# Testing the Compatibility of the Depth of the Shower Maximum Measurements performed at Telescope Array and the Pierre Auger Observatory

## Auger-TA Mass Composition Working Group Report

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# Context and History

Both TA and Auger measure the nuclear composition of UHECRs by observing the $X_{max}$ distribution with SD/FD hybrid observations.

The conclusions and interpretations of these measurements have differed between the two experiments which has created confusion amongst outside observers.

TA and Auger employ different strategies in selecting the data sets for the measurements.

- Auger selects events to minimize biases in $X_{max}$ acceptance and reconstruction, and corrects $X_{max}$ moments for remaining biases.
- TA selects all well-understood events, and models biases in MC simulations.

Direct comparison of $X_{max}$ distributions and the moments of those distributions is hampered by this difference in strategy,

# Context and History

Beginning with UHECR 2012, the Mass Composition Working Group has tried to assess the degree of agreement between Auger and TA $X_{max}$ distribution measurements.

The minimally-biased Auger $X_{max}$ distributions are compared to mixtures of four nuclear species (H, He, N, Fe) as produced by a high-energy interaction model. The relative fractions can be taken as representing the Auger measurement, at a given energy. This is the Auger-Mix.

Using the same high-energy interaction model, a full simulation of the TA detector and analysis is done, and the species are mixed (using “thrown” values) according to the Auger-Mix. This is taken as being what TA *would have seen* given Auger’s measurements. We compare this directly to TA measurements.

# Context and History

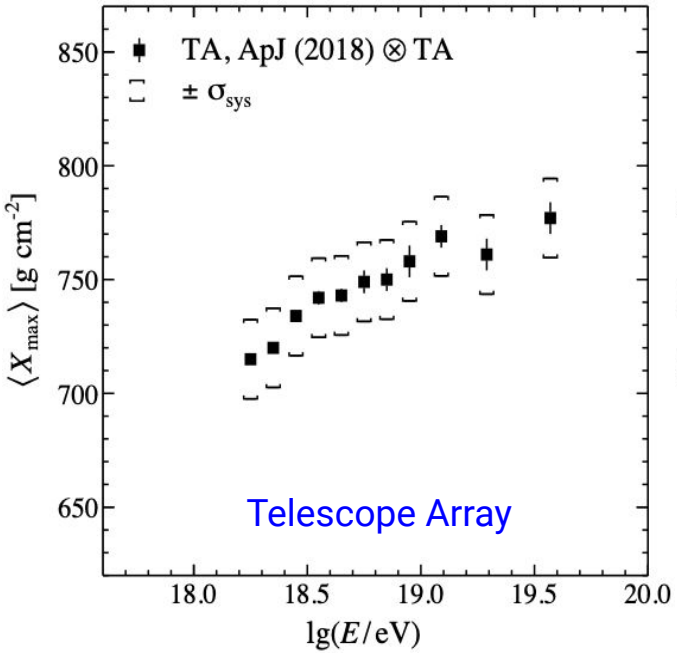
At UHECR 2014, the Auger-Mix was compared to TA MD hybrid using just $\langle X_{max} \rangle$. The result showed agreement within systematic uncertainties.

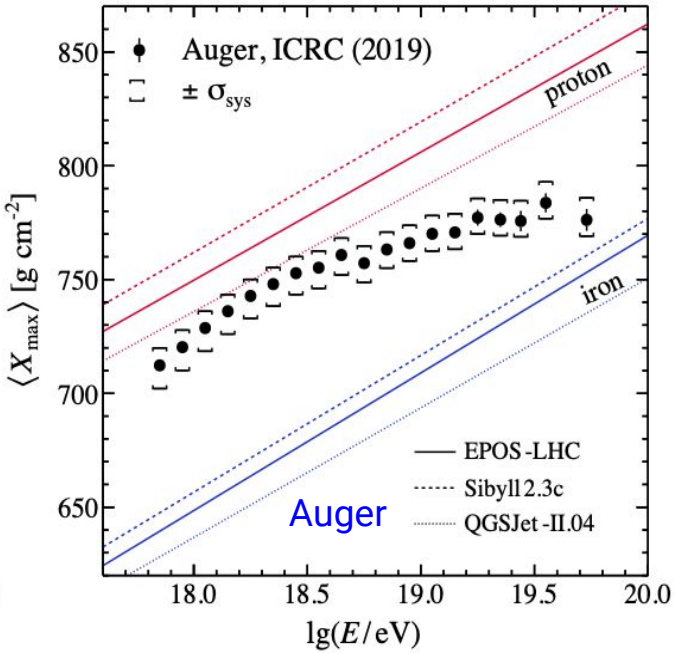
At UHECR 2016 & 2018, the Auger-Mix using the QGSJetII-04 and EPOS-LHC (by re-weighting of QGSJetII-04) high-energy interaction models was compared to TA BR/LR hybrid data, for both $\langle X_{max} \rangle$ and $\sigma(X_{max})$ (the 1$^{st}$ and 2$^{nd}$ moments of the distributions).

While QGSJetII-04 works well to simulate events in TA, it performs poorly in creating the Auger-Mix. Thus, we present a new comparison using the Sibyll 2.3d high-energy interaction model.

# TA and Auger Data, mean $X_{max}$

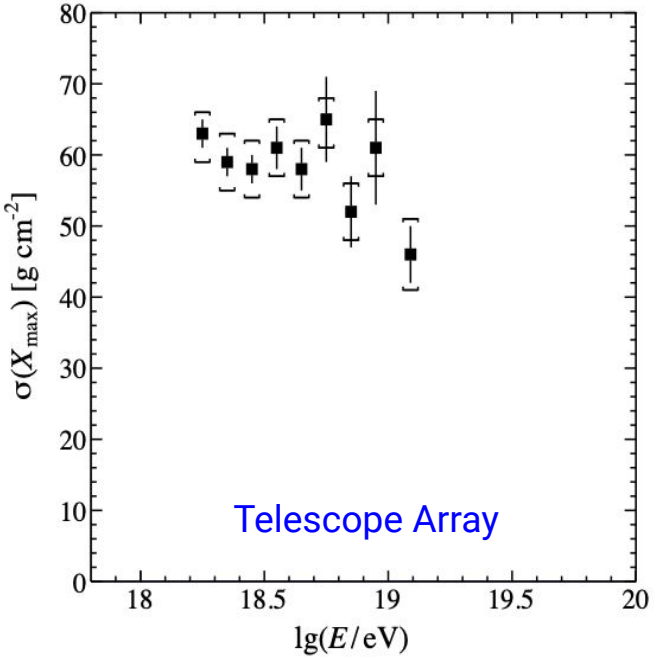
TA data from ApJ-858-76. Auger data from PoS(ICRC2019)482. Comparisons will only be made for energies above $10^{18.2}$ eV. Statistical and systematic errors are shown.

