The fractional analysis of mass composition measured by the Telescope Array FADC fluorescence detectors in hybrid mode

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MOTIVATION

Telescope Array (TA) and Pierre Auger Observatory (Auger), through their Joint Composition Working Group, are working to understand the composition of ultra-high energy cosmic rays (UHECRs). To compare results accounting for systematics, TA has been simulating Auger observations. This involves representing $X_{\max}$ distributions with fractions of different nuclear species (protons, helium, nitrogen, and iron) and using these in full detector simulations. This work presents the fitting TA's $X_{\max}$ distributions in order to determine similar fractions.

DATA

We use TA hybrid data from the Black Rock (BR) and Long Ridge (LR) fluorescence detectors taken through Nov. 2018[1] (10 years). This data has been used in previous TA compositions analyses and in TA & Auger working group comparisons.[2] Energy range: $10^{18.2}$ – $10^{19.4}$ eV. The template $X_{\max}$ distributions of single-species data as accepted and analyzed by TA, have been generated in the same way as in the works cited above, but using three different high-energy interaction models: QGSJetII-04, Sibyll 2.3d, and EPOS-LHC.

[1]Astrophys. J **858** (2018) 76.
[2]PoS(ICRC2023)249.

FITTING

To determine the UHECR composition, we used a Markov Chain Monte Carlo (MCMC) to fit the observed $X_{\max}$ distributions with fractions of different nuclear species. Initially, we considered four species (protons, helium, nitrogen, and iron), but due to strong anti-correlation between helium and nitrogen, leading to unstable results, we reduced the model to three species (protons, nitrogen, and iron) for a more reliable fit.

We used the `emcee`[3] implementation of an MCMC, with a likelihood calculated from the Poisson probability to observe n_i data events in an $X_{\max}$ bin with the expectation μ_i from the vector of fractions $\mathbf{f}$ of the templates.

$$\mathcal{L}(\mathbf{f}) = \prod_i \frac{\mu_i(\mathbf{f})^{n_i} e^{\mu_i(\mathbf{f})}}{n_i!}$$

The MCMC fit results are shown below in corner plots for the Sibyll 2.3d model. The other models have similar corner plots. Red lines indicate the fraction value for the maximum likelihood fraction fit, while blue lines indicate the range of fraction values within 1σ of the maximum. All three fractions are shown, although there are only two independent fractions. The upper-right corner contains the $X_{\max}$ distribution of the data compared to the best-fit result from the MCMC sampling.

[3]Pub. Ast. Soc. Pac. **125** (2013) 306.

