Extensive air showers measured parameters and the possibility of obtaining mass composition

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Introduction

Mass composition of ultra-high energy cosmic rays is very important for the search of their origins. In order to obtain it, one has to compare experimentally measured extensive air showers parameters to model predictions for different primaries. There is a hint toward a possible separation of primaries by selection of individual shower parameters.
At the Yakutsk EAS array, besides surface detectors registering charged component of extensive air showers, there are several underground muon detectors. Their availability extends our instrumentalities for multi-component analysis.
Here we consider a possibility to determine the kind of a primary particle by parameters of lateral distribution function for individual EAS events.

Initial problem

Methods of primary particle determination:

- studying longitudinal shower development ($X_{\max}$ distribution);
- estimate particle density fluctuations.

The main shower observable at the Yakutsk array is particle density at fixed core distance: $\rho_e(600)$, $\rho_\mu(600)$. There is no way of direct $X_{\max}$ observation, and it is not always possible to reconstruct $X_{\max}$ by Čerenkov light flux, since not all showers feature a Čerenkov light data. But it is possible to calculate slope parameter for individual showers, which roughly can be related to longitudinal development features.

We have prepared a set of artificial showers within effective energy range of our array ($E_0 \sim 10^{17} - 10^{19}$ eV) for two primaries (p, Fe) in zenith-angular interval $[0 - 45°]$.

Simulation

CORSIKA-6.710:

- QGSjet II-03, EPOS-1.61 (high-energy hadron interactions);
- FLUKA 2006.3b.9 (low-energy hadron interactions);

Thinning: $\epsilon = 10^{-5}$, $\omega_{\max} = 10^{10}$.

Initial parameters:

- primaries: p, Fe;
- E_0: 3×10^{17}, 9.5×10^{17}, 3×10^{18}, 9.5×10^{18}, 3×10^{19} eV;
- θ: 0, 27, 38.55, 45°.

100 events per parameter set

Lateral profile treatment

We considered lateral profiles for charged and muon components. For each shower, a radial binning with logarithmic step was performed. In each bin a direct particle density was calculated as

$$\rho(r_k) = \sum_i^n \omega_i^p / s_k,$$

where ω_i^p — particle weight, s_k — area of the k-th bin. Statistical weight ω_k was assigned to every bin, equal to the number of particles n in the bin.

For charged component, a sum of muons and electrons was calculated:

$$\rho_e(r_k) = \sum_i^n \left(\omega_i^e + \omega_i^\mu\right) / s_k;$$

for muon profile we selected muons with $\varepsilon_{\text{th}} > 1\ \text{GeV} \cdot \sec\theta$:

$$\rho_\mu(r_k) = \sum_i^n \omega_i^\mu (E > \varepsilon_{\text{th}}) / s_k.$$

LDF used for profile fit

Charged and muon component lateral distributions are described by approximation proposed by L. I. Kaganov:

$$\rho_e(r) = M_e \cdot \left(\frac{r}{R_0}\right)^a \cdot \left(1 + \frac{r}{R_0}\right)^{b-a}$$

$$\rho_\mu(r) = M_\mu \cdot \left(\frac{r}{R_{\text{m.s.}}}\right)^p \cdot \left(1 + \frac{r}{R_{\text{m.s.}}}\right)^{q-p}$$

here:

M_e, M_μ — shower size parameters,

R_0=65.314 — Moliere radius, $R_{\text{m.s.}}$=280 — mean square muon scattering radius,

a=-1, p=-0.55 — fixed slope parameters[a],

b, q — free slope parameters.

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[a] *canonical value of p is -0.75.*

LDF used for profile fit

$\rho(600)$, slope:

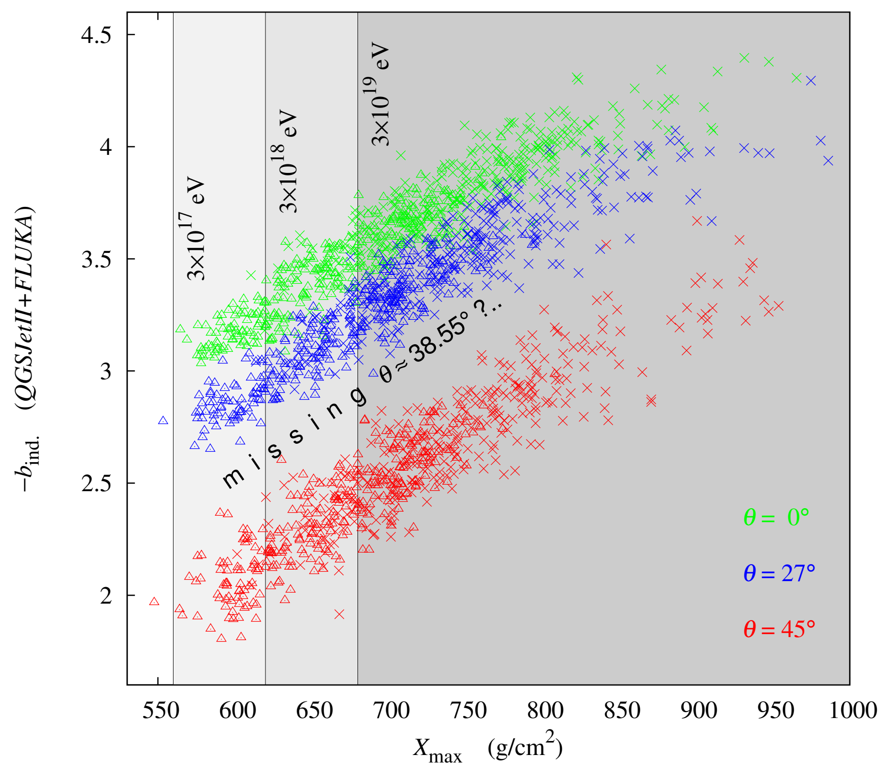
$$
\begin{aligned}
\rho_e(r) &= \rho_e(600) \cdot \left(\frac{r}{600}\right)^a \cdot \left(\frac{r+600}{R_0+600}\right)^{b-a} \\
\rho_\mu(r) &= \rho_\mu(600) \cdot \left(\frac{r}{600}\right)^p \cdot \left(\frac{r+600}{R_{\mathrm{m.s.}}+600}\right)^{q-p}
\end{aligned}
$$

$$
\begin{aligned}
X_{\max}(b) &= ? \\
X_{\max}(q) &= ?
\end{aligned}
$$

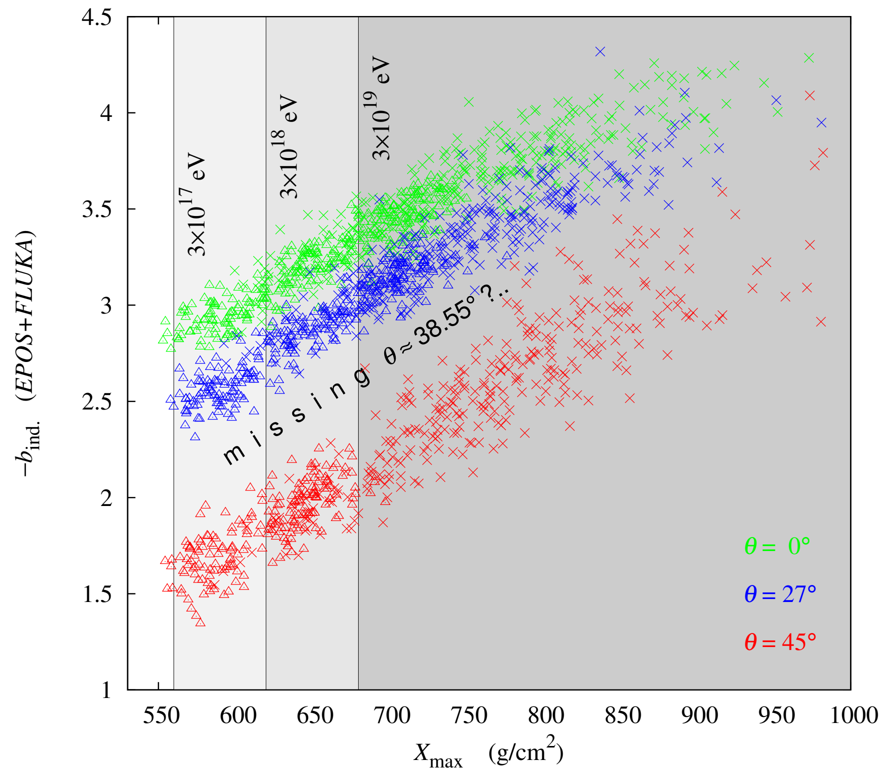
A first glimpse

Correlation between LDF slope parameter b and $X_{\max}$.

