Telescope Array 10 Year Composition

William Hanlon

University of Utah Dept. of Physics and Astronomy & High Energy Astrophysics Institute

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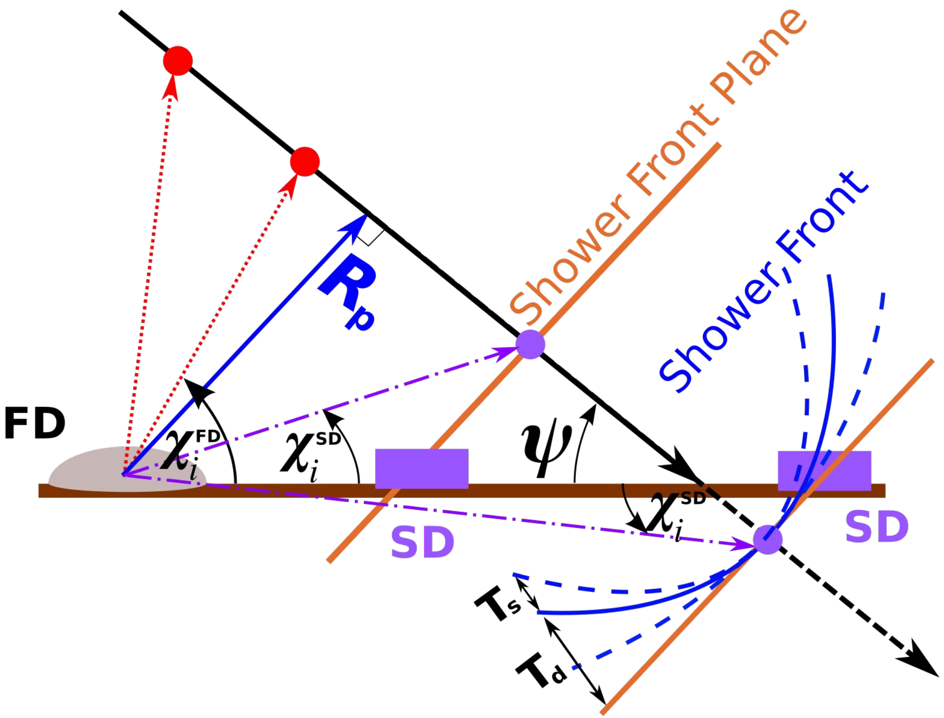
Outline

1. Ten year hybrid X_{max} Measurements
2. Single element UHECR composition
3. Two element UHECR composition
4. Four element UHECR composition
5. Summary

Telescope Array Ten Year Hybrid X_{max} Measurements



Hybrid UHECR reconstruction

Event trigger conditions

- ≥ 3 adjacent SD, 3 MIP, < 8 μs
- ≥ 5 adjacent PMT, ≥ 6σ background, < 25.6 μs
- SD & FD trigger coincidence < 500 μs,
  | hybrid core - SD core | < 1200 m

Hybrid X_{max} reconstruction resolution & bias

- 18 g/cm^2, < -1 g/cm^2 QGSJET II-04 proton
- 13 g/cm^2, 4 g/cm^2 QGSJET II-04 iron

Hybrid Energy reconstruction resolution and bias

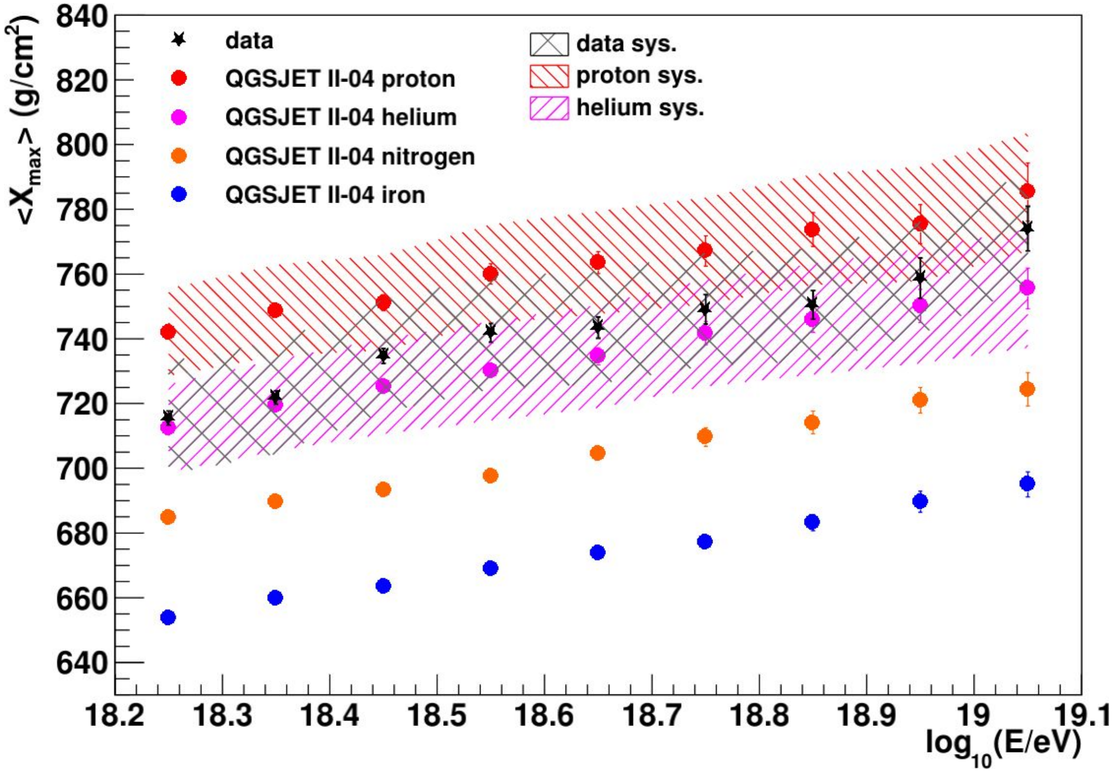
- 6%, 2% QGSJET II-04 proton
- 4%, -7% QGSJET II-04 iron

Zenith angles accepted: 0° - 55°

We analyze and present data and MC as *observed*, acceptance and reconstruction biases are folded in.

References

SD: Nucl.Instrum.Meth. A689 (2013) 87-97
FD: Nucl.Instrum.Meth. A609 (2009) 227-234, Nucl.Instrum.Meth. A676 (2012) 54-65
BR/LR hybrid: Astrophys.J. 858 (2018) no.2, 76
MD hybrid: Astropart.Phys. 64 (2015) 49-62



10 year BR/LR hybrid <X_{max}>

Hybrid events from TA BR/LR FD detectors in coincidence with SD array

3560 events, $18.2 \le \log_{10}(E/\mathrm{eV}) < 19.1$

Elongation rate

- $D_{10} = 66 \pm 5$ (g/cm^2)/decade
- χ^2/dof = 10.66/7 (p = 0.154)

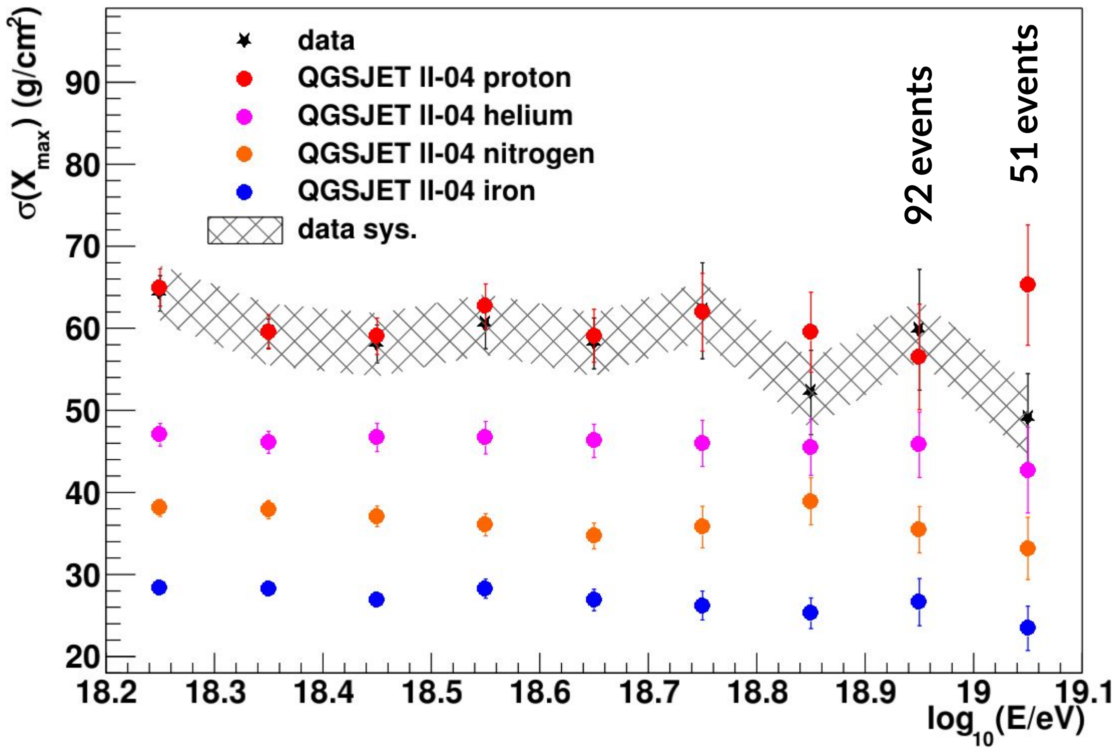
TA <X_{max}> appears consistent with <X_{max}> of predominantly light elements such as protons and helium using the QGSJET II-04 model.

<X_{max}> systematic uncertainty: ± 17 g/cm^2

Systematic uncertainty of QGSJET II-04 models are shown as well.

σ(<X_{max}>) of QGSJET II-04 p/He ≅ ± 3 g/cm^2 @ 10^{17} eV [lab] ($\sqrt{s}$ = 14 TeV)
σ(<X_{max}>) of QGSJET II-04 p/He ≅ ± 18 g/cm^2 @ $10^{19.5}$ eV [lab] ($\sqrt{s}$ = 250 TeV)
σ(<X_{max}>) of TA data = ±17.4 g/cm^2 ($10^{18.2} \le E < 10^{19.9}$ eV)

Conservative lower bounds on uncertainties from total cross-section, multiplicity, and elasticity dependence. (Abbasi & Thomson, arXiv:1605.05241 (2016))



