Composition of Ultra-High Energy Cosmic Rays

Blaž Bortolato

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arXiv:2212.04760

arXiv:2304.11197

arXiv:2409.06841

arXiv:2410.xxxxx

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Why Cosmic Rays?

Ultra High-Energy Cosmic Rays (UHECR)

→ atomic nuclei (H, He,..., Fe,...)

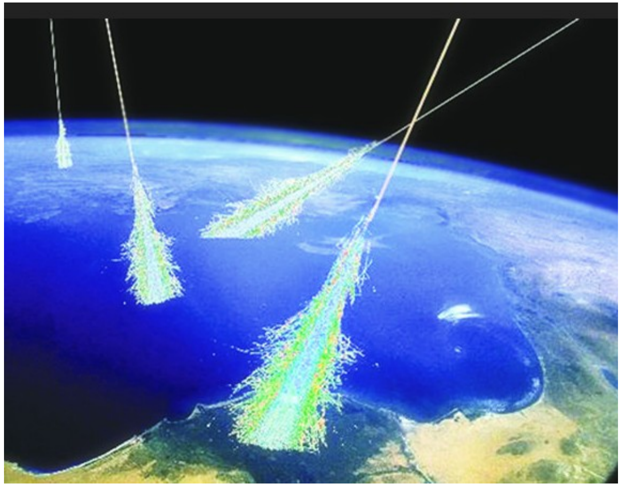
→ $E \geq 10^9$GeV (proton mass: 1GeV)

Unknowns:

→ acceleration mechanisms

→ sources

This Talk → composition (fractions of atomic nuclei)



Artist's impression of cosmic rays striking Earth
(Simon Swordy/University of Chicago, NASA)

Motivation

→ galactic & inter-galactic magnetic fields, propagation

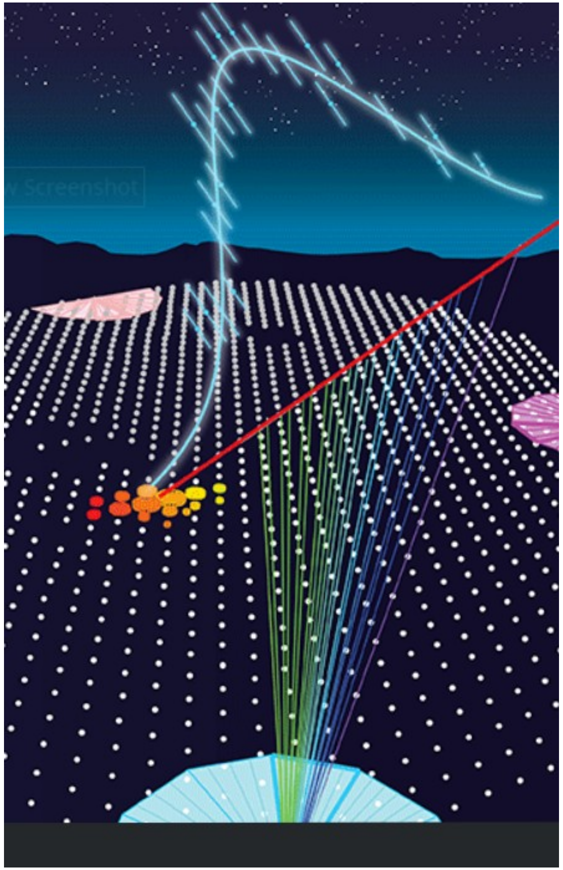
→ acceleration mechanisms (extreme events)

→ hadron interactions at ultra high energies

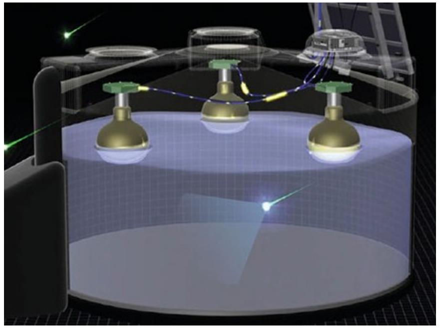
→ $10^5\times - 10^7\times$ the energy at LHC

→ **undiscovered particles**

Pierre Auger Observatory



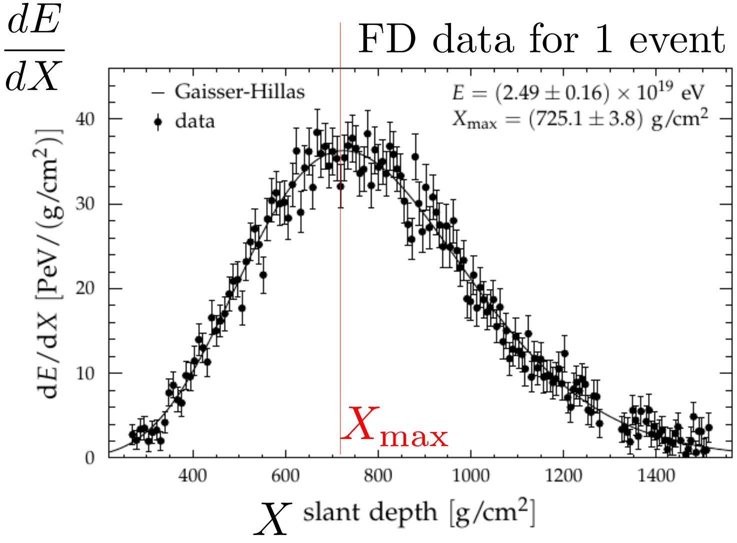
Surface Detectors (SD) are
water Cherenkov detectors



Fluorescence detectors (FDs) operate only in clear, moonless nights

$$X = \int \rho(\vec{r})\, dr$$

FD data for 1 event



→ 1600 Surface detectors, 1.5 km apart, cover 3000 km^2
→ 4×6 Fluorescence detectors, 330–380 nm

Pierre Auger Collaboration, Alexander Aab (Siegen U.) et al. 1409.4809 [astro-ph.HE] Phys.Rev.D 90 (2014) 12, 122005

