Statistical methods for cosmic ray composition analysis at the Telescope Array Observatory

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Telescope Array collaboration

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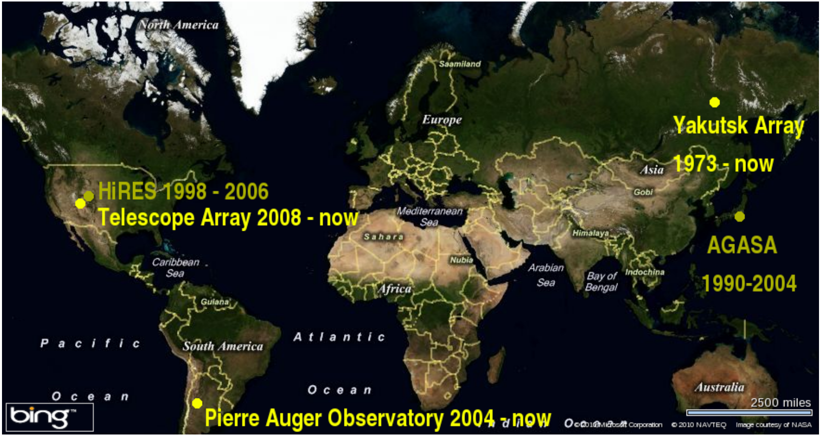
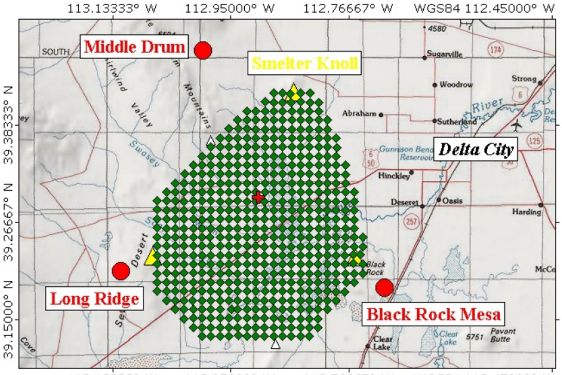
Belgium, Japan, Korea, Russia, USA

Ultra-high-energy cosmic ray experiments $E > 10^{18}$ eV



Telescope Array Observatory



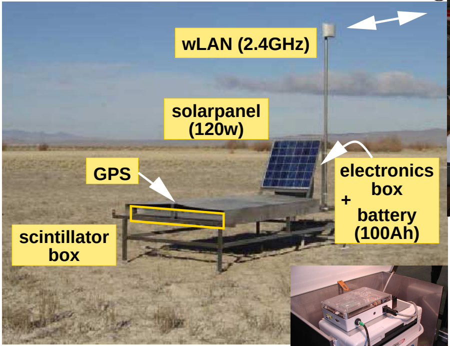
Largest UHECR statistics in the Northern Hemisphere

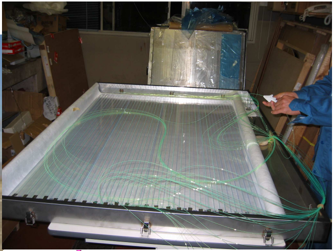
- Utah, 2 hrs drive from Salt Lake City
- 507 surface detectors, $S = 3m^2$, spacing 1.2 km
- 3 fluorescence detectors
- 6 years of operation

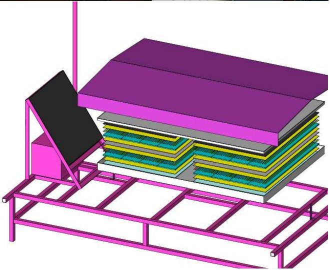
Telescope Array surface detector

< Surface Detector >

$\sim$200kg







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

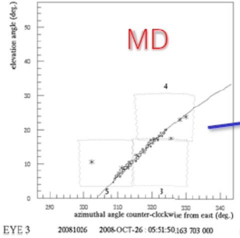
Telescope Array fluorescence detectors

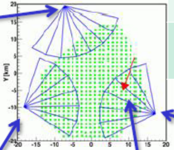
photo by Oleg Kalashev

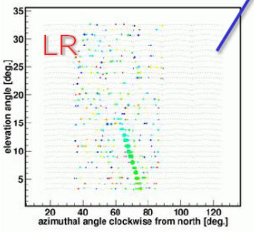
TA hybrid event example

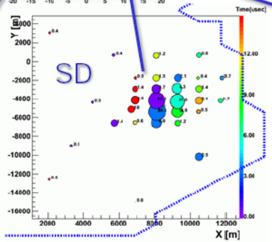
Triple FD Event (2008-10-26)

