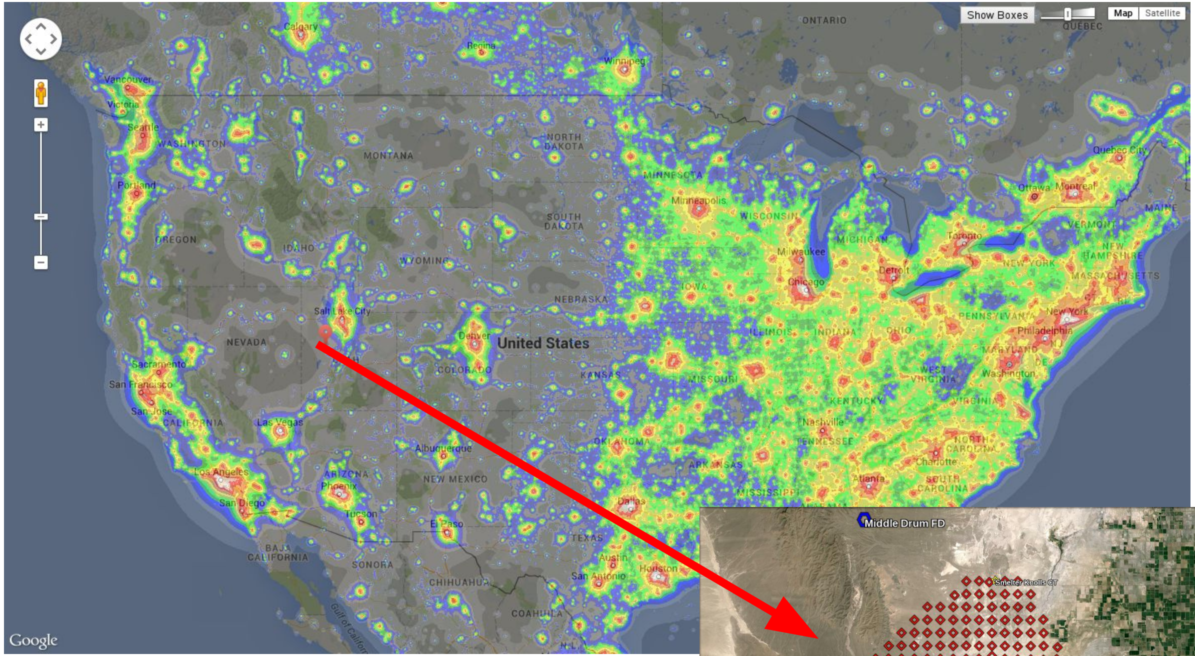
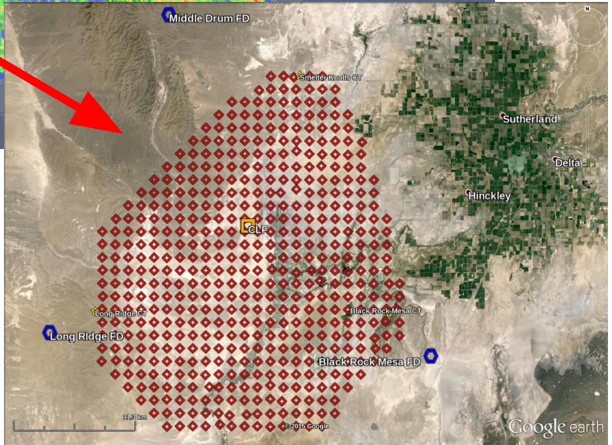
Telescope Array Hybrid Composition and Auger-TA Composition Comparison

William Hanlon
University of Utah & High Energy Astrophysics Institute

ISVHECRI 2018 - 名古屋市 日本 - 21 May 2018

TA Observatory





Light pollution map of the U.S.

http://telescopearray.org

~700 km^2 → ≲ *land* area of New York City.

Millard County, Utah

39° 17’ 48.90457”
112° 54’ 31.43708”
1370 m

876 g/cm^2 vertical depth

507 Scintillator surface counters

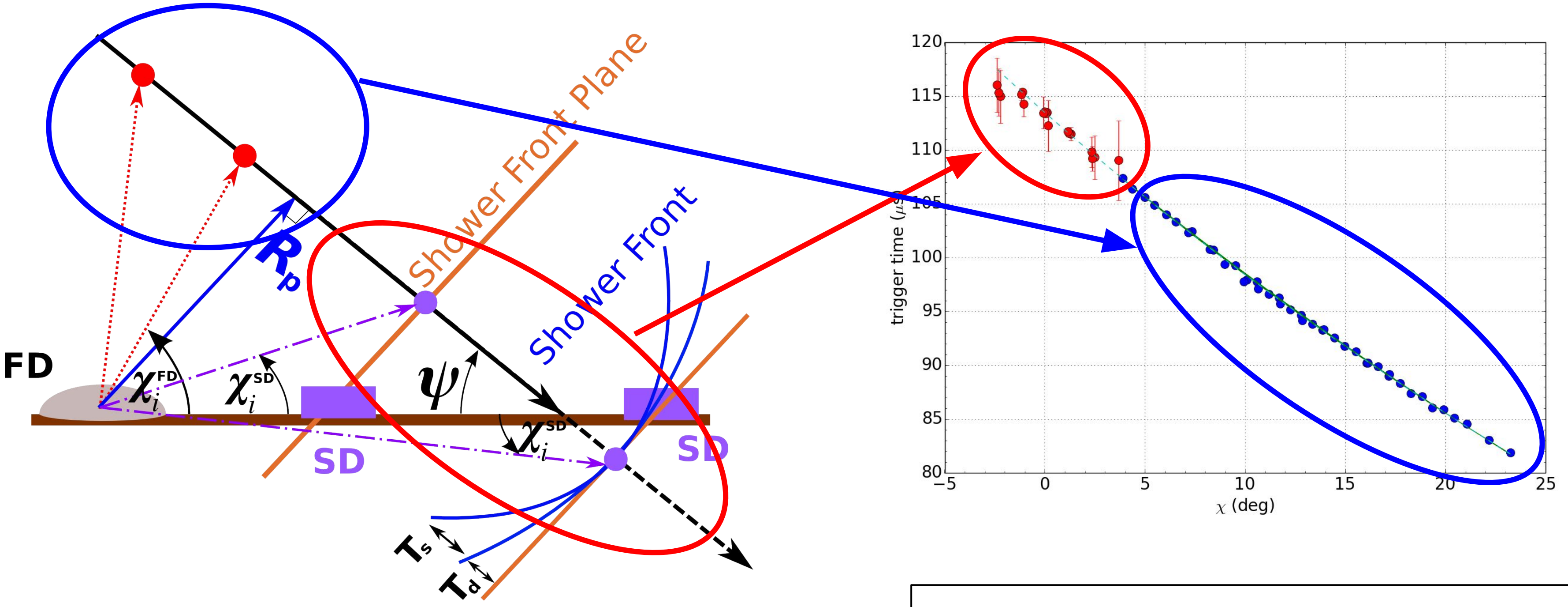
48 Air fluorescence telescopes

25 kW radar transmitter

Lightning detection array

40 MeV linear accelerator

Hybrid Reconstruction Method

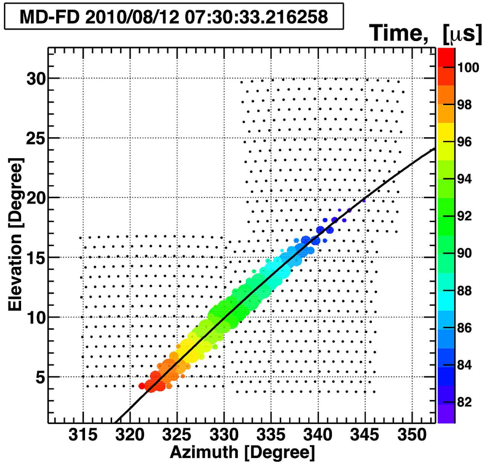


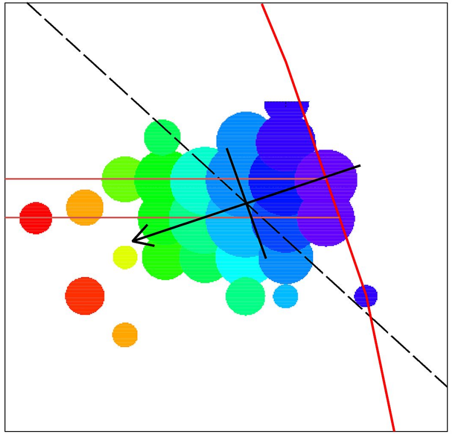
Hybrid combines timing and geometry of FD and SD.
Shower development is observed in the sky → $\Delta\psi$
Core location and time is recorded on the ground.

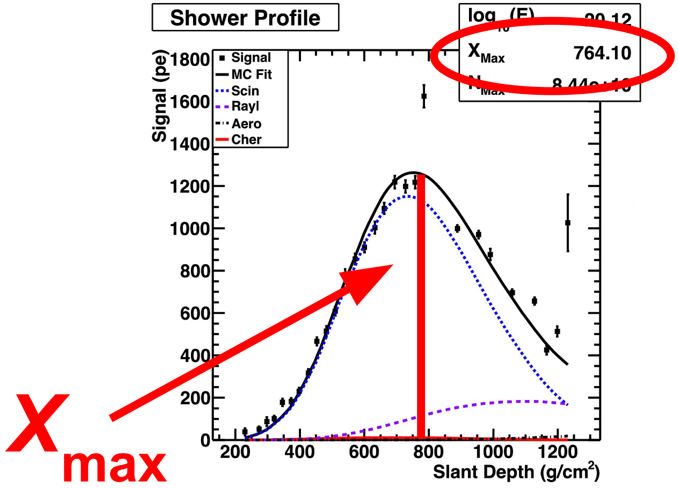
Time vs. Viewing Angle

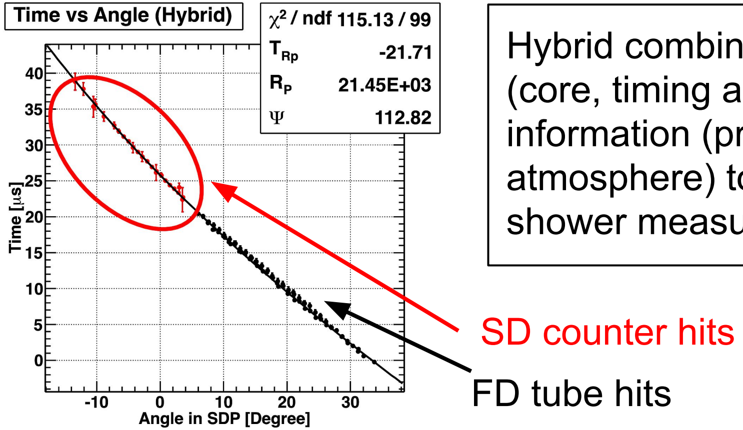
$$t_i = t_0 + \frac{r_{\rm p}}{c}\tan\left(\frac{\pi - \psi - \chi_i}{2}\right)$$

TA Hybrid High Energy Event





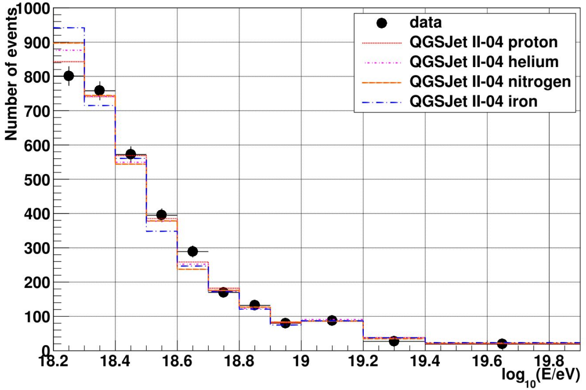




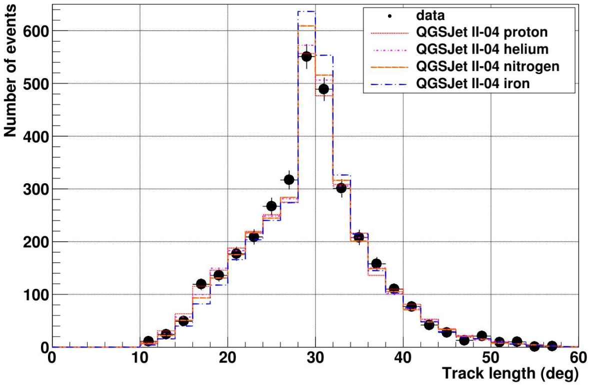
Hybrid combines SD information (core, timing at the ground) with FD information (profile, timing in the atmosphere) to make improved shower measurement.

