The Five Sigmas in Ultra-high-energy Cosmic Rays and more ...

An incomplete review of measurements

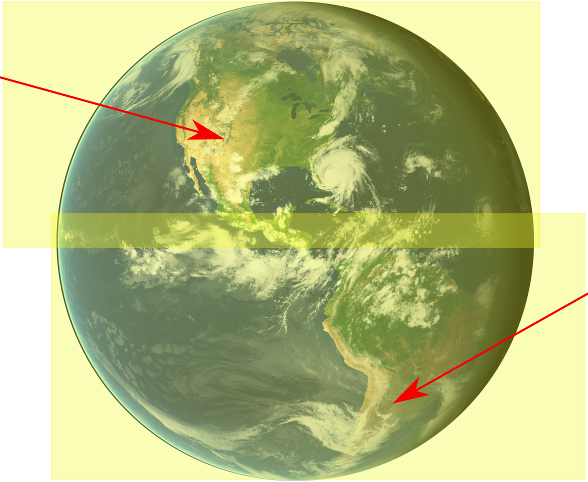
Ioana C. Mariș

Universite Libre de Bruxelles

CRIS-MAC 2024, Trapani

UHECRs with full sky coverage and complementary techniques

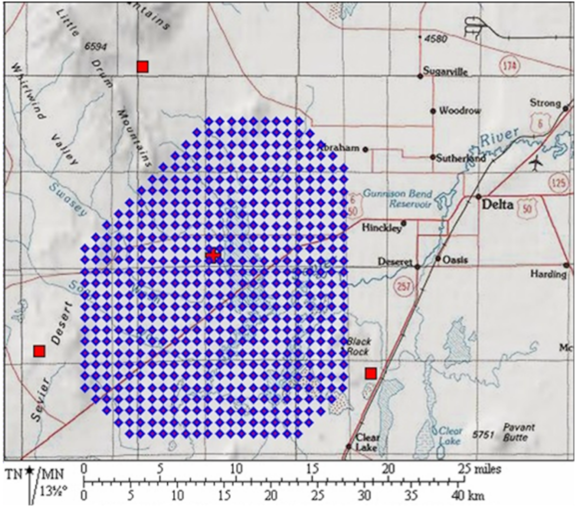
Telescope Array
Delta, Utah, USA
130 researchers
5 countries



Pierre Auger Observatory
Province of Mendoza, Argentina
370 researchers
18 countries

This talk focusing on the work or the common working groups (WG)

Telescope Array (Delta, Utah, USA)



680 km^2(507 scintillators), 36 telescopes, started in 2008

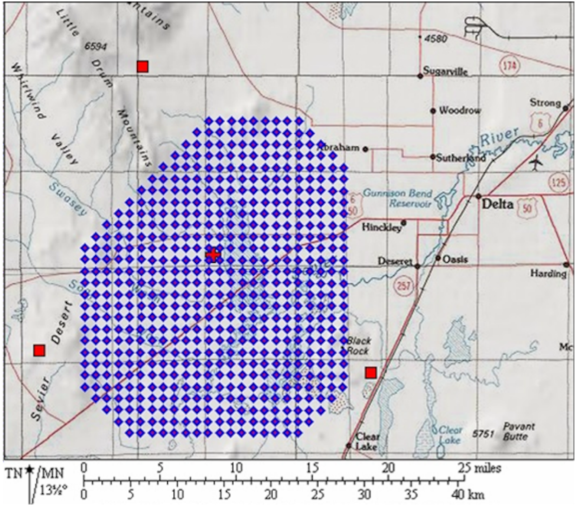
TA coll., NIM 689 (2012) 87-97

Fluorescence telescopes

Surface detectors

Next talk by Shunsuke Sakurai

Telescope Array (Delta, Utah, USA)



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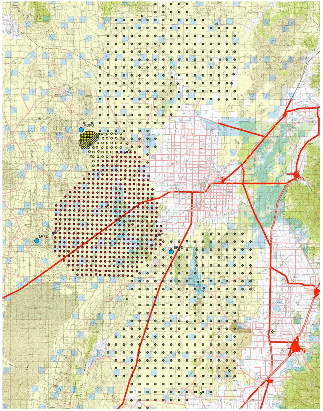
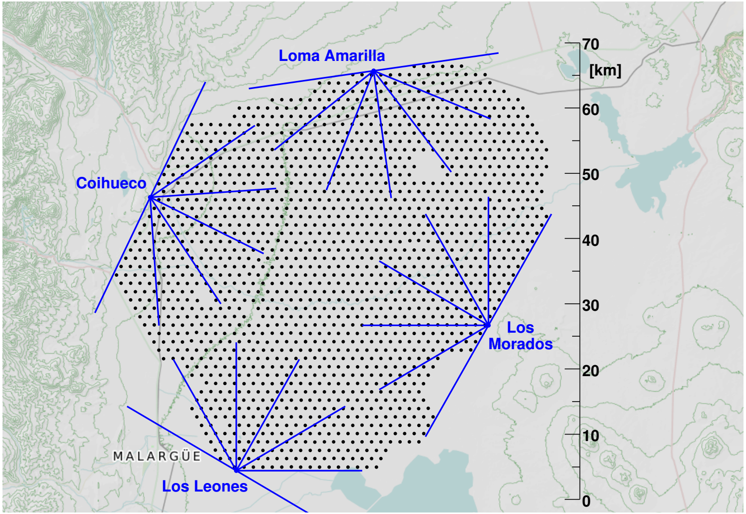


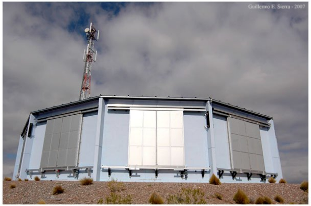
Surface detectors

Next talk by Shunsuke Sakurai

Pierre Auger Observatory (Malargue, Argentina)



