Composition of Ultra-High Energy Cosmic Rays

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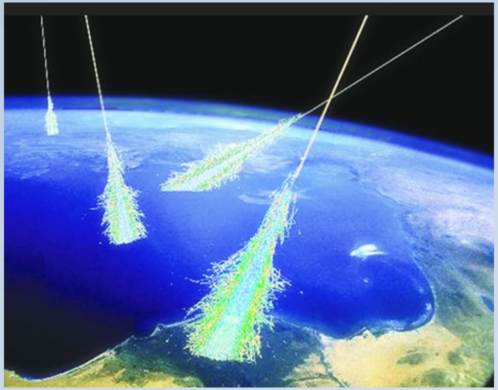
Glühwein Workshop 2024
Karlsruhe Institute of Technology

What & Why

Ultra High-Energy Cosmic rays



- → 1EeV = 10^9GeV
- → extra-galactic sources
- → 1 event / km^2 / year

Composition

$$w = (w_p, w_{\text{He}}, \ldots, w_{\text{Fe}}, \ldots)$$

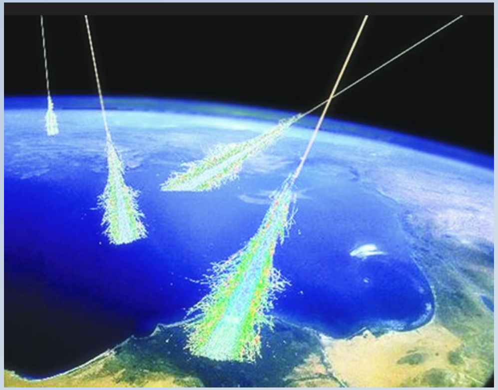
60% 15% 1%

Motivation

- $\rightarrow$ Composition not well known
- $\rightarrow$ Constraints on sources
- $\rightarrow$ Acceleration mechanism
- $\rightarrow$ Interactions $10^5 - 10^7$ x E_{CERN}

What & Why

Ultra High-Energy
Cosmic rays



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Composition

$$w = (w_p, w_{\mathrm{He}}, \ldots, w_{\mathrm{Fe}}, \ldots)$$

60% 15% 1%

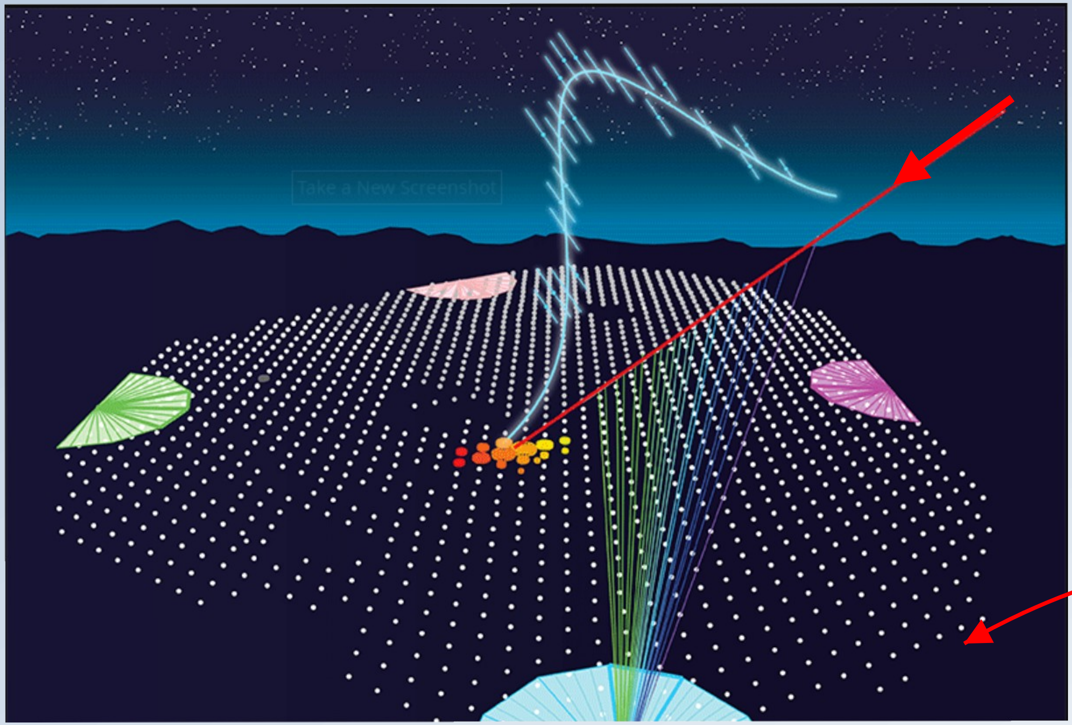
Problem:

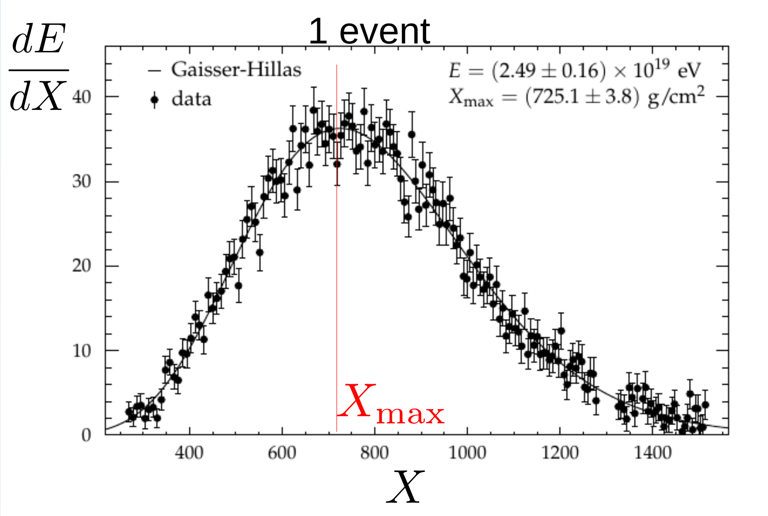
Data: 1000 events, 1value/event

↓

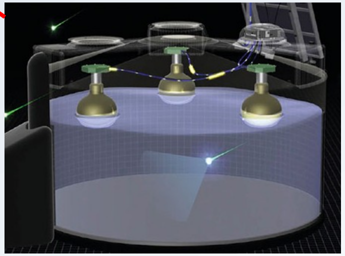
26 dim. distribution P(w)
(p, He,…,Fe)

