Depth of maximum of air-shower profiles:
testing the compatibility of measurements

performed at the Pierre Auger Observatory and the Telescope Array experiment

Telescope Array: John Belz, William Hanlon, Daisuke Ikeda, Pierre Sokolsky, Yoshiki Tsunesada

Auger: Jose Bellido, Vitor de Souza, Michael Unger, Alexey Yushkov

for the Pierre Auger and Telescope Array collaborations

UHECR, Paris, 09/10/2018

Results presented at the 35th ICRC

[V. de Souza, PoS (ICRC2017) 522]

Comparison of X_{max} distributions measured by Auger and TA

Data (8 years in both experiments):

Auger: PRD 90 (2014) 122005, 122006

Telescope Array: D. Ikeda and W. Hanlon, PoS (ICRC2017) 515

Energy range: $\lg(E/\mathrm{eV}) = 18.2 - 19.0$

Interaction model: QGSJet-II.04

Mass compositions: proton, AugerMix (composition describing Auger data)

"At the current level of statistics and understanding of systematics, the TA data is consistent with the proton models used in this paper for energies less than 10^{19} eV and it is also consistent with the AugerMix composition"

Changes in the current analysis

Data:

Auger: PRD 90 (2014) 122005, 122006;

J. Bellido, PoS (ICRC2017) 506, 11 years of data

Telescope Array: ApJ 858 (2018) 76, 8.5 years of data

Energy range: $\lg(E/\mathrm{eV}) = 18.2 - 19.0$

Interaction model: EPOS-LHC

Mass composition: AugerMix

Data

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

Pierre Auger

4 FD sites

11 years of data $(12/2004 - 12/2015)$

[J. Bellido, ICRC (2017), PoS 506]

10558 events

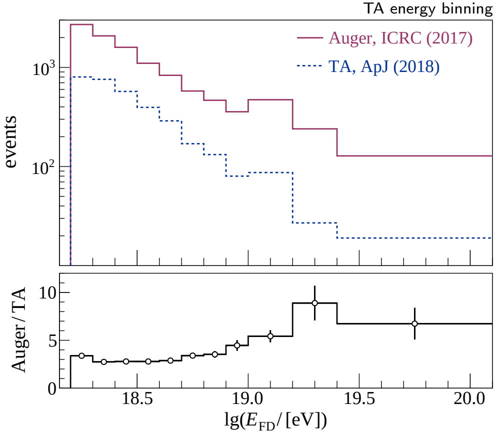
Telescope Array

FD sites: Black Rock Mesa and Long Ridge

8.5 years of data $(05/2008 - 11/2016)$

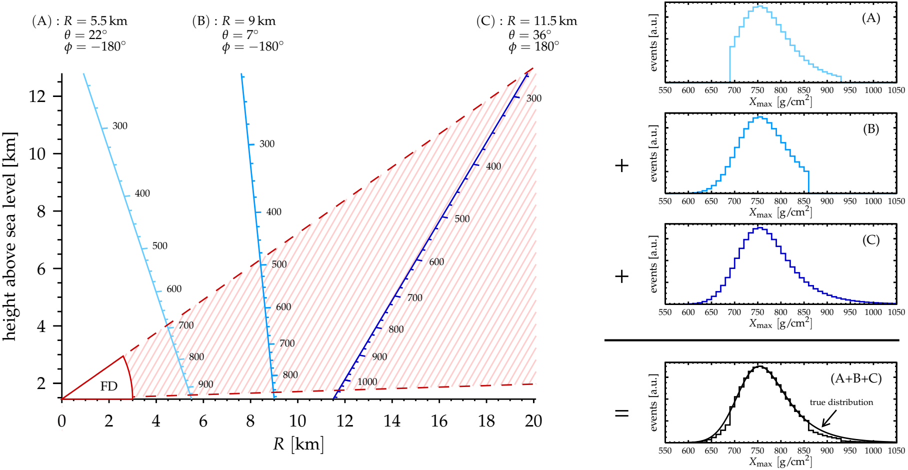
[ApJ 858 (2018) 76]

3330 events



Detector acceptance bias

Auger, PRD 90 (2014) 122005



(A) and (B): nearly vertical showers close to FD site, events with deep and shallow $X_{\rm max}$ are outside the FOV