10 year BR/LR hybrid $\sigma(X_{max})$

Hybrid events from TA BR/LR FD detectors in coincidence with SD array

3560 events, $18.2 \leq \log_{10}(E/\mathrm{eV}) < 19.1$

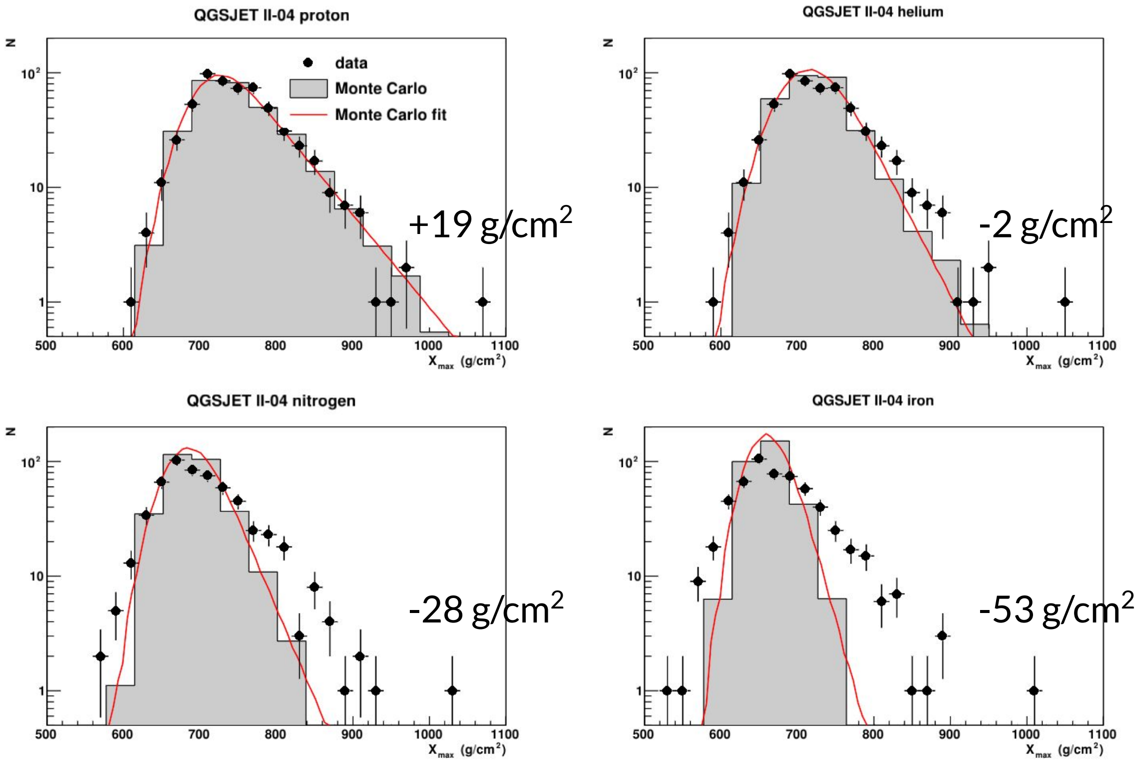
Where statistics are large, $\sigma(X_{max})$ is consistent with QGSJET II-04 protons. Note that $\sigma(X_{max})$ is relatively model independent, unlike $\langle X_{max} \rangle$ which can vary by 20 g/cm^2 between models.

Above $10^{19.1}$ eV, statistics are depleted* due to the combination of acceptance (primarily loss of small zenith angle events) and falling spectrum. TA loses its ability to distinguish between even single element predictions of composition.

*96 events, $19.1 \leq \log_{10}(E/\mathrm{eV}) < 19.9$

Single Element UHECR Composition

$18.4 \le \log_{10}(E/\mathrm{eV}) < 18.5$

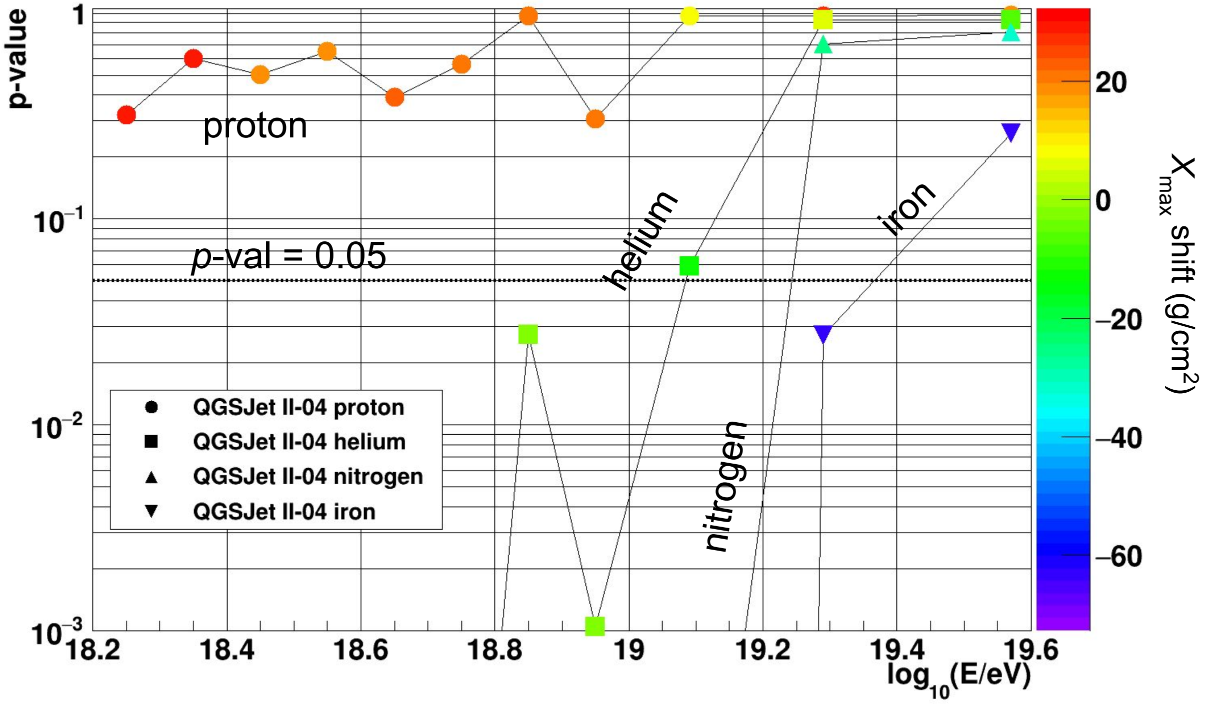


Depth of Ultra High Energy Cosmic Ray Induced Air Shower Maxima Measured by the Telescope Array Black Rock and Long Ridge Fluorescence Detectors and Surface Array in Hybrid Mode, Abbasi, et al., Astrophys.J. 858 (2018) no.2, 76

In Astrophys.J. 858 (2018) no.2, 76 we tested TA hybrid X_{max} data against predictions of single element composition using the QGSJET II-04 model (Phys.Rev. D83 (2011) 014018).

To account for systematic uncertainties in X_{max} of our data and the model, we fit the data to reconstructed distributions of each element with a systematic shift in X_{max} and found the shift which maximized the likelihood of data and MC. This tests *the shapes* of the distributions.

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.



We demonstrated that at the 95% confidence level, TA data is compatible with a pure QGSJET II-04 proton composition for all energies $18.2 \leq \log_{10}(E/\mathrm{eV}) < 19.9$, with X_{max} shifts ~+20 g/cm^2 applied to the data. TA $\langle X_{max} \rangle$ systematic uncertainty is ± 17 g/cm^2.

Below 10^{19} eV all other single elements tested were not compatible with TA data. For iron, shifts of 50 g/cm^2 were needed to make the data match the MC prediction.

Above 10^{19} eV TA data is compatible with all four pure QGSJET II-04 elements using this test because statistics are poor and the deep X_{max} tail is not seen.

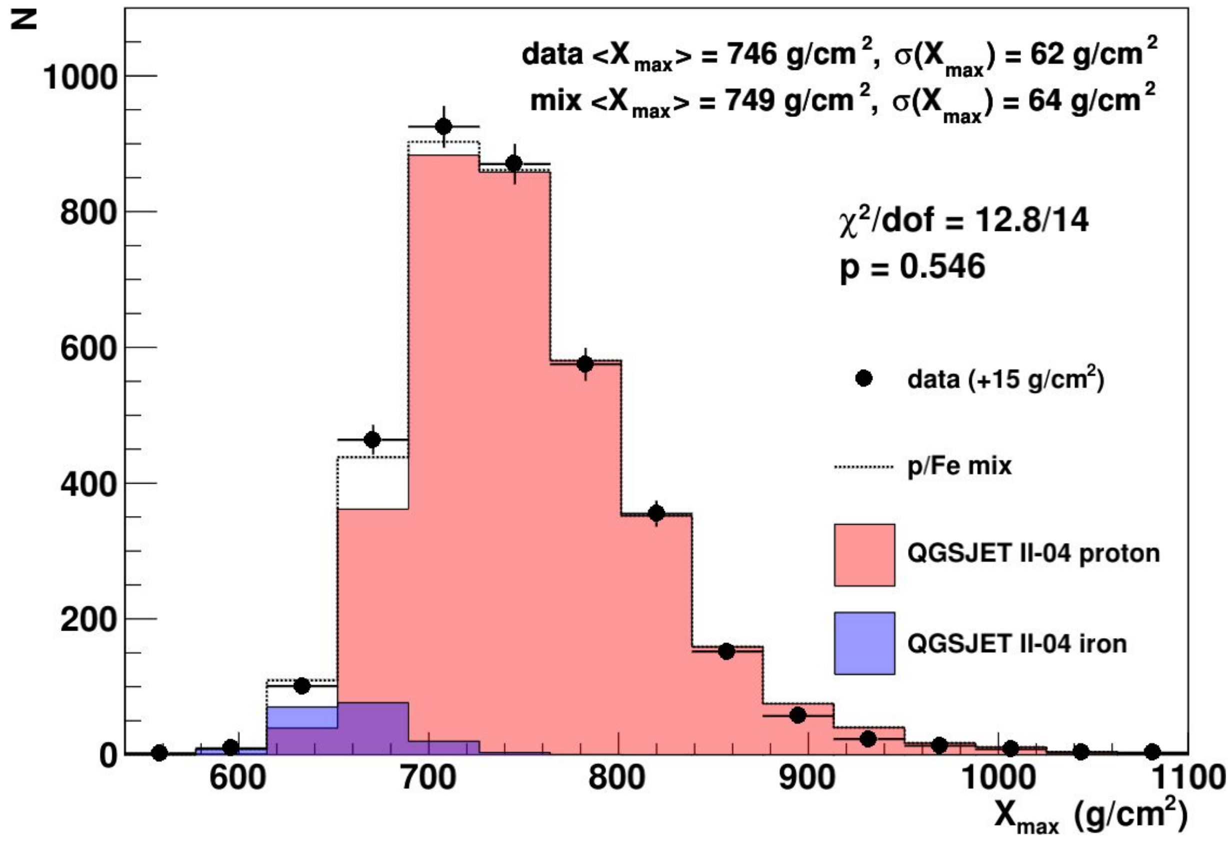
Depth of Ultra High Energy Cosmic Ray Induced Air Shower Maxima Measured by the Telescope Array Black Rock and Long Ridge Fluorescence Detectors and Surface Array in Hybrid Mode, Abbasi, et al., Astrophys.J. 858 (2018) no.2, 76

Two element UHECR Composition

Fitting Multi-source <X_{max}> Data

- Fitting binned data to a model consisting of the sum of *N* sources, where the source PDFs are not specified analytically, but instead estimated by Monte Carlo.
- Using the method of Barlow & Beeston, Comput.Phys.Commun. 77 (1993) 219-228, implemented in ROOT package TFractionFitter.
- Likelihood is maximized with respect to weights of the source distributions and the Poisson nature of the binned data *and* binned sources (i.e., Monte Carlo fluctuations considered as well).
- Multi-component source weights are measured in each energy bin.
- To understand effects of correlations and uncertainties of source weights, fitting is performed many times in a bootstrap fashion by randomly sampling the data and recording fit information.
- See also Comput.Phys.Commun. 180 (2009) 269-275, Phys.Lett. B407 (1997) 73-78, and Astropart.Phys. 26 (2006) 28-40.