Energy: 1.3×10^{20} eV
R_p: 21 km
zenith: 55.7 deg

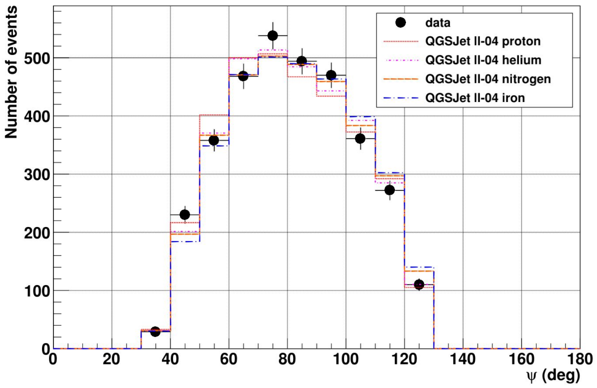
Data/MC Comparison



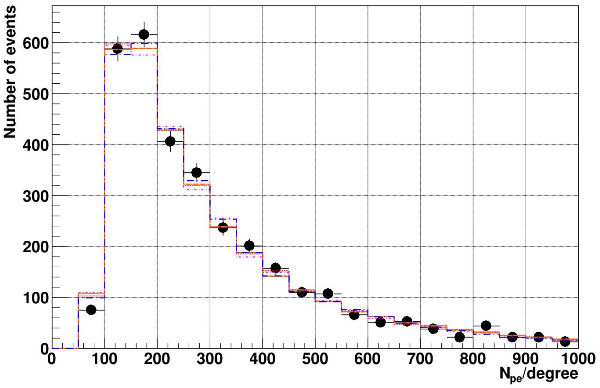
Data/MC energy



Data/MC track length

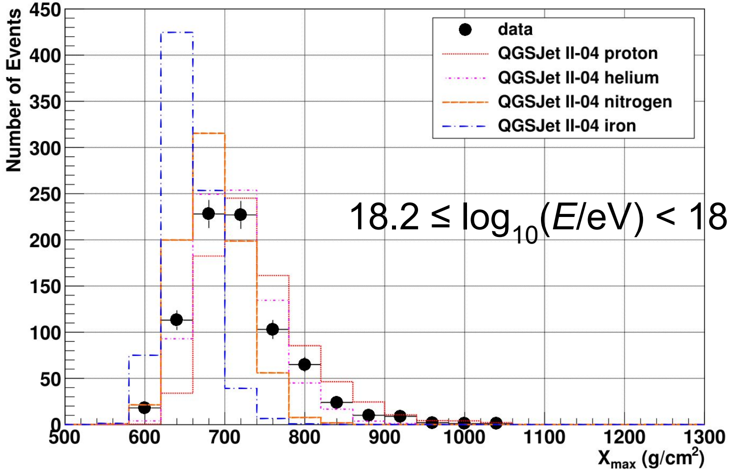


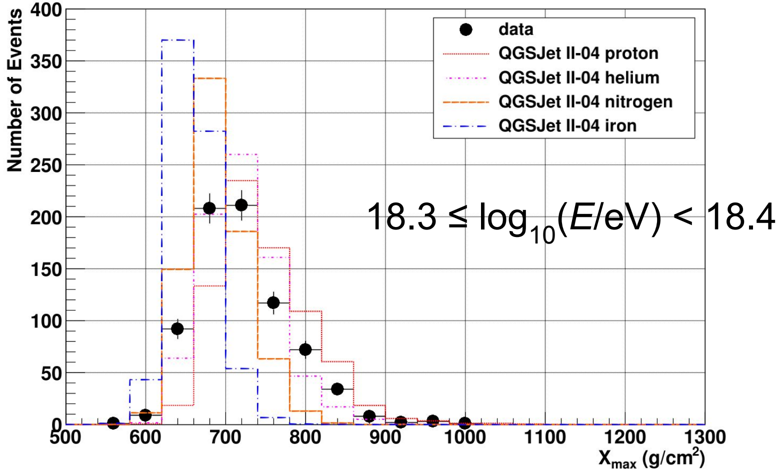
Data/MC ψ

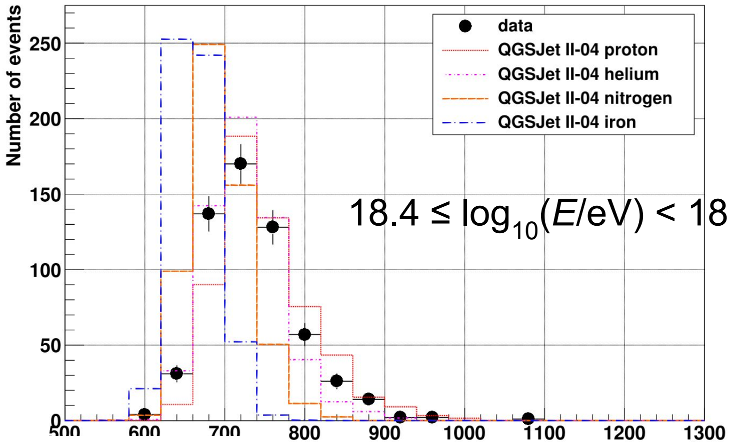


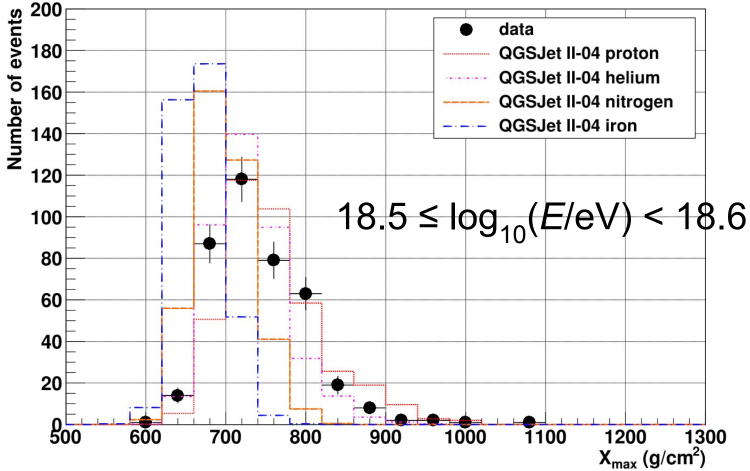
Data/MC N_{pe}/degree

	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

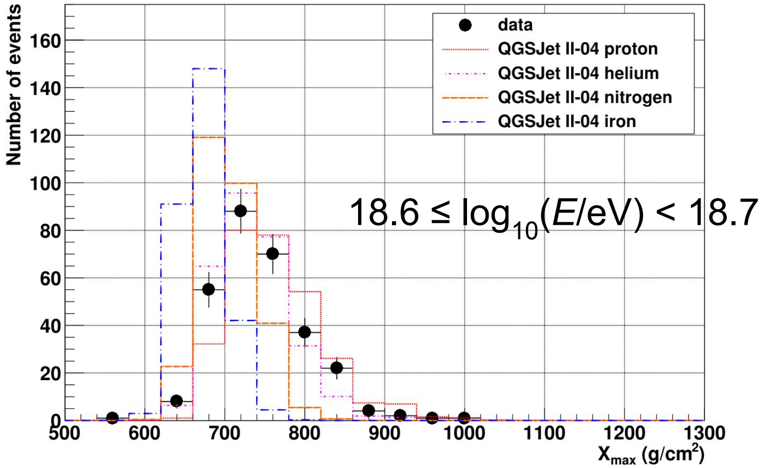


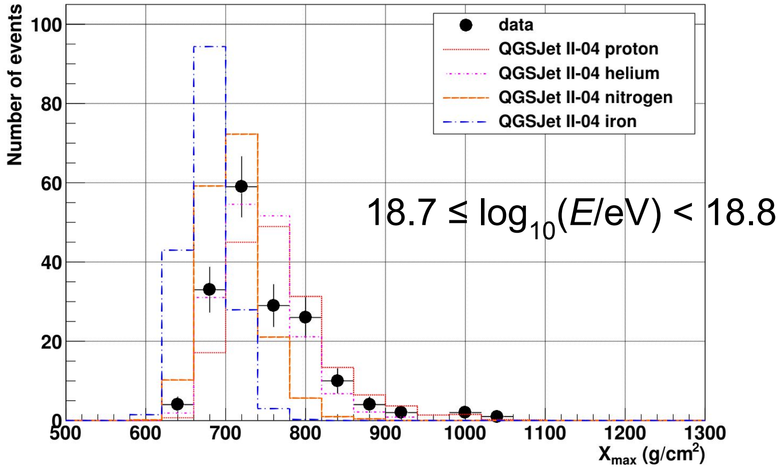


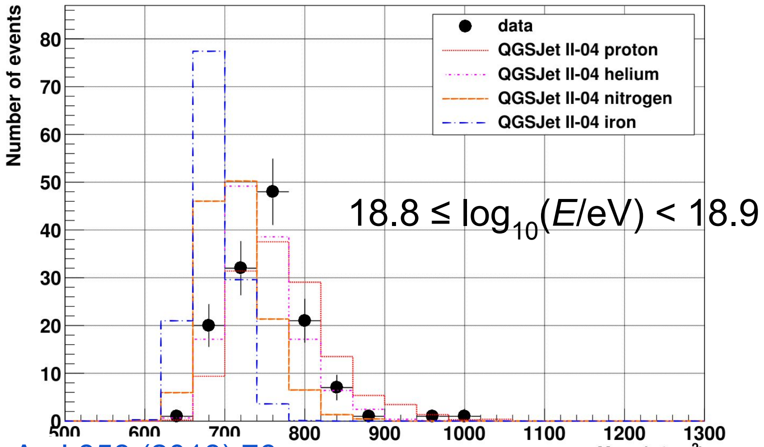


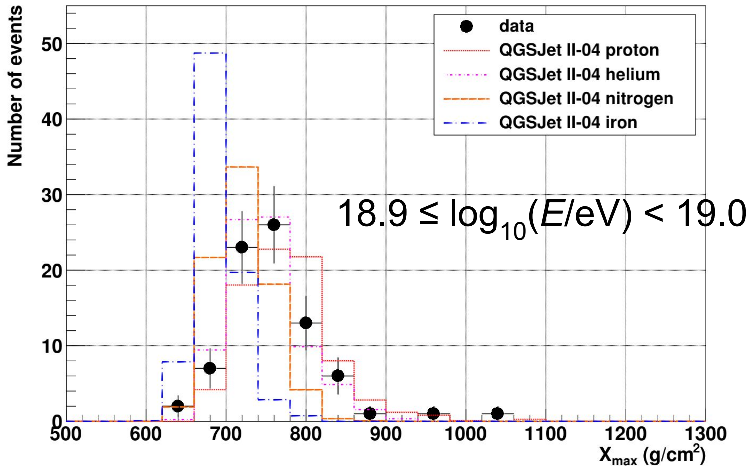


ApJ 858 (2018) 76

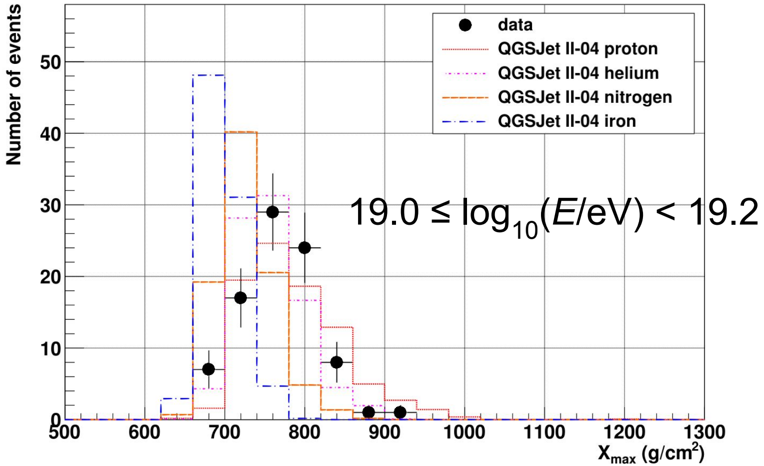


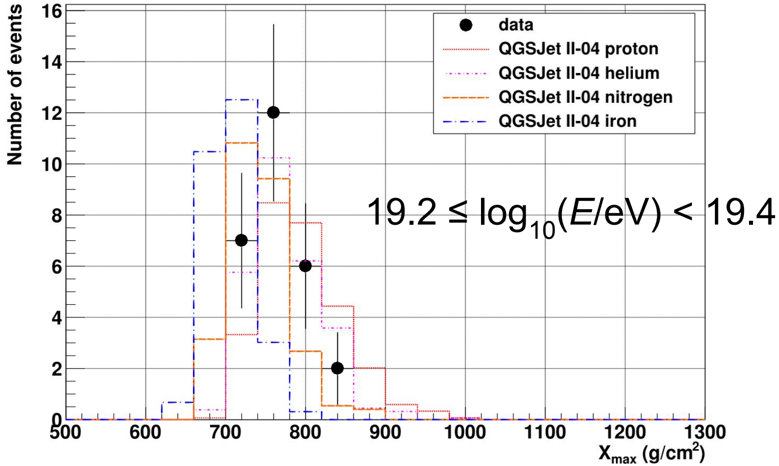


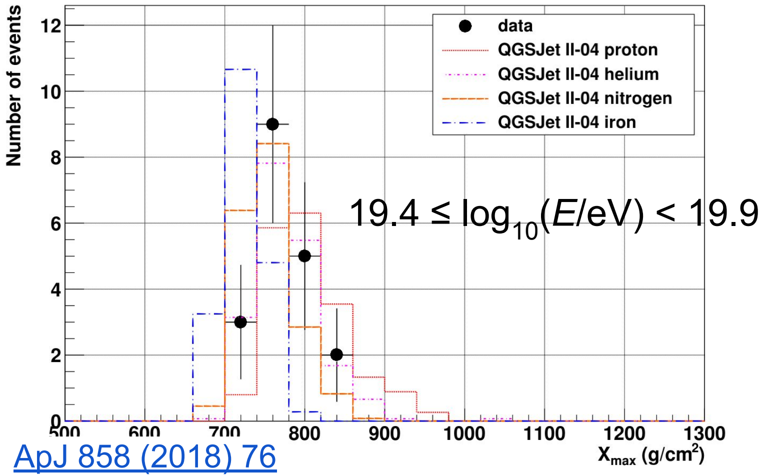




ApJ 858 (2018) 76



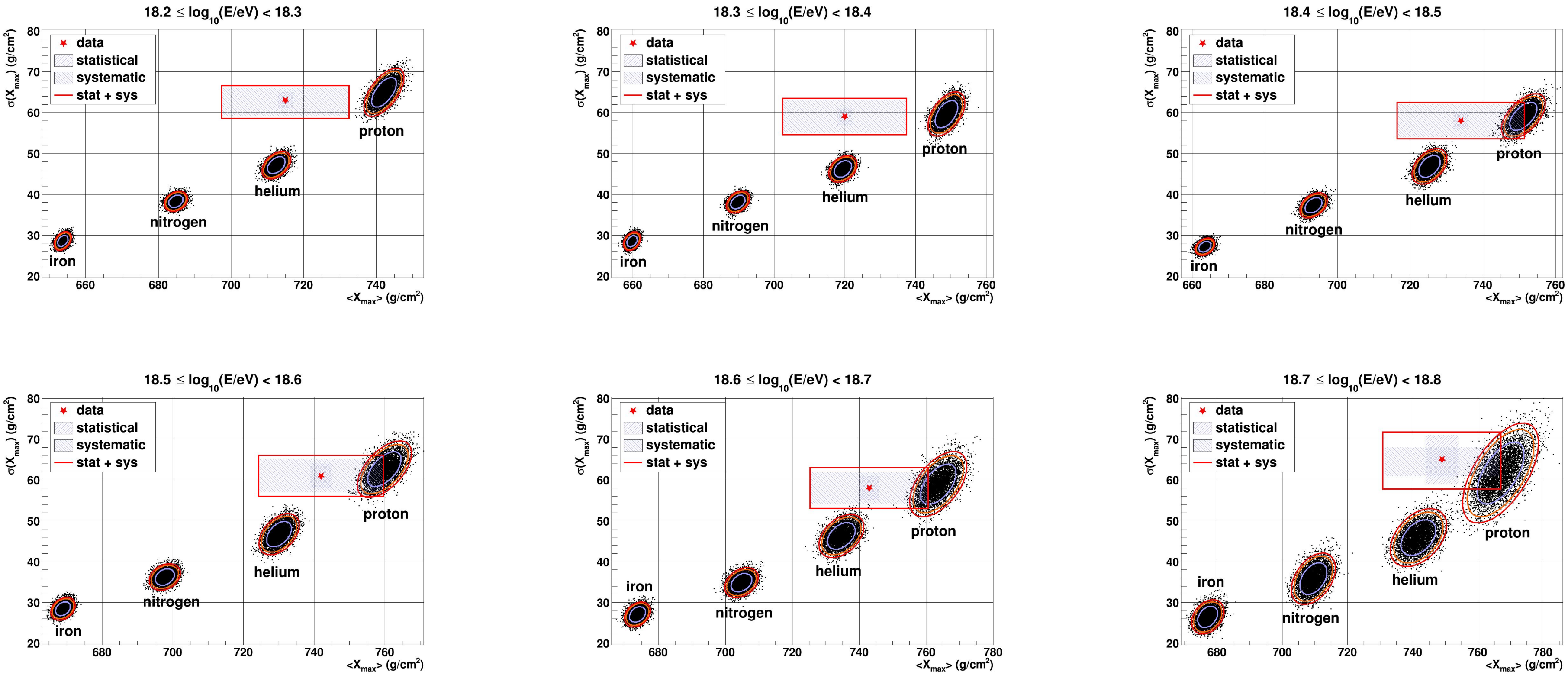




ApJ 858 (2018) 76

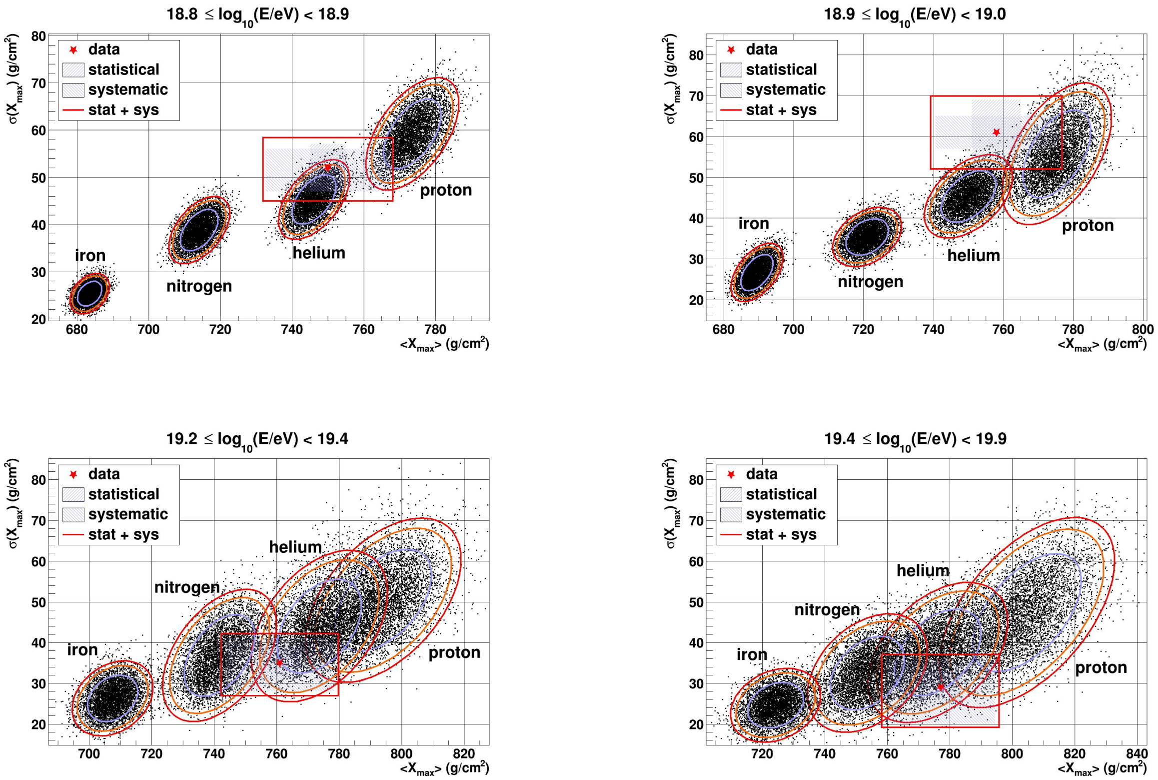
Below 10^{19} eV data X_{max} has a deep X_{max} tail resembling light composition (proton or helium).

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 limited by the constraint of SD coincidence.



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

ApJ 858 (2018) 76



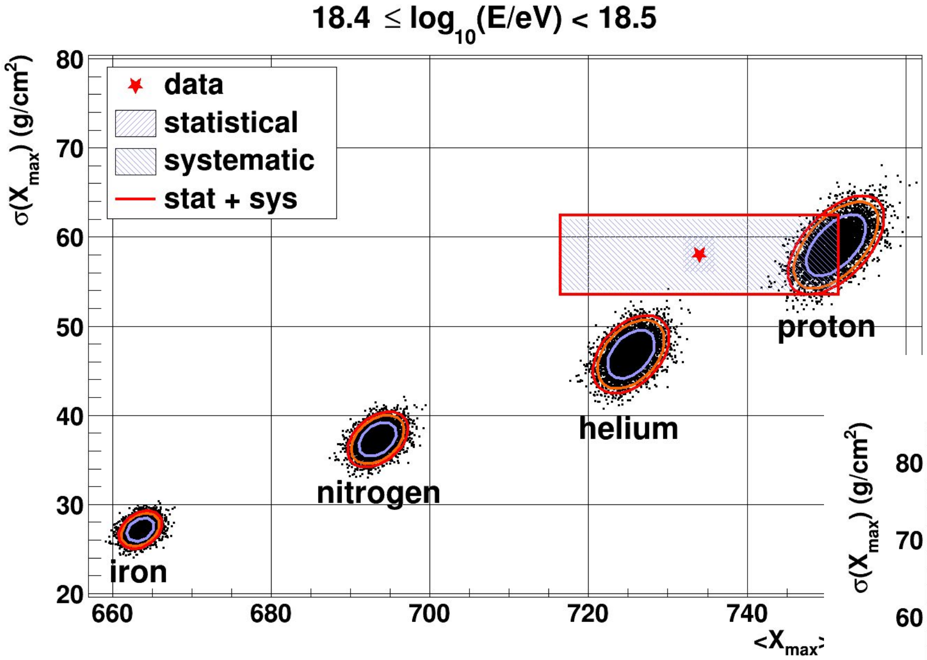
Systematic uncertainties

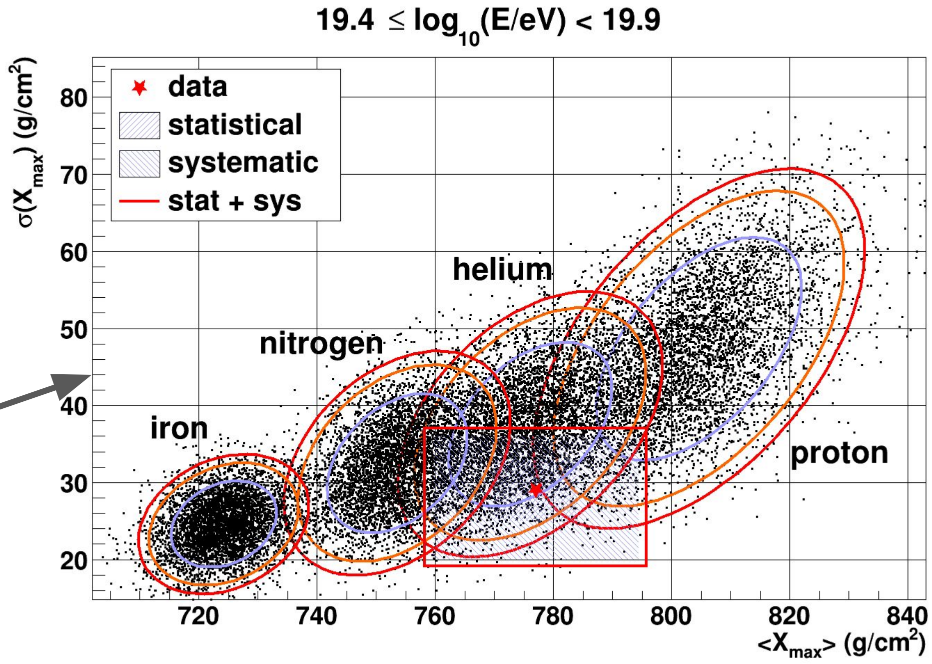
$<X_{max}>$: 17.4 g/cm^2
$\sigma(X_{max})$: 21.2 g/cm^2

