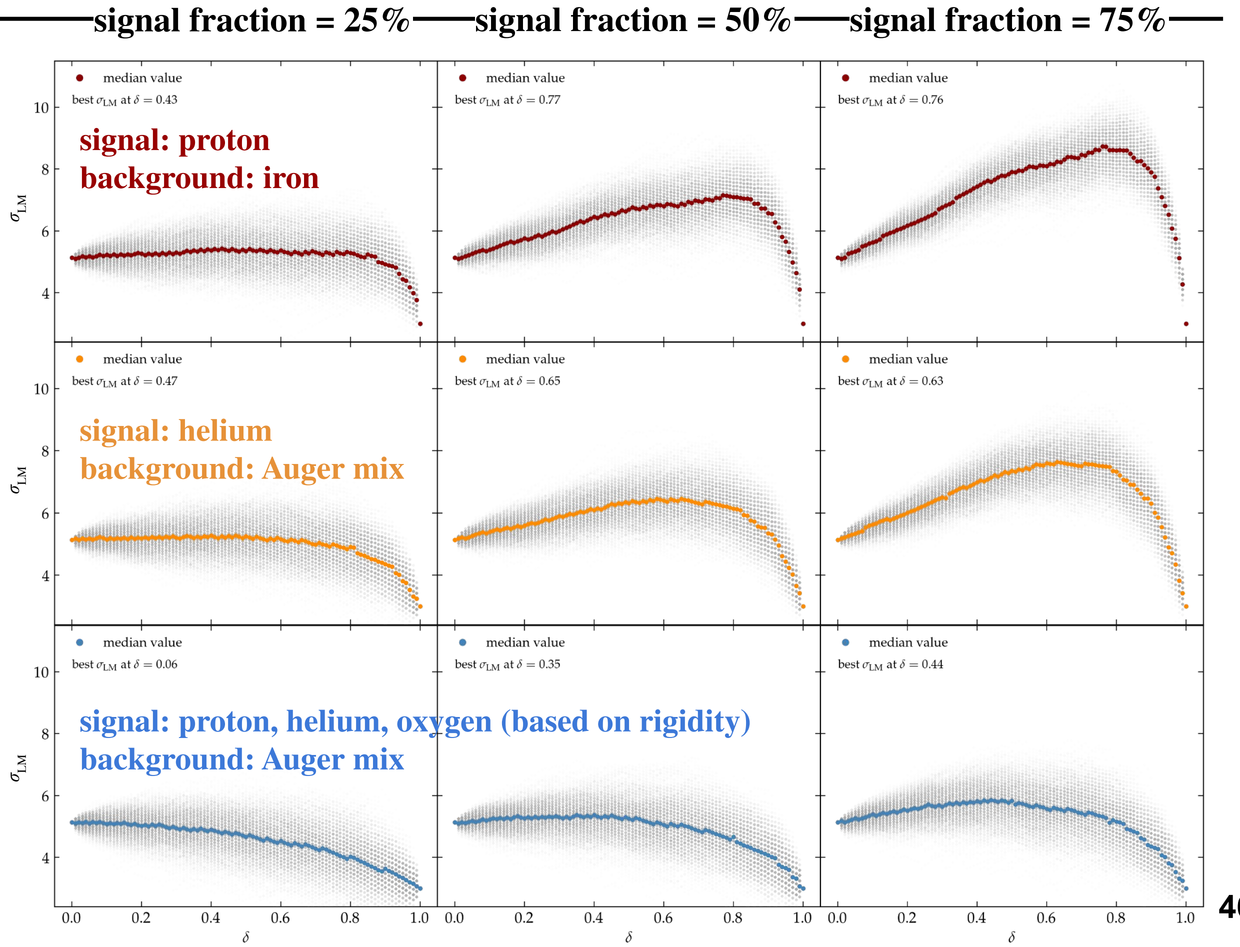
hypothesis: excess in Centaurus region is formed by high-rigidity events

- suppose a **signal** (high-rigidity) and **background** (low-rigidity) population
- select a **fraction of signal events** among all the vertical events in Centaurus region, and **randomly select vertical events to be signal** assigning a mass accordingly
- assign a **reconstructed $X_{\mathbf{max}}$** from a Universality simulated library according to the selected mass
- assign a **simulated mass** and a r**econstructed $X_{\mathbf{max}}$** to all the **other vertical events** (both inside and outside the Centaurus region) according to the **background** population
- **do not assign** a mass or X_{max} to the **inclined events**

Can we enhance a signal by using it?

