Depth of maximum of air-shower profiles: testing the compatibility of the measurements at the Pierre Auger Observatory and the Telescope Array

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for the Pierre Auger and Telescope Array Collaborations

UHECR 2024 MALARGÜE

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Data sets from the Fluorescence Detectors

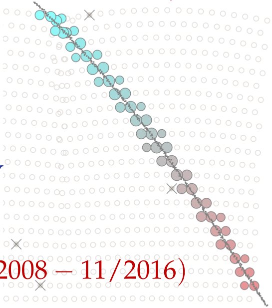
Pierre Auger

Surface Detector: 3000 km^2

13 years of data (12/2004 – 12/2017)

12773 events†

[Auger, ICRC (2019), PoS 482]



Telescope Array

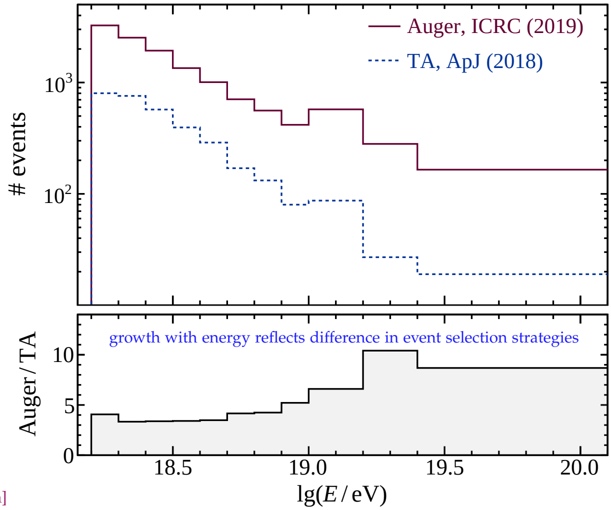
Surface Detector: 700 km^2

8.5 years of data (05/2008 – 11/2016)

3330 events

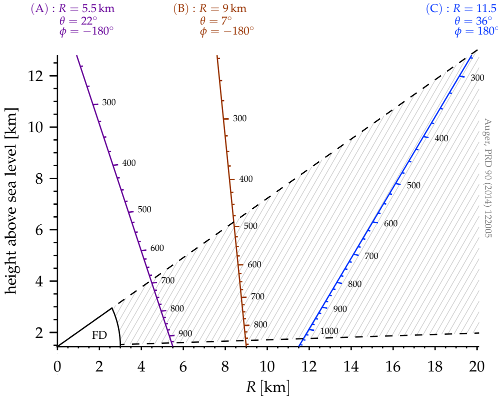
[ApJ 858 (2018) 76]

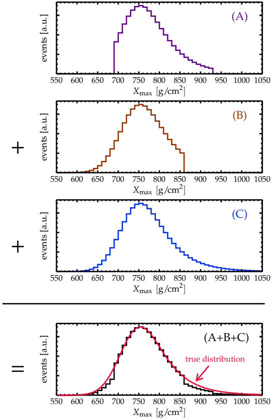
common energy range: $\lg(E/\mathrm{eV}) > 18.2$, TA energy binning



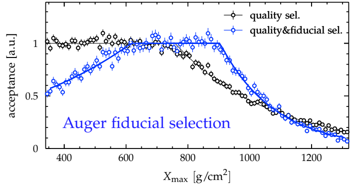
† Auger (12/2004 – 12/2021): 17605 events (+38%) [T. Fitoussi, this session]

Event selection strategies: detector acceptance





Taking all geometries:
smaller relative acceptance
to shallow and deep events



Pierre Auger select geometries similar to (C), efficiency ≈ 40% $\lg(E/\mathrm{eV}) = 18.2$, 60% $\lg(E/\mathrm{eV}) = 19.2$

Telescope Array keep all geometries to maximize statistics

X_{max} moments measured at Auger

Event selection

◇ fiducial selection: minimal acceptance biases on tails of X_{max} distributions

