Primary composition of ultra-high-energy cosmic rays with the Telescope Array surface detector

G. Rubtsov, S. Troitsky for the Telescope Array Collaboration

18th Quarks $\begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_L$

Suzdal, June 7, 2014

Telescope Array Collaboration

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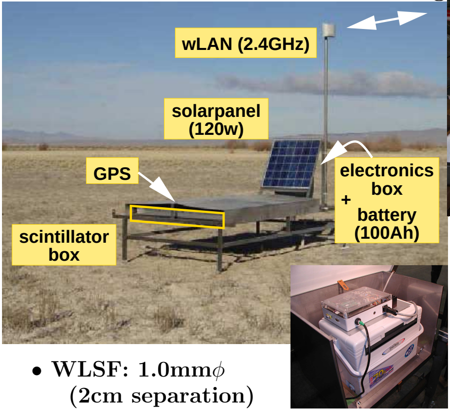
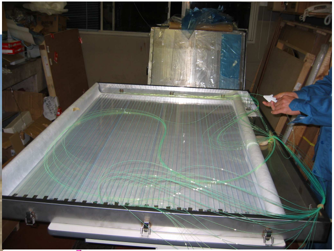
Belgium, Japan, Korea, Russia, USA

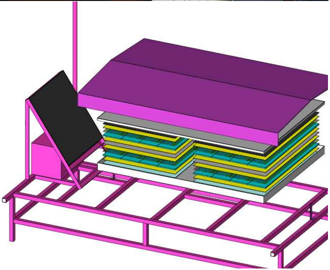
Telescope Array surface detector

< Surface Detector >

~200kg

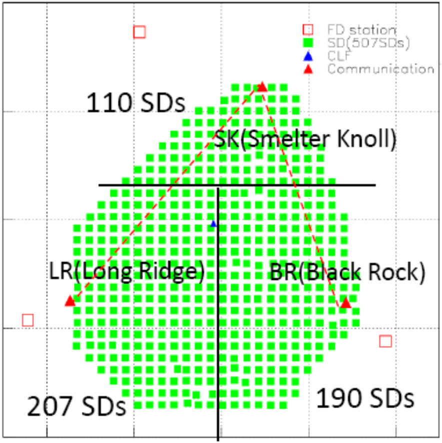






- WLSF: 1.0mmϕ (2cm separation)
- PMTs: ET 9123SA $\times$ 2
- 3m^2 (12mm $\times$ 2 layers)

Telescope Array surface detector



- 507 SD's, 3 m^2 each
- 680 km^2 area
- 6 years of operation

Largest UHECR statistics in the Northern Hemisphere

Outline

- **I. UHECR ($\gtrsim 10^{18}$ eV) composition overview**
- II. New method proposal
- III. Data set and results

Why primary composition is important?

- understand the physics of the sources
  - acceleration mechanism for bottom-up models
  - top-down: incompatible with heavy
- predict the flux of cosmogenic photons and neutrino
- probe the interaction cross-section at the highest energies
- precision tests of Lorentz-invariance

UHECR $\gtrsim 10^{18}$ eV composition measurements

Experiment	detector	Observable
HiRes	fluorescence stereo	X_{MAX}
Pierre Auger	fluorescence + SD (hybrid)	X_{MAX}
Telescope Array	stereo	X_{MAX}
Telescope Array	hybrid	X_{MAX}
Yakutsk	muon	$\rho_\mu(1000)$
Pierre Auger	SD	X^{μ}_{MAX}
Pierre Auger	SD	risetime asymmetry

SD – surface detector

X_{MAX} *– depth of the shower maximum*

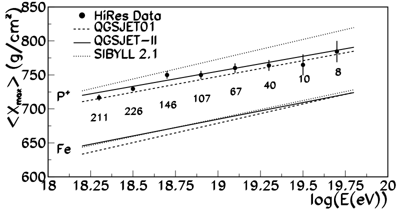
X^{μ}_{MAX} *– muon production depth*

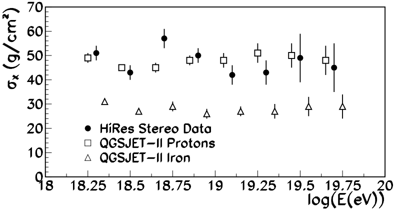
risetime – time from 10% to 50% for the total integrated signal

