Lower limit on the ultra-high-energy proton-to-helium ratio from the measurements of the tail of X_{max} distribution

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Introduction

The mass composition of the ultra-high-energy cosmic rays lies among the key tasks of major present-day and upcoming experiments. The precise knowledge of the composition is important for understanding the cosmic-ray production mechanism in the sources and its population [1]. Moreover, composition at the highest energies is the decisive factor for the observable flux of cosmogenic photons [2, 3] and neutrinos [4, 5].

Another implication of the mass composition at ultra-high energies is the investigation of safety of the future colliders [6]. The collider safety investigations are based on the constraints on the black hole production derived from the stability of dense astrophysical objects, such as white dwarfs and neutron stars interacting with the ultra-high-energy cosmic rays. The primary protons play an important role as the production of the black holes is determined by the energy per nucleon.

One of the most common approaches is the measurement of the longitudinal shape of the extensive air showers (EAS). The depth of a shower maximum, or X_{max}, is used as a composition-sensitive variable. The measurements of the mean X_{max} gives the estimate of the average atomic mass, while the study of the X_{max} distribution and its moments may resolve the multicomponent composition.

Although the tail of the X_{max} distribution may be studied independently on the main part of the distribution. It may be fit with an exponential function $\exp(-X_{\mathrm{max}}/\Lambda)$, where Λ is called the attenuation length. The attenuation length is found to be sensitive to the proton-air interaction cross-section. It was shown in [7] that the attenuation length may be used to estimate the proton-to-helium ratio $\mathrm{p/He}$. The latter estimate has only minor dependence on the hadronic interaction models and X_{max} experimental systematic uncertainties.

The present work is dedicated to the determination of proton-to-helium ratio of ultra-high-energy cosmic rays in the energy range from $10^{18.3}$eV to $10^{19.3}$eV based on the Telescope Array measurements of the attenuation length [8]. The data is compared to the Monte-Carlo simulations using the CORSIKA package along with the QGSJET II-04 and EPOS-LHC hadronic interaction models.

Method

The method generally follows the work of Yushkov et. al [7] to derive the proton-to-helium ratio using the measurements of the attenuation length by the Telescope Array collaboration [8].

At first, the simulated sets of extensive air showers initiated by primary protons, helium and carbon are produced with the use of the CORSIKA package. Simulations are performed separately with QGSJET II-04 and EPOS-LHC hadronic interaction models. For the Telescope Array, $17\,354$ events are simulated for each species in the energy range from $10^{18.3}$eV to $10^{19.3}$eV with the spectrum obtained by the Telescope Array collaboration defined by the spectral index -3.226 for $E < 10^{18.72}$ eV and -2.66 for $E > 10^{18.72}$ eV.

At the second step, the simulated sets are "mixed" in different proportions from $\mathrm{p/He} = 0.01$ to $\mathrm{p/He} = 100.0$. For each mixture the X_{max} distribution slope is fitted exponentially to derive the attenuation length for a mixed composition model.

Finally, after performing the fit of each mixture's X_{max} distribution, Λ_i values are obtained as a function of $\mathrm{p/He}$ ratio. The constraints on the proton-to-helium ration are then obtained by comparing these values with the experimental Λ values [8].

An important constituent of this method is the choice of the starting point of the fit: it can be defined in many different ways. Yushkov et. al [7] have proposed another determination of lower fit range, which involves carbon X_{max} distribution: the lower limit is defined as a value at which only $\approx 0.5\%$ of the carbon-initiated showers get into the fitting range. In the present work we follow the method implemented by Abbasi et al. [8], where the lower limit is defined as the $X_i = \langle X_{max}\rangle + 40\mathrm{g/cm}^2$, where $\langle X_{max}\rangle$ is the average value of a given distribution.