QGSJET II-04 proton/iron mix

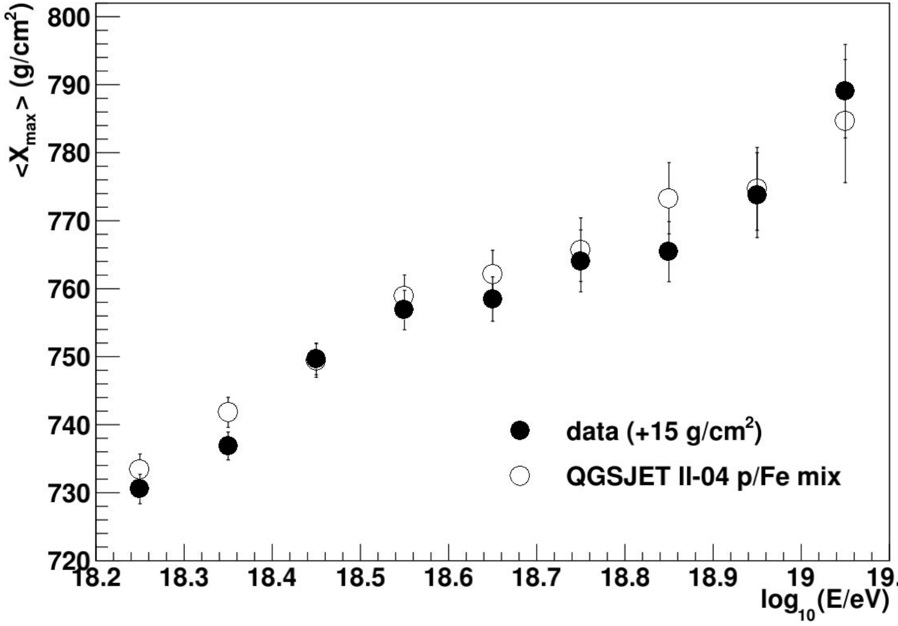


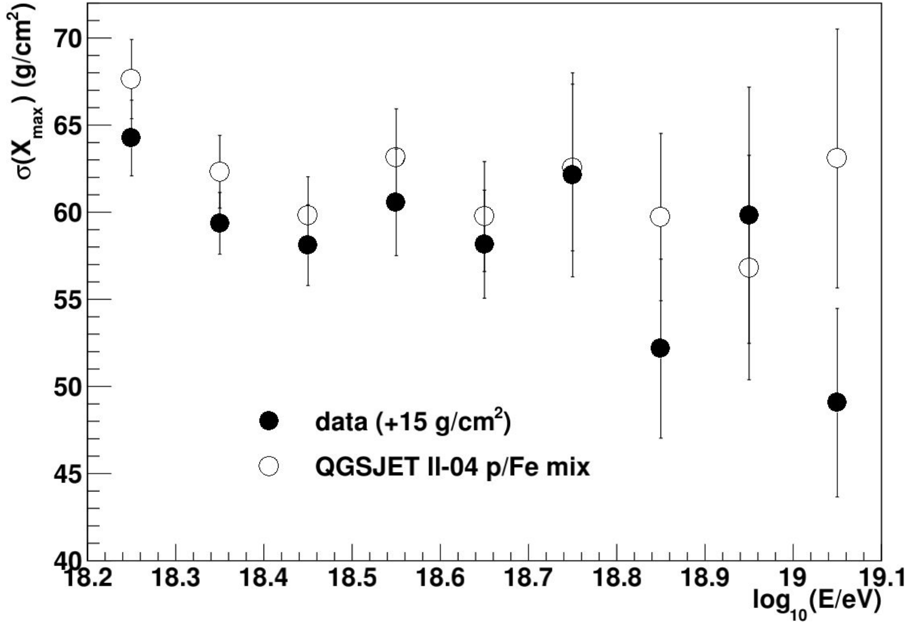
Classic UHECR composition ansatz: two components classified as *light* and *heavy* → proton and iron sources.

As with single element fitting to TA hybrid data, some systematic shifting of the data is required to measure a reasonable χ^2. In this case data is uniformly shifted within ± 17 g/cm^2 and the minimum χ^2 is found for a +15 g/cm^2 shift.

f_p = 95.0 ± 1.6%
f_{Fe} = 5.0 ± 0.4%

$18.2 \leq \log_{10}(E/\mathrm{eV}) < 19.1$



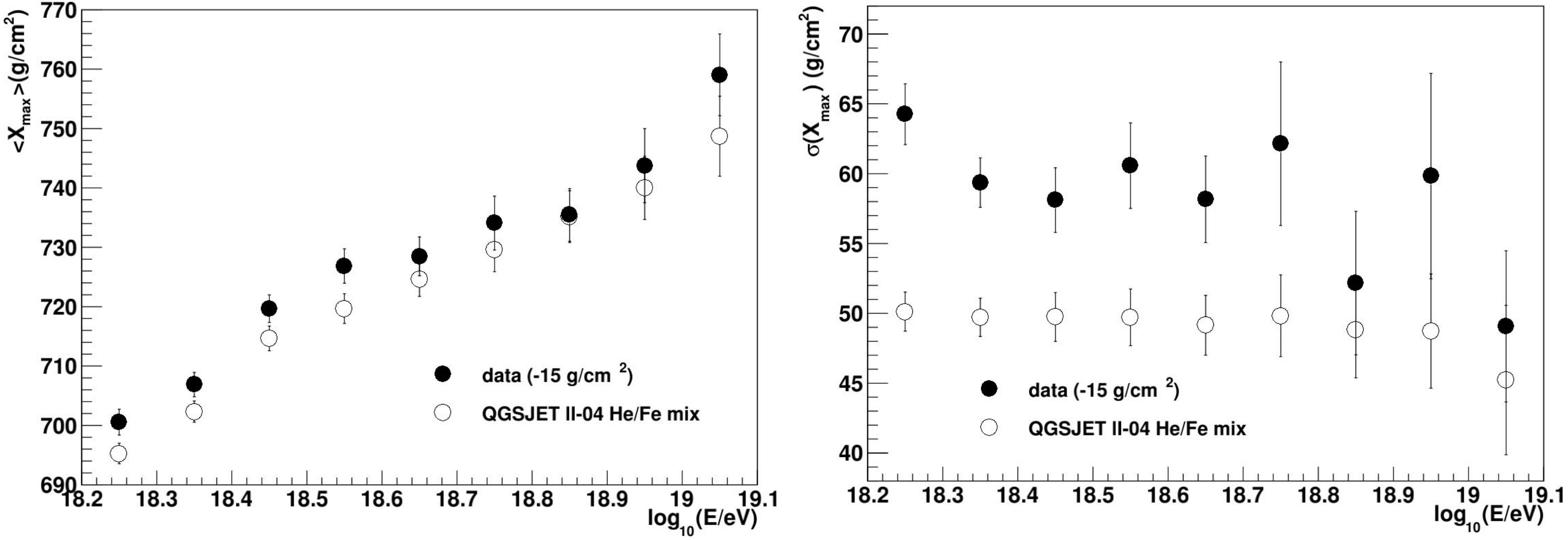


$\langle X_{max} \rangle$ and $\sigma(X_{max})$ of QGSJET II-04 p/Fe mix with +15 g/cm^2 uniform shift applied to TA 10 year data

Other QGSJET II-04 two component mixtures

- p/He and p/N mixture $\langle X_{max} \rangle$ look similar to TA data with little to no shifting at all. But p/He results in poor χ^2 because the distributions are too narrow (~10 g/cm^2 narrower than the data). (χ^2/dof = 86.2/14) *Note: systematic shifting of data does not change $\sigma(X_{max})$.*

- p/N mixture results in ~70/30 p/N mix up to $10^{19.2}$ eV, then becomes 50/50. (χ^2/dof = 8.9/14)



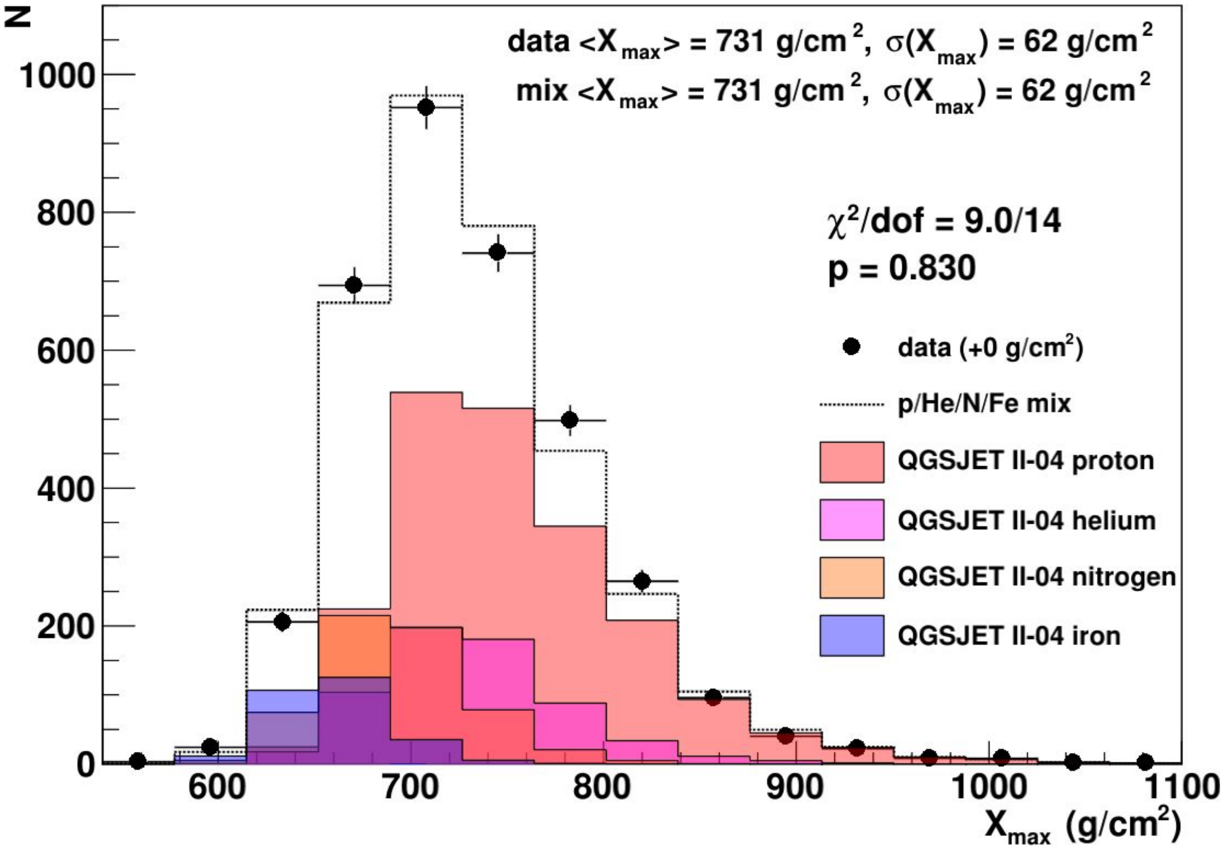
$<X_{max}>$ and $\sigma(X_{max})$ of QGSJET II-04 He/Fe mix with -15 g/cm^2 uniform shift applied to TA 10 year data

Perhaps the next logical light/heavy model to try is helium and iron. After a -15 g/cm^2 shift to the data, a He/Fe mixture has similar means as the data and results in a ~80/20 He/Fe mix for all energies. But σ(Xmax) looks very different because the lack of proton does not replicate the tails of the distributions. The χ^2/dof of the data/mix distributions is an unacceptable 79.3/14. *Note: systematic shifting of data does not change $\sigma(X_{max})$.*

We can use a model such as this to estimate a lower bound on the amount of protons present in the data.