Pierre Auger Observatory





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



Cherenkov detector

Data

Measured data:
Pierre Auger Open Data
(publicly available)
10% of all measured events

$E/\mathrm{EeV} \in [0.6, 1]$

events: 1000

$E/\mathrm{EeV} \in [1, 2]$

events: 1200

$E/\mathrm{EeV} \in [2, 5]$

events: 650

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

Simulated data: CORSIKA

→ primaries: p, He, Li,…, Fe

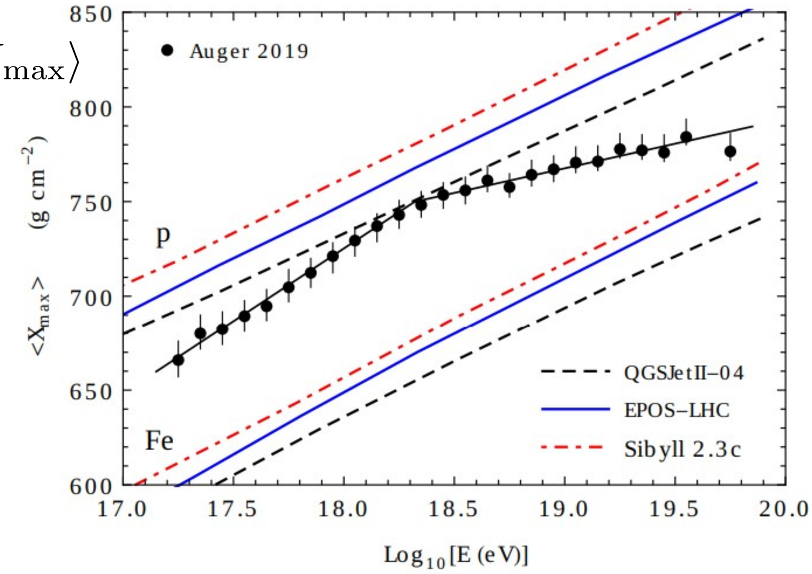
→ 10000 events/primary

→ 4 hadronic models

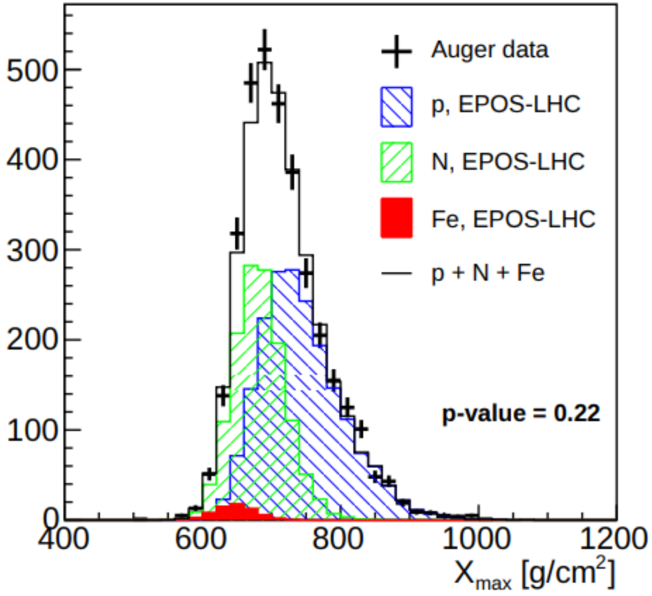
$$\{X_{\mathrm{max},1}, \ldots, X_{\mathrm{max},M} | Z\}$$
$$Z = 1, 2, 3, ...26$$

Previous studies

$\langle X_{\max} \rangle$



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



$w_p \sim 60\%$

$w_{He} \sim 0$

$w_N \sim 35\%$

$w_{Fe} \sim 5\%$

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

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

→ 4 – 8 primaries,

→ uncertainties...

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.

Our goal

→ Event classification

→ primaries: p, He,…, Fe

→ inclusion of all uncertainties

→ reliable uncertainties on the composition

↓

Training a classifier

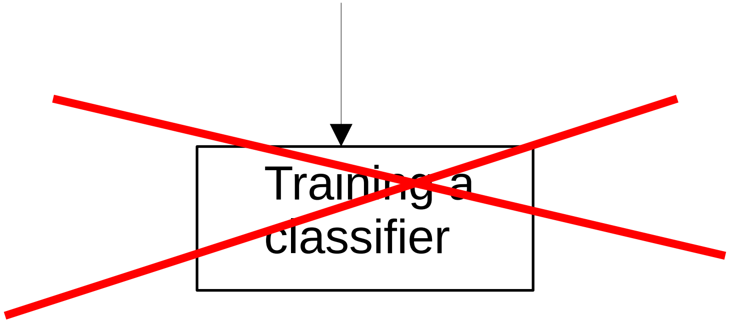
Our goal

→ Event classification

→ primaries: p, He,…, Fe

→ inclusion of all uncertainties

→ **reliable uncertainties on the composition**



"Composition can be arbitrary weird"