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

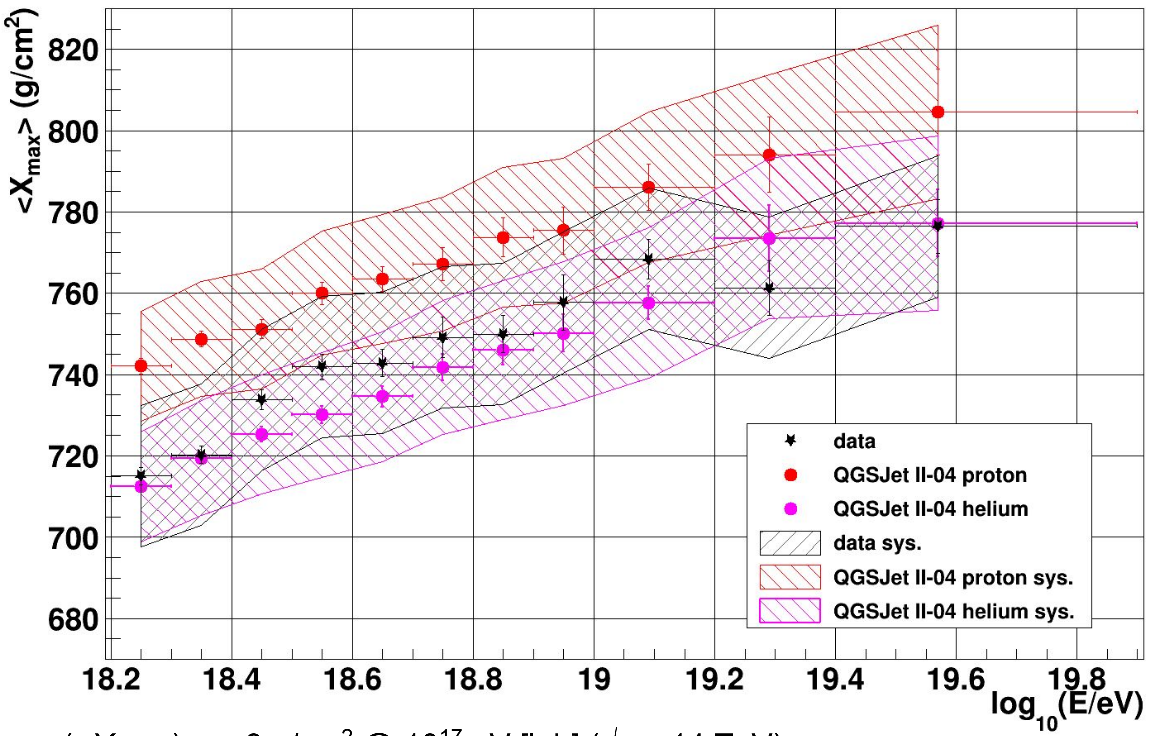
ApJ 858 (2018) 76

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.



$\sigma(<X_{max}>) = \pm$ 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

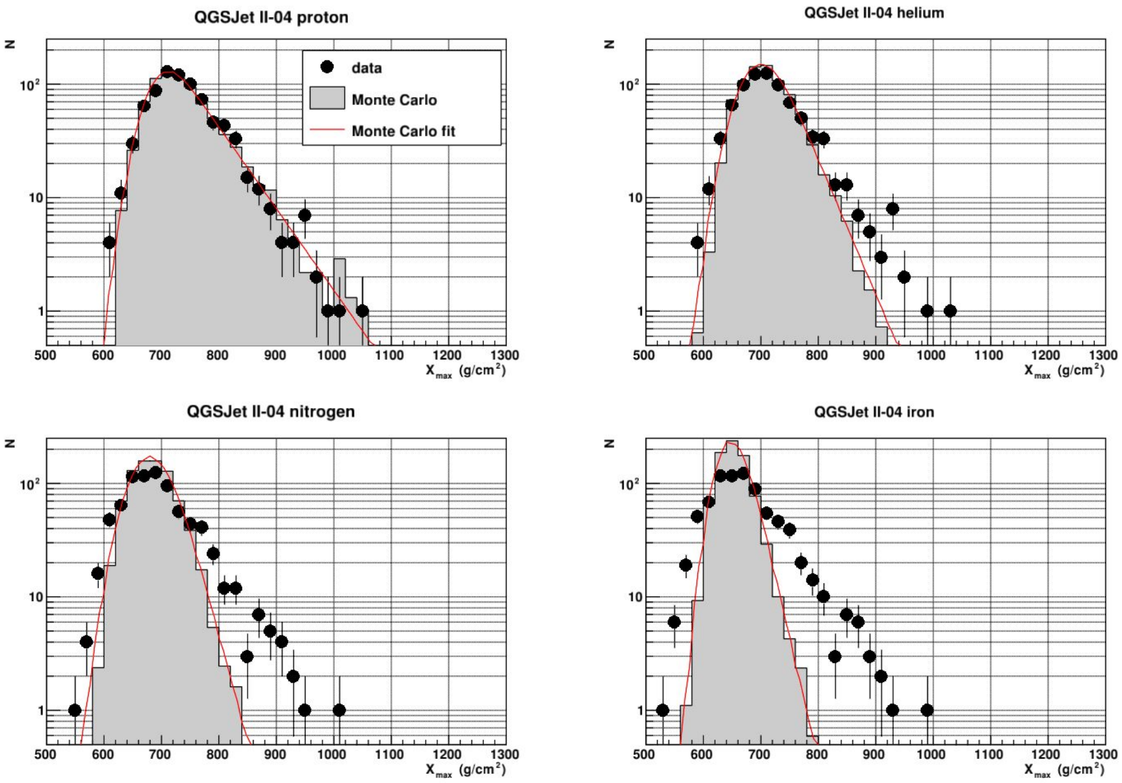
Conservative lower bounds on uncertainties from total cross-section, multiplicity, and elasticity dependence.

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] Phys.Rev.D83:054026 (2011)
[2] arXiv:1605.05241 (2016)



$18.2 \le \log_{10}(E/\text{eV}) < 18.3$

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

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

Morphological test of composition

Assume composition consists primarily of a single element.

Monte Carlo and reconstruct those elements as observed by TA.

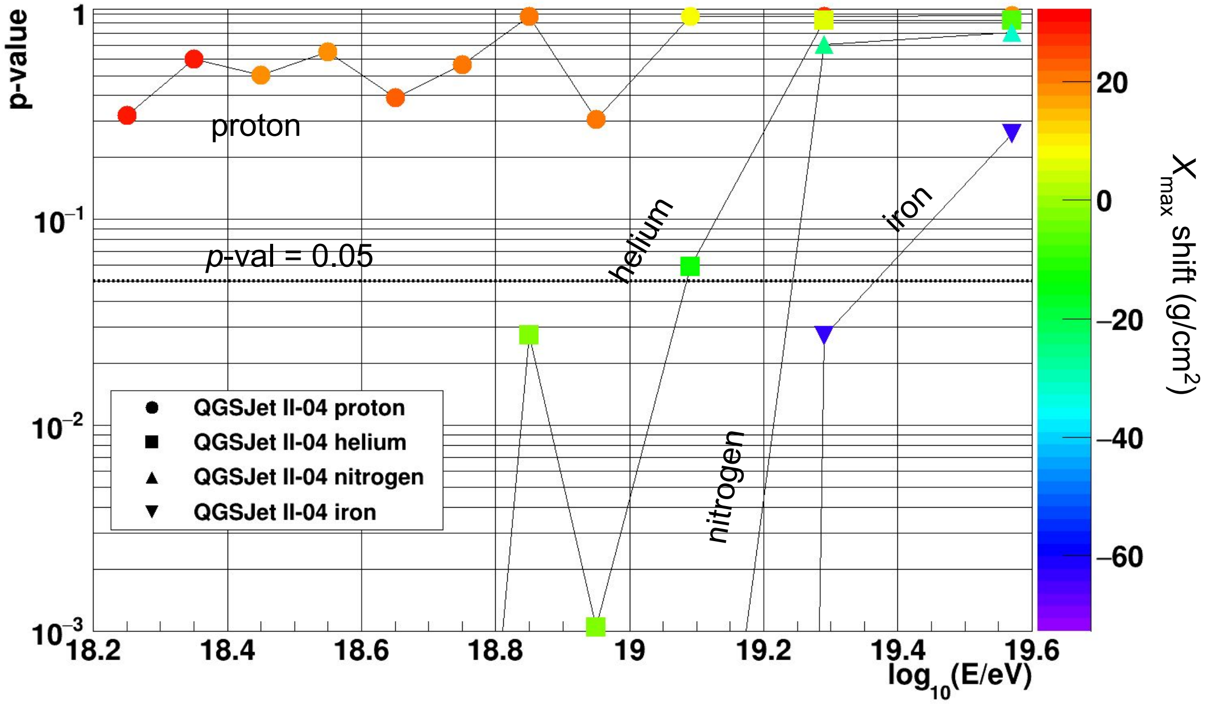
How can we compare the data and models given large potential systematic uncertainties in $\langle X_{max} \rangle$ of either?

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.

ApJ 858 (2018) 76

Test of Data vs. Models



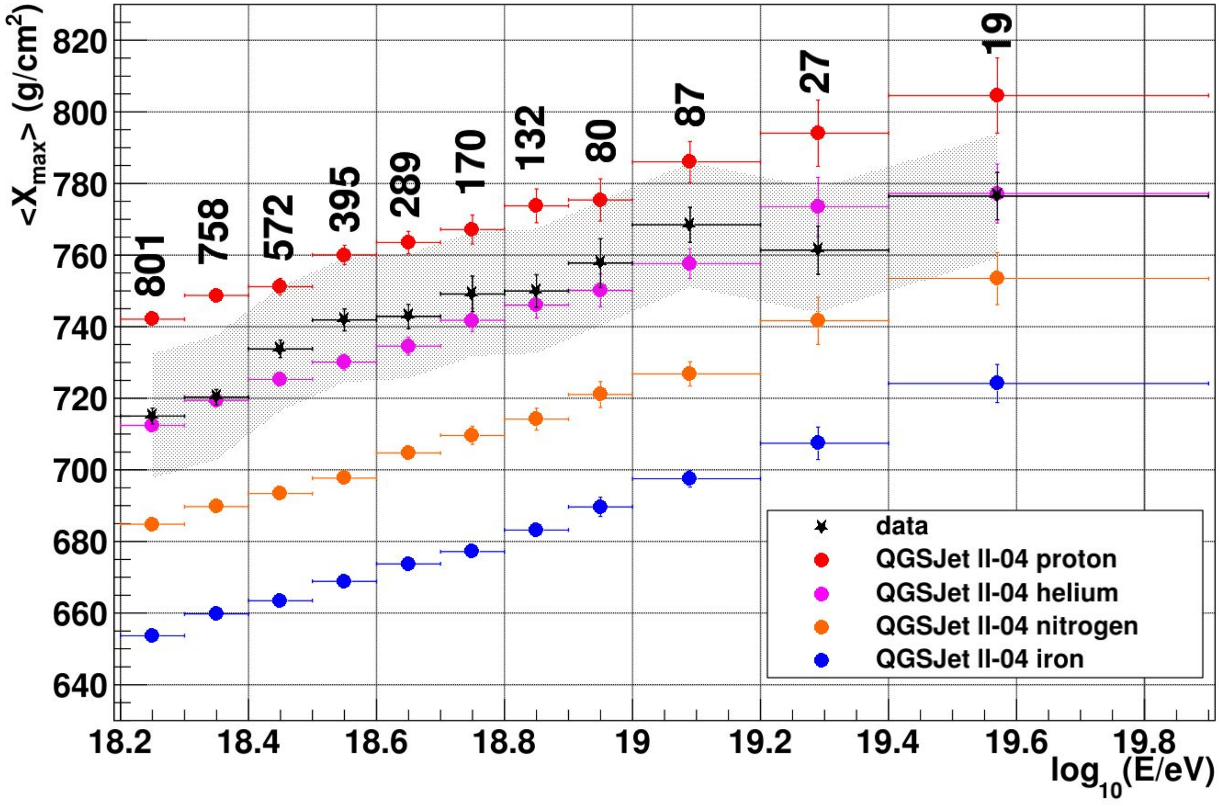
For a given energy bin, if the *p*-value is less than 0.05 we reject the data and Monte Carlo as being compatible.

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.

[ApJ 858 (2018) 76]

TA BR/LR Hybrid <X_{max}>



8.5 years of TA BR/LR hybrid data. First X_{max} results from the BR/LR FD stations.

3330 events in the BR/LR hybrid set. This is TA's highest statistics measure of X_{max}.

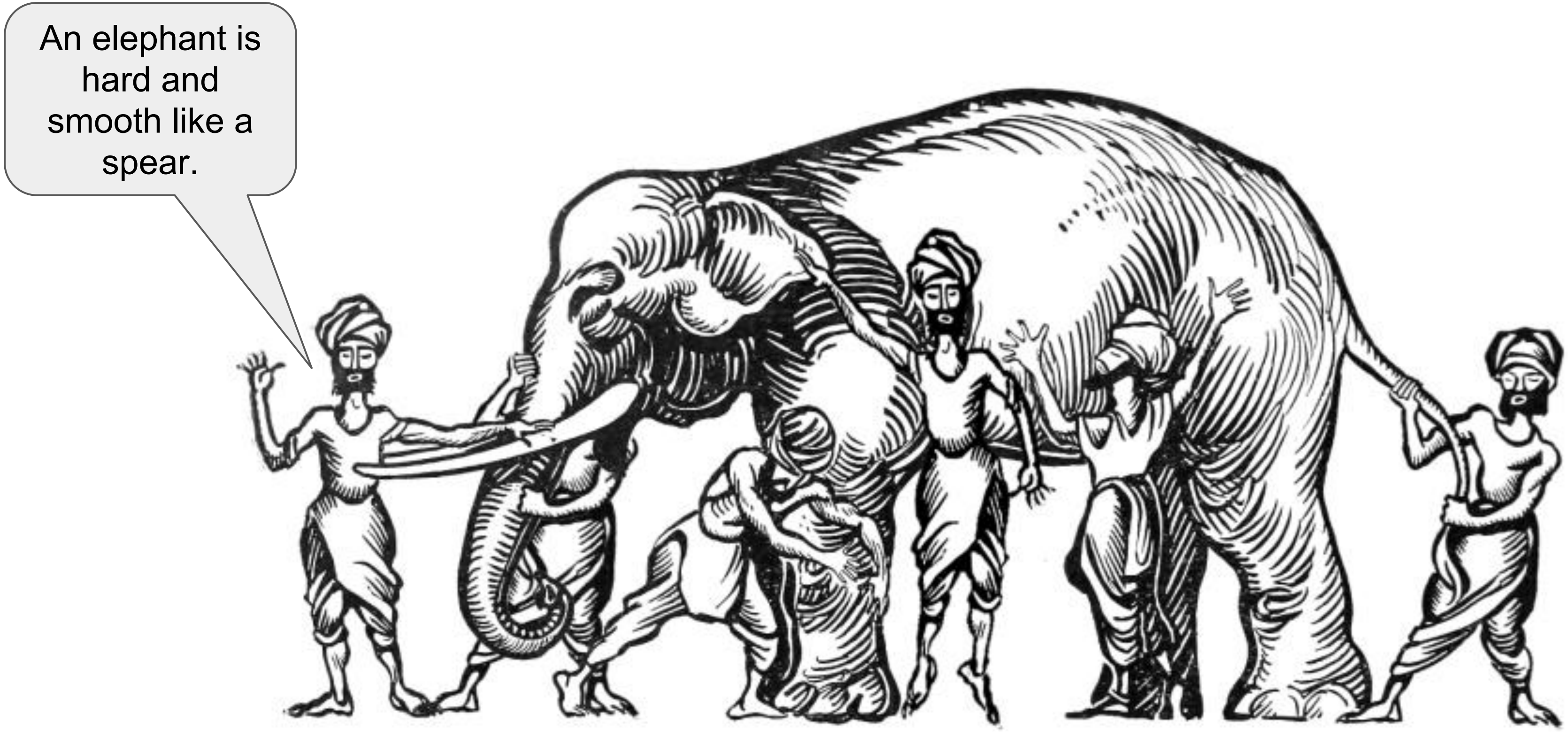
Other methods, hybrid and stereo, using other fluorescence detector provide very similar results.