$\langle X_{max} \rangle$

◇ corrected for residual acceptance and reconstruction biases

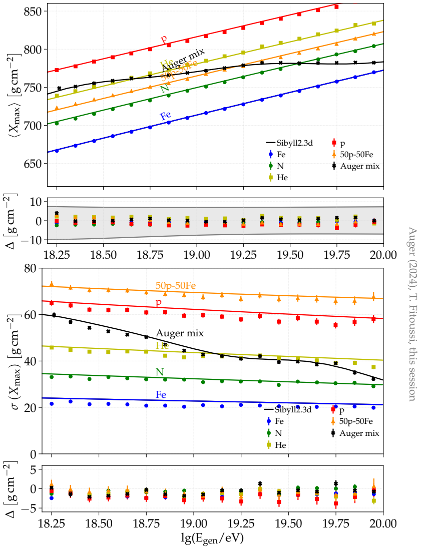
$\sigma(X_{max})$

◇ detector resolution (including atmosphere) is subtracted

$\langle X_{max} \rangle$, $\sigma(X_{max})$ are unbiased, directly comparable to predictions of air-shower simulation codes

X_{max} distributions

◇ simulations should be folded with the detector effects ⊗ Auger



lines — air-shower simulations
points — simulations after full analysis chain

X_{max} moments measured at Auger

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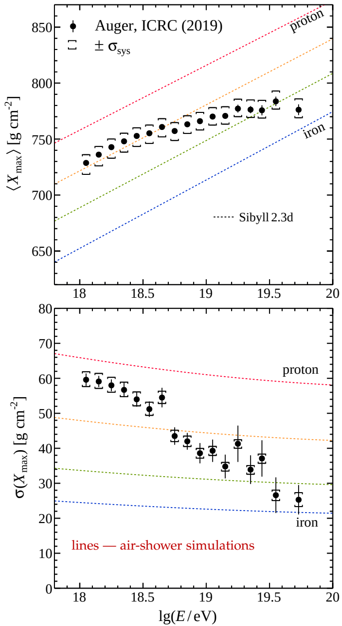


Auger, PoS (ICRC 2019) 482

X_{max} moments measured at TA

Event selection

◇ no fiducial selection, acceptance biases on tails of X_{max} distributions

$\langle X_{max} \rangle$

◇ acceptance biases are mostly seen for protons

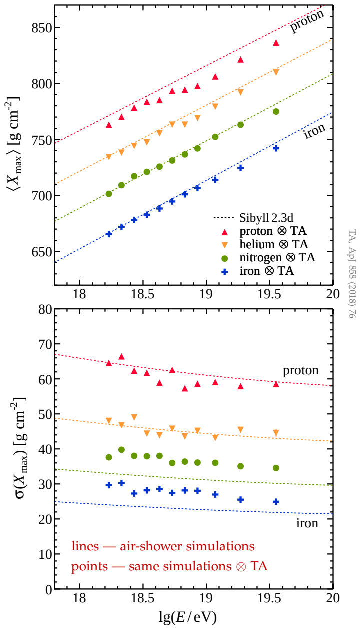
$\sigma(X_{max})$

◇ detector resolution effect is visible for nitrogen and iron

$\langle X_{max} \rangle$, $\sigma(X_{max})$ are not corrected for experimental biases and are not directly comparable to predictions of air-shower simulation codes