$$w = (w_p, w_{\mathrm{He}}, w_{\mathrm{Li}}, \ldots, w_{\mathrm{Fe}}, \ldots)$$

$60\% \quad 1\% \quad 39\%$

Plan B – improvise

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

$$\mathbf{z} = (z_1, z_2, z_3, z_4)$$

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

bootstrap method

measured data: $P(z)$

simulated data: $P(z|w)$

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

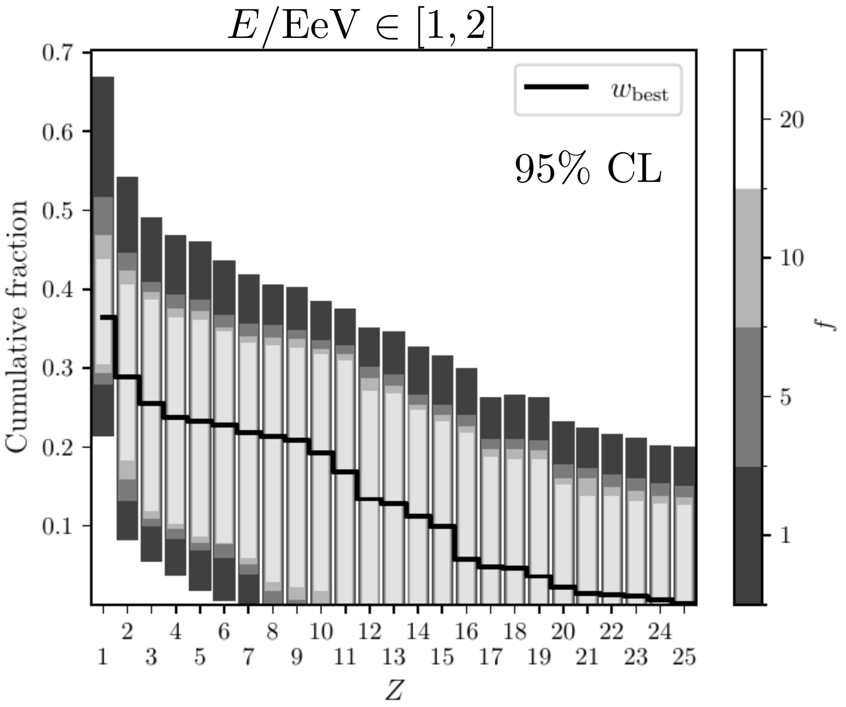
$$\log L(\mathbf{w}) = \int \log[P(\mathbf{z}|\mathbf{w})]\; P(\mathbf{z})\; d^n\mathbf{z}$$

Bayes theorem

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

Nested sampling; sample $P(\mathbf{w})$

Fraction of elements heavier than Z



A) fraction of primaries with Z>2:

$$w(Z > 2) \in [8\%, 54\%]$$

B) projections: $f\times$ more data

C) Extension to heavy primaries:

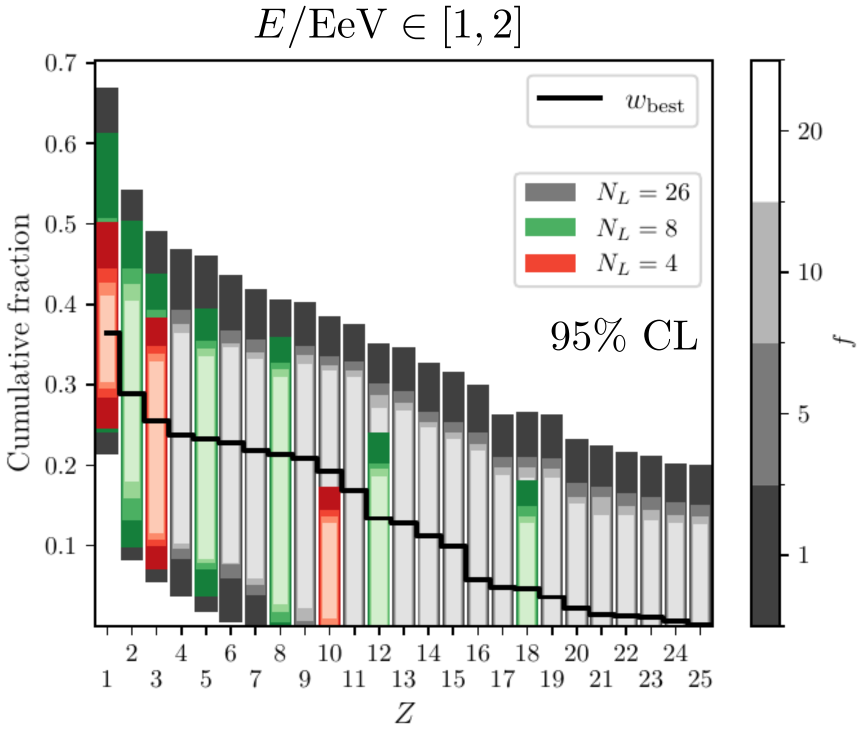
H,…,Fe,…,Pu
1,…,26,….,94

$$w(Z > 26) < 18\%$$

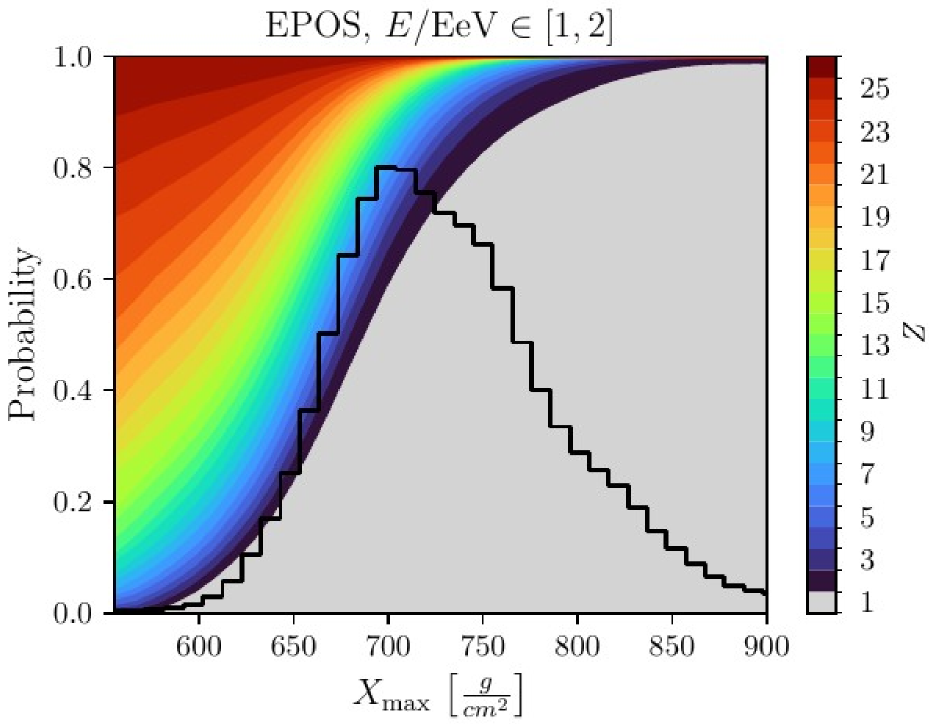
$$w(Z > 94) < 6\%$$

Fraction of elements heavier than Z

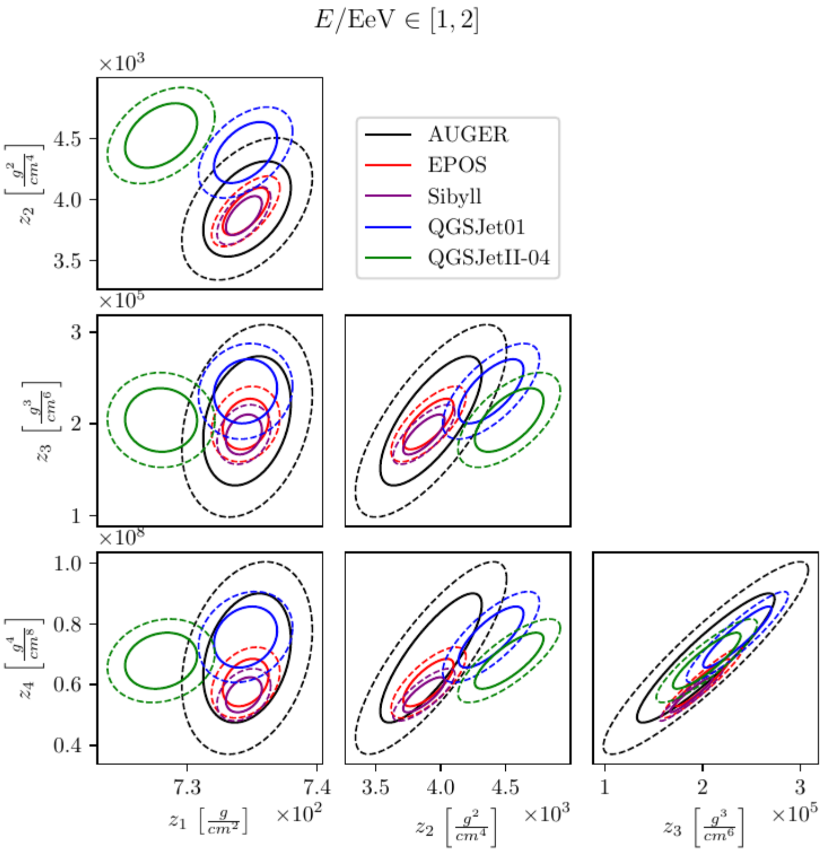
D) Consider ≥ 16 primaries



E) Classification



Systematic studies



F) Which hadronic models?

CL by comparing moments
of the best fit with measured ones

G) How many moments?

EPOS : 3, (4)
Sibyll : 3, (4)
QGSJet01 : 1, (2)
QGSJetII-04: 0, (1)

I really want a classifier...

(for Christmas)

$$P(\text{class}|\text{values}) = \frac{\mathrm{P}(\text{values}|\text{class})\ \mathrm{w}_{\text{class}}}{\sum_{\text{class}} \mathrm{P}(\text{values}|\text{class})\ \mathrm{w}_{\text{class}}}$$

Classification requires composition of the dataset

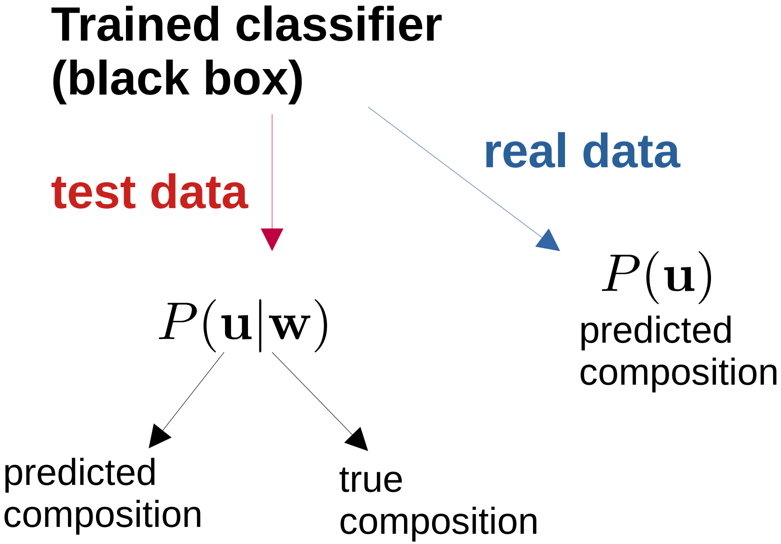
$w_{\text{real data}}$

If $w_{\text{train data}} \neq w_{\text{real data}}$ → **results are biased**

→ large number of inputs
→ classifier can be bad

Composition bias can be fixed even for bad classifiers

Wrapping a classifier



Wrapping a classifier

Trained classifier (black box)

test data

real data

$P(\mathbf{u}|\mathbf{w})$

predicted composition

true composition

$P(\mathbf{u})$

predicted composition

test data **real data**

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

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

→ reliable P(w)
→ reweighted classifier
→ probabilities with uncertainties

Summary

Method to infer the composition

- sys. & stat. uncertainties
- number of classes <100
- projections
- systematic studies