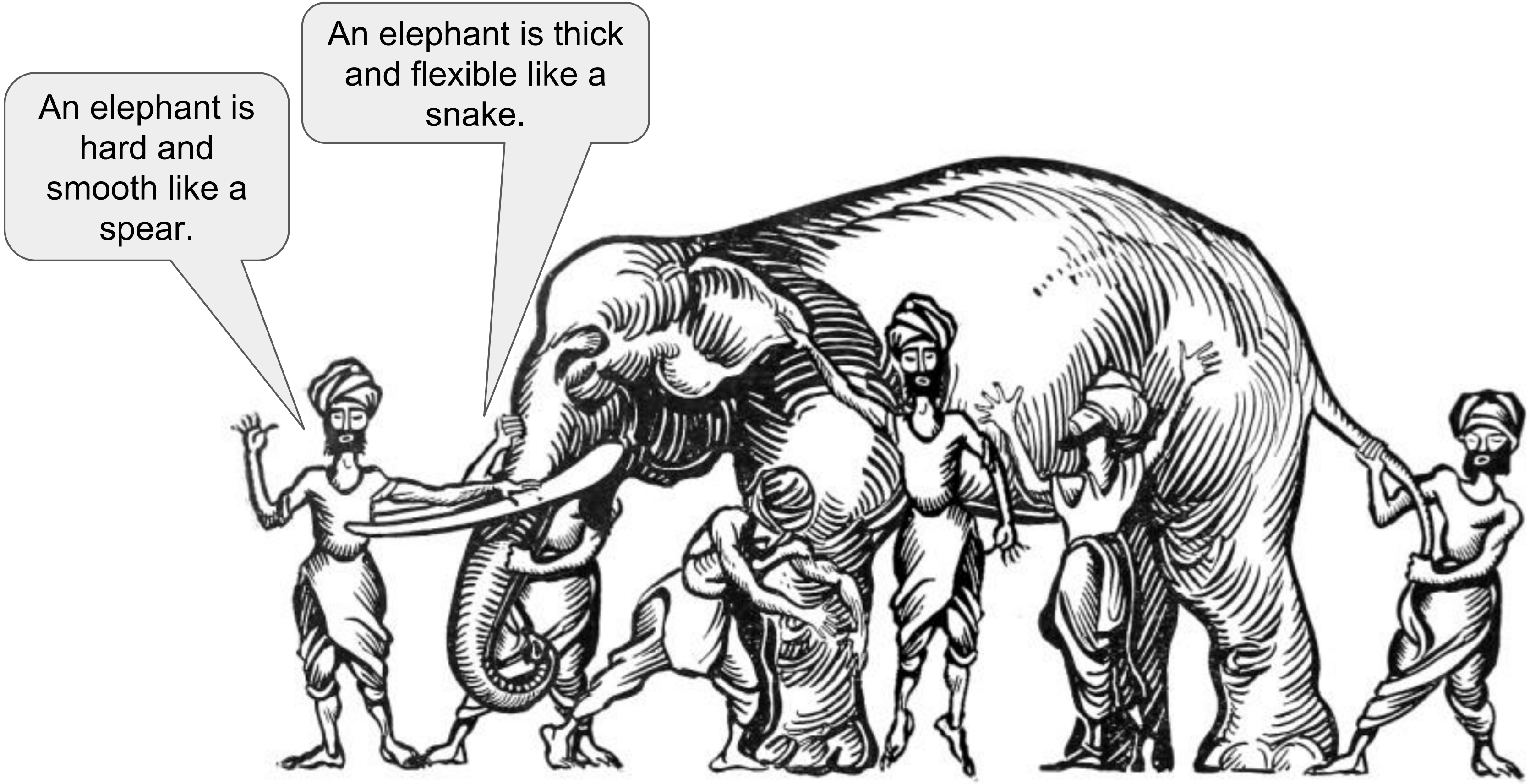
Stereo FD X_{max} will provide more statistics at high energies because we can extend the analysis to higher zenith angles.

ApJ 858 (2018) 76

TA-Auger Composition Comparison

Parable of the ~~blind men~~ COSMIC RAY PHYSICISTS and the elephant.

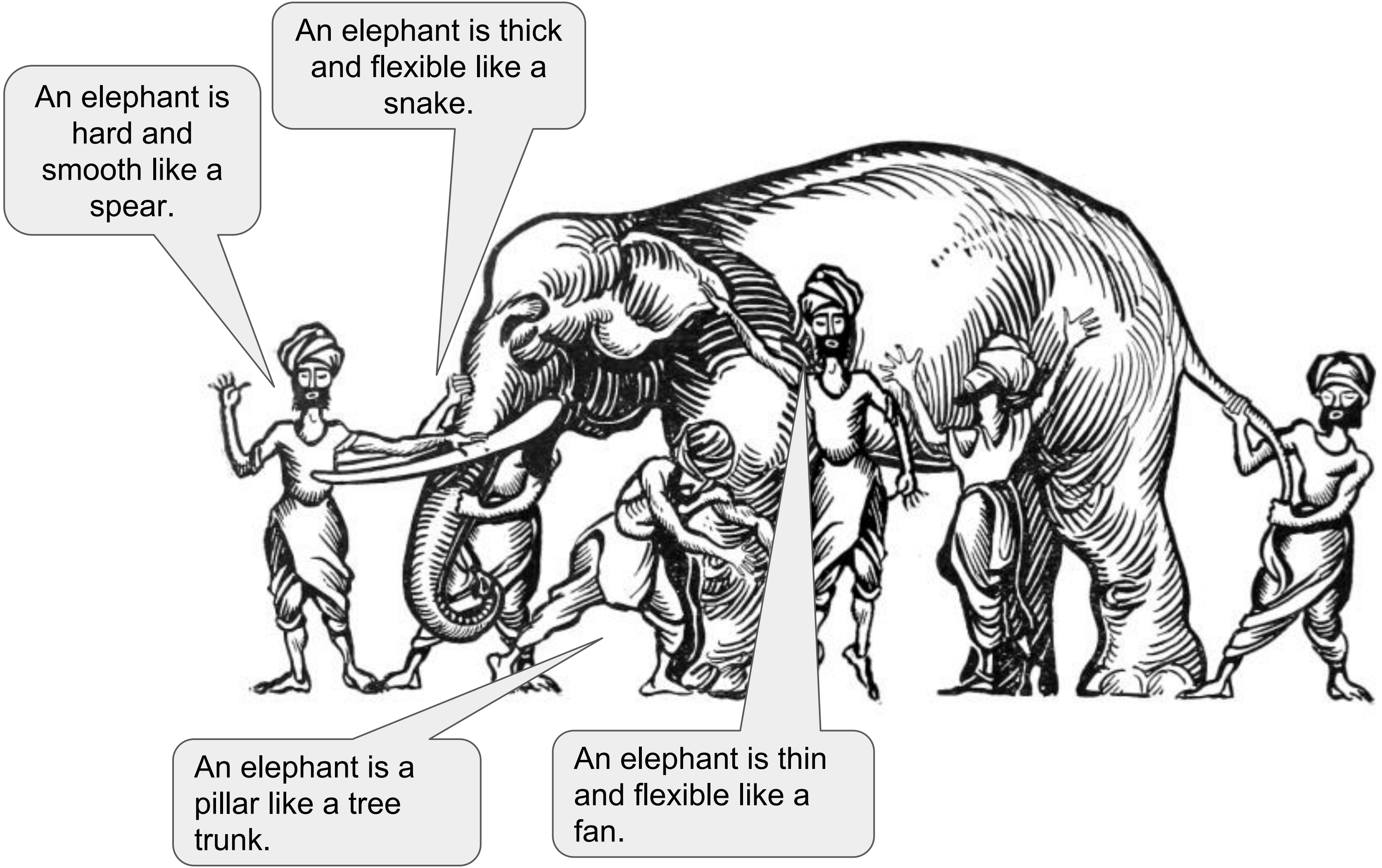

An elephant is hard and smooth like a spear.


An elephant is hard and smooth like a spear.
An elephant is thick and flexible like a snake.

An elephant is hard and smooth like a spear.

An elephant is thick and flexible like a snake.

An elephant is a pillar like a tree trunk.


An elephant is hard and smooth like a spear.
An elephant is thick and flexible like a snake.
An elephant is a pillar like a tree trunk.
An elephant is thin and flexible like a fan.


An elephant is hard and smooth like a spear.
An elephant is thick and flexible like a snake.
An elephant is a pillar like a tree trunk.
An elephant is thin and flexible like a fan.
An elephant is flat and hard like a wall.

An elephant is hard and smooth like a spear.

An elephant is thick and flexible like a snake.

An elephant is thin and supple like a rope.

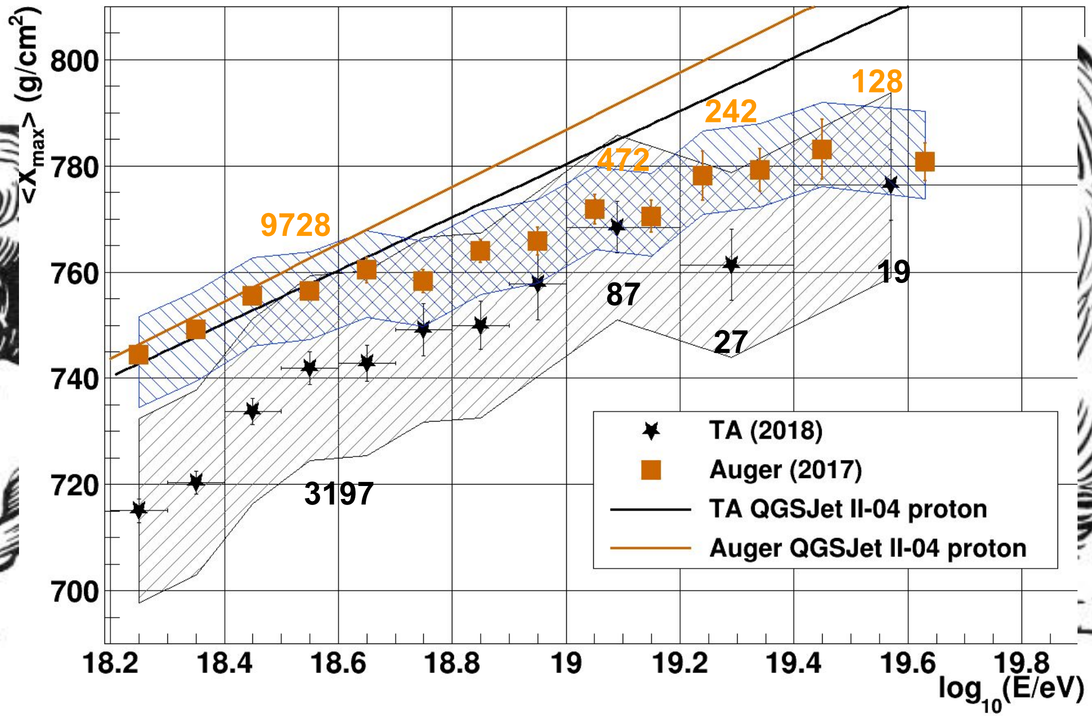
An elephant is a pillar like a tree trunk.

An elephant is thin and flexible like a fan.

An elephant is flat and hard like a wall.

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

Cosmic rays are heavy like iron.

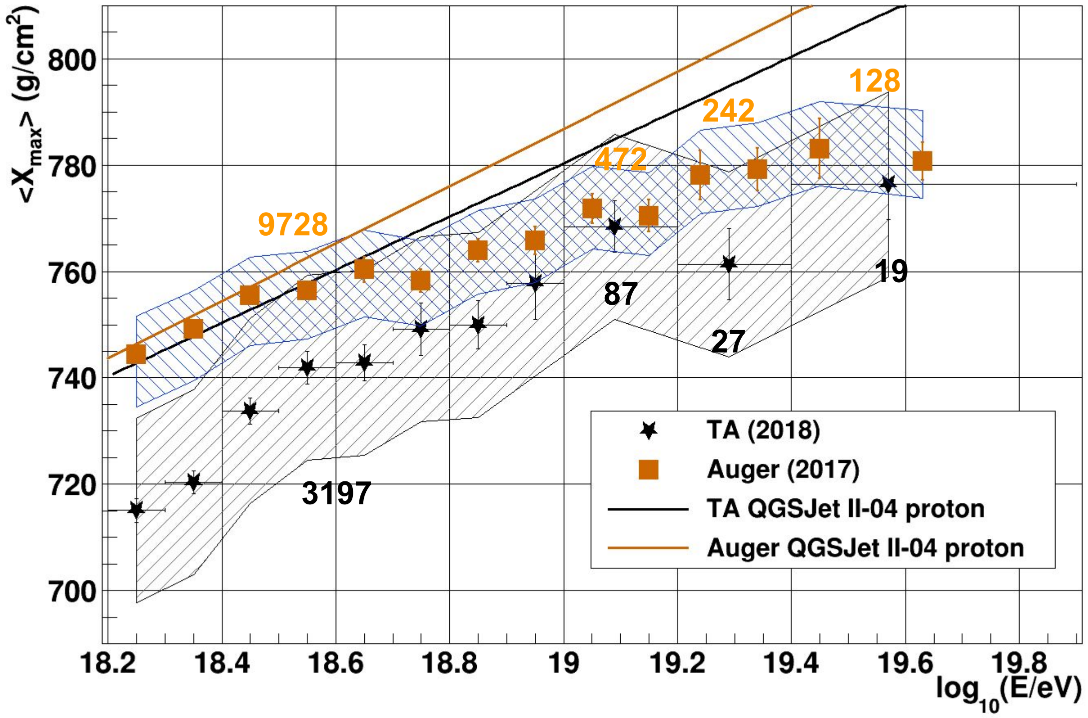


Cosmic rays are light like protons.

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)

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

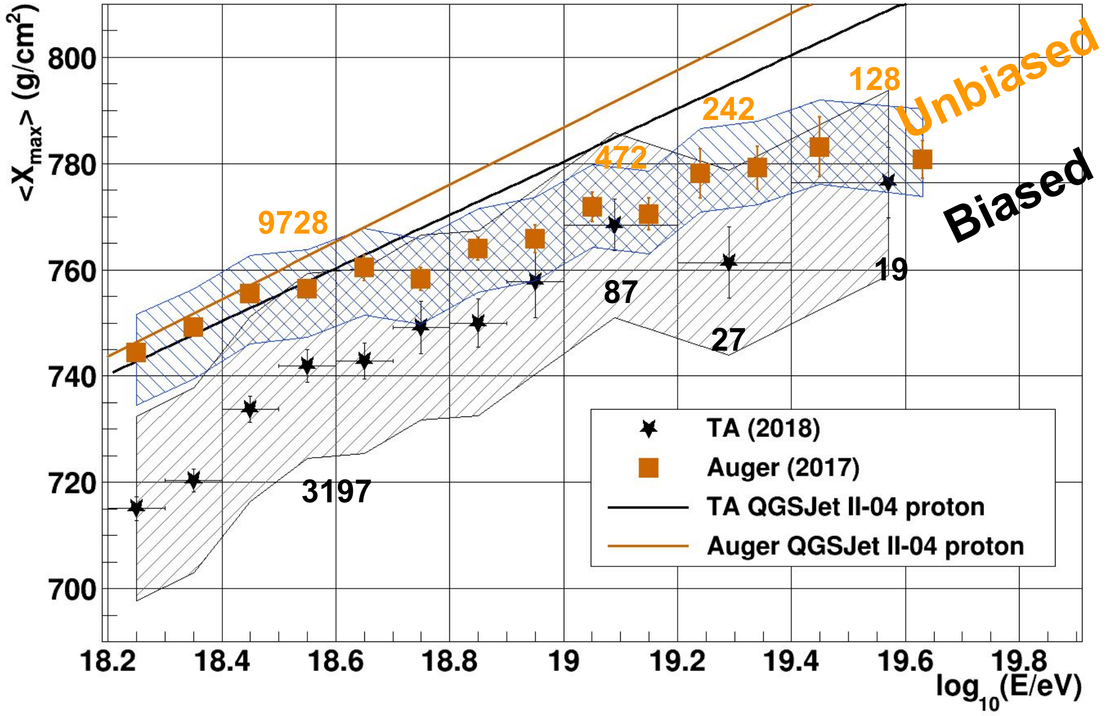
“Disagreement” of Auger and TA results mainly from the interpretation of what happens to observed X_{max} relative to single species X_{max} expectation.

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



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.

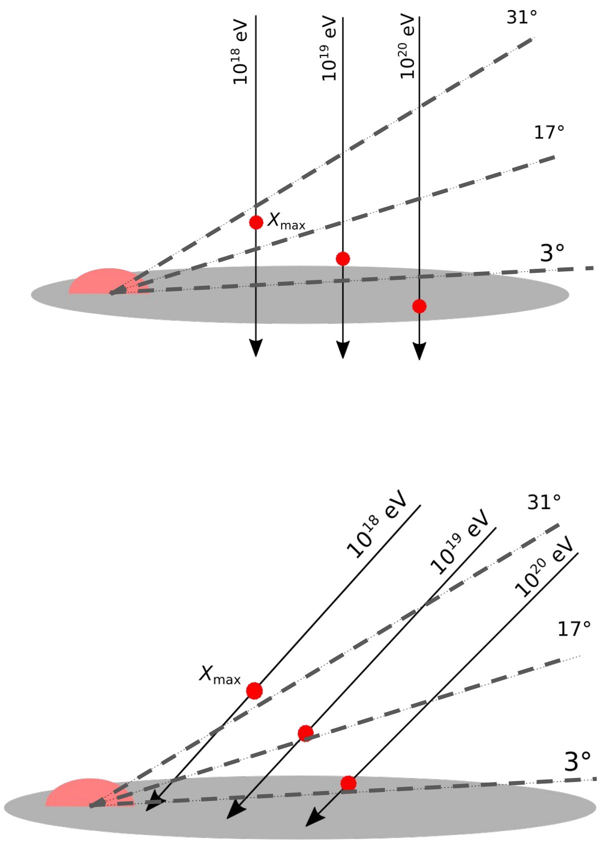
TAx4, stereo, 1 SD hybrid will provide more statistics.