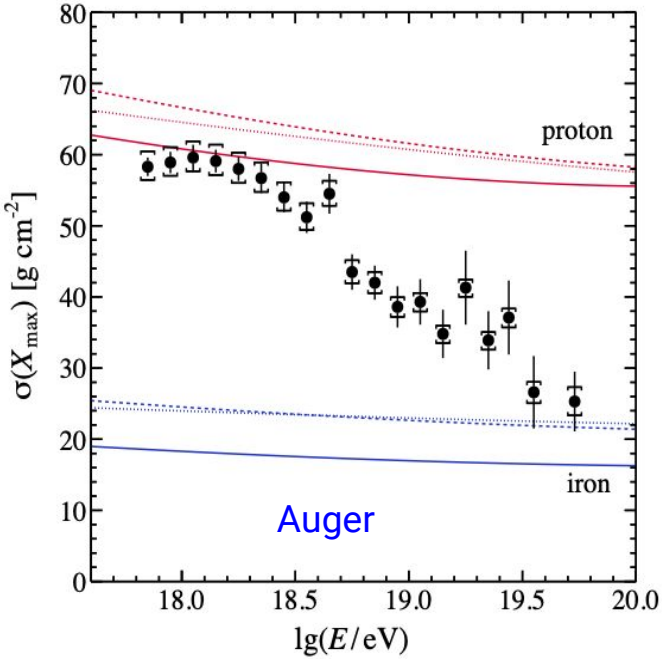


# TA and Auger Data, $\sigma(X_{max})$ (width)

TA data from ApJ-858-76. Auger data from PoS(ICRC2019)482. Comparisons will only be made for energies above $10^{18.2}$ eV. Statistical and systematic errors are shown. TA data above $10^{19.2}$ eV is not shown due to having fewer than 50 events in the bins.

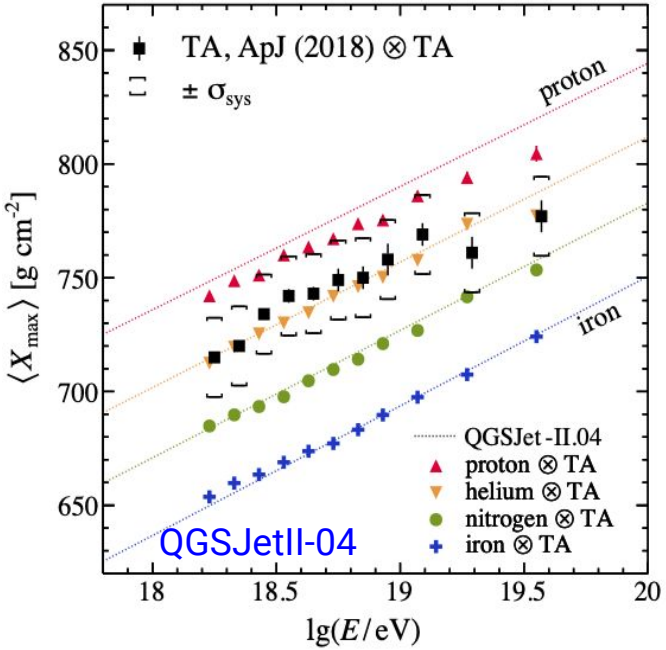


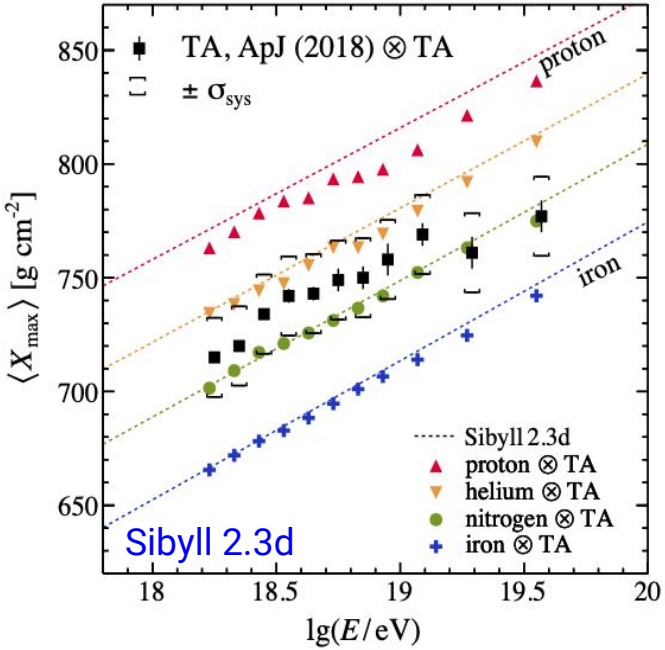



# The effect of different HE interaction models

The effect of using different high-energy interaction models can be seen in comparing $<X_{max}>$ from TA to the predictions for single species depths from the models.

We also see the effect of TA acceptance and reconstruction biases. Protons, with a long deep tail in $X_{max}$ are more strongly affected by acceptance bias



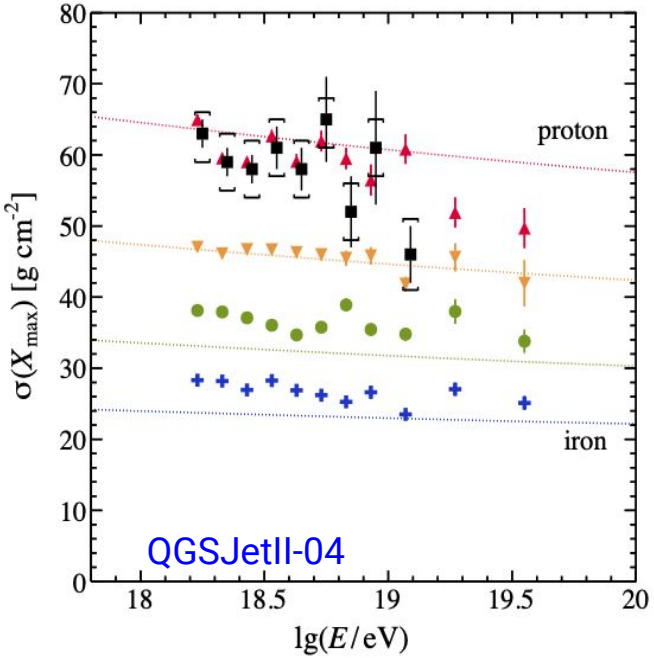



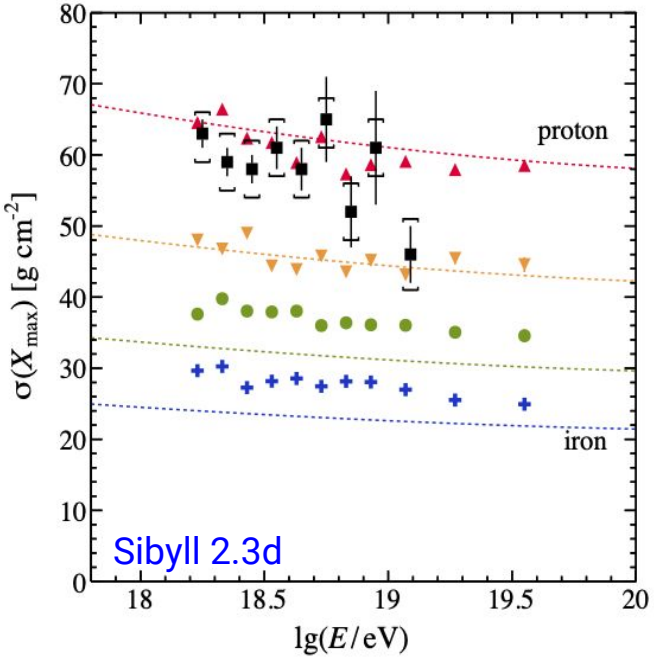
# The effect of different HE interaction models

The difference between QGSJetII-04 and Sibyll 2.3d in $\sigma$ ($X_{max}$) is much smaller.