$(\mathsf{A}+\mathsf{B}+\mathsf{C})$: all events, tails of $X_{\rm max}$ distribution are biased by the detector acceptance

Detector acceptance bias: different analysis strategies

Auger and TA $X_{\max}$ measurements can not be compared directly

Auger

fiducial FOV selection:

flat acceptance for major part of data events

$\langle X_{\max} \rangle$, $\sigma(X_{\max})$

unbiased, compare to ideal MC

TA

no fiducial FOV selection:

maximize size of the data set

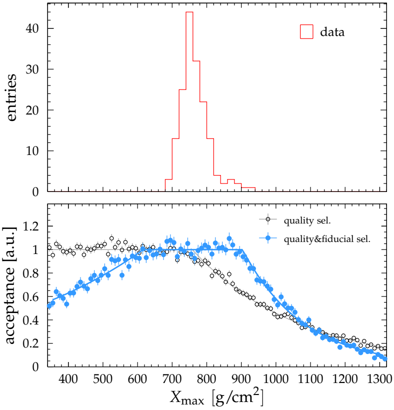
$\langle X_{\max} \rangle$, $\sigma(X_{\max})$

biased, compare to MC in TA detector

$X_{\max}$ distributions in both Auger and TA:

compare to MC in corresponding detectors

Auger, PRD 90 (2014) 122005



Auger acceptance, $\lg(E/\mathrm{eV}) = 19.0 - 19.1$

Method to transport Auger data into TA detector

Step 1: find MC mix of nuclei reproducing the best Auger $X_{\max}$ distributions (AugerMix in the following)

Step 2: pass AugerMix through TA detector simulations, reconstruction, analysis;

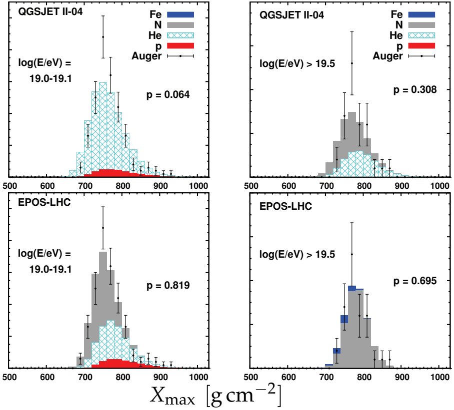
compare AugerMix in TA detector to TA data

Examples of fits of $X_{\max}$ distributions :

points — Auger data

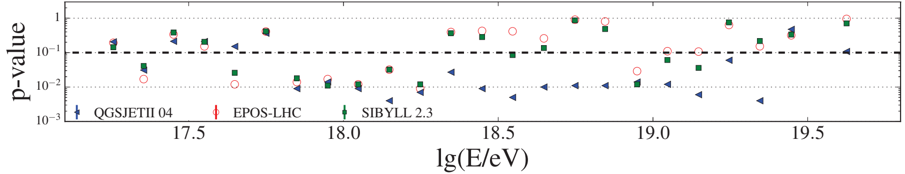
histograms — (p, He, N, Fe) nuclei in AugerMix