Composition from the depth of the shower maximum

HiRES

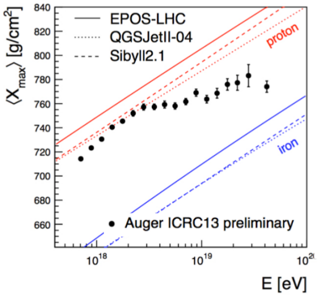
Phys.Rev.Lett.104.161101

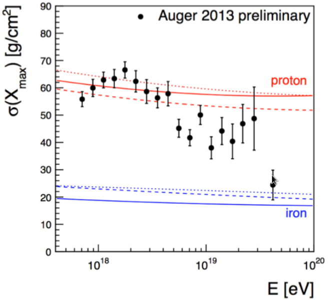




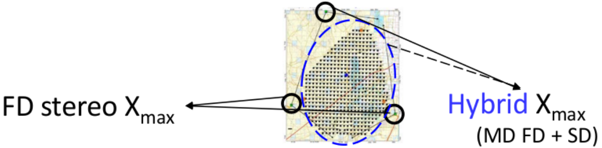
Auger

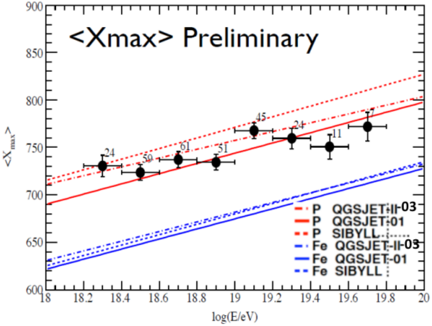
ICRC'2013; Phys.Rev.Lett.104.091101

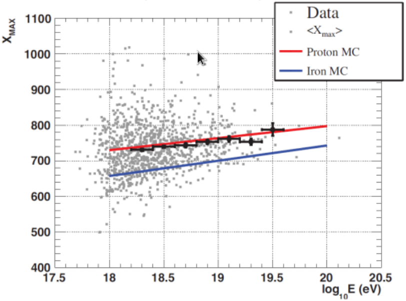




Telescope Array fluorescence stereo & hybrid

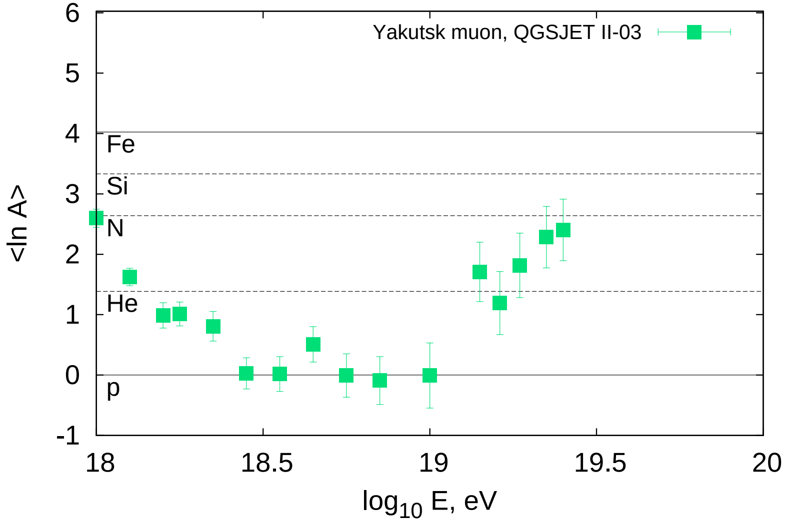






[Telescope Array] JPS'2014, ICRC'2013

Yakutsk array muon density

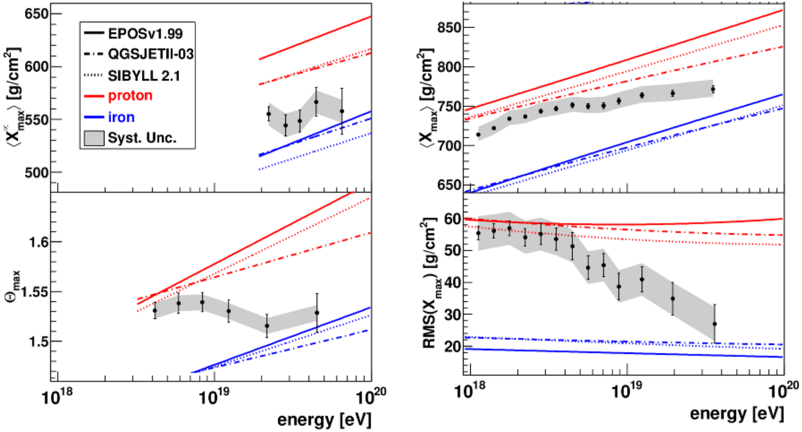


L.G. Dedenko et al., J.Phys.G 39 095202 (2012)

Auger SD composition

Two composition sensitive SD observables:

- muon production height
- asymmetry of risetime



[Auger] ICRC'11, arXiv:1107.4804

Arguments for light and heavy composition

light	**HEAVY**
Experiment:	
HiRes	Auger
TA	Yakutsk
Theory:	
nuclei abundance and survival in cosmic accelerators are questionable	nuclei are accelerated to higher energies than protons
$\sigma(X_{MAX})$ data indicate sharp composition change	density of sources; non-observation of clustering

Non-observation of clustering

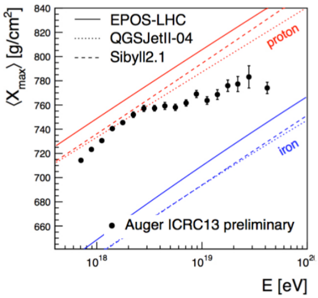
- If the highest energy events are protons, the nearest sources should identify themselves as bright spots of a few degree angular size (for $E \sim 10^{20}$ eV)
- No cosmic ray small scale clustering is observed. TA hotspot is of a larger size ($\sim 20^\circ$).