Fractional Fit Results

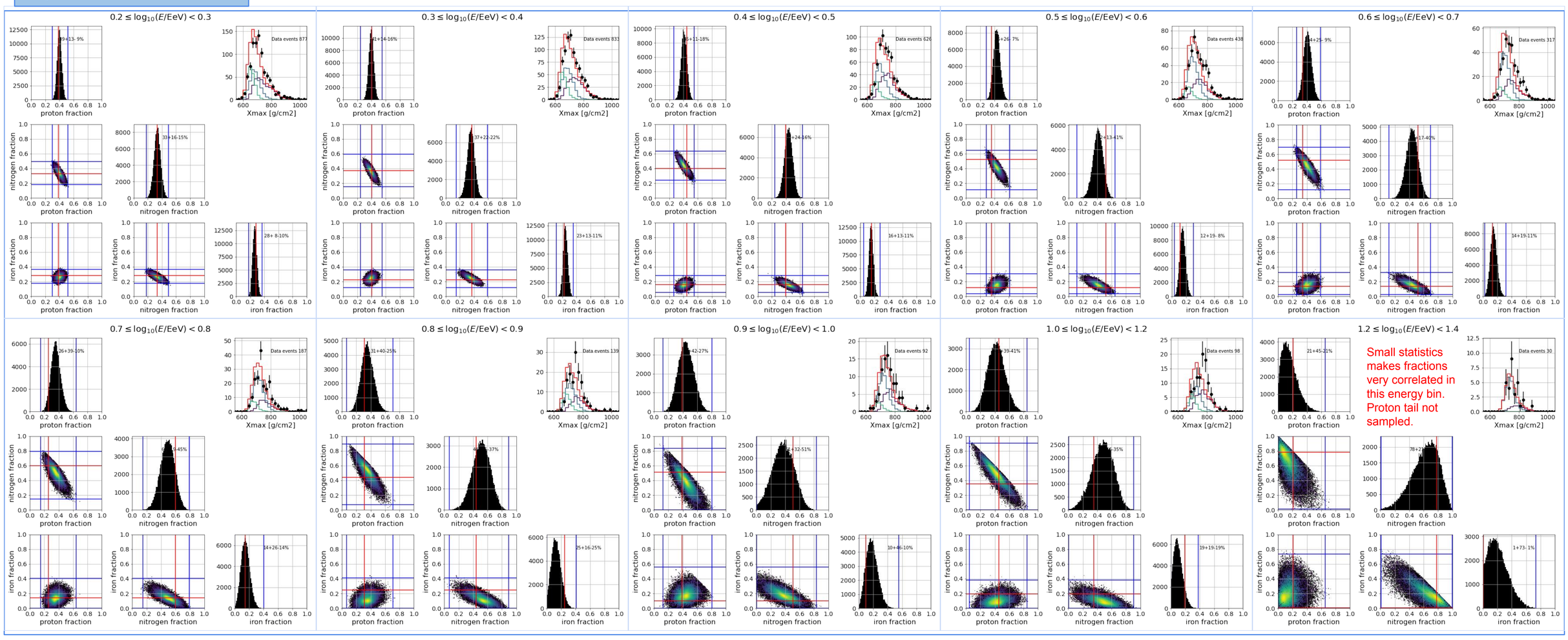
	QGSJetII-04			Sibyll 2.3d			EPOS-LHC		
$\log_{10}E$/EeV	proton	nitrogen	iron	proton	nitrogen	iron	proton	nitrogen	iron
0.2-0.3	56_{-4}^{+4}	33_{-7}^{+7}	11_{-3}^{+4}	40_{-3}^{+3}	34_{-5}^{+5}	26_{-3}^{+3}	50_{-3}^{+4}	21_{-5}^{+5}	29_{-3}^{+3}
0.3-0.4	52_{-4}^{+4}	45_{-6}^{+6}	3_{-3}^{+4}	40_{-3}^{+4}	36_{-5}^{+5}	24_{-3}^{+3}	55_{-3}^{+3}	16_{-5}^{+5}	29_{-3}^{+3}
0.4-0.5	68_{-5}^{+5}	30_{-7}^{+6}	2_{-2}^{+3}	41_{-4}^{+4}	44_{-6}^{+6}	15_{-3}^{+3}	58_{-4}^{+4}	27_{-5}^{+5}	15_{-3}^{+3}
0.5-0.6	69_{-4}^{+4}	31_{-5}^{+5}	0_{-0}^{+2}	43_{-5}^{+5}	42_{-7}^{+4}	15_{-4}^{+4}	58_{-4}^{+4}	23_{-6}^{+6}	20_{-3}^{+4}
0.6-0.7	70_{-5}^{+6}	26_{-7}^{+7}	4_{-3}^{+4}	41_{-6}^{+6}	45_{-8}^{+8}	15_{-4}^{+5}	52_{-5}^{+5}	29_{-7}^{+7}	19_{-4}^{+5}
0.7-0.8	57_{-7}^{+8}	43_{-13}^{+7}	0_{-0}^{+7}	36_{-7}^{+7}	50_{-10}^{+10}	14_{-6}^{+6}	49_{-7}^{+7}	31_{-10}^{+10}	20_{-6}^{+6}
0.8-0.9	62_{-8}^{+8}	38_{-9}^{+8}	0_{-0}^{+3}	35_{-9}^{+9}	54_{-13}^{+13}	12_{-7}^{+7}	46_{-8}^{+8}	38_{-12}^{+12}	15_{-6}^{+7}
0.9-1.0	63_{-10}^{+11}	37_{-17}^{+11}	1_{-1}^{+9}	44_{-11}^{+11}	40_{-16}^{+15}	16_{-8}^{+9}	57_{-11}^{+11}	26_{-15}^{+14}	18_{-7}^{+8}
1.0-1.2	83_{-10}^{+12}	17_{-17}^{+10}	0_{-0}^{+6}	40_{-12}^{+13}	52_{-17}^{+16}	8_{-6}^{+7}	67_{-10}^{+10}	16_{-14}^{+14}	17_{-7}^{+7}
1.2-1.4	37_{-16}^{+18}	63_{-18}^{+16}	0_{-0}^{+5}	9_{-8}^{+13}	78_{-23}^{+19}	13_{-13}^{+18}	20_{-12}^{+15}	56_{-21}^{+19}	25_{-12}^{+14}