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)

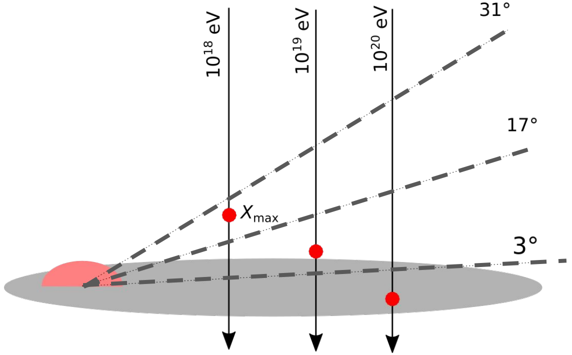
TA & Auger X_{max} distributions <u>cannot be directly be compared</u>

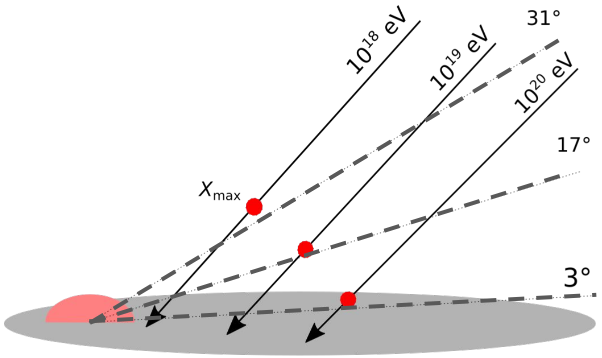
- TA reconstructs X_{max} distributions as seen by the detector.
  - TA imposes minimal cuts.
  - FD reconstruction causes acceptance bias through loss of events in the tails of the distributions.
  - Reconstruction bias is controlled by accurate reconstruction, choice of quality cuts.
  - TA Monte Carlo simulates these biases.
  - Why like this? This best represents *how the detector actually sees cosmic ray distributions* with minimal altering of the data.
- Auger reconstructs X_{max} distributions as seen in the atmosphere.
  - Through simulation find event geometries and energies that allow selection of events that upon reconstruction cause no distortion of the X_{max} distributions.
  - Auger accepted and reconstructed X_{max} distributions minimize bias from thrown cosmic ray distributions.
  - Auger can directly compare reconstructed X_{max} distributions with those thrown straight out of an air shower generator. Their distributions are corrected for acceptance in a similar way spectrum measurements are corrected for individual detector exposure and aperture.
  - In theory if all experiments did this, then all X_{max} measurements could be directly compared regardless of size.
  - Need good statistics for this approach though, especially at the highest energies.



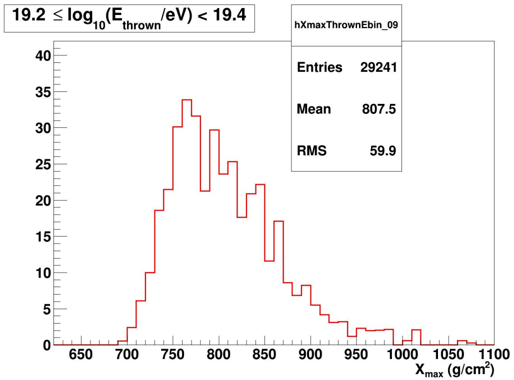
Geometry, energy, particle mass, and atmospheric mass overburden limit ability to observe and reconstruct X_{max}. Vertical showers of sufficient energy can hit shower maximum in the ground. Inclined showers provide sufficient atmosphere to allow shower max in air, but geometry, distance, and field of view limit reconstruction here as well.

Geometry, energy, particle mass, and atmospheric mass overburden limit ability to observe and reconstruct X_{max}. Vertical showers of sufficient energy can hit shower maximum in the ground. Inclined showers provide sufficient atmosphere to allow shower max in air, but geometry, distance, and field of view limit reconstruction here as well.

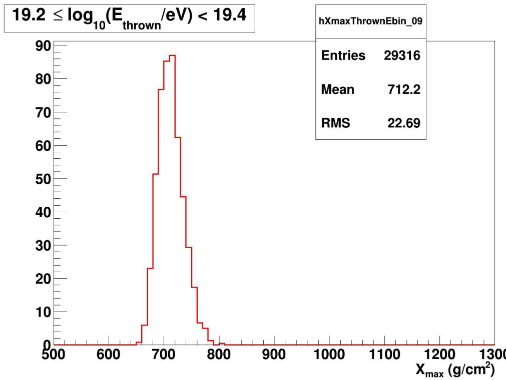




Acceptance and reconstruction bias turns thrown X_{max} from this:

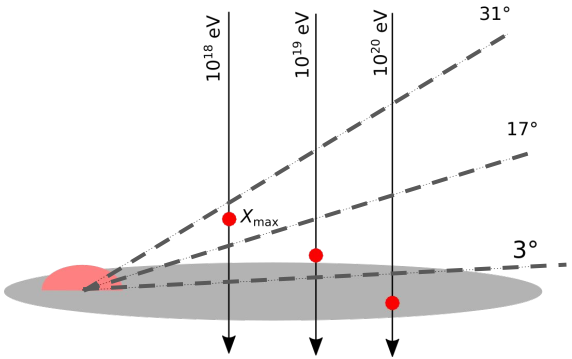


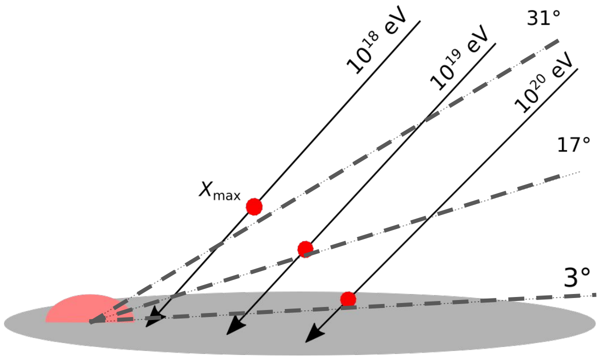
Thrown proton



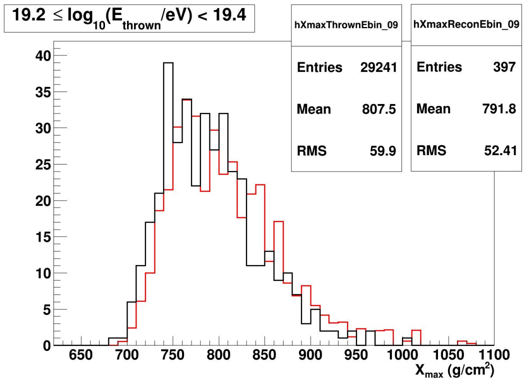
Thrown iron

Geometry, energy, particle mass, and atmospheric mass overburden limit ability to observe and reconstruct X_{max}. Vertical showers of sufficient energy can hit shower maximum in the ground. Inclined showers provide sufficient atmosphere to allow shower max in air, but geometry, distance, and field of view limit reconstruction here as well.

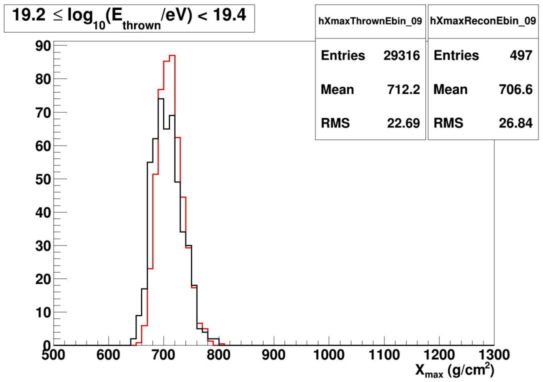




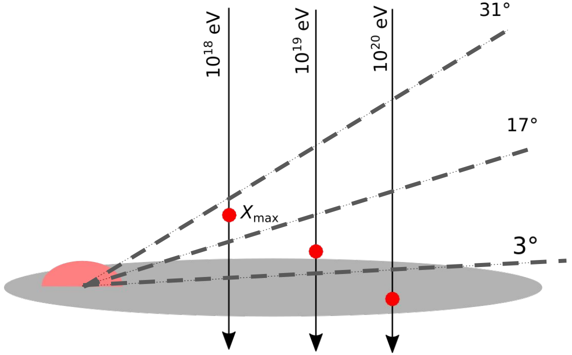
to this:



Thrown and recon proton

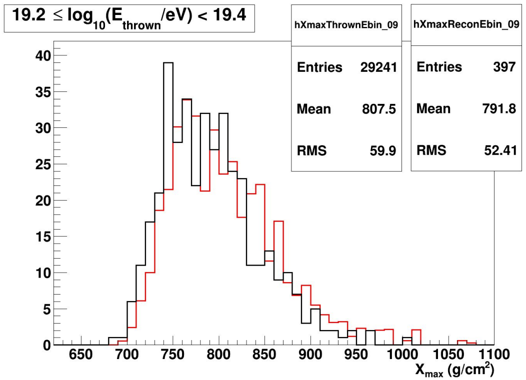


Thrown and recon iron

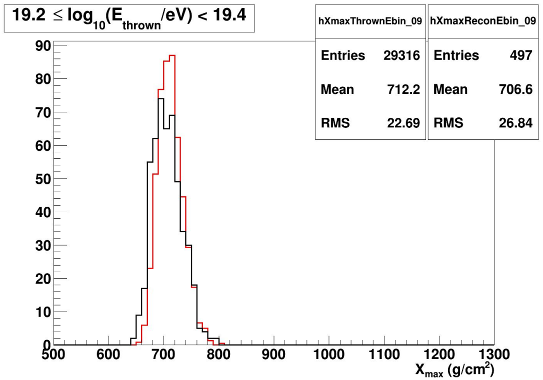


Geometry, energy, particle mass, and atmospheric mass overburden limit ability to observe and reconstruct X_{max}. Vertical showers of sufficient energy can hit shower maximum in the ground. Inclined showers provide sufficient atmosphere to allow shower max in air, but geometry, distance, and field of view limit reconstruction here as well.

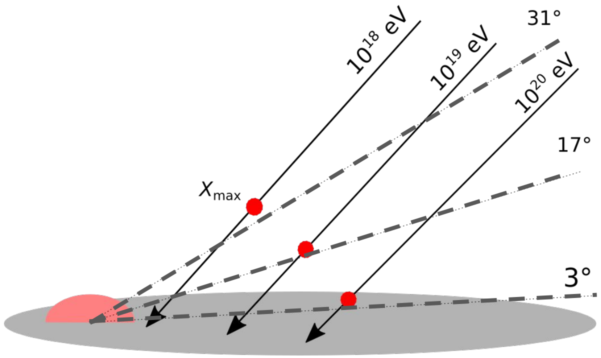
to this:



Thrown and recon proton

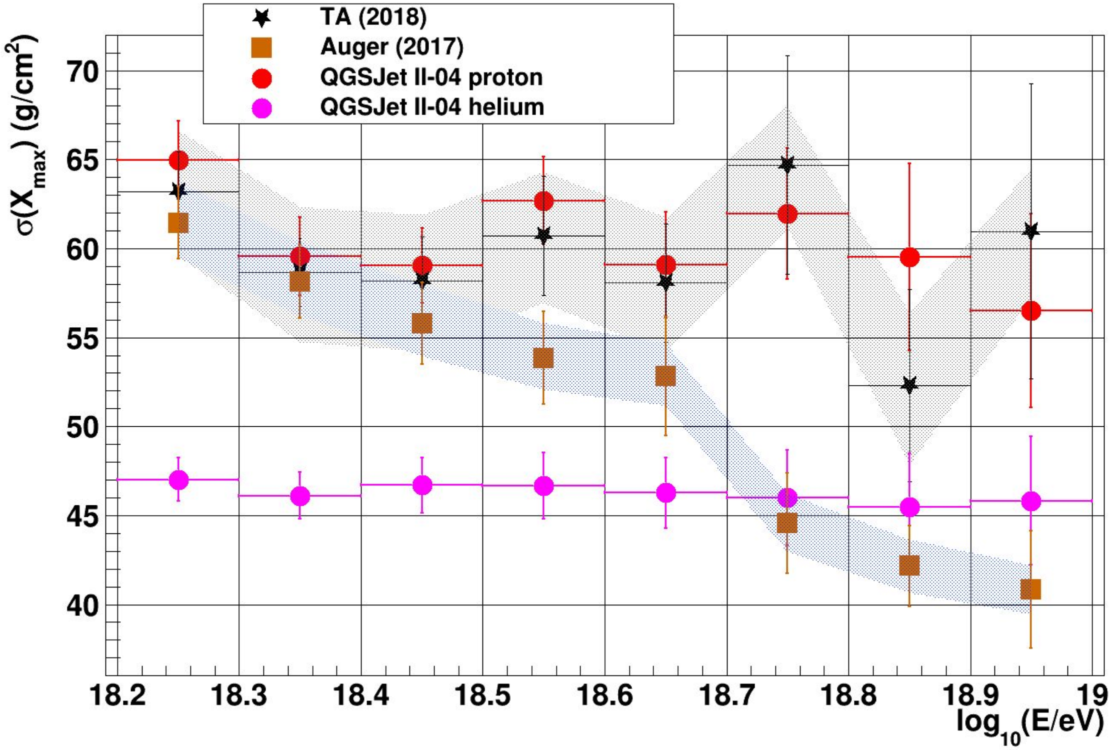


Thrown and recon iron



Resolution broadens shallow X_{max} tail slightly. For protons, which penetrate more deeply than iron, the deep tail is more heavily affected. Proton $\Delta\langle X_{max}\rangle = -15$ g/cm^2.

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.

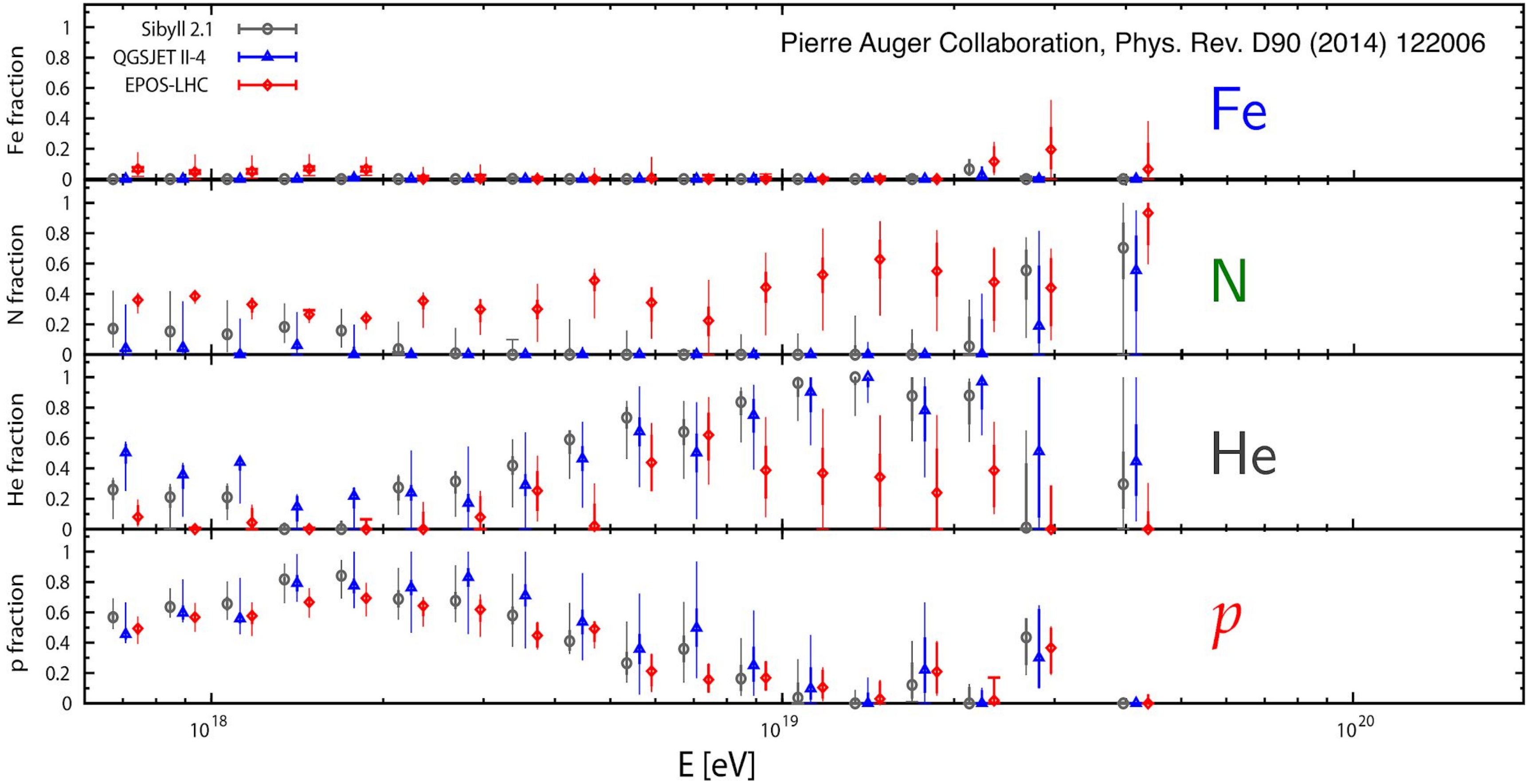
Abbasi, et al., ApJ 858 (2018) 76

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

How to compare TA & Auger X_{max} distributions

- Auger data is unbiased compared to thrown mixtures of X_{max} distributions.
- Auger fits their data to an ad-hoc mixture of proton, helium, nitrogen, and iron.
  - EPOS-LHC reduces discrepancies of models and is their preferred model.
  - QGSJet II-04 slightly worse but this is the Monte Carlo TA has readily available.
- Auger provides the energy dependent 4-component mixture fractions to TA.
- TA generates a Monte Carlo data set of the mixture.
- Check if the TA *thrown* mix agrees with Auger *reconstructed* data.
  - Because of the previous explanation Auger reconstructed data should be directly comparable to a thrown CORSIKA X_{max} distribution.
- Reconstruct the mix through TA's standard analysis chain.
- This imposes acceptance and reconstruction bias of the TA detector on the mixture.
- Compare the biased mixture to TA biased reconstructed data.
- If the mixture, after TA detector acceptance, looks like TA data, then we say TA data and Auger data are in agreement (at some level…)

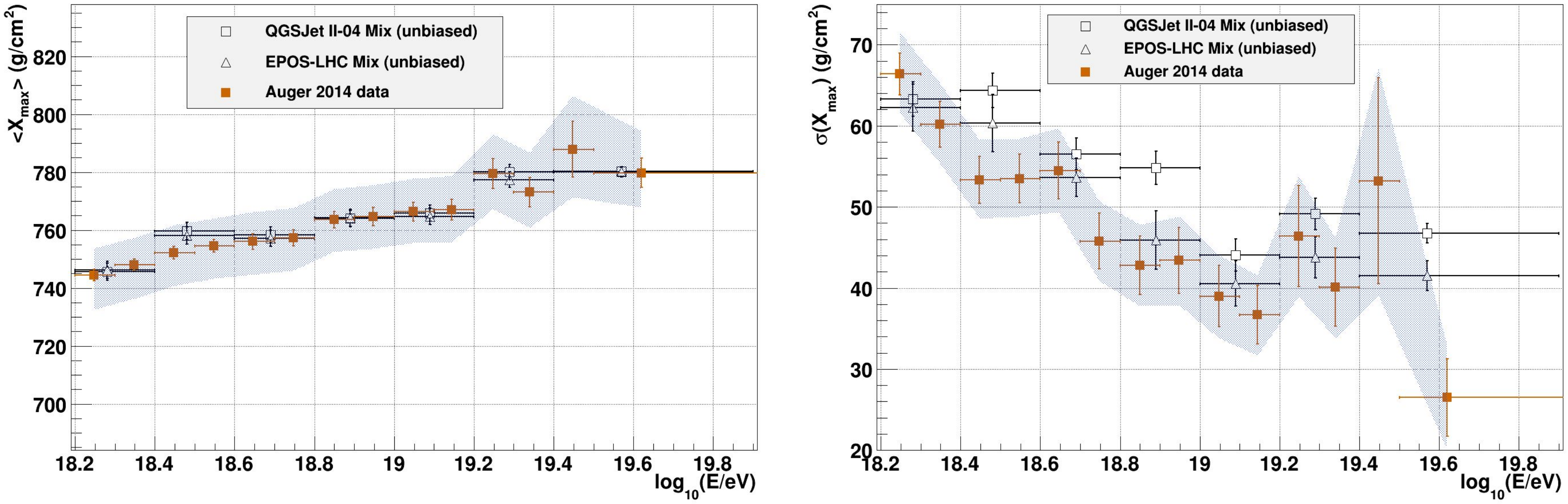
- Prior to 2017, we check agreement by looking at the means.
- In 2017, we checked agreement through more rigorous tests.



