Measurements of UHECR Mass Composition by Telescope Array

TALE @ Middle Drum

ISS

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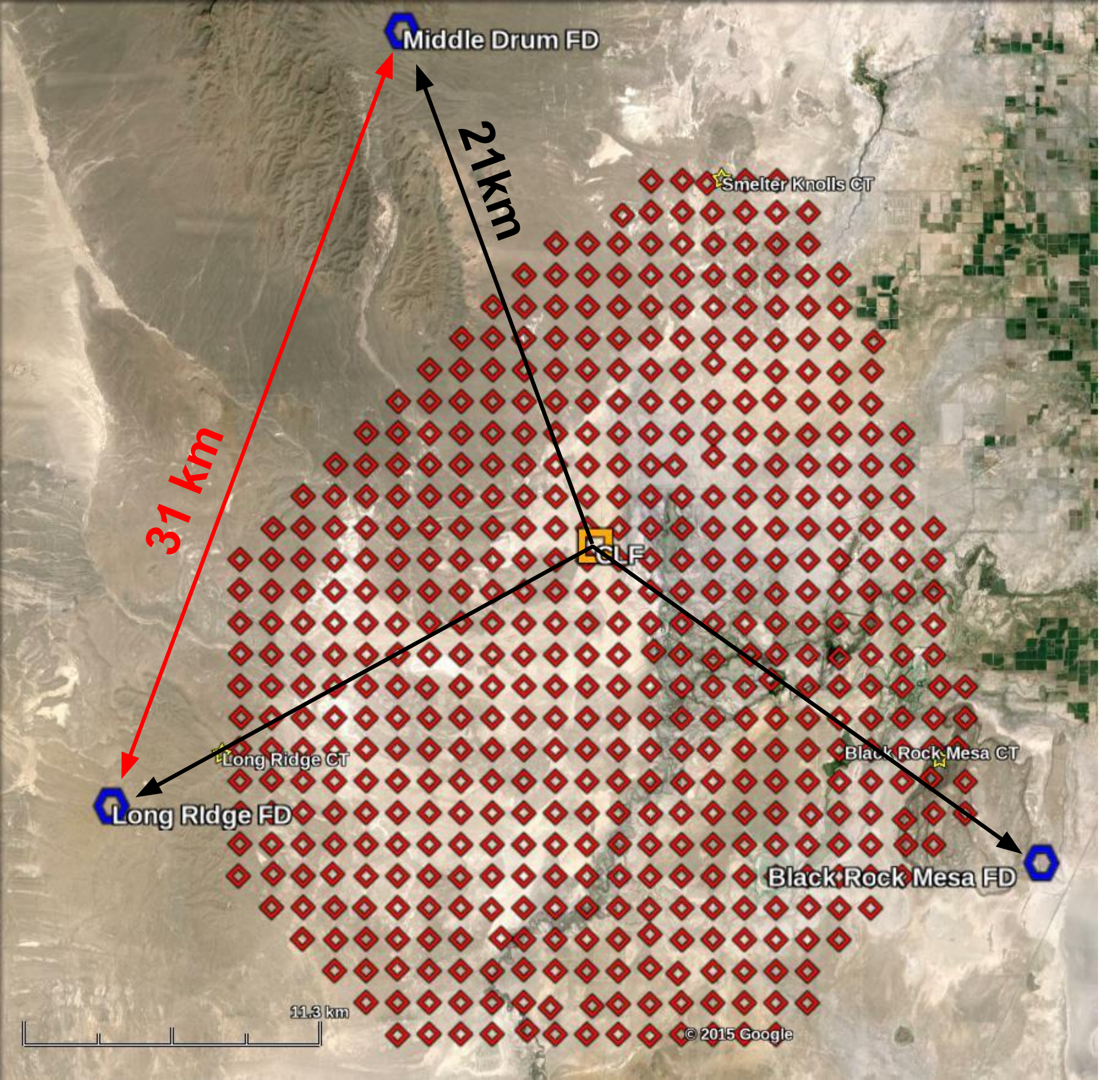


TA has been in operation since 2007.

700 km^2 SD array (1.2 km spacing)

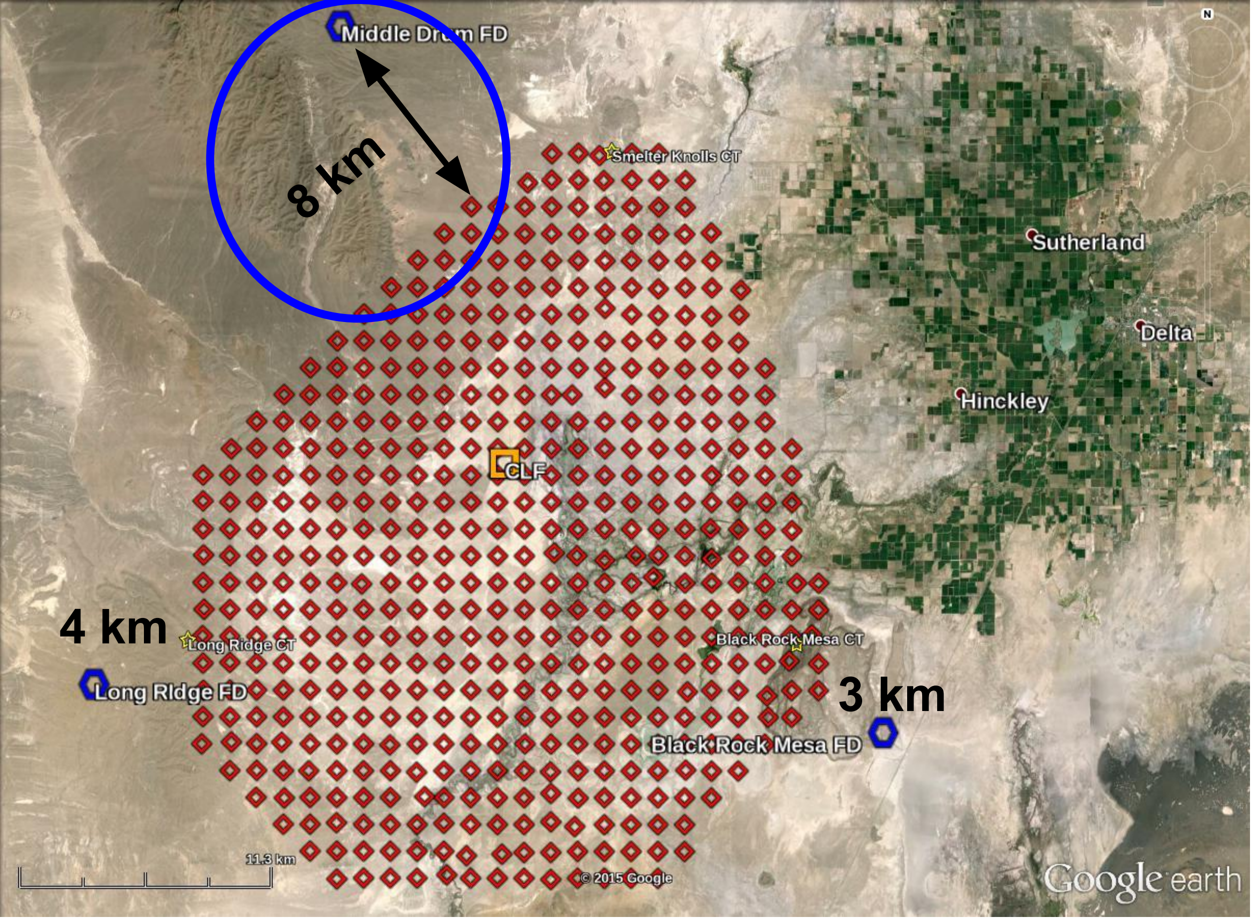
3 FD stations each located 21 km from the center of the SD array

Four measurements of composition at Telescope Array

- MD Hybrid
- Stereo FD
- BR/LR Hybrid
- SD MVA

All three FD based composition measurements have

- X_{max} resolution $\lesssim$ 20 g/cm^2
- Energy resolution $\lesssim$ 7%
- Angular resolutions $\lesssim$ 1°
- ~ 10% duty cycle



Middle Drum Hybrid

Sample and Hold electronics repurposed from HiRes1.

5.1 m^2 mirrors

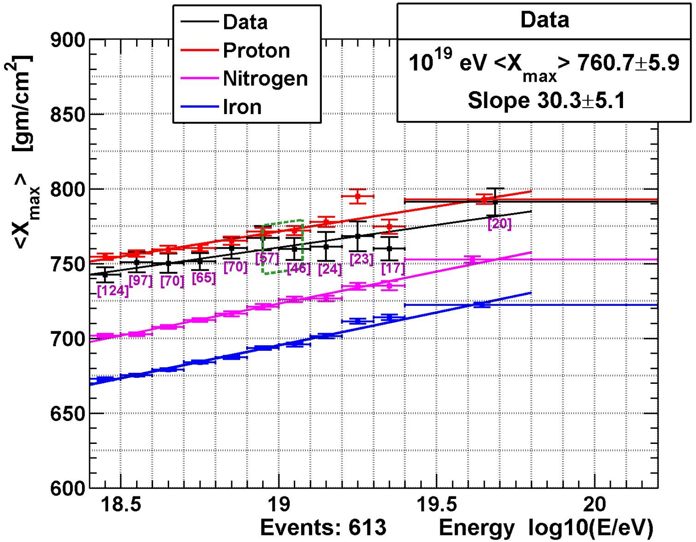
8 km from SD array border

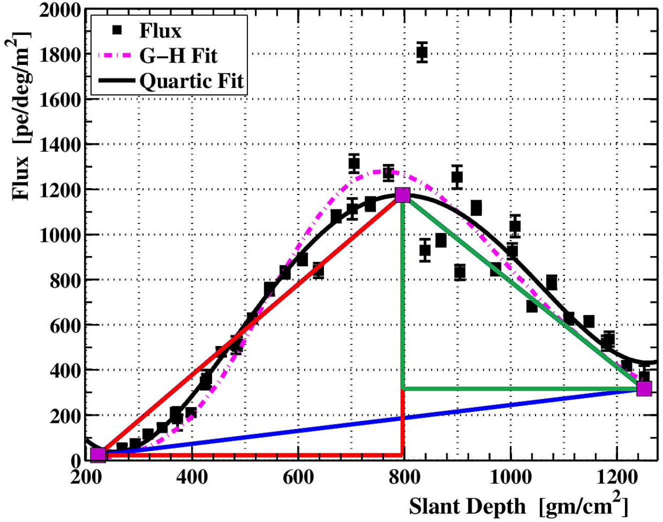
2 rings, 7 mirrors/ring
Ring 1: $3° \leq \theta \leq 17°$
Ring 2: $17° \leq \theta \leq 31°$
$\Delta\phi = 112°$

First measurement of TA composition:
Five years of hybrid data, later updated to seven years.

