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 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 Cherenkov light flux, since not all showers feature a Cherenkov 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 $[0 - 45^\circ]$.

Simulation

CORSIKA-6.710:

QGSjet II-03, EPOS-1.61 — high-energy hadron interactions;

FLUKA 2006.3b.9 — low-energy hadron interactions;

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

Initial parameters:

primaries: p, Fe;

E_0: $3 \times 10^{17}, 9.5 \times 10^{17}, 3 \times 10^{18}, 9.5 \times 10^{18}, 3 \times 10^{19}$ eV;

θ: $0, 27, 38.55, 45^\circ$.

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 $\varepsilon_{\text{th}} > 1\ \text{GeV} \cdot \sec\theta$: $\rho_\mu(r_k) = \sum_i^n \omega_i^\mu (E > \varepsilon_{\text{th}}) / s_k$.

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*,

b, q — free slope parameters.

**canonical value of p is -0.75.*

LDF form used for proflie fit

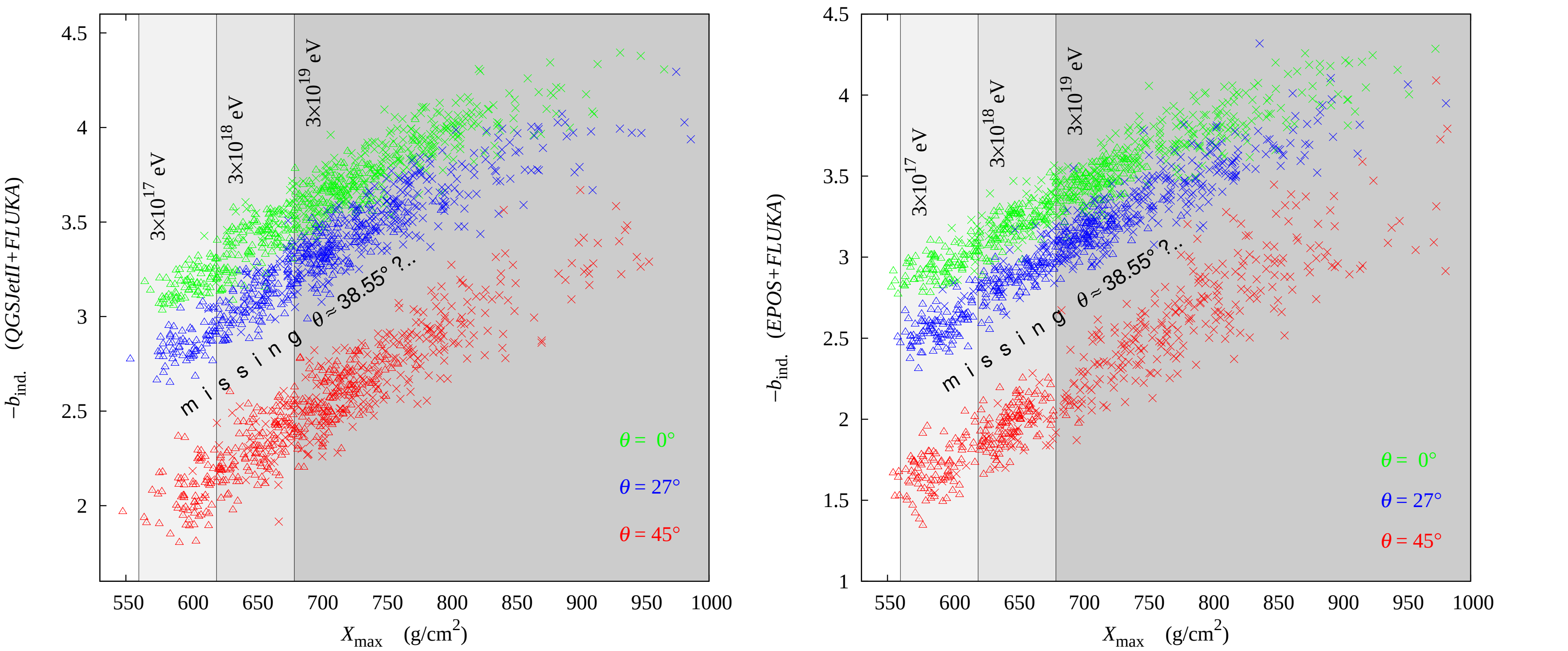
LDFs above can be expressed in terms of $\rho(600)$:

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

$\longrightarrow$ weighted χ^2 fit of obtained lateral profiles.

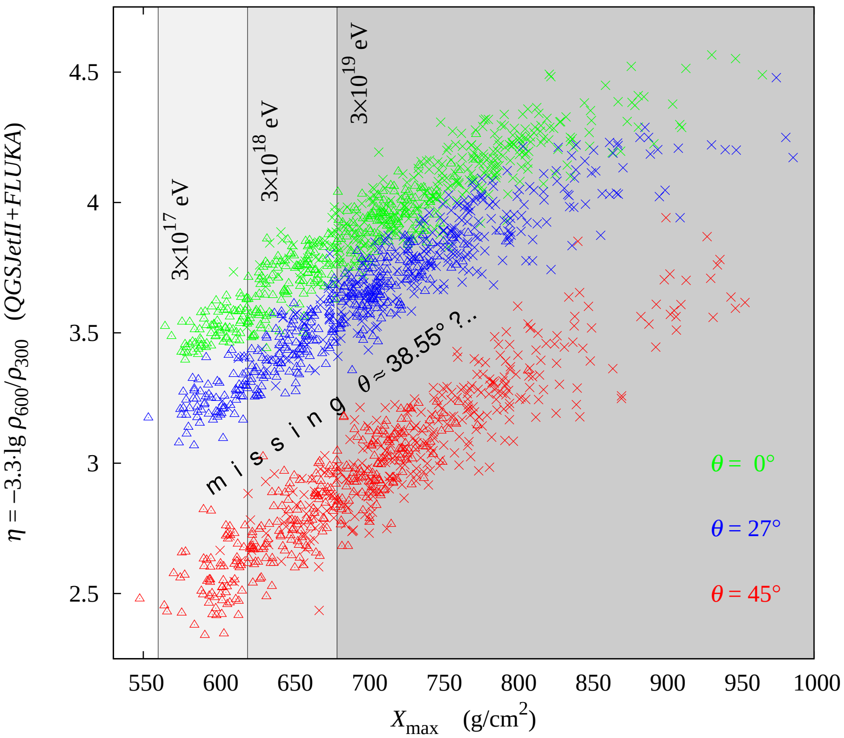
$X_{\mathrm{max}}(b)$ ($X_{\mathrm{max}}(q)$) — ?

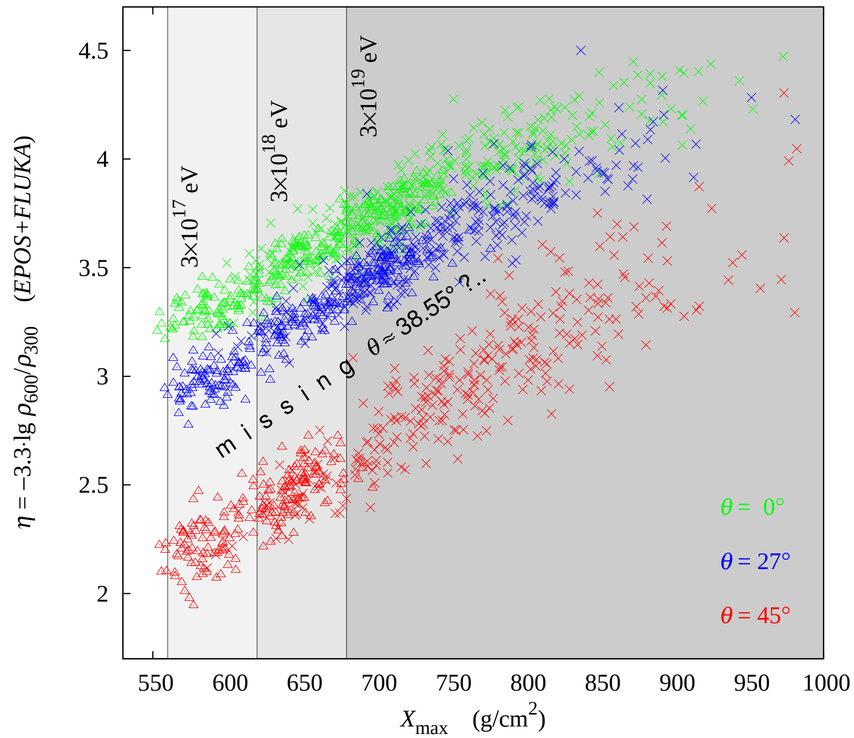
A first glimpse



Correlation between LDF slope parameter b and X_{max} according to QGSjet II (left) and EPOS (right).