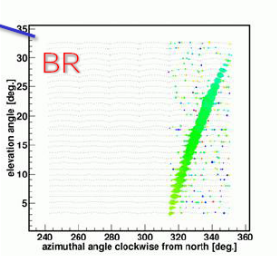
	θ[deg]	φ[deg]	X[km]	Y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88











Outline

- **I. Ultra-high-energy cosmic rays ($\gtrsim 10^{18}$ eV) composition overview**
- II. New method for composition study
- 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	ρ_μ
Pierre Auger	SD	X^{μ}_{MAX}
Pierre Auger	SD	risetime asymmetry

SD – surface detector

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

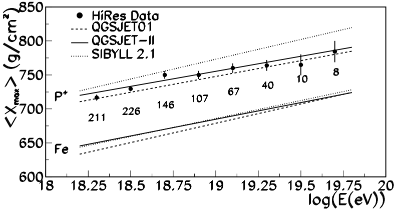
X^{μ}_{MAX} – *muon production depth*

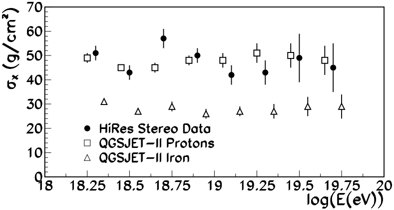
risetime – time from 10% to 50% for the total integrated signal

Composition from the depth of the shower maximum

HiRES

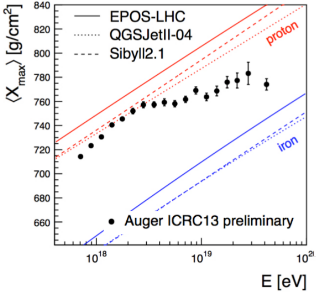
Phys.Rev.Lett.104.161101

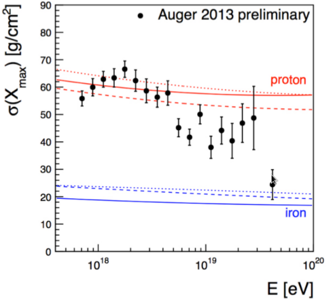




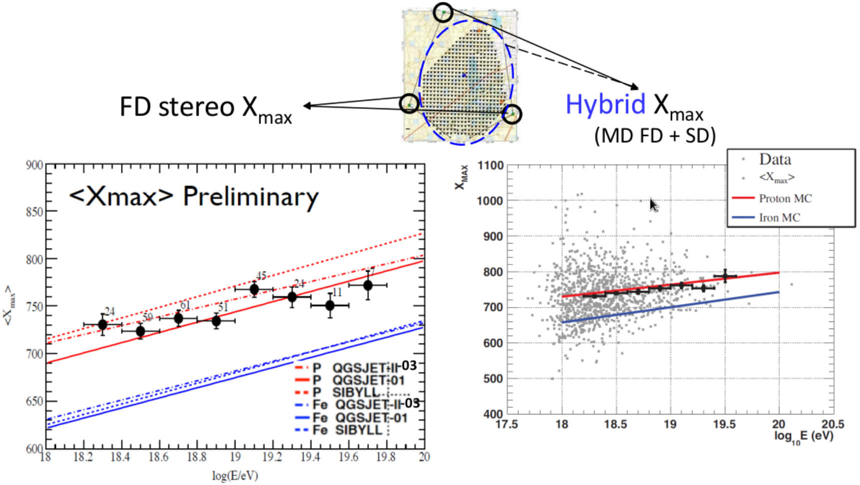
Auger

ICRC'2013; Phys.Rev.Lett.104.091101



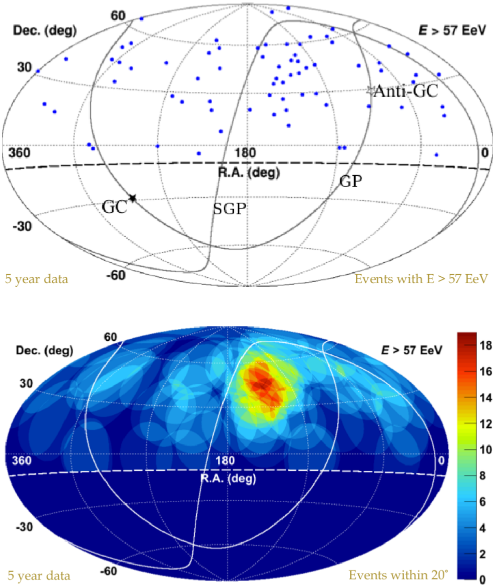


Telescope Array fluorescence stereo & hybrid



[Telescope Array] JPS'2014, ICRC'2013

TA hotspot, $E > 5.7 \times 10^{19}$ eV



TA, ApJ 790 L21 (2014)