Abu-Zayyad, et al., [Nucl.Instrum.Meth. A450 (2000) 253-269]

Middle Drum Hybrid X_{max}



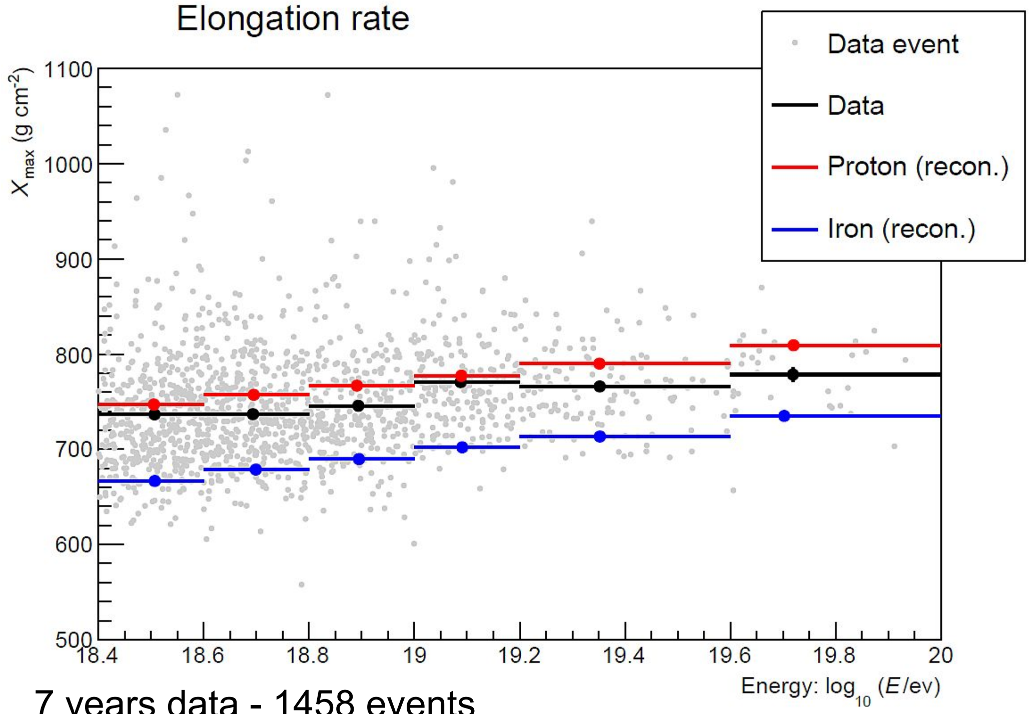


7 years of MD FD hybrid data - 613 events [$\log_{10}(E/\mathrm{eV}) > 18.4$]

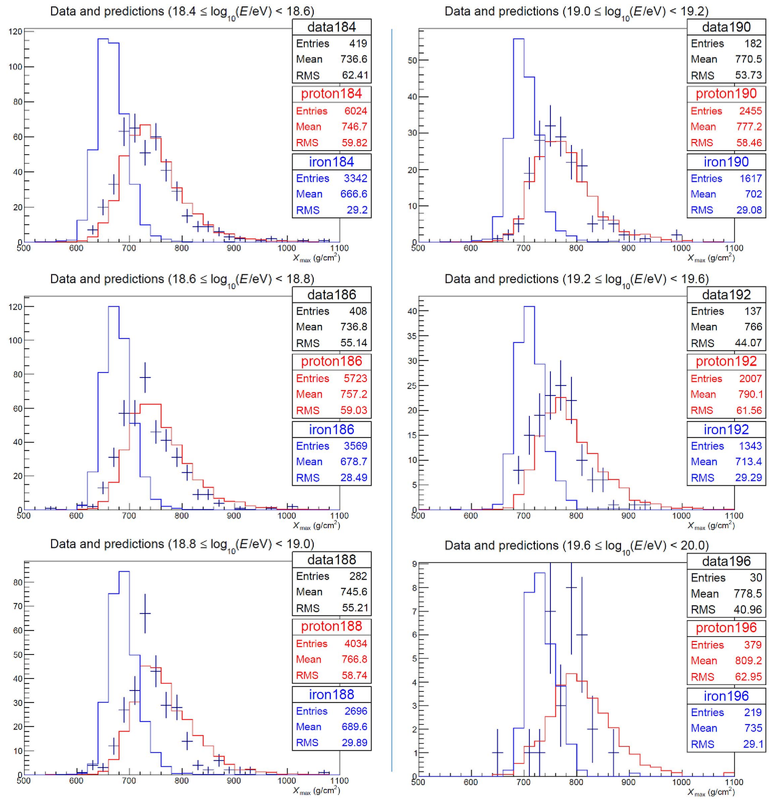
Improved reconstruction via *pattern recognition* method → ensures curvature of profile is well measured.
X_{max} resolution ~ 22 g/cm^2, reconstruction bias < 2 g/cm^2
Energy resolution ~ 7%

Lundquist, PoS ICRC2015 (2016) 441
Abbasi, et al., Astropart.Phys. 64 (2015) 49-62

FD Stereo X_{max}

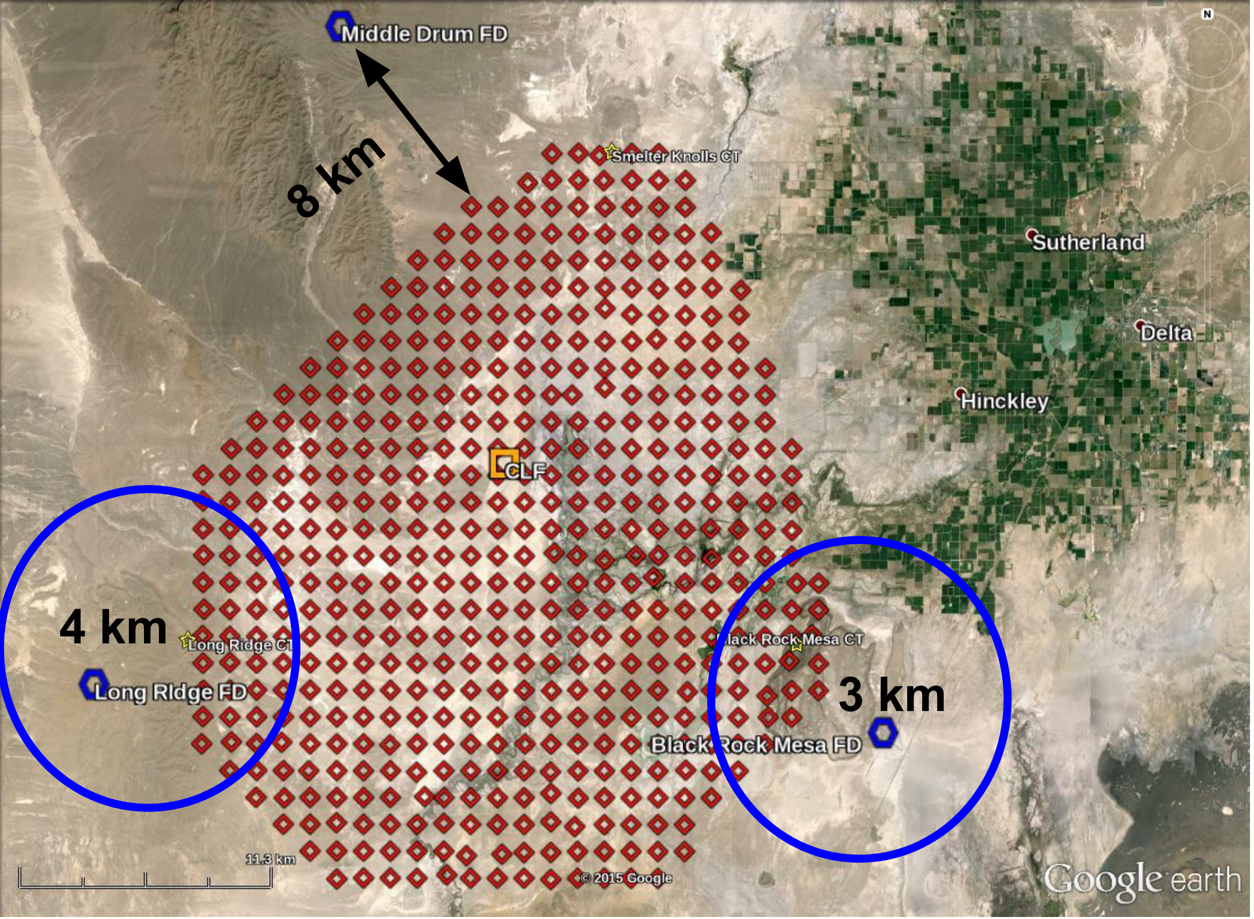


7 years data - 1458 events
Stereo has better zenith angle acceptance compared to hybrid → more events $E > 10^{19}$ eV



QGSJet II-03 models shown, reconstruction systematics ± 15 g/cm^2, X_{max} resolution = 21 g/cm^2, energy resolution = 5%

Bergman & Stroman, PoS ICRC2017 (2018) 538



Black Rock/Long Ridge Hybrid

Newly built for TA project.

FADC, 10 MHz sample rate

3 & 4 km from SD array border

Larger mirrors than Middle Drum ($6.8\ m^2$ vs $5.1\ m^2$)

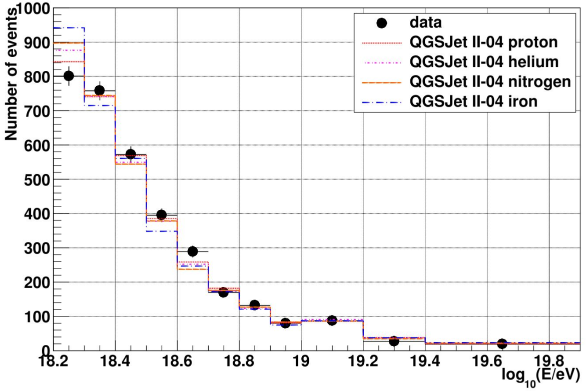
2 rings, 6 mirrors/ring
Ring 1: $3° \leq \theta \leq 18°$
Ring 2: $18° \leq \theta \leq 33°$
$\Delta\phi = 108°$

Closer to the SD array border → low energy hybrid acceptance differs from Middle Drum.

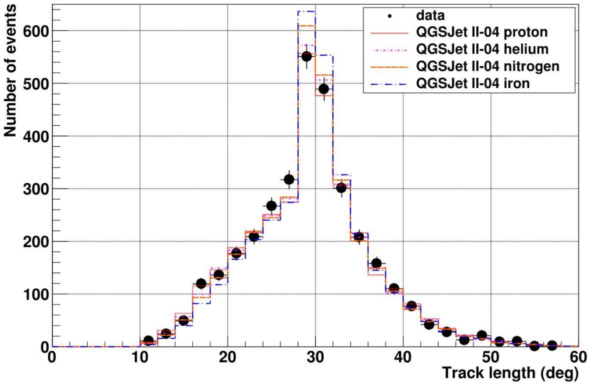
Highest statistics measure of composition.

Tameda, et al., Nucl.Instrum.Meth. A609 (2009) 227-234
Tokuno, et al., Nucl.Instrum.Meth. A676 (2012) 54-65