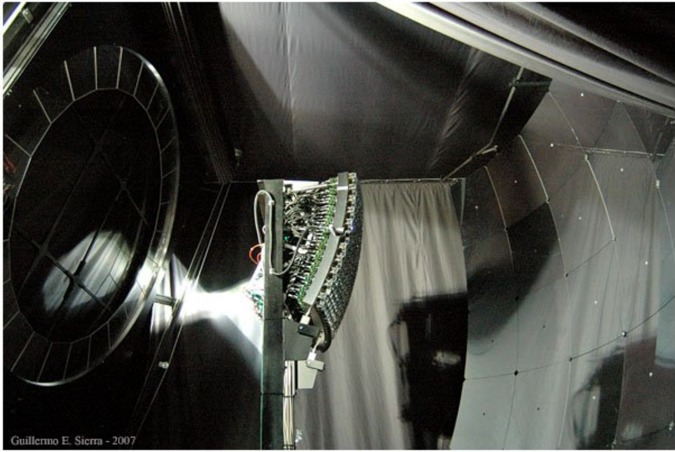
Fluorescence Telescopes



Surface detectors

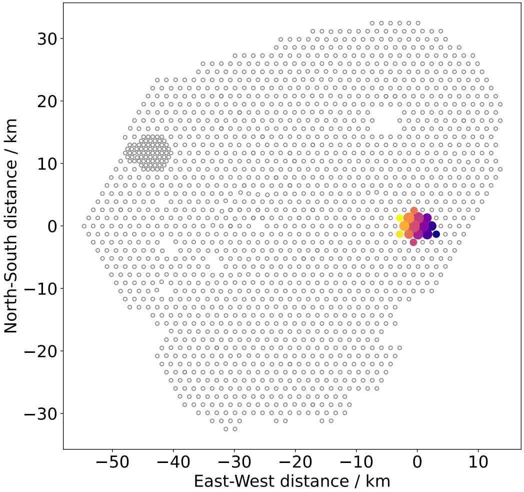
3000 km^2 (1660 detecteurs), 27 telescopes, started in 2004

Auger coll., NIM A 798 (2015) 172-213

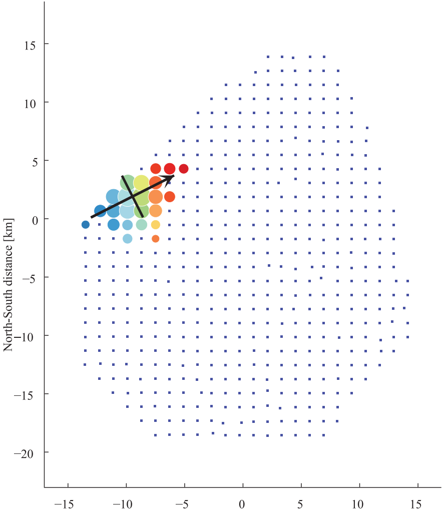

Guillermo E. Sierra - 2007

Examples of the higest energy events

Auger: 72 EeV, 36 degrees



TA: 244 EeV, 38 degrees



TA coll. Science 382, 903-907 (2023)

Auger coll. ApJS 264 50 (2023)

Examples of the higest energy events

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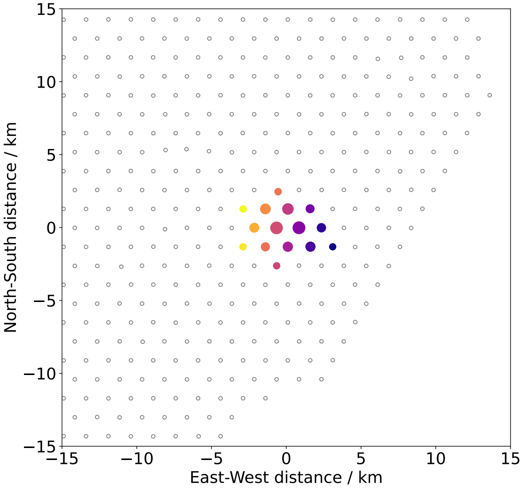

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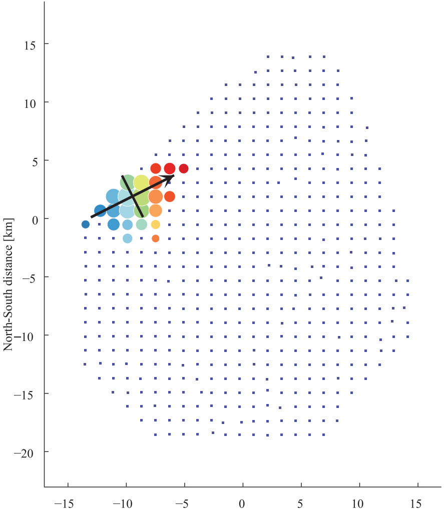


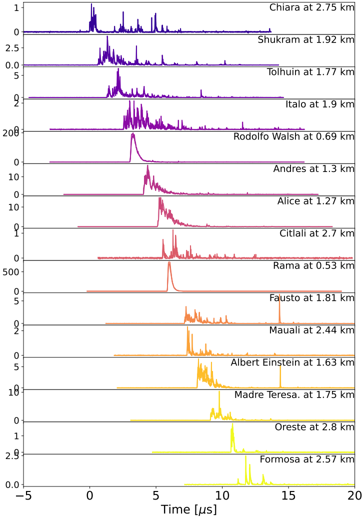
Auger coll. ApJS 264 50 (2023)

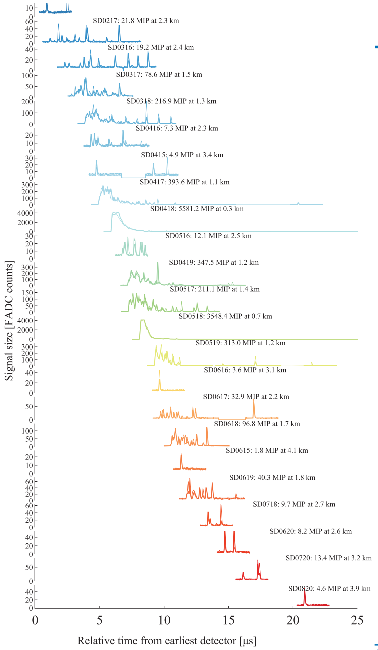
TA coll. Science 382, 903-907 (2023)

Signals in individual detectors

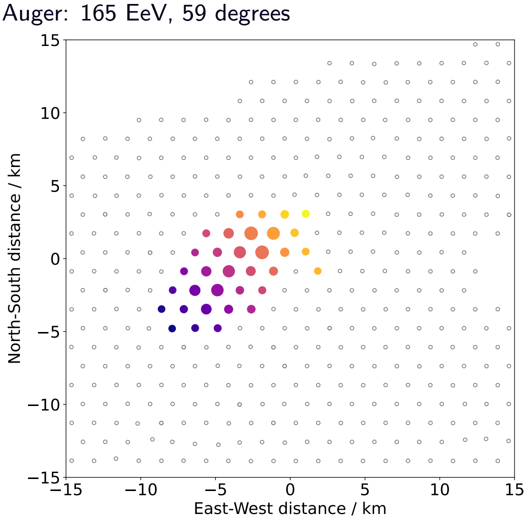
Raw level signals are follow the structure of the air-shower particles