- hotspot may be indication of the nearest source

- in this case: size represents deflection in extragalactic and galactic magnetic fields

- composition is important to understand the whole picture

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- **II. New method for composition study**
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Method outline

1. Reconstruct every event, get values of composition-sensitive observables

2. Transform the observables

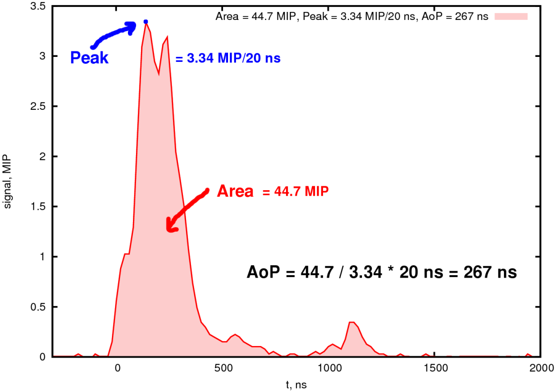
3. Multivariate analysis: $(\mathcal{C}^i_\alpha, \mathcal{C}^i_\beta, \theta^i) \rightarrow \xi^i$

4. Compare distribution of ξ with Monte-Carlo

5. Result: average atomic mass $< \log A >$ as a function of energy.

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

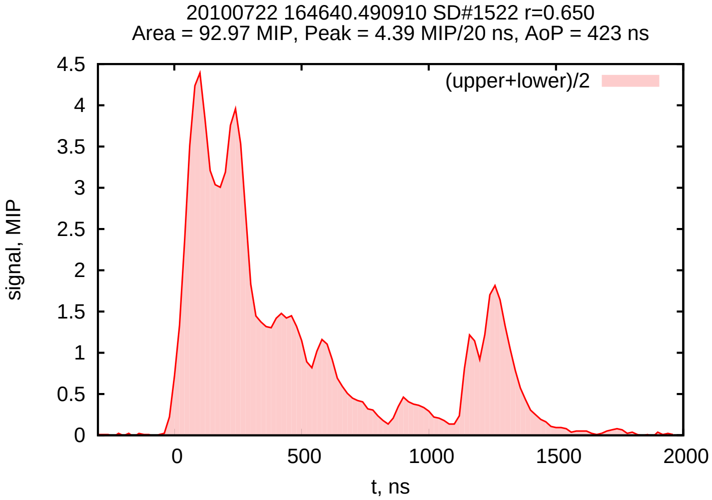
- First introduced by Auger in the context of neutrino search

Phys.Rev.Lett. 100 (2008) 211101

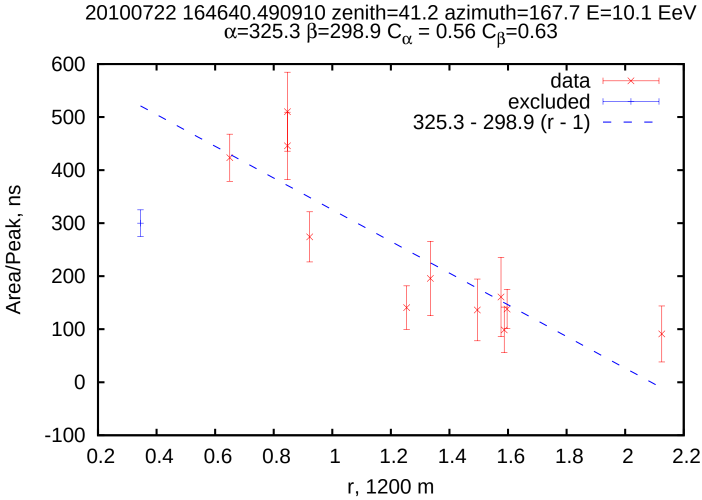
AoP for event

- We calculate AoP for each not-saturated detector with core distance $r > 600$ m
- We fit $AoP(r)$ with a linear fit:
  - $AoP(r) = \alpha - \beta(r/r_0 - 1.0)$
  - $r_0 = 1200\,\text{m}$, 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



Data preparation

- For each event we reconstruct α, β, zenith angle θ and energy *E*
- α and β depend strongly on θ and *E*
- The dependence is nonlinear and may not be resolved with simple techniques
- We propose a transformation which remove a significant part of this dependence $(\alpha, \beta) \to (\mathcal{C}_\alpha, \mathcal{C}_\beta)$

Observable transformation

- 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 was introduced and successfully applied for TA photon flux limits.