Auger composition mix fractions for three different hadronic models
Phys. Rev. D 90, 122006

TA/Auger X_{max} - UHECR 2016

[JPS Conf.Proc. 19 (2018) 011013]

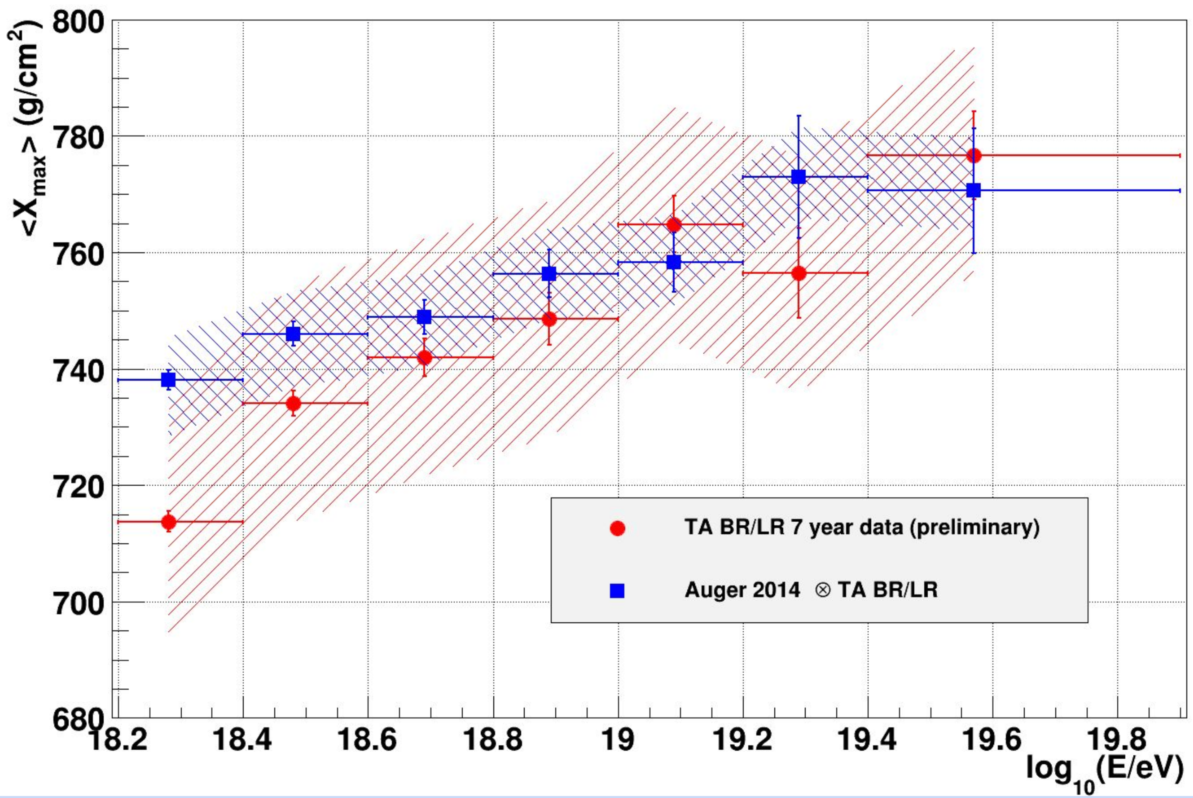


- TA generates a Monte Carlo data set of the mixture.
- Check if the TA *thrown* mix agrees with Auger *reconstructed* data.

TA successfully generates a simulation that uses the prescribed mixture that fits their data. Before it is reconstructed and subjected to detector acceptance and bias, we verify that it agrees with Auger data.

TA/Auger X_{max} - UHECR 2016

JPS Conf.Proc. 19 (2018) 011013



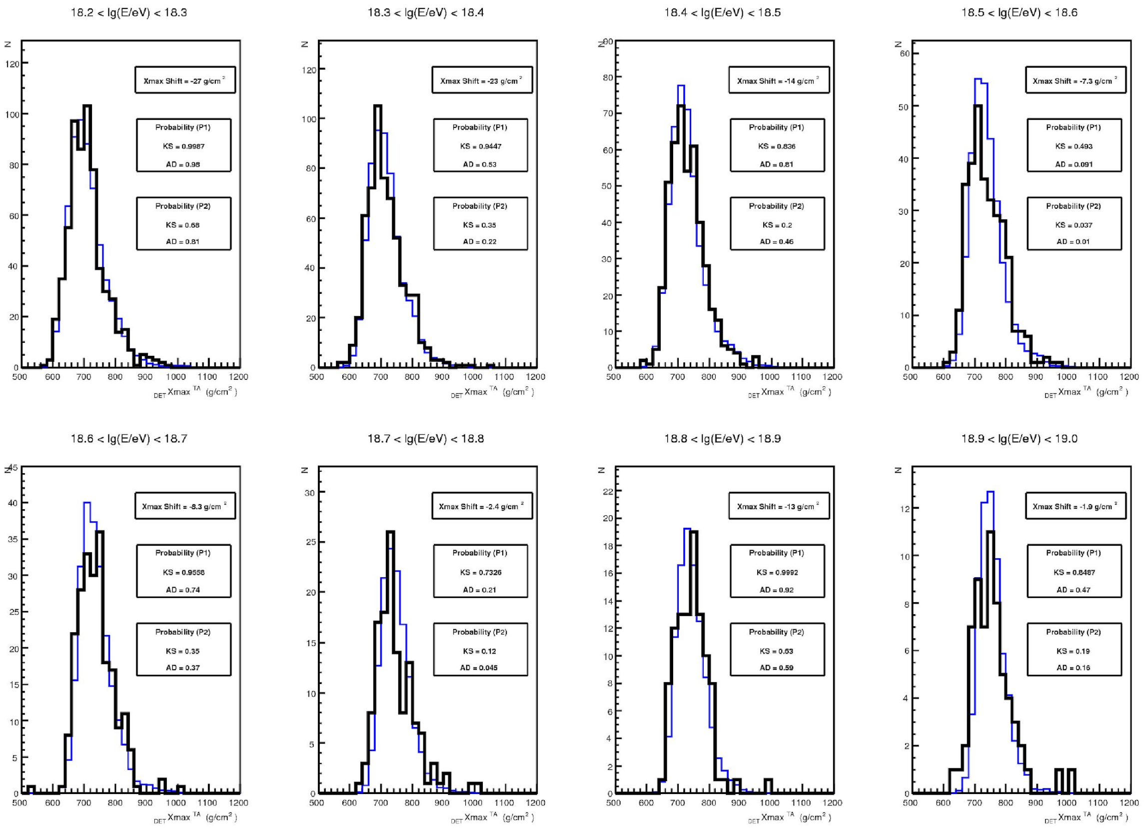
TA and Auger data can not be directly compared because they use different approaches to data analysis.

We can indirectly compare our data by using a composition mixture made up of proton, helium, nitrogen, and iron that is fit to their data. Then TA generates and reconstructs a Monte Carlo data set using the same composition mix. This simulates acceptance and biases of the TA detector and reconstruction algorithms.

Compare the agreement of this reconstructed mix to TA data.

TA and Auger data are in agreement within systematic uncertainties.

TA/Auger X_{max} - ICRC 2017



Generate and reconstruct the Auger mix, biasing it through TA acceptance and reconstruction.

Compare the entire *distributions* of TA data (black) and TA reconstructed Auger mix (blue).

Shift the entire Monte Carlo distribution by the difference in mean X_{max} of data and MC.

Calculate the test statistics of Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) tests.

Sample the MC distributions 10^5 times to find the probability of measuring a test statistic at least as extreme as found for the data.

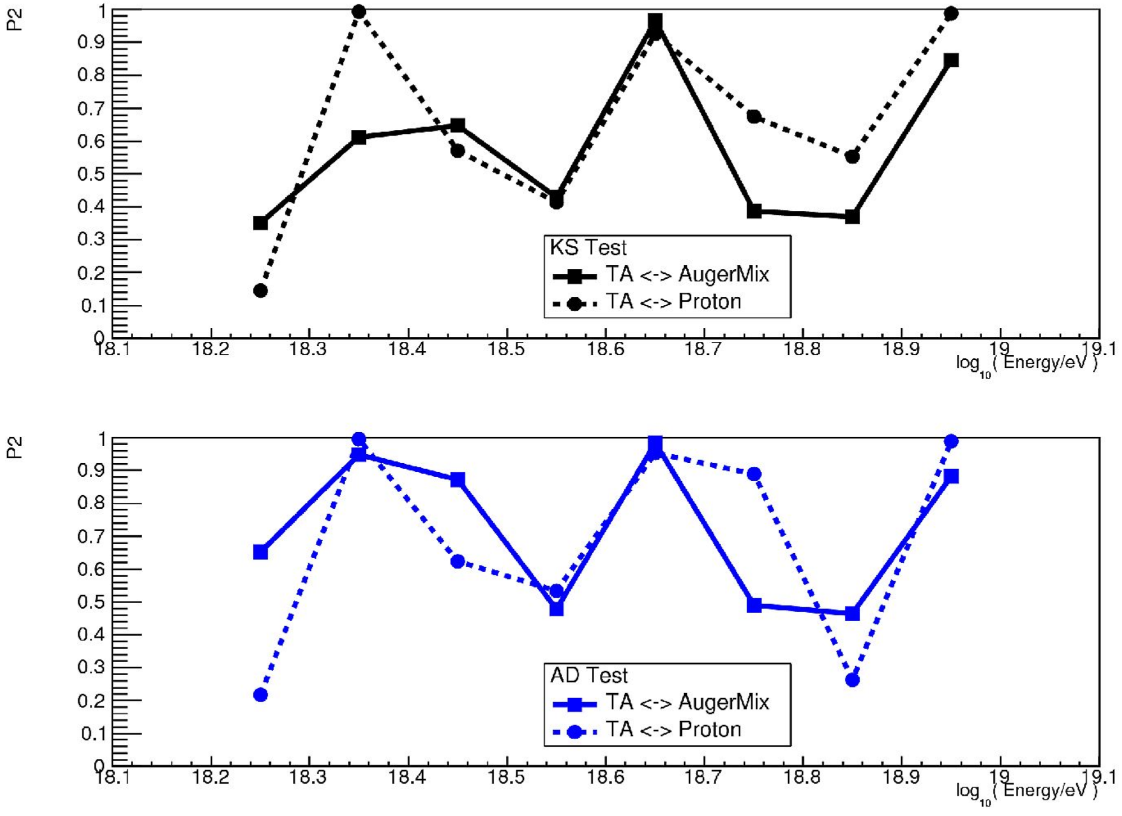
The same test of data and pure QGSJet II-04 protons was also performed.

All tests: $\log_{10}(E/\mathrm{eV}) < 19.0$.

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

	No X_{max} shift		TA & Auger mix			TA & QGSJet II-04 proton		
$\log_{10}(E/eV)$	KS prob	AD prob	ΔX (g/cm^2)	KS prob	AD prob	ΔX (g/cm^2)	KS prob	AD prob
18.2-18.3	$< 10^{-5}$	$< 10^{-5}$	-23	0.35	0.65	-31	0.14	0.21
18.3-18.4	$< 10^{-5}$	$< 10^{-5}$	-26	0.61	0.95	-33	0.99	0.99
18.4-18.5	$< 10^{-5}$	$< 10^{-5}$	-16	0.65	0.87	-22	0.57	0.62
18.5-18.6	9×10^{-5}	1.1×10^{-4}	-12	0.43	0.48	-21	0.41	0.53
18.6-18.7	0.014	0.0019	-12	0.97	0.98	-24	0.92	0.95
18.7-18.8	0.018	0.043	-6	0.39	0.49	-20	0.67	0.88
18.8-18.9	0.065	0.0085	-15	0.37	0.47	-31	0.55	0.26
18.9-19.0	0.49	0.5	-4	0.85	0.88	-20	0.98	0.98

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

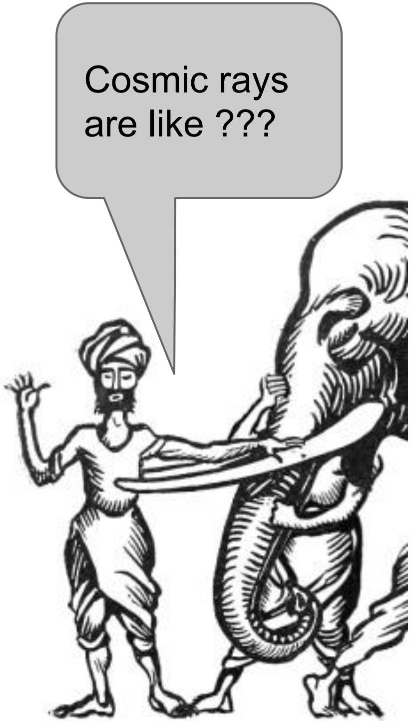
Below 10^{19} eV:

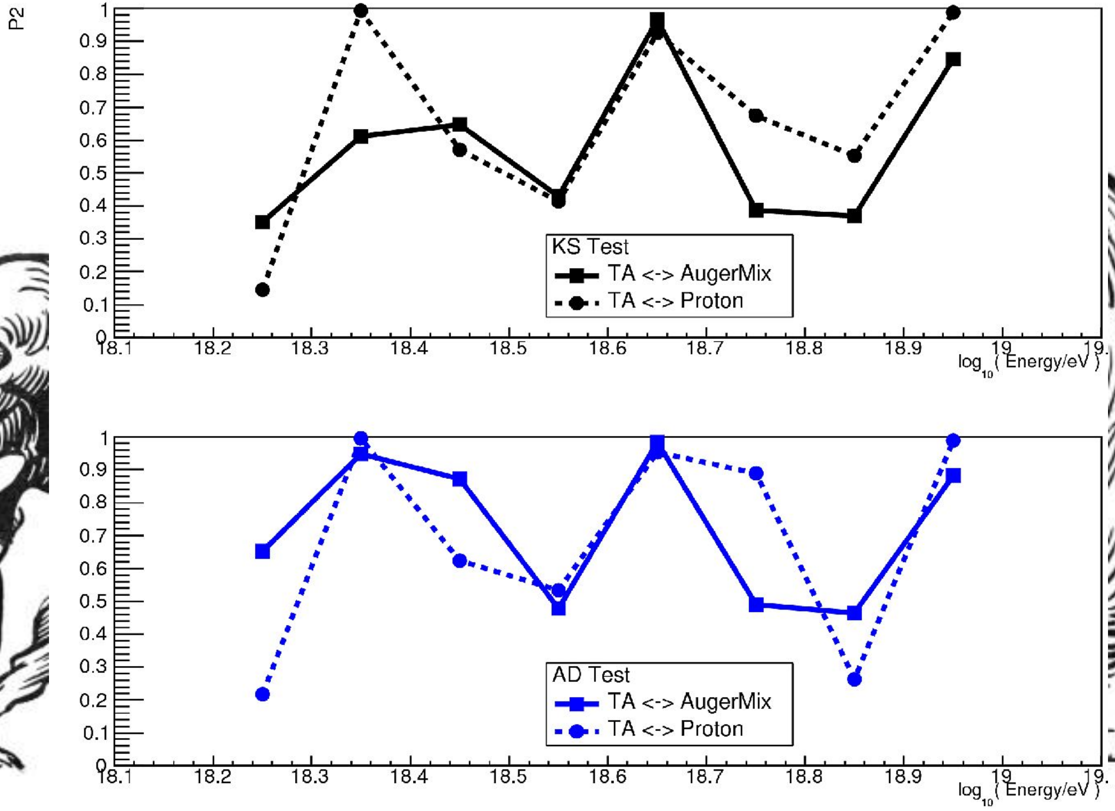
TA data agrees with Auger data within systematic uncertainties.

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.