TA reconstruction biases tend to broaden the narrow distributions.

*(N.B. Sibyll 2.3d MC has considerably higher event statistics than QGSJetII-04, which affects the reconstruction of high-energy proton events.)*



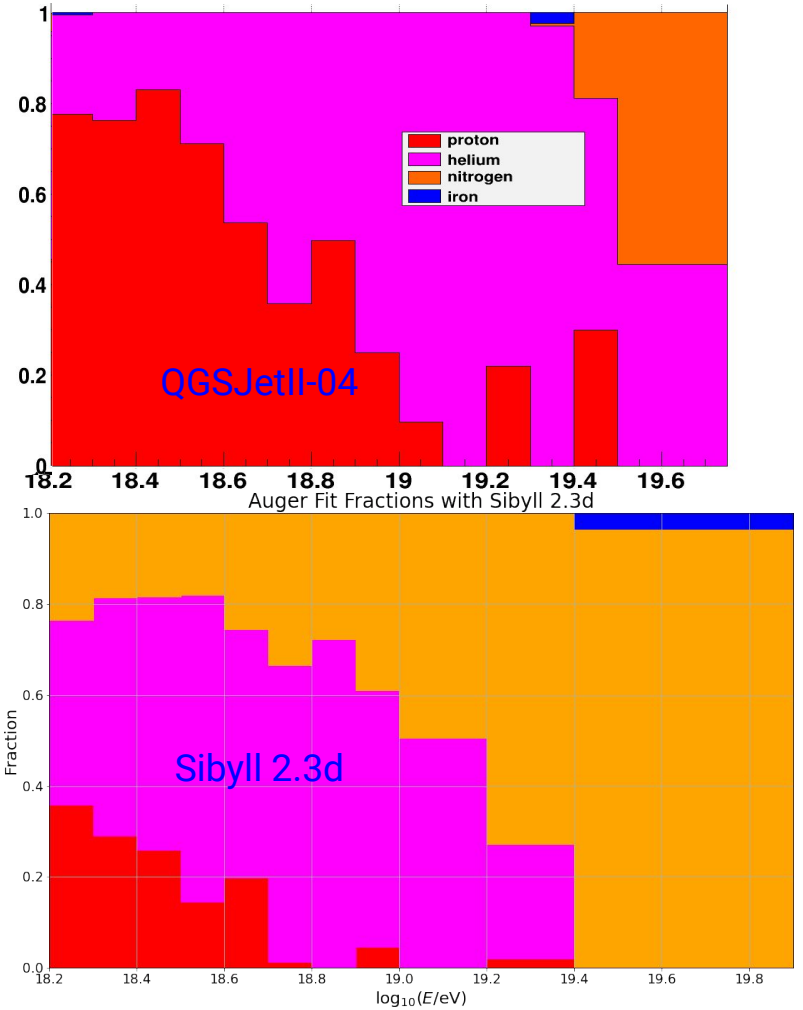



# Finding the Auger-Mix

To find the best fractions of H, He, N and Fe to describe the Auger data, template $X_{max}$ distributions from each species and for a given HE model are fit to the observed Auger $X_{max}$ distribution. This is done in appropriate energy bins.

Putting together the appropriately weighted templates, should reproduce *both* the $\langle X_{max} \rangle$ and the $\sigma(X_{max})$ of the Auger data.

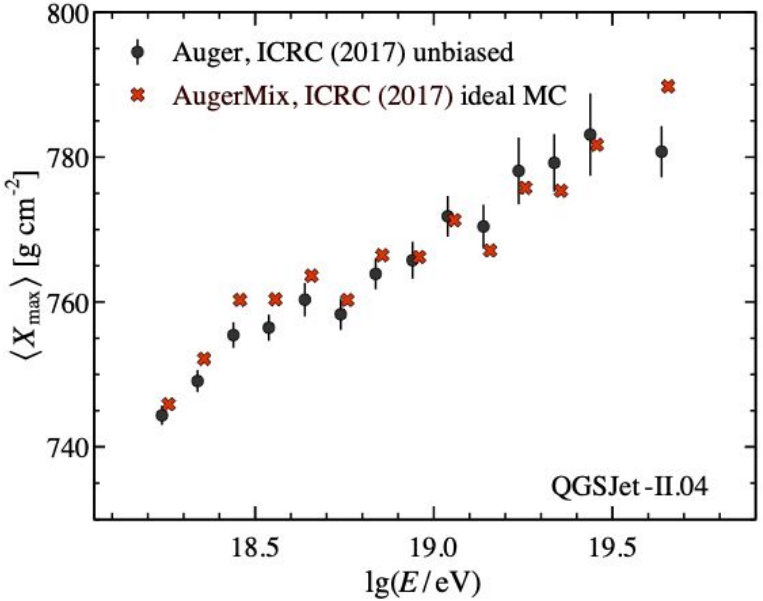
QGSJetII-04 (used in UHECR 2018 comparisons) can't reproduce both mean and sigma.

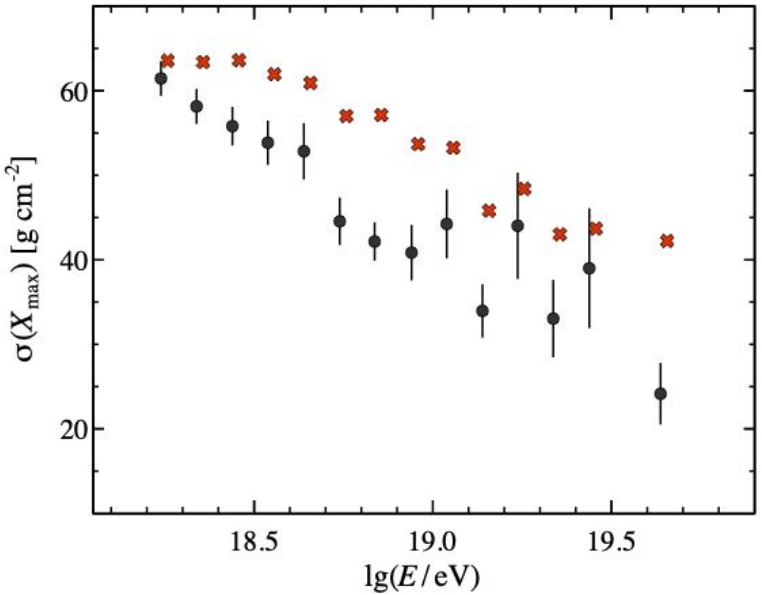


# Problems with QGSJetII-04

QGSJetII-04 fraction-fits of Auger can reproduce $<X_{max}>$ but cannot reproduce $\sigma(X_{max})$ at the same time.