A first glimpse





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

$\rho(600) - E_0$ relation

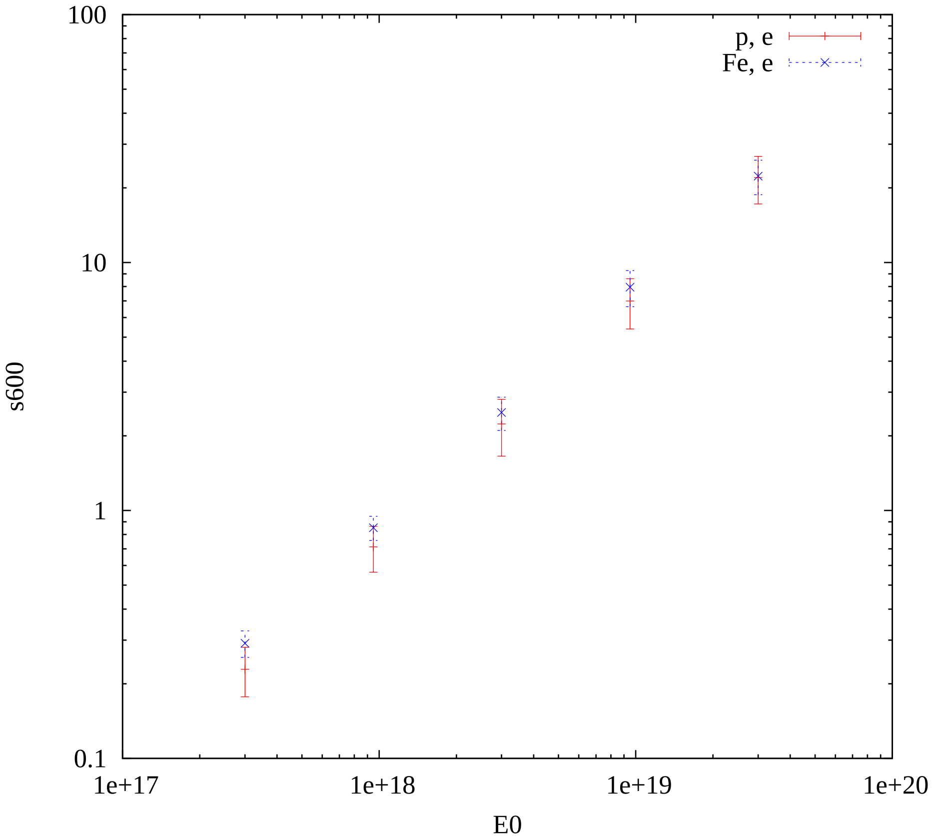
As seen from figures above, it is quite tricky to estimate $X_{\max}$ or distinguish between possible primaries due to fluctuations at fixed θ and E_0.

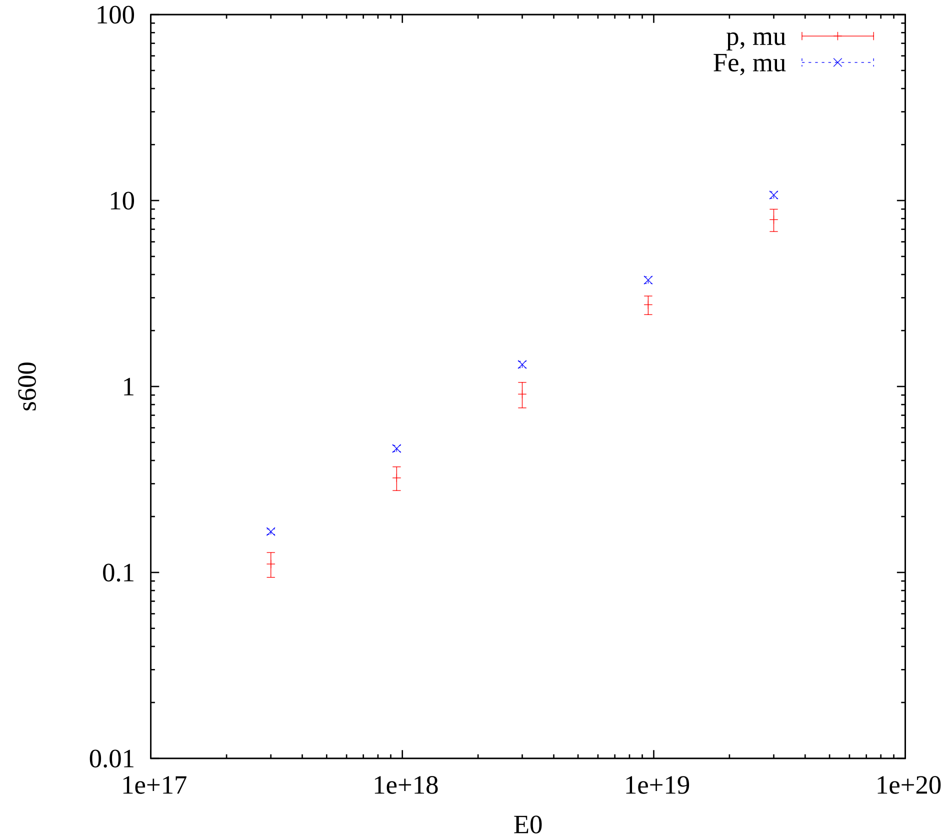
Calorimetric method used in the Yakutsk experiment does not take into account the kind of primary particle. Basically, we have following shower parameters, measured more or less precisely:

- 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.