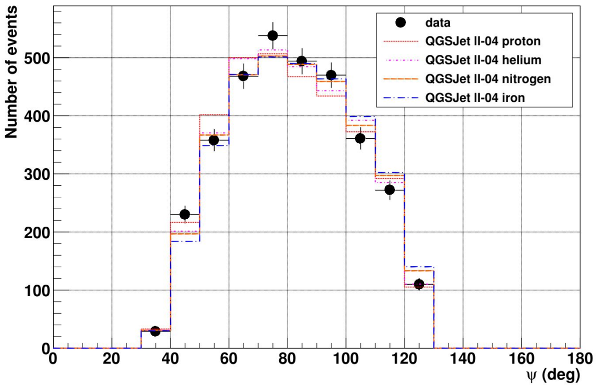
Data/MC Comparison



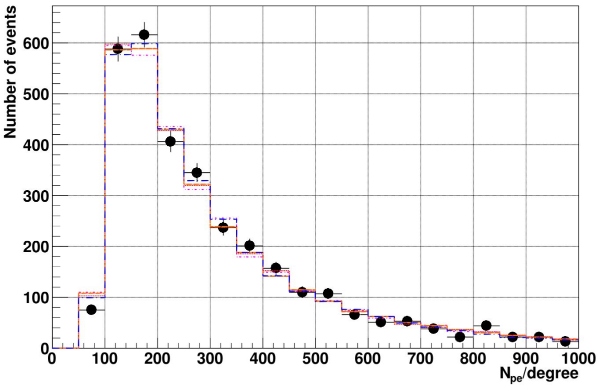
Data/MC energy



Data/MC track length



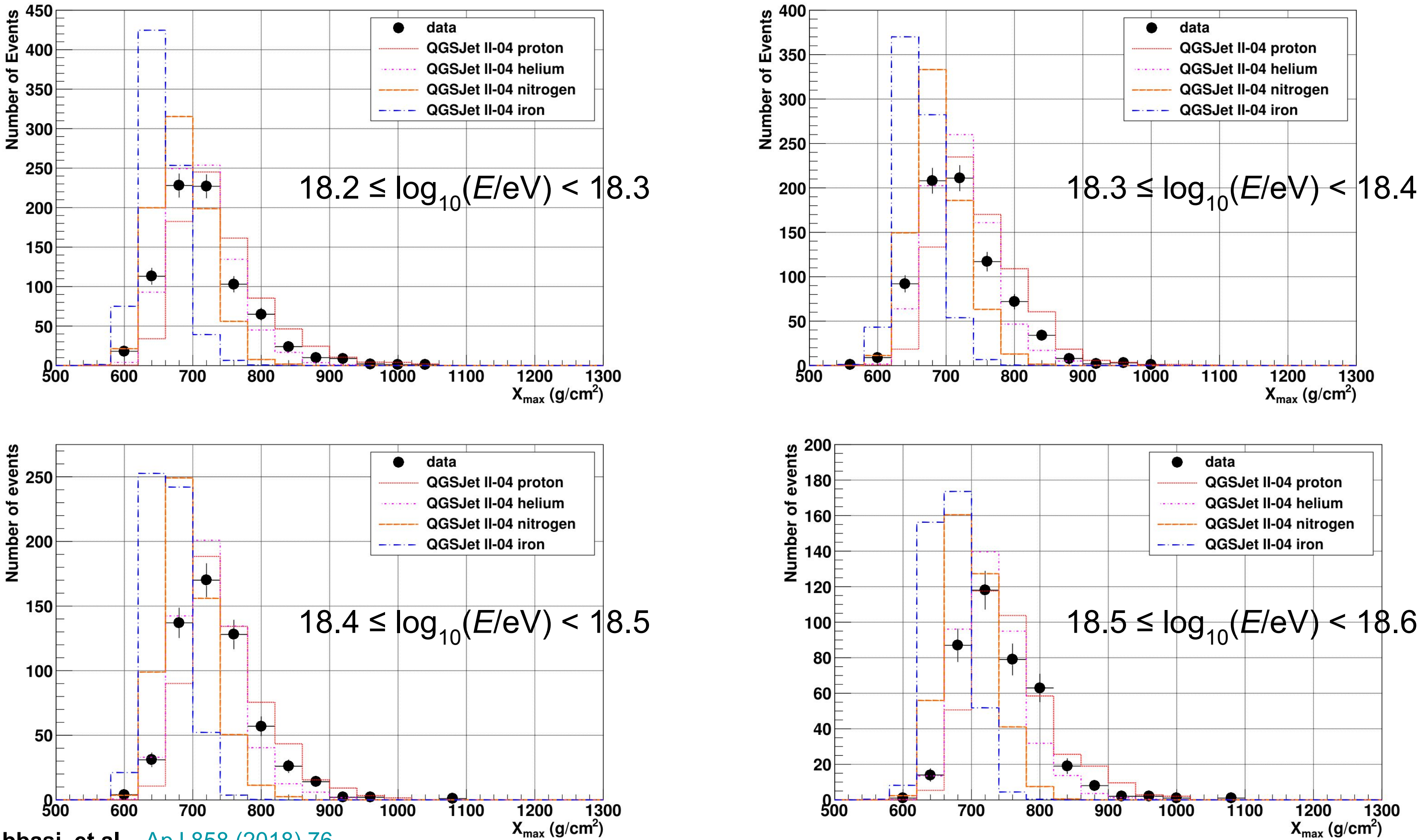
Data/MC ψ



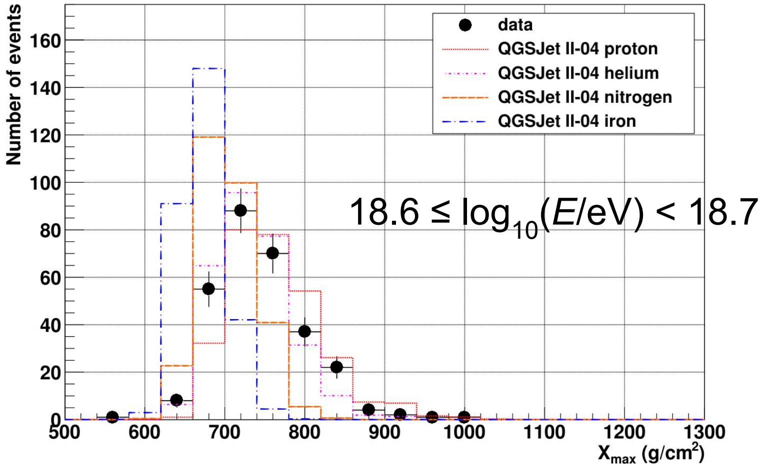
Data/MC N_{pe}/degree

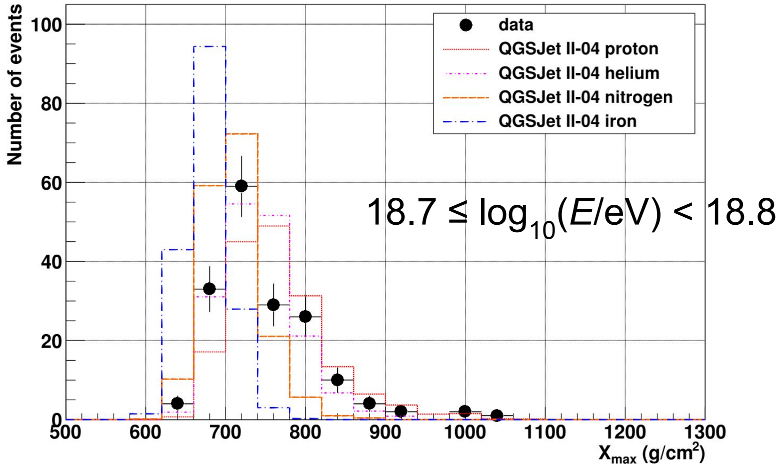
	Bias	Res
X_{max} (g/cm^2)	-1.1	17.2
Energy (%)	1.7	5.7
θ (deg)	0.014	0.337
ϕ (deg)	-0.020	0.410
ψ (deg)	0.074	0.397
R_p (m)	18.9	39.8
X_{core} (m)	-3.6	49.8
Y_{core} (m)	8.7	42.9