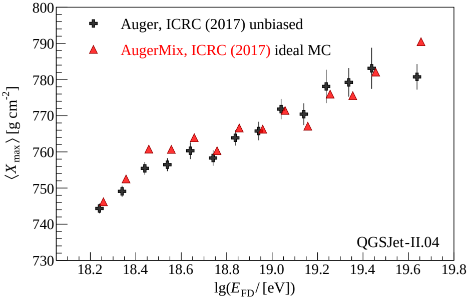
Auger, PRD 90 (2014) 122005

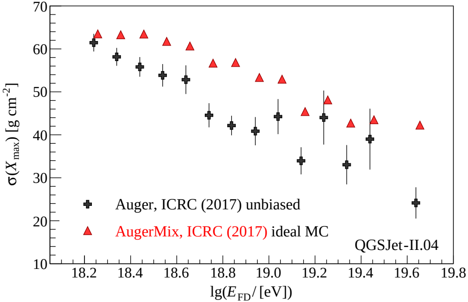


Choice of the interaction model

J. Bellido, PoS (ICRC2017) 506





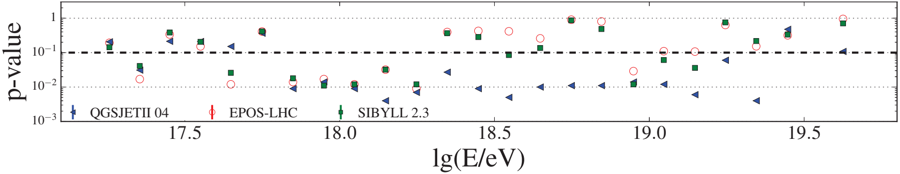


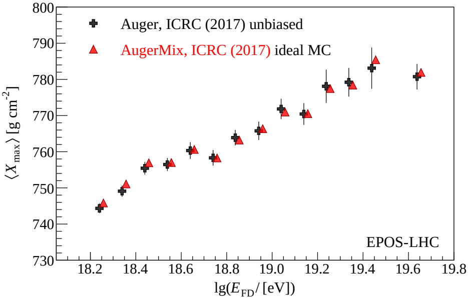
QGSJet-II.04: p-values for AugerMix vs Auger data are ≈ 0.01 for $\lg(E/\mathrm{eV}) = 17.8 - 19.2$
width of the X_{max} distributions is larger than in data of Auger

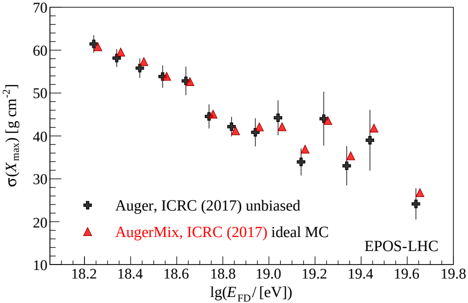
AugerMix (QGSJet-II.04) is not equivalent to Auger data, not a best choice for comparison to TA

Choice of the interaction model

J. Bellido, PoS (ICRC2017) 506







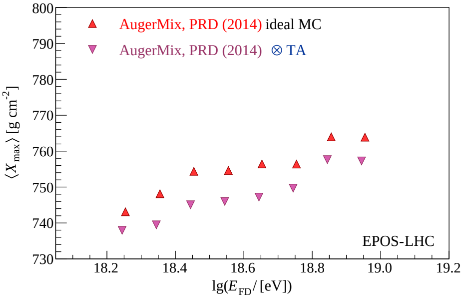
EPOS-LHC: good description of $X_{\rm max}$ distributions measured by Auger

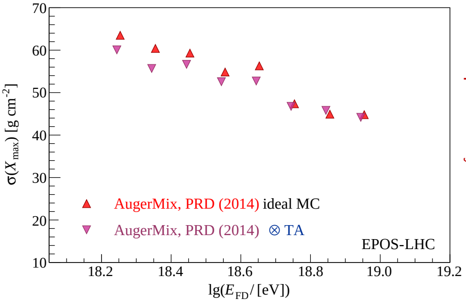
comparison to TA will be done using AugerMix (EPOS-LHC)

AugerMix in TA detector

Step 2: Pass AugerMix through TA detector simulations, reconstruction and analysis

AugerMix $\otimes$ TA: bias on $\langle X_{\max}\rangle$ of $\approx -5\ \mathrm{g\,cm^{-2}}$
bias on $\sigma(X_{\max})$ of few $\mathrm{g\,cm^{-2}}$





preliminary

EPOS-LHC simulations are unavailable for TA and are obtained via re-weighting of QGSJet-II.04 simulations
[W. Hanlon et al., JPS Conf. Proc. 19 , 011013 (2018)]

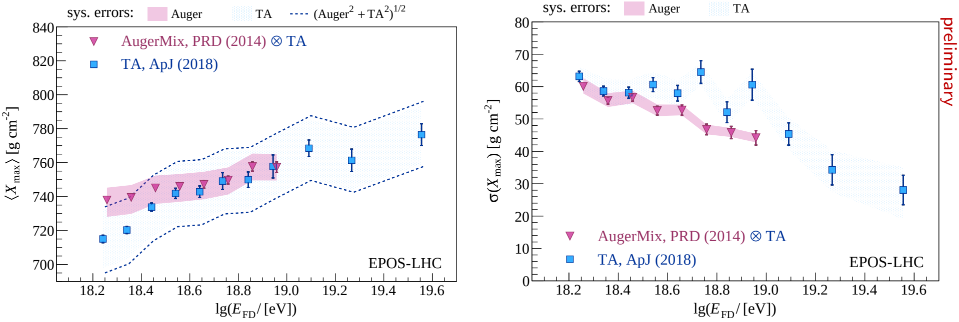
currently the re-weighting is done up to $\lg(E/\mathrm{eV}) = 19.0$ using AugerMix from [Auger, PRD 90 (2014) 122006]