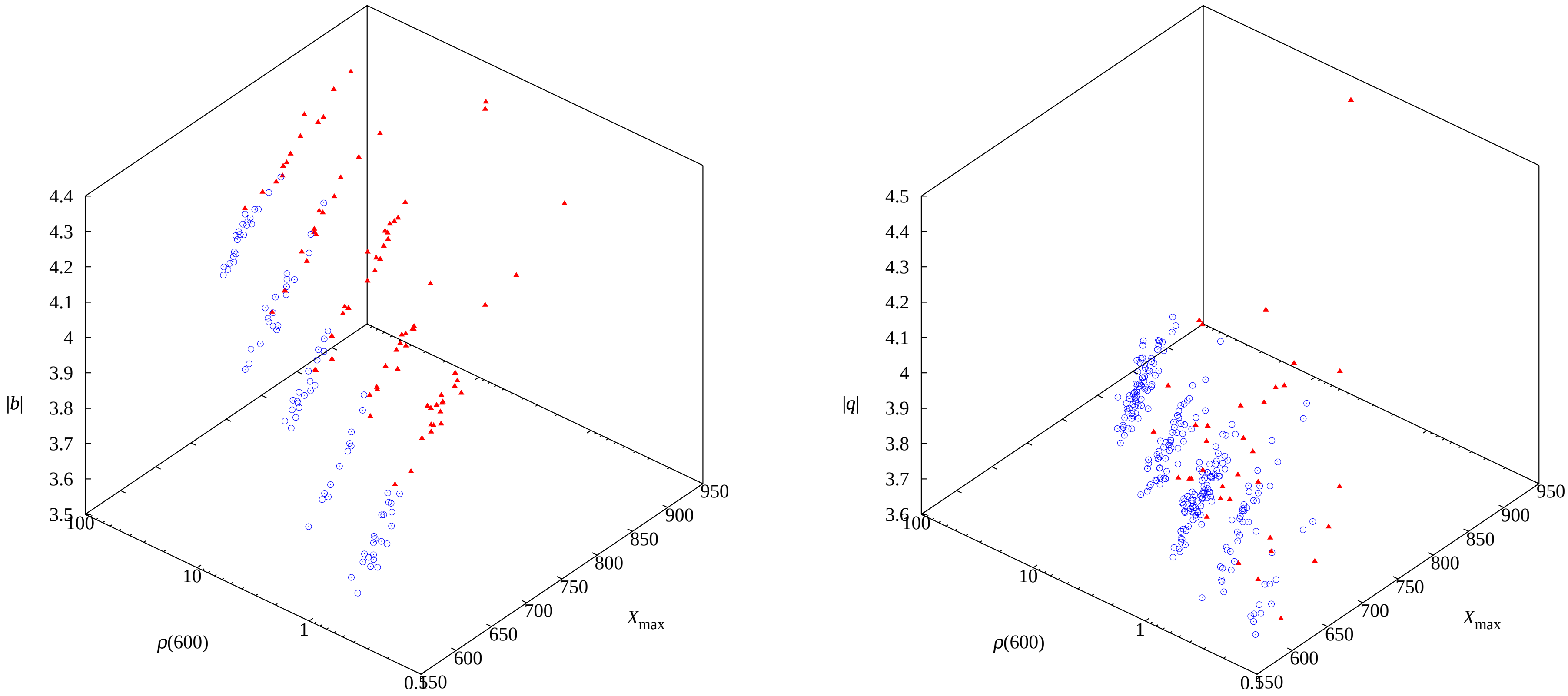
$\rho(600) - E_0$ relation





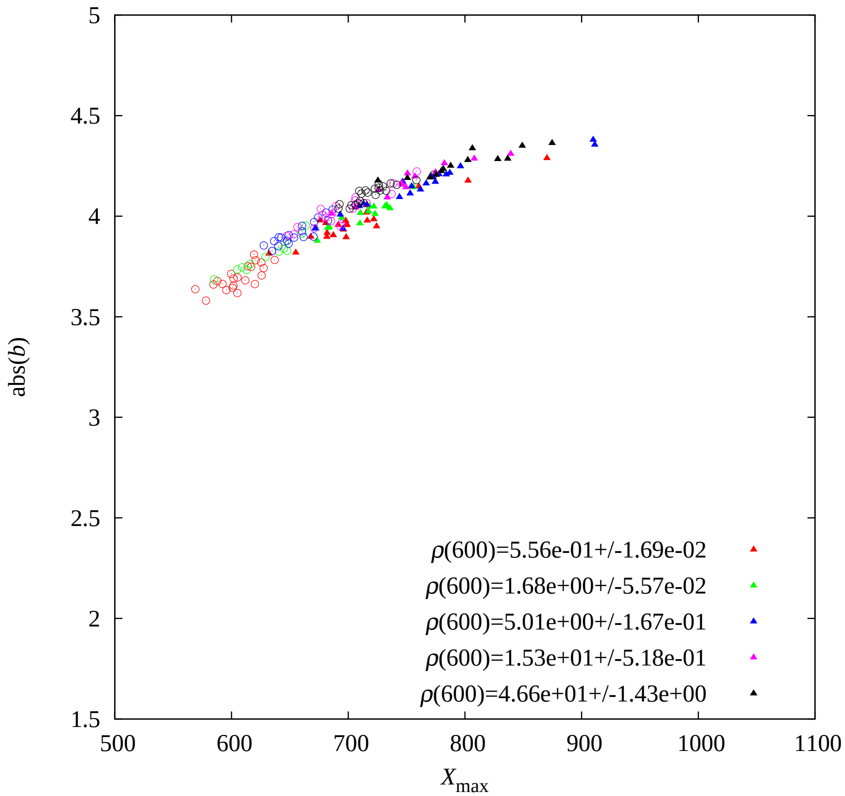
Averaged QGSjet II $\rho(600)$ data (p + Fe, $\theta = 45^\circ$). Left — charged particles, right — muons.

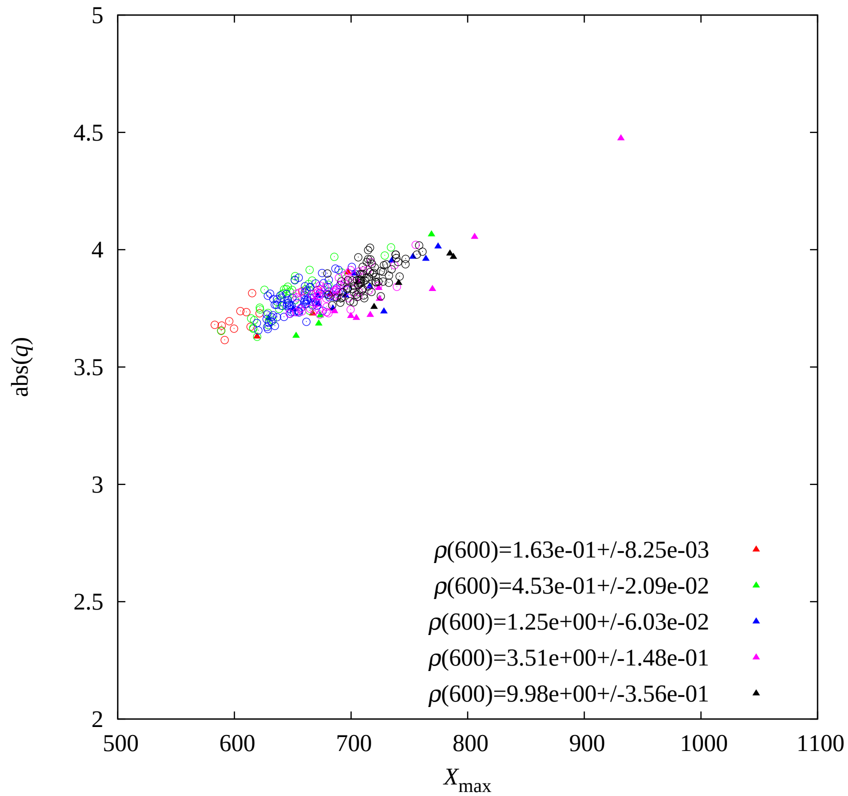
Example of a narrow $\rho(600)$ selection



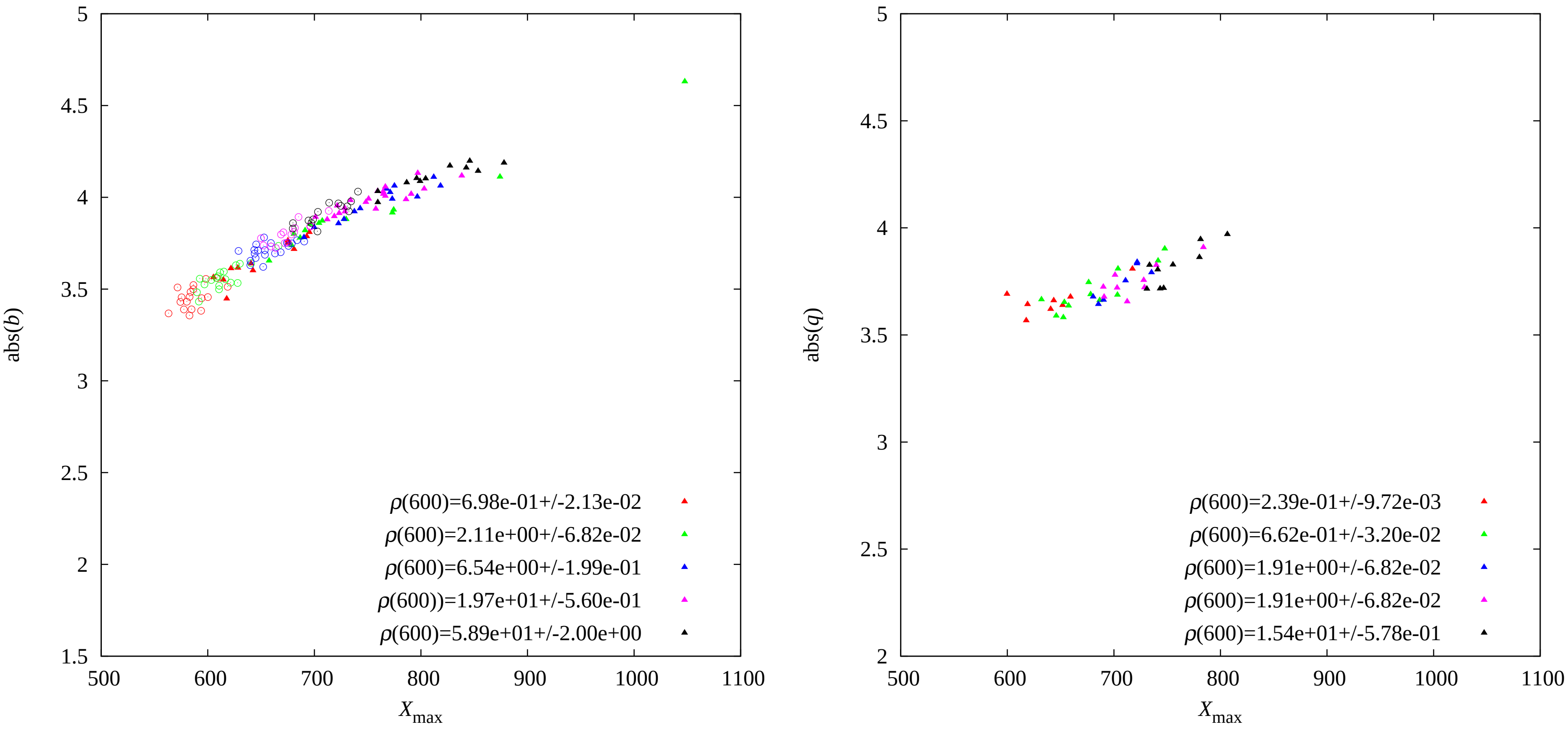
Individual slope parameters selected by $\rho(600)$. Left — charged particles, right — muons (QGSjet II model).