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

MVA analysis

Method:

- Boosted decision trees (TBDT in root)
- Independent MVA forest is constructed for each energy bin, $\Delta \log E = 0.2$

Variables:

- $\mathcal{C}_\alpha^i$
- $\mathcal{C}_\beta^i$
- θ^i

Training:

- Background: proton MC
- Signal: iron MC

Note. MVA technique is used by Pierre Auger for photon search

Auger, arXiv:1406.2912, ApJ

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Data set

- Data collected by TA surface detector:
  2008-05-11 — 2013-07-13

Cuts:

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

10242 events after cuts

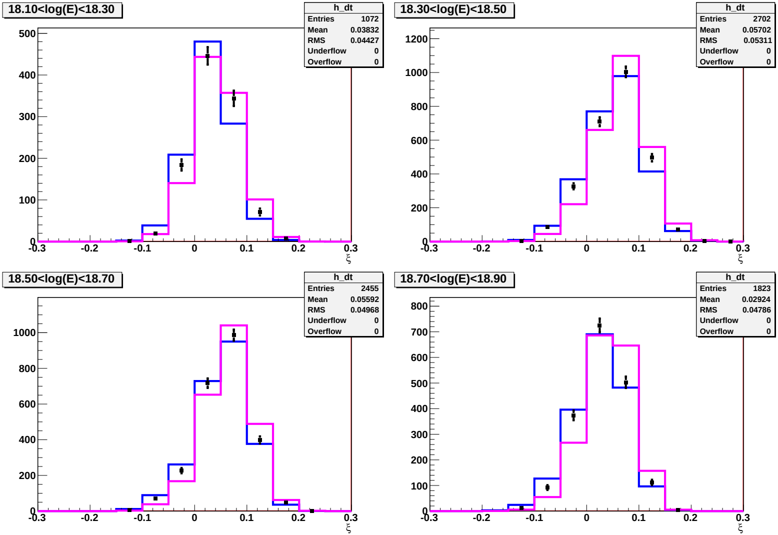
Monte-Carlo set

- 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

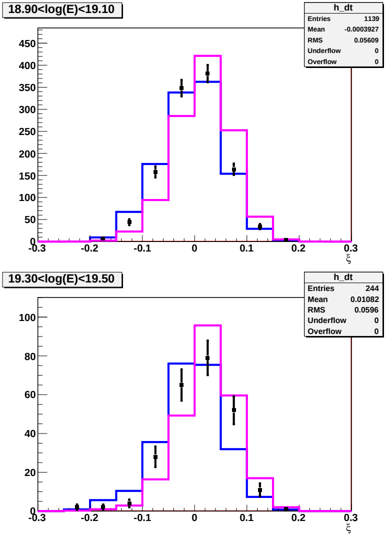
  Stokes et al, Astropart.Phys.35:759,2012
- Detector response is calculated with GEANT sampler
- Same reconstruction code with exactly same cuts is applied to both data and Monte-Carlo sets