QGSjet II



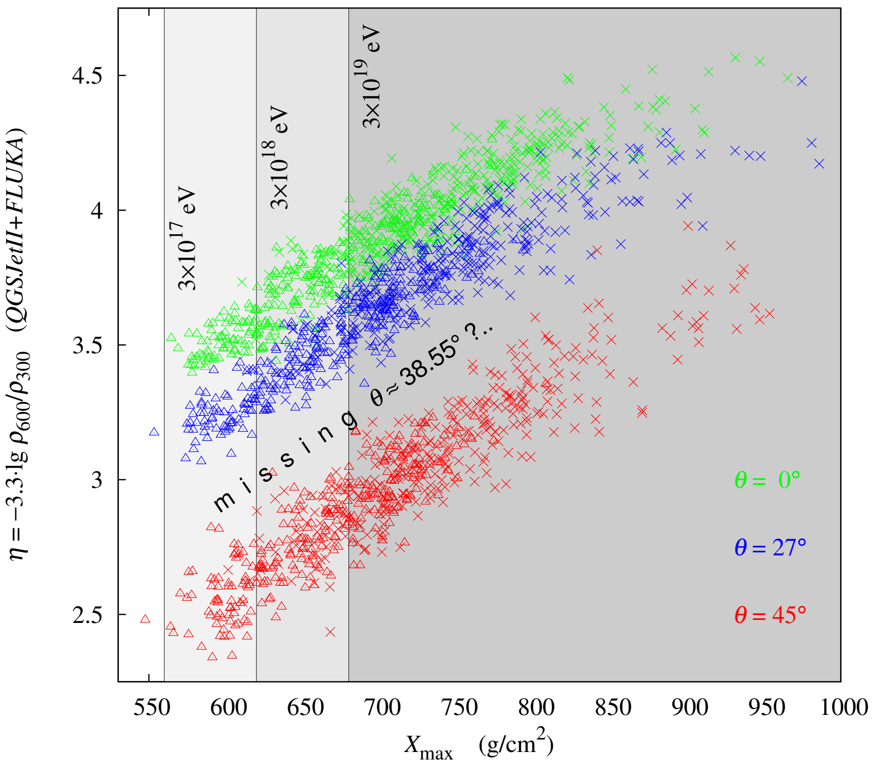
EPOS



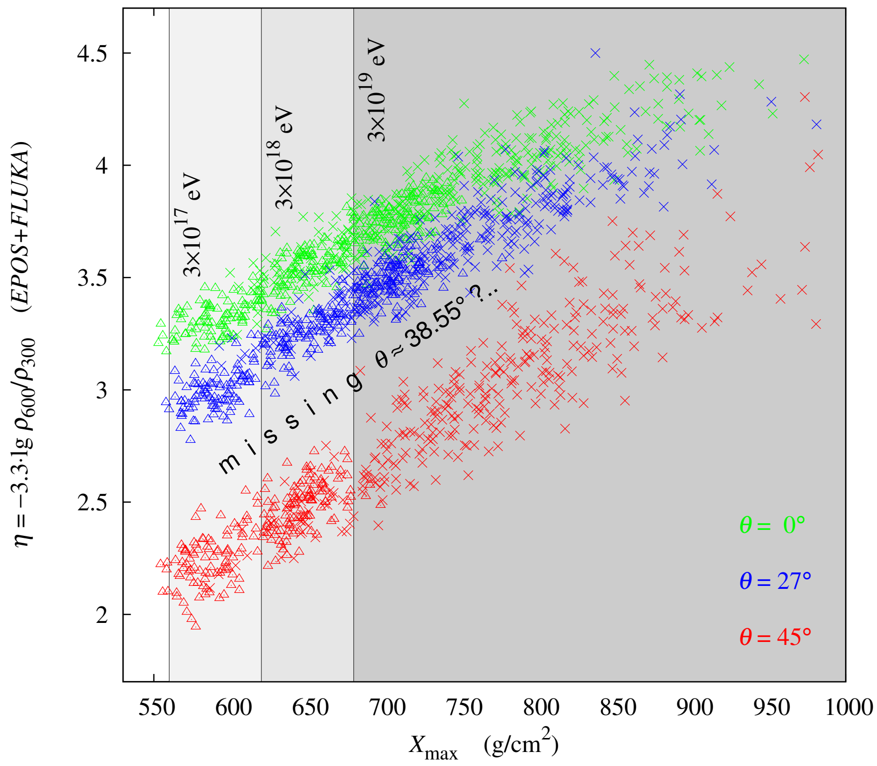
A first glimpse

Same for the local slope parameter $\eta = -3.3 \cdot \lg \rho(600)/\rho(300)$.

QGSjet II



EPOS



$\rho(600) - E_0$ relation

As seen from figures above, it is quite tricky to estimate $X_{\max}$ or distinguish between possible primaries due to fluctuations at fixed θ and E_0.

Calorimetric method used in the Yakutsk experiment does not take into account the kind of primary particle. Basically, we have following shower parameters, measured more or less precisely:

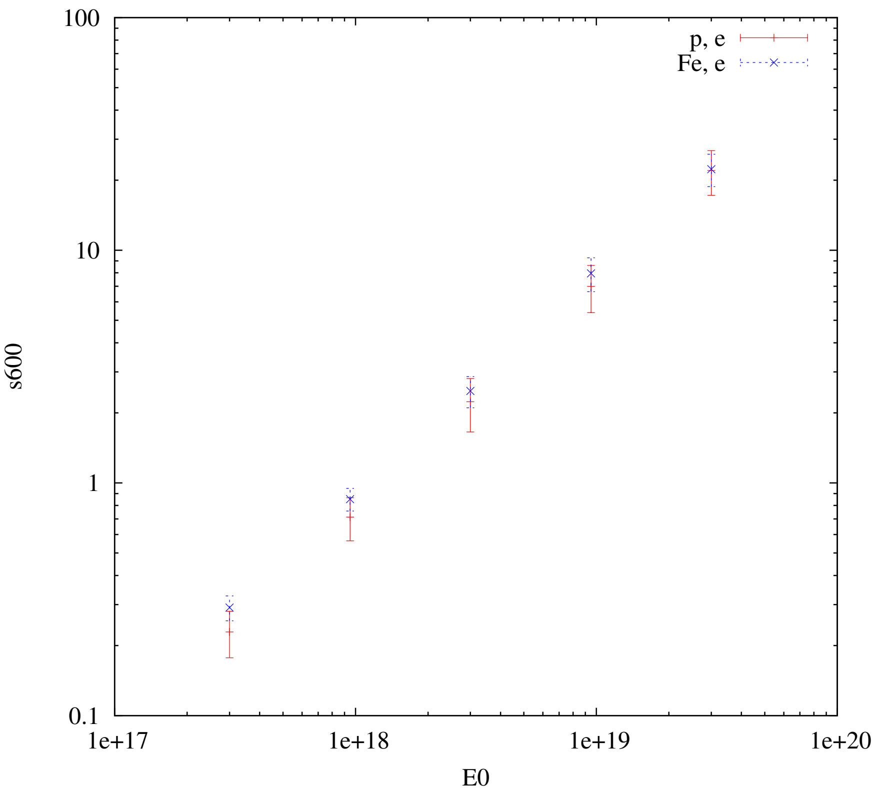
- θ;
- $\rho_e(600)$, $\rho_\mu(600)$;
- recalculated LDF slope parameter.

$\Longrightarrow$ as there is some dispersion of $\rho(600)$ for given (E_0, θ), showers should be selected by $\rho(600)$ within a narrow interval.

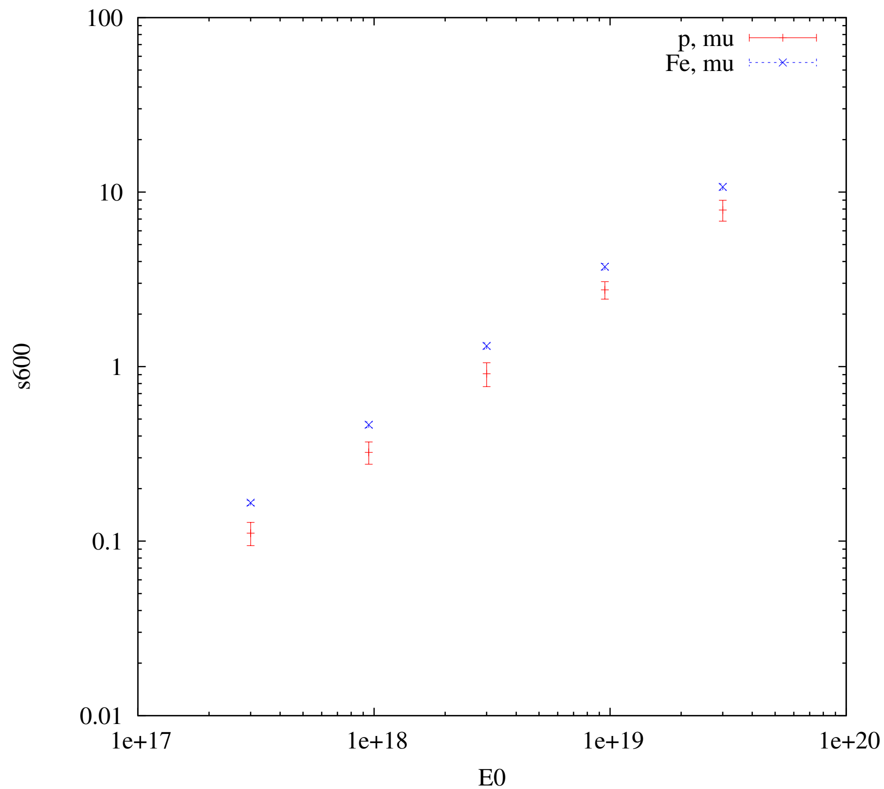
$\rho(600) - E_0$ relation

Averaged QGSjet II $\rho(600)$ data (p + Fe, $\theta = 45°$).