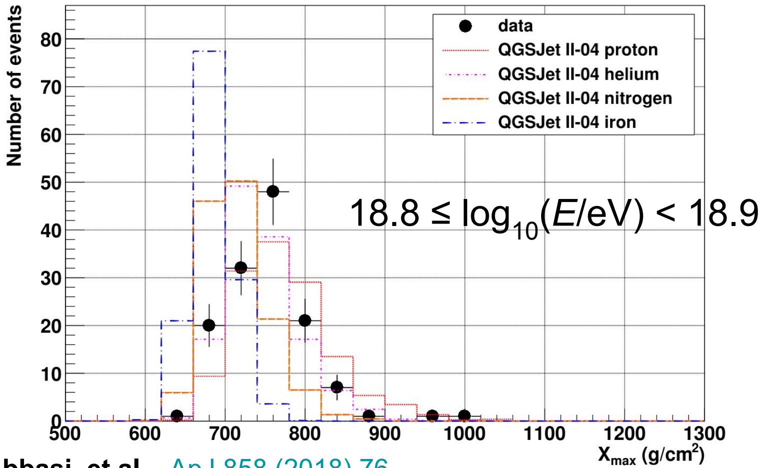
Abbasi, et al., ApJ 858 (2018) 76

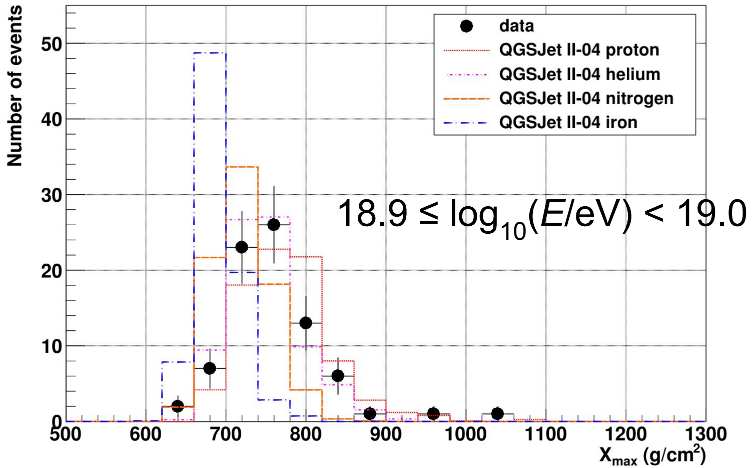


Abbasi, et al., ApJ 858 (2018) 76

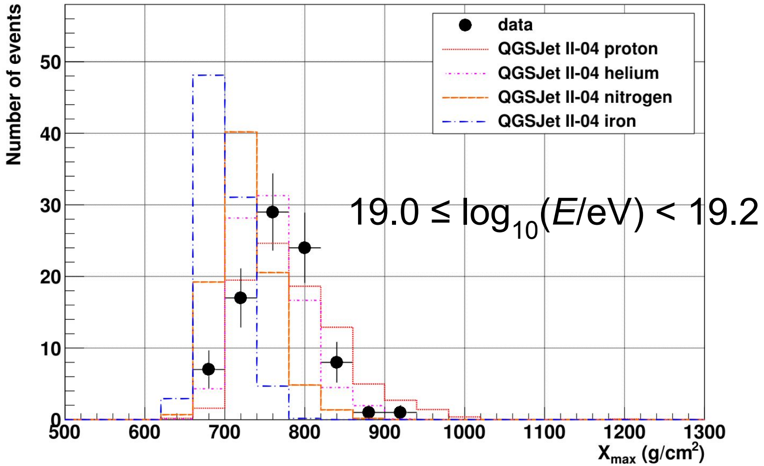


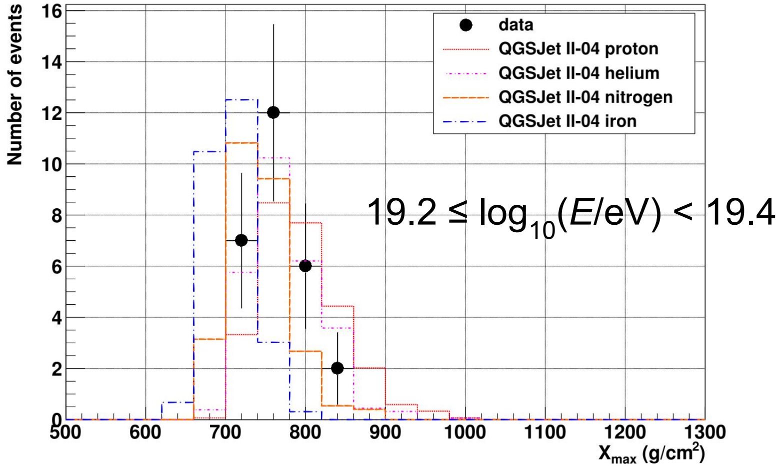


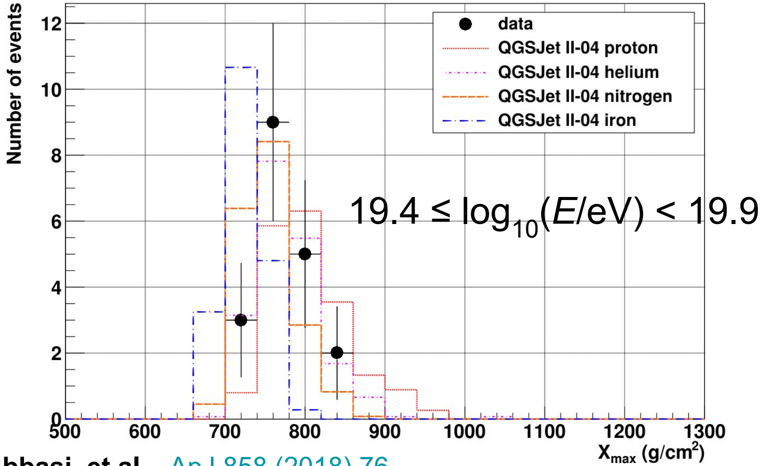




Abbasi, et al., ApJ 858 (2018) 76



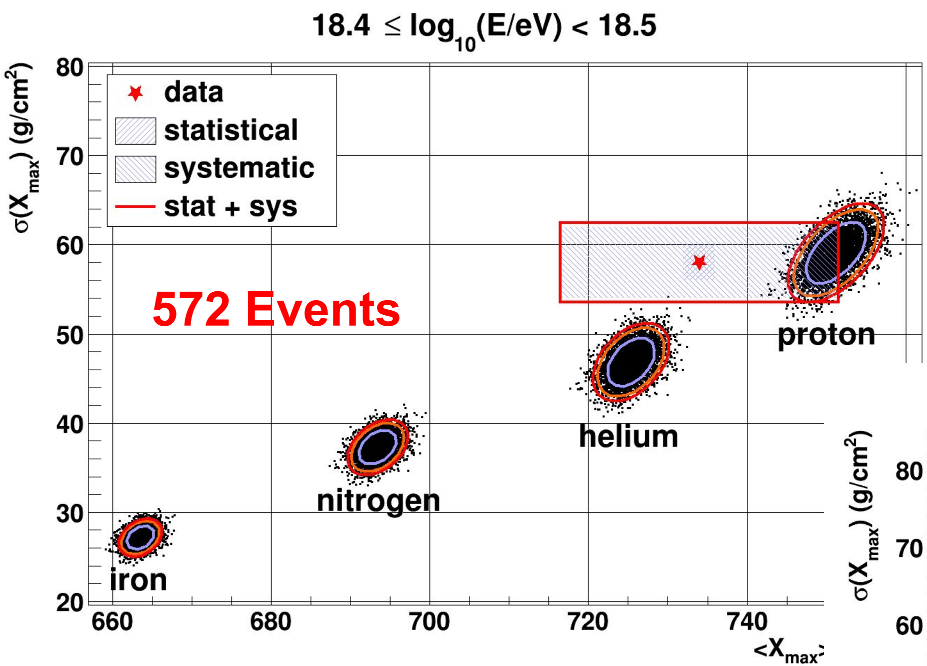




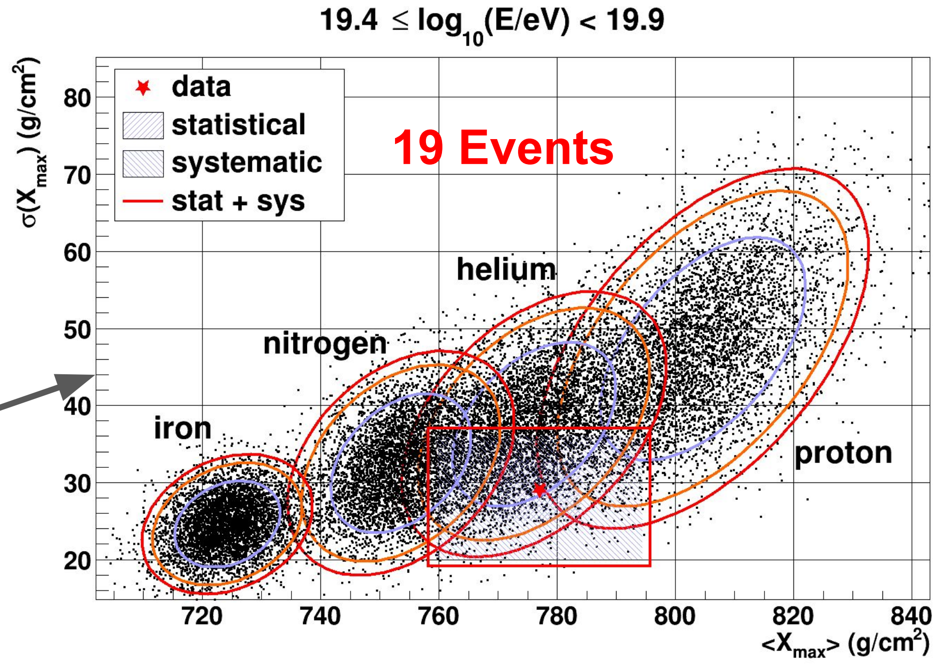
Below 10^{19} eV data X_{max} has a deep X_{max} tail resembling light composition (proton or helium).

Above 10^{19} eV, the deep X_{max} tail disappears in the data. Does this happen due to composition or detector acceptance? As shower energy grows zenith angle acceptance decreases because X_{max} occurs closer to the ground. So we must be able to see further inclined tracks for full acceptance. This analysis is also limited by the constraint of SD coincidence.

Abbasi, et al., ApJ 858 (2018) 76

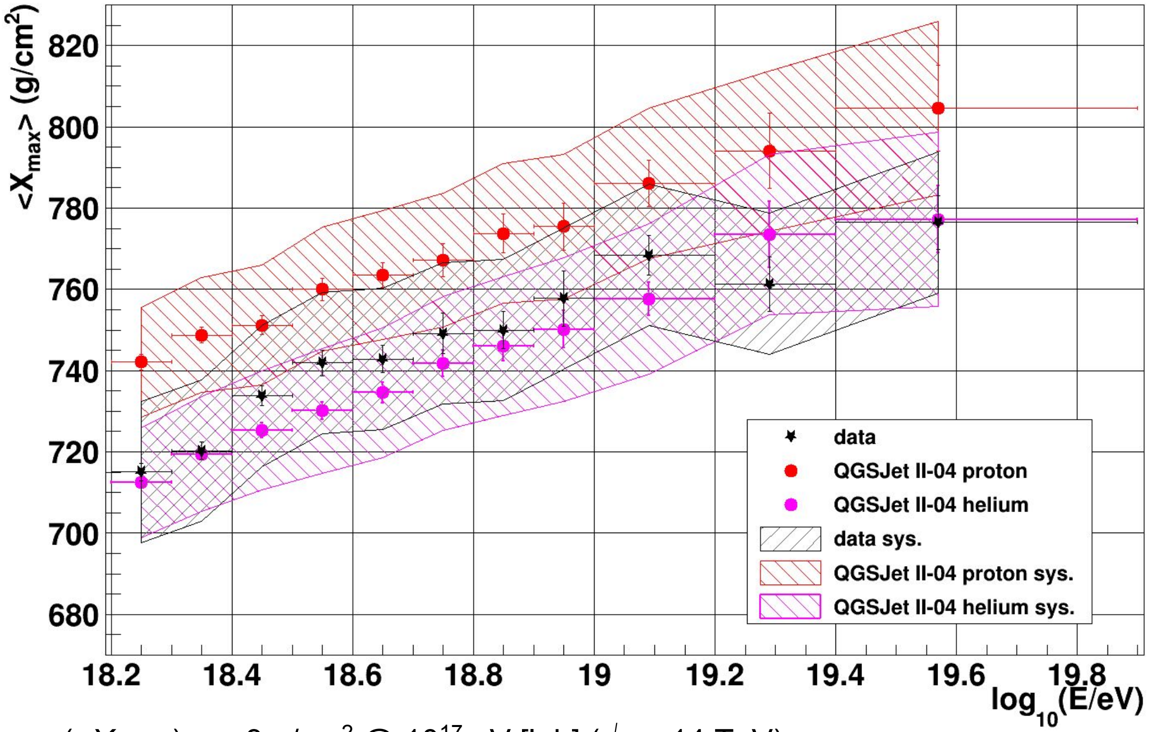


Below 10^{19} eV, TA has sufficient sensitivity to make a good measurement of composition under the assumption of a single species composition. Ellipses represent MC distributions for equivalent exposure as the data.



Above 10^{19} eV, sensitivity falls due to steeply falling flux and acceptance of light deeply penetrating primaries is limited by maximum atmospheric mass overburden (zenith angle dependence). Data overlaps the MC expectation of multiple species; TA has lost sensitivity to distinguish them.

UHECR Hadronic Model Systematics



$\sigma(<X_{max}>) = \pm$ 3 g/cm^2 @ 10^{17} eV [lab] ($\sqrt{s}$ = 14 TeV)
$\sigma(<X_{max}>) = \pm$ 18 g/cm^2 @ $10^{19.5}$ eV [lab] ($\sqrt{s}$ = 250 TeV)
$\sigma(<X_{max}>)$ of TA data = ±17.4 g/cm^2

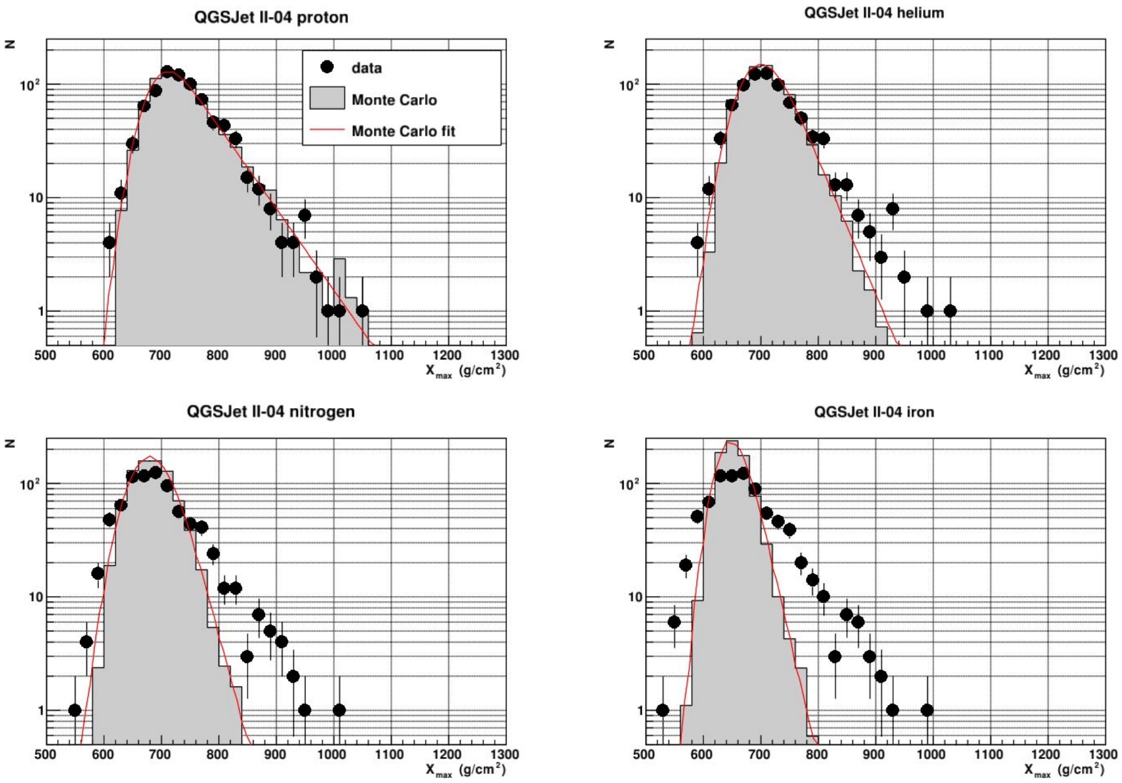
Conservative lower bounds on uncertainties from total cross-section, multiplicity, and elasticity dependence.

Hadronic models are still subject to large uncertainties as related to air shower observables.

Ulrich, Engel, & Unger[1] investigated the dependence of several UHECR-induced air shower observables e.g., $<X_{max}>$ and $\sigma(X_{max})$, by varying fundamental hadronic model parameters such as cross-section, multiplicity, elasticity using CONEX/SYBILL at $10^{19.5}$ eV.

Abbasi & Thomson[2] extended that work to measure $<X_{max}>$ uncertainty for CONEX & four different models (QGSJet01c, QGSJet II-03/04, & EPOS-LHC) at 10^{17} and $10^{19.5}$ eV.

[1] **Ulrich, Engel, Unger**, Phys.Rev.D83:054026 (2011)
[2] **Abbasi & Thomson**, JPS Conf.Proc. 19 (2018) 011015



Morphological test of composition

Assume composition consists primarily of a single element.

Monte Carlo and reconstruct those elements as observed by TA.

How can we compare the data and models given large potential systematic uncertainties in $<X_{max}>$ of either?

For a given energy bin systematically shift the data X_{max} distribution, compute the log likelihood of observing the data, under the assumption the true distribution is pure QGSJet II-04 protons, or helium, or nitrogen, or iron.

For the shift which provides the maximum likelihood, calculate the probability of observing a ML at least as extreme as observed in the shifted data.