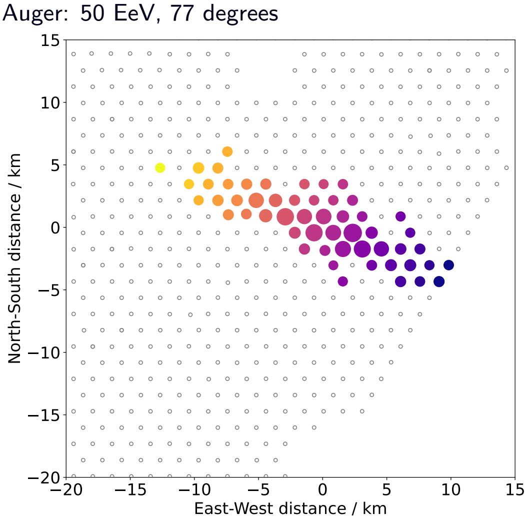
Similar in Auger and TA





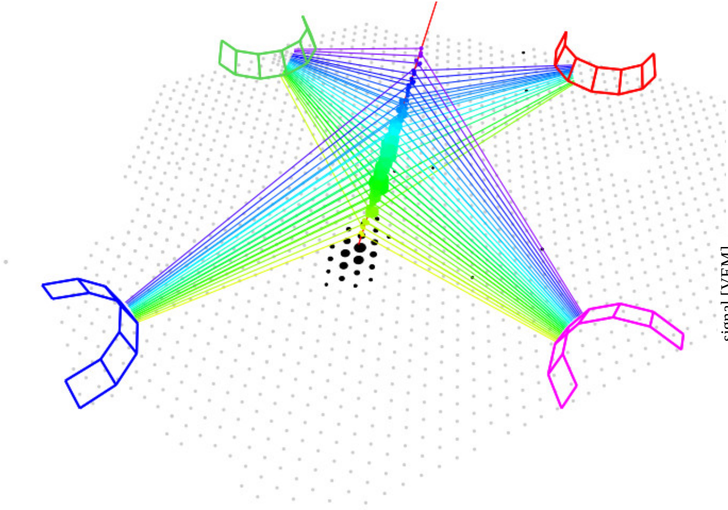
Some more examples of the most energetic events