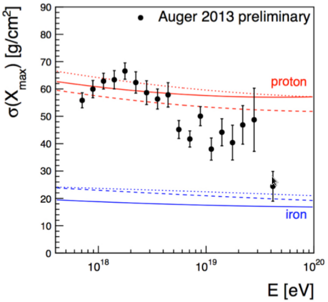
K.-H. Kampert,P. Tinyakov Comptes Rendus Physique, 15, 4, 2014

- In case of protons, non-observation of clustering at $E > 5 \times 10^{19}$ eV means that the density of sources is high, $\rho > 10^{-4}\,\mathrm{Mpc}^{-3}$
- Hard to explain large density of sources (not impossible)

Kalashev,Ptitsyna,Troitsky, Phys.Rev. D86 (2012) 063005

Sharp composition change





- Mixed composition has larger $\sigma(X_{MAX})$ than uniform. $\sigma(X_{MAX})$ is monotonic only if the change is very sharp: switch from p to He, then switch from He to N, etc.

  D. Hooper, A.M. Taylor Astropart.Phys. 33 (2010) 151-159

- Alternatively: the enhancement of cross-section at high energies will explain both X_{MAX} and $\sigma(X_{MAX})$ with protons

  R. Engel, 31th ICRC, arXiv:0906.0418v1

Outline

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Why surface detector?

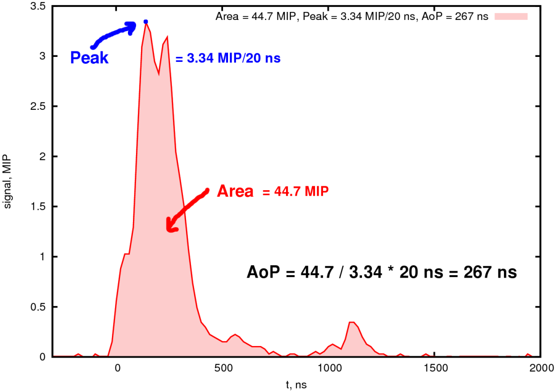
- Best separation power is achieved with X_{MAX}, but SD provides an independent technique which has different systematics.
- Cross-check of techniques possible for hybrid events.
- SD has $\sim$ 10 times larger duty cycle (important for highest energy range)

Composition analysis merit factor		
	X_{MAX}	SD
precision	☺	☹
duty cycle	☹	☺
systematics	☹	☹

- one needs new methods to improve precision and understand systematics

Area over peak - new SD observable

- Consider a surface station time-resolved signal



- Both peak and area are well-measured and not much affected by fluctuations

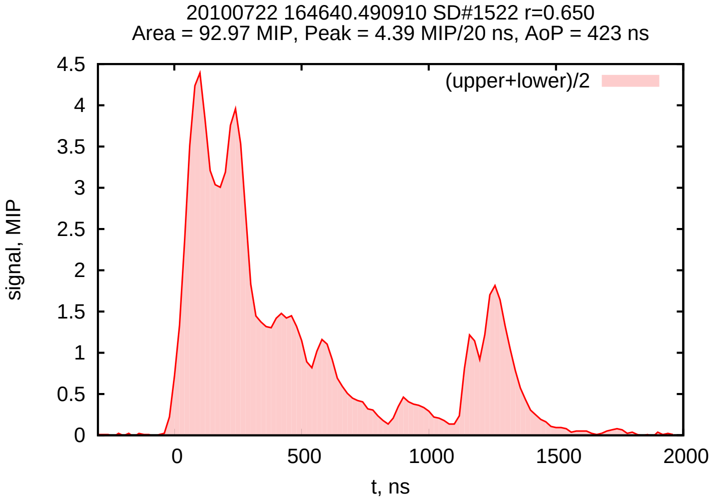
- First introduced by Auger in the context of neutrino search

Phys.Rev.Lett. 100 (2008) 211101

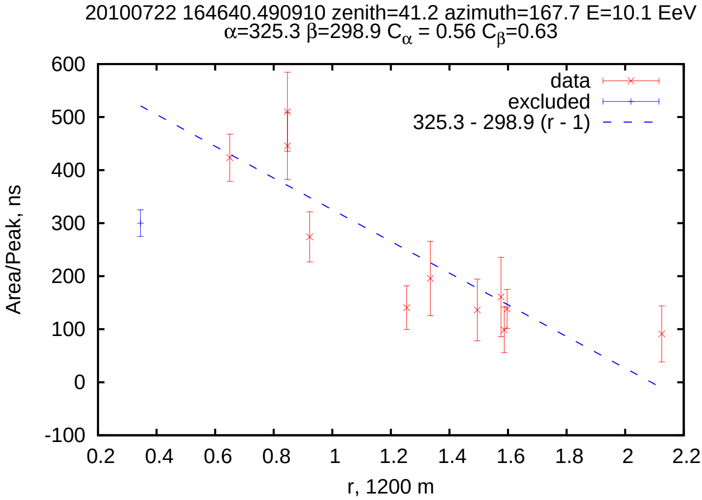
AoP for event

- We calculate AoP for each not-saturated detector with core distance $r > 600$ m
- We fit $AoP(r)$ with a linear fit:
  - $AoP(r) = \alpha - \beta(r/r_0 - 1.0)$
  - $r_0 = 1200\,\mathrm{m}$, α - value at 1200 m, β - slope
- Both α and β are sensitive to composition

AoP for one detector $SD\#1522$, $r = 780\,\mathrm{m}$



AoP fit for typical event



- We define the percentile ranks of α and β parameters for proton primaries $\mathcal{C}_\alpha$,$\mathcal{C}_\beta$:

$$\mathcal{C}^i_\alpha = \int_{-\infty}^{\alpha^i} f^i_{MC,p}(\alpha) d\alpha \,,$$

$$\mathcal{C}^i_\beta = \int_{-\infty}^{\beta^i} f^i_{MC,p}(\beta) d\beta \,,$$

  where $f^i_{MC,p}(\alpha)$ is an α distribution function for proton Monte-Carlo events compatible by zenith angle with the real event “i”.