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

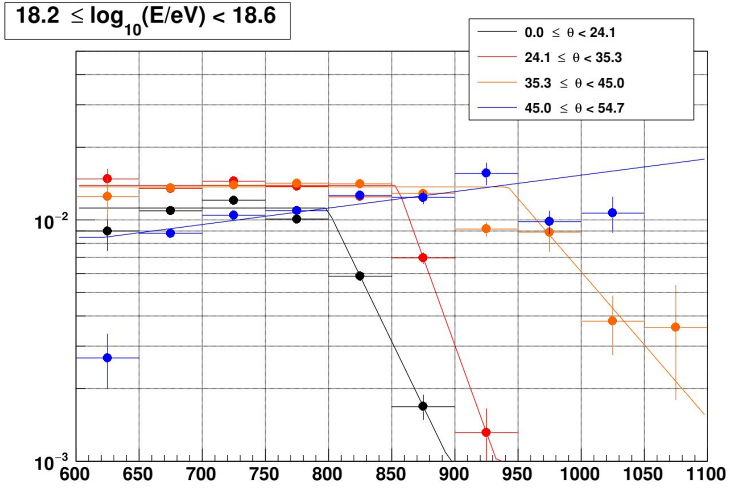
Summary

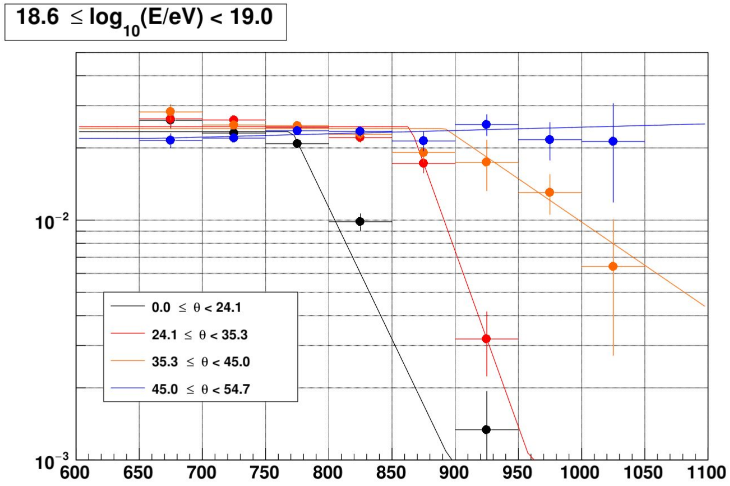
- First results of TA BR/LR hybrid X_{max} published this month. [ApJ 858 (2018) 76]
- This is TA's highest statistical measure of X_{max}, but other methods are required to reach above 10^{19} eV, e.g., stereo.
- TA tests compatibility of observed X_{max} distributions by finding the systematic X_{max} shift required to maximize the likelihood between data and Monte Carlo, then measuring the probability of observing a likelihood of observing a likelihood at least this extreme from the 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.
- Further work measuring upper bounds on elements such as iron, mixtures, and EPOS-LHC generation to follow.

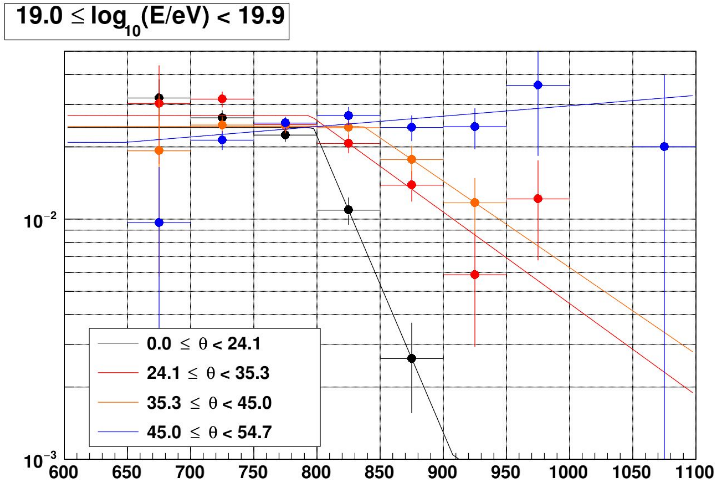
- TA and Auger $\langle X_{max} \rangle$ plots can not be directly compared as they are published.
- Each experiment has different analysis approach.
  - TA: loose cuts and simulate acceptance effects by Monte Carlo.
  - Auger: tight cuts ro remove acceptance effects as much as possible.
- We test compatibility by processing MC mixture through TA analysis exposing to detector acceptance and bias.
- When this is done, observed $\langle X_{max} \rangle$ and shapes of distributions agree within systematic uncertainties of the two experiments.
- And the shapes of TA distributions agree within systematic uncertainties of QGSJet II-04 protons.
- Possible North/South discrepancy? More TA data is required, especially above 10^{19} eV.
- TA and Auger are advancing our understanding of composition at the highest energies through improved statistical power and analysis → moving beyond the first two moments of the X_{max} distributions.

The ~~blind men~~ COSMIC RAY PHYSICISTS are touching the same elephant. They just need to talk to each other to figure this out!
And build larger detectors… And meet grant deadlines…

Extra







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}.**

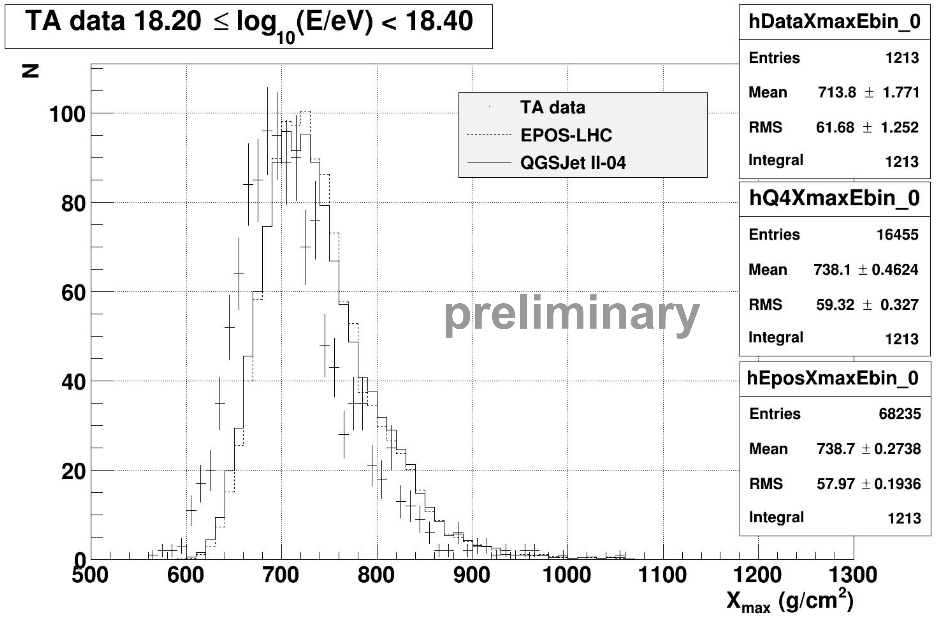
We have a steeply falling spectrum, higher energy events on average penetrate deeper, statistics are rapidly depleted for $E > 10^{19}$ eV.

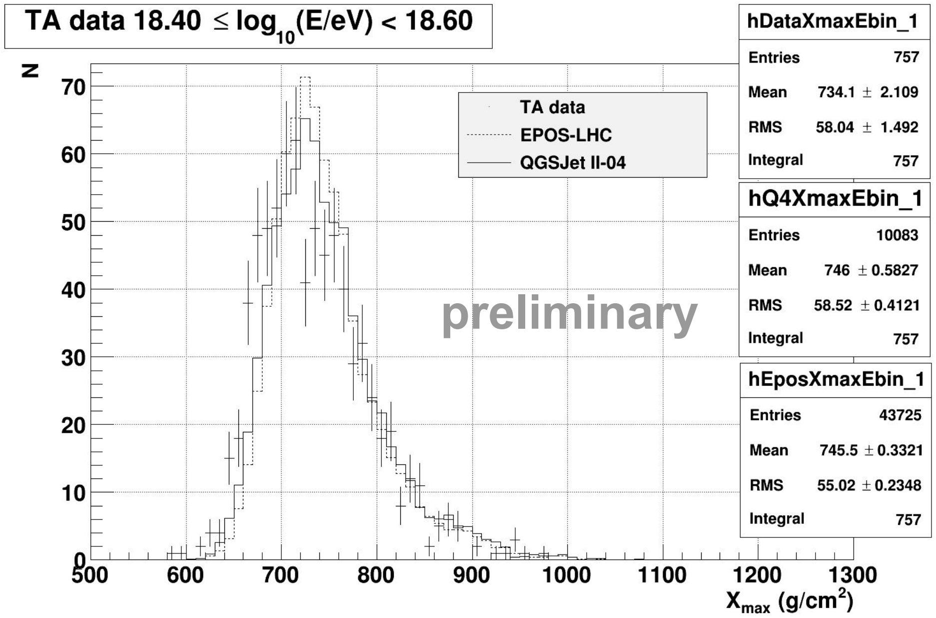
TA needs greater exposure for accurate measurement of composition for $E > 10^{19}$ eV. Nearly 9 years of data ⇒ 133 events above 10^{19} eV.

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

X_{max} Distributions

JPS Conf.Proc. 19 (2018) 011013



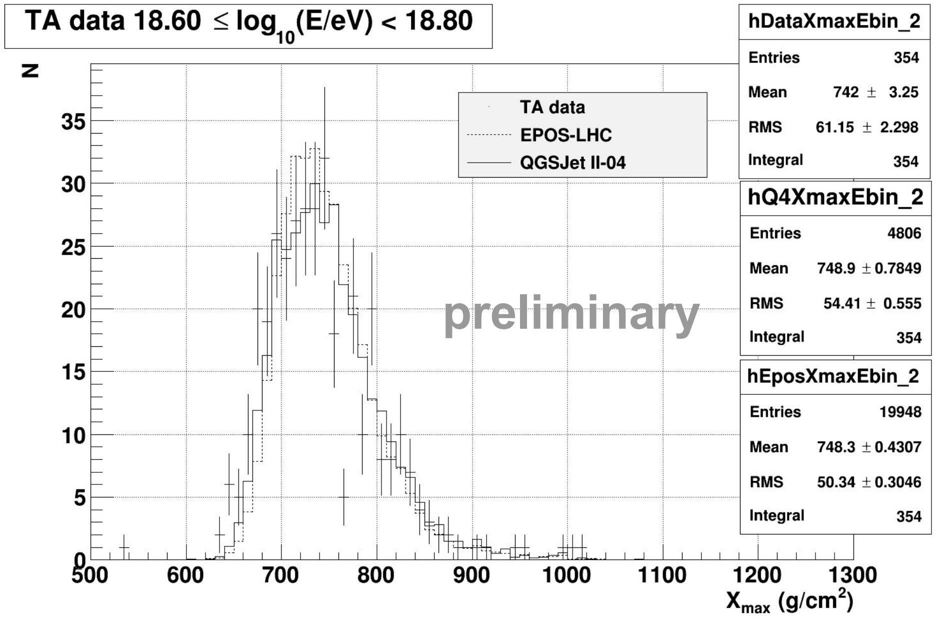


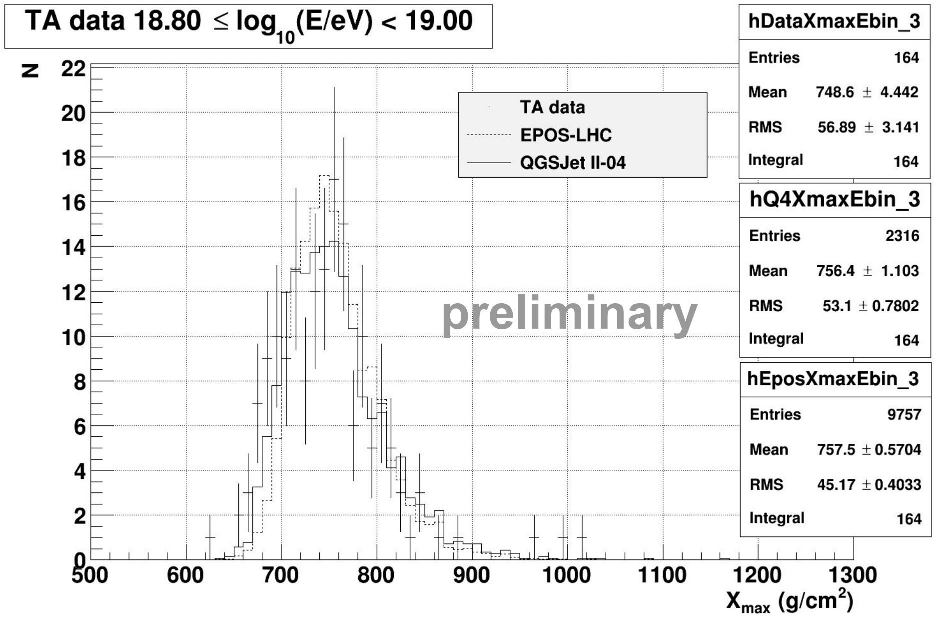
Auger mix after full exposure to Telescope Array analysis routines. Same analysis procedures used for all TA data and Monte Carlo. Data is seven years of preliminary BR/LR hybrid X_{max} analysis.

Reconstructed mix distributions are normalized to the data.

X_{max} Distributions

JPS Conf.Proc. 19 (2018) 011013



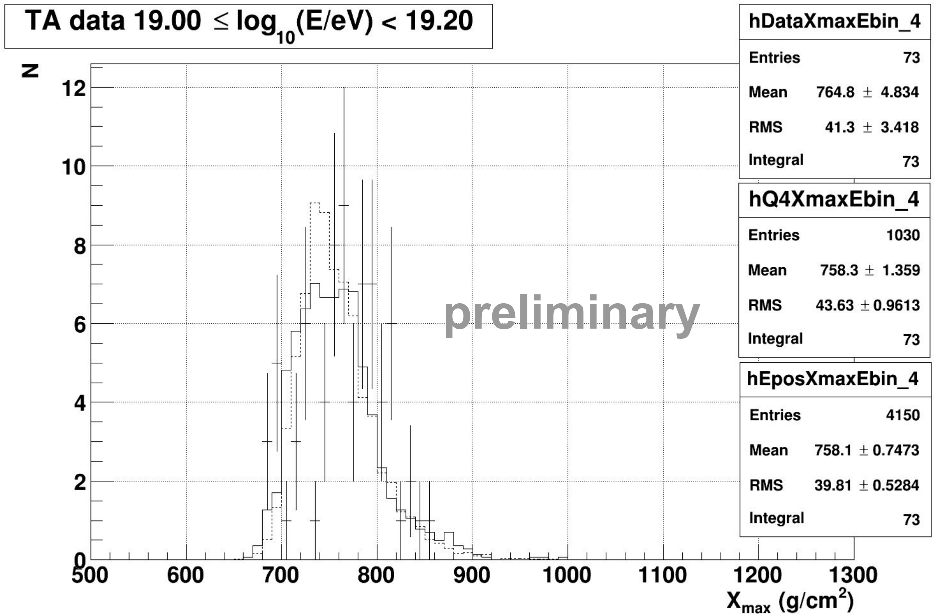


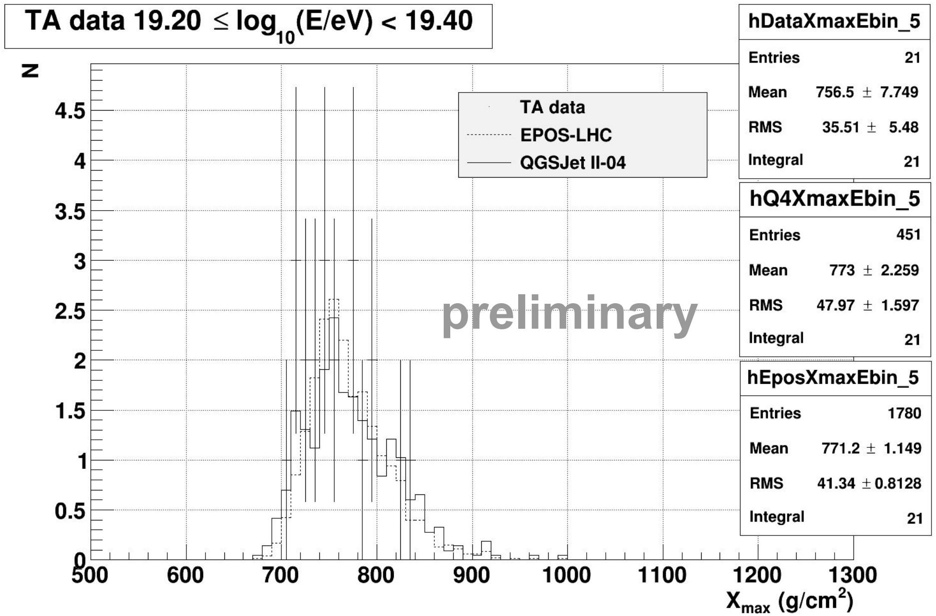
Auger mix after full exposure to Telescope Array analysis routines. Same analysis procedures used for all TA data and Monte Carlo. Data is seven years of preliminary BR/LR hybrid X_{max} analysis.

Reconstructed mix distributions are normalized to the data.

X_{max} Distributions

JPS Conf.Proc. 19 (2018) 011013



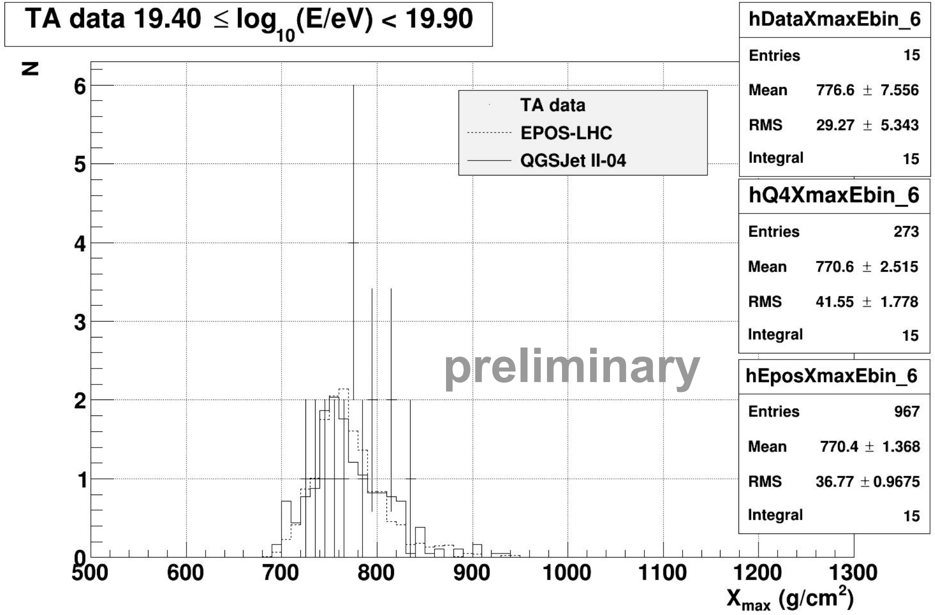


Auger mix after full exposure to Telescope Array analysis routines. Same analysis procedures used for all TA data and Monte Carlo. Data is seven years of preliminary BR/LR hybrid X_{max} analysis.

