On the Combined Analysis of Muon Shower Size and Depth of Shower Maximum

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Abstract

The mass composition of ultra-high energy cosmic rays can be studied from the distributions of the depth of shower maximum and/or of the muon shower size. We study the dependence of the mean muon shower size on the depth of shower maximum in more details. Air showers induced by four nuclei were simulated with two models of hadronic interactions already tuned with LHC data (run I-II). The generated air showers were combined to obtain various types of mass composition of the primary beam. We investigate the shape of functional dependence of the mean muon shower size (at ~1400m a.s.l.) on the depth of shower maximum and its dependency on the composition mixture. Fitting this dependence we can derive the primary fractions and the muon rescaling factor with a statistical uncertainty at a level of few percent. The difference between the reconstructed primary fractions was mostly below ~25% when different models were considered. The difference in the muon shower size between the two models was observed to be around 6%.

1. CONEX[1,2] Simulations

10^5 showers with $10^{18.5}$ eV induced by i = **p**, **He**, **N** and **Fe** for θ = <0°, 60°>, $\sigma(X_{max})$ = 20 g/cm², $\sigma(N_\mu)/N_\mu$ = 10%

Fig. 1: Parametrized X_{max} distributions
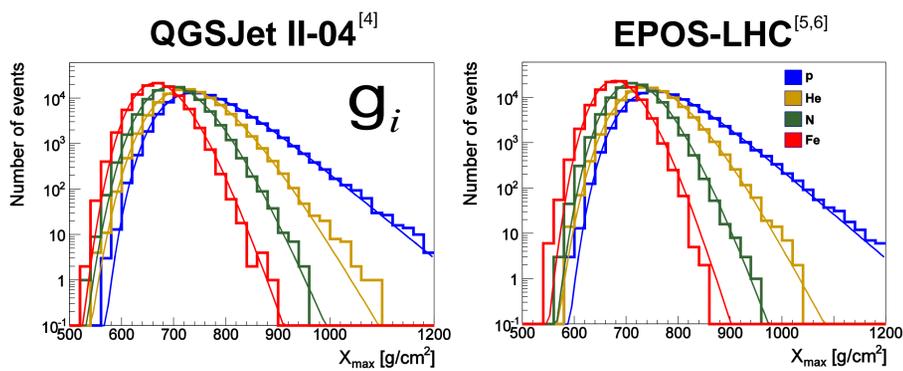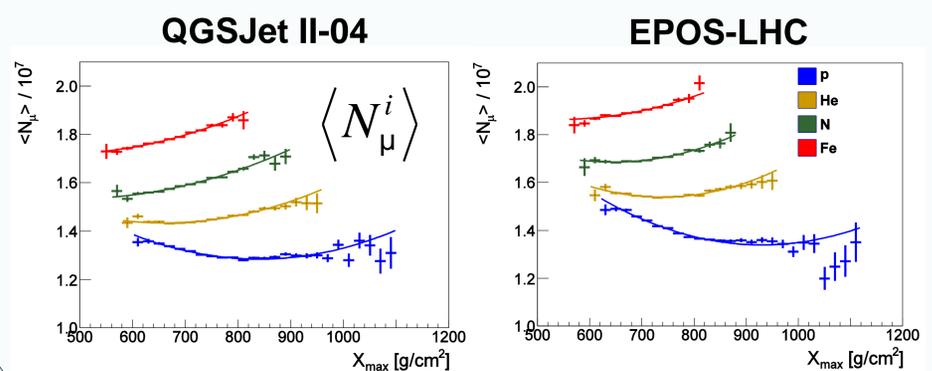with Gumbel[3] functions g_i for each primary

QGSJet II-04[4]   EPOS-LHC[5,6]

Fig. 2: Parametrized $<N_\mu>(X_{max})$
with quadratic functions $<N_\mu^i>$ for each primary

QGSJet II-04   EPOS-LHC

2. Method

- X_{max} distribution is parametrized (Fig. 1) with Gumbel function $g_i(X_{max})$ for each of 4 primaries.
- $<N_\mu>(X_{max})$ is parametrized (Fig. 2) with quadratic function $<N_\mu^i>(X_{max})$ for each of 4 primaries.
- R_μ is rescaling of $<N_\mu^i>$.
- $<N_\mu>(X_{max})$ of a combination of showers induced by 4 primaries with relative fractions f_i is fitted with **4 parameter (f_p, f_{He}, f_N, R_μ) fit** (example in Fig. 3).

$$\langle N_\mu \rangle = \sum_i \left(w_i \langle N_\mu^i \rangle \right) \cdot R_\mu$$

$$w_i = \frac{f_i \cdot g_i}{\sum_j (f_j \cdot g_j)} \qquad i,j = \mathrm{p, He, N, Fe} \qquad \sum_i f_i = 1$$