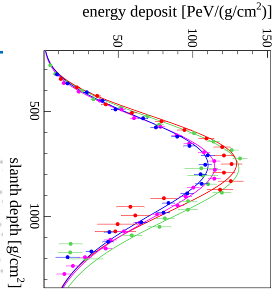


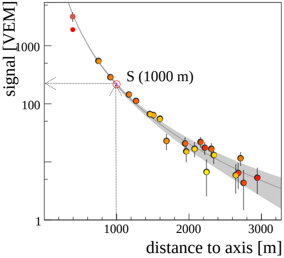


opendata.auger.org, 20/03/2024, release 3, DOI 10.5281/zenodo.10488964

From air-showers to primary particle

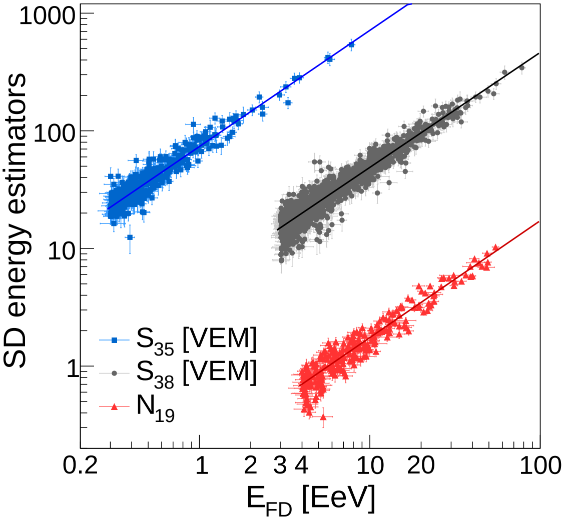


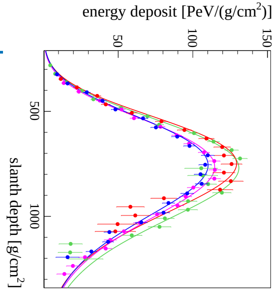


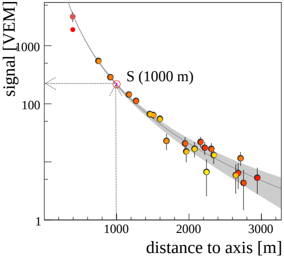


$E_{FD} = \int dE/dX +$ invisible energy correction, $E_{SD} = f(\theta, S1000)$

Cross calibration with the fluorescence detectors

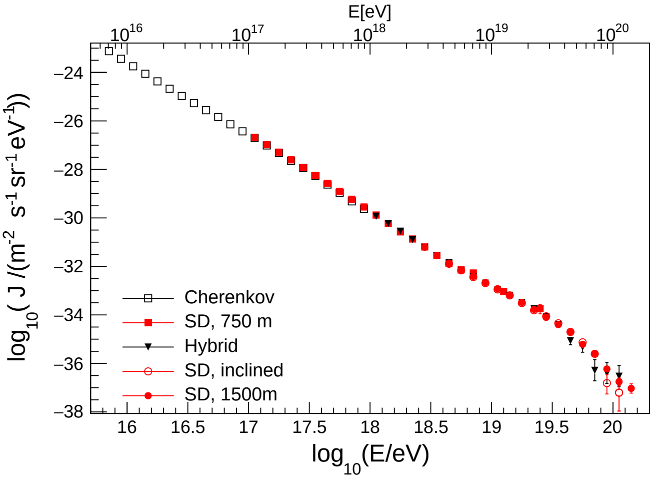


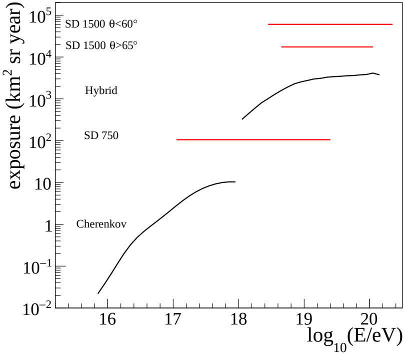




$E_{FD} = \int dE/dX +$ invisible energy correction, $E_{SD} = f(\theta, S1000)$

The second knee and the instep

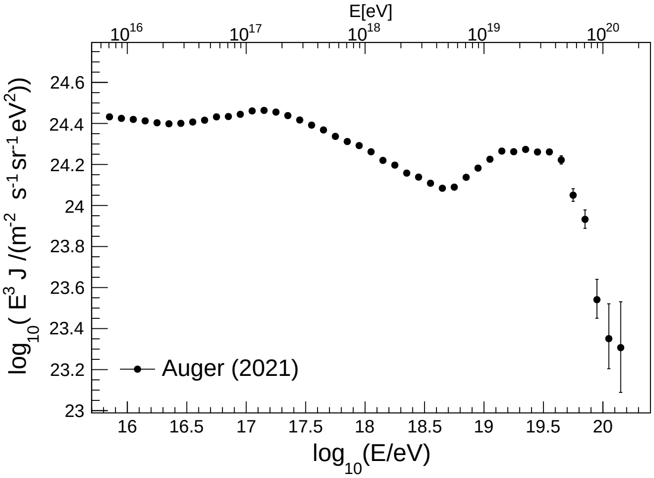




- spectrum obtained from the combination of 5 energy spectra

- common energy scale (14% systematic uncertainty)

The second knee and the instep

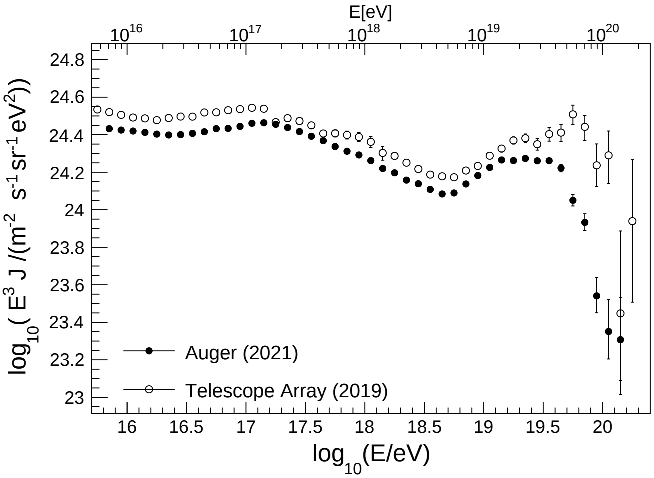


Presence of the second knee and a new feature: the instep

Auger coll., PRL 125 (2020) 121106,

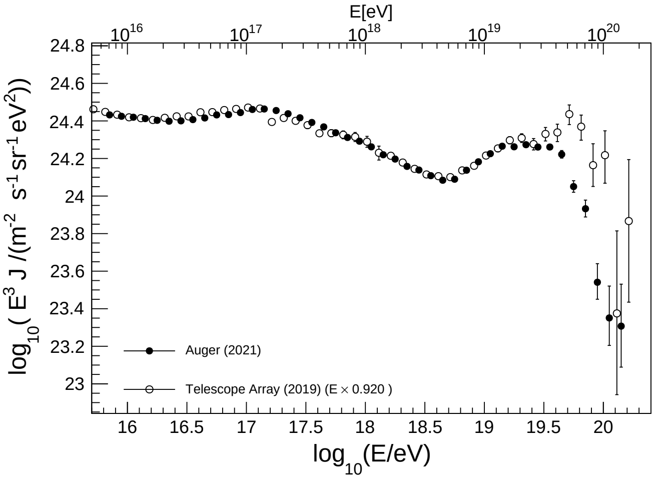
Eur. Phys. J. C 81 (2021) 966,

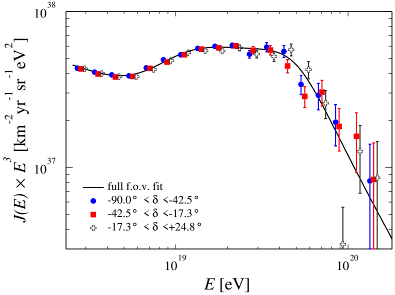
Comparison with Telescope Array measurement

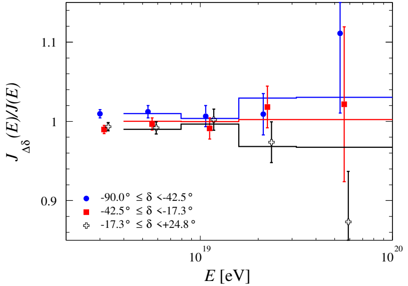


TA coll. ApJ 865 (2018) 74, Astropart.Phys. 80 (2016) 131-140

Comparison with Telescope Array measurement: declination dependency?



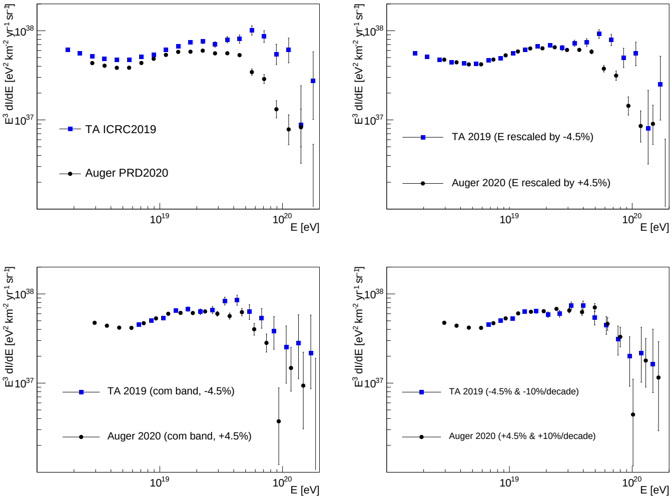




TA coll. ApJ 865 (2018) 74, Astropart.Phys. 80 (2016) 131-140

Auger data: just the expected flux difference from the dipole

Energy spectrum in the common declination band

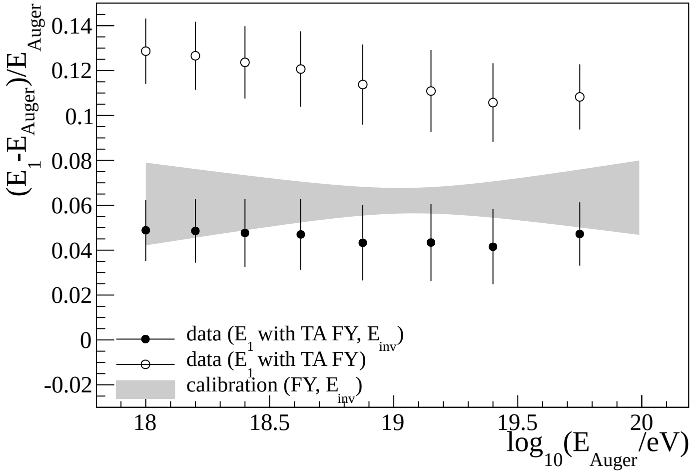


Constant 9% and a 10% per decade difference

Can it be explained by the different systematic uncertainties? (14% Auger, 21% TA)