$\rho(600)$ selection, $\theta = 0°$; charged particles (left), muons (right)

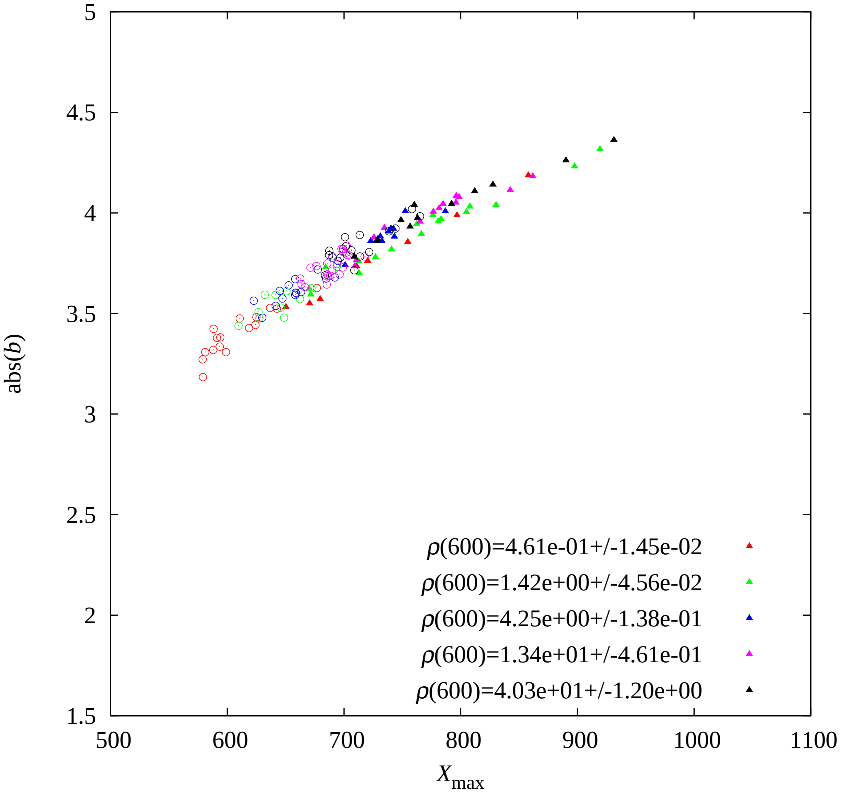


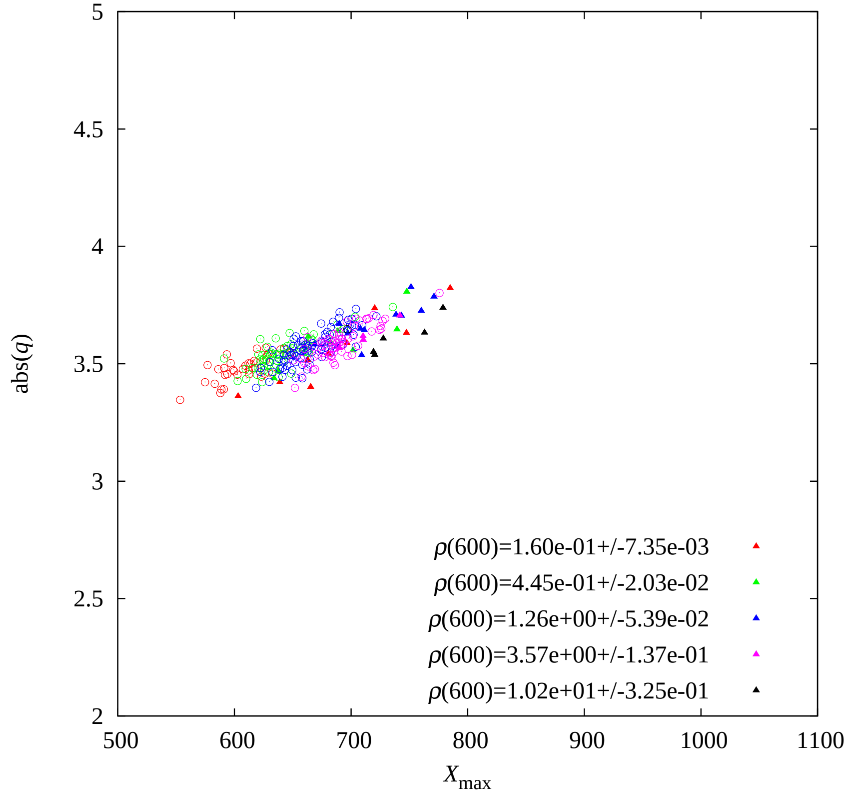


$\rho(600)$ selection, $\theta = 0°$; charged particles (left), muons (right)

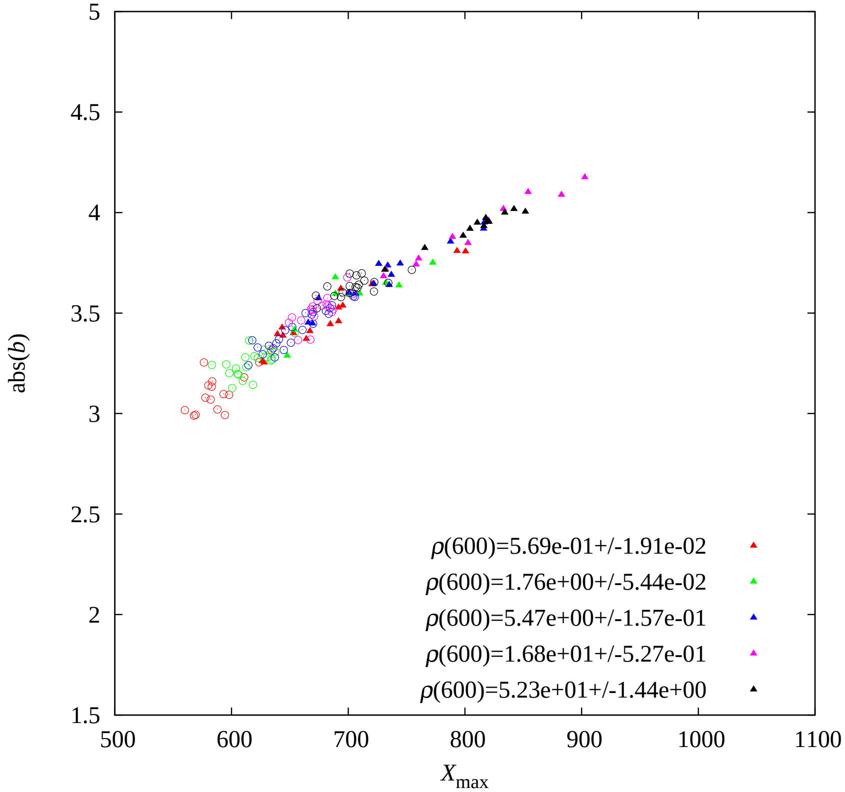


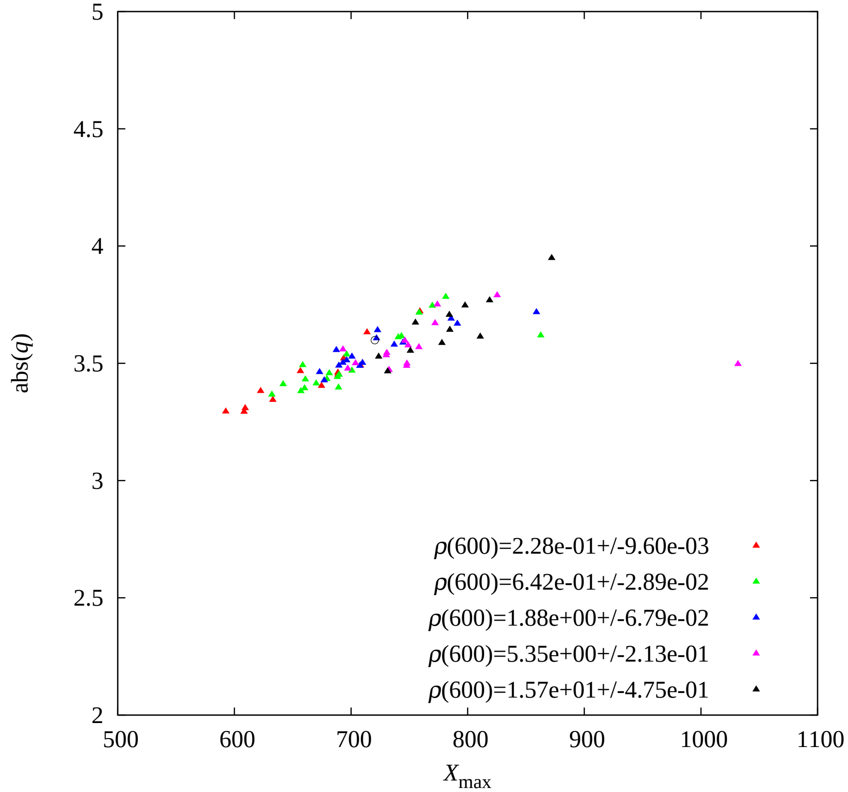
$\rho(600)$ selection, $\theta = 27^\circ$; charged particles (left), muons (right)