X_{max} distributions

◇ simulations should be folded with the detector effects ⊗ TA



X_{max} moments measured at TA

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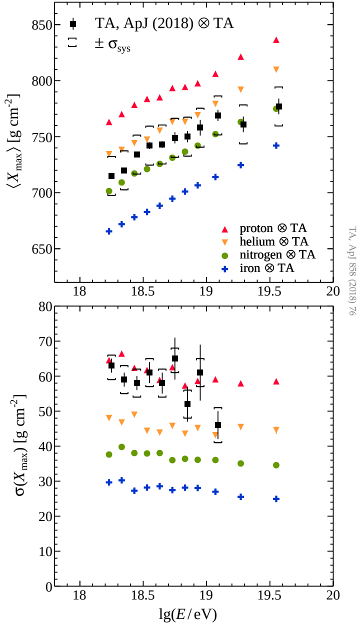
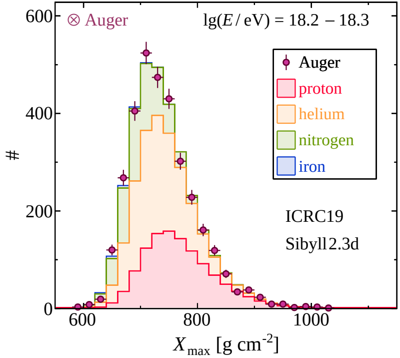
X_{max} distributions

◇ simulations should be folded with the detector effects $\otimes$ TA

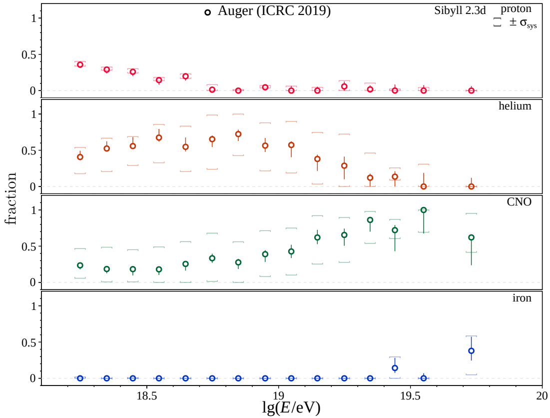


Method to transfer Auger data into TA detector

Combine (p, He, N, Fe) of Sibyll 2.3d to fit Auger X_{max} distributions



Energy evolution of nuclear fractions in fits of the Auger X_{max} distributions

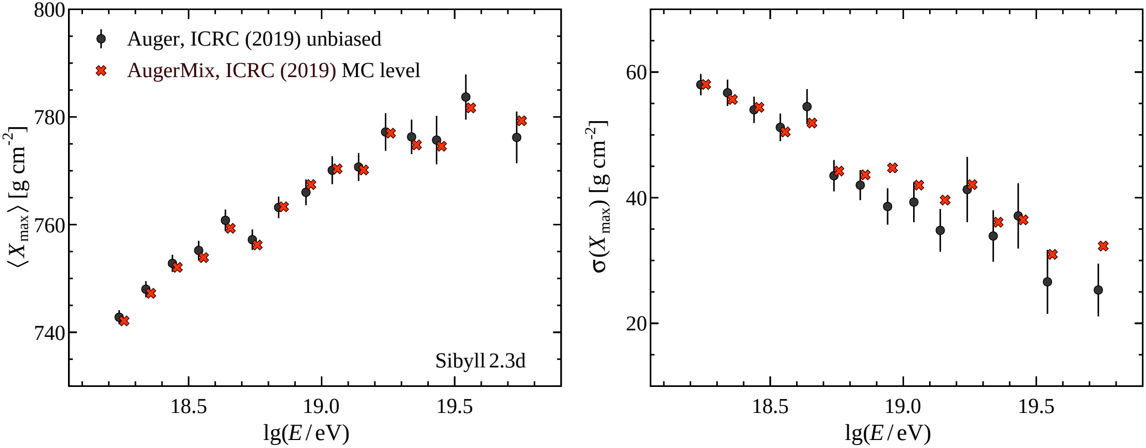


Use as a proxy simulated X_{max} mixes (AugerMix) and process them with the TA machinery

Result: AugerMix ⊗ TA — representation of Auger X_{max} distributions folded with the TA detector and analysis effects