Results

- 95% conf. Intervals: p,…,Fe,…,Pu
- event classification

Wrapped classifier

- fixed composition bias
- outputs with stat. interpretation

Wish you happy holidays

Presented results are part of following publications:

2212.04760, Phys. Rev. D 108, 043023,
2304.11197, Phys. Rev. D 108, 022004,
2409.06841, EPJ (accepted),
2411.10223, (submitted to EPJ),

done in collaboration with:

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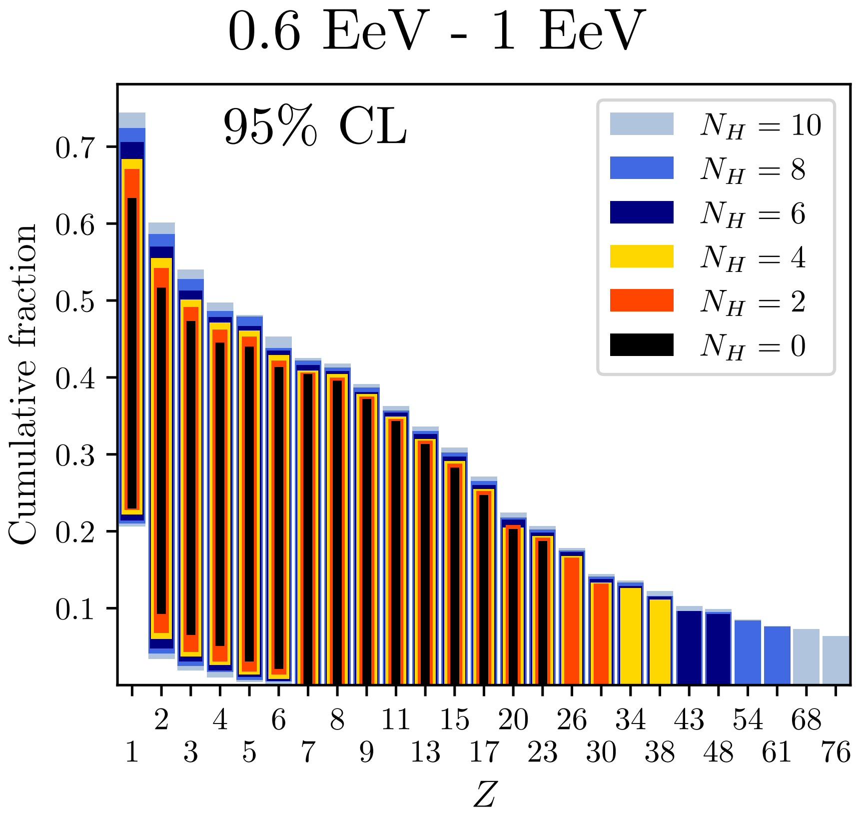
The End

Fraction of elements heavier than Z

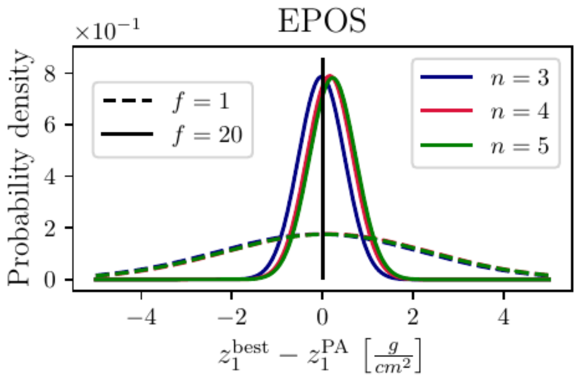


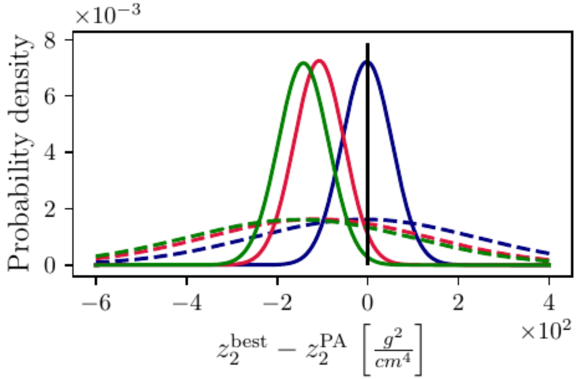
95% upper bounds

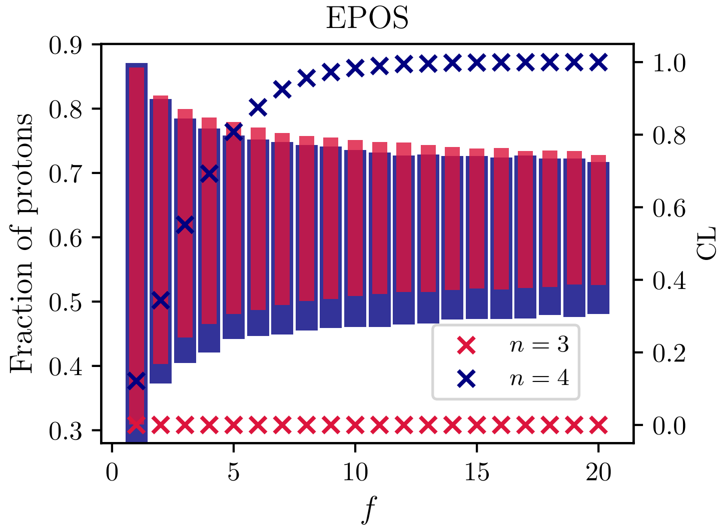
$$w(Z > 26, E \in [1,2] \text{ EeV}) \leq 18\%,$$
$$w(Z > 94, E \in [1,2] \text{ EeV}) \leq 6\%,$$

