News on muon puzzle! Pierre Auger Observatory measures muon fluctuations.

nn-119 Seminar - 18, 03

ALIBAT MA

No fluctuations puzzle!



(Pierre Auger Collaboration, Phys. Rev. Lett. 2021 arXiv: 2102.07797)

From the beginning..

20 years ago ..



The Pierre Auger Observatory







The Pierre Auger Observatory



Surface detector array

1600 stations, 1.5km grid, 3000km² 61 stations, 0.75km grid, 25km²

~100% duty-cycle

Fluorescence detector

4 sites

24 Telescopes with 1-30deg field-of-view 3 Telescopes with 30-60deg field-of-view

~15% duty-cycle

Plus: Engineering radio array underground muon detectors atmospheric monitoring ..





The spectrum, now



Flux suppression confirmed!

UHECR == protons ?

Getting the mass I: fluorescence only



Measurement of shower maximum

Fluorescence only!



Getting the mass II: muons!

Hybrid + inclined -> muons!



Measurement of muon content



Muon puzzle!

"Xmax- and muon-based observables of extensive air showers when compared with simulations give inconsistent interpretations for the cosmic ray mass"

Air shower development: the start



UHE interaction (~100 TeV)

- Hadronic!
- Exotic?
 - Black holes? •
 - Fireball? •
 - Chiral symmetry? •

- New (exotic) particles? ٠
- Lorentz invariance?

EAS according to SM ?

Air shower development: two cascades



Air shower development: energy flow



Air shower development: observables



Shower profile & Xmax: EM cascade, first few hadronic interactions

 $E_n^{\rm EM} = (1 - 0.8^n) E_0$

muons: **Full** hadronic cascade muons produced at end

 $\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}$

The muon puzzle



EM cascade

Two scenarios

 $E_{\rm had}$

 \mathcal{U}



New physics scenario
First (UHE) interaction modified,
Process missing in interaction models

- exhibit Lorentz Invariance Violation?
- Chiral Symmetry Restoration
- severe enhancement of strangeness? (fireball, string-percolation)
- => all increase E_{had} => increase μ

2) Standard physics scenario all hadronic interactions modified by a small amount interaction models essentially correct

Air shower development: fluctuations







"fluctuations are dominated by the 1st interaction"

Measurement of muon fluctuations



All fluctuations



Muon fluctuations



4-mass-Xmax-fit:

Ansatz: 4 different primaries

Take: Xmax measurements, Sibyll model

==> at 10**19eV:

0% iron 60% nitrogen 37% helium 3% proton

Muons at 10**19eV



 $\langle X \rangle_{mix} = f \langle X \rangle_1 + (1-f) \langle X \rangle_2$

$$\sigma_{mix}^2(X) = f\sigma_1^2 + (1-f)\sigma_2^2 + f(1-f)\Delta(\langle X)^2$$

Muons & Xmax



Conclusion

* new physics scenario for muon puzzle -> not dead but also not needed.

* fine-tuning of hadronic models (hadronic shower) sufficient



* fluctuations good probe of high energy interactions & new physics \rightarrow watch out for future publications !

Outlook

AugerPrime upgrade