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**



Can we enhance a signal by using it?

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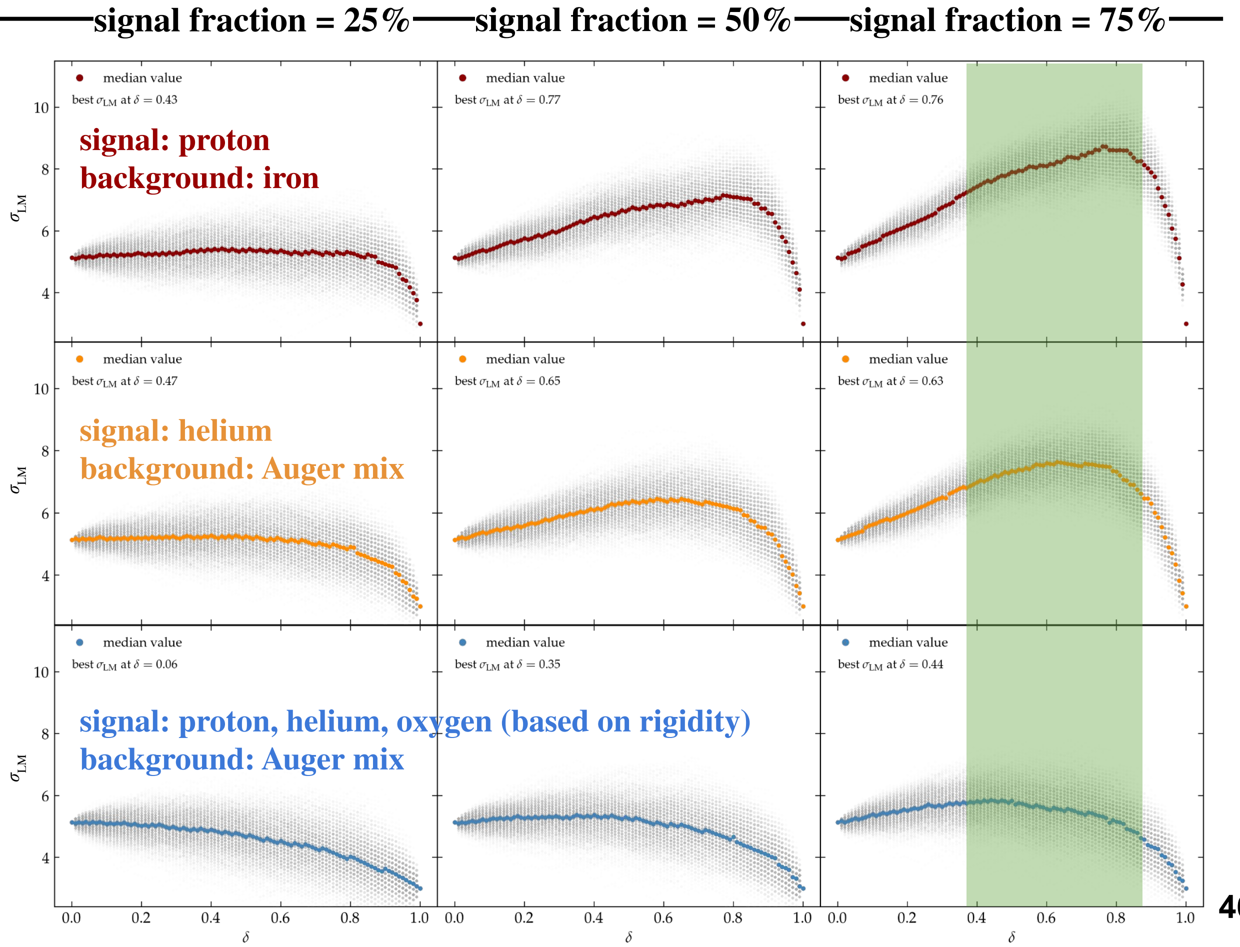


And the penalization factor?