Inference Procedure

Compare **measured data** with **simulated data**

Pierre Auger Observatory
Open Data 2021

→ 10% of all observed events

∼ **3000 events with FD**

∼ 1600 events with SD and FD data

∼ 22000 events with only SD data

→ $\{X_{\text{max},1}, \ldots, X_{\text{max},N}\}$

→ 0.6 EeV - 5 EeV

→ 4 hadronic models

→ 26 primaries: p, He, Li,..., Fe

→ 6000 events/model/element

→ **only FD**

→ $\{X_{\text{max},1}, \ldots, X_{\text{max},M} | Z\}$

Z=1,...,26

Inference Procedure

$$\{X_{\max,1}, \ldots, X_{\max,N}\}$$

We represent data with moments
$\mathbf{z} = (z_1, z_2, z_3, z_4)$

$$z_1 = \frac{1}{N} \sum_{i=1}^{N} X_{\max,i}$$

$$z_n = \frac{1}{N} \sum_{i=1}^{N} (X_{\max,i} - z_1)^n$$

Systematic and statistical uncertainties are included via bootstrap method

Problem

Distribution of compositions

observed data

simulations

$$P(\mathbf{z}) = \int P(\mathbf{z}|\mathbf{w})\ P(\mathbf{w})\ d\mathbf{z}^n$$

Solution

simulations

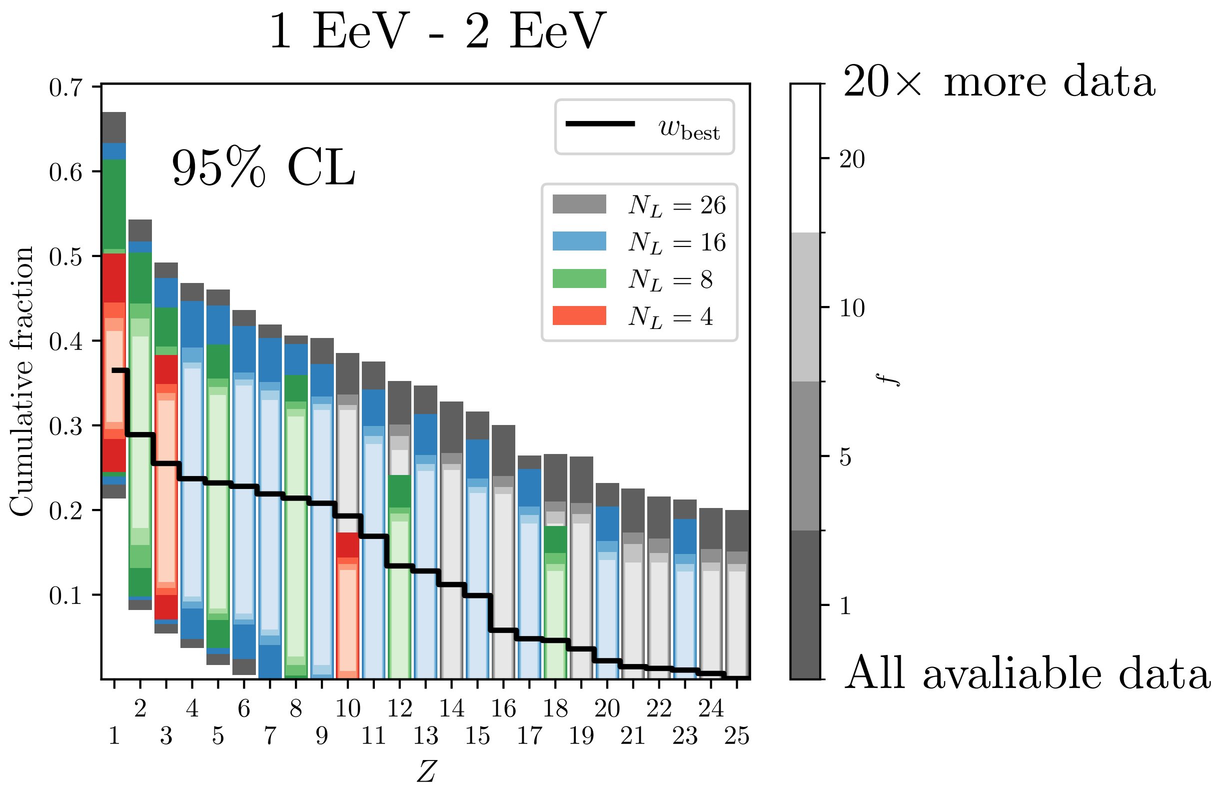
observed data

$$\log L(\mathbf{w}) = \int \log[P(\mathbf{z}|\mathbf{w})]\ P(\mathbf{z})\ d^n\mathbf{z}$$