O. Deligny for the WG, ICRC 2019, PoS 234

Energy changes for Auger with TA settings



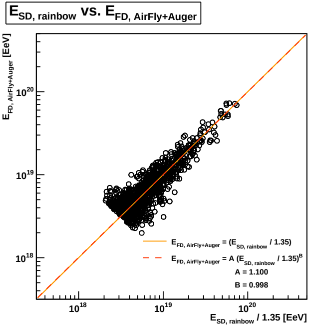
⇒ Using the TA assumptions of FY and invisible energy (proton, QGSJetII-03) the Auger energy scale would change by 6%

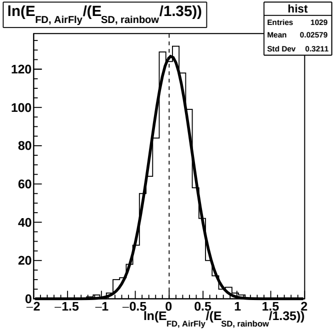
FY: NIM A 372, 527 (1996)

Astropart. Phys. 25, 129 (2006)

I.C. Mariș for the WG, UHECR Symposium, 2014

Energy changes for TA with Auger settings





⇒ Using the Auger assumptions on FY and invisible energy the TA energy scale would also change by a constant 8% (standard FD scale 1.27 becomes 1.35)

FY: Astropart. Phys., 42, 90 (2013), Astropart. Phys., 28, 41 (2007)

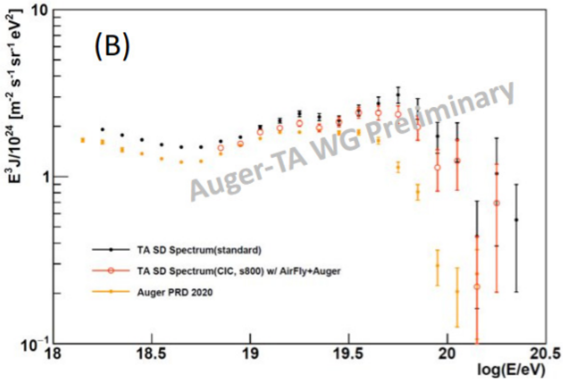
Inv. en.: Phys. Rev. D 100 (2019) 082003

Remaining independent energy systematic uncertainties after the same energy scale: 13% Auger, 17% TA

Using a common/unified parameter set between the UHECR experiments is still in discussion.

Y. Tsunesada for the WG, ICRC 2023, PoS 406

Energy changes for TA with Auger settings



Remaining independent energy systematic uncertainties after the same energy scale: 13% Auger, 17% TA

$\Rightarrow$ Using the Auger assumptions on FY and invisible energy the TA energy scale would also change by a constant 8% (standard FD scale 1.27 becomes 1.35)

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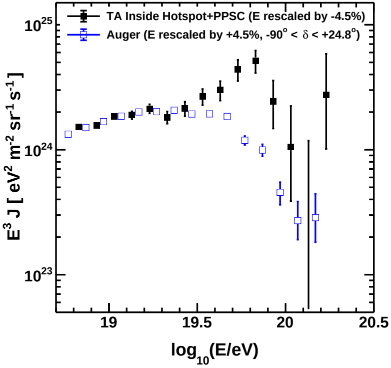
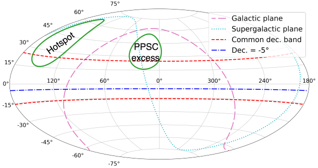
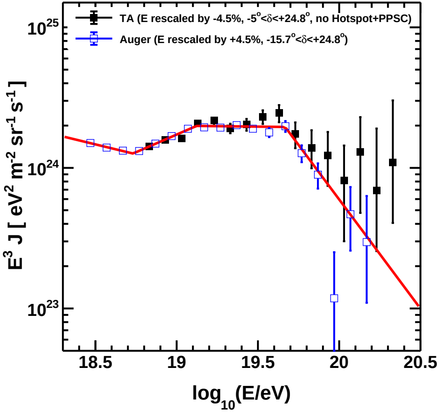
Y. Tsunesada for the WG, ICRC 2023, PoS 406

Is the flux difference caused by a specific part of the sky?

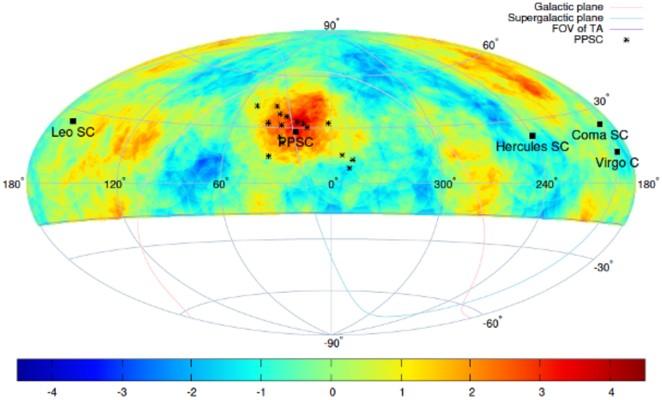






Hints of contributions from the Hotspot and the Perseus-Pieces cluster TA coll, arXiv:2406.08612v1

Perseus-Pieces Supercluster



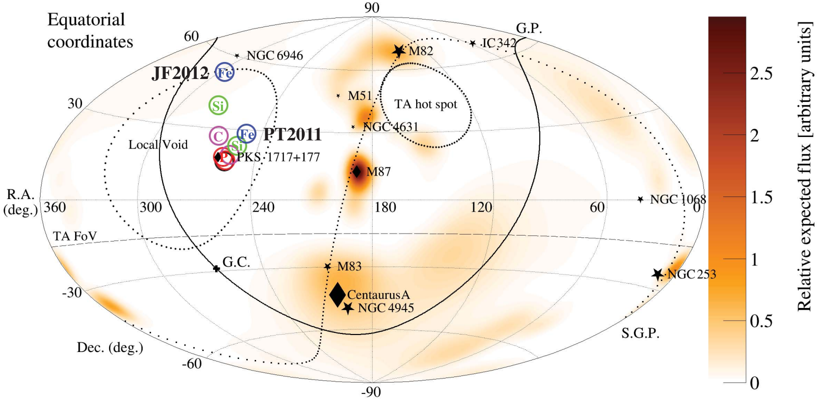
PPSC at 70 Mpc

Energies above 25 EeV in a 20°-radius circle

Significance: 3.5σ (4.2σ local)