Number of moments

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







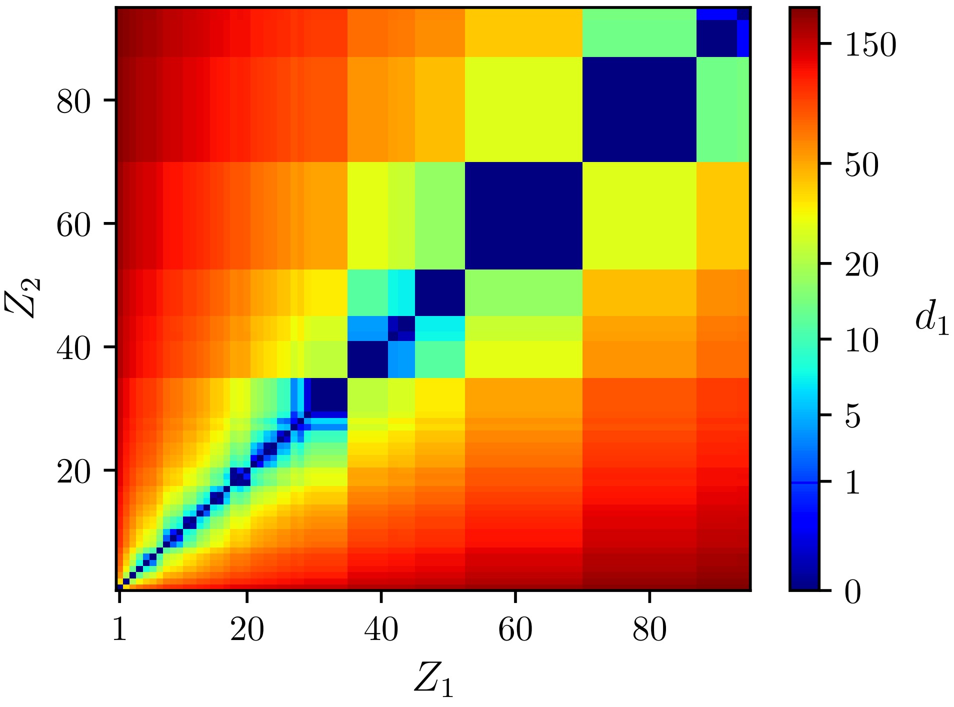
→ Get CL of the hadronic model

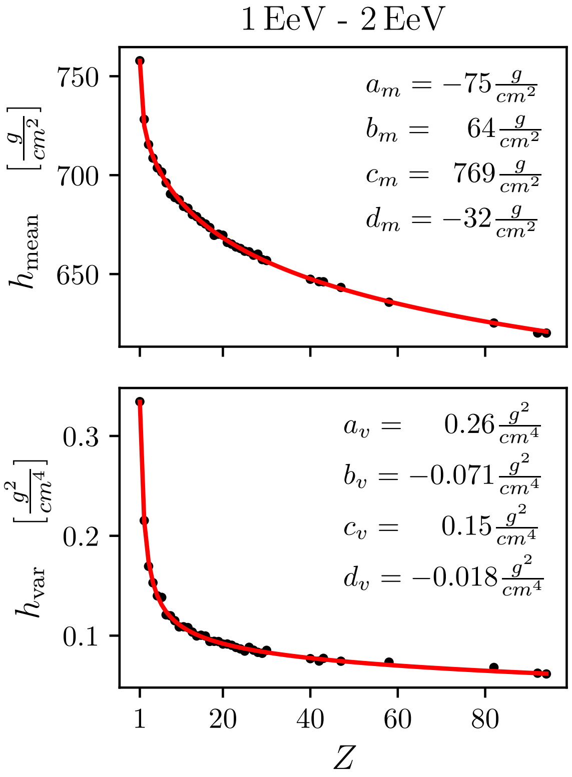
→ Improve simulations of events

→ Avoid using inconsistent moments

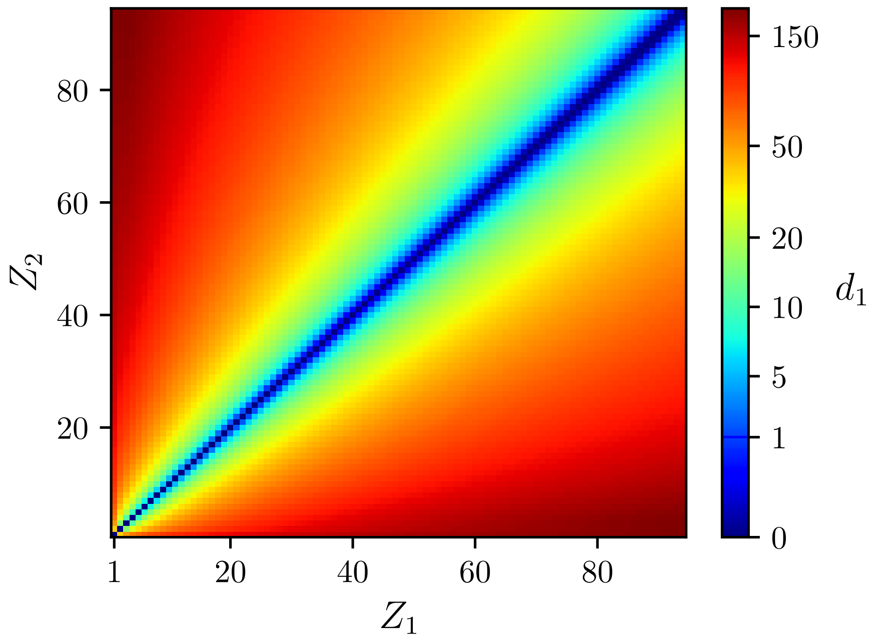
Distance between elements

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





List of elements



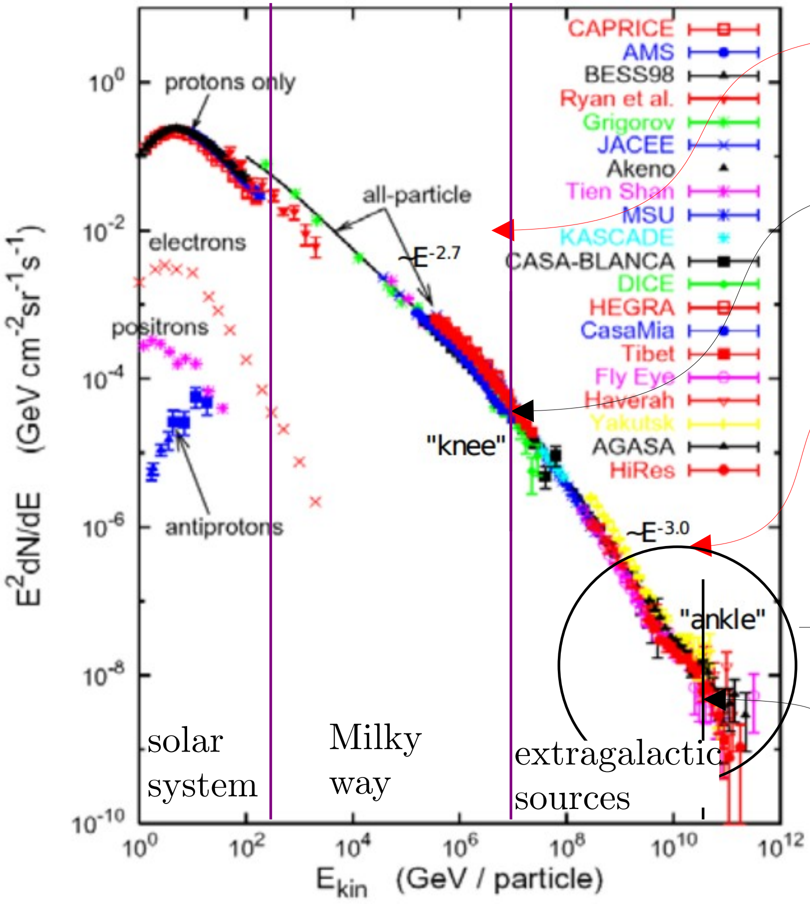
d_0	N_L (N_H)	List of atomic numbers Z
16.6	4 (2)	1, 3, 10, 24, 52, 94
6.4	8 (5)	1, 2, 4, 6, 9, 13, 19, 27, 37, 50, 67, 89
4.0	12 (7)	1, 2, 3, 4, 5, 7, 9, 11, 14, 17, 21, 26, 31, 37, 44, 53, 63, 75, 89