Results

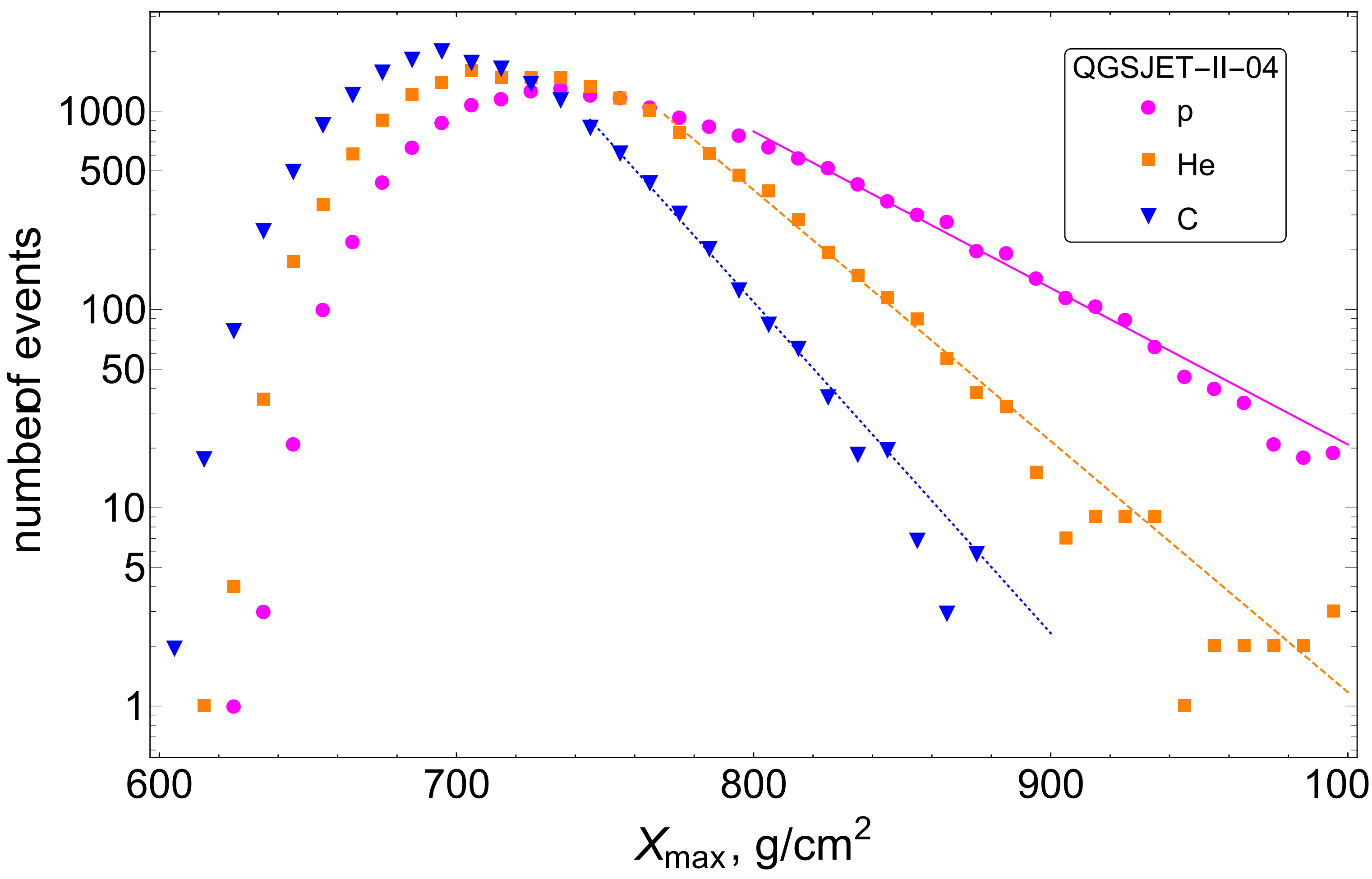

Figure 1: X_{max} distributions for $10^{18.3}\mathrm{eV} < E < 10^{19.3}\mathrm{eV}$ for proton (magenta), helium (orange) and carbon (blue) Monte-Carlo distributions simulated with QGSJET II-04. X_{max} distribution's tail exponential fit $\exp(-X_{\mathrm{max}}/\Lambda)$ is shown for each Monte-Carlo with a line of the corresponding color.

We present the X_{max} distributions and corresponding fits of exponential tails for proton, helium and carbon Monte-Carlo simulated sets in Figure 1.