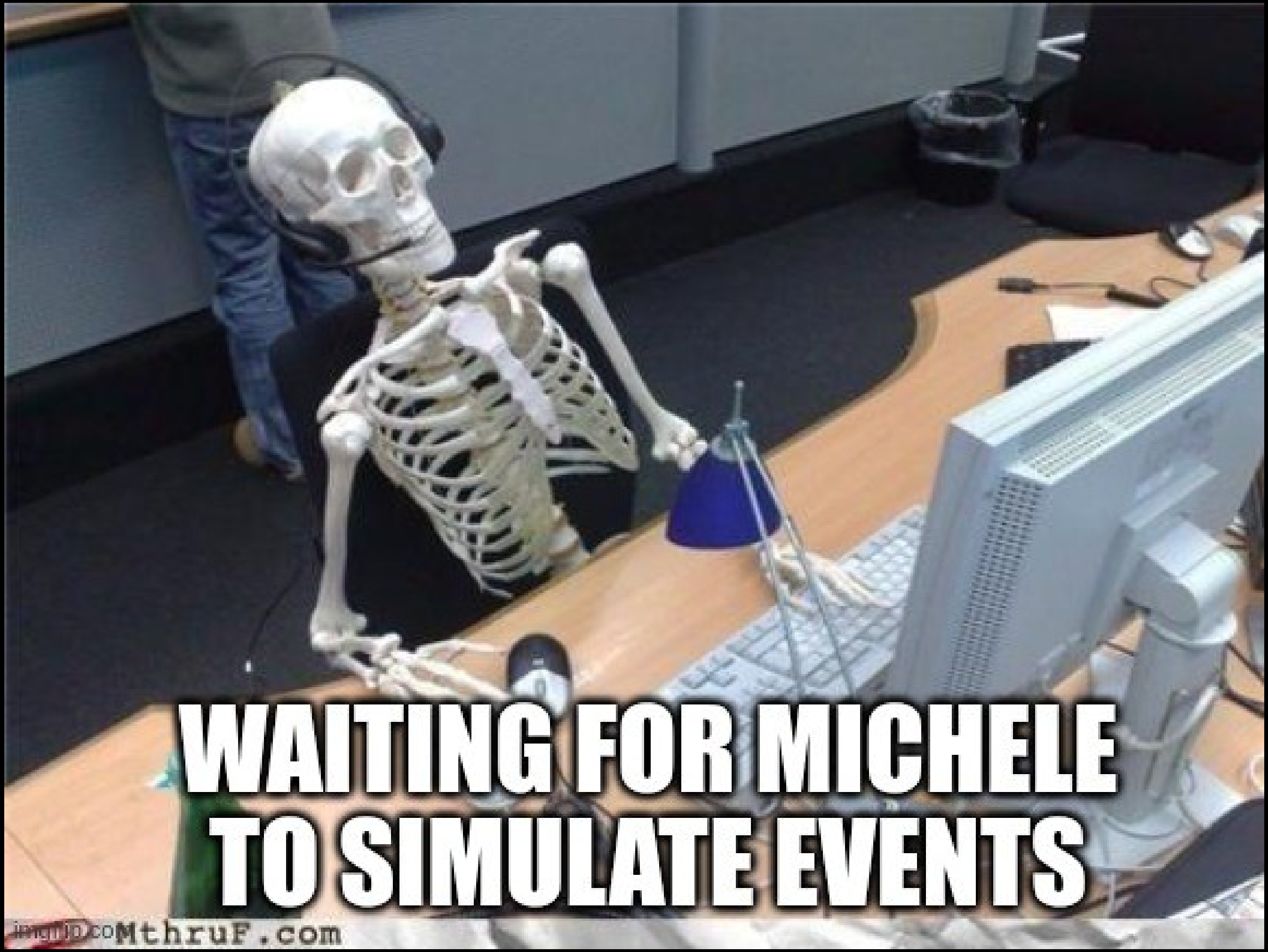
Bayes theorem

$$P(\mathbf{w}) \propto L(\mathbf{w})\ \text{Prior}(\mathbf{w})$$

Fraction of elements heavier than Z

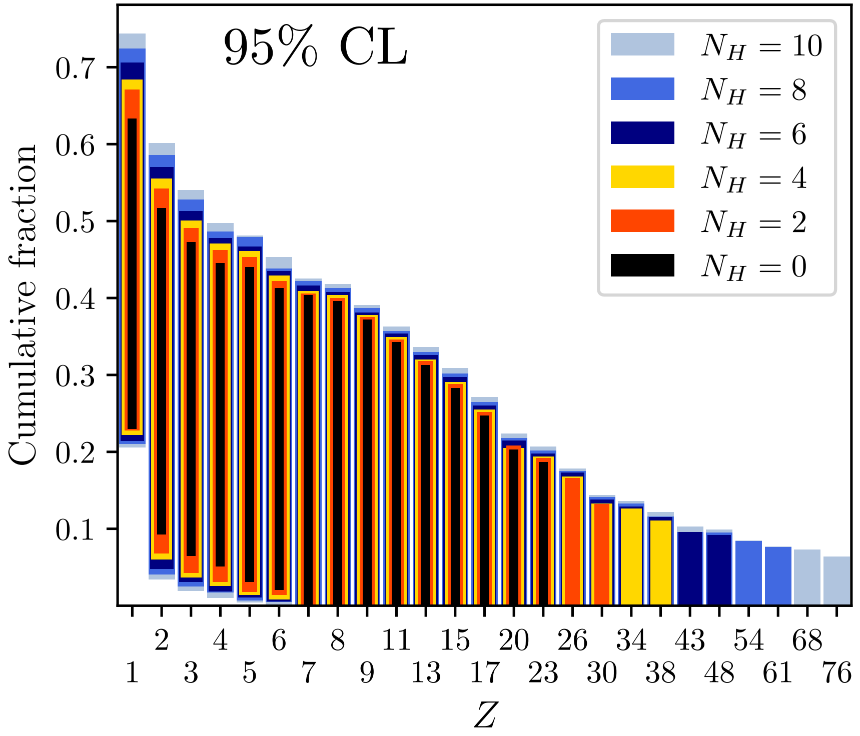


What about elements beyond Fe?