TA coll, arXiv:2110.14827

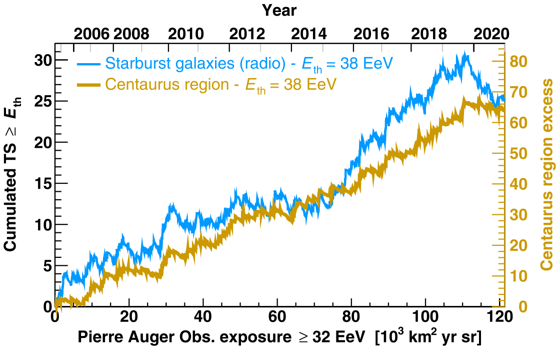
Where does the 224 EeV event come from?

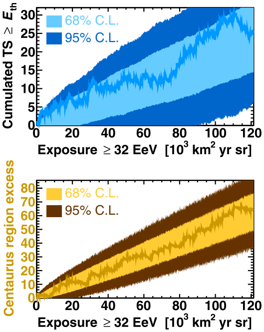


Nowhere?

TA coll. Science 382, 903-907 (2023)

Auger anisotropies at smaller scales





Catalog	E_{th} [EeV]	Fisher Search Radius, Θ [deg]	Signal Fraction, α [%]	TS_{max}	Post-trial p-value
All galaxies (IR)	40	16^{+11}_{-6}	16^{+10}_{-7}	18.0	7.9×10^{-4}
Starbursts (radio)	38	15^{+8}_{-4}	9^{+6}_{-4}	25.0	3.2×10^{-5}
All AGNs (X-rays)	39	16^{+8}_{-5}	7^{+5}_{-3}	19.4	4.2×10^{-4}
Jetted AGNs (γ-rays)	39	14^{+6}_{-4}	6^{+4}_{-3}	17.9	8.3×10^{-4}

Current significance 4.2σ

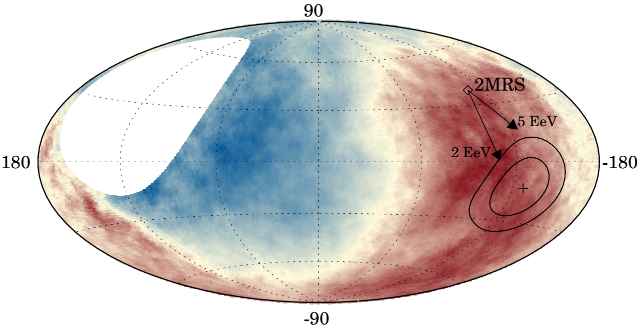
Auger coll. ApJ 935 170 (2022)

Expected 5σ reach in 2025-2030

Large scale anisotropy

Harmonic analysis in right ascension α

Significant dipolar modulation (6.6σ) above 8×10^{18} eV: $(7.3^{+1.1}_{-0.9})$% at $(\alpha, \delta) = (95^\circ, -36^\circ)$

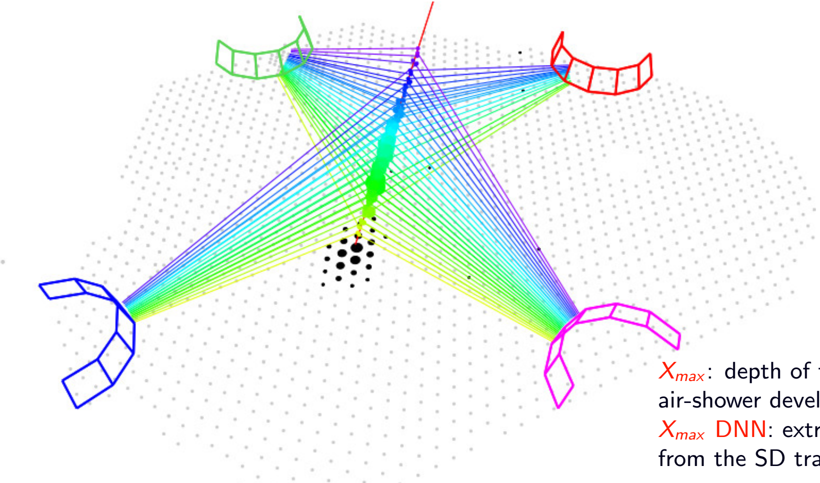


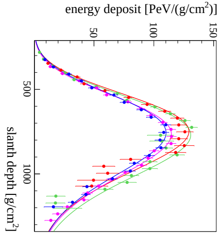
Auger coll., Science 357 (2017) 1266-1270

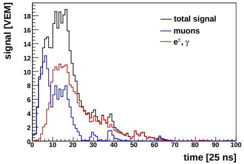
- Expected if cosmic rays diffuse in Galaxy from sources distributed similar to nearby galaxies (dipole structure in near-IR)
- Anti-dipole in the direction of the local void

Sensitivity to mass composition with FD and SD

FD: heavier particles develop higher in the atmosphere, with less fluctuations
SD: heavier particles produce more muons on the ground, thus smaller risetime

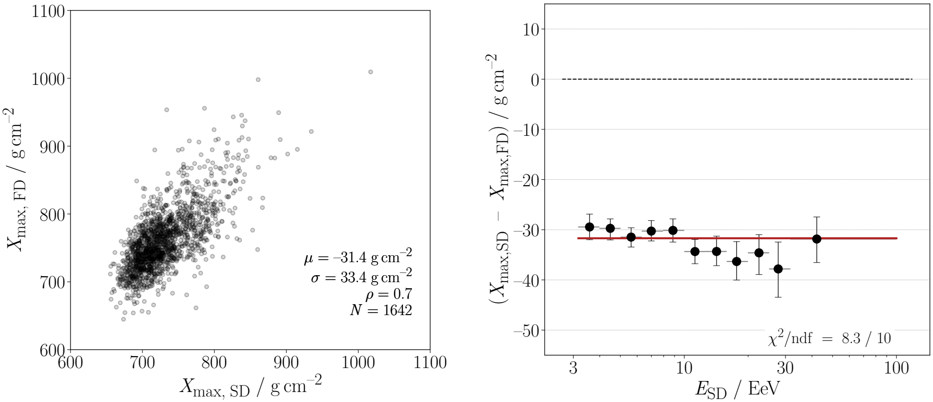






X_{max}: depth of the maximum of the air-shower development
X_{max} DNN: extract the mass composition from the SD traces