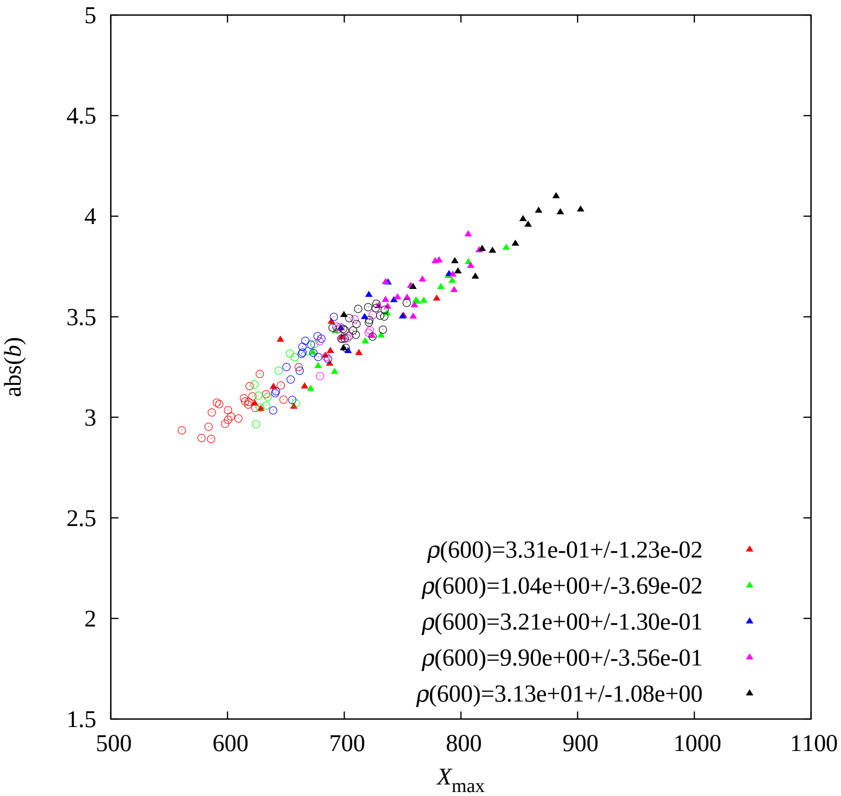


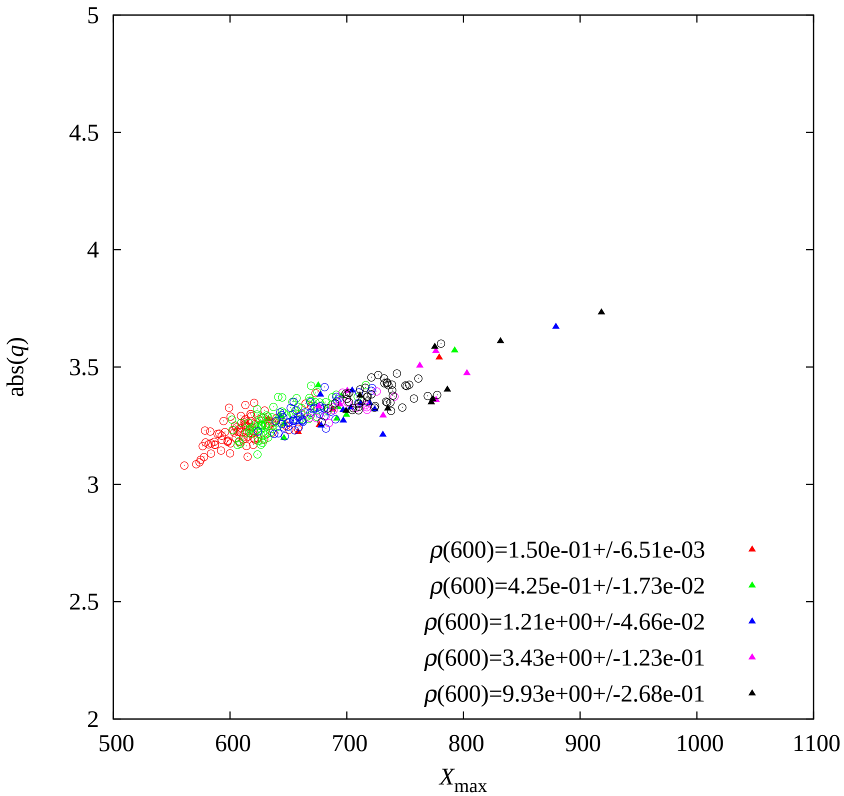
$\rho(600)$ selection, $\theta = 27^{\circ}$; charged particles (left), muons (right)



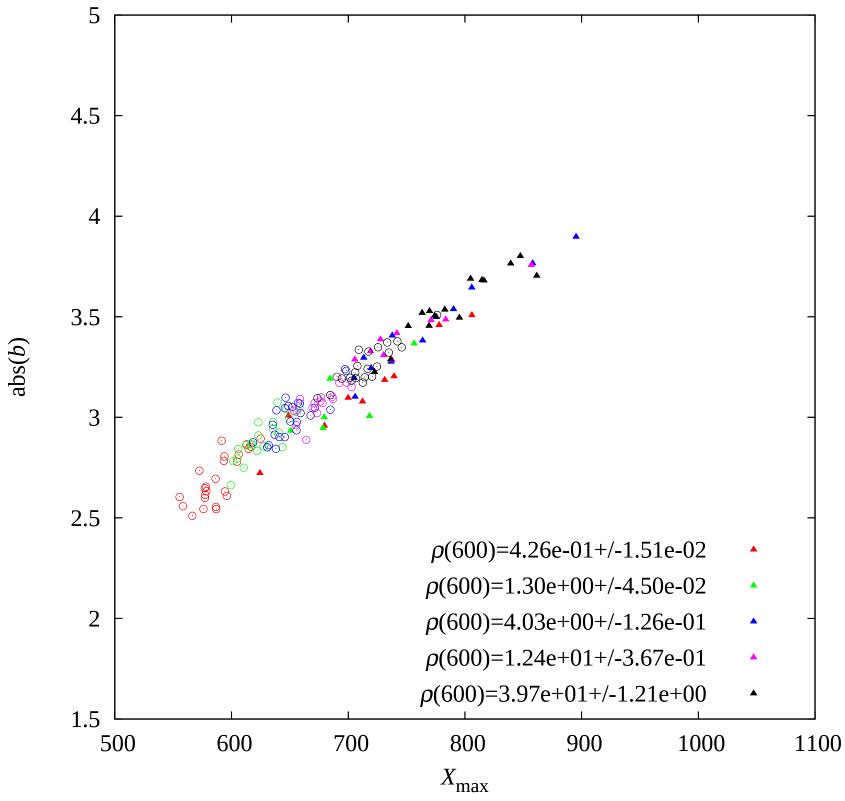


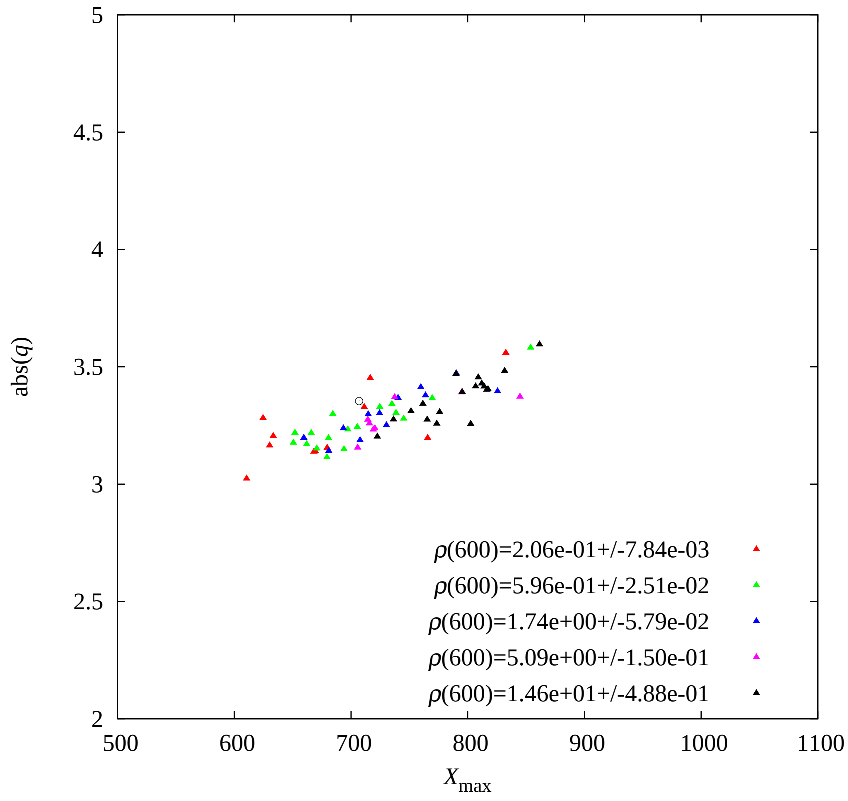
$\rho(600)$ selection, $\theta = 38.55°$; charged particles (left), muons (right)