(*N.B.: QGSJetII-04 can be used to describe TA SD data very well.*)



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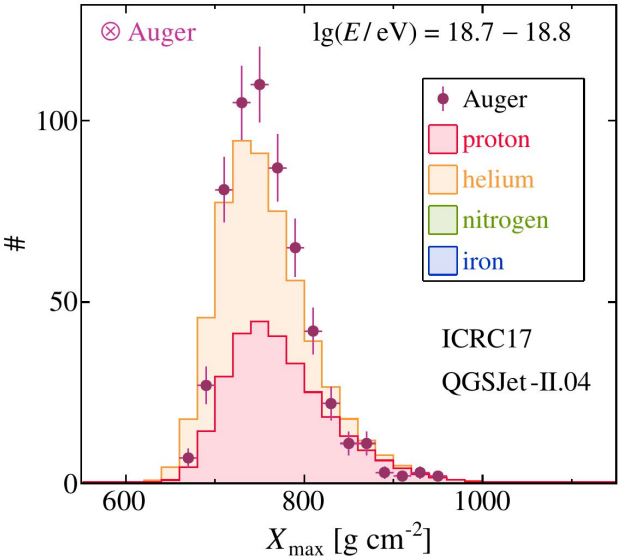
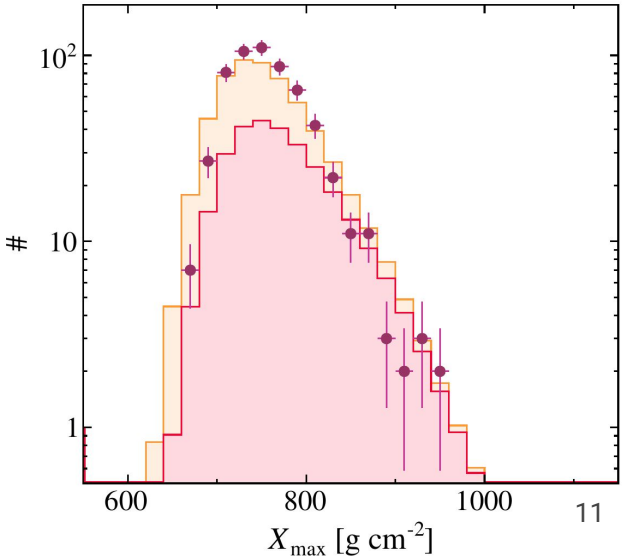
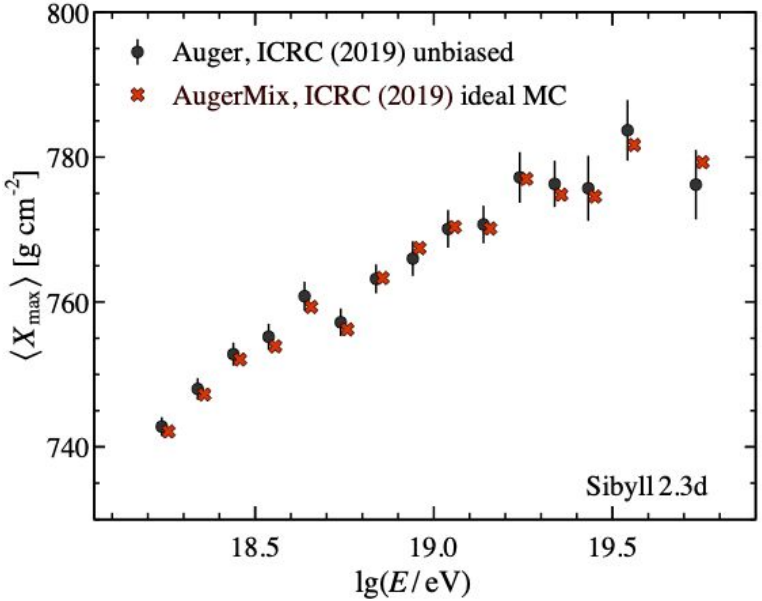
Note that the width of the mix is too wide in this energy bin

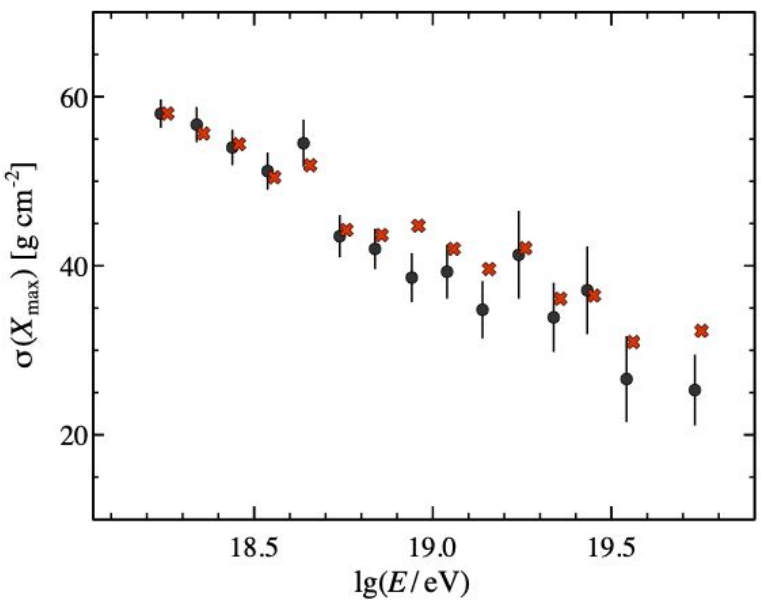


# Better with Sibyll 2.3d

Sibyll 2.3d fraction-fits of Auger can reproduce $\langle X_{max} \rangle$ and $\sigma(X_{max})$ at the same time.



# Generating Sibyll 2.3d MC sets for TA

Used CORSIKA (v7.74_02) to generate events:

- 250 events in 0.1 dex steps from $10^{18}$ to $10^{20.5}$ eV, and for each species (H, He, N, Fe).
- Zenith angle drawn from sin.cos distribution to get isotropic selection.
- CORSIKA particle file output is de-thinned (Stokes *et al.*, arXiv:1104.3182) and GEANT simulation "tile file" is created (TA SD response in many tiles around detector).

Tile files are multi sampled around TA detector to create isotropic dataset and with a spectrum as found by HiRes.

- Fluorescence response of BR/LR also simulated using longitudinal profile from CORSIKA.

TA SD and FD response is simulated, including digitization of signals and triggering.

MC data is analyzed identically to actual TA data, with same cuts.