WAITING FOR MICHELE
TO SIMULATE EVENTS
MthruF.com

Fraction of elements heavier than Z

0.6 EeV - 1 EeV



95% upper bounds

$$w(Z > 26, E \in [0.65, 1] \text{ EeV}) \leq 24\%,$$
$$w(Z > 26, E \in [1, 2] \text{ EeV}) \leq 18\%,$$

$$w(Z > 94, E \in [0.65, 1] \text{ EeV}) \leq 10\%,$$
$$w(Z > 94, E \in [1, 2] \text{ EeV}) \leq 6\%,$$

Conclusion

Methods

→ infer the composition

→ generate list of elements

→ validate models

→ map: ground to $X_{\max}$

Results

→ Composition with 95% CL

→ Upper bounds on Fe, Uranium

→ Projections

→ Classification based on $X_{\max}$

Conclusion

Methods

→ infer the composition

→ generate list of elements

→ validate models

based on moments

→ map: ground to $X_{\max}$

Results

→ Composition with 95% CL

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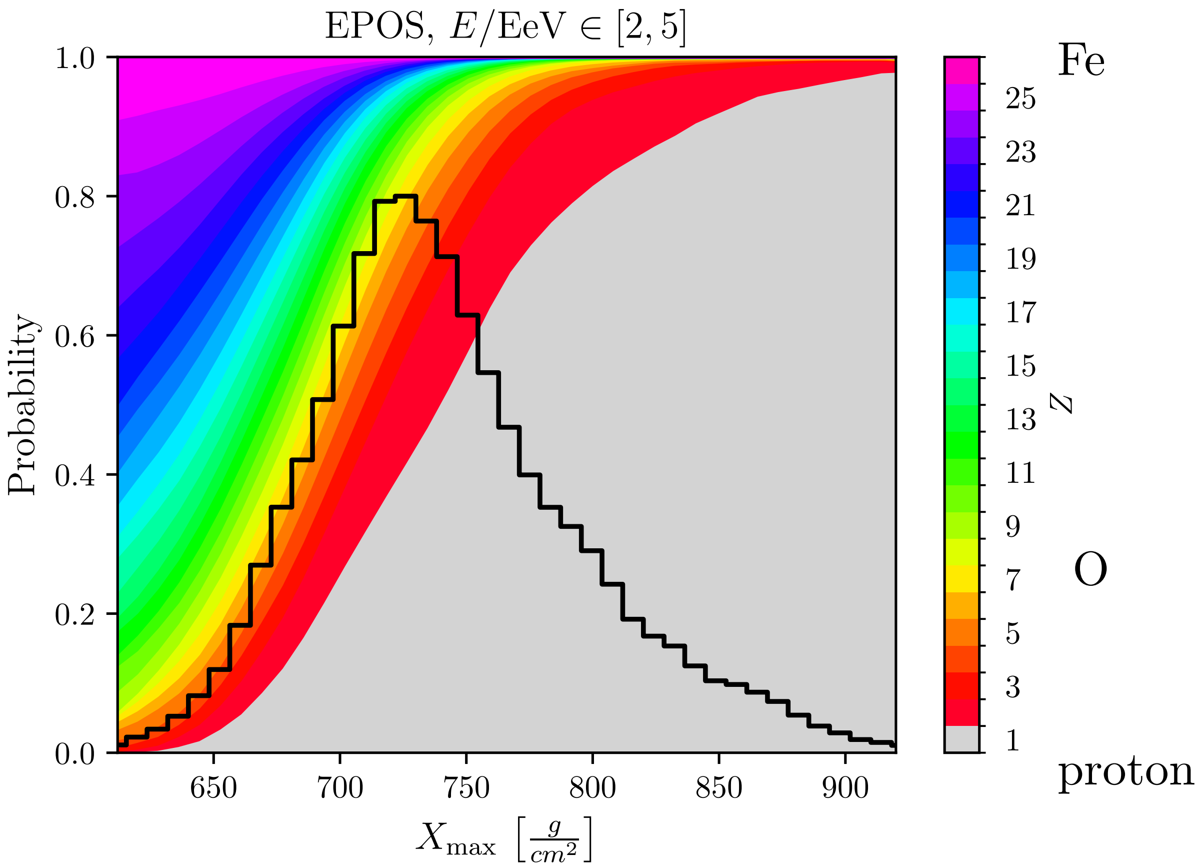
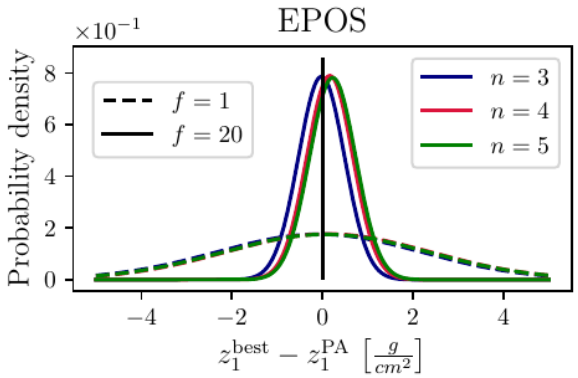
The End