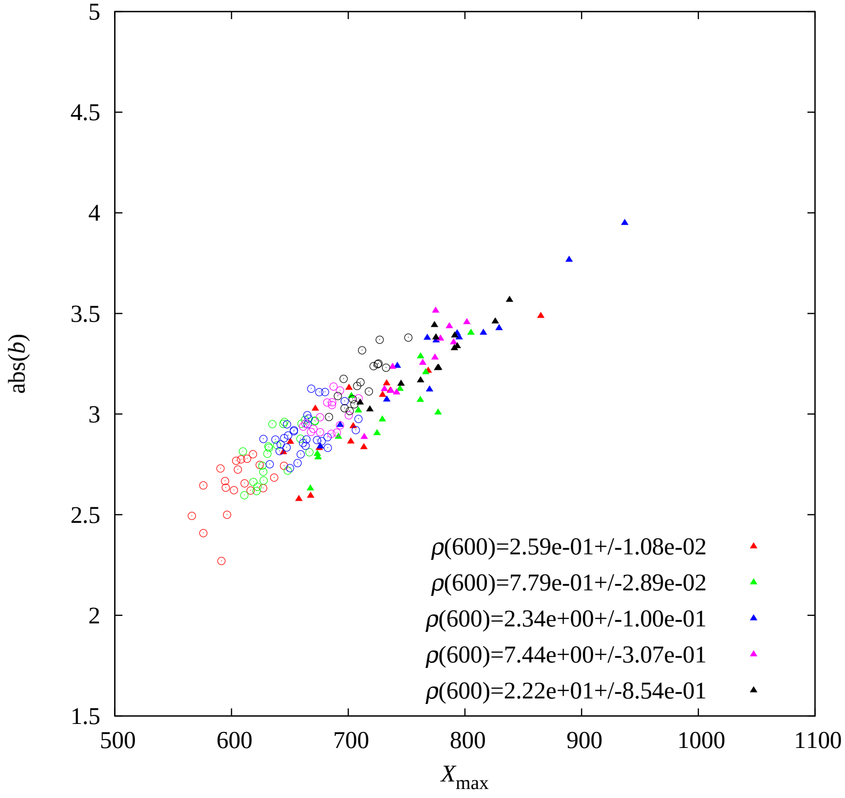


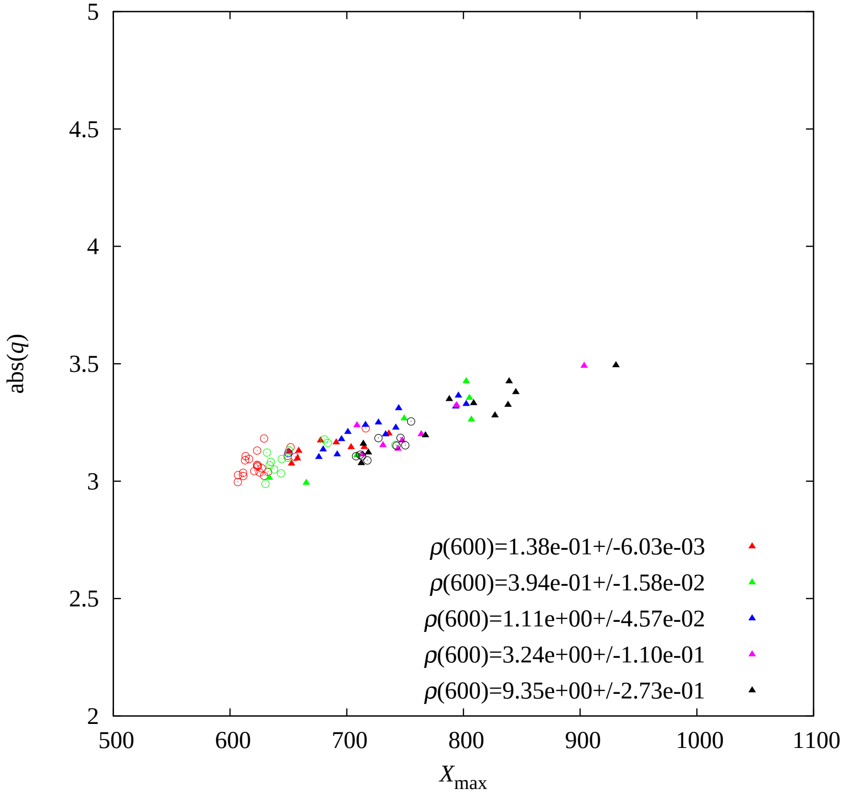
$\rho(600)$ selection, $\theta = 38.55°$; charged particles (left), muons (right)



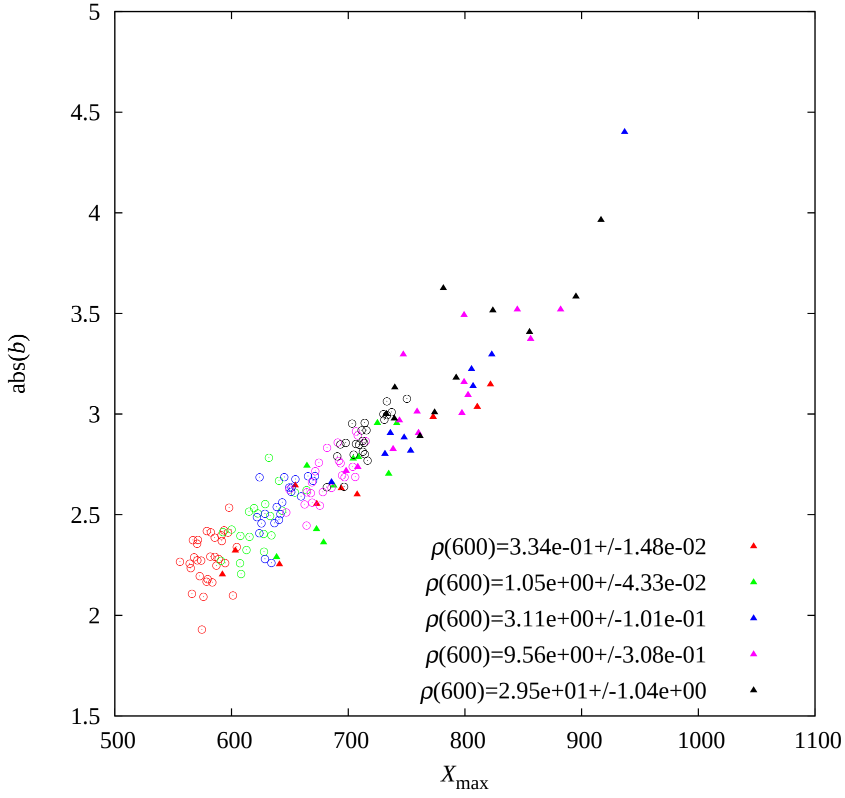


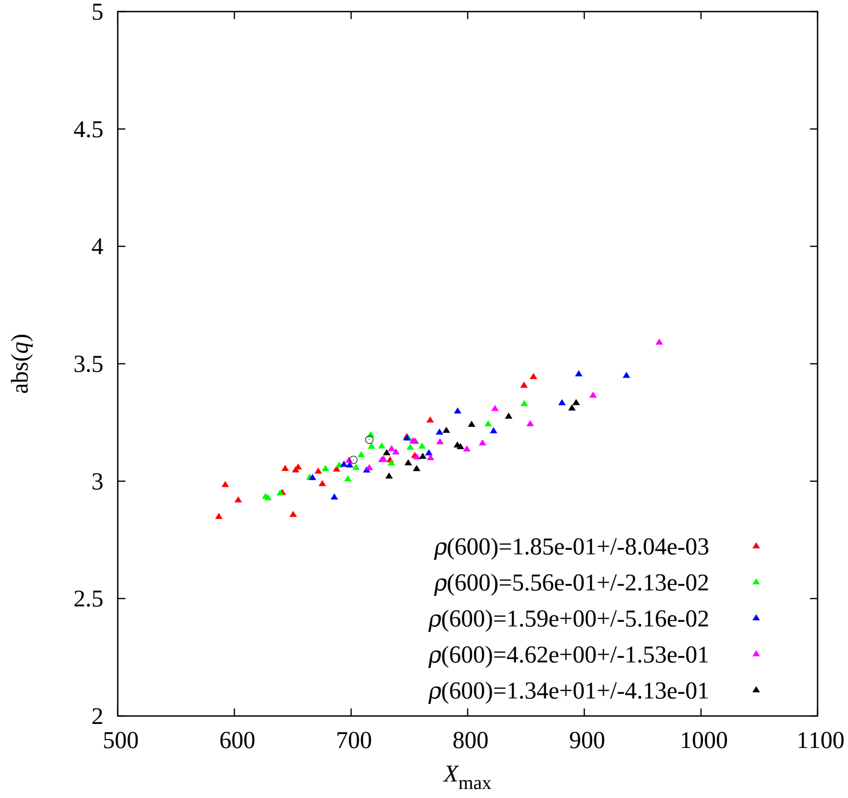
$\rho(600)$ selection, $\theta = 45°$; charged particles (left), muons (right)