Charged



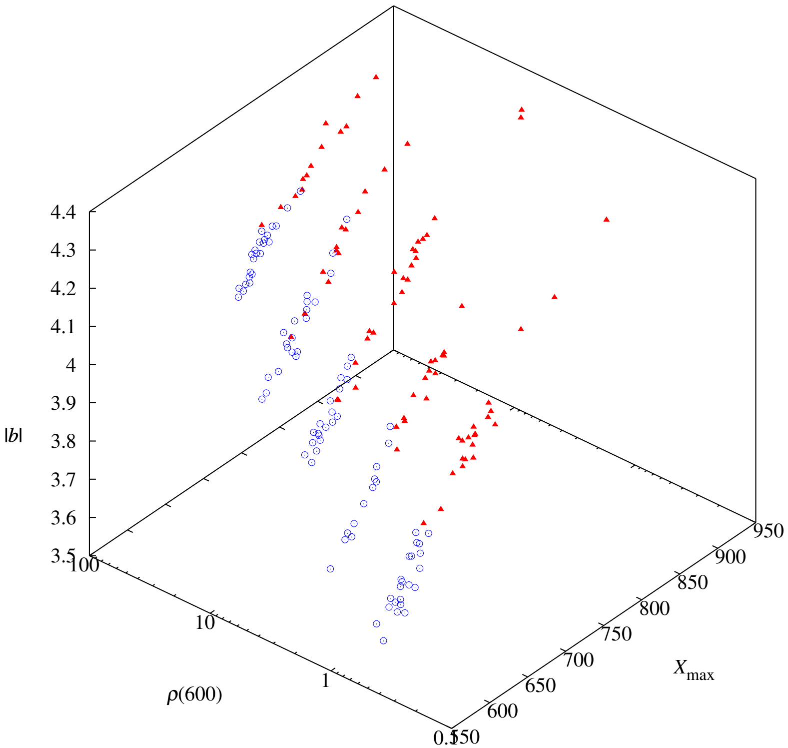
Muons



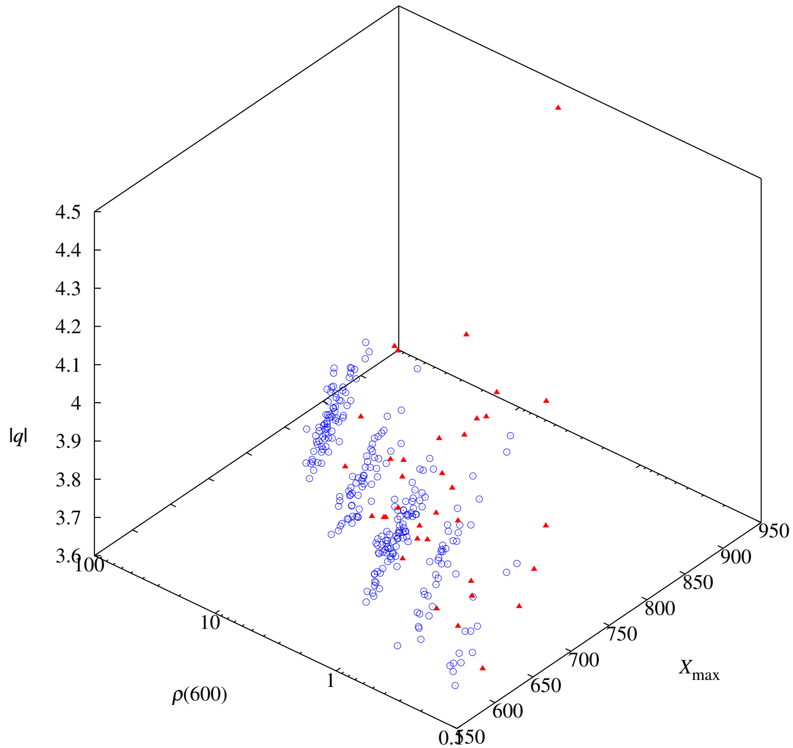
Example of a narrow $\rho(600)$ selection

Individual slope parameters selected by $\rho(600)$ (QGSjet II model).

Charged

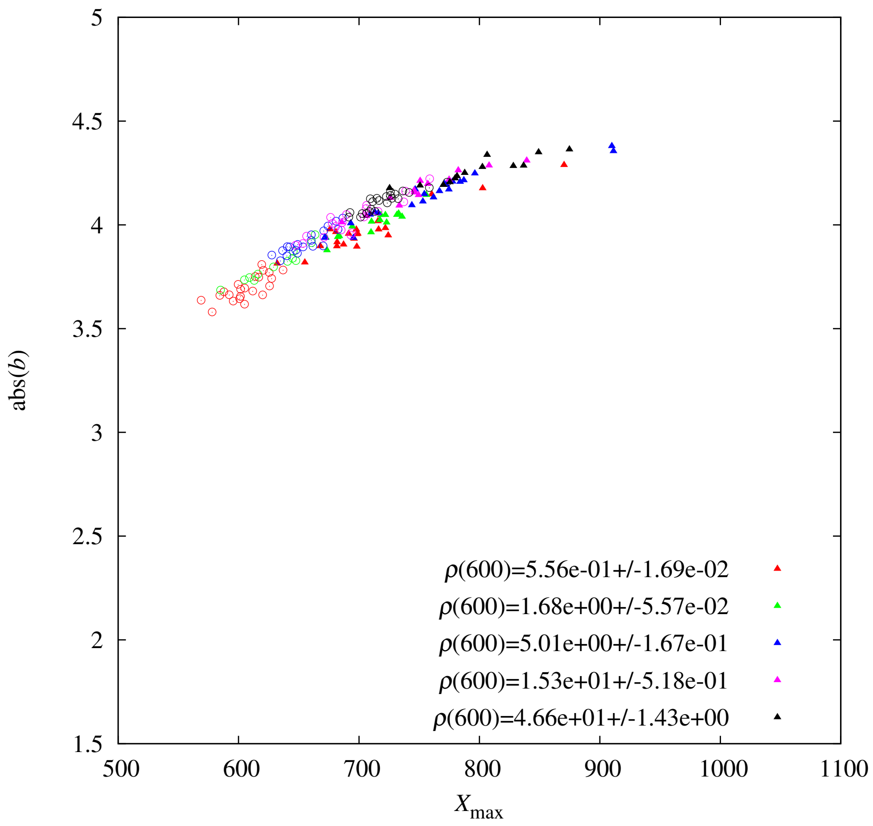


Muons

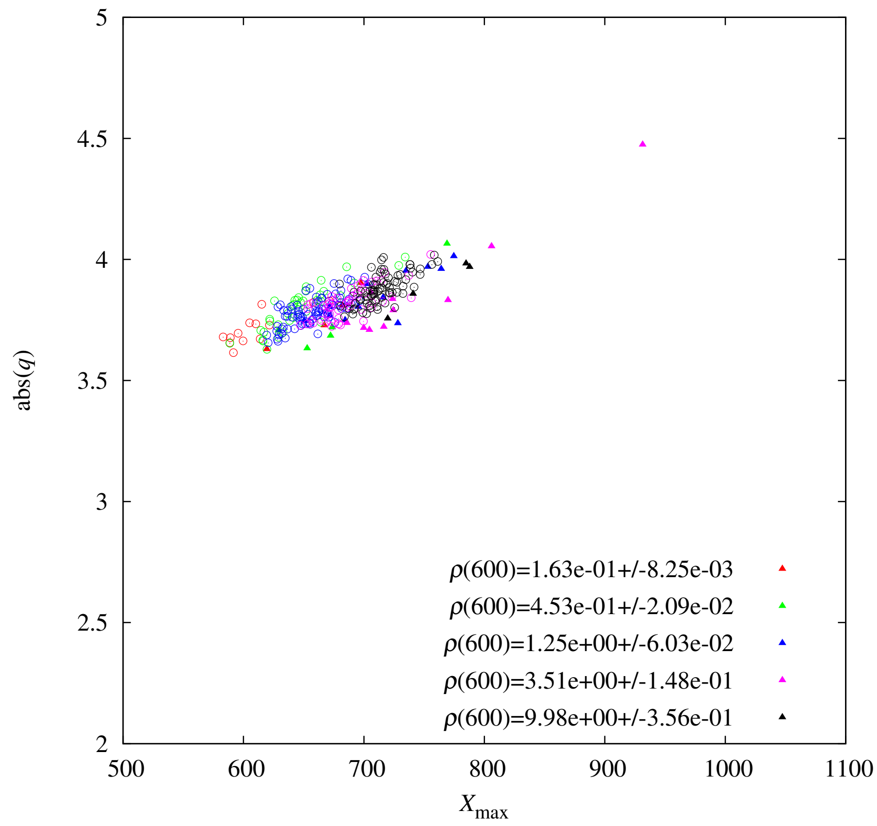


$\rho(600)$ selection, $\theta = 0^\circ$ (QGSjet II)