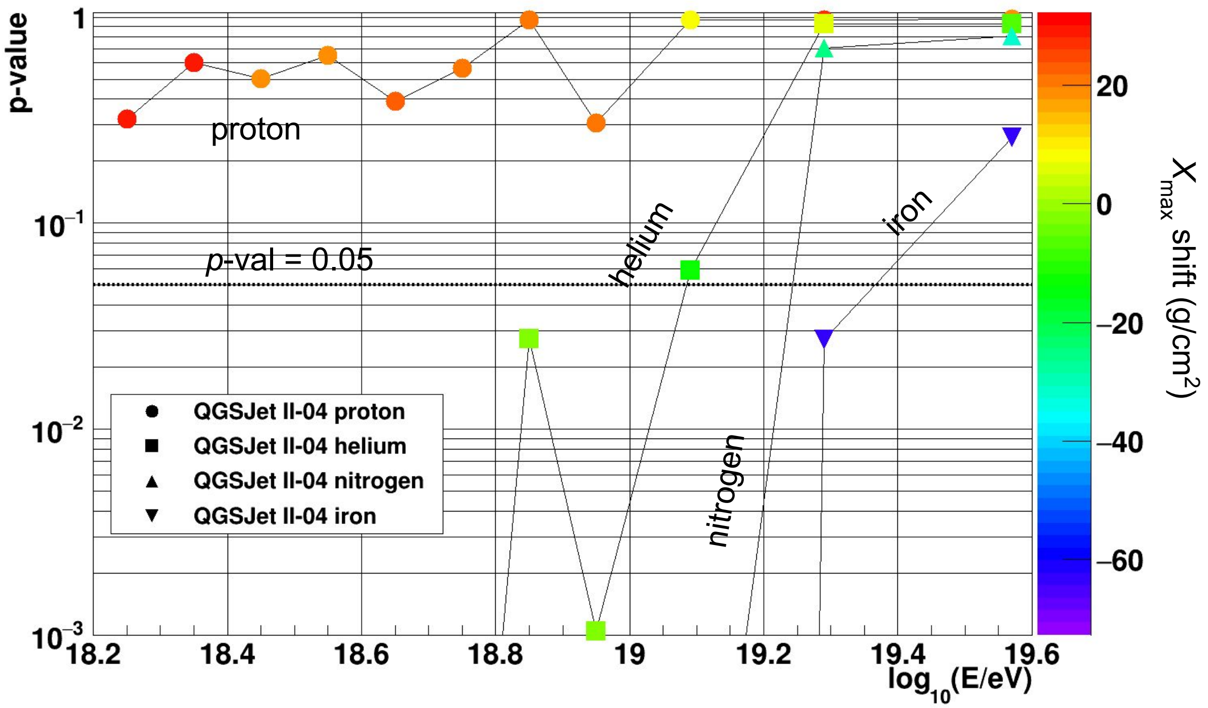
$18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

Proton $<\Delta X_{max}>$: +29 g/cm^2
Helium $<\Delta X_{max}>$: +7 g/cm^2
Nitrogen $<\Delta X_{max}>$: -19 g/cm^2
Iron $<\Delta X_{max}>$: -41 g/cm^2

$<X_{max}>$ Systematic uncertainties in hadronic models: ~ ±10 - 18 g/cm^2

Abbasi, et al., ApJ 858 (2018) 76

Test of Data vs. Models



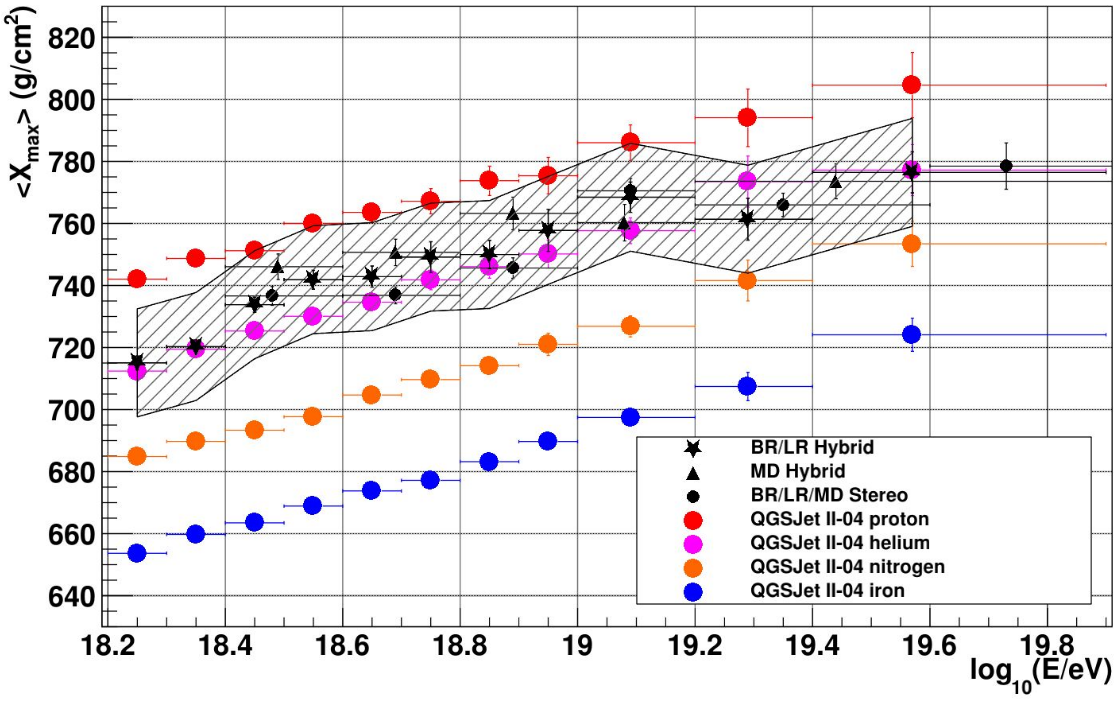
For a given energy bin, if the *p*-value is less than 0.05 we reject the data and Monte Carlo as being compatible.

If it is greater than 0.05, we fail to reject the model and data as compatible. In other words, given this test we can not exclude the possibility that data and Monte Carlo are compatible at the 95% confidence level.

This figure shows that for all energy bins after systematic shifting of X_{max} distributions, TA data fails to exclude QGSJet II-04 protons as being compatible with observations. Above 10^{19} eV, helium, nitrogen, and iron fail to be excluded but large systematic shifts are needed for iron.

Abbasi, et al., ApJ 858 (2018) 76

TA X_{max} Measurements Compared



Abbasi, et al., ApJ 858 (2018) 76
Lundquist, PoS ICRC2015 (2016) 441
Bergman & Stroman, PoS ICRC2017 (2018) 538

<*X_{max}*> for all measurements at TA which observe *X_{max}*.

All three measurements done by independent analysis.

BR/LR hybrid utilizes BR & LR FD stations + surface array.

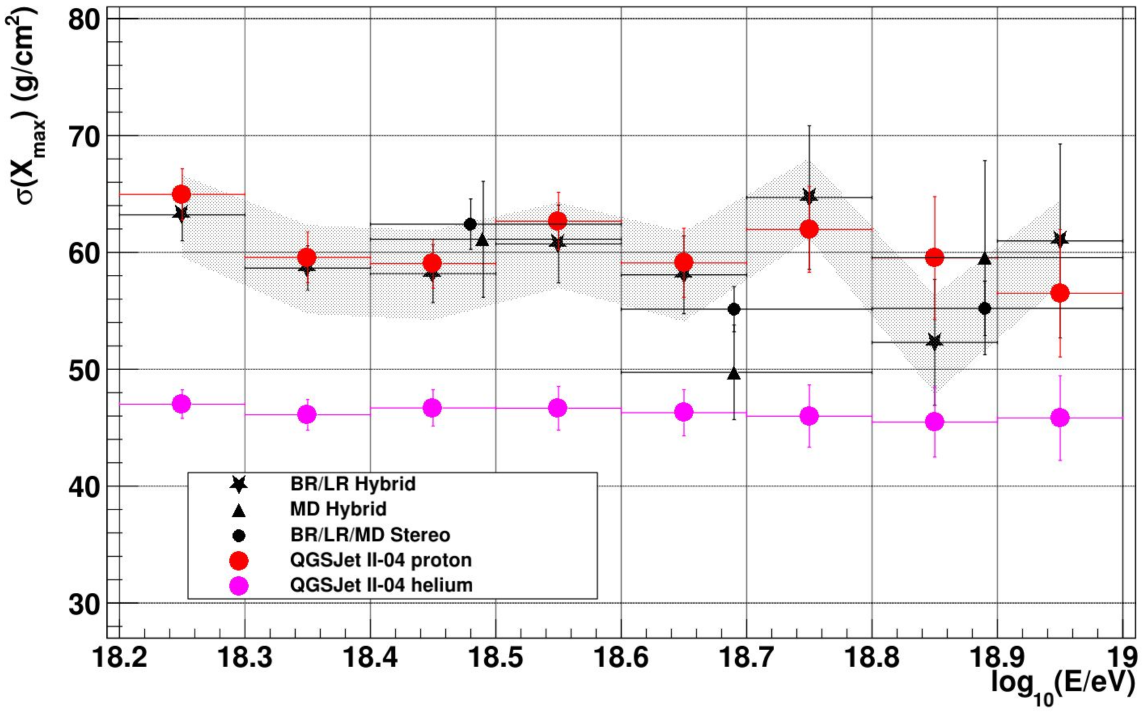
BR/LR/MD stereo is FD-only measurement using multiple coincidences of 2 or more FD stations.

MD hybrid uses the MD FD station and surface array.

All measurements are in agreement with each other (BR/LR systematics shown).

Model systematics swamp the region between proton and helium. See slide 12.

TA X_{max} Measurements Compared



$\sigma(X_{max})$ for all measurements at TA which observe X_{max}.

Above 10^{19} eV TA has insufficient exposure to make a careful measurement of the widths of X_{max} distributions.

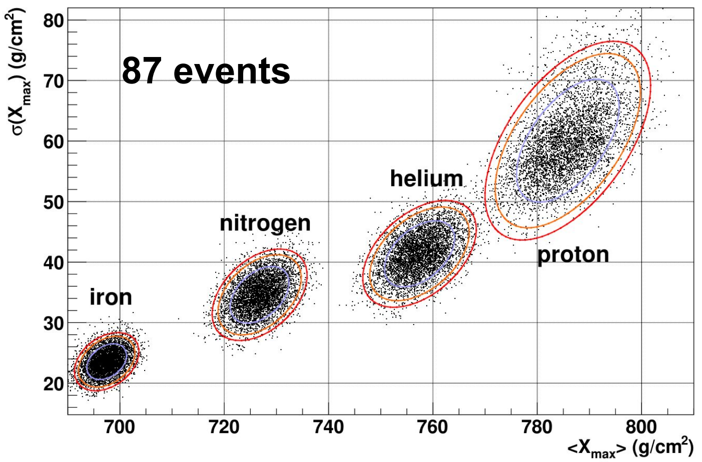
Highest energy events can have distortions in the relatively unpopulated tails due to acceptance (e.g., X_{max} in the ground, reduced zenith angle acceptance) or because of change in composition.

TA sees no narrowing of $\sigma(X_{max})$ up to 10^{19} eV. Auger sees evidence of narrowing beginning at ~$10^{18.45}$ eV.

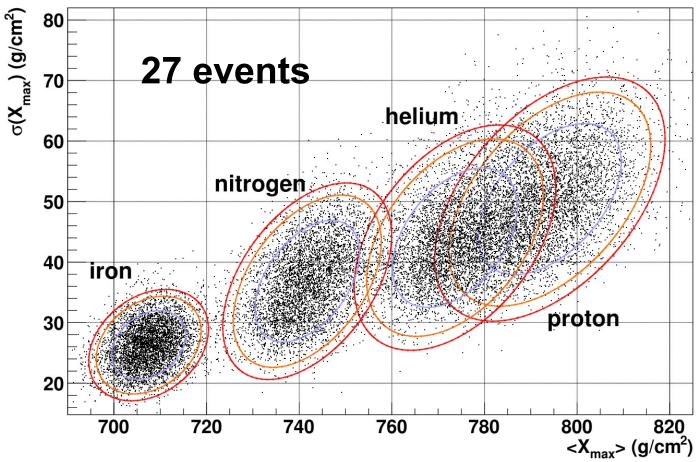
Moments of distributions require many events, especially when dealing with skewed distributions. A fluctuation of even two or three events in the tails of a distribution of N = 100, is enough to cause $\sigma(X_{max})$ to fluctuate by 10 g/cm^2.