Four Element UHECR Composition

QGSJET II-04 proton, helium, nitrogen & iron mix

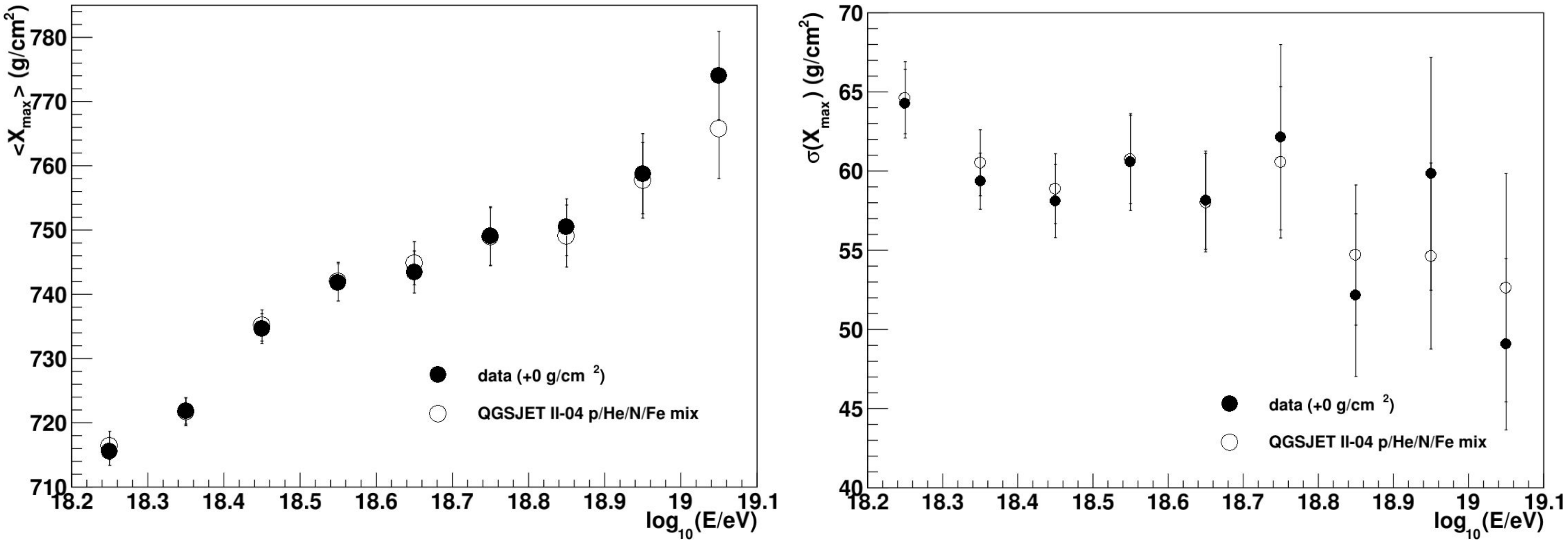


Fitting to a four component mix, proton, helium, nitrogen, and iron, results in a fit to TA hybrid data without a need to shift to find acceptable χ^2. Proton and helium combined (light elements) result in 75% of the mix between $18.2 \leq \log_{10}(E/\mathrm{eV}) < 19.1$.

Fitting with elements with similar shapes and $\langle X_{max} \rangle$, mainly proton and helium, is problematic due to correlations.

f_p = 57.3 ± 1.3%
f_{He} = 18.0 ± 0.7%
f_N = 16.8 ± 0.7%
f_{Fe} = 8.0 ± 0.5%

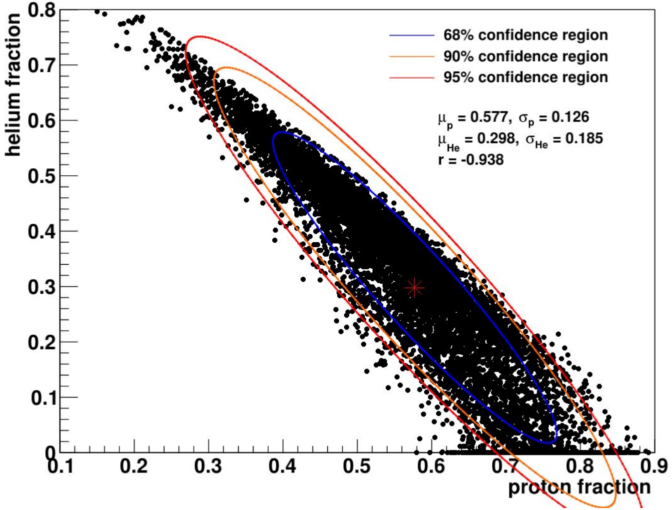
Light components (p + He): 75%

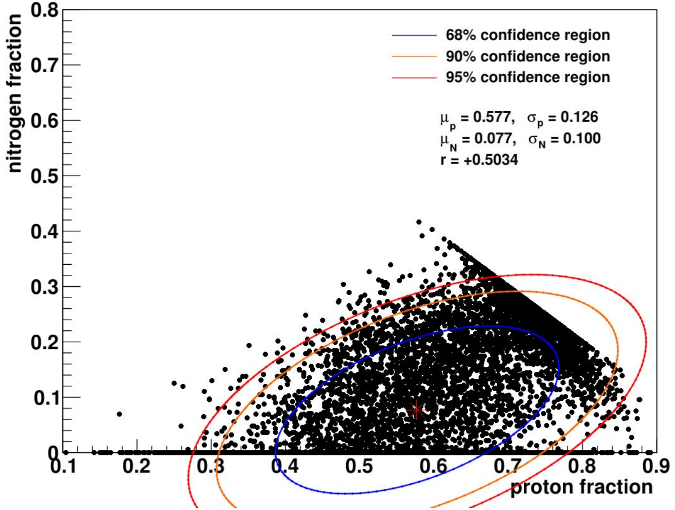


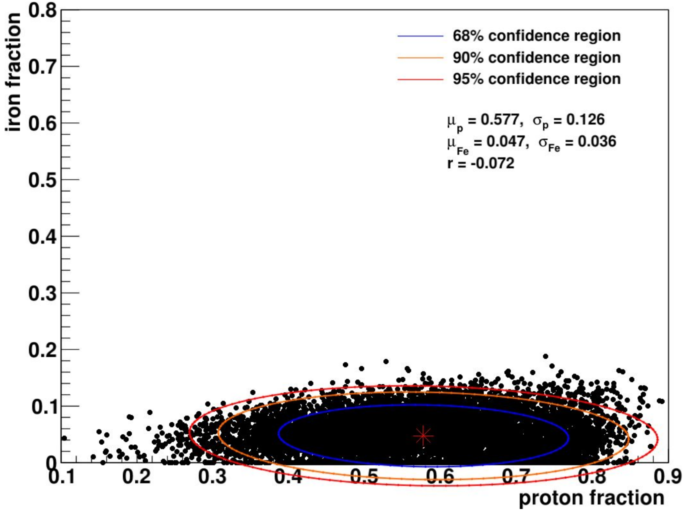
<X_{max}> and $\sigma(X_{max})$ of QGSJET II-04 p/He/N/Fe mix with +0 g/cm^2 uniform shift applied to TA 10 year data

Why investigate a four component ad hoc model? We do not know what the composition is at UHE and we should not presuppose without further evidence that it is solely extra-galactic protons. New UHECR experiments such as TA may be able to answer this question via direct measurement, being mindful of our limitations due to resolution, acceptance, and statistics.

A similar, independent experiment has already made such a measurement using the same methods we have access to, and we may be able to verify or refute their claims.



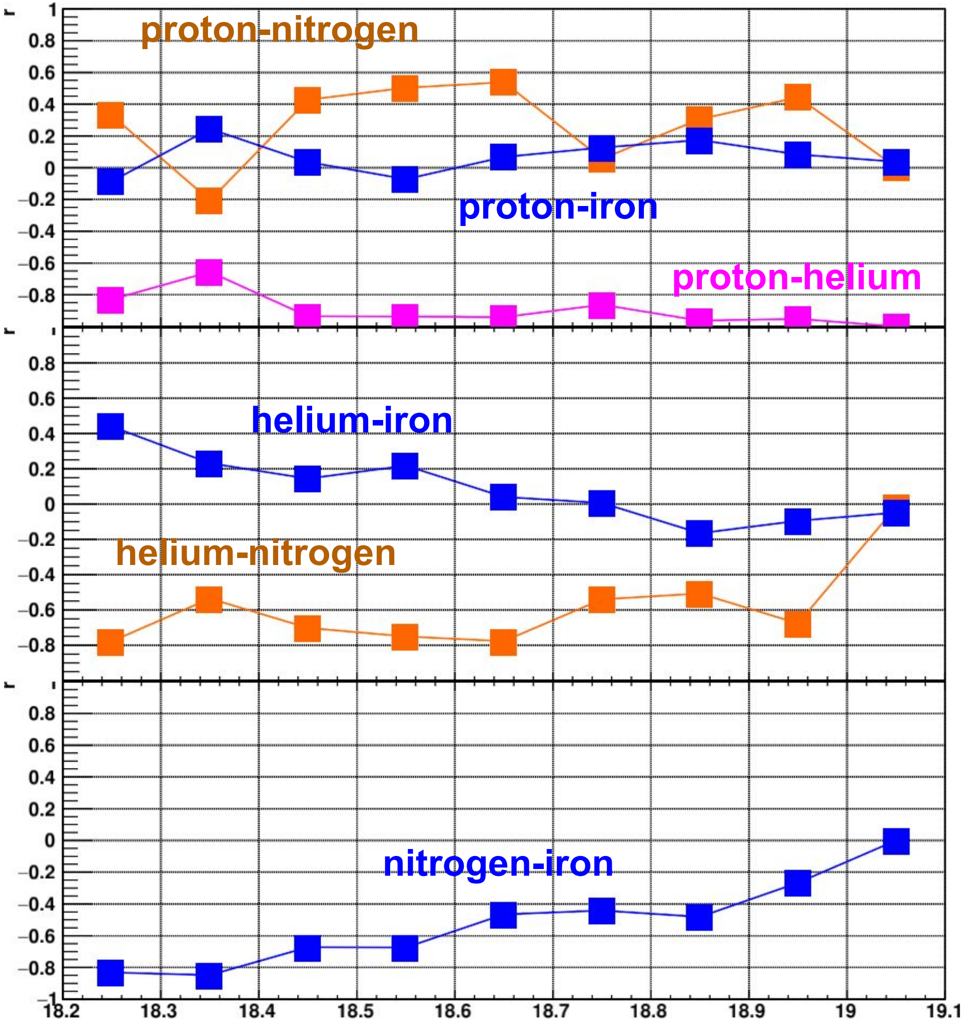




Here proton-helium are highly correlated (r = -0.9), proton-nitrogen are somewhat correlated (r = +0.5), and proton-iron are slightly correlated (r = -0.1)

Multiple components exhibit correlations. Two component mix elements are 100% correlated since there is only a single degree of freedom in the fractions.

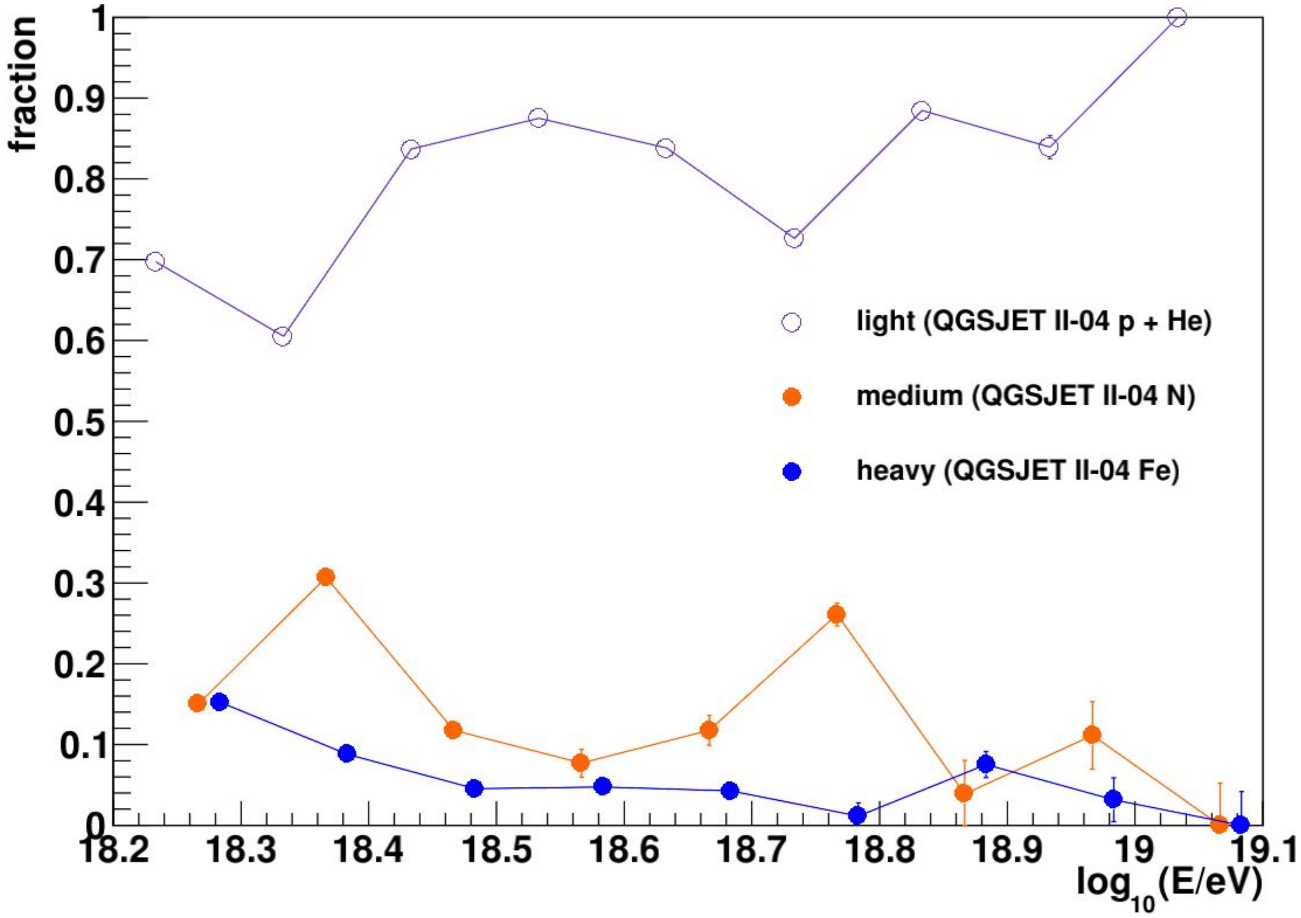
For more than two components, reconstruction resolution will limit our ability to accurately measure the fractions of some elements that have similar means or tail features. Difference in $\langle X_{max} \rangle$ of QGSJET II-04 proton and helium is 25 g/cm^2, TA X_{max} resolution is 17 g/cm^2.