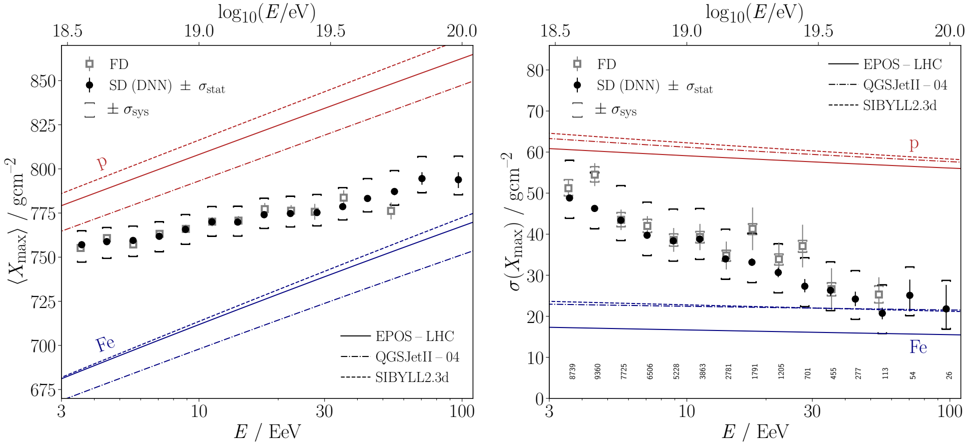
Mass composition using deep learning



Extract the $X_{\max}$ from the surface detector data
Systematic ucnertaities: between 9 and 13 g/cm^2

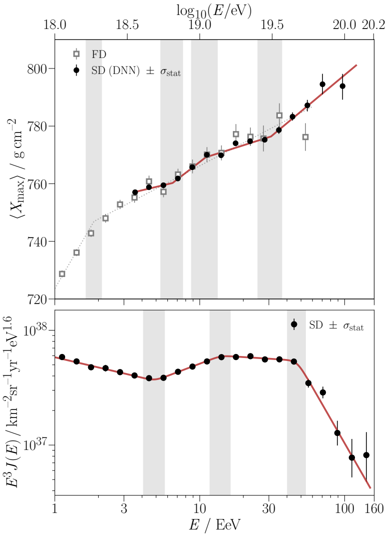
Auger coll. arxiv:2406.06315, arXiv:2406.06319, submitted to PRL/PRD

Mass composition using deep learning



First measurement of the fluctuations up to 100 EeV using the SD

Large statistics: better characterisation of the features

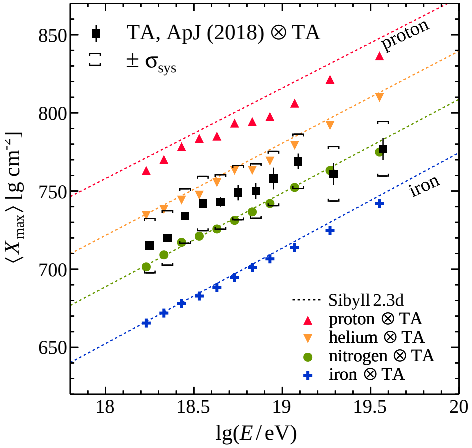


Positions of the features:

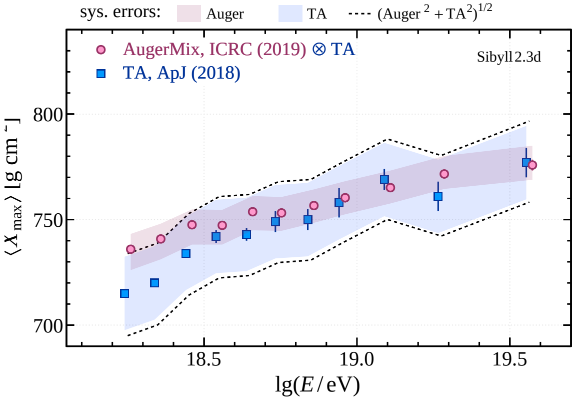
TABLE I: Best-fit parameters with statistical and systematic uncertainties for the identified elongation model that features three changes at energies (E_1, E_2, E_3) in the elongation rate (D_0, D_1, D_2, D_3) and an offset b of $\langle X_{\max}\rangle$ at 1 EeV. The positions of the features of the energy spectrum [53] are also given.

parameter val $\pm\,\sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{sys}}$	3-break model val $\pm\,\sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{sys}}$	energy spectrum val $\pm\,\sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{sys}}$
b / g cm^{-2}	$750.5 \pm 3 \pm 13$	
D_0 / g cm^{-2} decade^{-1}	$12 \pm 5 \pm 6$	
E_1 / EeV	$6.5 \pm 0.6 \pm 1$	$4.9 \pm 0.1 \pm 0.8$
D_1 / g cm^{-2} decade^{-1}	$39 \pm 5 \pm 14$	
E_2 / EeV	$11 \pm 2 \pm 1$	$14 \pm 1 \pm 2$
D_2 / g cm^{-2} decade^{-1}	$16 \pm 3 \pm 6$	
E_3 / EeV	$31 \pm 5 \pm 3$	$47 \pm 3 \pm 6$
D_3 / g cm^{-2} decade^{-1}	$42 \pm 9 \pm 12$	

TA-Auger mass composition



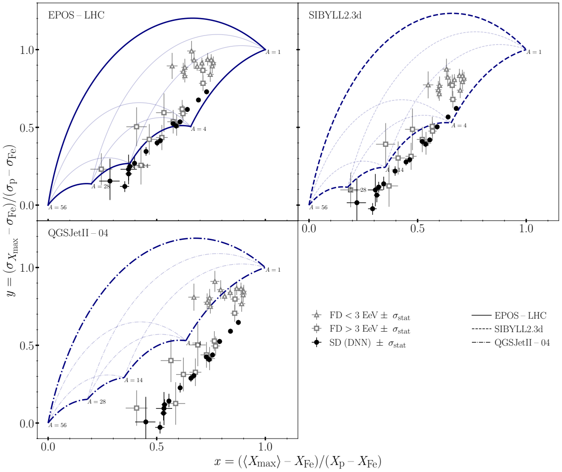
TA coll., Astrophys. J. 858 (2018) 76.