$X_{max}$ histograms are created by *weighting* species according to AugerMix fractions

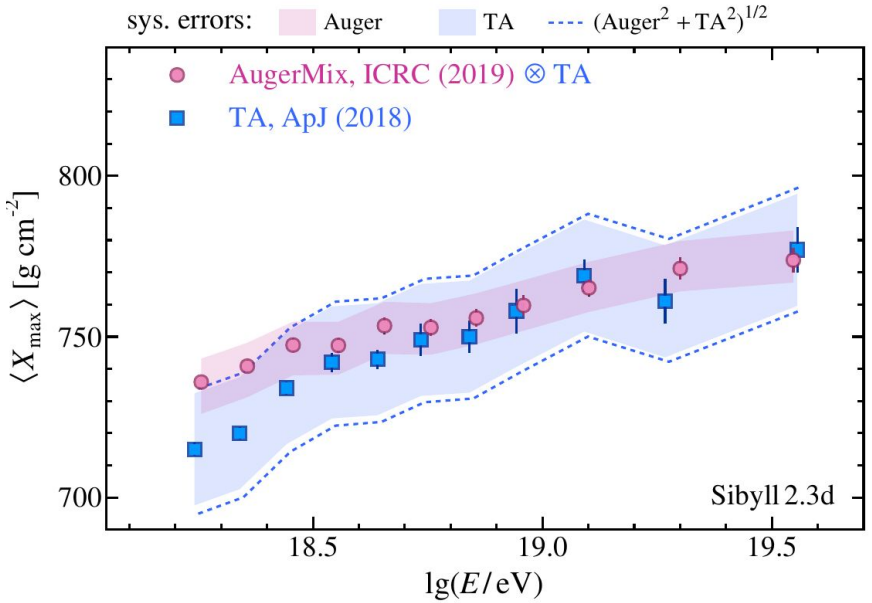
# Results of Comparison with Sibyll 2.3d

Now compare <$X_{max}$> results from AugerMix@TA with TA BR/LR measurements.

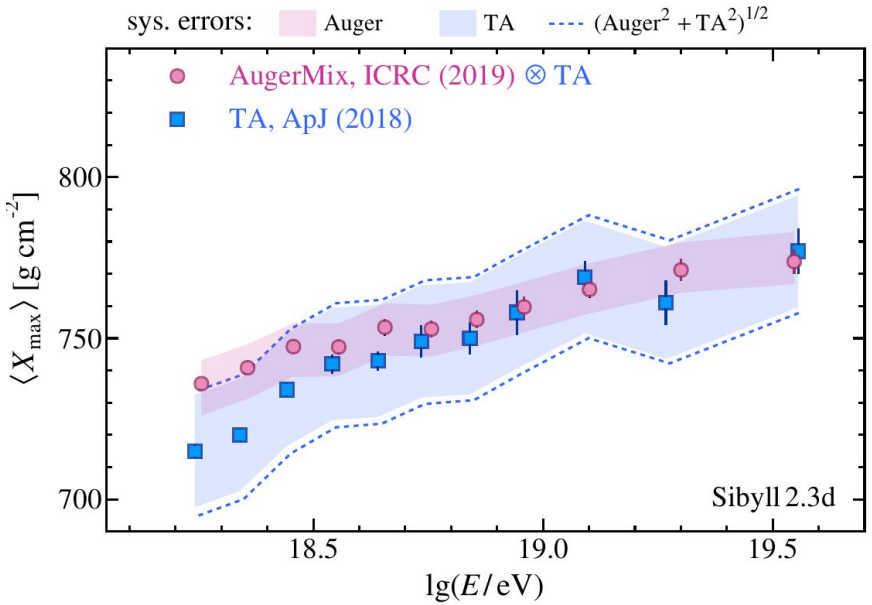
Blue band includes TA systematic error with dotted lines having Auger systematic added in quadrature

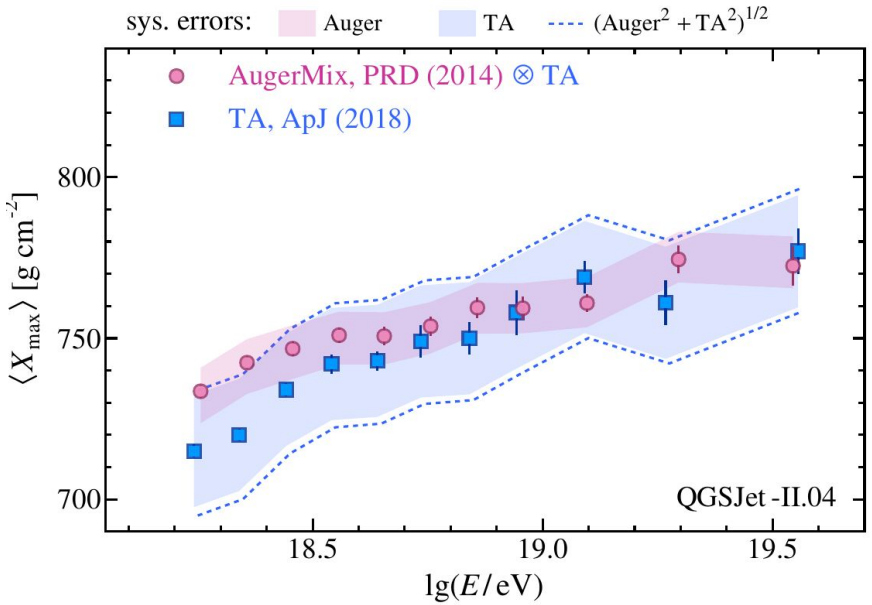
Red band includes Auger systematic errors

**Means of AugerMix (Sibyll 2.3d) agree well with TA BR/LR hybrid measurements**



# Comparing Sibyll to QGSJet




The AugerMix result using Sibyll 2.3d is very similar to the old AugerMix result with QGSJetII-04

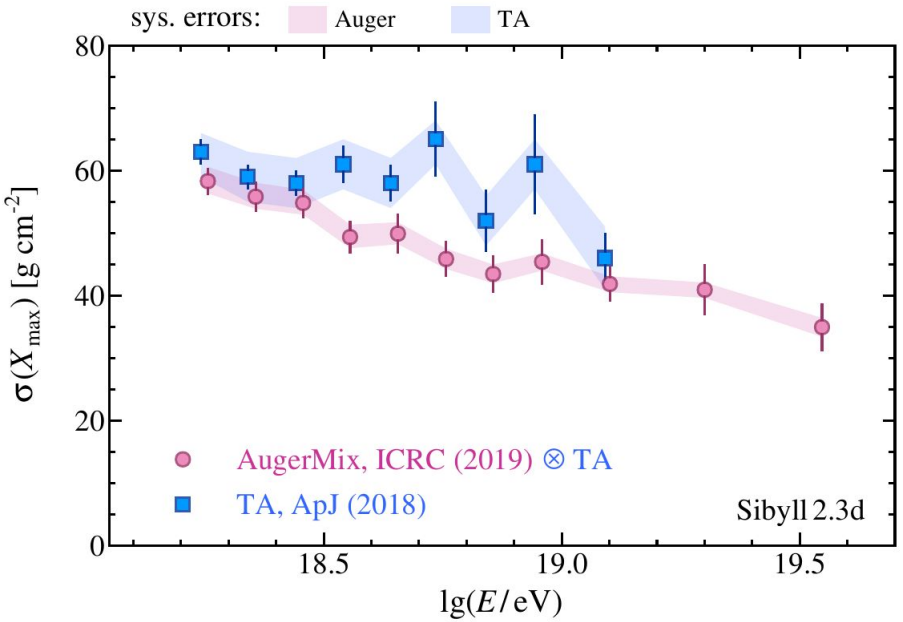
# Results of Comparison with Sibyll 2.3d

Now compare $\sigma(X_{max})$ results from AugerMix@TA with TA BR/LR measurements.