Fractional Fit Results

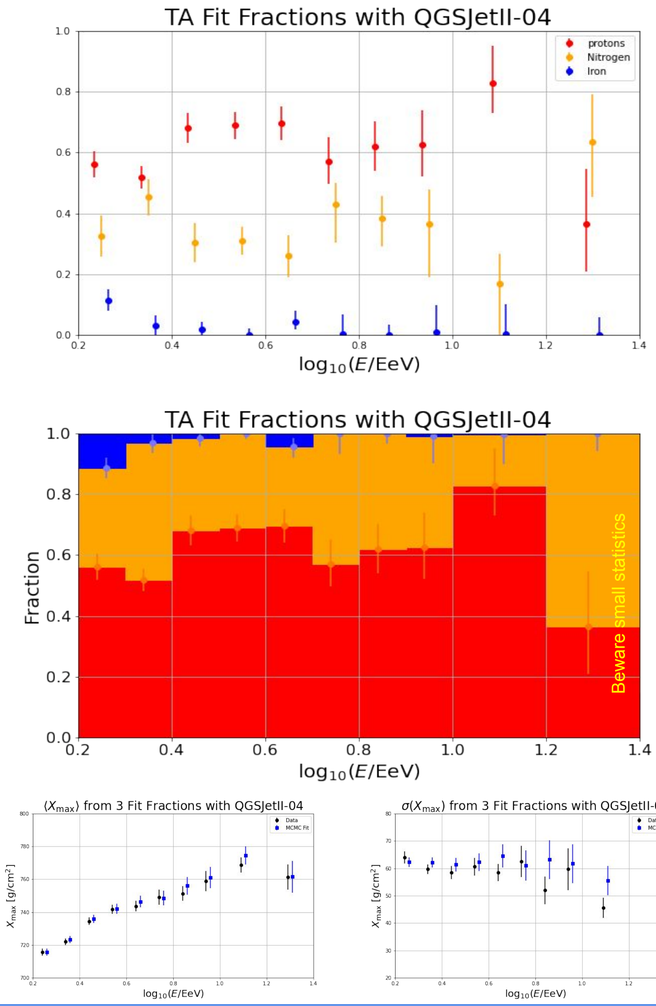
The best-fit fractions from MCMC with 1σ uncertainties are given in the table above as percentages. The fractions are plotted, in the figures below. In the stacked plots, proton fraction uncertainties are shown the bottom, iron fraction uncertainties on top.

The fit should reproduce the mean and RMS of the data Comparisons are shown below the stacked histograms. We don't display the RMS with less than 50 events, which precludes a comparison of the width in the $10^{1.2}$–$10^{1.4}$ EeV bin. We also don't show any fit results for energies above $10^{1.4}$ EeV due to data statistics.

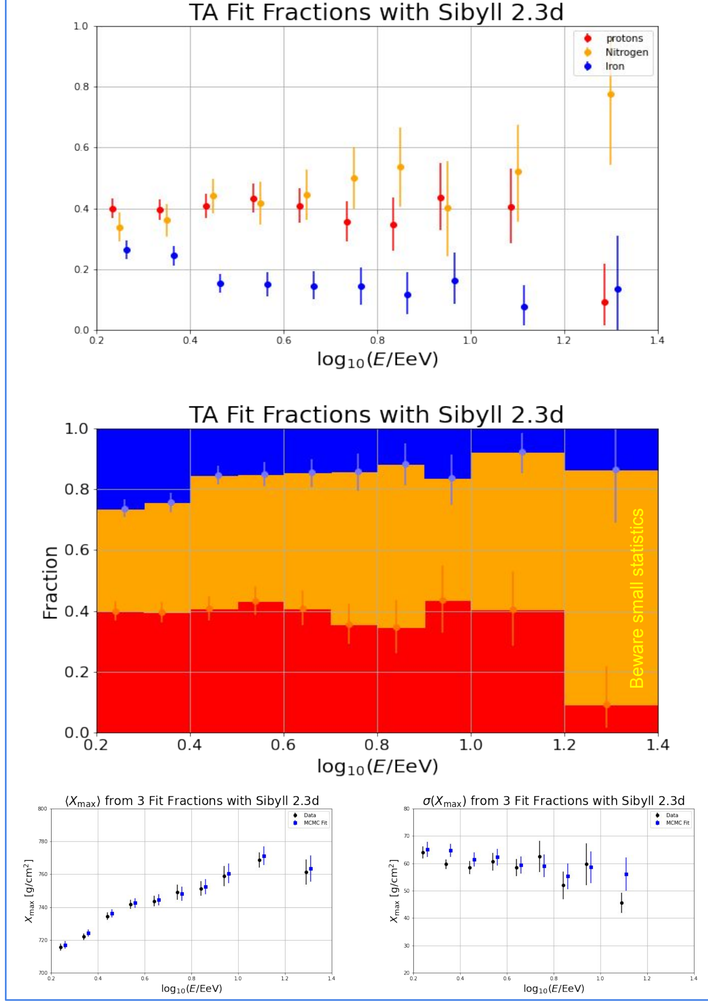
Sibyll 2.3d Fits, Corner Plots



QGSJetII-04 Fit Fractions



Sibyll 2.3d Fit Fractions



EPOS-LHC Fit Fractions