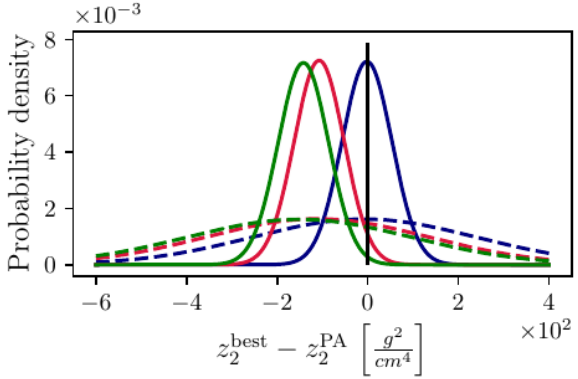
Classification

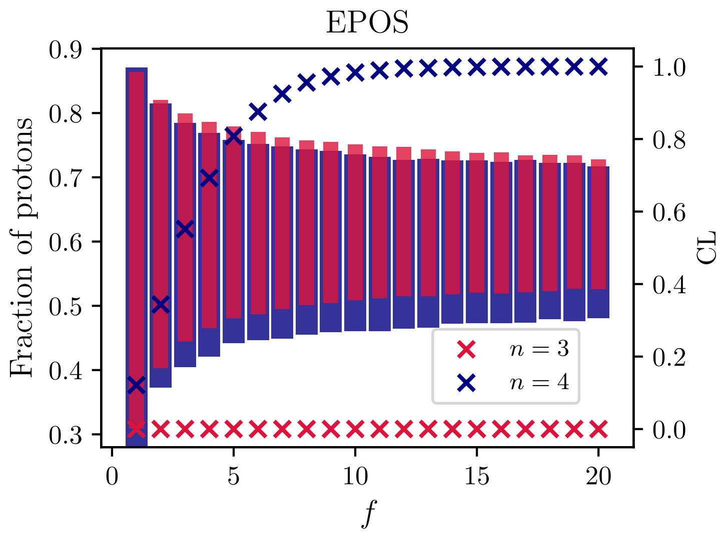


Number of moments

Compare moments of w_{best}
to moments from measured data







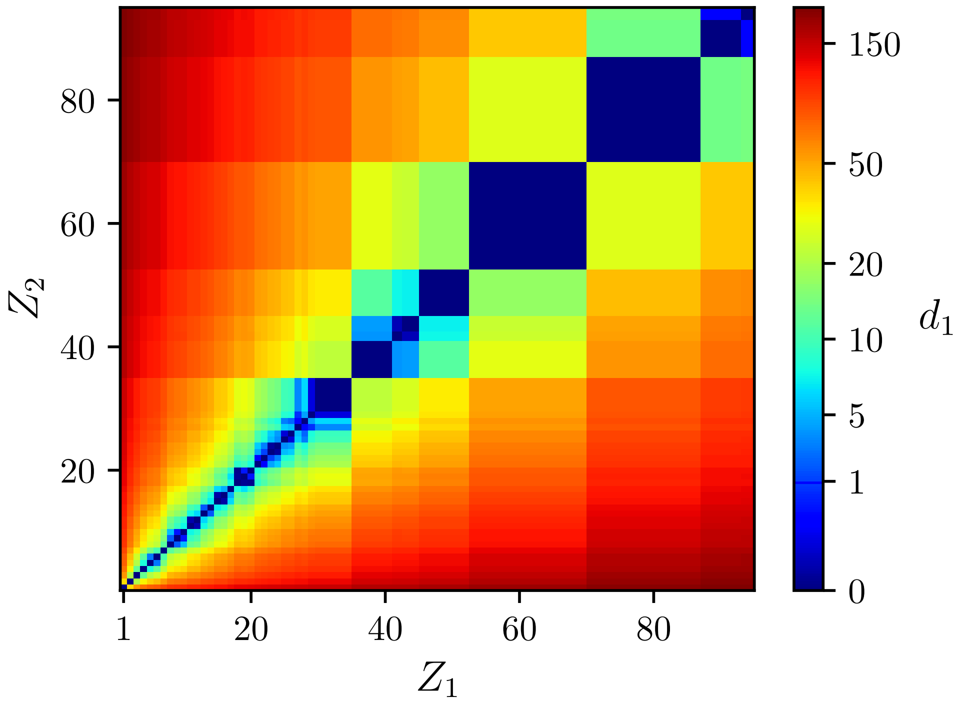
→ Get CL of the hadronic model

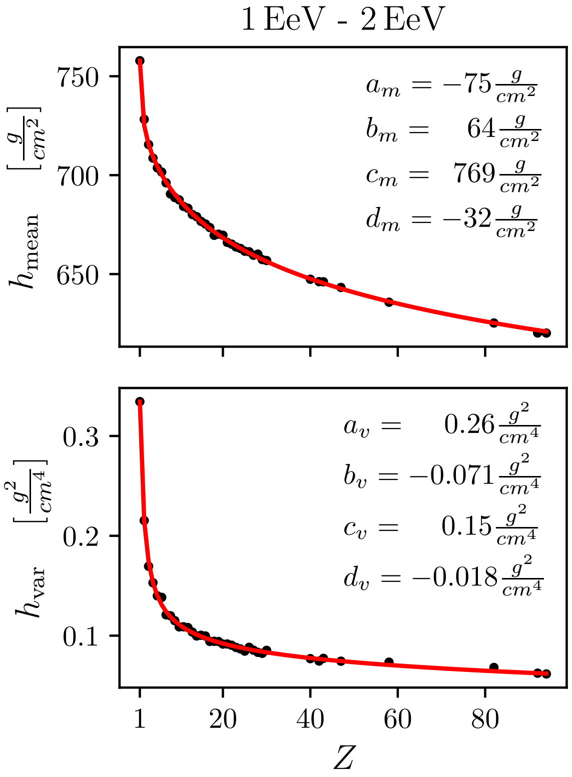
→ Improve simulations of events

→ Avoid using inconsistent moments

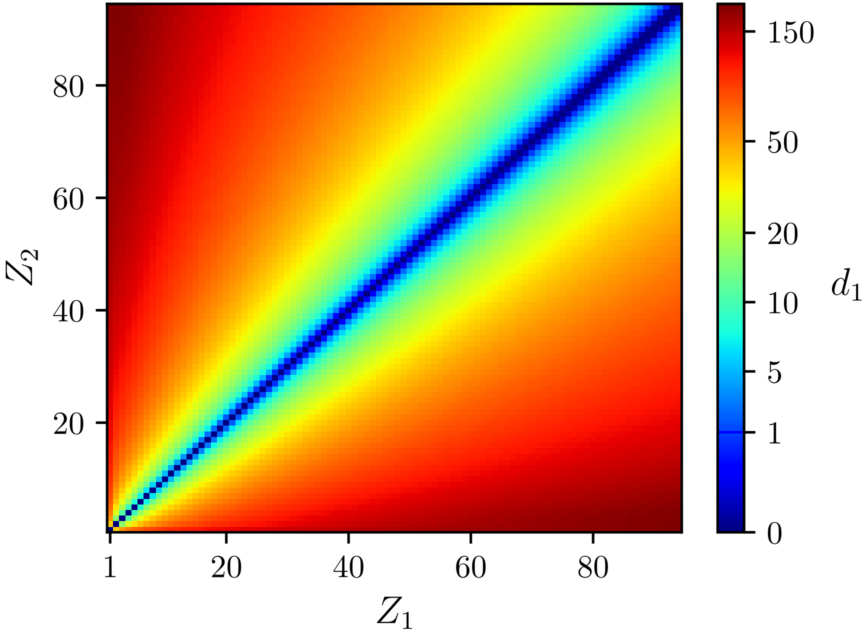
Distance between elements

$$d_n^2(Z_1, Z_2) \equiv (\mu_{Z_1} - \mu_{Z_2})^T (\Sigma_{Z_1} + \Sigma_{Z_2})^{-1} (\mu_{Z_1} - \mu_{Z_2})$$