Blue band includes TA systematic uncertainty on width (*not* including aerosols)

Red band includes on Auger systematic errors

**The widths of the AugerMix (Sibyll 2.3d) distributions show considerable tension with TA BR/LR hybrid measurements in the upper $10^{18}$ eV decade**



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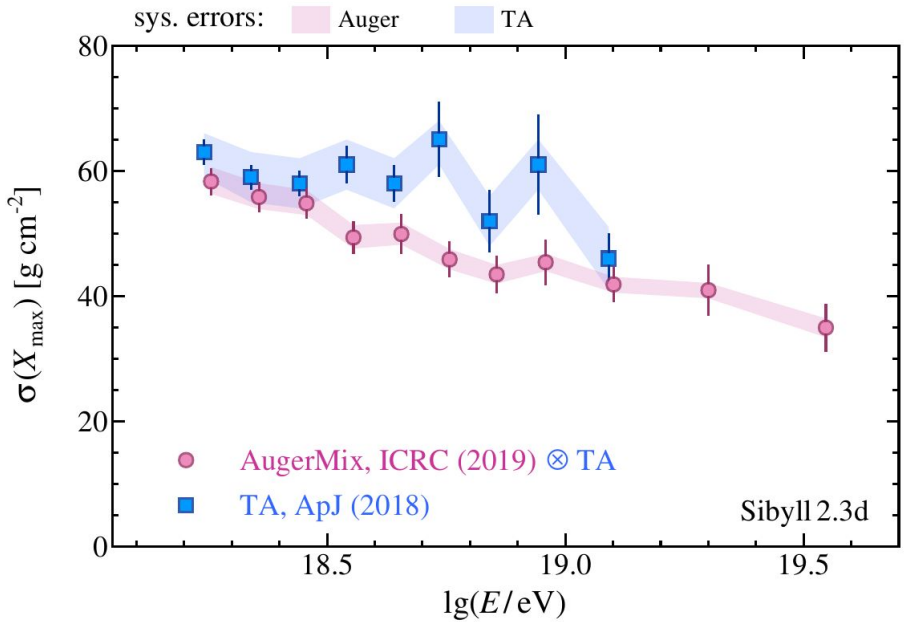
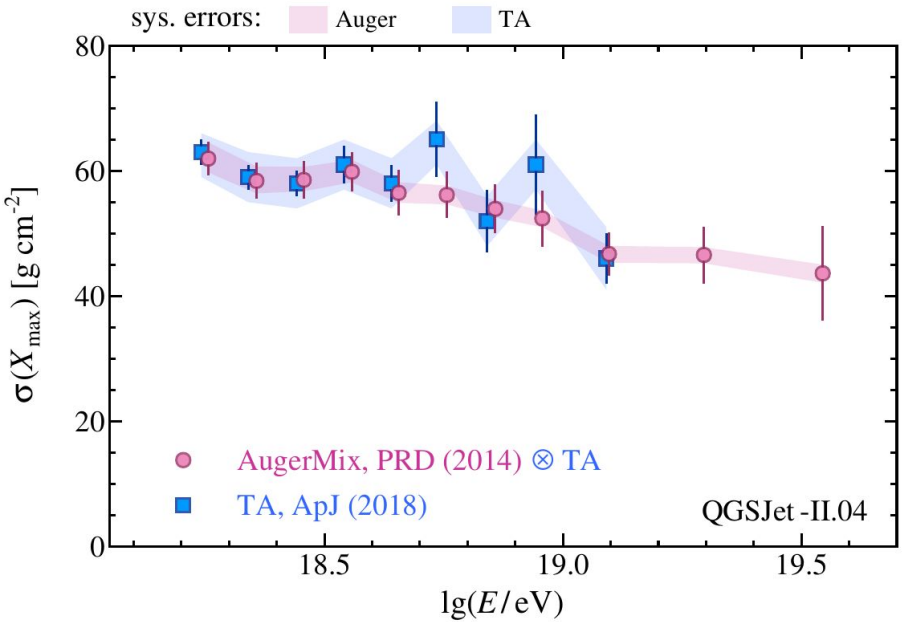


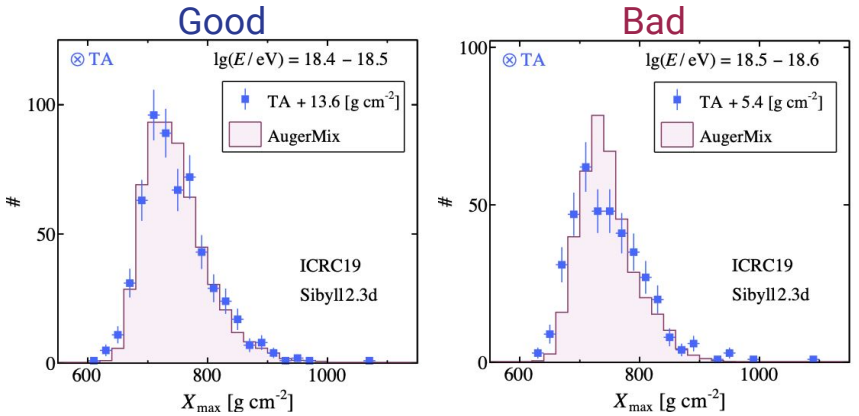



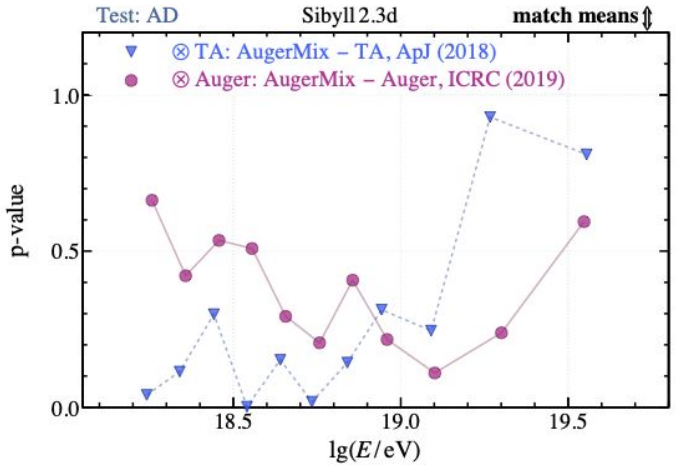

The AugerMix result using Sibyll 2.3d is significantly narrower than the old AugerMix result with QGSJetII-04. This is consistent with the QGSJetII-04 AugerMix producing wider distributions than data