Elements close to each other in mass are highly correlated. Tightest correlation is between proton and helium, which are nearly fully correlated. Least correlated are proton and iron. Helium-iron correlation is nearly 0 above $10^{18.6}$ eV.

None of this should be surprising. For this analysis (essentially summing weighted histograms), correlation is probably due to convolution of detector resolution and the separation of the central X% of the intrinsic distributions in relation to each other. Tail discrimination plays a role as well.

Adding in too many elements not sufficiently resolved by detector resolution will lead to biases when determining the source weights. Monte Carlo study of these biases is underway.



TA hybrid resolution, ~20 g/cm^2, which is about the difference in <X_{max}> of QGSJET II-04 proton and helium, is not sufficient to make accurate measurements of proton and helium individual fractions in a mixture.

Until resolutions are significantly improved, we should still think in terms of light. medium, and heavy composition.

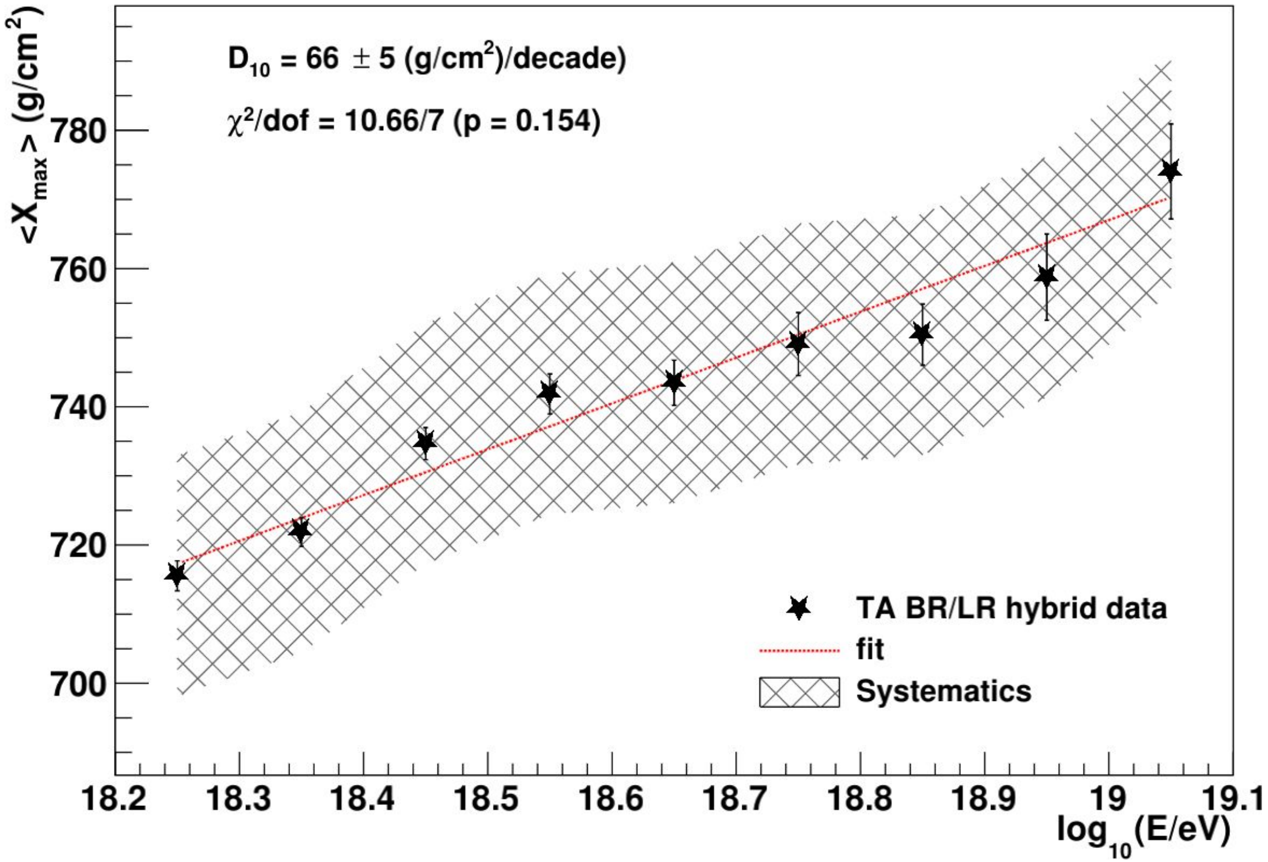
Summary

- Ten years of TA BR/LR hybrid composition is now analyzed. This is TA's highest statistics measurement of UHECR X_{max}.
- Traditional measures of composition such as $<X_{max}>$ and $\sigma(X_{max})$ are in agreement with light composition as described by the QGSJET II-04 model.
- Past comparisons of TA X_{max} to single element QGSJET II-04 predictions with systematic shifting shows agreement with QGSJET II-04 protons for all observed energies.
- The simple light/heavy proton/iron model fits the data well with systematic shifting, resulting in 95% proton mixture below $10^{19.1}$ eV.
- A light/heavy model of helium/iron does not fit the data because the lack of protons in the mix does not replicate the tail of the data distribution.
- A four component proton, helium, nitrogen, and iron mix fits the data well with 75% light (p + He) component below $10^{19.1}$ eV.
- This analysis has been done with EPOS-LHC as well, but there are technical problems with the model in CORSIKA.

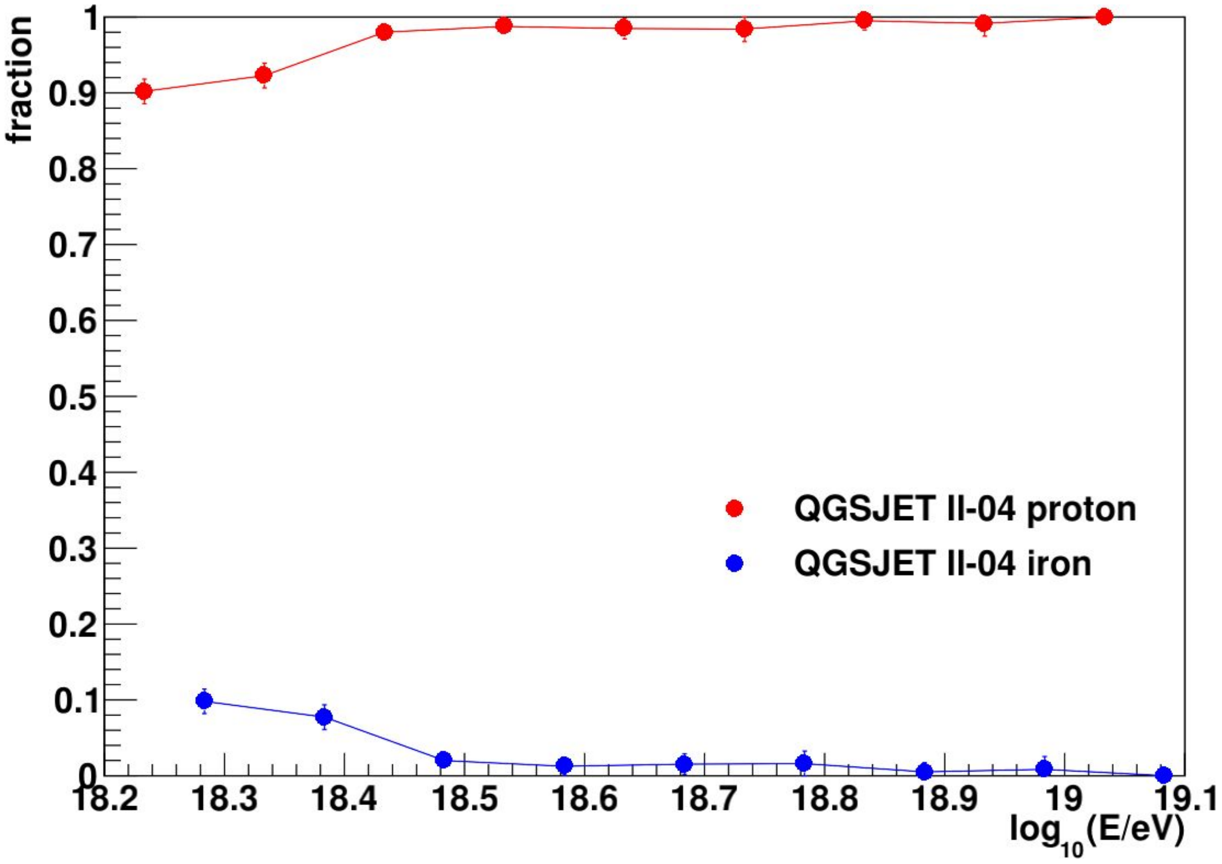
Telescope Array Composition @ ICRC 2019

CRI2e	TALE FD Cosmic Rays Composition Measurement	Tareq AbuZayyad
CRI2f	Telescope Array 10 Year Composition	William Hanlon
CRI11c	Anisotropy in the Mass Composition from the Telescope Array Surface Detector	Yana Zhezher
PS-146	Combined Fit of Spectrum and Composition from Telescope Array	Douglas Bergman
PS-147	TA 10 Year Stereo Composition Measurement	Douglas Bergman