2.8	16 (10)	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 17, 20, 23, 26, 30, 34, 39, 44, 50, 57, 64, 72, 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

Flux

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

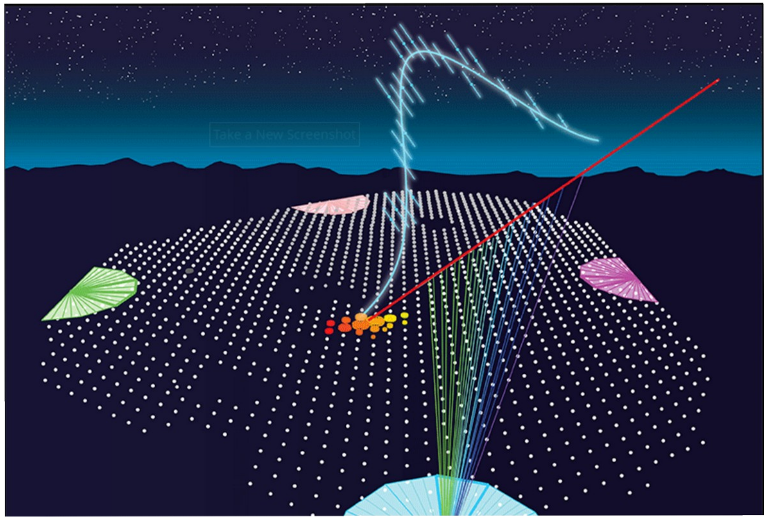
$E \geq 10^9$ GeV

$E \geq 1$ 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



- $\rightarrow$ 4×6 Fluorescence detectors, 330–380 nm
- $\rightarrow$ 1600 Surface detectors, 1.5 km apart, cover 3000 km^2
- $\rightarrow$ 15 years collecting data ($\sim 10^5$ observed events)
- $\rightarrow$ Argentina, southern hemisphere.
- $\rightarrow$ under upgrade