Abbasi, et al., ApJ 858 (2018) 76
Lundquist, PoS ICRC2015 (2016) 441
Bergman & Stroman, PoS ICRC2017 (2018) 538

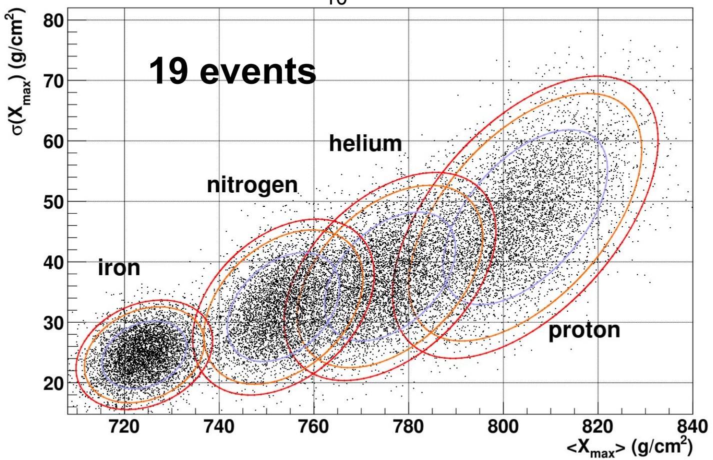
19.0 ≤ $\log_{10}(E/eV)$ < 19.2



19.2 ≤ $\log_{10}(E/eV)$ < 19.4

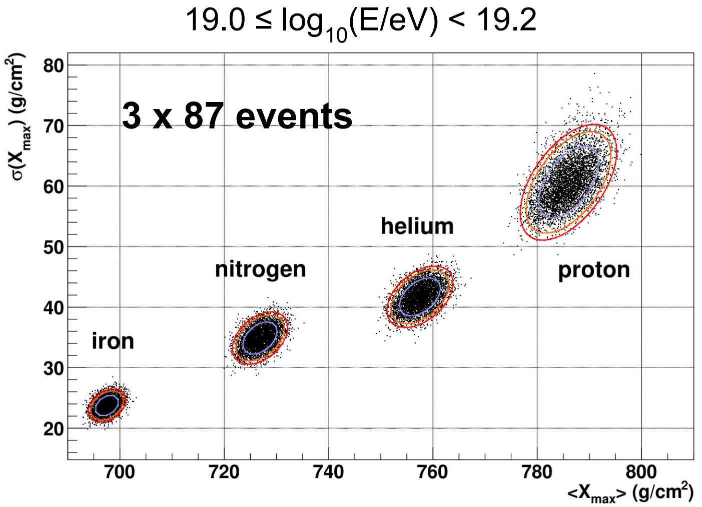


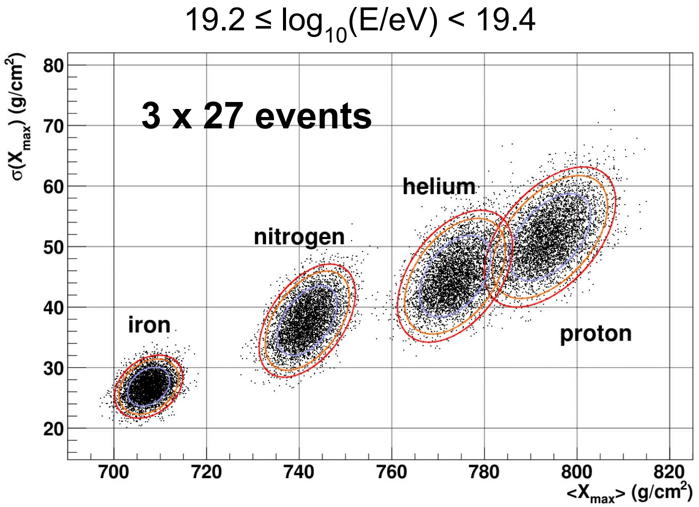
19.4 ≤ $\log_{10}(E/eV)$ < 19.9

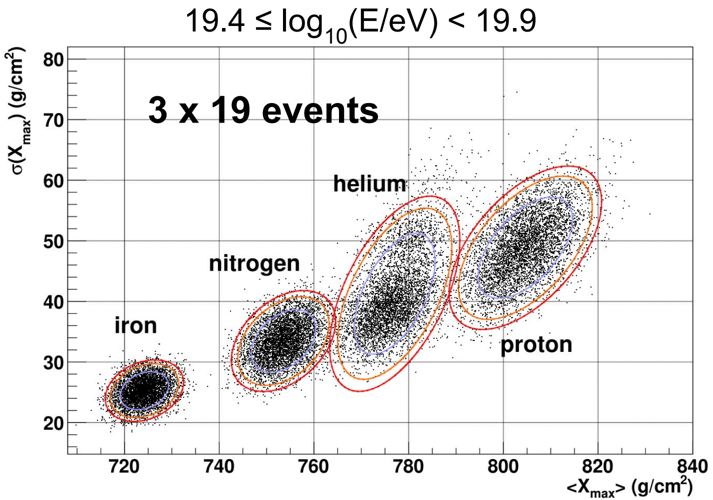


Reconstructed $\langle X_{max} \rangle$, $\sigma(X_{max})$ QGSJet II-04 Monte Carlo sampled according to BR/LR data statistics for three highest energy bins.

Ellipses indicate 68%, 90%, 95% confidence intervals of the joint $\langle X_{max} \rangle$, $\sigma(X_{max})$ distribution based upon the detector exposure of ~9 years.





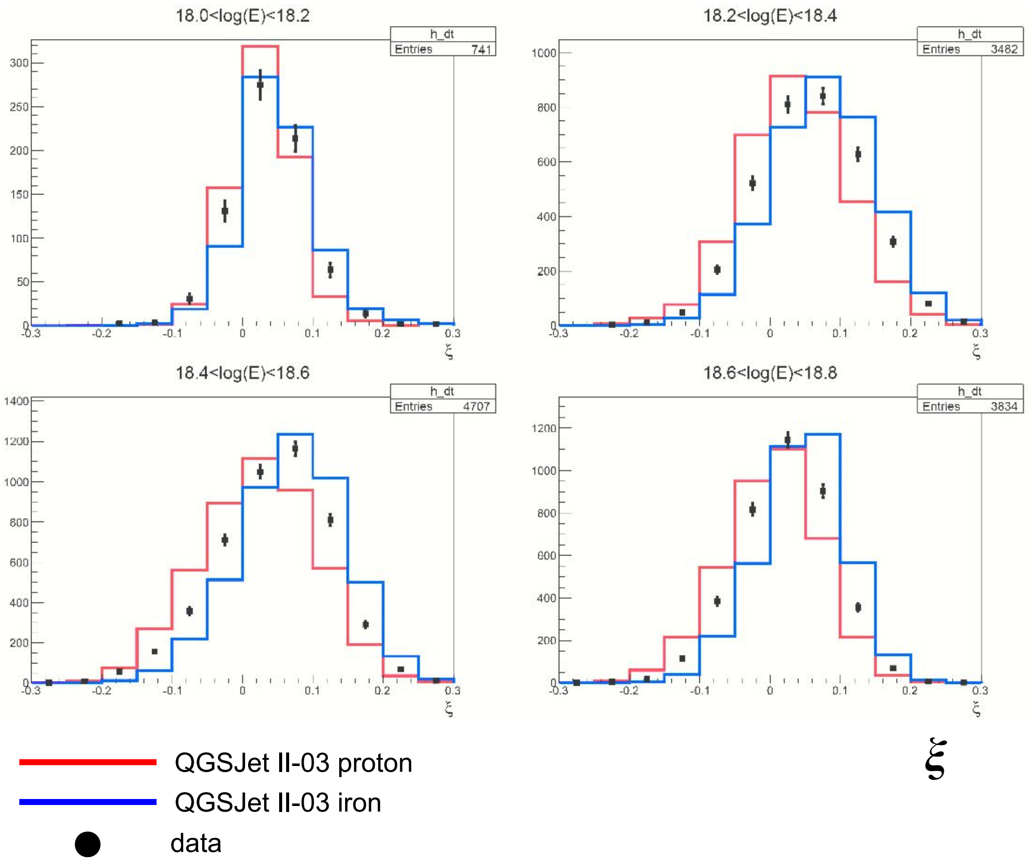


TAx4 will provide ~3x the number of events we currently have for BR/LR hybrid X_{max} by 2021.

Data + systematics currently overlap multiple predictions of single chemical elements. Greater exposure will give hybrid X_{max} measurement more power to measure composition at least up to $10^{19.2}$ eV.

TAx4 is starting operations now.

Composition Measurement by SD



Use Monte Carlo proton showers as classifier background and iron as “signal”.

Train boosted decision tree to classify individual events as proton-like or iron-like based mainly upon the shower observables related to muon production. Larger $A \rightarrow$ more muons.

MVA and BDT analysis technique using 14 parameters measured in SDs

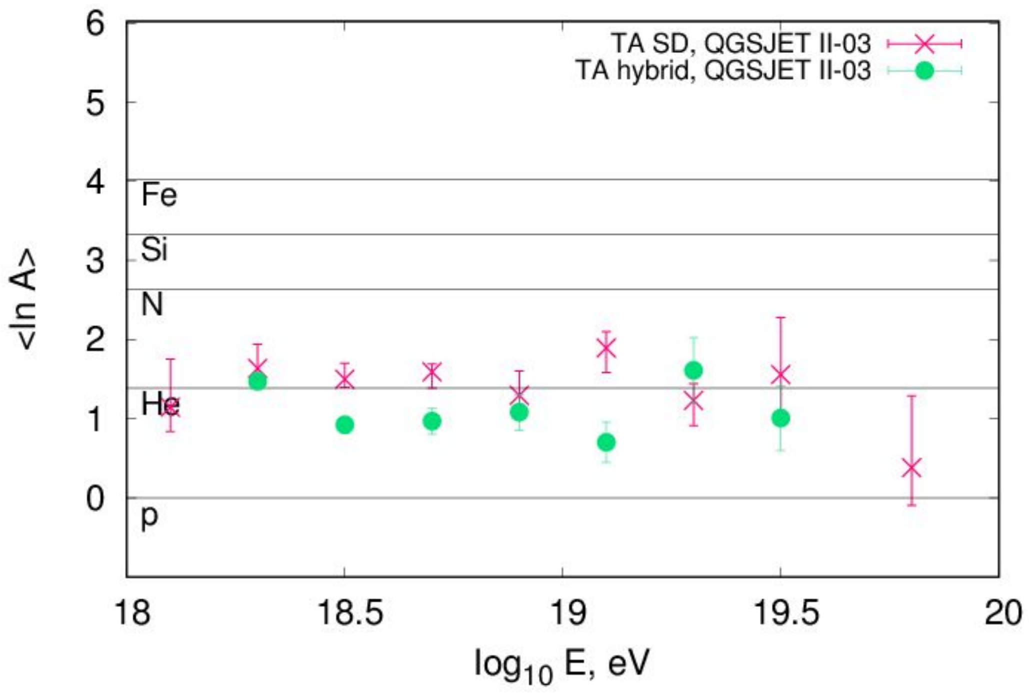
- Shower front curvature
- Signal Area over Peak
- Upper/Lower scintillator layer asymmetry
- Peak distributions in FADC waveforms

Divide Monte Carlo into 3 parts:

- Training set using 14+2 (+2 $\rightarrow$ energy, θ) variables to compute classification variable ξ for each event: -1 $\rightarrow$ pure bkgnd, 1 $\rightarrow$ pure signal.
- Create mixtures of proton/iron X_{max} distributions in 2.5% steps to compute <ln A> observed in the data.
- Use third part to correct for bias in ξ.

Abbasi, et al., arXiv:1808.03680

Composition Measurement by SD



<ln *A*> = 1.52 ± 0.08 (stat) ± 0.36 (sys)

SD composition opens a window into much higher statistics measurements.

~100% duty cycle

Hybrid X_{max}: 3330 events
SD MVA: 18007 events

Model systematics. Models underestimate rate of muon production in showers by ~30 - 80%

Nine years of TA SD data: 2008 - 2017

New technique. Needs comprehensive checks to verify.