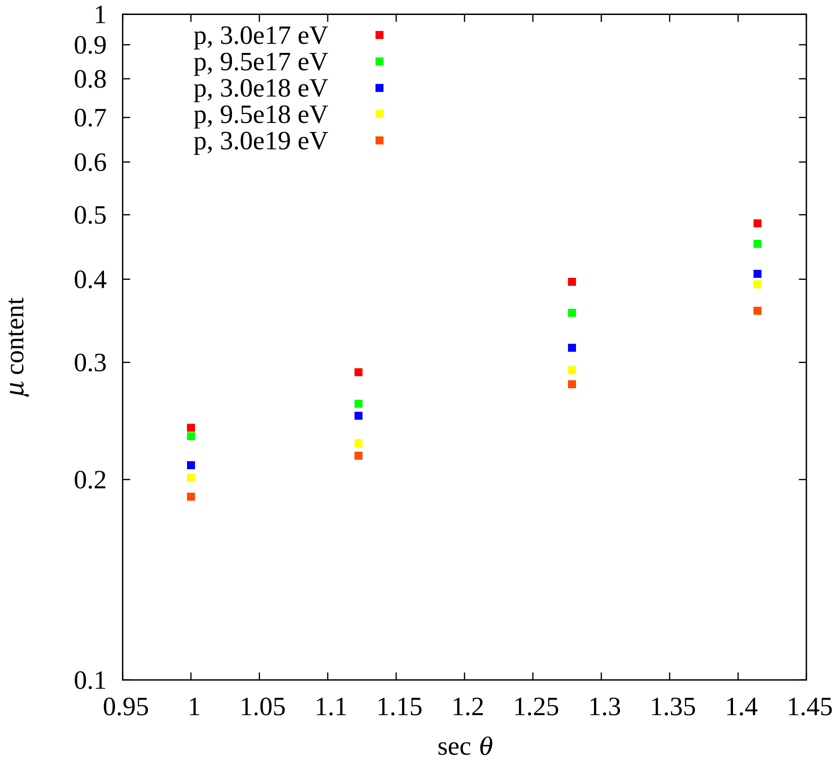


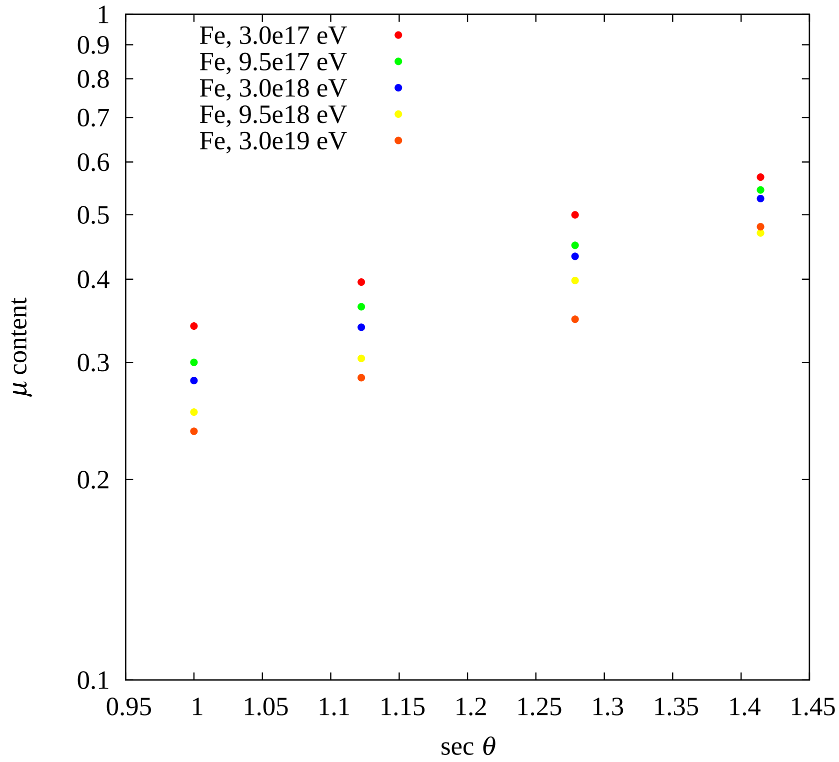
$\rho(600)$ selection, $\theta = 45^{\circ}$; charged particles (left), muons (right)



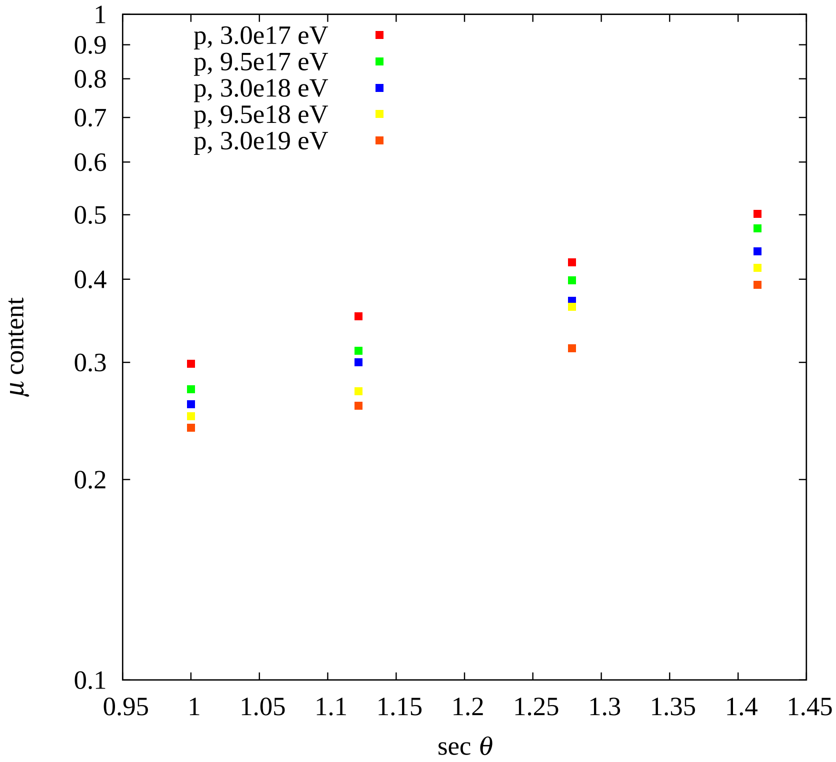


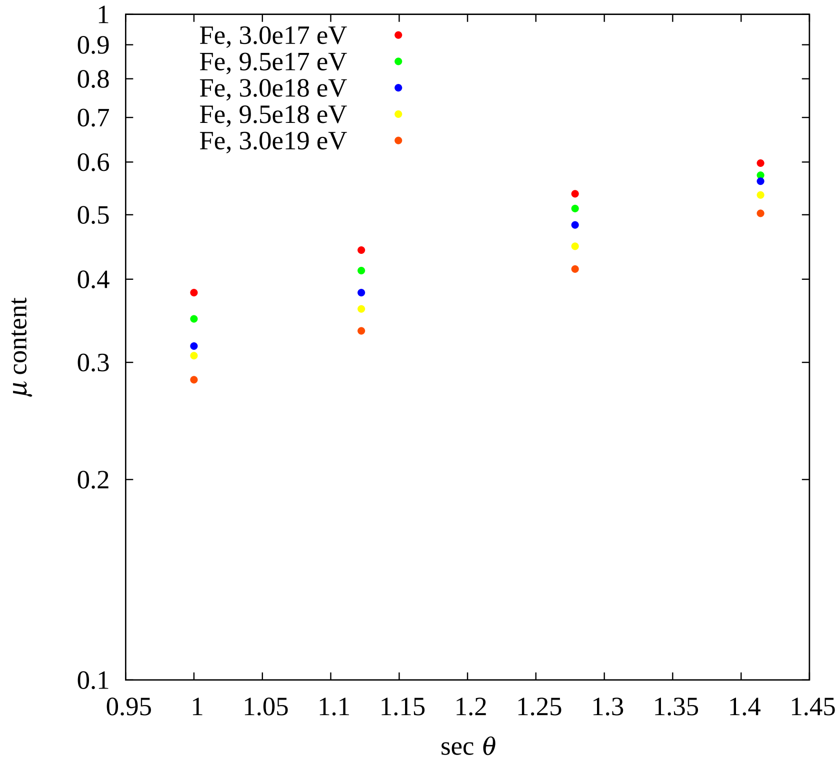
Mean muon content, **QGSjet II**, left — p, right — Fe