AugerPrime

- $\rightarrow$ Surface Scintillator Detector (SSD) will be attached on each SD

Ground correlation

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

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

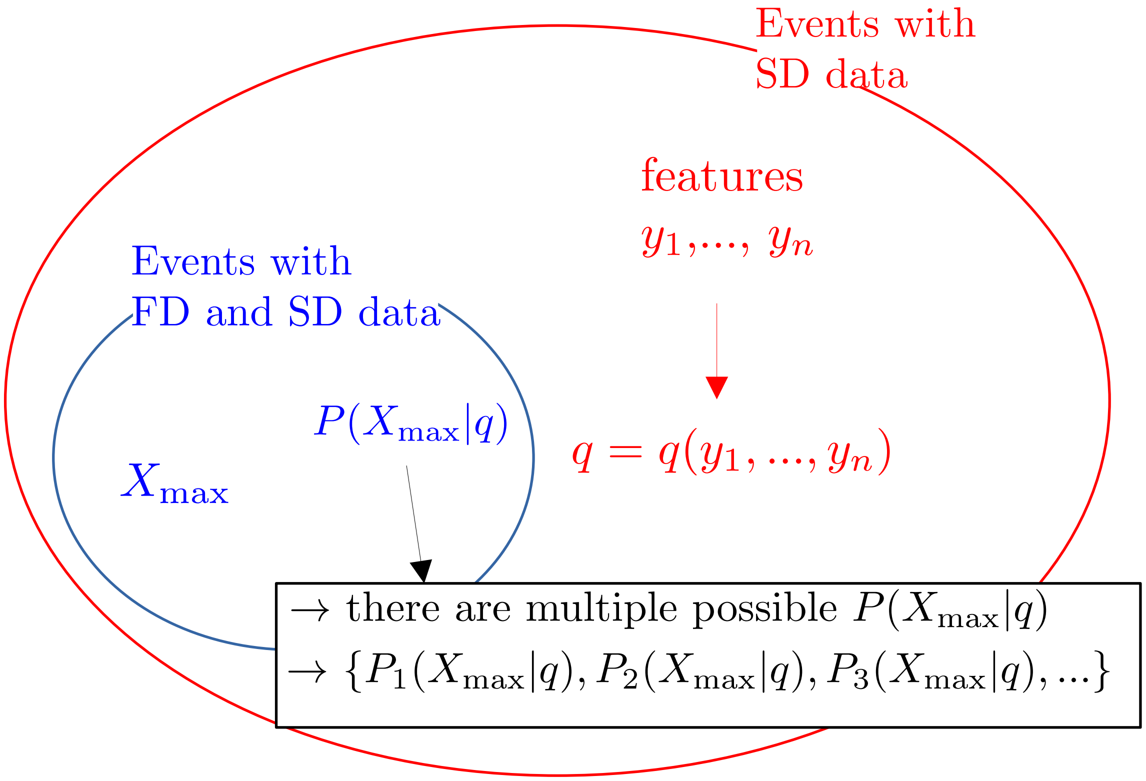
$X_{\max}$

Events with ONLY SD data
(22000 events)

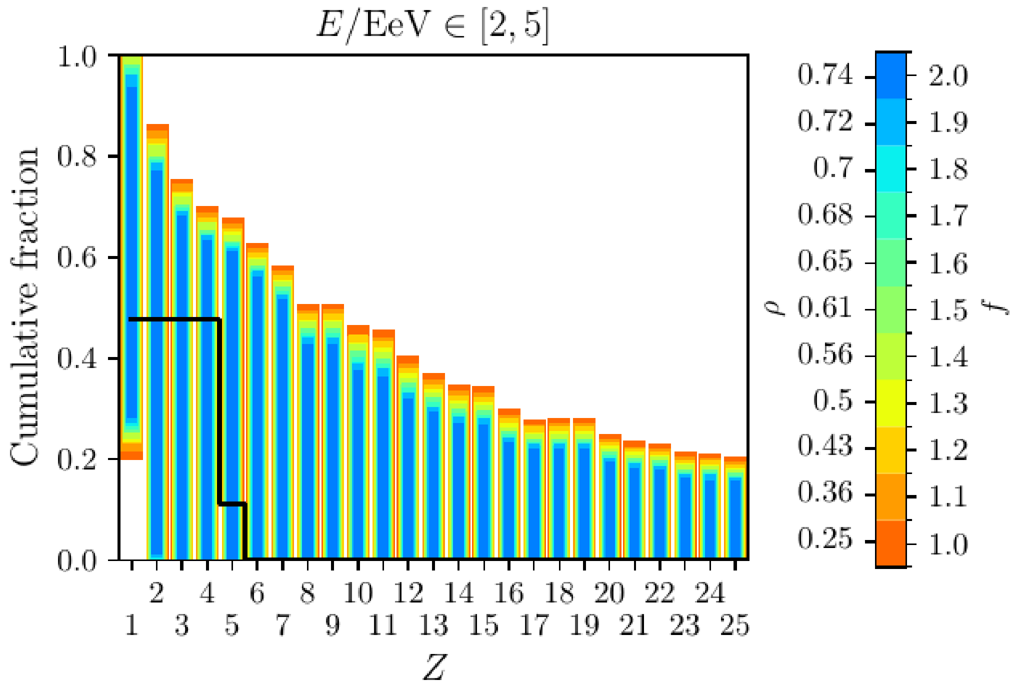
$X_{\max} \sim P(X_{\max}|q)$
(large uncertainties)

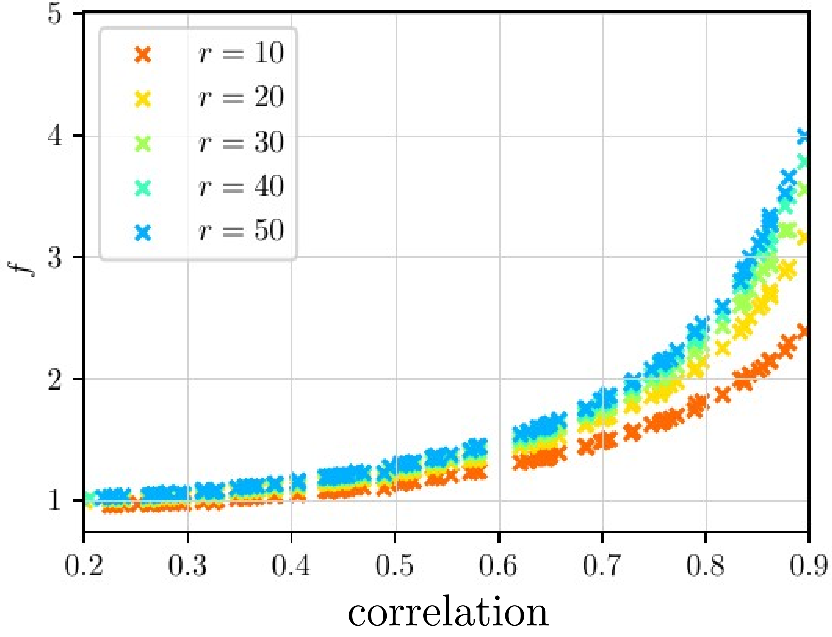
Effectively $>$ 200 events with FD and SD

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



Ground correlation





Pierre Auger Collaboration $\rightarrow \rho = 63\%$