Auger – TA

$\langle X_{max}^{TA} \rangle < \langle X_{max}^{Auger} \rangle$ for almost all energies

agreement within $(\text{stat} + \text{sys})$ errors

$\sigma(X_{max}^{TA}) > \sigma(X_{max}^{Auger})$ for $\lg(E/\text{eV}) = 18.5 - 19.0$

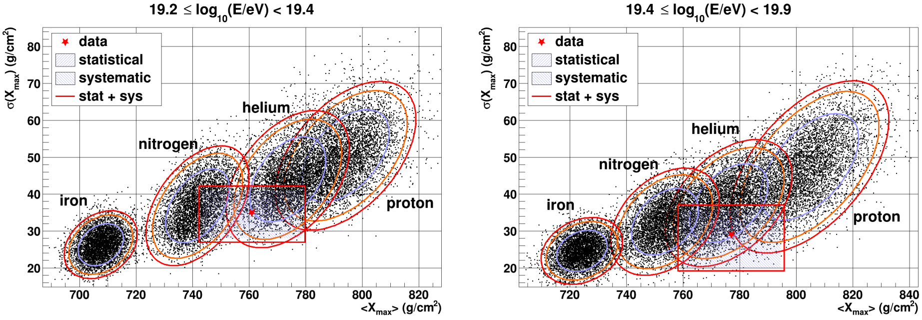


TA $\sigma(X_{\max})$ interpretation

[TA, ApJ 858 (2018) 76]

"TA's ability to resolve individual QGSJet-II.04 elements is degraded owing to the overlap of the confidence intervals. According to these figures, when considering only the joint distributions of $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$, within the data's systematic uncertainty the data may resemble QGSJet-II.04 proton, helium, or nitrogen."

Confidence intervals for QGSJet-II.04 MC: 68.3% (blue ellipse), 90% (orange ellipse), 95% (red ellipse)



27 events in data

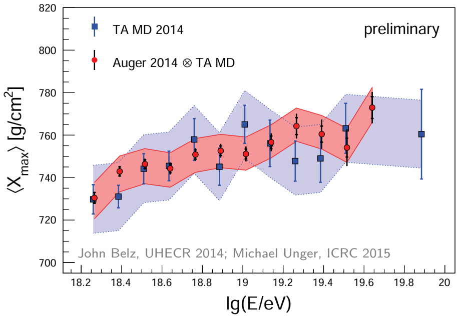
19 events in data

$\langle X_{max} \rangle$: Auger vs different TA measurements

Discrepancy Auger – TA (Black Rock Mesa/Long Ridge) is larger and energy-dependent

TA Middle Drum

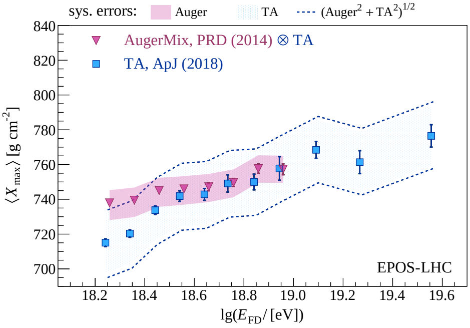
[ApP 64 (2015) 49]



average difference: $\langle \Delta \rangle = (2.9 \pm 2.7 \text{ (stat.)} \pm 18 \text{ (syst.)})$ g/cm^2

TA Black Rock Mesa/Long Ridge

[ApJ 858 (2018) 76]