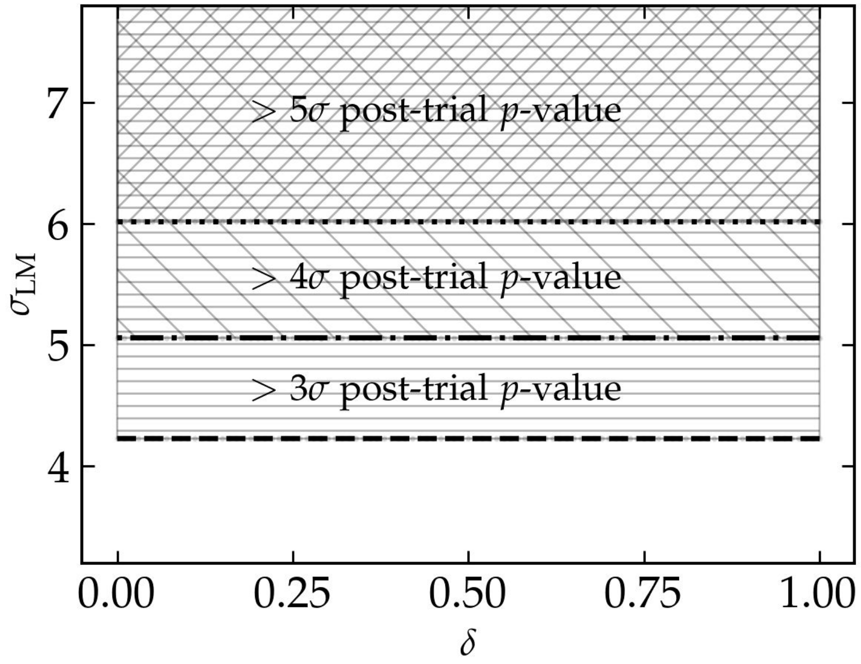
Penalization factor is not dependent on the fraction of events discarded

- ~6σ of Li-Ma significance are required to surpass the post-trial discovery threshold
- ~5σ of Li-Ma significance are required to surpass the 4σ post-trial threshold (similar to what happened in previous analysis)

Analysis strategy

→ <u>We can discard 50% of low rigidity events as first trial</u>

→ <u>If a signal is not enhanced discarding 50% we can perform a scan in fraction of events discarded, from 10% to 90% in step of 10%</u>



CAN WE GO TO DATA NOW???

CAN WE GO TO DATA NOW???

NOW YES!

Conclusion and outlook

UHECR deflections are determined by their **rigidities**, identifying the **mass** of the recorded events can help us in **finding the least deflected particles**
In **arrival direction** studies, **mass estimators** able to act on the **SD data** are required

- using **universality** in combination with **Phase I data** of the Pierre Auger Observatory, we are limited to the $X_{\mathbf{max}}$ **information**
- with **Phase II** we will be able to have a **better muon information reconstruction** and perform a more consistent rigidity determination

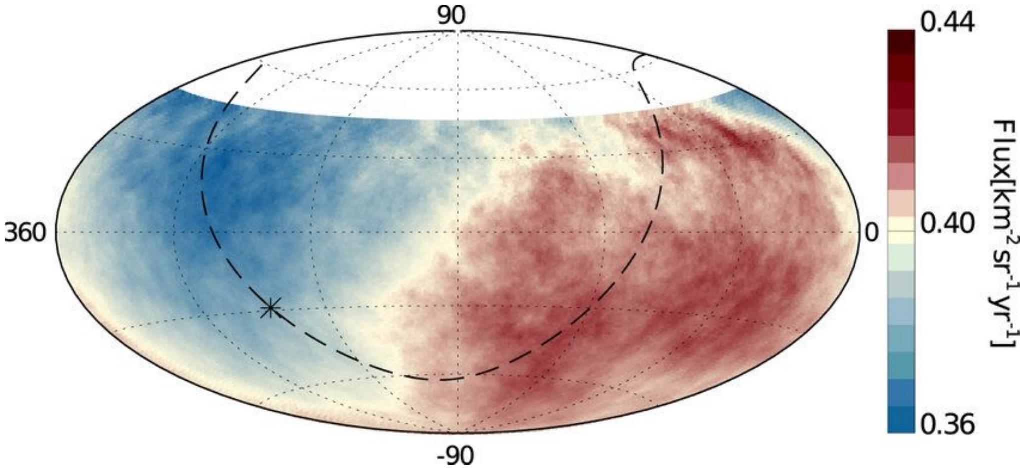
An exhaustive **work on** the presence of possible **unphysical dependences** is required
Possible problematic dependences for Arrival Direction studies are