  α_i, β_i - measured AoP and slope for event “i”.
- The values $\mathcal{C}^i_\alpha$ and $\mathcal{C}^i_\beta$ belong to [0,1] by definition.
- The transformation removes strong dependencies on zenith angle and energy and was successfully applied before for TA photon flux limits.

[TA] Phys.Rev. D88 (2013) 112005

Outline

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Data set

- Data collected by TA surface detector for the five years:
  2008-05-11 — 2013-05-04

Cuts:

1. quality cuts used for spectral analysis
2. $\theta < 45^\circ$
3. 7 or more detectors triggered
4. $E > 10^{18}$ eV

10733 events after cuts

Monte-Carlo set

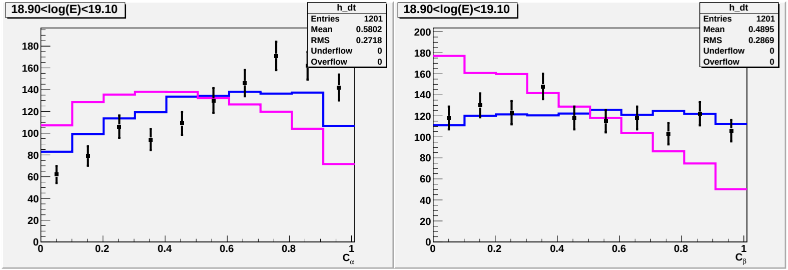
- CORSIKA with QGSJET-II-03, FLUKA and EGS4. Additional set with SIBYLL 2.1.
- Thinning with weight optimisation ($\varepsilon = 10^{-6}$)

  Kobal, Astropart.Phys.15:259,2001
- Dethinning technique is used

  Stokes et al, Astropart.Phys.35:759,2012
- Detector response is calculated with GEANT sampler
- Same reconstruction code with exactly same cuts is applied to both data and Monte-Carlo sets

Results

- The events are split by energy bins. For each bin $\mathcal{C}_\alpha$ and $\mathcal{C}_\beta$ histograms are produced. Below is an example for $10^{18.9} < E < 10^{19.1}$

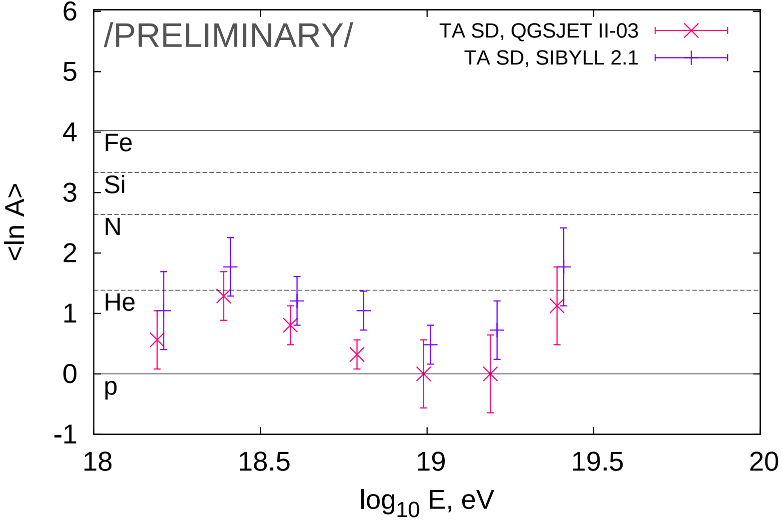


- We define a likelihood for a mixed composition:

$$\log \mathcal{L} = (1 - \frac{r}{2})(\log(p_{KS}(\mathcal{C}_\alpha) + \log(p_{KS}(\mathcal{C}_\beta)) \,,$$

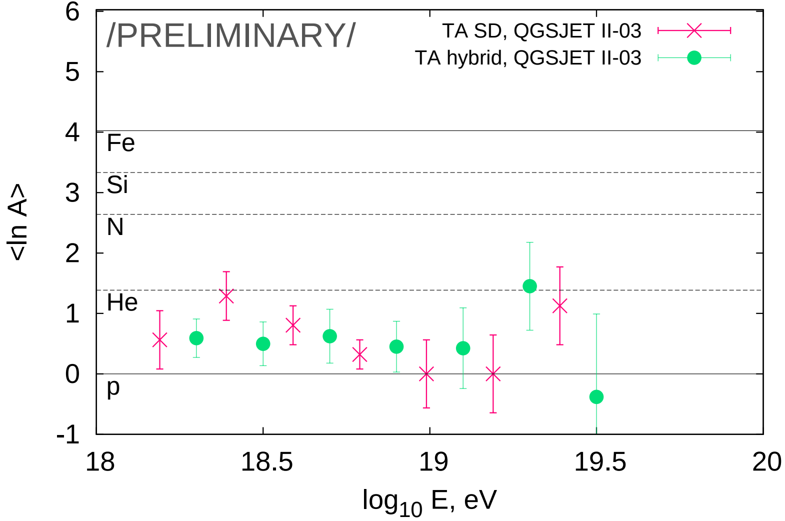
  where r is the correlation coefficient for $\mathcal{C}_\alpha$ and $\mathcal{C}_\beta$, p_{KS} – Kolmogorov-Smirnov test probability.
- confidence intervals obtained assuming a flat prior on $ln(A)$