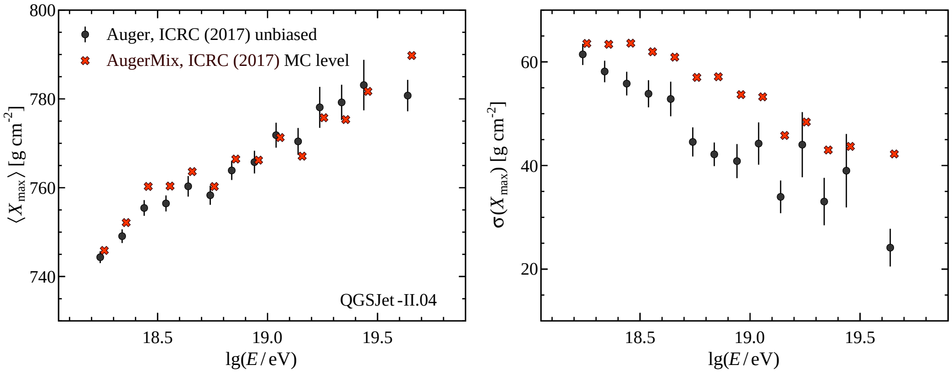
X_{max} moments in AugerMix and Auger data

Good description with AugerMix of $\langle X_{max} \rangle$ and $\sigma(X_{max})$ measured at Auger



MC level — X_{max} moments directly from Monte-Carlo air-shower simulation codes (no detector effects)

X_{max} moments in AugerMix and Auger data: why QGSJet-II.04 can not be used



◇ width of the observed X_{max} distributions is not reproduced well

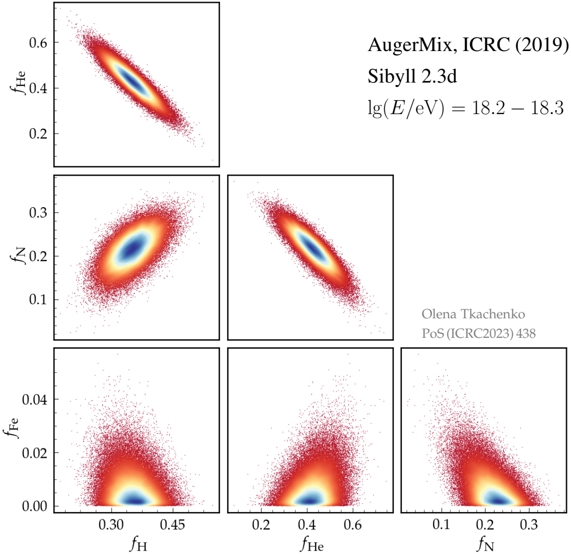
◇ p-values in the fits Auger data are ≈ 0.01 for $\lg(E/\mathrm{eV}) = 17.8 - 19.2$

QGSJet-II.04 $\langle X_{max} \rangle$ predictions are strongly disfavored by the Auger data

[most recent Auger papers: PRD 109 (2024) 102001; DNN SD X_{max} with $> 10 \times$ FD statistics, accepted by PRD and PRL]

Estimation of statistical uncertainties on X_{max} moments $\otimes$ TA

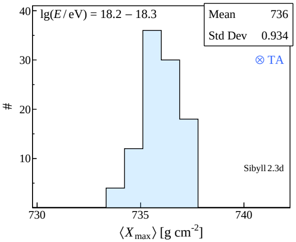
Markov Chain Monte Carlo fits: posterior distributions of fractions

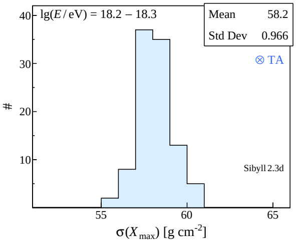


AugerMix, ICRC (2019)
Sibyll 2.3d
$\lg(E/\mathrm{eV}) = 18.2 - 18.3$

Olena Tkachenko
PoS (ICRC2023) 438

- ◇ pick randomly 100 mixes from posterior distributions
- ◇ prepare 100 AugerMix samples $\otimes$ TA
- ◇ use 1σ of their $\langle X_{max}\rangle$ and $\sigma(X_{max})$ distributions as an estimate of statistical uncertainties