List of elements



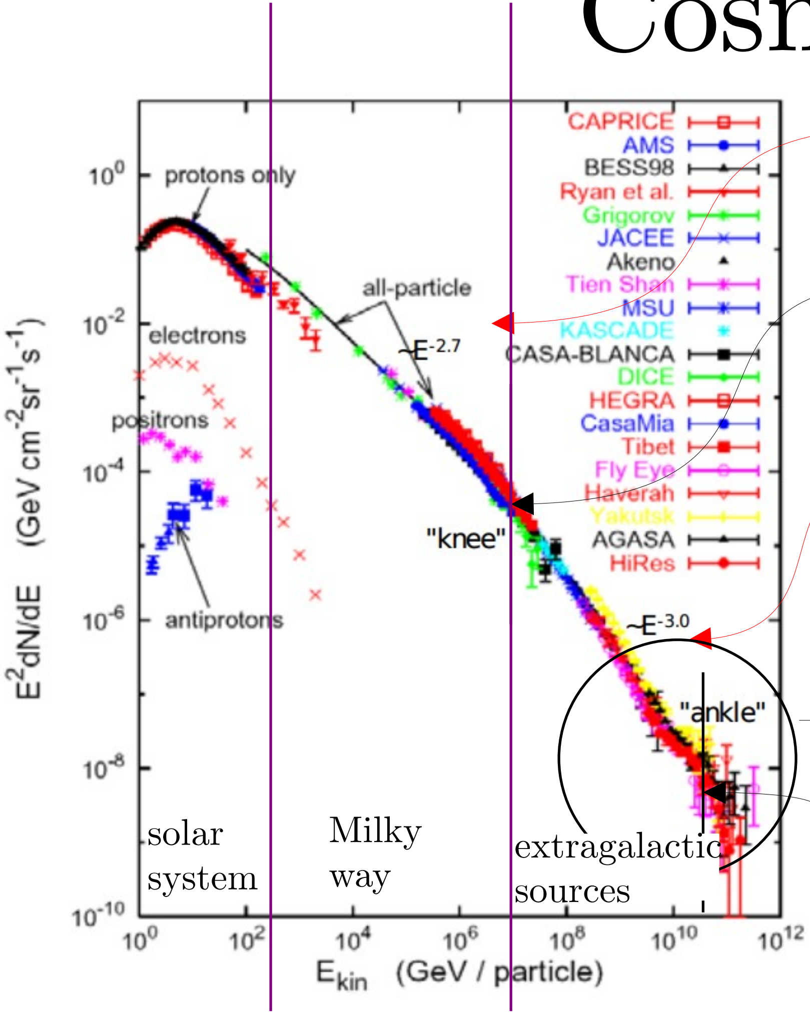
d_0	N_L (N_H)	List of atomic numbers Z
16.6	4 (2)	1, 3, 10, 24, 52, 94
6.4	8 (5)	1, 2, 4, 6, 9, 13, 19, 27, 37, 50, 67, 89
4.0	12 (7)	1, 2, 3, 4, 5, 7, 9, 11, 14, 17, 21, 26, 31, 37, 44, 53, 63, 75, 89
2.8	16 (10)	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 17, 20, 23, 26, 30, 34, 39, 44, 50, 57, 64, 72, 81, 91
2.0	20 (14)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 18, 20, 22, 24, 26, 29, 32, 35, 38, 42, 46, 50, 54, 59, 64, 70, 76, 82, 89
1.3	24 (21)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 43, 46, 49, 52, 55, 58, 62, 66, 70, 74, 78, 83, 88, 93


HE INTERPOLATED DATA
SEE NOBODY CARES

Cosmic Rays

proton mass: 1 GeV

LHC: $E \sim 10^4$ GeV



$$\frac{dN}{N} \propto E^{-2.7}$$

$$\frac{1 \text{ event}}{m^2 \cdot \text{ year}}$$

$$\frac{dN}{N} \propto E^{-3}$$

Ultra-High Energy Cosmic Rays (UHECR)

$$\frac{1 \text{ event}}{(km)^2 \cdot \text{ year}}$$

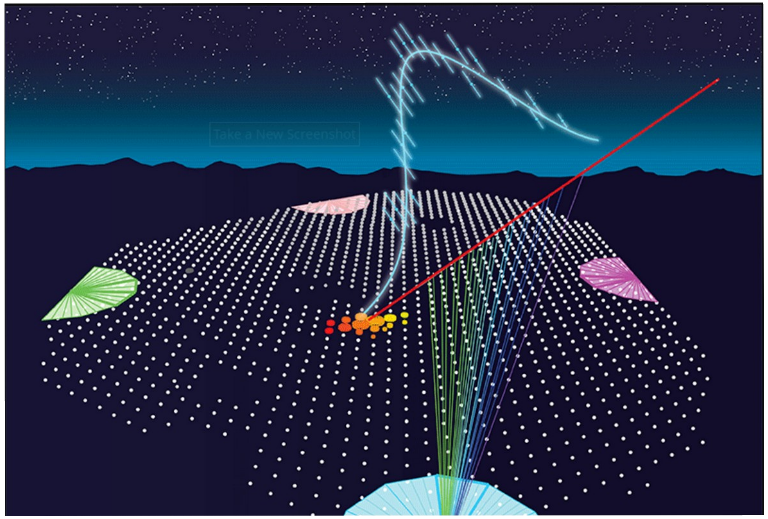
$E \geq 10^{18}$ eV

$E \geq 10^9$ GeV

$E \geq 1$ EeV

Diehl, Roland. (2009). Particle acceleration in cosmic sites.
The European Physical Journal D. 55. 10.1140/epjd/e2009-00183-8.