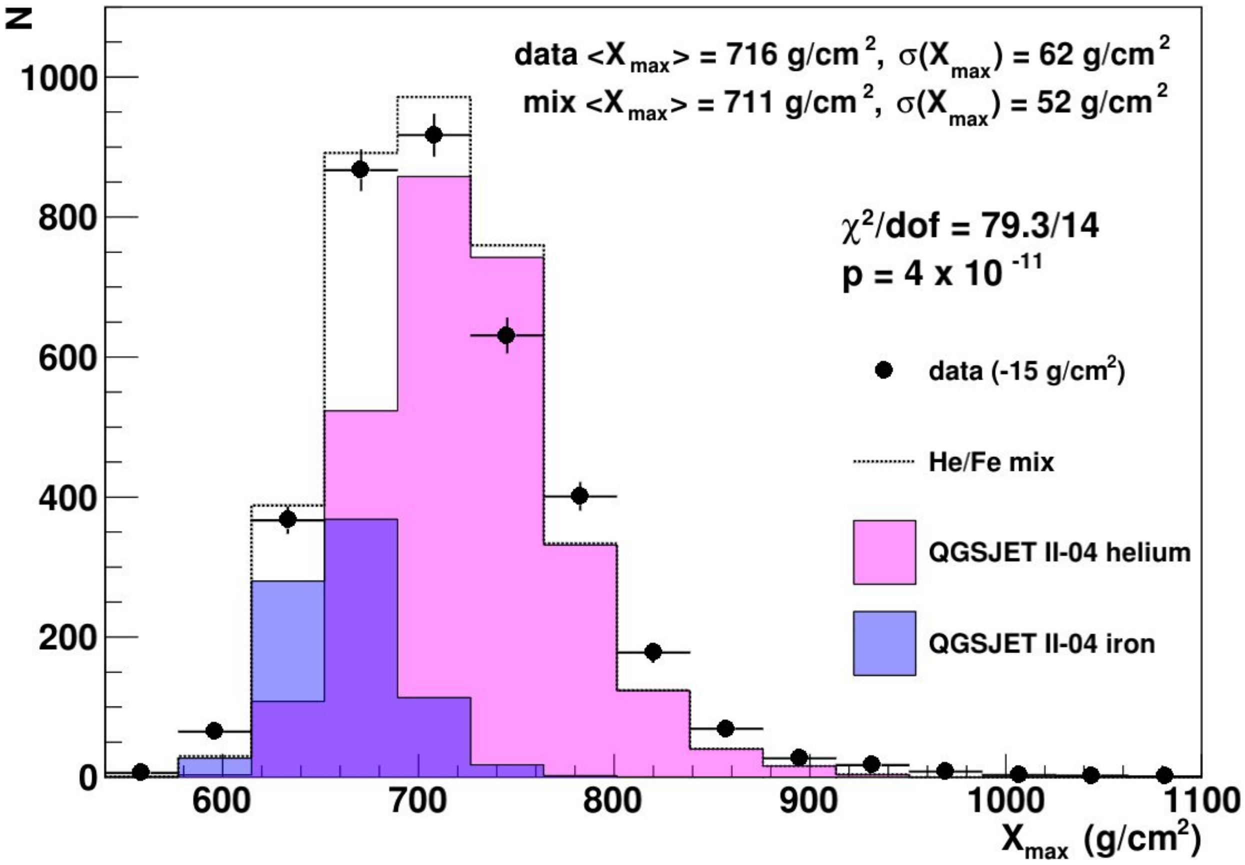
Backup



TA BR/LR Hybrid < X_{max} > and elongation rate, $18.2 \le \log_{10}(E/\mathrm{eV}) < 19.1$



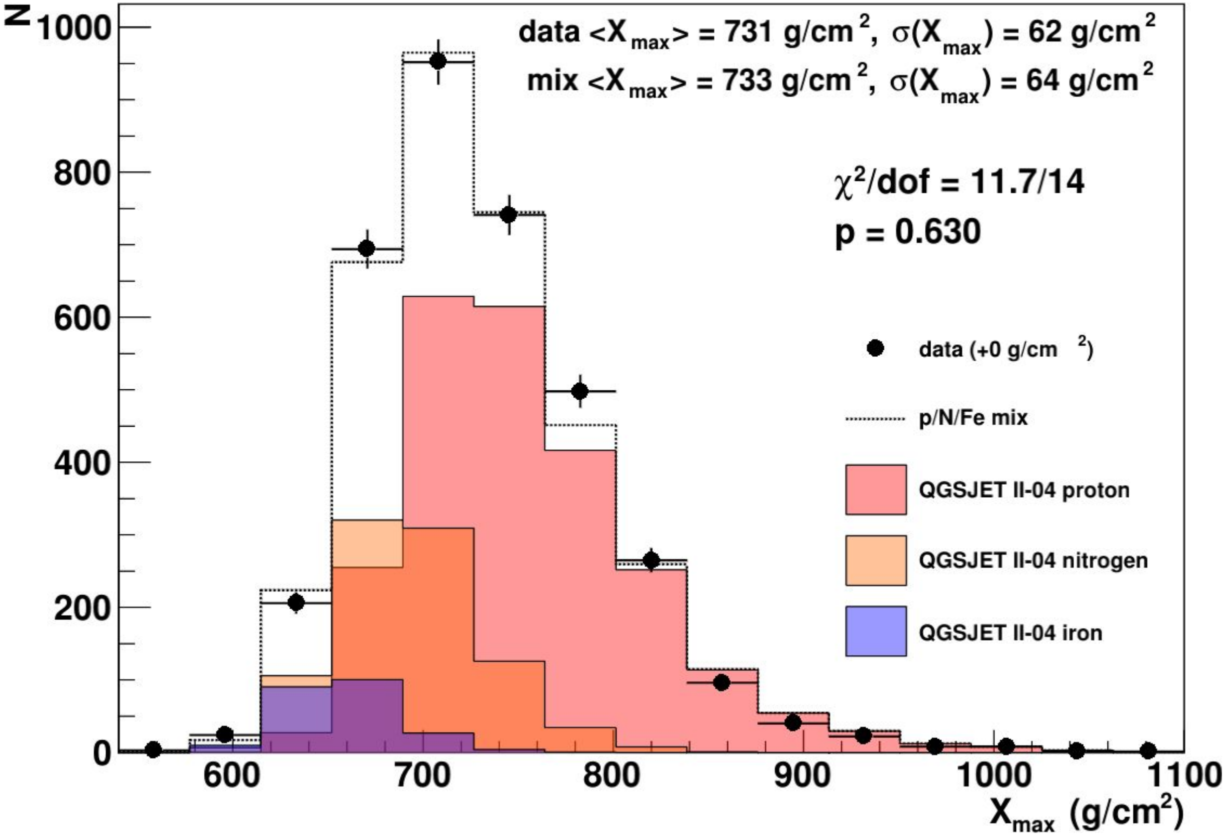
Fractions of QGSJET II-04 proton and iron found by fitting to 10 year TA hybrid X_{max} data (+15 g/cm^2 systematic shift applied to data).



f_{He} = 77.3 ± 1.5%
f_{Fe} = 22.7 ± 0.8%

QGSJET II-04 helium and iron mix fitted to 10 year TA hybrid X_{max} data with -15 g/cm^2 uniform shift.

QGSJET II-04 proton, nitrogen & iron mix

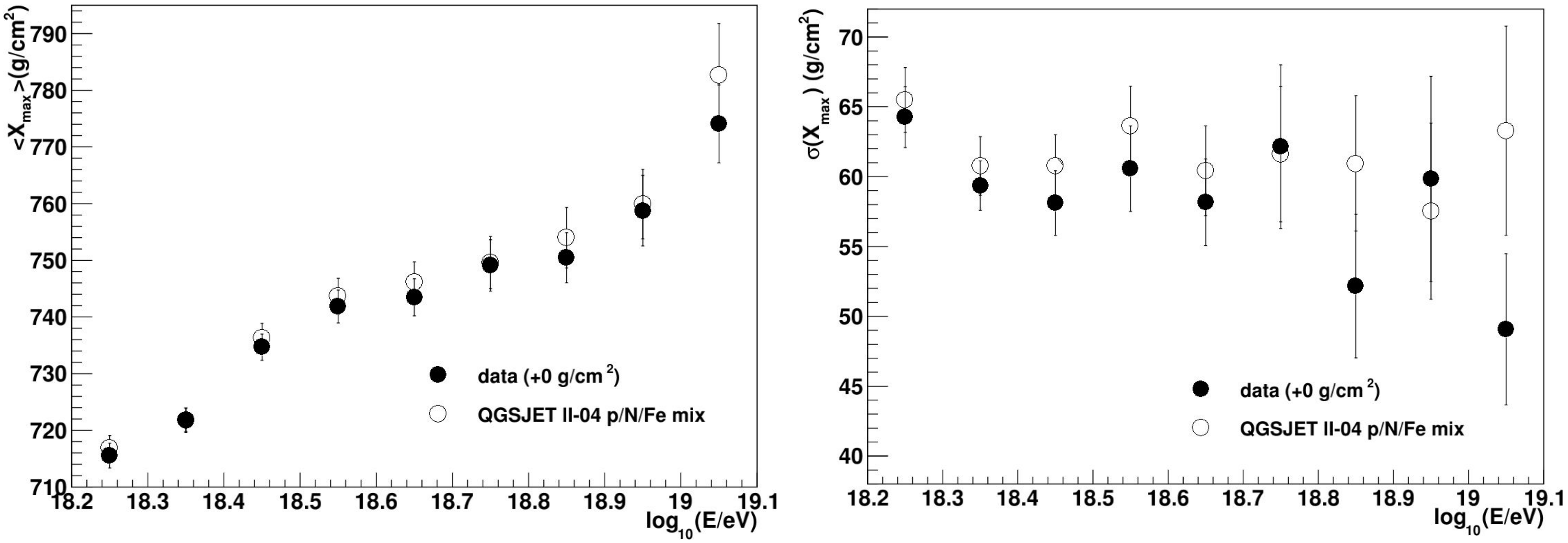


Three component mix: proton, nitrogen, and iron, aka light, medium, and heavy.

f_p = 67.9 ± 1.4%
f_N = 25.6 ± 0.8%
f_{Fe} = 6.5 ± 0.4%

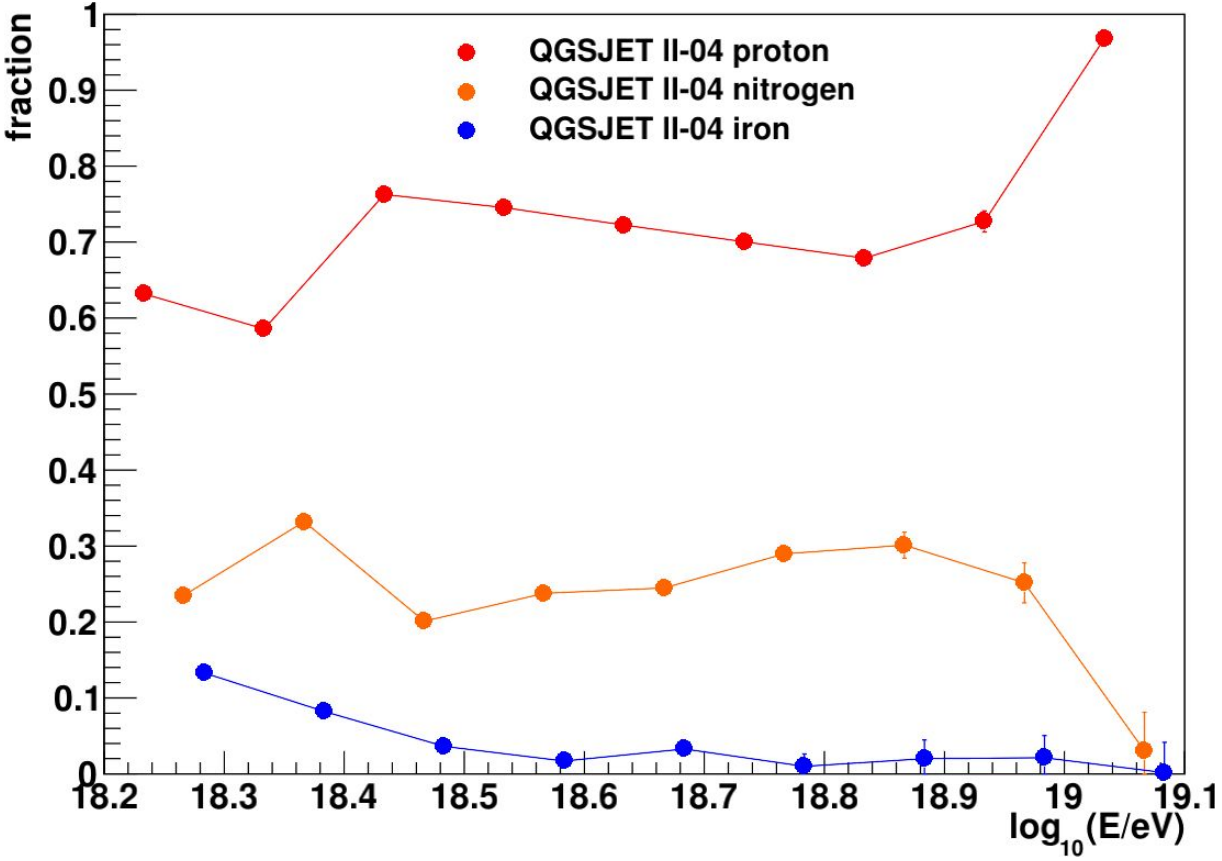
For the four component mix, helium represented 18% of the total content. When it is removed from fitting, ~10% of that is now attributed to protons and ~8% is attributed to nitrogen.