Results: Telescope Array SD composition



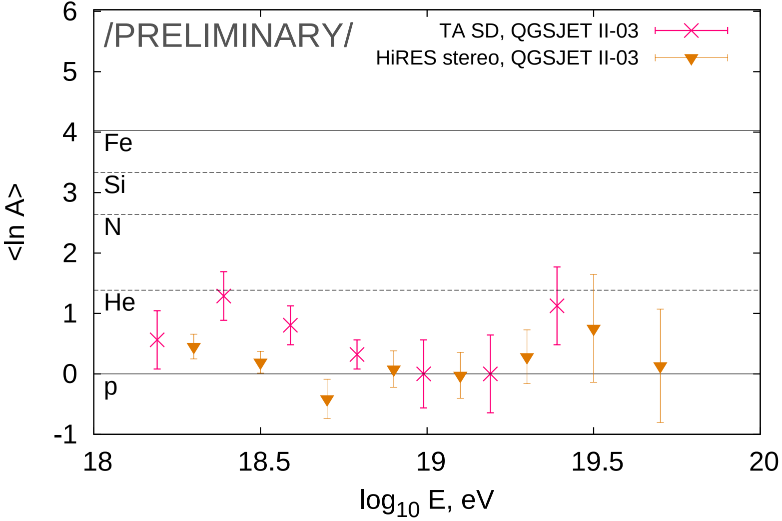
this talk; ICRC'13

Results comparison: TA SD vs TA hybrid



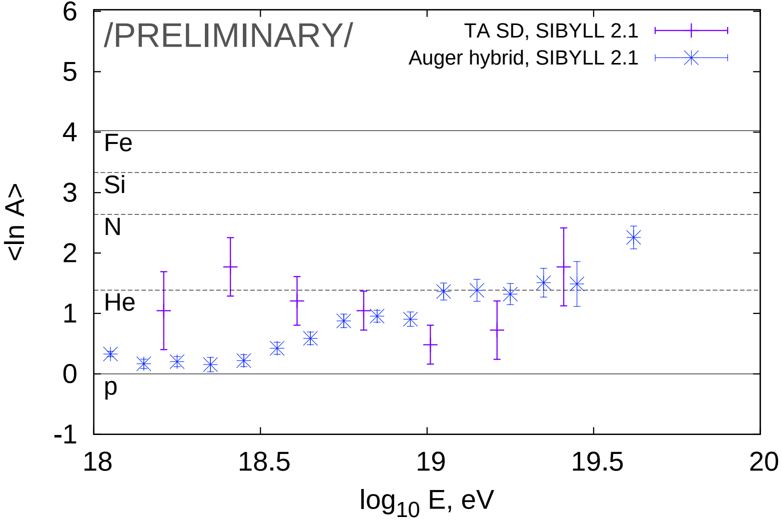
[TA] H.Sagawa, JPS'14

Results comparison: TA SD vs HiRes stereo



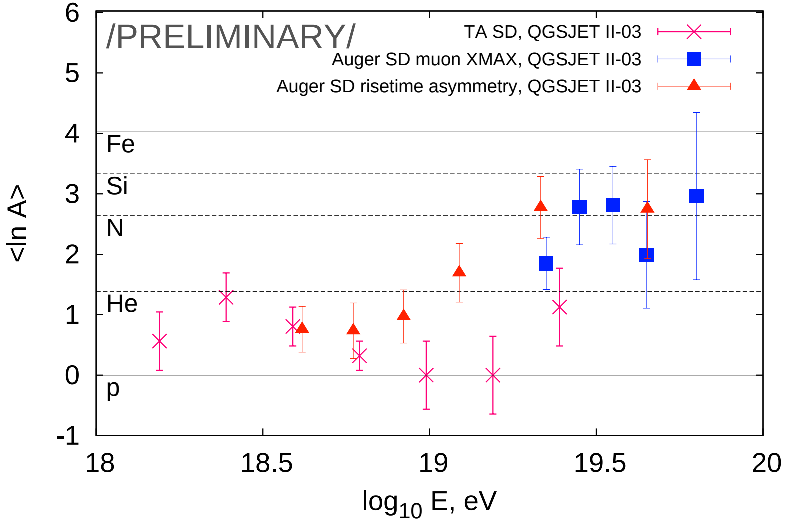
[HiRes] Phys.Rev.Lett.104.161101

Results comparison: TA SD vs Auger hybrid



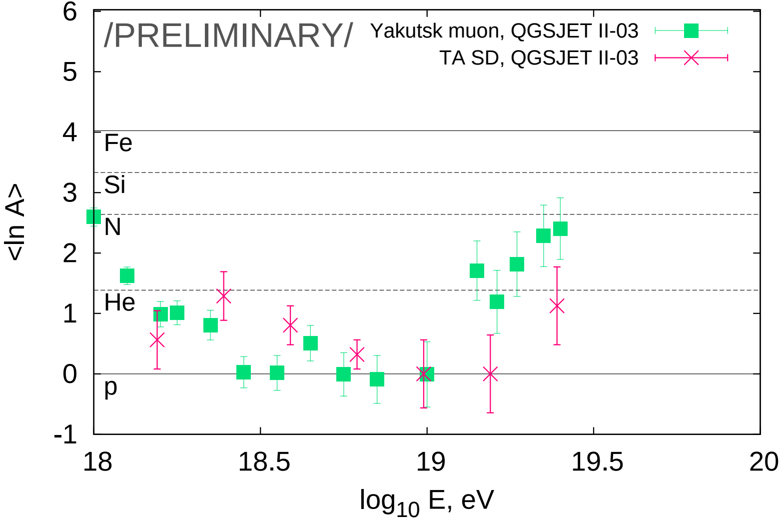
[Auger] ICRC'2013; Phys.Rev.Lett.104.091101

Results comparison: TA SD vs Auger SD



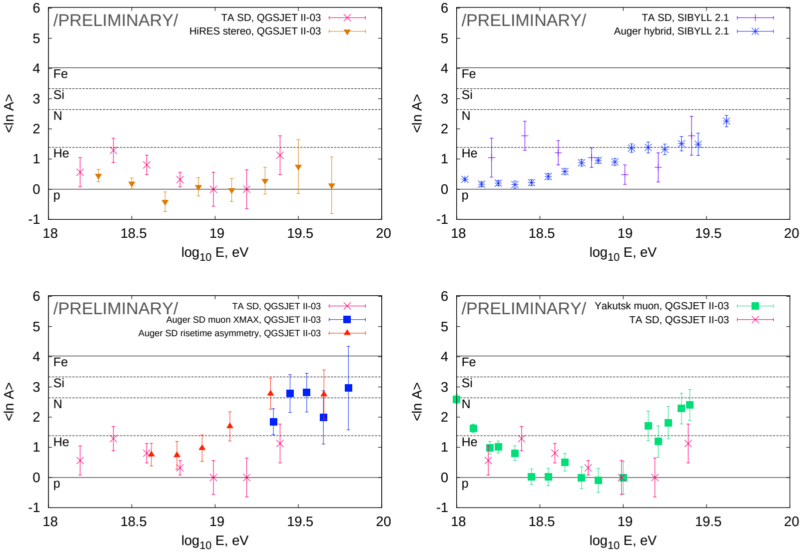