Charged

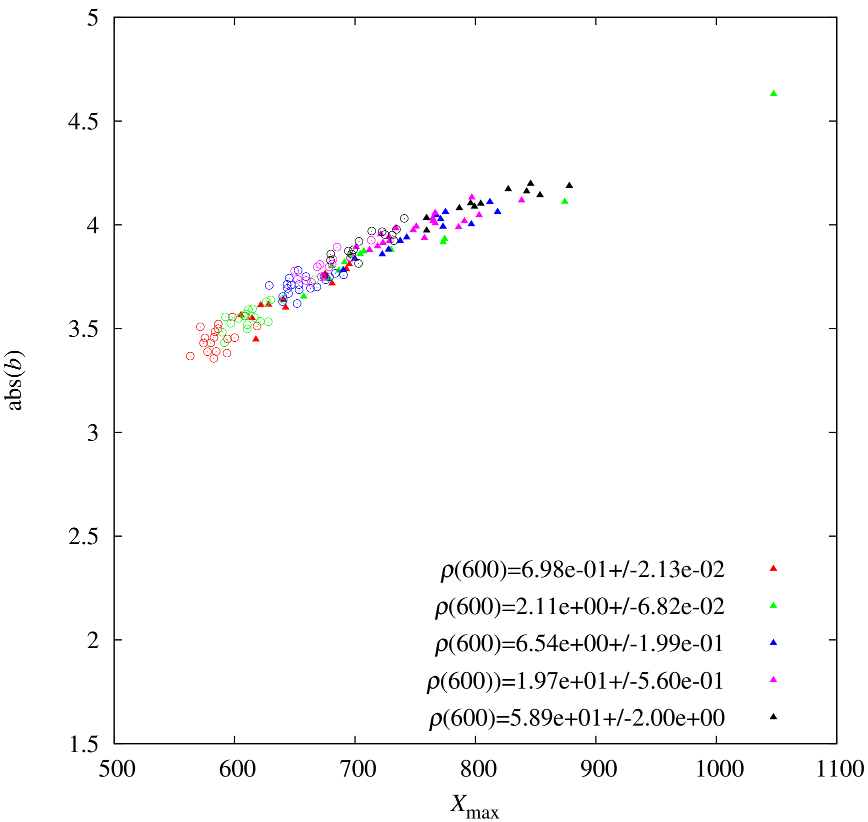


Muons

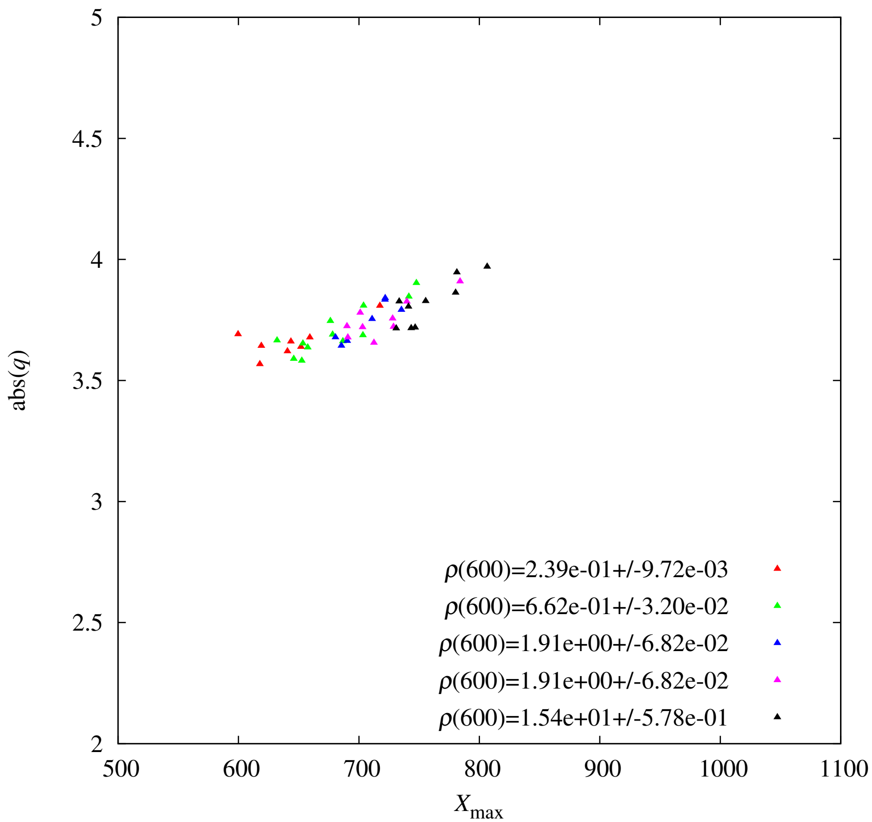


$\rho(600)$ selection, $\theta = 0^\circ$ (EPOS)