Observatories & Upgrades



Pierre Auger Observatory

→ 4×6 Fluorescence detectors, 330–380 nm

→ 1600 Surface detectors, 1.5 km apart, cover 3000 km^2

→ 15 years collecting data ($\sim 10^5$ observed events)

→ Argentina, southern hemisphere.

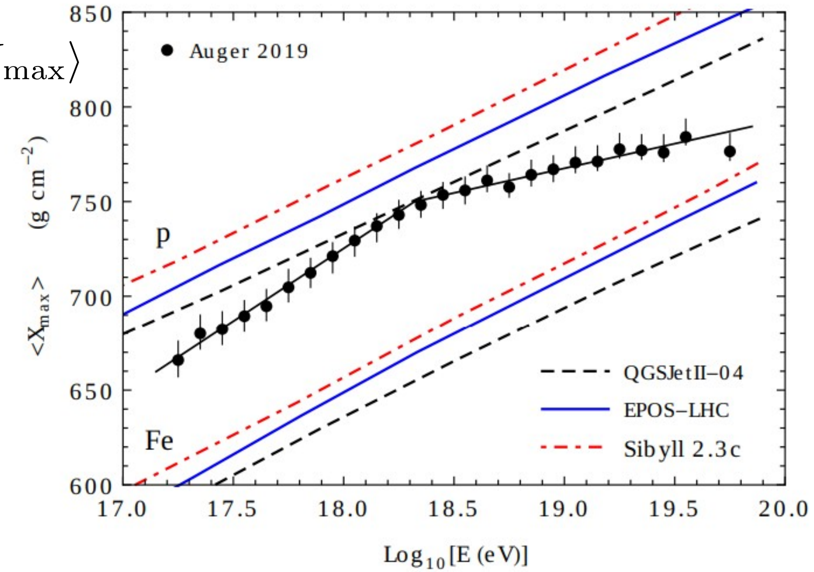
→ under upgrade

AugerPrime

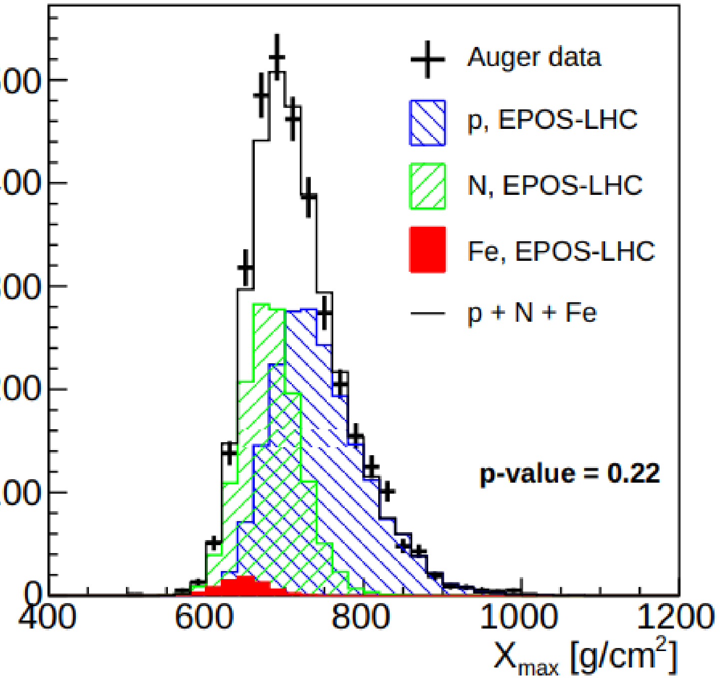
→ Surface Scintillator Detector (SSD) will be attached on each SD

Composition from literature

$\langle X_{\max} \rangle$



$\log_{10}(E/\mathrm{eV}) \in [17.9, 18.0]$



$w_p \sim 60\%$
$w_{He} \sim 0$
$w_N \sim 35\%$
$w_{Fe} \sim 5\%$

$\text{Likelihood}(w) \sim \prod_{bin} \text{Poisson distribution}$

$w = \text{argmax}(\text{Likelihood})$

N. Arsene, O. Sima, 2001.02667 [astro-ph.HE], Eur.Phys.J.C 80 (2020).
P. Lipari, 2012.06861 [astro-ph.HE], Phys.Rev.D 103 (2021) 10, 103009.

$E/\mathrm{EeV} \in [2.5, 5]$

Results

Events with
FD and SD data
($\sim$ 200 events)