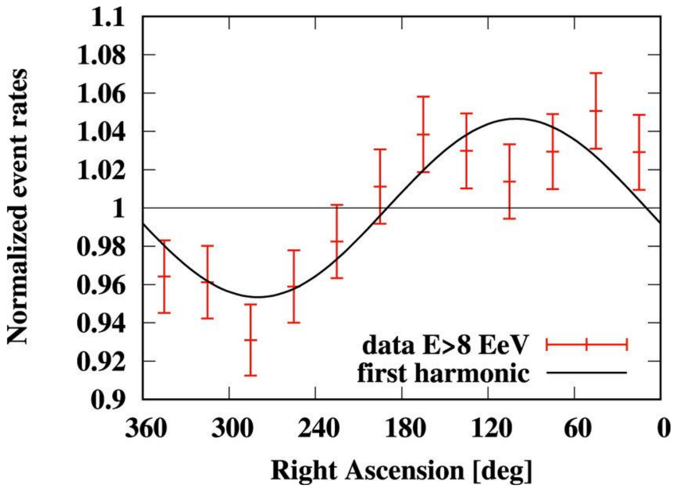
- *solar hour*
- *time of the year*
- *azimuth angle*
- *zenith angle*

It is mandatory to **not enhance the penalization factor** in small-scale Arrival Direction studies
In the **Centaurus A** analysis we expect that **discarding a consistent fraction of low-rigidity (50%)** events we are able to **enhance** a high-rigidity **signal** present in the region

BACKUP

Large-scale anisotropies





Correlation with catalogs

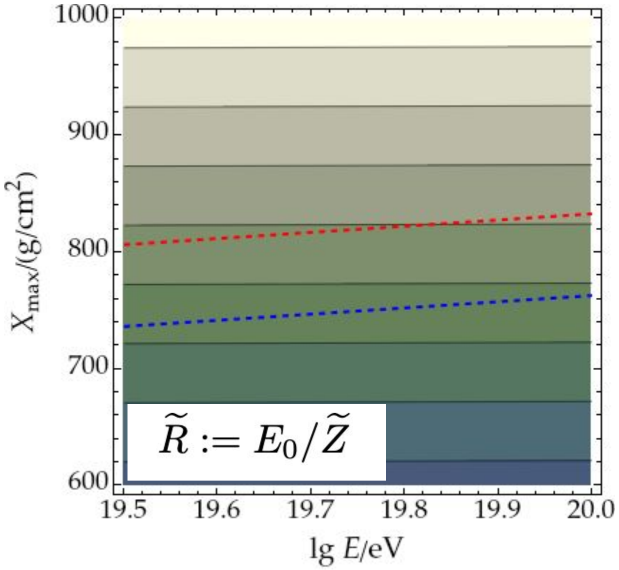
Parameters space: Fisher search radius θ and the signal fraction; scan in E_{th} in [32, 80] EeV, steps of 1 EeV