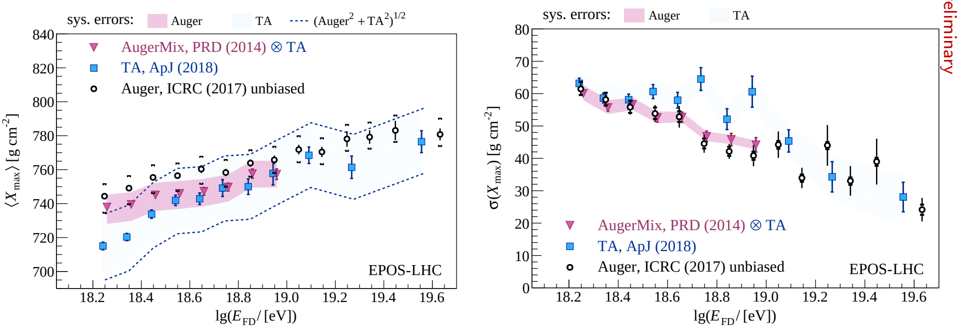
Summary

$\langle X_{max}^{TA} \rangle < \langle X_{max}^{Auger} \rangle$ for almost all energies

agreement within $(\mathrm{stat} + \mathrm{sys})$ errors

$\sigma(X_{max}^{TA}) > \sigma(X_{max}^{Auger})$ for $\lg(E/\mathrm{eV}) = 18.6 - 19.0$

Next: comparison to Auger ICRC (2017) data and energies $\lg(E/\mathrm{eV}) > 19.0$



Further required steps

Understand differences between Black Rock Mesa/Long Ridge and Middle Drum data

Analyze the differences between TA and Auger in $\sigma(X_{\mathrm{max}})$

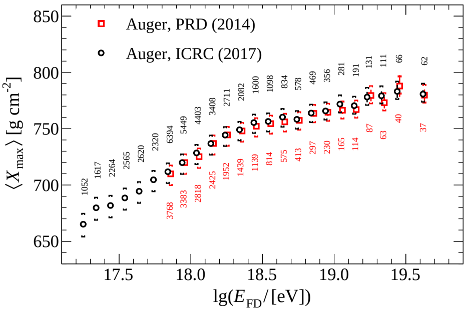
Take into account difference in energy scales of Auger and TA

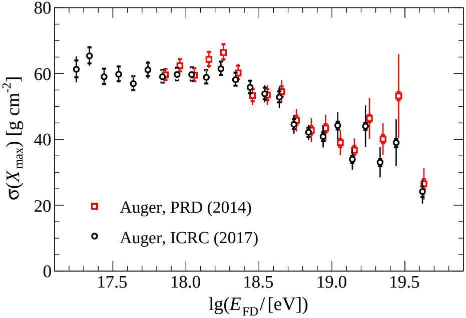
Take into account systematic errors on nuclei fractions in AugerMix

Produce EPOS-LHC simulations for TA

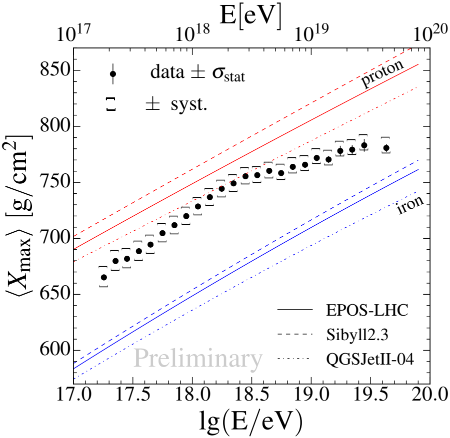
backups

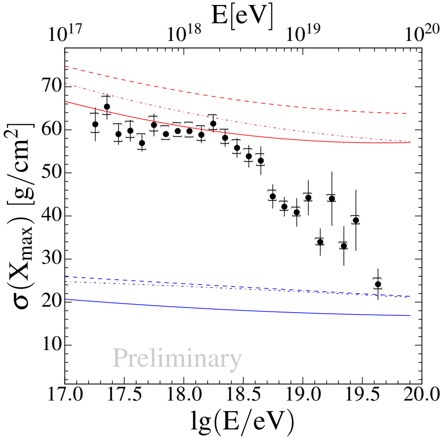
Auger $X_{\max}$ moments from PRD (2014) and ICRC (2017)