Abbasi, et al., arXiv:1808.03680

Summary

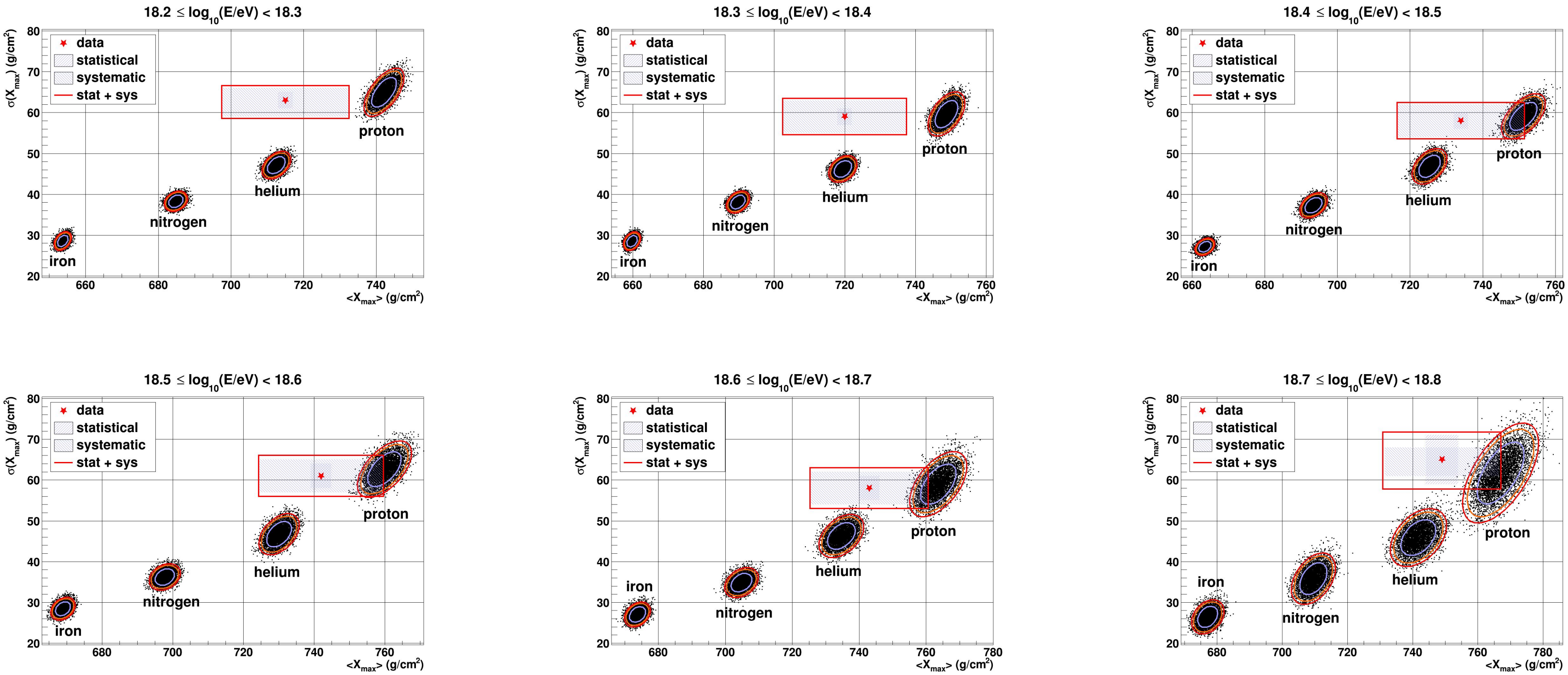
- TA has four quasi-independent measures of composition (overlapping equipment, independent analysis techniques)
- Three through X_{max} observations by FDs, one through μ sensitive observables observed by SD array.

- FD measurements are consistent with *light* composition well measured up to 10^{19} eV through comparison of first and second moments of X_{max} distributions with QGSJet II-03/04 models of four primary elements.
- More detailed analysis which measures the compatibility of entire X_{max} distributions are performed by finding systematic X_{max} shift which maximizes the likelihood between data and Monte Carlo, then measuring the probability of observing a likelihood at least as this extreme from single element reconstructed MC.
- TA $\langle X_{max} \rangle$ systematic uncertainty: ±17.4 g/cm^2.
- QGSJet II-04 $\langle X_{max} \rangle$ systematic uncertainies: ~±3 g/cm^2 - ±18 g/cm^2 from 10^{17} - $10^{19.5}$ eV.
- Below 10^{19} eV, TA full X_{max} distributions are compatible with QGSJet II-04 protons.
- Above 10^{19} eV, TA can not rule out single element models such as QGSJet II-04 helium, nitrogen, and iron.

- SD measurement has much more powerful statistics, this technique is still under development.
- $\langle \ln A \rangle$ = 1.52 ± 0.08 (stat) ± 0.36 (sys)
- No significant evolution of <ln A> with energy including E > 10^{19} eV where there is no deficit of events using this technique.

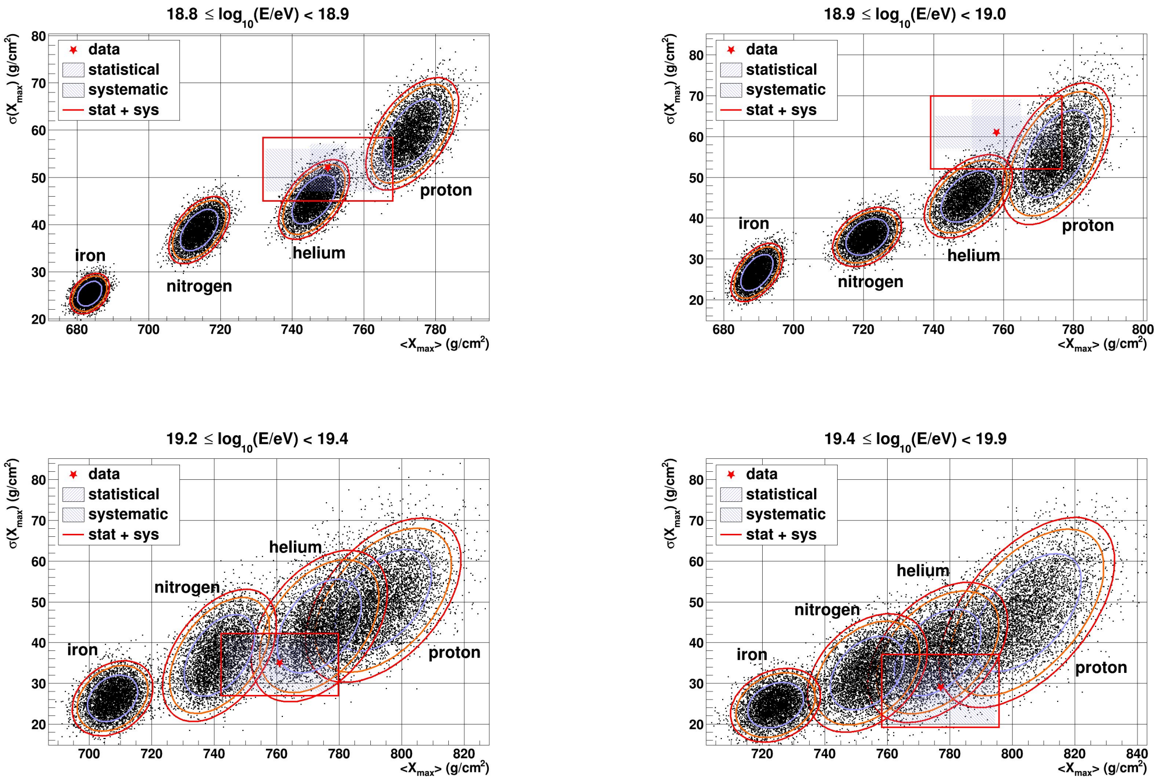
- Further work measuring upper bounds on elements such as iron, mixtures, and EPOS-LHC generation to follow.
- TA stereo FD can improve statistical sensitivity above 10^{19} eV (larger zenith angle acceptance).
- TAx4 which is starting operation now will increase statistics above 10^{19} eV.

Extra



$<X_{max}>$ and $\sigma(X_{max})$ of TA hybrid data and QGSJet II-04 Monte Carlo

ApJ 858 (2018) 76

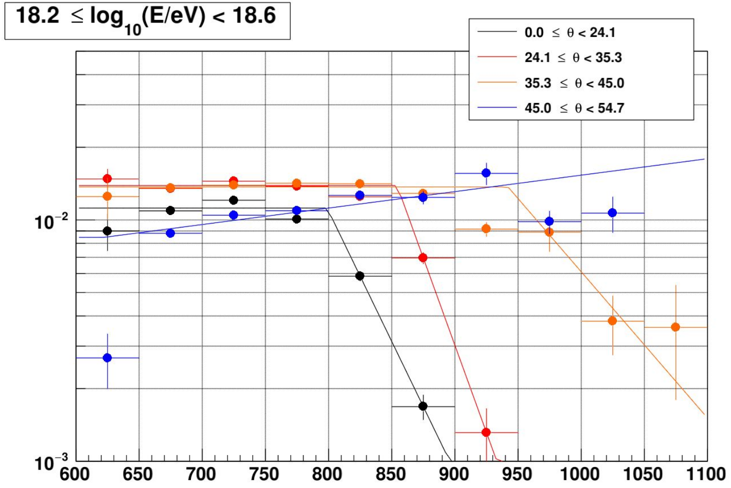


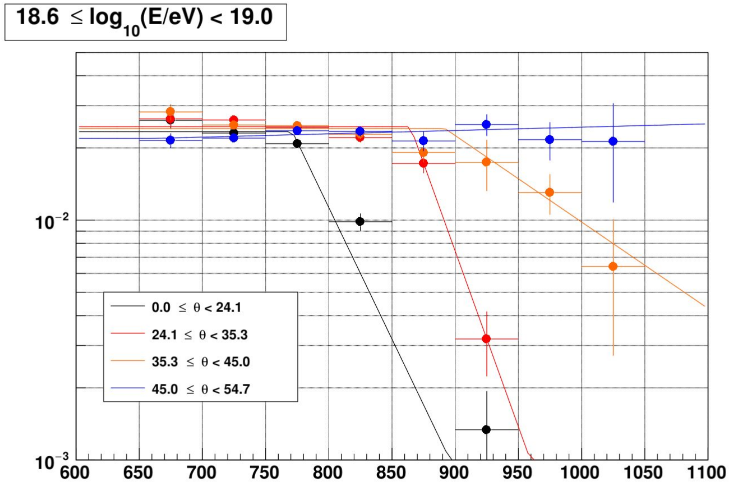
Systematic uncertainties

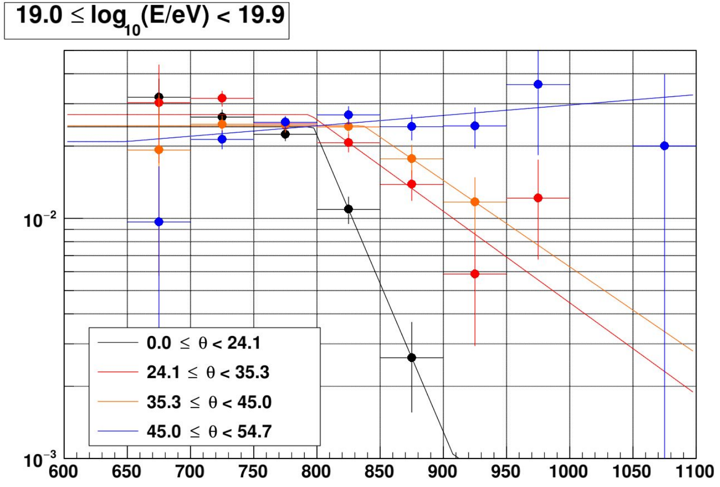
$\langle X_{max} \rangle$: 17.4 g/cm^2
$\sigma(X_{max})$: 21.2 g/cm^2

$\langle X_{max} \rangle$ and $\sigma(X_{max})$ of TA hybrid data and QGSJet II-04 Monte Carlo

ApJ 858 (2018) 76







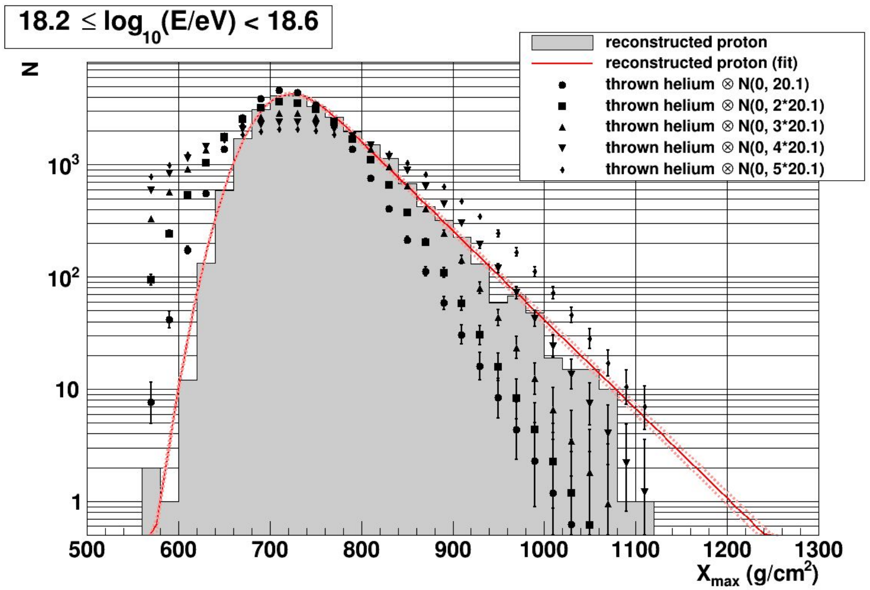
Hybrid X_{max} acceptance as a function of zenith angle in three energy ranges.