<X_{max}>, σ(X_{max}), and the distribution all compare well to the data.

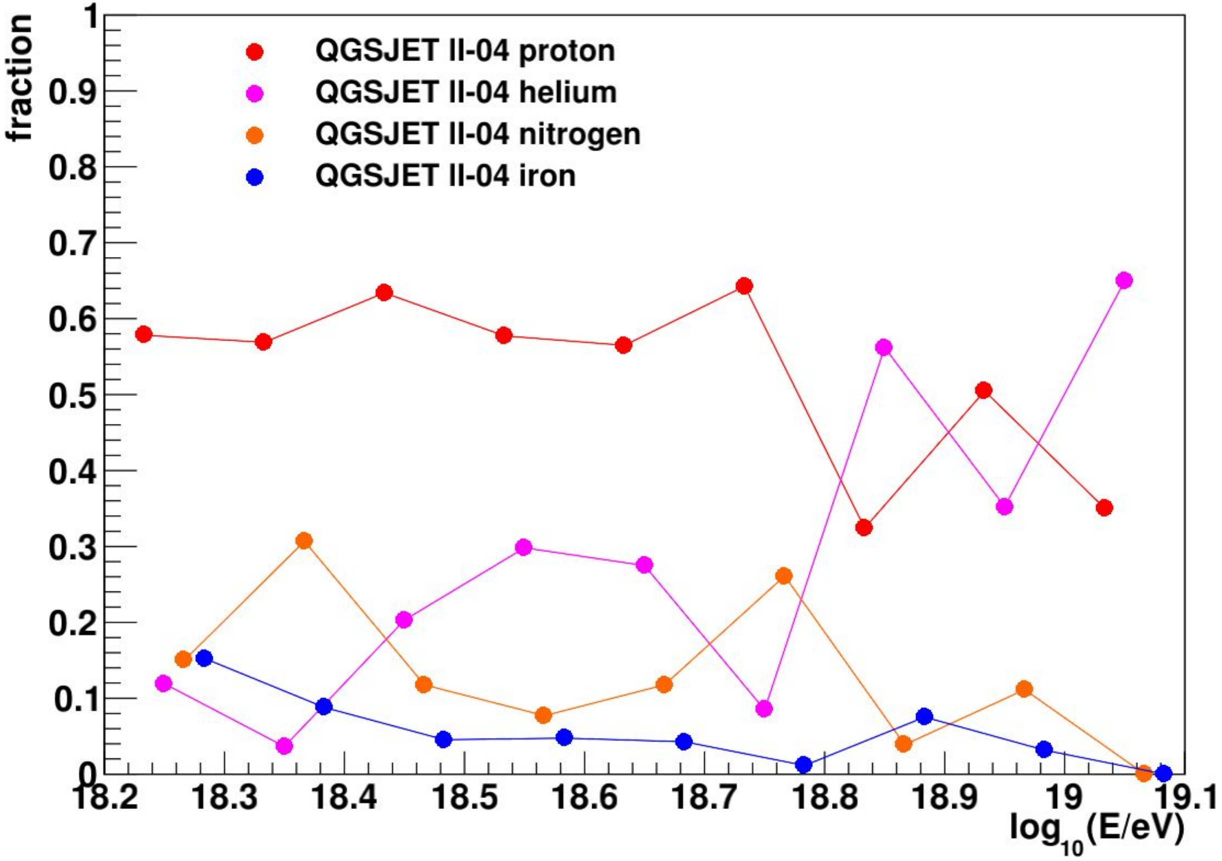


$<X_{max}>$ and $\sigma(X_{max})$ of QGSJET II-04 p/N/Fe mix with +0 g/cm^2 uniform shift applied to TA 10 year data

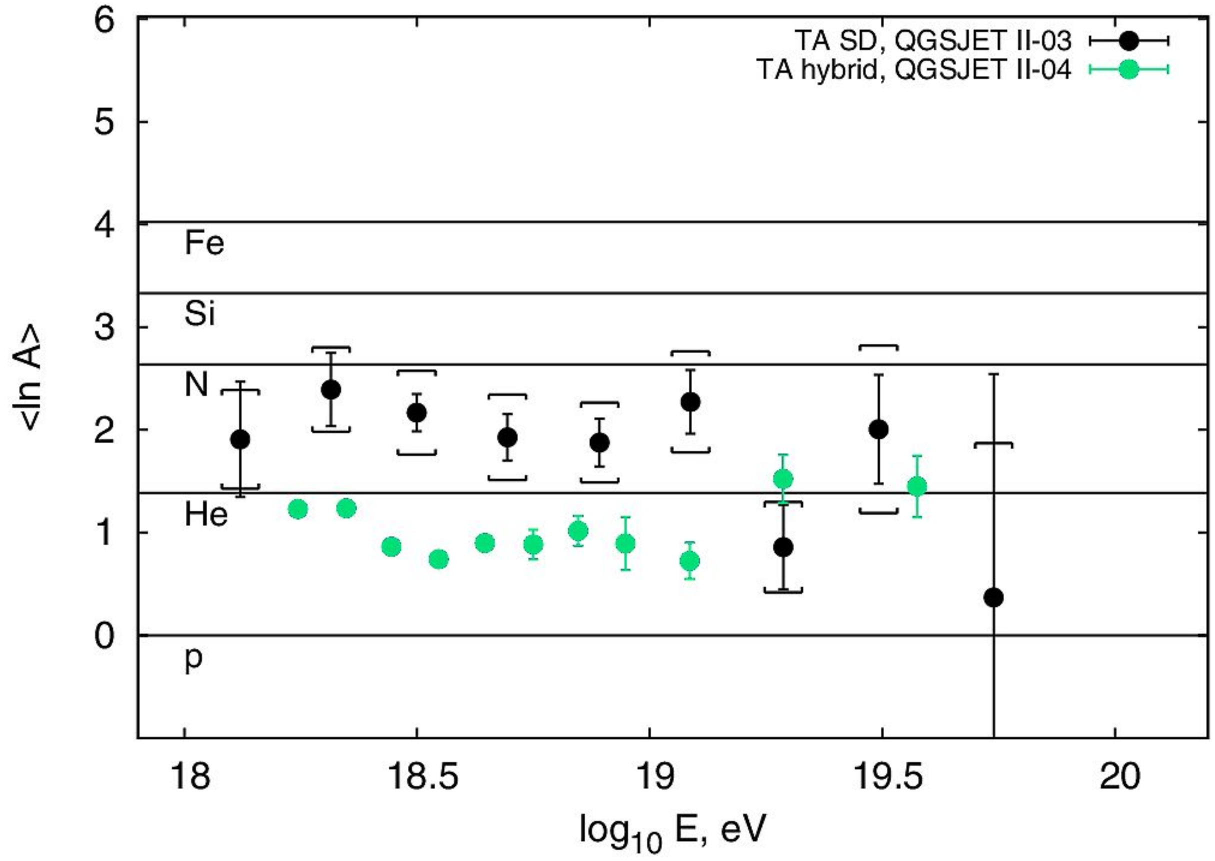
Bin by bin this three component mix, appears slightly narrower than the four component mix.



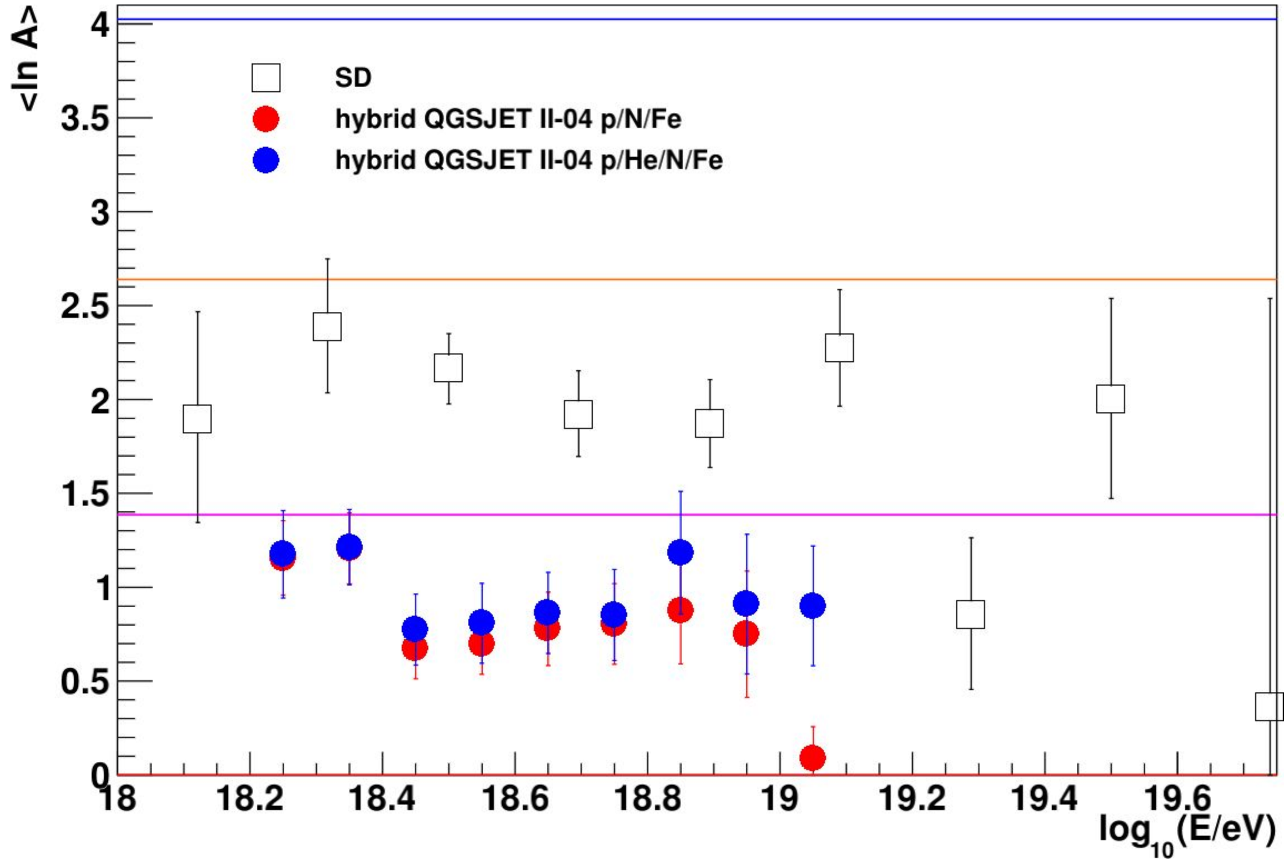
Fractions of QGSJET II-04 proton, nitrogen, and iron found by fitting to 10 year TA hybrid X_{max} data (no systematic shift applied to data).