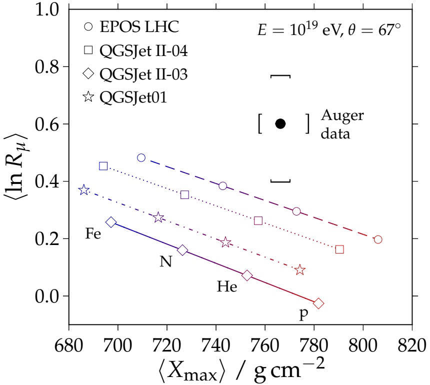


No discrepancies beyond the statistical and systematic errors in X_{max} and $\sigma(X_{max})$ of the two observatories could be identified... the TA and Auger measurements are found to be consistent with each other.

A. Yushkov for the WG, ICRC 2023. PoS 249, paper in preparation

Probing hadronic interactions at ultra high energies

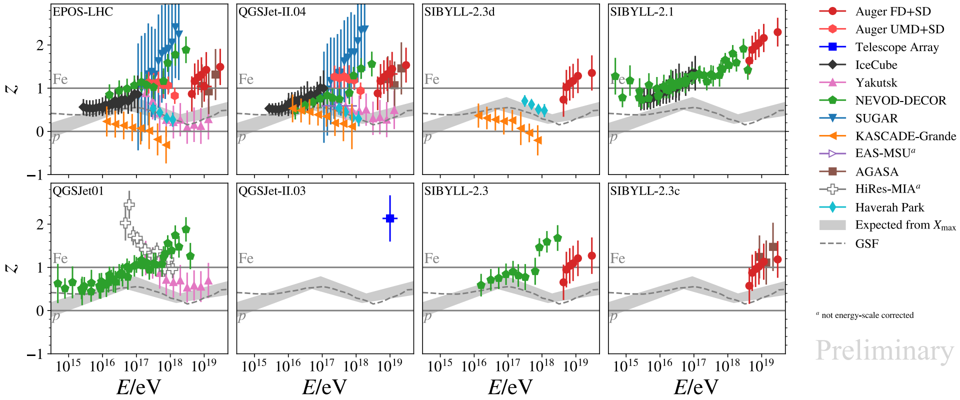




Discrepancy between data and simulations, *the muon puzzle*

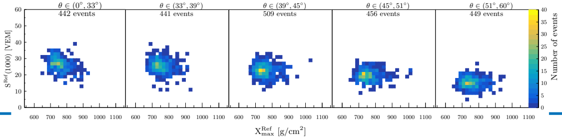
Auger coll. arxiv:2406.06315, arXiv:2406.06319, submitted to PRL/PRD

Probing hadronic interactions at ultra-high energies

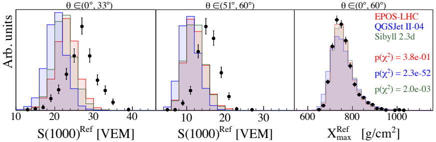


$z = [\ln(N_\mu) - \ln(N_{\mu,\mathrm{proton}})]/[\ln(N_{\mu,\mathrm{iron}}) - \ln(N_{\mu,\mathrm{proton}})]$ J. Arteaga-Velazquez for the WHISP WG, ICRC 2023, PoS 466

Modification of hadronic interaction models

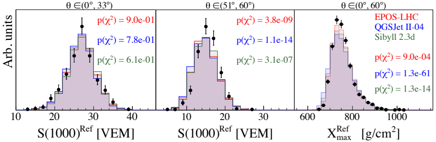


Combined fit of (S1000, X_{max})
(hybrid events, 3 EeV - 10 EeV)



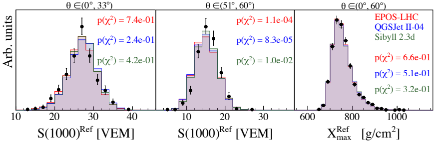
(a) No MC corrections

Combined fit of (S1000, X_{max}) allowing for an angular dependent rescaling of N_{μ}



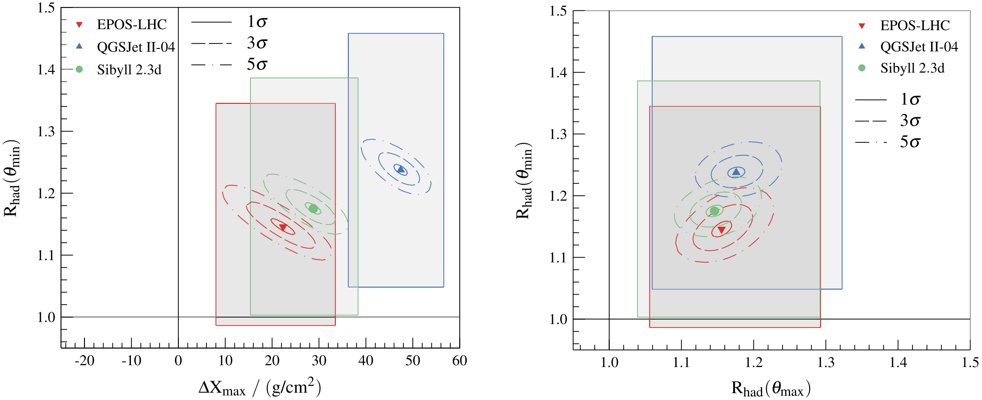
(b) MC corrections: $R_{\mathrm{Had}}(\theta)$

Combined fit of (S1000, X_{max}) allowing for an angular dependent rescaling of N_{μ} and shifting X_{max} of all primaries



(c) MC corrections: ΔX_{max} and $R_{\mathrm{Had}}(\theta)$

A shift in $X_{\max}$ and muon number



Main effect from re-scalling muon component in a zenith angle dependent way

A deeper $X_{\max}$ leads to further improvements

Auger coll., Phys. Rev. D 109, 102001 (2024)

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Conclusion

The two ultra-high-energy cosmic rays Observatories provide more and more data with better resolutions and deeper understading of the systematic uncertainties.

Modern techniques provide further insights in the air-shower physics and measurements, revealing features in the $X_{\max}$ and flux distributions

Indications for the sources of UHECRs in the PPSC, Centaurus A region and an undoubtful energy dependent dipolar pattern present at the highest energies

Looking forward to the results from the next years with AugerPrime and TAx4!