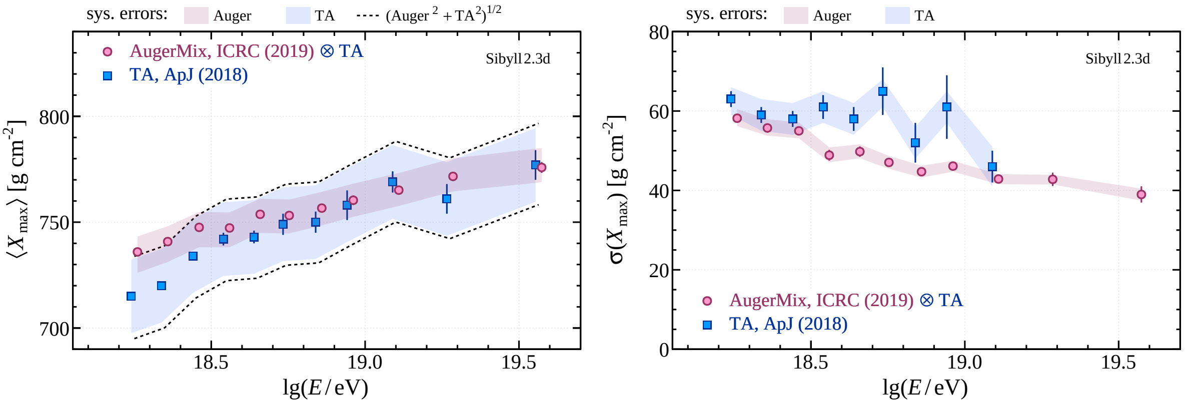
Comparison of the X_{max} moments measured at TA and Auger ⊗ TA

$\langle X_{max} \rangle$ — agreement withing statistical and systematic uncertainties, in particular for $\lg(E/\mathrm{eV}) > 18.5$

$\sigma(X_{max})$ — larger values in TA for $\lg(E/\mathrm{eV}) = 18.5 - 19.0$, possible reasons:

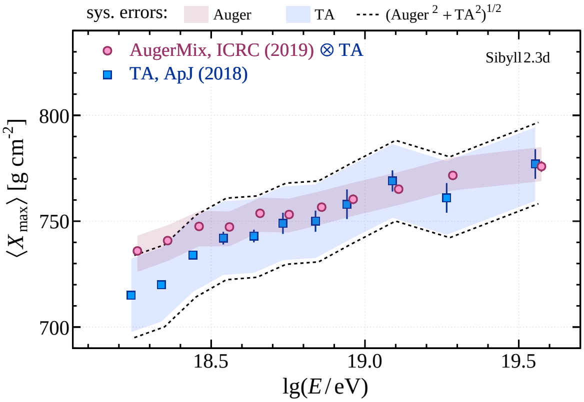
◇ constant aerosol profiles used in TA increase $\sigma(X_{max})$ by 18.9 g cm^{-2} (in quadrature) [ApJ 858 (2018) 76]

◇ a few deep events in data can increase $\sigma(X_{max})$ significantly (see X_{max} distributions in next slides)



Discrepancy in $\langle X_{max} \rangle$ at lower energies

TA $\langle X_{max} \rangle$ is shallower at $\lg(E/\mathrm{eV}) < 18.7$; difference is $\sim 20\ \mathrm{g\,cm^{-2}}$ for $\lg(E/\mathrm{eV}) = 18.2 - 18.4$