[Auger] ICRC'11, arXiv:1107.4804

Results comparison: TA SD vs Yakutsk



L.G. Dedenko et al., J.Phys.G 39 095202 (2012)

Summary: comparisons to other experiments



Conclusions and outlook

- A new method is proposed for UHECR composition analysis
- Method is applied to TA SD five-year data: first results are presented
- Preliminary composition is compatible with protons

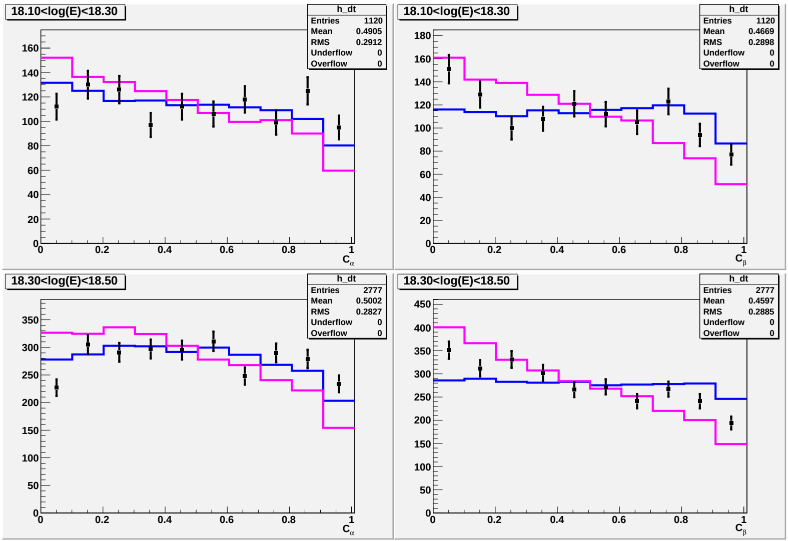
Plan:

- Cross-calibration with hybrid events
- Extend to lower energies with TALE SD data


Thank you!