Distribution of MVA estimator ξ



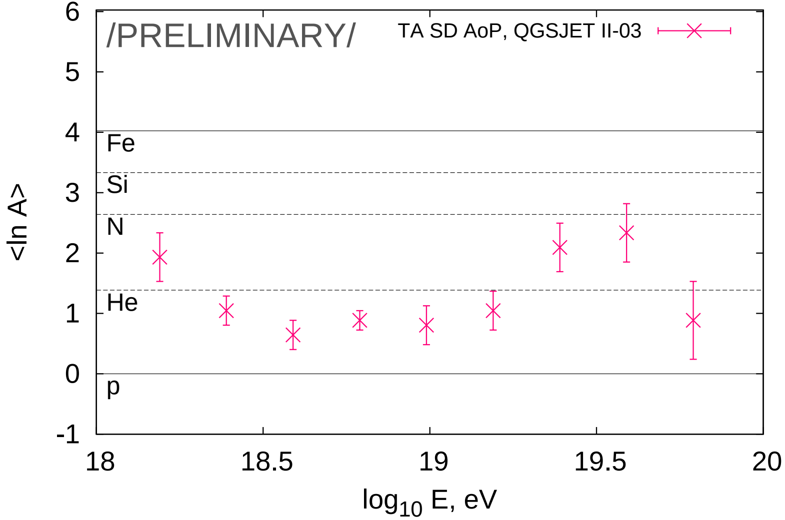
proton, iron

Distribution of MVA estimator ξ

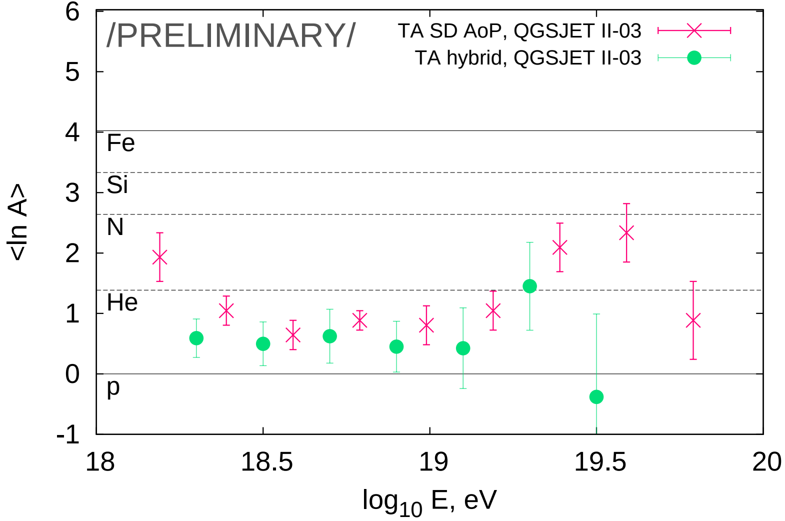


proton, iron

Results: Telescope Array SD (MVA) composition

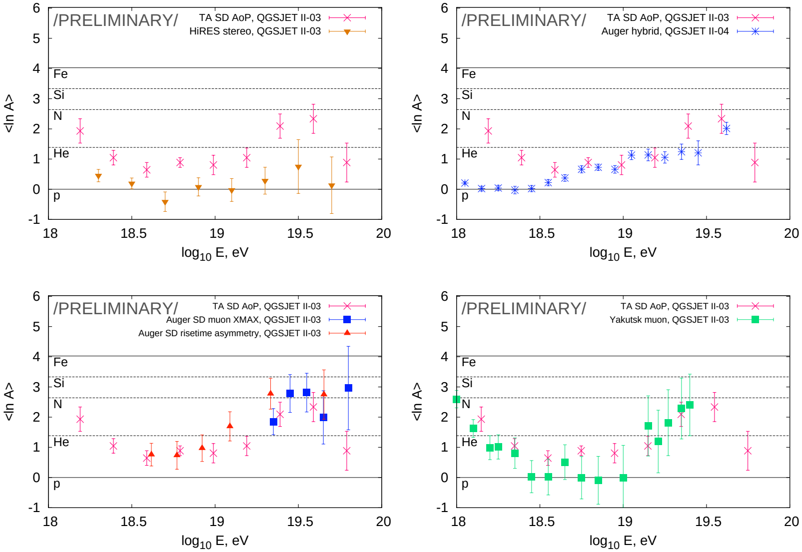


Results comparison: TA SD (MVA) vs TA hybrid



[TA] H.Sagawa, JPS'14

MVA result compared to other experiments



Conclusions

- A new method is proposed for UHECR composition analysis
- TA SD five-year composition is presented
- Further sensitivity improvement is required to discriminate between mono and mixed composition

Plan:

- Evolution of method: include additional composition sensitive observables
- Evolution of observatory: array extension TAx4

Thank you for attention!

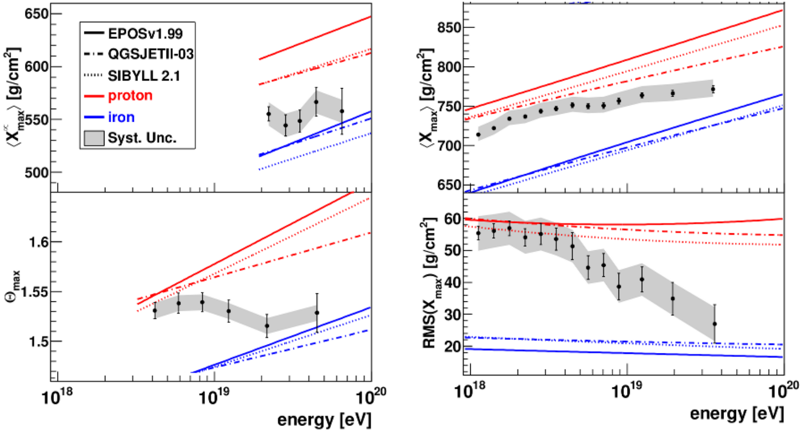
Backup slides

Auger SD composition

Two composition sensitive SD observables:

- muon production height

- asymmetry of risetime



[Auger] ICRC'11, arXiv:1107.4804