# Shape Comparisons

Use Anderson-Darling test to compare TA data in an energy bin with the AugerMix, removing difference in mean

While many AD p-values are reasonable, some (including the energy bin with the largest difference in width) are too small to show agreement in shape (less than 5%)



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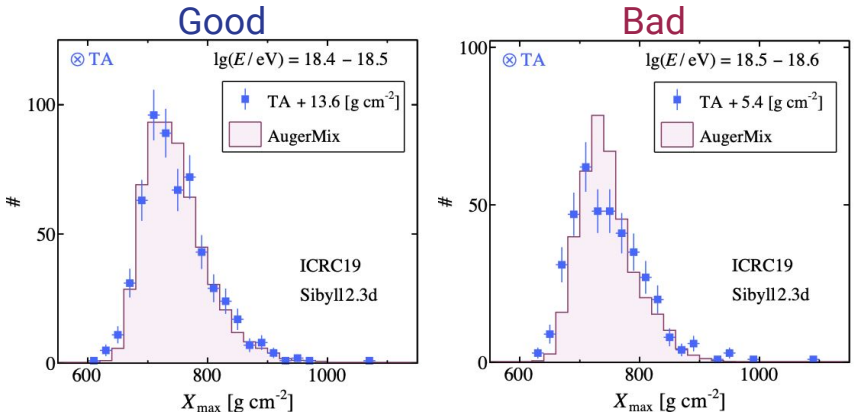
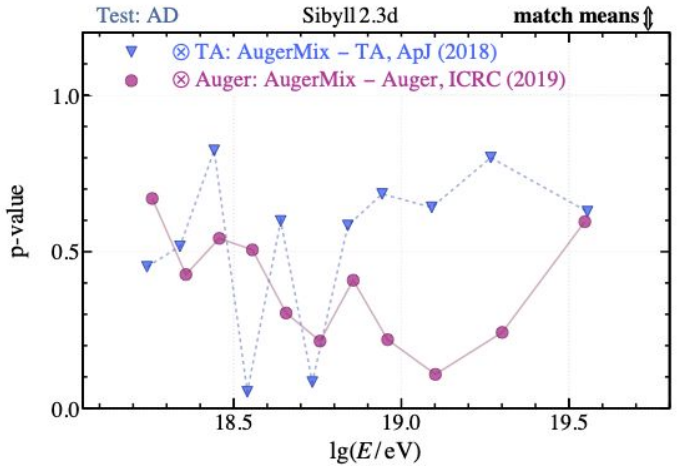
Smearing the AugerMix by an additional 18.9 g/cm$^2$ (to account for aerosol variation in TA data but not in the MC) makes the agreement much better



# Conclusion

We have constructed a representation of Auger $X_{max}$ measurements as would have been seen in the TA detector using the Sibyll 2.3d high-energy interaction model.

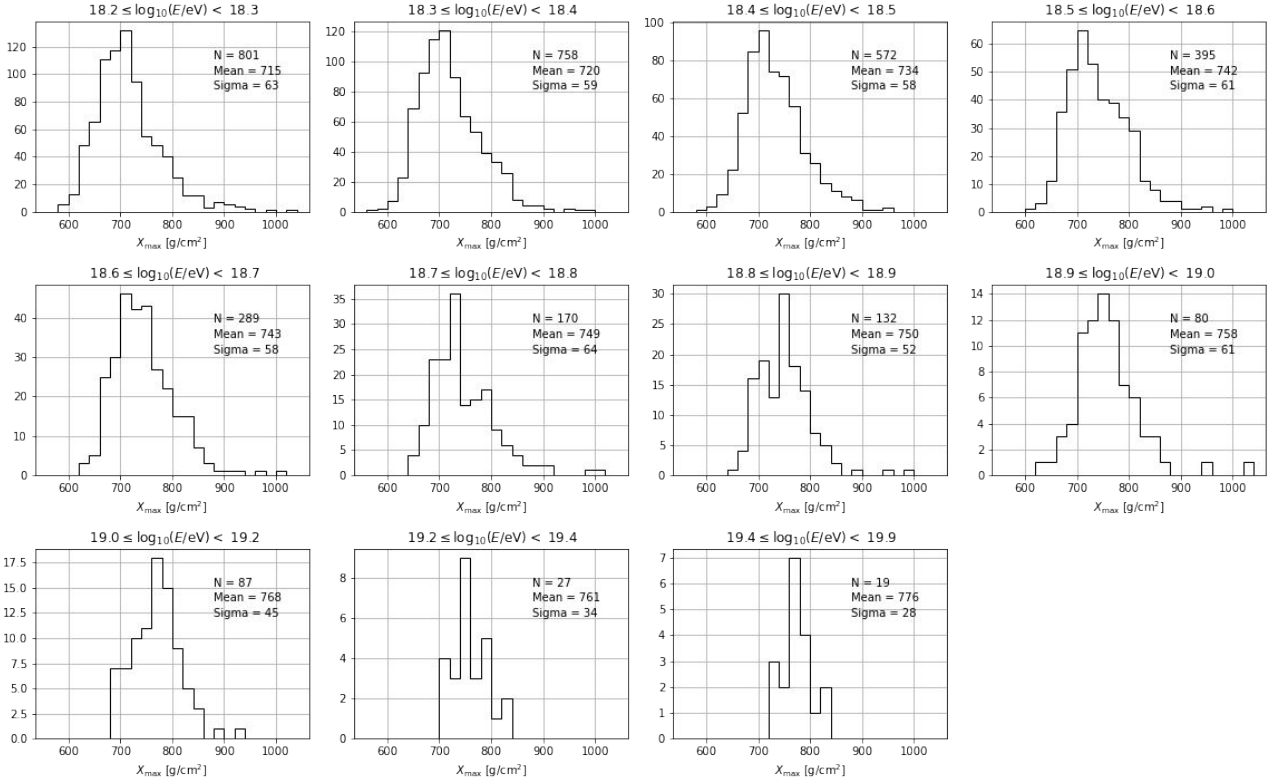
This representation agrees with TA $<X_{max}>$ measurements well, but there is disagreement at some energies in $\sigma(X_{max})$. This disagreement is plausibly due to the handling of $X_{max}$ resolution due to varying aerosols at TA

A robust difference between the Auger and TA $X_{max}$ measurements **has not been found**

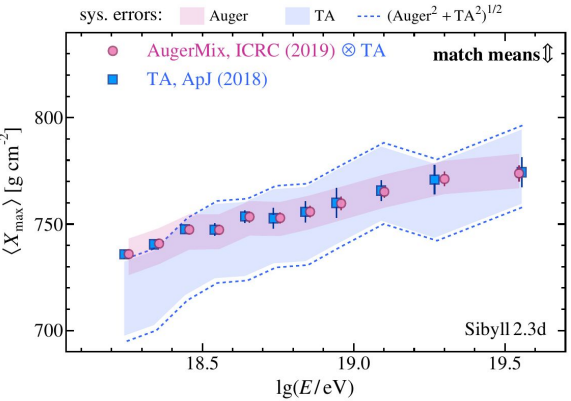
A journal publication from the Mass Composition Working Group is forthcoming