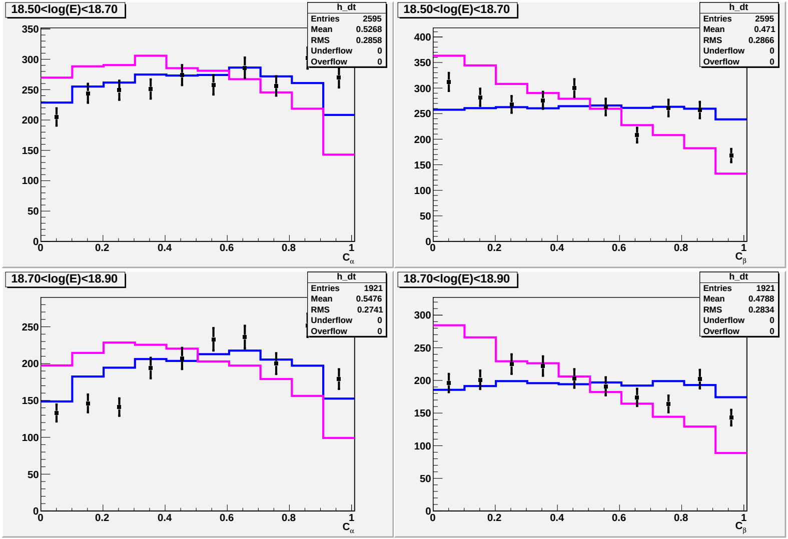
Backup slides

QGSJET-II-03



18.10<log(E)<18.30
h_dt
Entries 1120
Mean 0.4905
RMS 0.2912
Underflow 0
Overflow 0
C_α
18.10<log(E)<18.30
h_dt
Entries 1120
Mean 0.4669
RMS 0.2898
Underflow 0
Overflow 0
C_β
18.30<log(E)<18.50
h_dt
Entries 2777
Mean 0.5002
RMS 0.2827
Underflow 0
Overflow 0
C_α
18.30<log(E)<18.50
h_dt
Entries 2777
Mean 0.4597
RMS 0.2885
Underflow 0
Overflow 0
C_β

QGSJET-II-03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RMS 0.2858
Underflow 0
Overflow 0
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h_dt
Entries 2595
Mean 0.471
RMS 0.2866
Underflow 0
Overflow 0
C_β
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h_dt
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C_α
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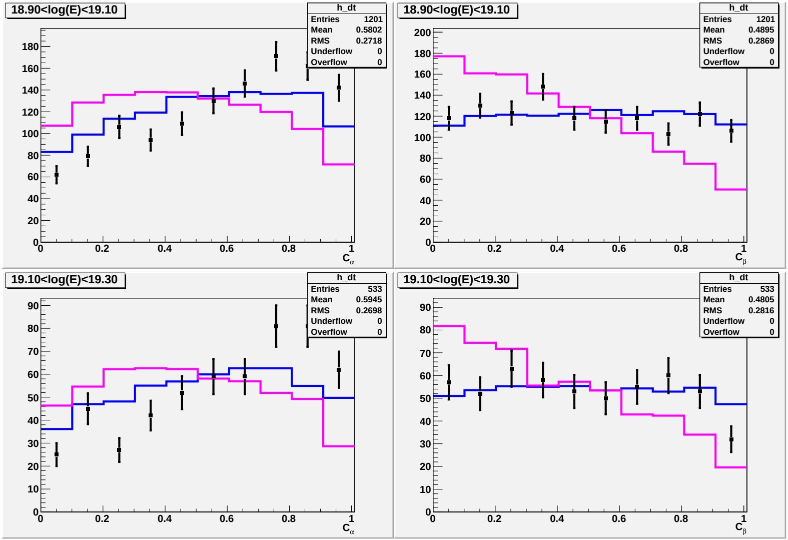
QGSJET-II-03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h_dt
Entries 1201
Mean 0.4895
RMS 0.2869
Underflow 0
Overflow 0
C_β
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RMS 0.2698
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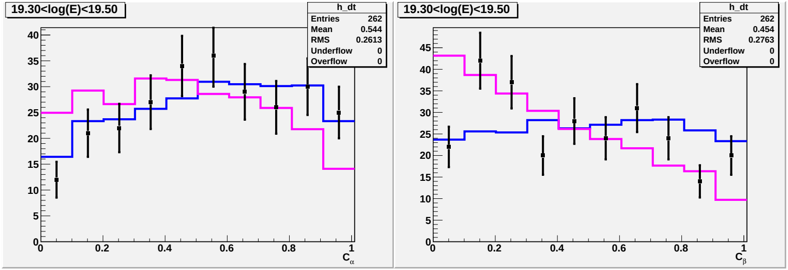
QGSJET-II-03



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RMS 0.2613
Underflow 0
Overflow 0
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20
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30
35
40
0
0.2
0.4
0.6
0.8
1
C_α
19.30<log(E)<19.50
h_dt
Entries 262
Mean 0.454
RMS 0.2763
Underflow 0
Overflow 0
0
5
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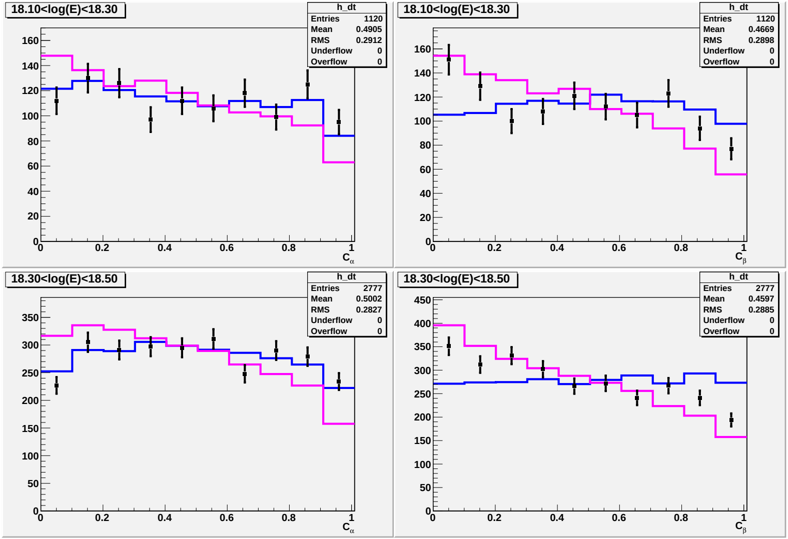
0.8
1
C_β