Charged

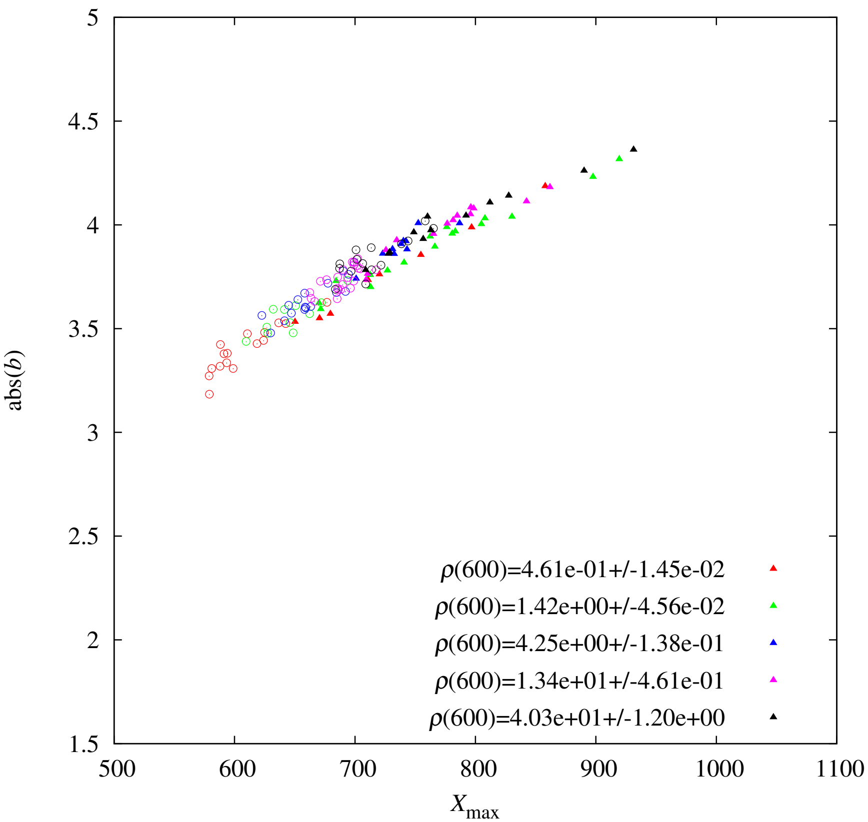


Muons

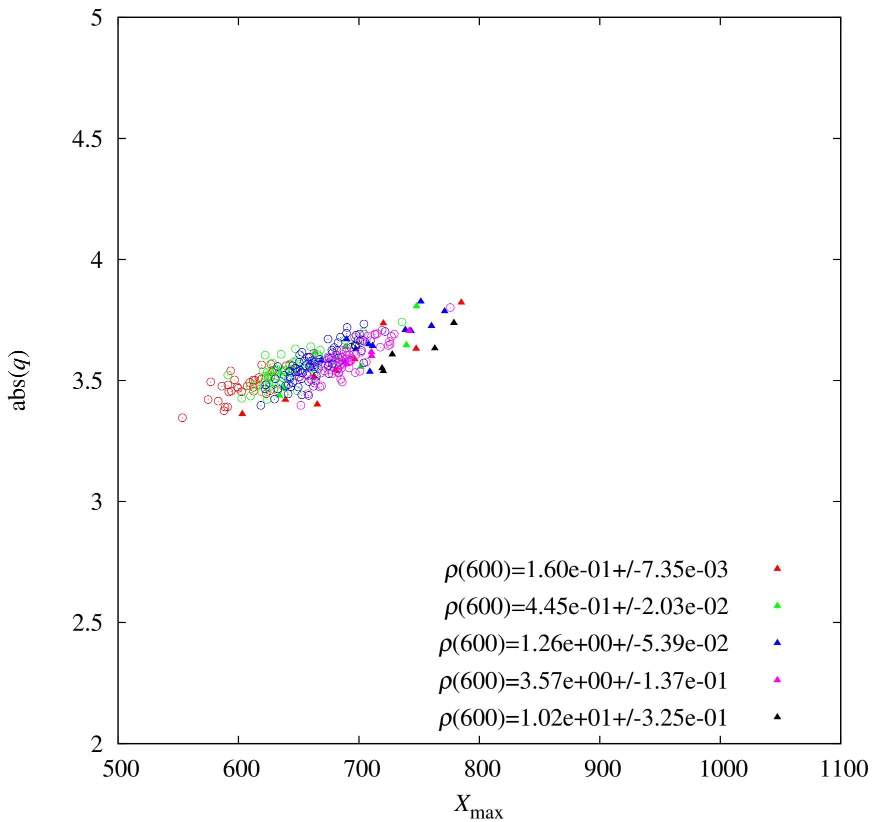


$\rho(600)$ **selection,** $\theta = 27^\circ$ **(QGSjet II)**

Charged

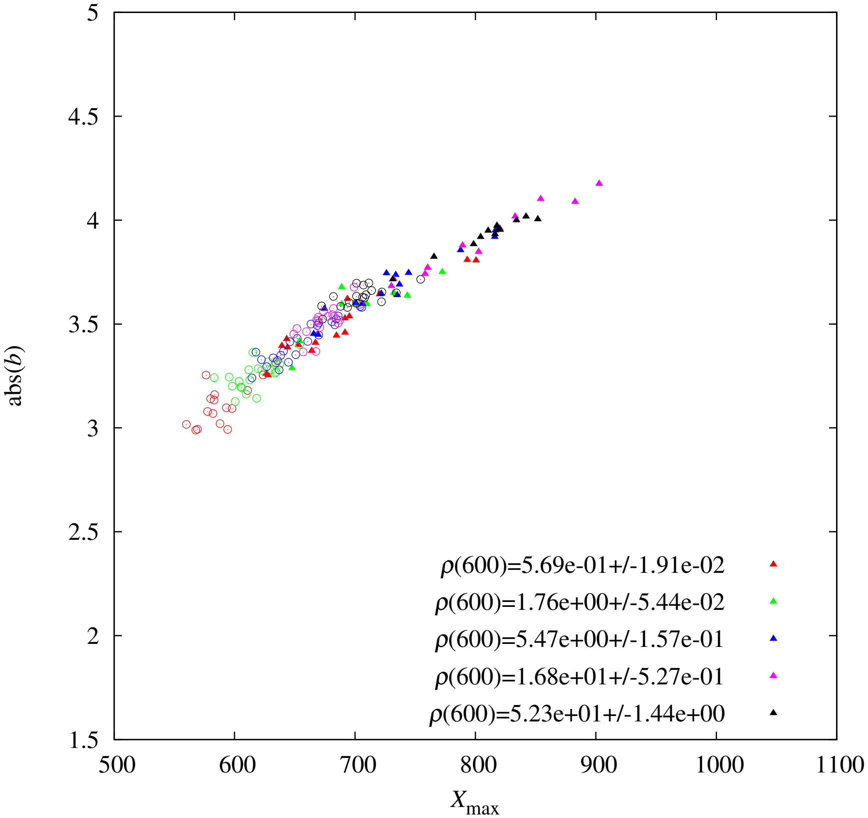


Muons

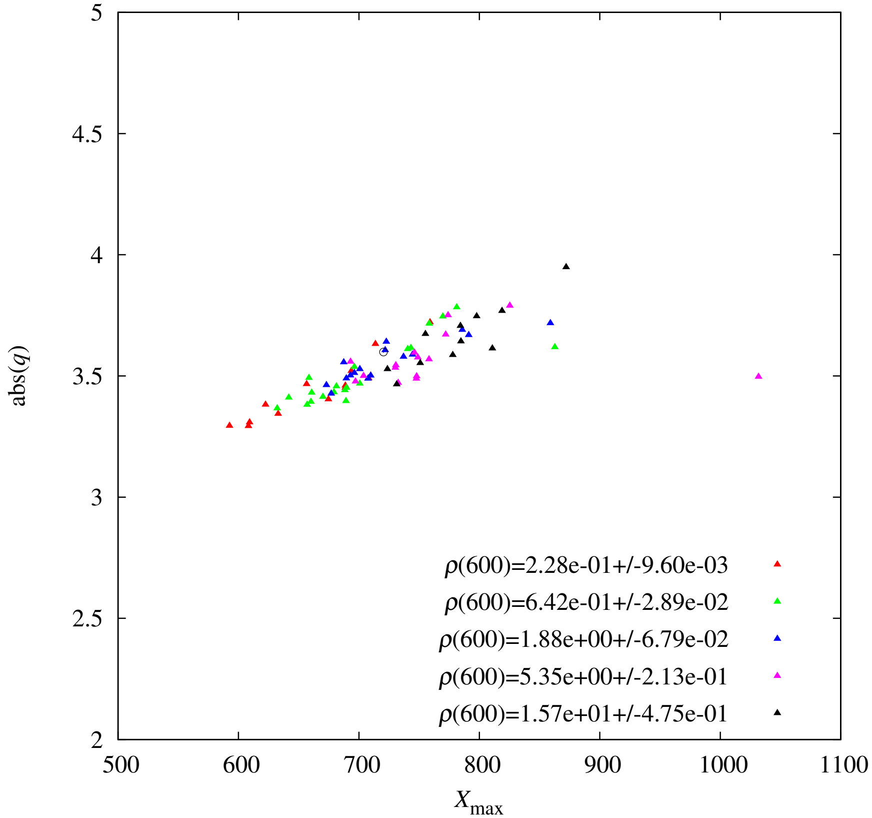


$\rho(600)$ selection, $\theta = 27^\circ$ (EPOS)