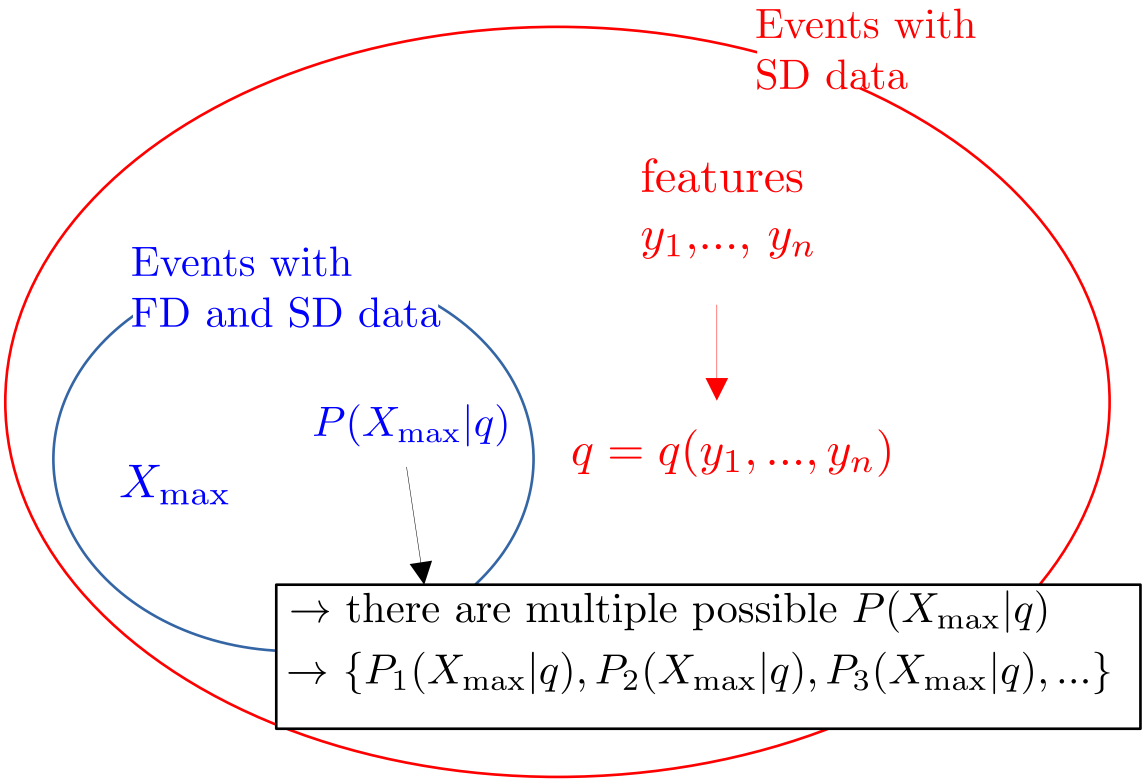
X_{max}

Events with
ONLY SD data
(22000 events)

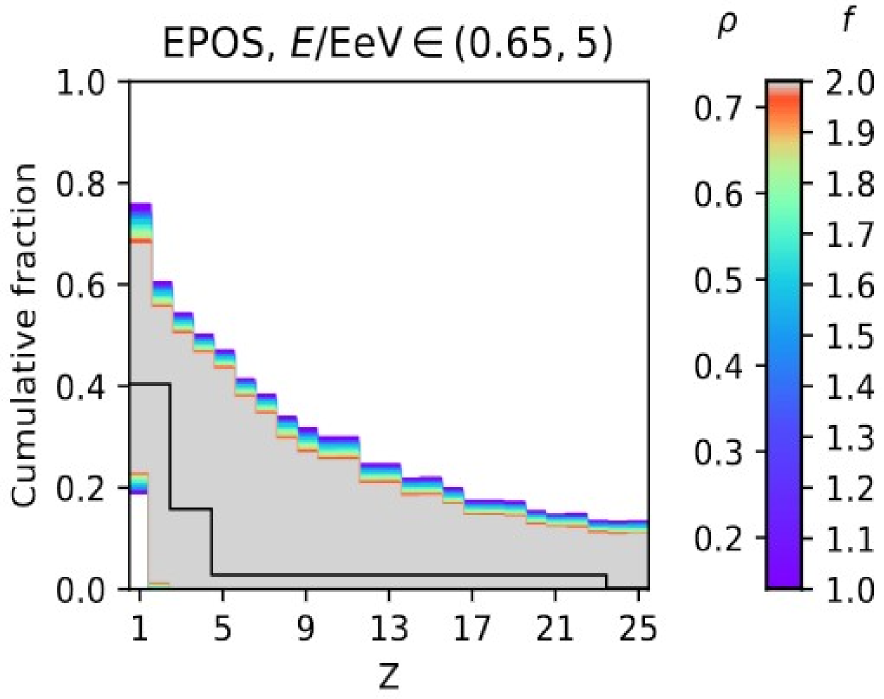
$X_{\mathrm{max}} \sim P(X_{\mathrm{max}}|q)$
(large uncertainties)

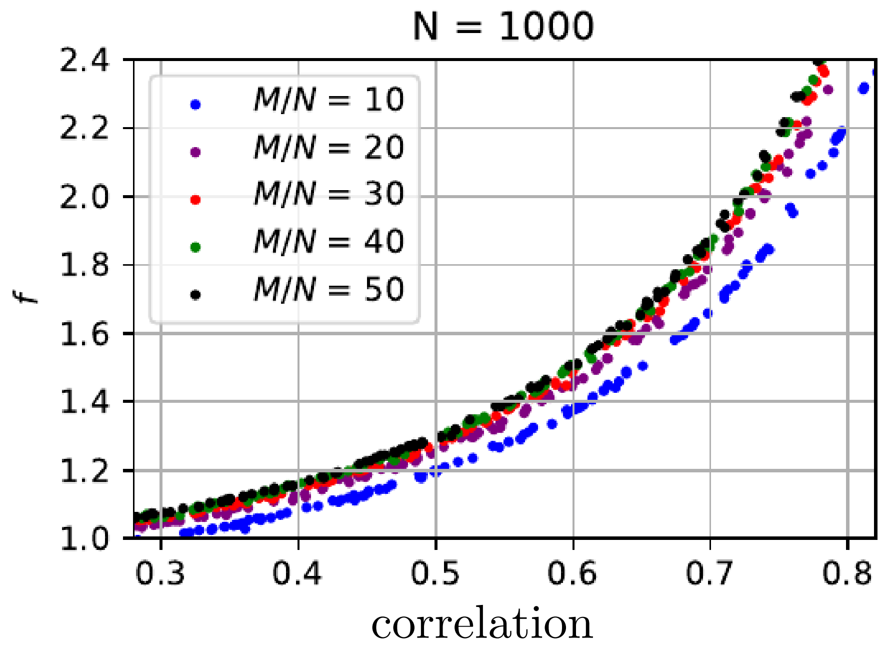
Effectively $>$ 200 events
with FD and SD

If correlation $|\rho(X_{\mathrm{max}}, q)| \sim 75\%$,
2 $\times$ 200 events with FD and SD



Results





Pierre Auger Collaboration implemented a machine learning model with $\rho = 63\%$

Effective number of events can be increased by 80%