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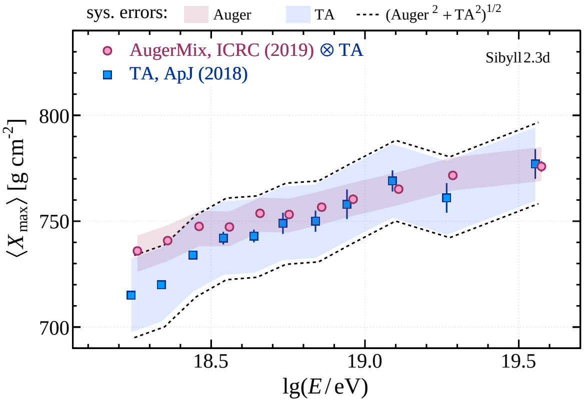
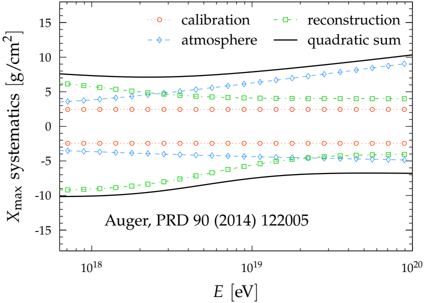


Far beyond $\sigma_{sys}(X_{max})$ energy dependence

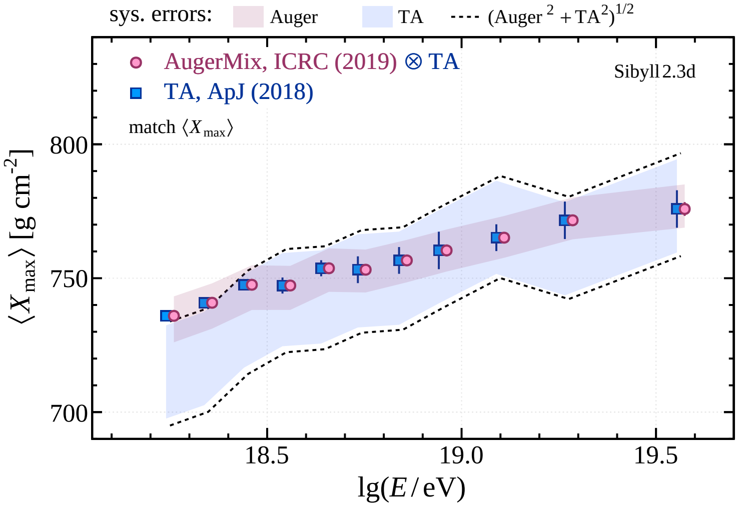
TA: constant $\sigma_{sys}(X_{max}) = 17.4\ \mathrm{g\,cm^{-2}}$

Auger: $\lesssim 5\ \mathrm{g\,cm^{-2}}$ change in this energy range



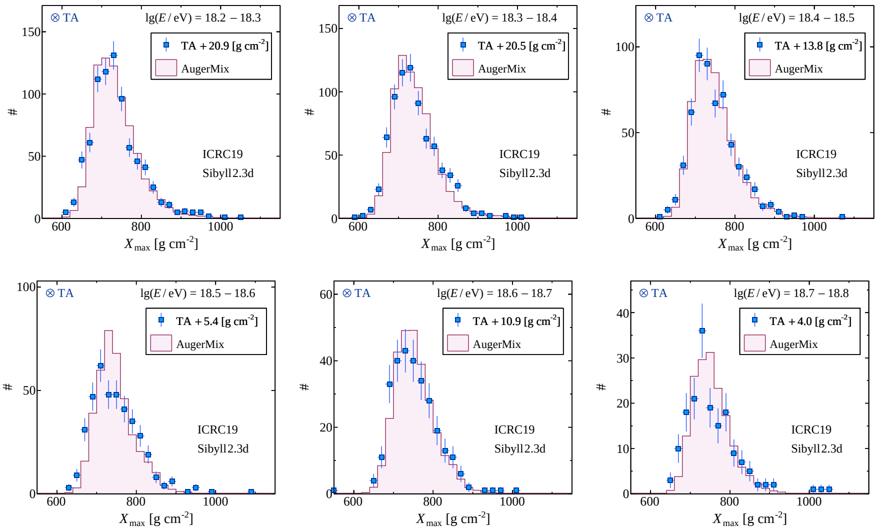
Compatibility of X_{max} distributions

To compare shapes, we align $\langle X_{max} \rangle$ of AugerMix and TA X_{max} distributions