Fig. 3: Example for EPOS-LHC
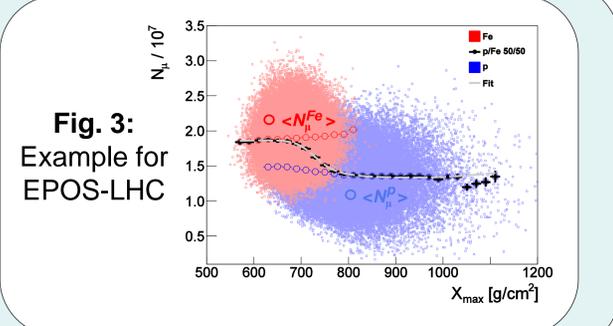
3. Applications & tests

QGSJet II-04: QGSJet II-04 showers reconstructed with QGSJet II-04 parametrization — Tests of method precision
EPOS-LHC: EPOS-LHC showers reconstructed with EPOS-LHC parametrization
Scenario 1: QGSJet II-04 showers reconstructed with EPOS-LHC parametrization — Tests of systematics wrt. models
Scenario 2: EPOS-LHC showers reconstructed with QGSJet II-04 parametrization

Fig. 4: Comparison of fitted and true primary fractions
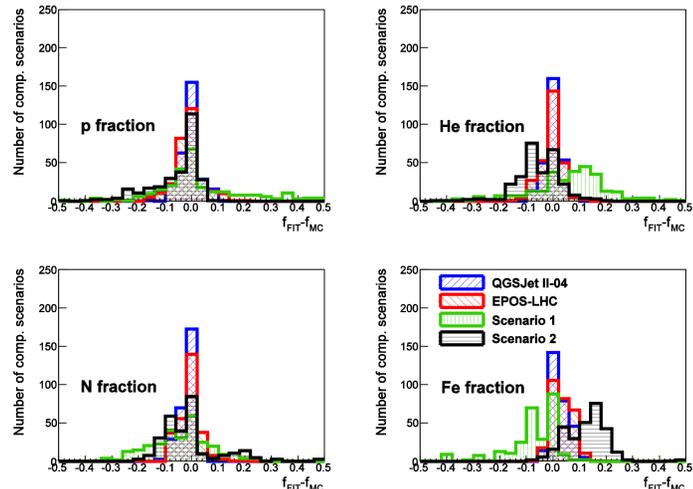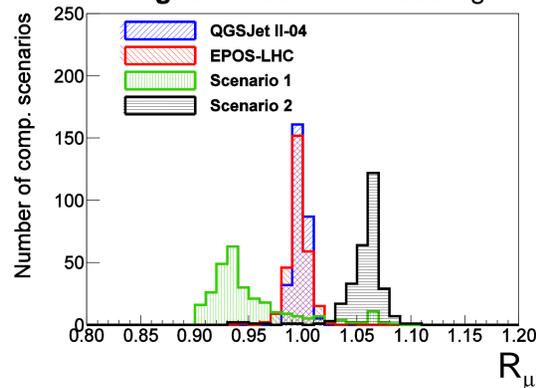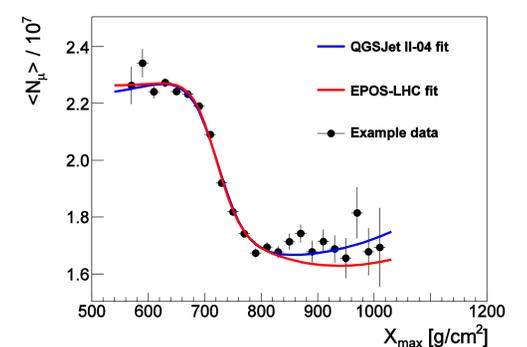

Fig. 5: Fitted muon rescaling

All 286 combinations of 4 primaries in steps of 10%

Fig. 6: Example data
5000 p and 5000 Fe QGSJet II-04:
X_{max} + 7 g/cm², N_μ x 1.3

Tab. 1	f_p [%]	f_{He} [%]	f_N [%]	R_μ
QGSJet II-04 parametrization	41 ± 2	0 ± 1	0 ± 1	1.29 ± 0.01
EPOS-LHC parametrization	52 ± 3	4 ± 3	0 ± 1	1.21 ± 0.01

4. Conclusions

- When the **proper parametrization** of X_{max} distribution and $<N_\mu>(X_{max})$ for 4 primaries is known, the primary fractions and the muon rescaling factor can be **determined within few %** (red and blue in Figs. 4, 5).
- The difference of the **primary fractions** reconstructed with two parametrizations based on the **most recent models** of hadronic interactions was observed **below ~ 25%** (green and black in Fig. 4, Tab. 1).
- The **muon rescaling factor** reflected the relative difference (**around 6%**) in the average muon shower size of the **two models** (green and black in Fig. 5, ratio of R_μ in Tab. 1).

References

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