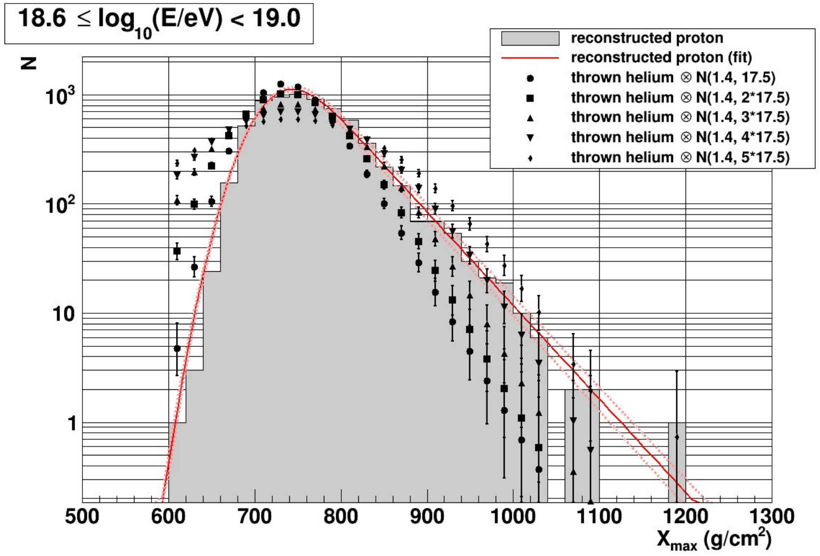
Low zenith angle events (near vertical) have lower acceptance. This will mostly affect deeply penetrating events (low mass primaries). ***X*$_{max}$ must be bracketed to ensure a profile fit with small ΔX_{max}.**

We have a steeply falling spectrum, higher energy events on average penetrate deeper, statistics are rapidly depleted for $E > 10^{19}$ eV.

TA needs greater exposure for accurate measurement of composition for $E > 10^{19}$ eV. Nearly 9 years of data ⇒ 133 events above 10^{19} eV.

TAx4 will give us the exposure needed to measure composition here.

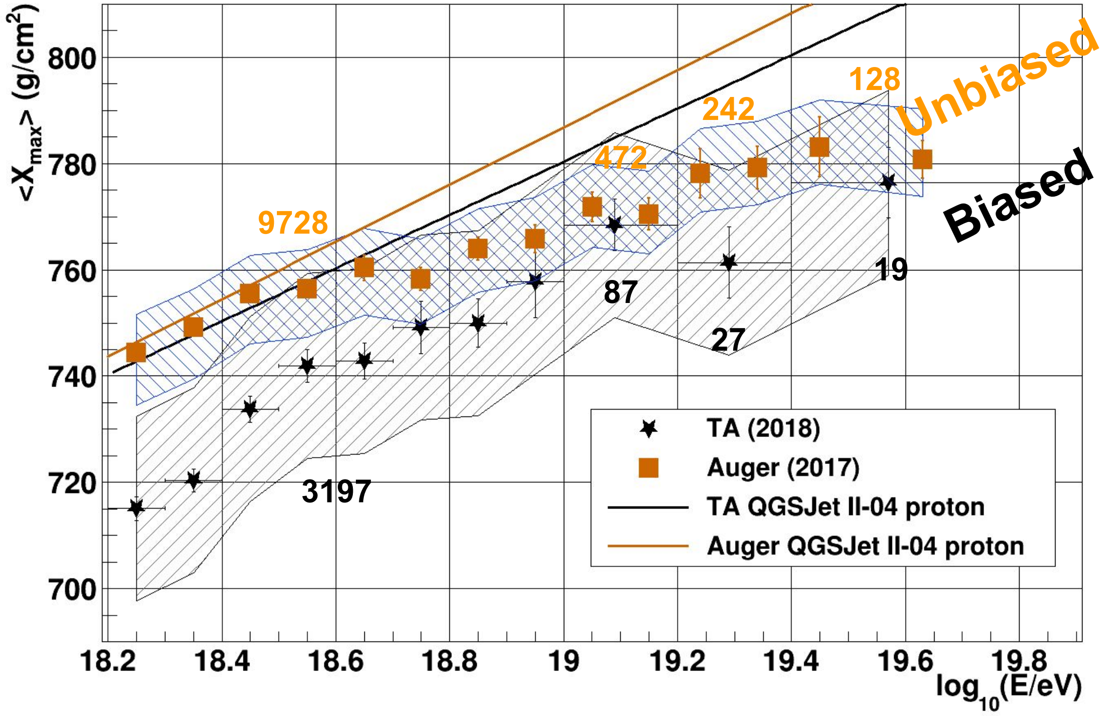




Can poor X_{max} resolution cause heavier elements to look like protons in TA's detector? In other words can resolution be smearing shallow events up into the deep X_{max} tail, increasing the widths of the distributions to look like protons?

No. TA requires resolutions 3-4 times worse than what we simulate to make tails of helium X_{max} distribution look like QGSJet II-04 protons for $E < 10^{19.0}$ eV. Nitrogen and iron require much worse resolution to populate the proton X_{max} tails.

TA & Auger X_{max} distributions cannot be directly compared



Abbasi, et al., ApJ 858 (2018) 76

Bellido, Depth of maximum of air-shower profiles at the Pierre Auger Observatory: Measurements above $10^{17.2}$ and Composition Implications (ICRC 2017)

Auger data is unbiased through event selection.

TA data is biased mostly by detector acceptance.

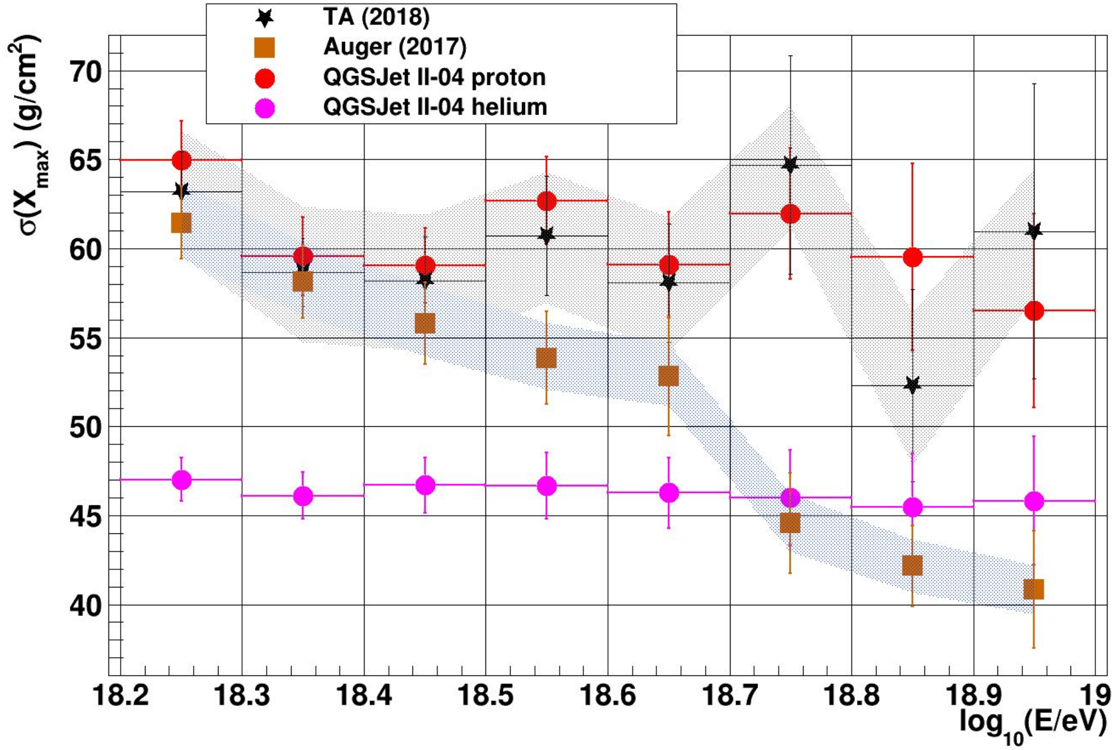
"Disagreement" of Auger and TA results mainly from the ***interpretation*** of what happens to observed X_{max} relative to single species X_{max} expectation.

Above ~$10^{18.3}$ eV Auger $<X_{max}>$ begins to fall away from proton expectation and X_{max} fluctuations narrow.

TA is systematically shifted from protons but shows no break in the slope and fluctuations look like protons. Above 10^{19} eV TA hybrid has insufficient exposure to make a meaningful measurement of either.

TAx4, stereo, 1 SD hybrid will provide more statistics.

TA & Auger X_{max} distributions cannot be directly be compared



Below $10^{18.5}$ eV TA and Auger observe $\sigma(X_{max})$ consistent with protons.

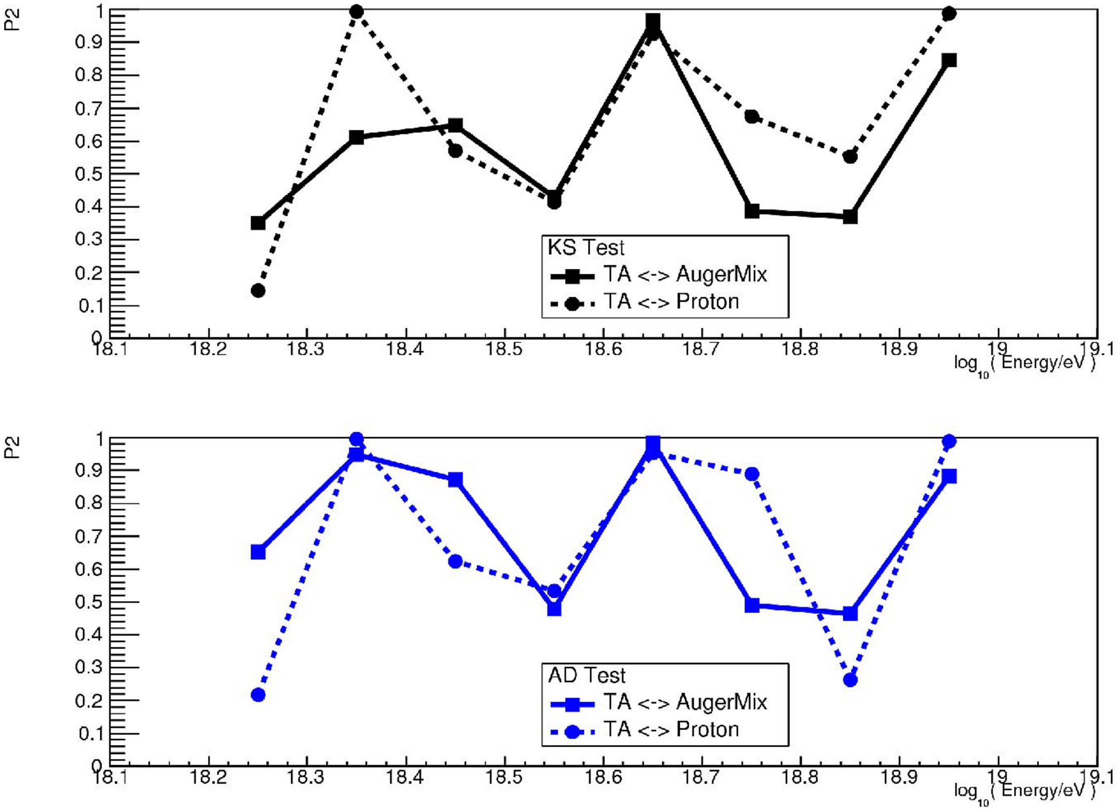
From $10^{18.5}$ - $10^{19.0}$ eV a North/South discrepancy is observed, with TA remaining consistent with pure protons and Auger trending towards heavier elements.

Above $10^{19.0}$ eV, TA has insufficient statistics to interpret $\sigma(X_{max})$.

Moments of distributions require many events, this is even more so true when dealing with skewed distributions. A fluctuation of even two or three events in the tails of a distribution of N = 100, is enough to cause $\sigma(X_{max})$ to fluctuate by 10 g/cm^2.

Abbasi, et al., ApJ 858 (2018) 76

Bellido, Depth of maximum of air-shower profiles at the Pierre Auger Observatory: Measurements above $10^{17.2}$ and Composition Implications (ICRC 2017)



Auger fits their unbiased data to a composition mixture of proton, helium, nitrogen, iron → TA reconstructs this mixture → exposure to full detector and reconstruction → now we can compare for compatibility.

Nonparametric tests (KS and AD) fail to reject the null hypothesis at the 90% confidence level.

Below 10^{19} eV:

TA data agrees with Auger data within systematic uncertainties.

TA and pure QGSJet II-04 protons show a similar level of compatibility.

V. De Souza, *Testing Agreement of X_{max} Between Auger and TA,* ICRC 2017

Statement approved by TA and Auger collaborations - ICRC 2017.