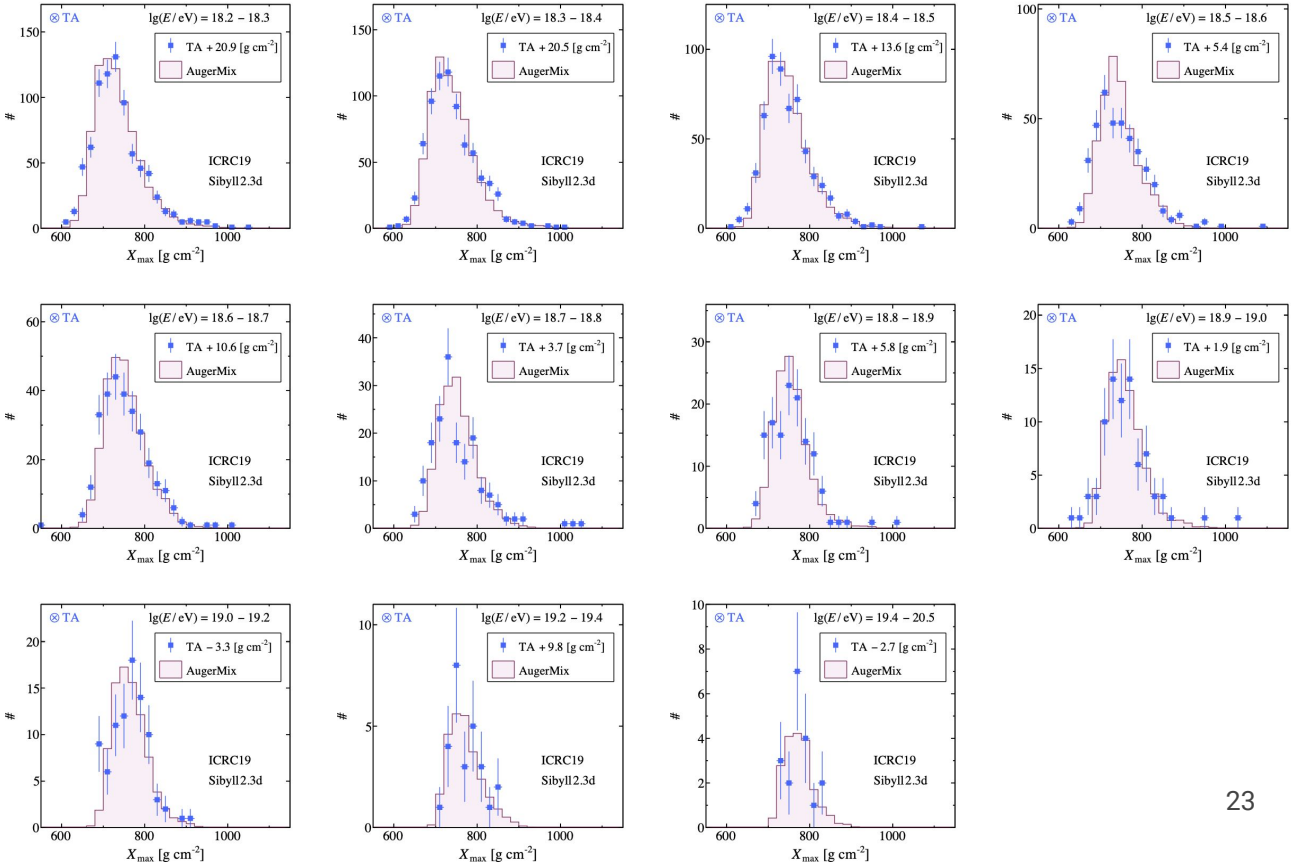
# Back-up

# Telescope Array $X_{max}$ Distributions

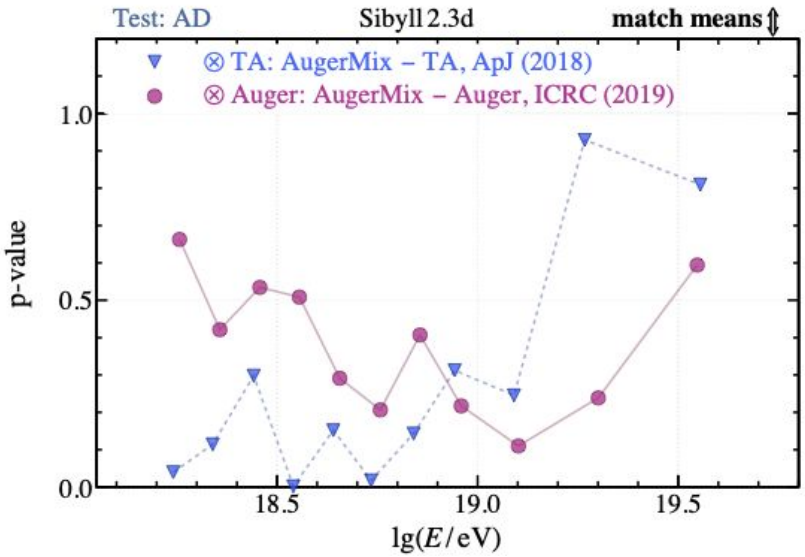


# Comparing AugerMix shapes to TA

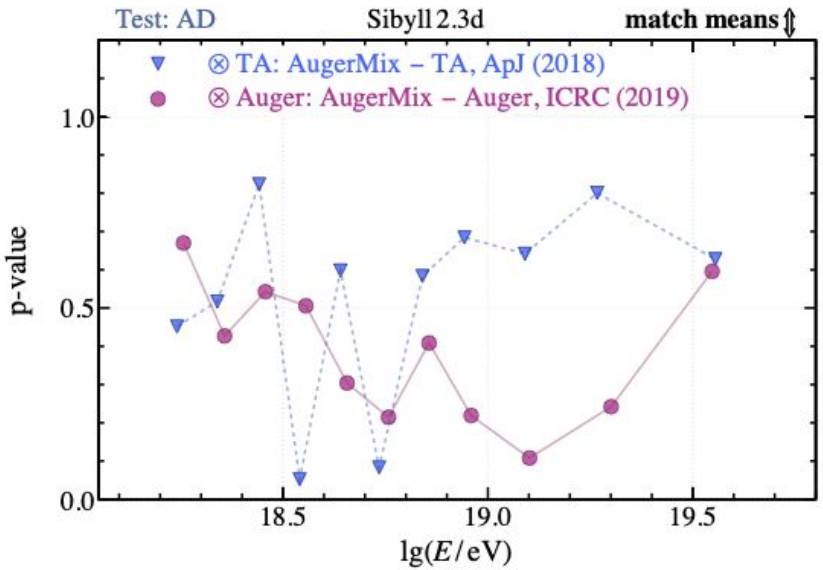


# Anderson-Darling Comparison of shapes




As shown




With additional 18.9 g/cm$^2$ $X_{max}$ smearing for aerosol variation