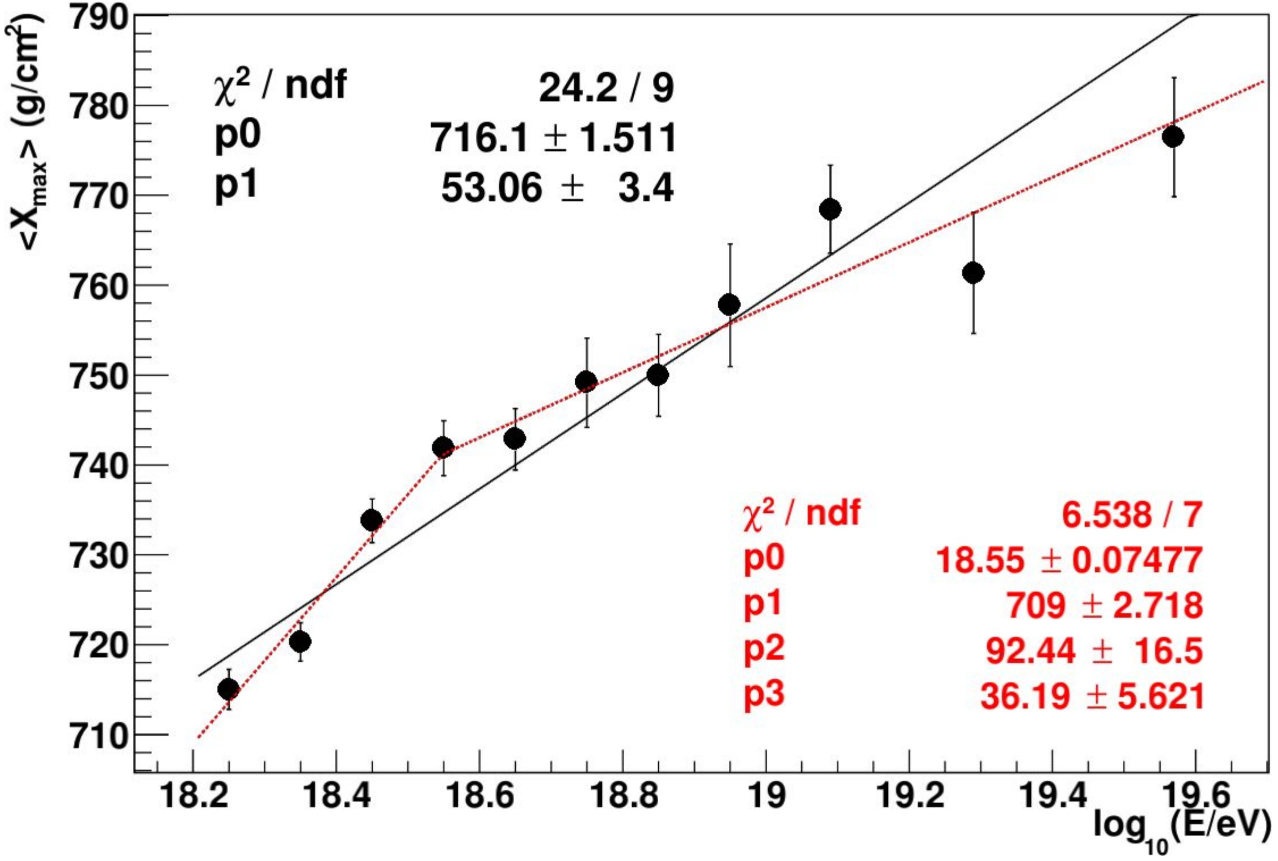
Fractions of QGSJET II-04 proton, helium, nitrogen, and iron found by fitting to 10 year TA hybrid X_{max} data (no systematic shift applied to data).



<ln *A*> measured using TA SD technique - Phys.Rev. D99 (2019) no.2, 022002



<ln *A*> measured using TA SD technique and predictions using hybrid models - three and four component



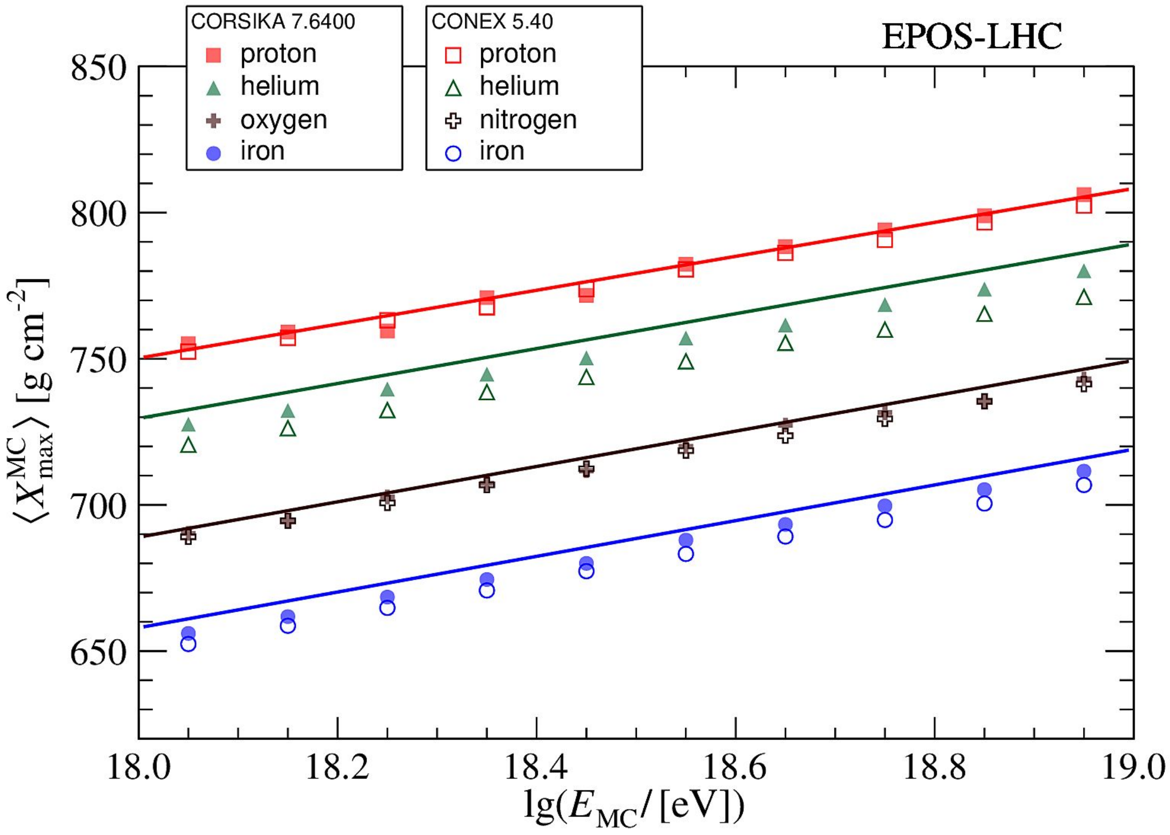
The breakpoint fit 95% c.l. critical χ^2 = 14.1.

Probability of observing $\chi^2 \geq$ 14.1 for the linear fit: 0.12

Significance of p = 0.12: 1.1 σ

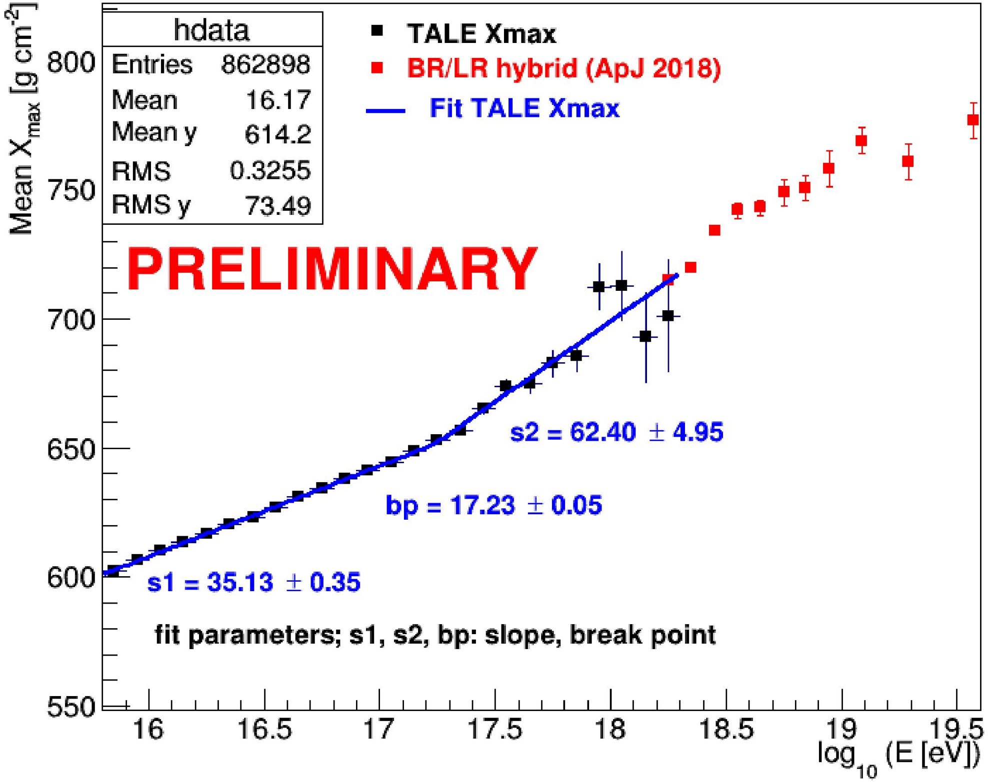
The significance of a break in the hybrid elongation rate is only 1.1 σ and well within our systematic uncertainty (± 17 g/cm^2).

Significance of a break in TA hybrid <X_{max}> full energy range elongation rate.



EPOS-LHC <X_{max}> of thrown elements for Auger (points) and TA (solid lines).

TALE Mean X_{max} vs energy



Low energy and high energy <X_{max}> between TALE and BR/LR hybrid analysis.

Systematic Sources of Uncertainty - <X_{max}>

Source (Independent)	$\Delta\langle X_{max}\rangle$ (g/cm^2)	Note
Detector	5.1	Relative timing between FD & SD (3.8 g/cm^2), telescope pointing direction (3.3 g/cm^2)
Atmosphere	6.8	Aerosol (3.4 g/cm^2), atmospheric depth (5.9 g/cm^2)
Fluorescence Yield	5.6	Difference between AIRFLY vs Kakimoto/FLASH
Sum	**10.2**	(Quadratic sum)

Source (Not independent)	$\Delta\langle X_{max}\rangle$ (g/cm^2)	Note
Detector	10.0	Difference between BR & LR
Reconstruction	4.1	Hanlon vs Ikeda analsys
Sum	**14.1**	(Linear Sum)

Total systematic uncertainty on $\langle X_{max}\rangle$: **17.4 g/cm^2** (energy independent)

Systematic Sources of Uncertainty - $\sigma(X_{max})$

Source (Independent)	$\Delta\sigma(X_{max})$ (g/cm^2)	Note
Detector	4.3	Relative timing between FD & SD (1.7 g/cm^2), telescope pointing direction (4.0 g/cm^2)
Atmosphere	20.3	Aerosol (18.9 g/cm^2), atmospheric depth (7.4 g/cm^2)
Fluorescence Yield	3.7	Difference between AIRFLY vs Kakimoto/FLASH
Sum	**21.1**	(Quadratic sum)

This systematic uncertainty is added/subtracted in quadrature with $\sigma(X_{max})$ observed in data.
For example, if $\sigma(X_{max})$ of data = 60 g/cm^2:
Upper: $\sqrt{(60^2 + 21.1^2)} - 60 = 3.6$ g/cm^2
Lower: $60 - \sqrt{(60^2 - 21.1^2)} = -3.8$ g/cm^2
$\sigma(X_{max})$ of data is quoted as 60 [+3.6, -3.8] g/cm^2
This is calculated for each energy bin.