Comparison of TA and AugerMix X_{max} distributions

Visually, good agreement in most of the energy bins



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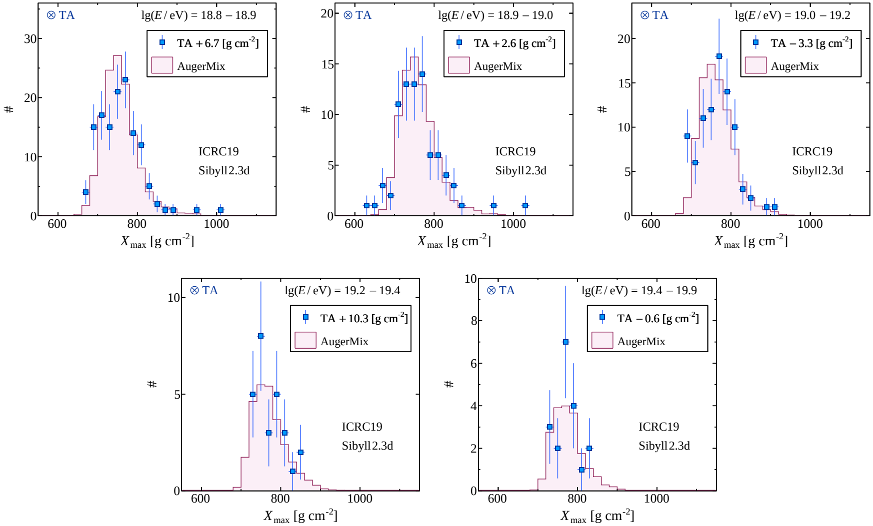

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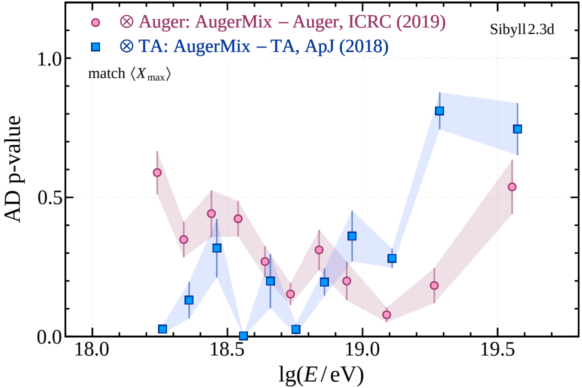

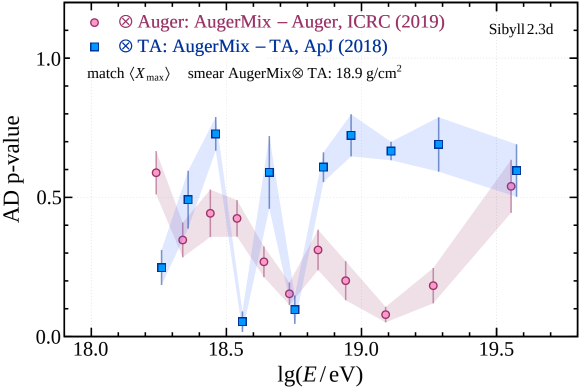

Constant aerosols: AugerMix ⊗ TA smeared by 18.9 $\mathrm{g\,cm^{-2}}$

Conclusions

$\langle X_{\rm max} \rangle$ and $\sigma(X_{\rm max})$ generally agree within statistical and systematic uncertainties

- ◇ origin of the energy trend in $\langle X^{\rm Auger}_{\rm max} \rangle - \langle X^{\rm TA}_{\rm max} \rangle$ at lower energies is not clear
- ◇ $\sigma(X^{\rm TA}_{\rm max}) > \sigma(X^{\rm Auger}_{\rm max})$ — partly can be attributed to the use of a static atmosphere model at TA

Shapes of $X_{\rm max}$ distributions agree well in most energy bins

Auger and TA measurements are compatible at the current level of statistics and understanding of systematics

Draft of the joint paper is under collaborations review