Charged

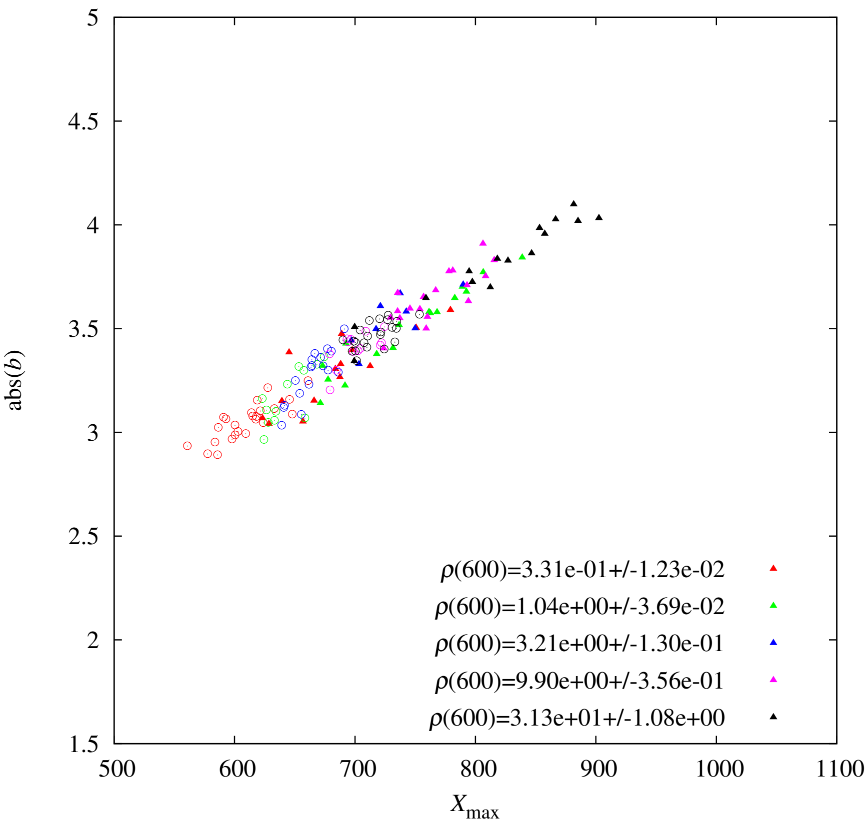


Muons

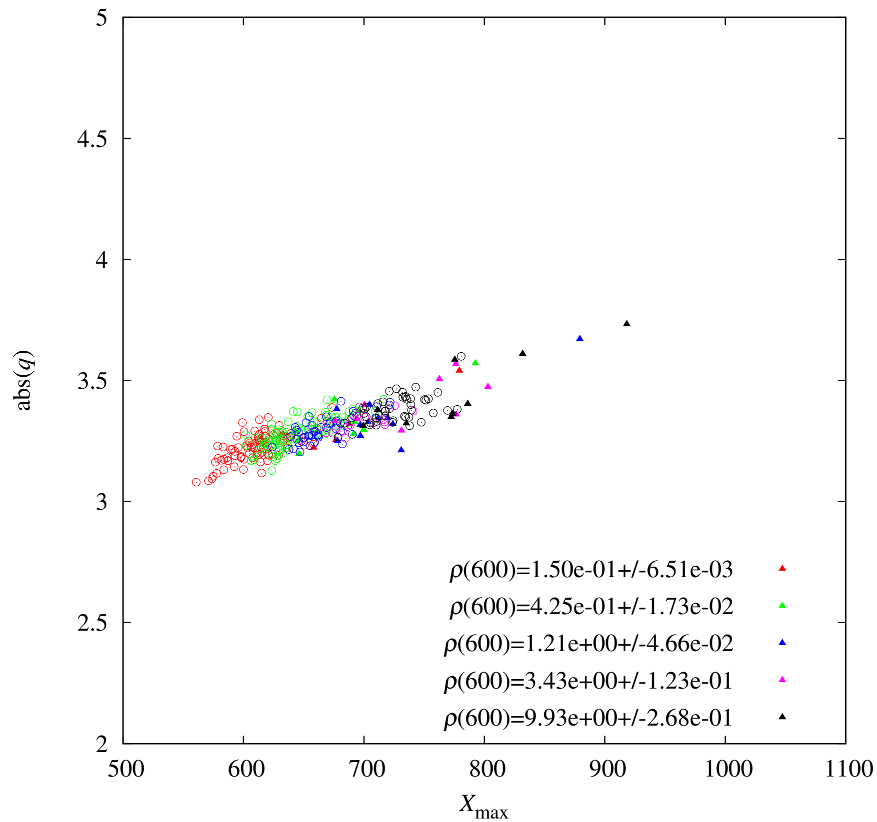


$\rho(600)$ selection, $\theta = 38.55°$, QGSjet II

Charged

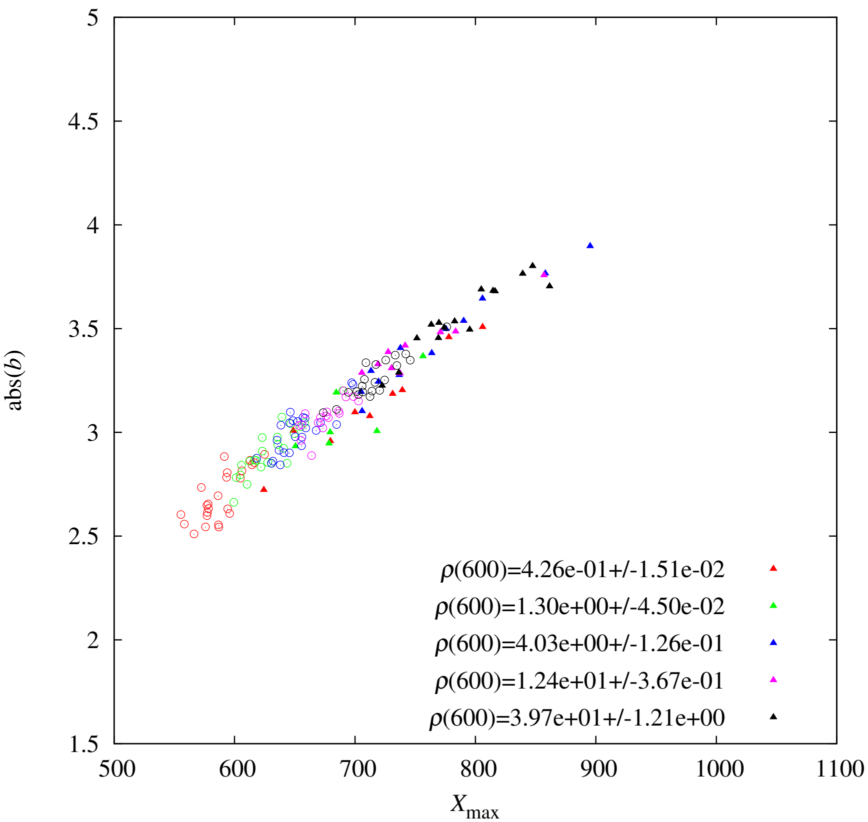


Muons

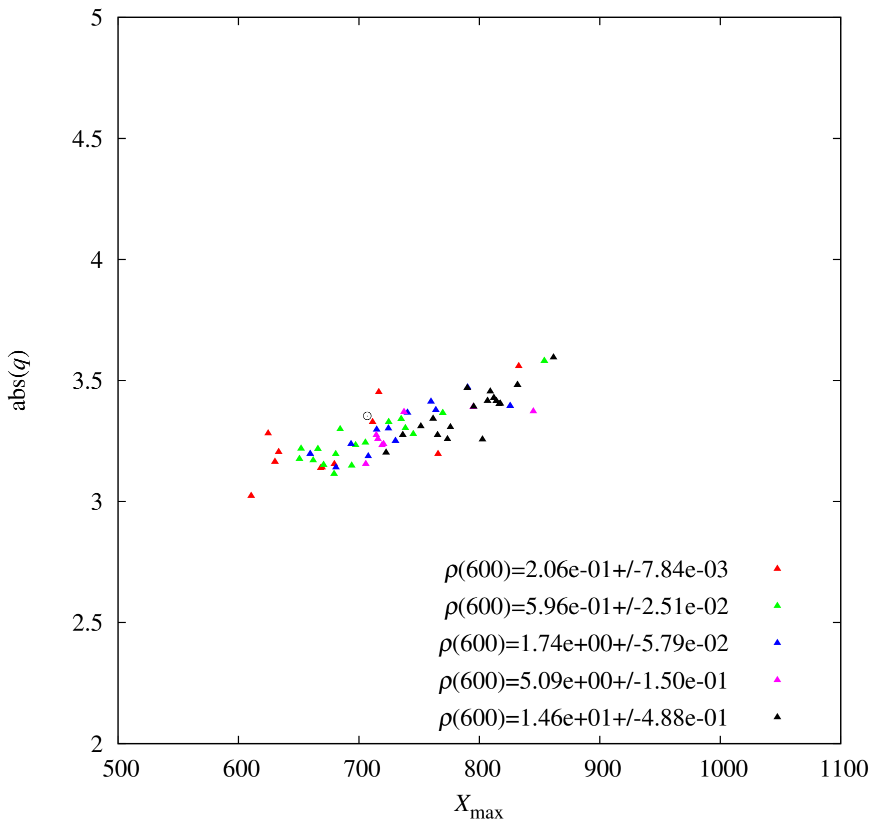


$\rho(600)$ selection, $\theta = 38.55^\circ$, EPOS

Charged

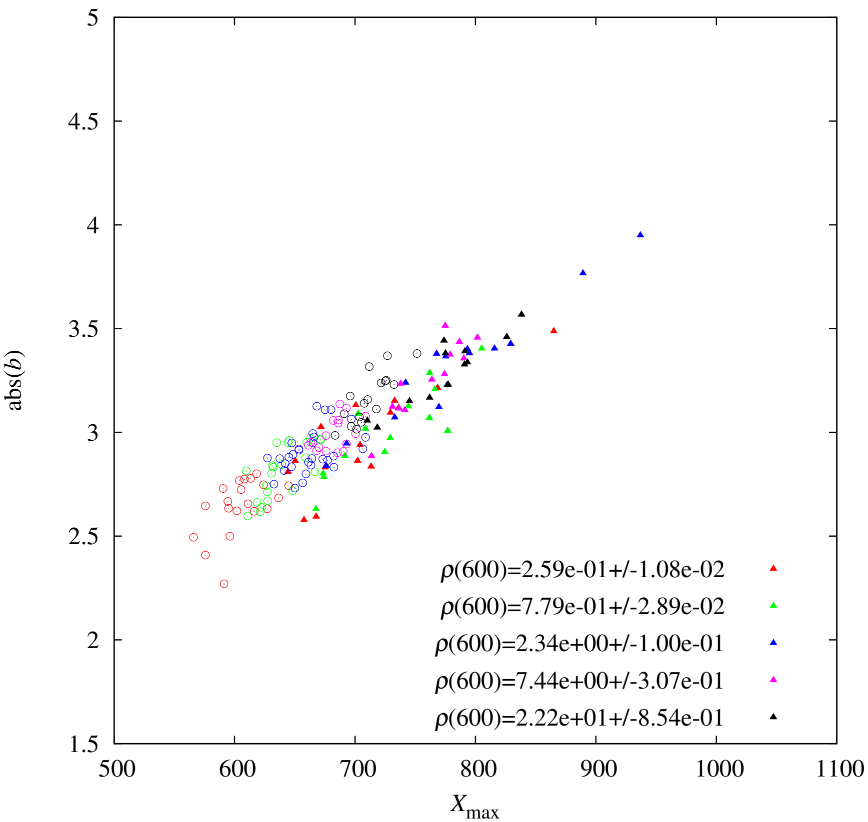


Muons

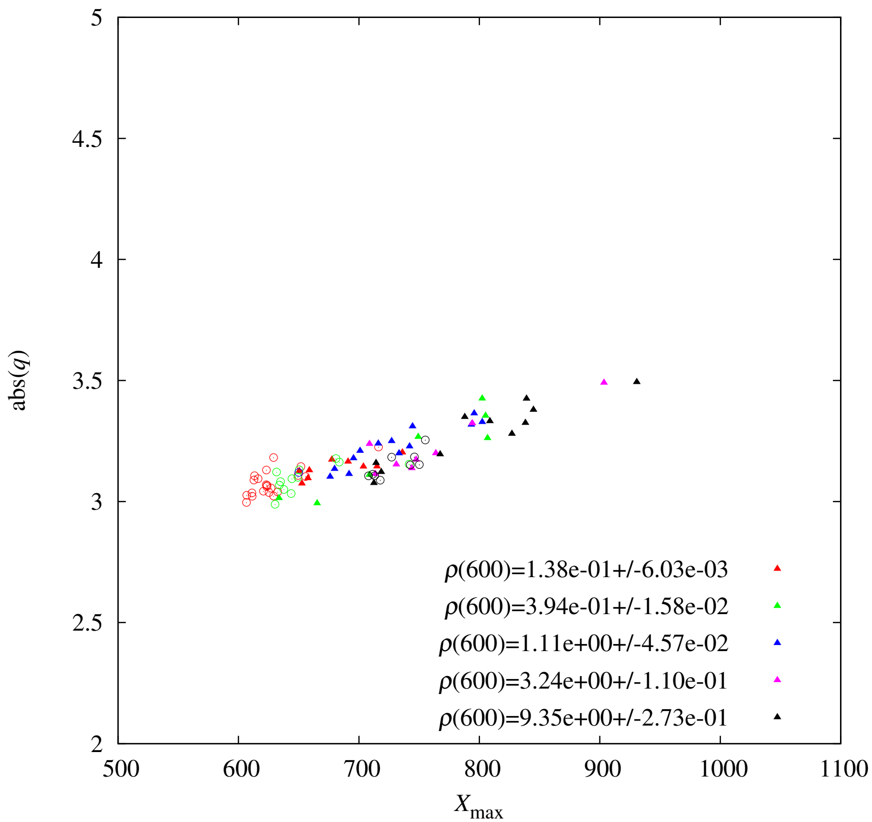