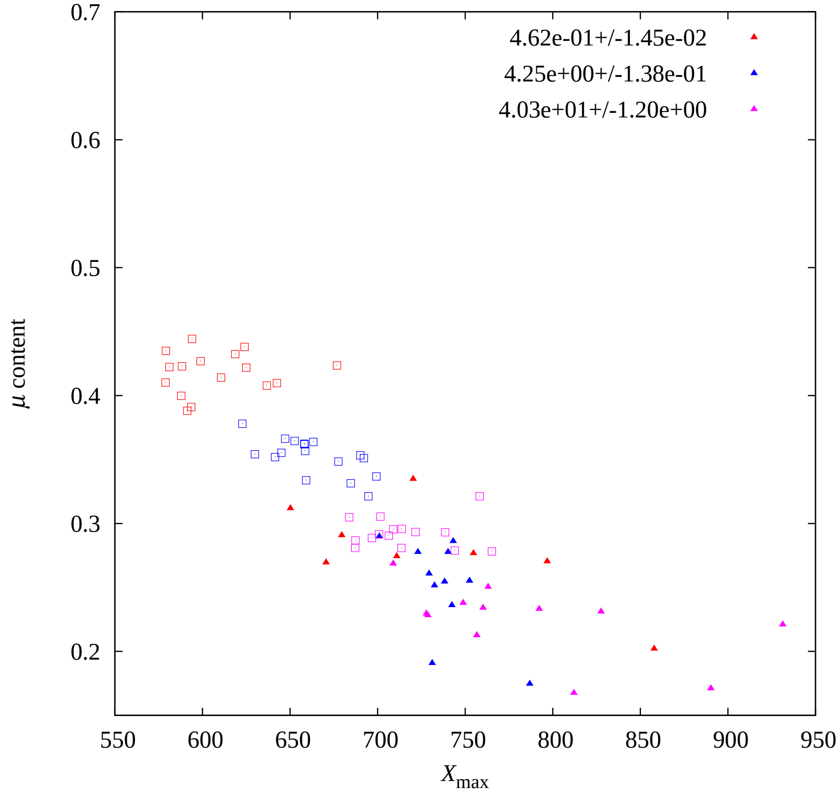


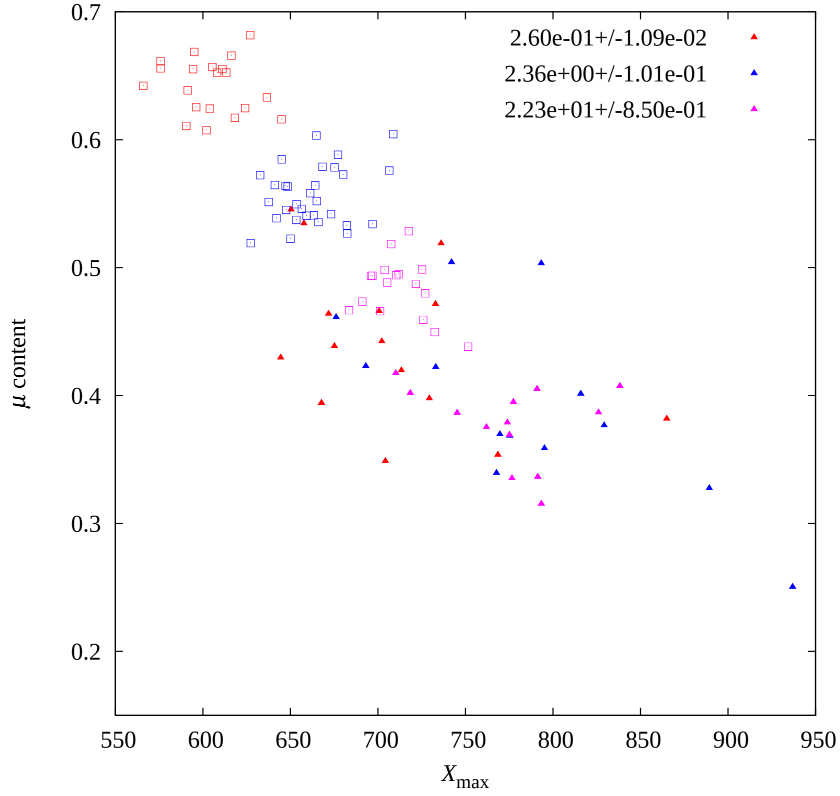
Mean muon content, **EPOS**, left — p, right — Fe



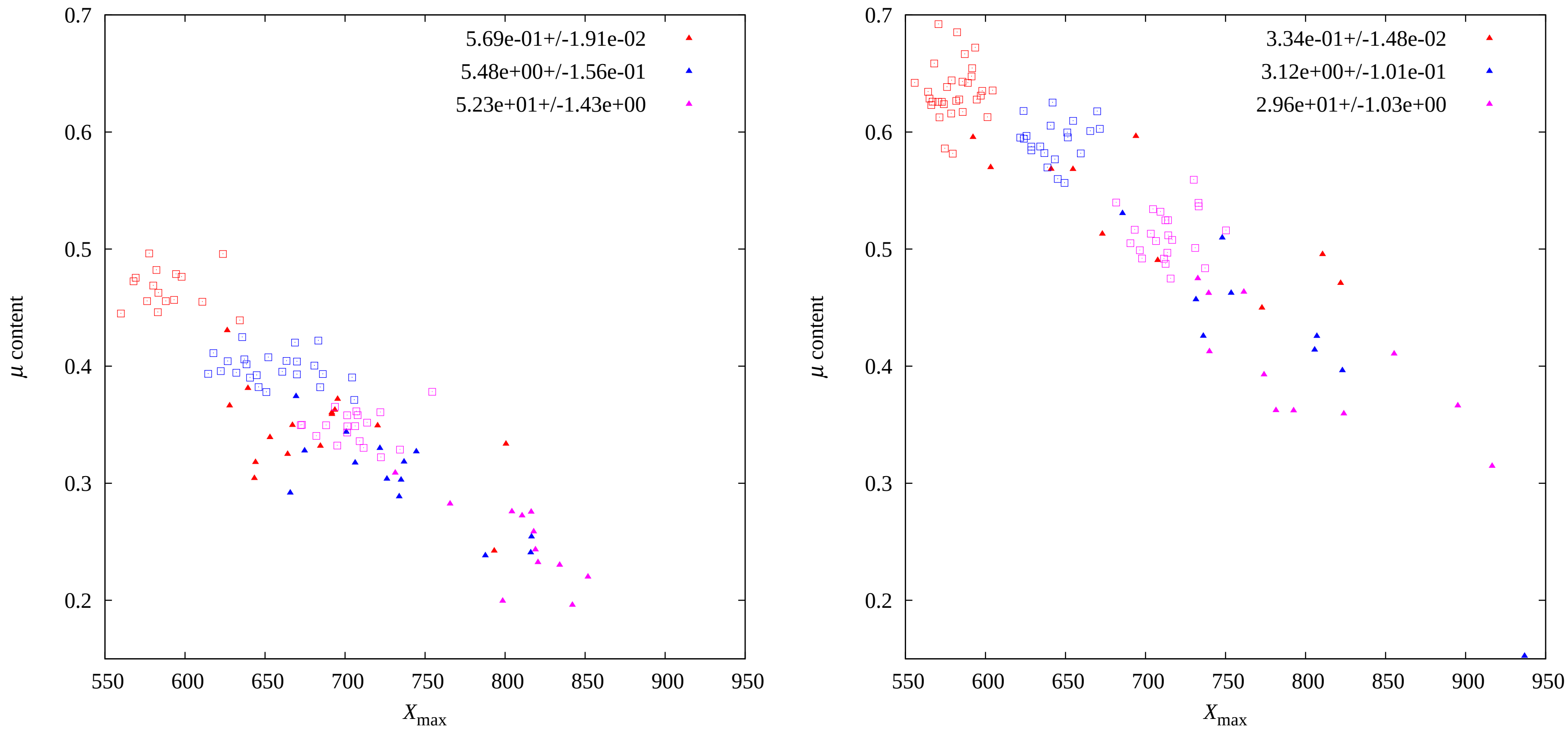


$\rho_\mu(600)/\rho_e(600) - X_{\text{max}}$: **QGSjet II**, $\theta = 27^\circ$ (left), $\theta = 45^\circ$ (right)





$\rho_\mu(600)/\rho_e(600) - X_{\max}$: **EPOS**, $\theta = 27^\circ$ (left), $\theta = 45^\circ$ (right)



Conclusions

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 Cherenkov light data and expand X_{max} reconstruction by Cherenkov light flux distribution.

However, individual LDF parameters are quite model dependent and a comparison with the experimental data is to be done.