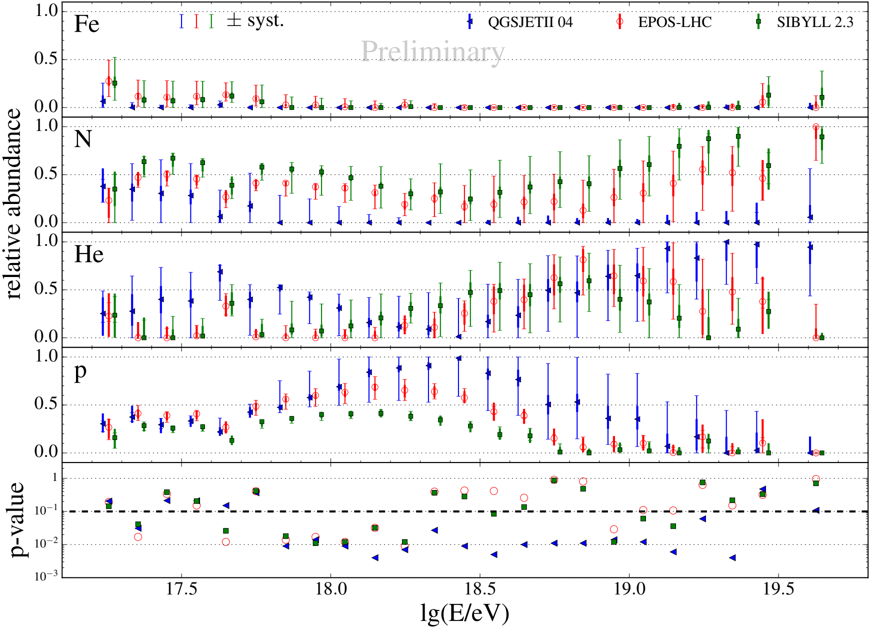
Auger $X_{\max}$ moments vs MC predictions





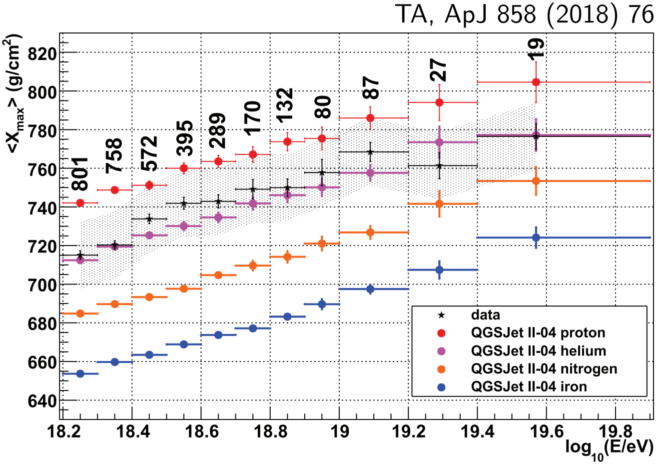
[J. Bellido, PoS (ICRC2017) 506]

Auger: mass composition from fits of $X_{\max}$ distributions



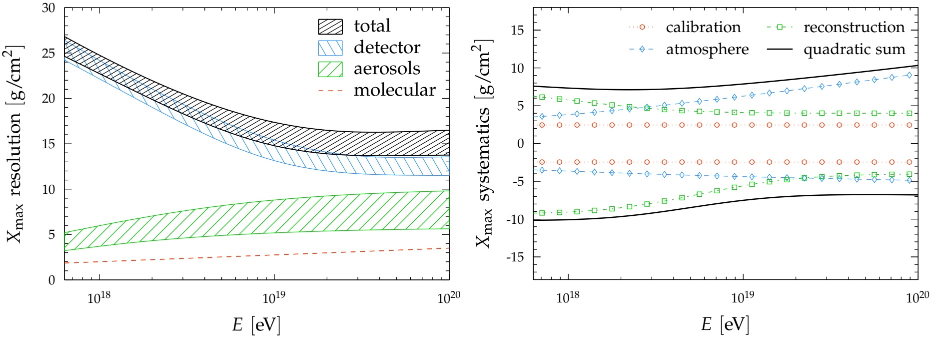
J. Bellido, PoS (ICRC2017) 506

TA Black Rock Mesa/Long Ridge $\langle X_{\max} \rangle$



Auger X_{max} resolution and systematic uncertainties

Auger, PRD 90 (2014) 122005



TA data – proton (QGSJet-II.04)

TA $\langle X_{\max} \rangle$ is shifted within systematic errors: $+17.4\ \mathrm{g\,cm^{-2}}$ for all energies

$\langle X_{\max} \rangle$ and $\sigma(X_{\max})$

good agreement to TA for $\lg(E/\mathrm{eV}) < 19.0$