$\rho(600)$ selection, $\theta = 45^\circ$, QGSjet II

Charged

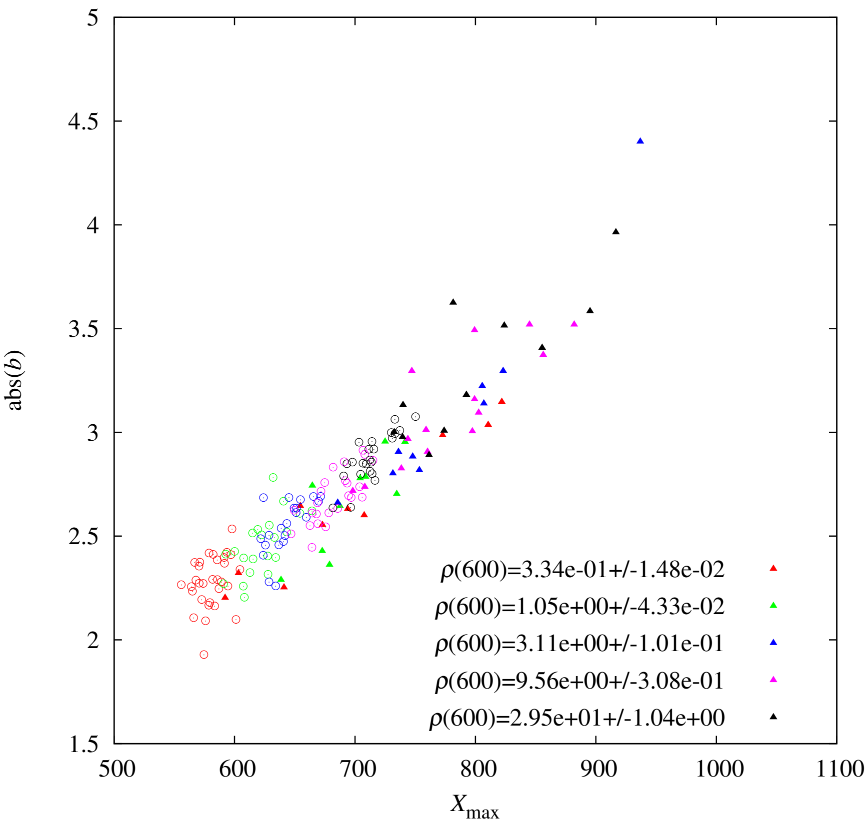


Muons

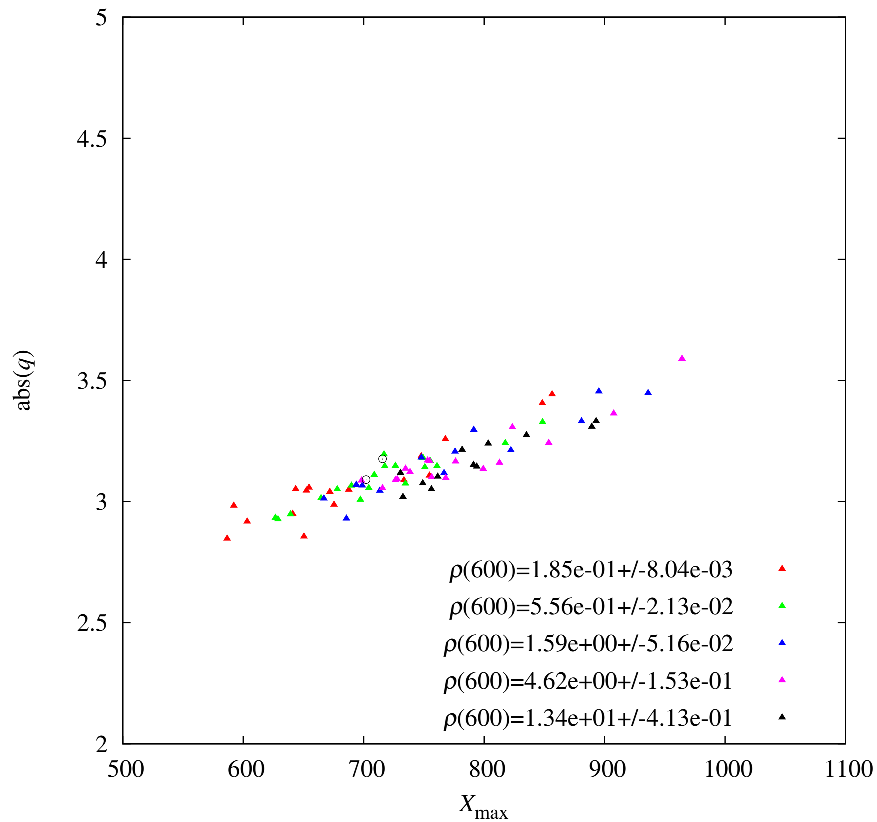


$\rho(600)$ selection, $\theta = 45^\circ$, EPOS

Charged

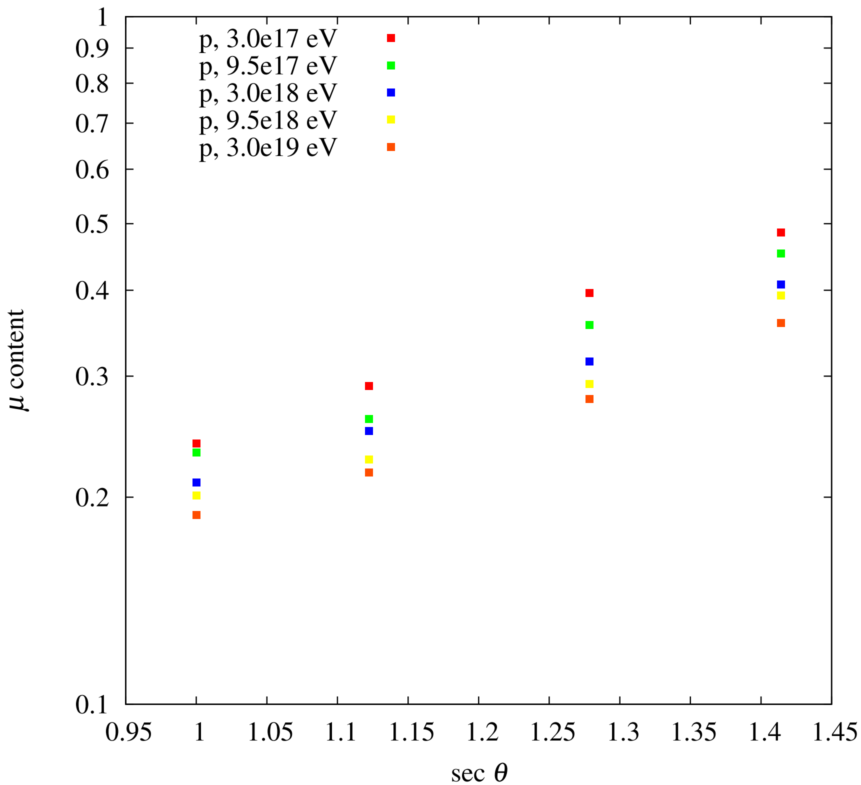


Muons

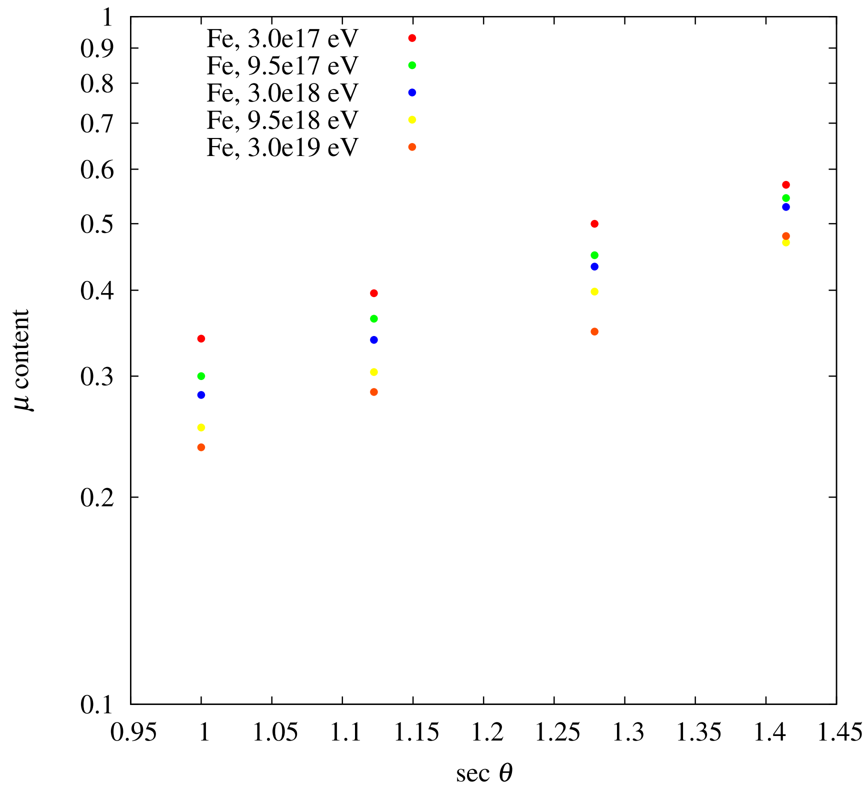


Mean muon content, QGSjet II:

p

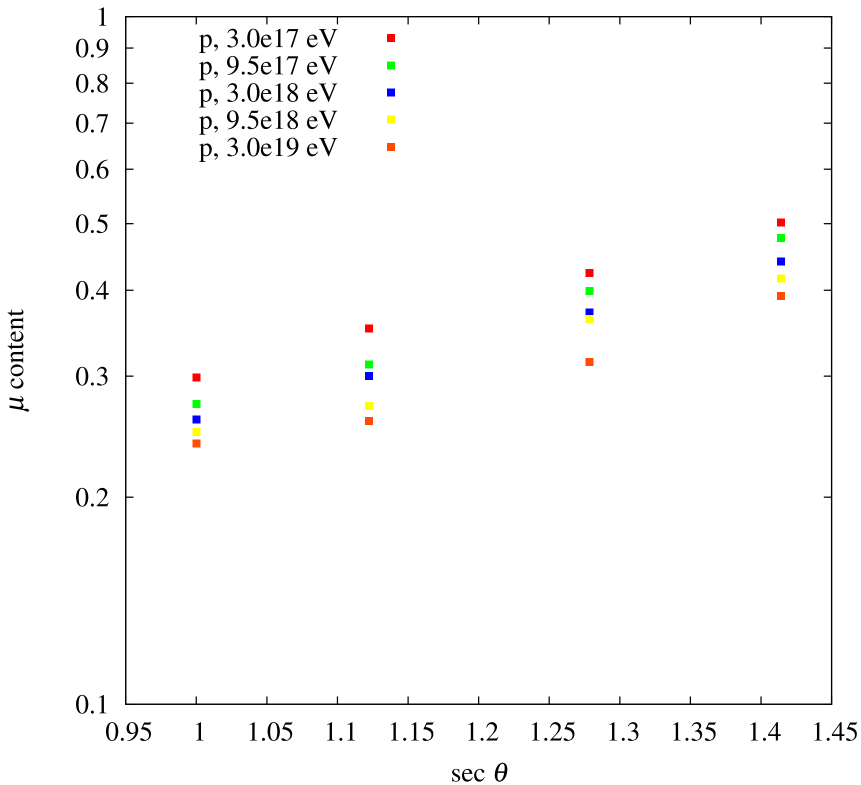


Fe

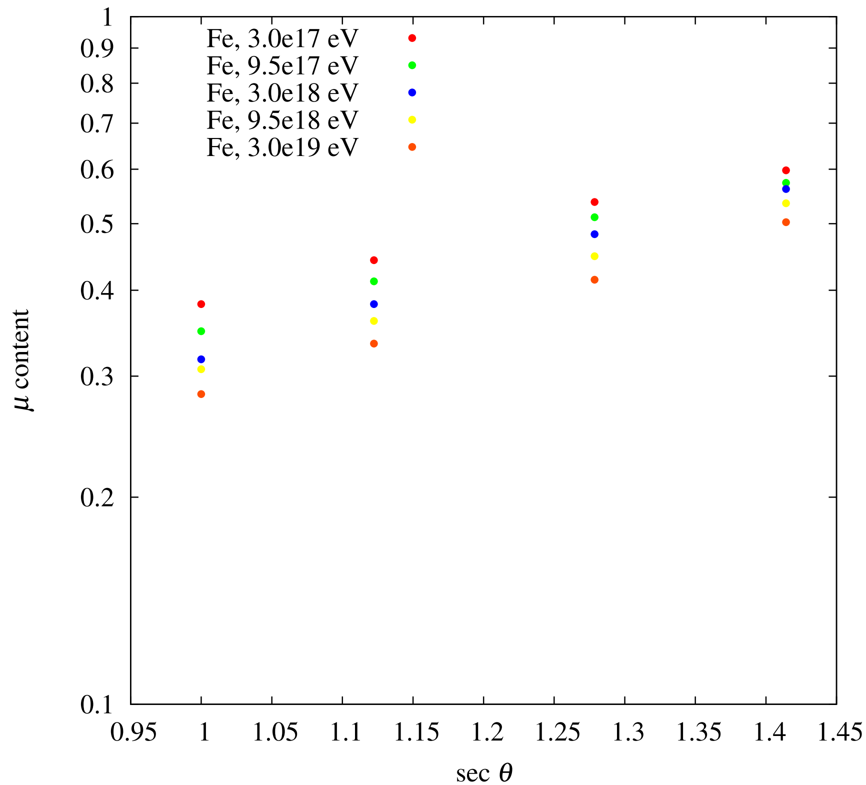


Mean muon content, EPOS:

p

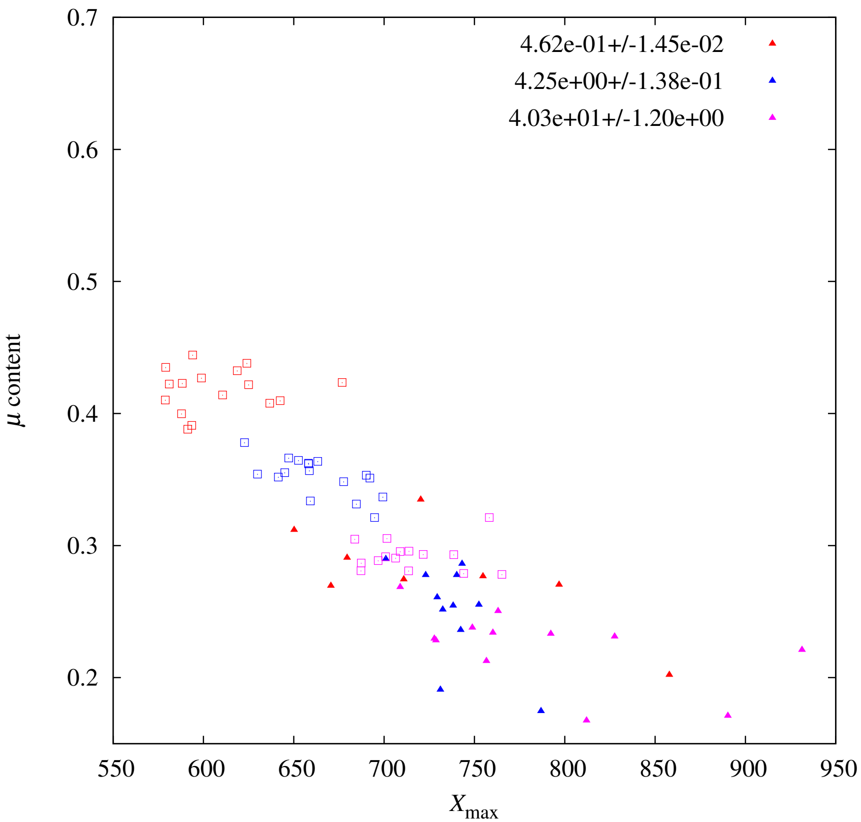


Fe

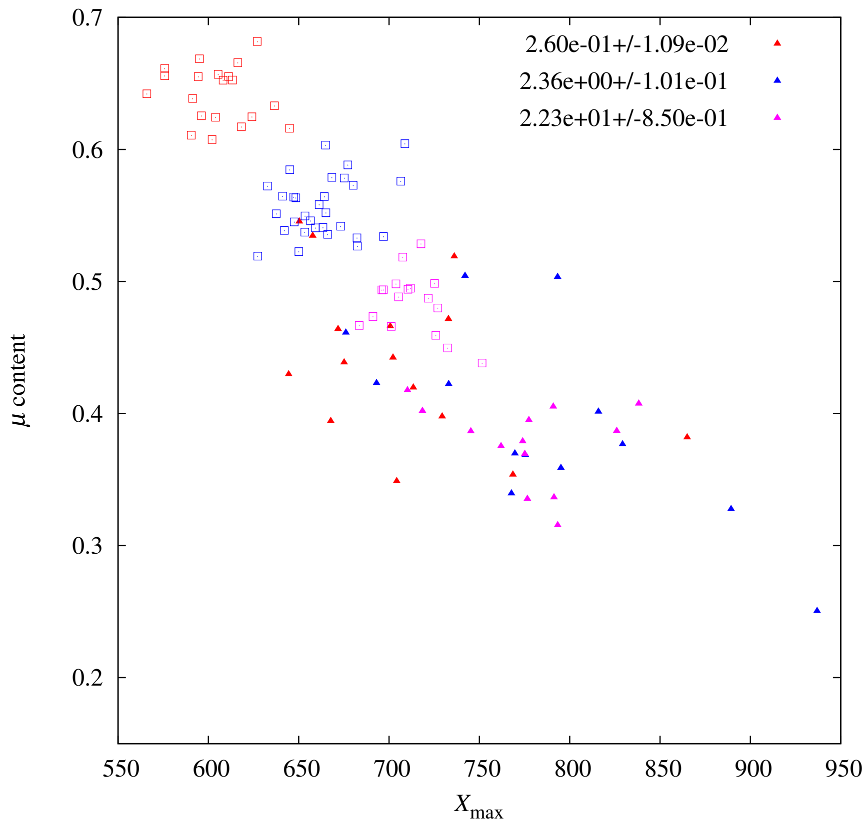


$\rho_\mu(600)/\rho_e(600)$ – $X_{\mathbf{max}}$, QGSjet II:

$\theta = 27^\circ$

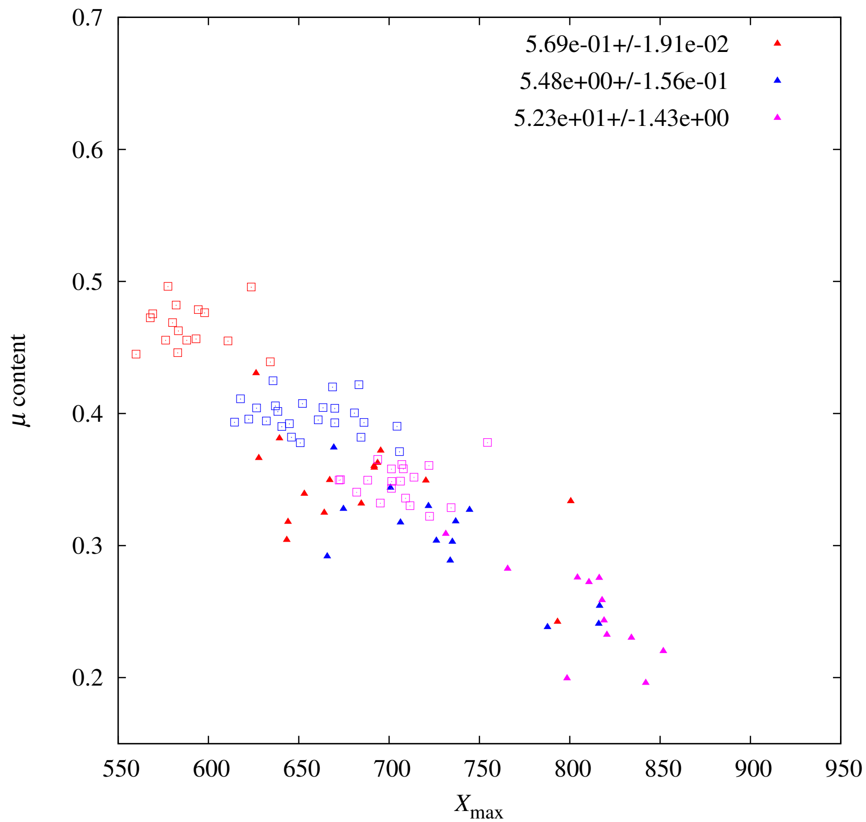


$\theta = 45^\circ$

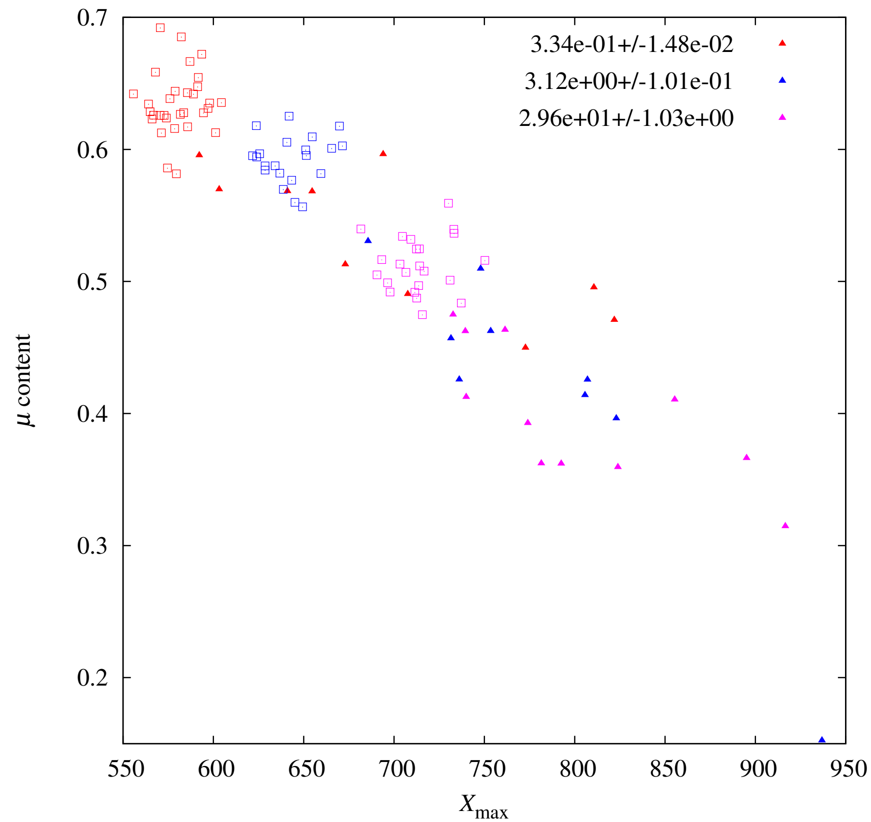


$\rho_\mu(600)/\rho_e(600) - X_{\mathbf{max}}$, EPOS:

$\theta = 27^\circ$



$\theta = 45^\circ$



Summary

It is possible to estimate $X_{\max}$ and even mass composition if showers are selected by $\rho(600)$ within a narrow interval of zenith angle. For showers with muon data, additional analysis of the muon content could be carried out. These methods may fill the gap in lacking Čerenkov light data and expand $X_{\max}$ reconstruction by Čerenkov light flux distribution.
However, individual LDF parameters are quite model dependent and a test on the experimental data is to be done.