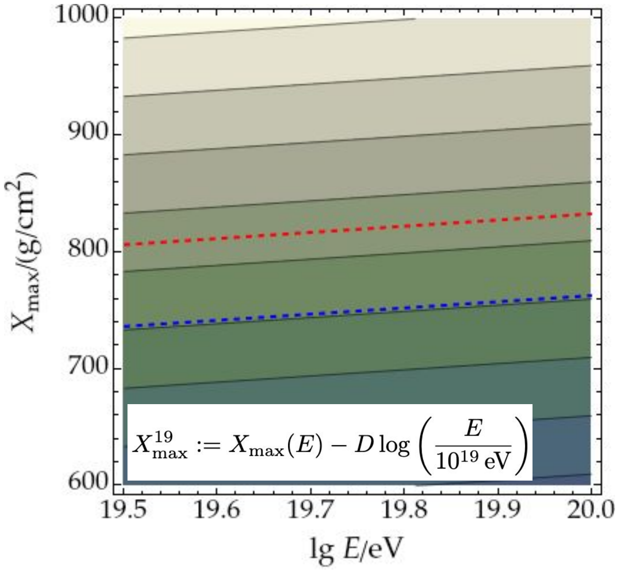
Catalogs (and their fux proxy):

- all galaxies (IR) from 2MRS (K-band)
- starbursts (radio) based on Lunardini+19 (1.4 GHz)
- all AGNs (X-rays) from Swift-BAT (14-195 keV)
- jetted AGNs (g-rays) from Fermi 3FHL (E>10 GeV)

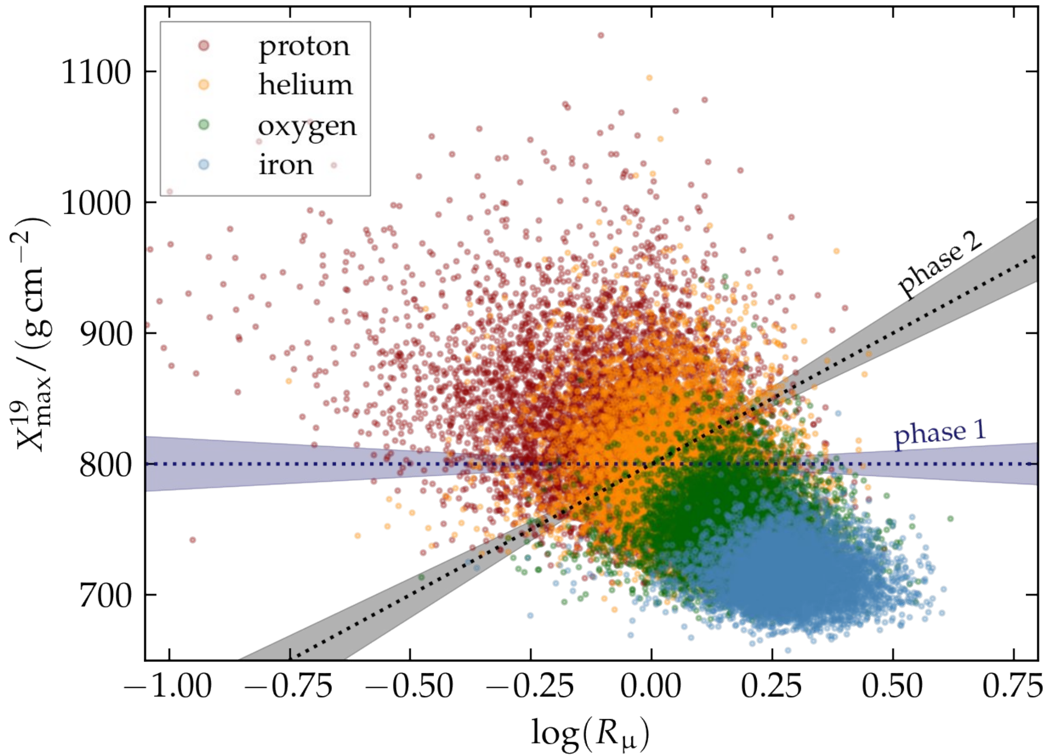
Catalog	$E_{\rm th}$ [EeV]	Ψ [°]	α [%]	TS	Post-trial p-value	
All galaxies (IR)	38	24^{+15}_{-8}	14^{+8}_{-6}	18.5	6.3×10^{-4}	→ 3
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}	→ 3
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}	→ 3
Jetted AGNs (γ-rays)	38	23^{+8}_{-7}	6^{+3}_{-3}	19.2	4.6×10^{-4}	→ 3

Difference rigidity-like and mass





Mass discrimination



Rate declination