SIBYLL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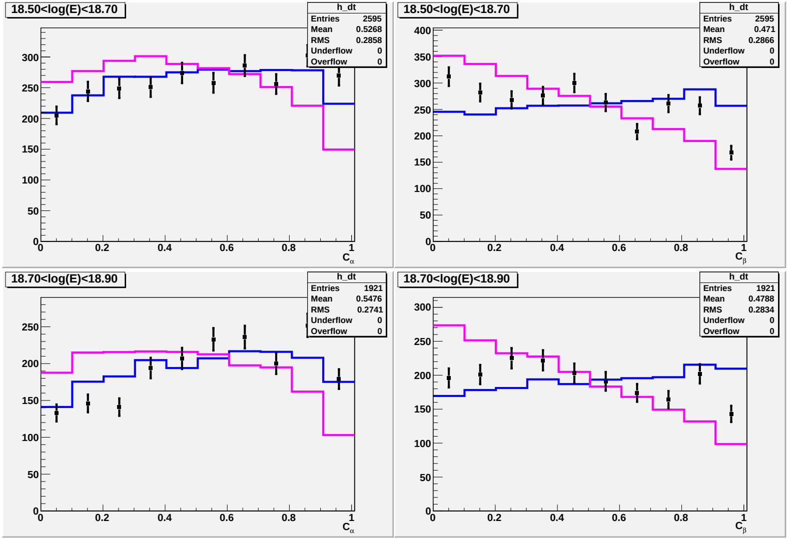
Mean 0.4597
RMS 0.2885
Underflow 0
Overflow 0
C_β

SIBYLL



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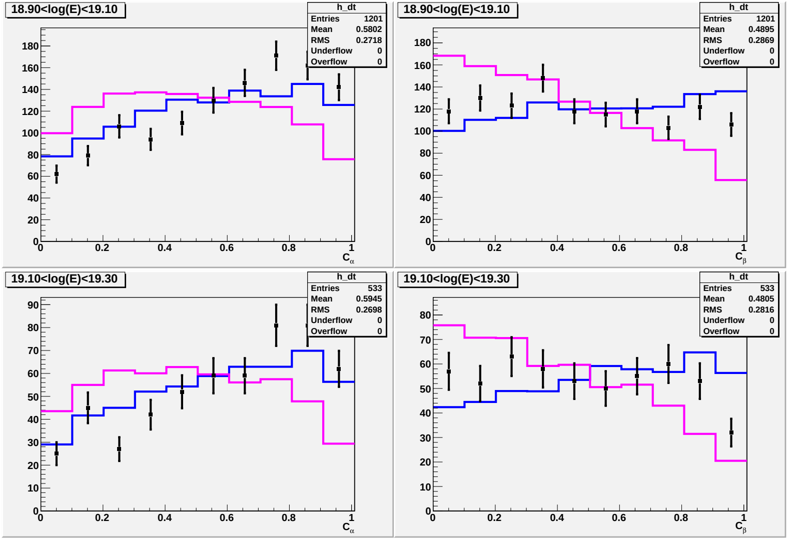
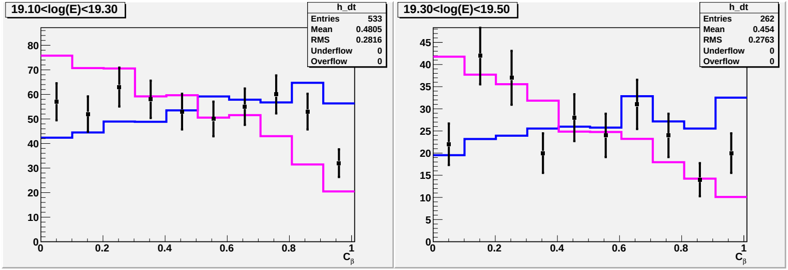
Overflow 0
C_α
18.50<log(E)<18.70
h_dt
Entries 2595
Mean 0.471
RMS 0.2866
Underflow 0
Overflow 0
C_β
18.70<log(E)<18.90
h_dt
Entries 1921
Mean 0.5476
RMS 0.2741
Underflow 0
Overflow 0
C_α
18.70<log(E)<18.90
h_dt
Entries 1921
Mean 0.4788
RMS 0.2834
Underflow 0
Overflow 0
C_β

SIBYLL



18.90<log(E)<19.10
h_dt
Entries 1201
Mean 0.5802
RMS 0.2718
Underflow 0
Overflow 0
C_α
18.90<log(E)<19.10
h_dt
Entries 1201
Mean 0.4895
RMS 0.2869
Underflow 0
Overflow 0
C_β
19.10<log(E)<19.30
h_dt
Entries 533
Mean 0.5945
RMS 0.2698
Underflow 0
Overflow 0
C_α
19.10<log(E)<19.30
h_dt
Entries 533
Mean 0.4805
RMS 0.2816
Underflow 0
Overflow 0
C_β

SIBYLL



19.10<log(E)<19.30
h_dt
Entries 533
Mean 0.4805
RMS 0.2816
Underflow 0
Overflow 0
C_β
19.30<log(E)<19.50
h_dt
Entries 262
Mean 0.454
RMS 0.2763
Underflow 0
Overflow 0
C_β