Reconstructed mix distributions are normalized to the data.

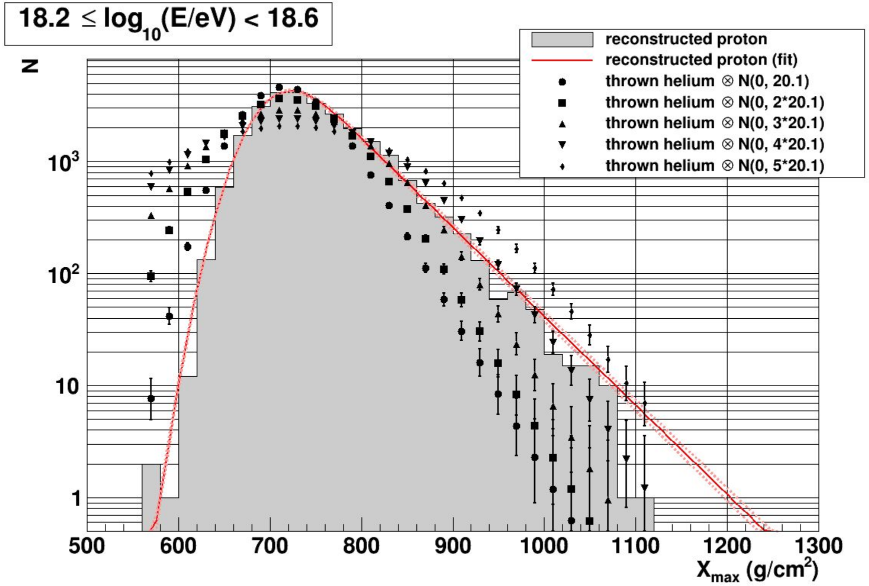
X_{max} Distributions

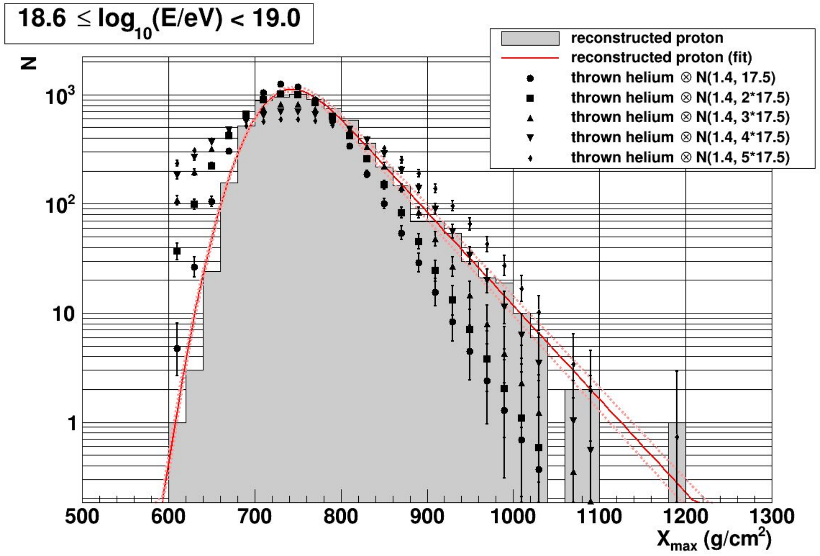
JPS Conf.Proc. 19 (2018) 011013



Auger mix after full exposure to Telescope Array analysis routines. Same analysis procedures used for all TA data and Monte Carlo. Data is seven years of preliminary BR/LR hybrid X_{max} analysis.

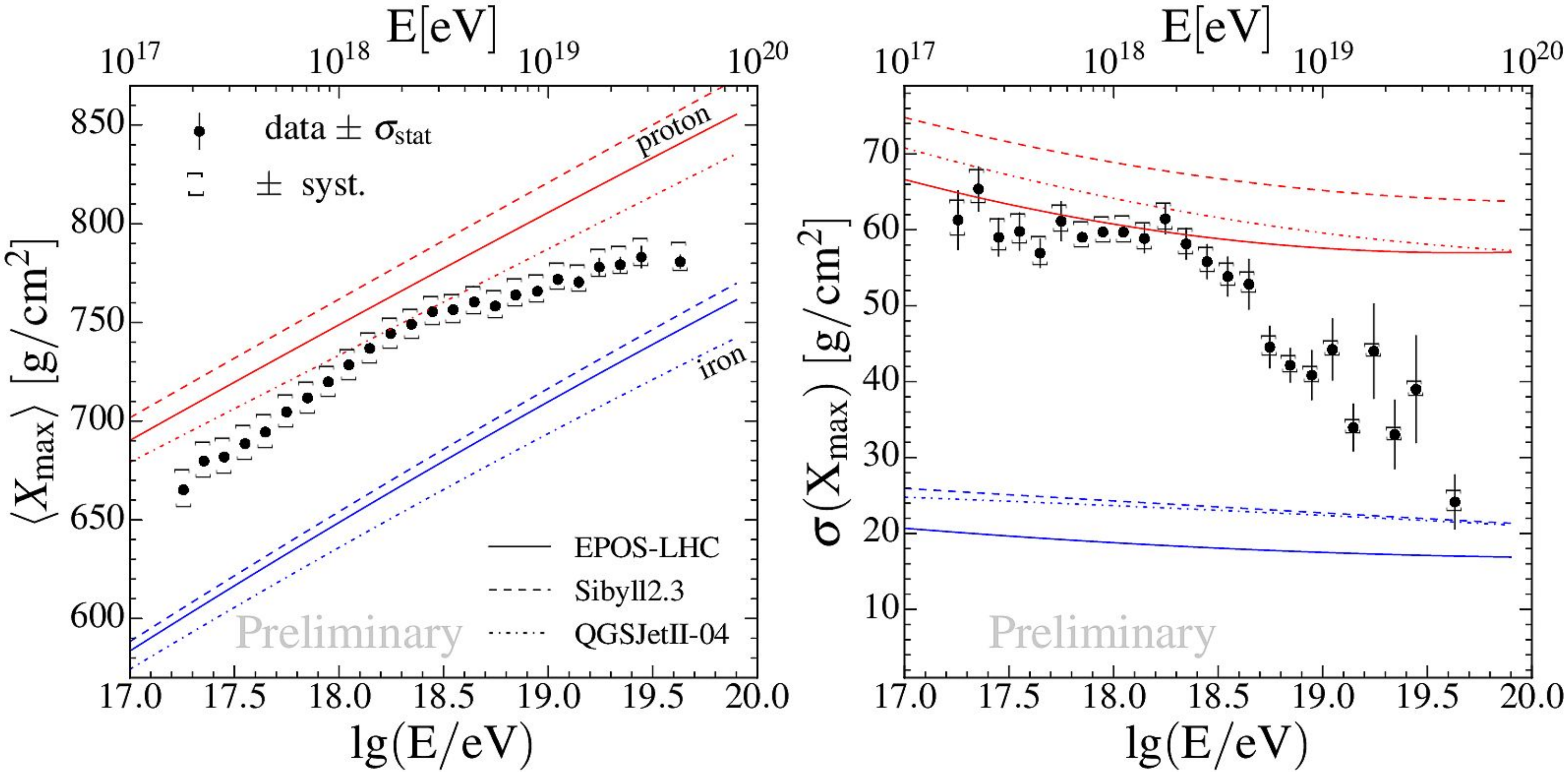
Reconstructed mix distributions are normalized to the data.





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 calculate 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.



Auger <X_{max}> and σ(X_{max}) (ICRC 2017)

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

TA Expansion (TA × 4)

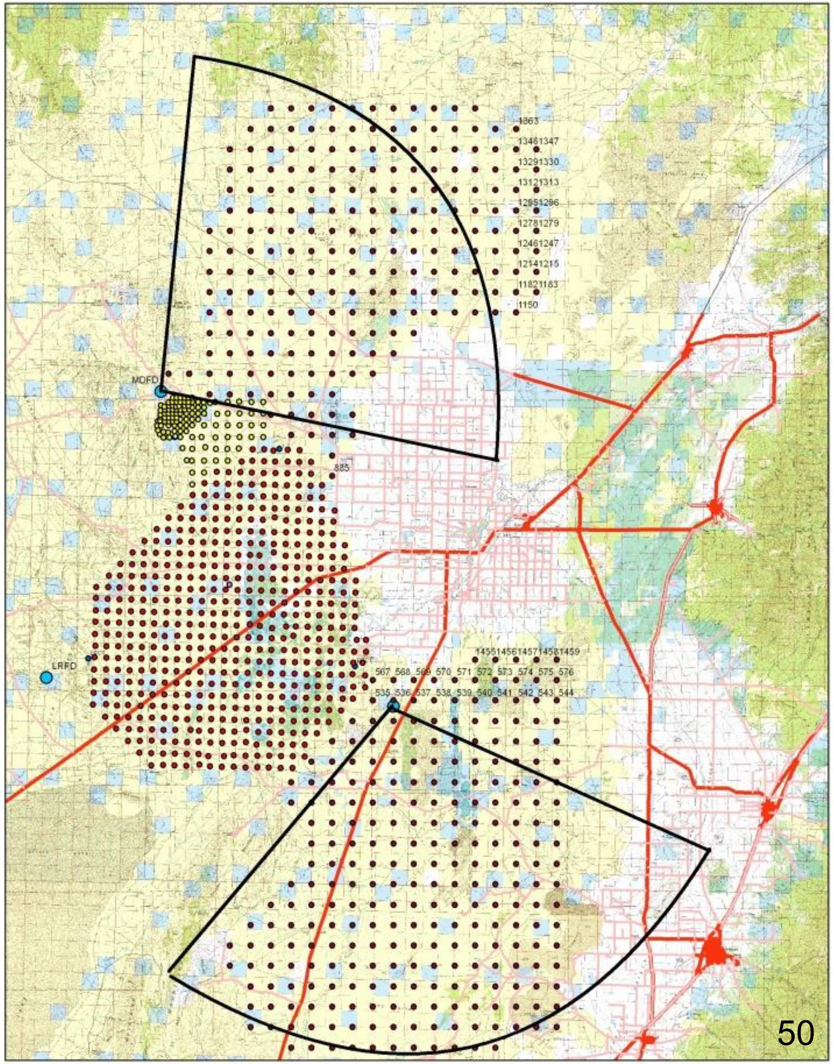
Fourfold increase in the size of the TA SD array.

Add 500 scintillator SDs @ 2.08 km spacing.

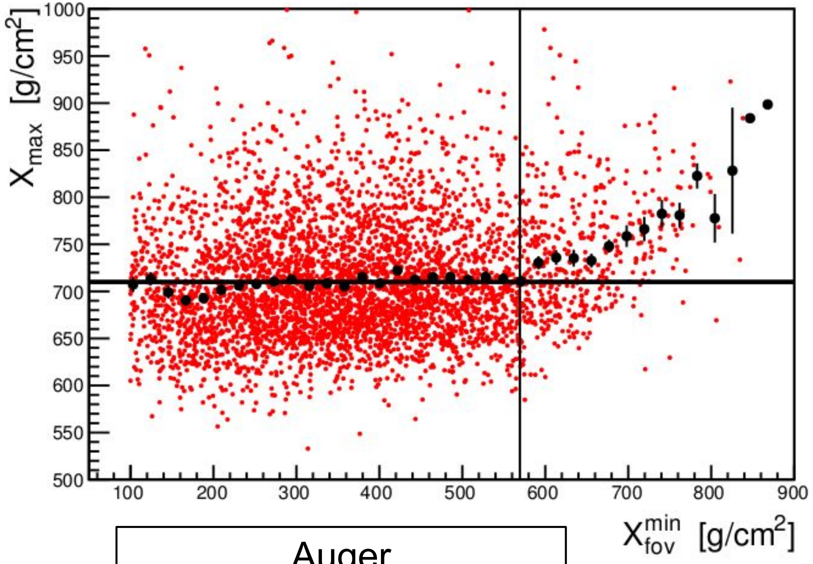
Add 2 FD stations, 28 telescopes

Get 20 TA years of data by 2020.

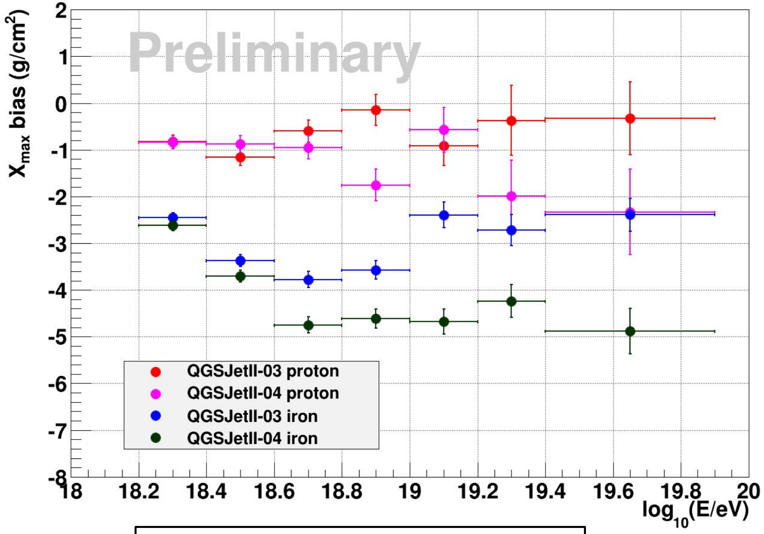
Increased statistics for highest energy range (> 57 EeV) to answer the question of the hotspot.



Analysis Methodology



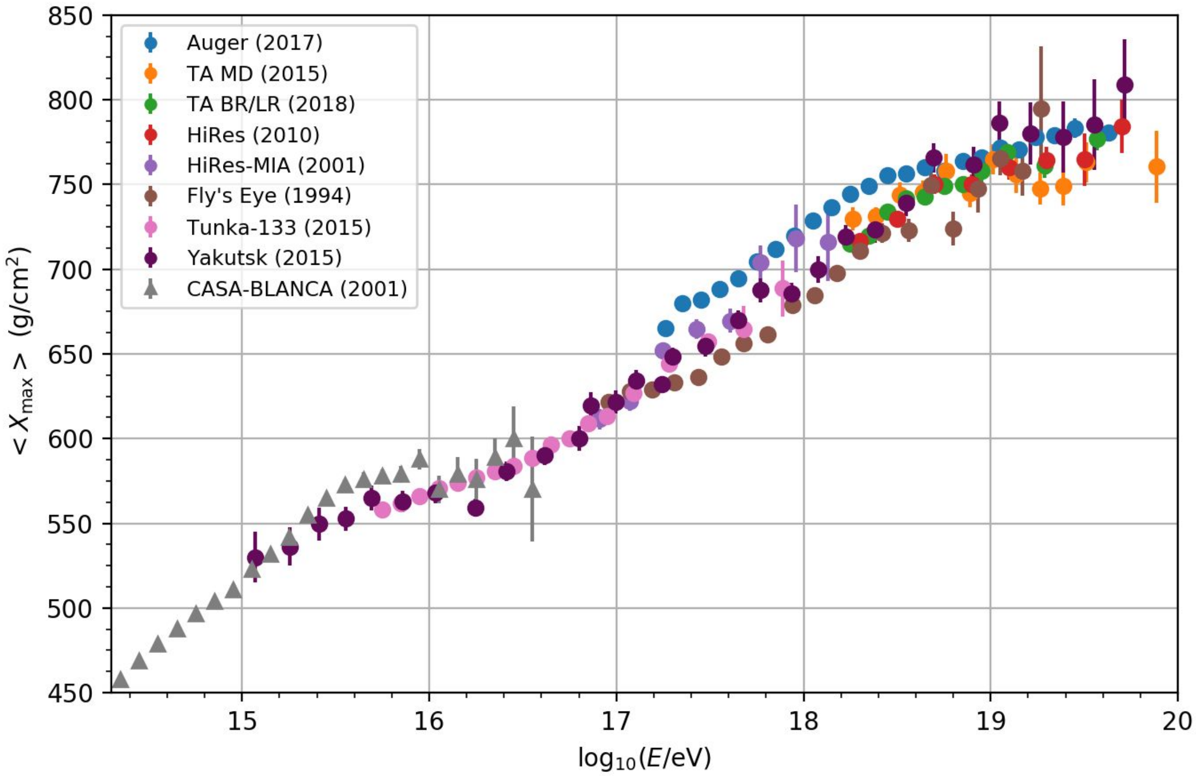
Auger



TA

- Fiducial volume cuts based on shower geometry are applied to select showers with minimum resolution bias and covers the full X_{max} distribution.
- Moments of the unbiased X_{max} distribution are obtained.
- X_{max} moments can be directly compared to unbiased, thrown distributions from models.
- Identical reconstruction procedure, software, and event selection algorithm.

- Simulate X_{max} biases via detailed detector Monte Carlo
- Compare measured X_{max} distributions with Monte Carlo predictions including effects of detector biases.
- Identical reconstruction procedures, software, & cuts are applied to data and Monte Carlo.
- Biases in data and MC due to unique aperture, efficiency, & reconstruction shown.



X_{max} measurements over the past 25 years.

Even without correcting for acceptance of the individual experiments such as Auger does most experiments agree very well in their overlap regions.