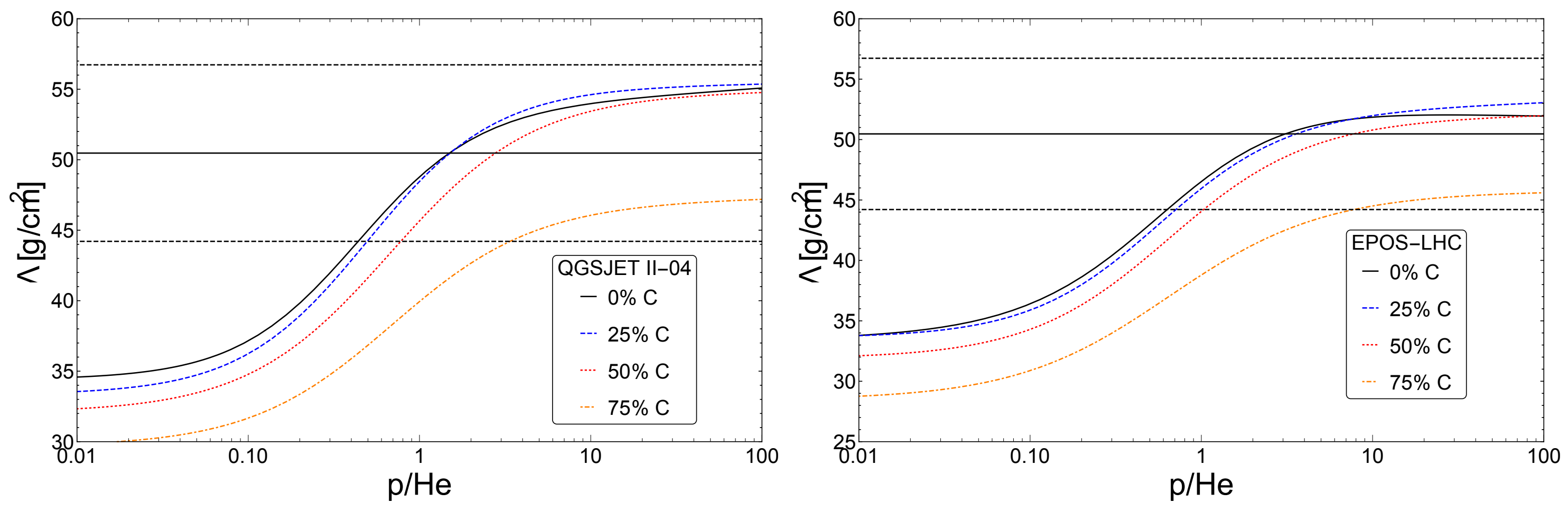

Figure 2: Λ parameter as a function of proton-to-helium ratio for two-component mixture (p and He, black line) and three component mixtures (p, He and 25 % C – green line; p, He and 50 % C – red line; p, He and 75 % C – orange line) of Monte-Carlo events simulated with QGSJET II-04 (left) and EPOS-LHC (right). Black solid and dashed lines correspond to the experimental value $\Lambda = 50.47 \pm 6.26\ \mathrm{g/cm}^2$ obtained by the Telescope Array collaboration [8].

Λ as a function of proton-to-helium ratio in QGSJET II-04 and EPOS-LHC models is shown in Figure 2 with a black line. The plot includes the proton-to-helium ratio range from $\mathrm{p/He} = 0.01$ to $\mathrm{p/He} = 100$ with a step $\Delta = 10^{0.2}$. Comparing the Monte-Carlo function with the experimental value $\Lambda = 50.47 \pm 6.26\ \mathrm{g/cm}^2$ obtained by the Telescope Array collaboration [8] we arrive at the following lower limits on the proton-to-helium ratio:

$$\begin{aligned} &\mathrm{p/He} > 0.43\ (68\%\ \mathrm{CL}) \quad \text{QGSJET II-04},\\ &\mathrm{p/He} > 0.63\ (68\%\ \mathrm{CL}) \quad \text{EPOS-LHC}. \end{aligned} \tag{1}$$

We note that the pure proton composition is well compatible with the measured attenuation length.

The stability of the method in respect to the admixture of the heavier elements is studied. For this reason, the analysis is repeated for three-component mixtures containing 25%, 50% and 75% of carbon and corresponding Λ is shown in Figure 2 by red triangles and green squares respectively. One may see that the (1) are conservative to addition of the heavier elements as expected in [7].

One may further study the three-component mixture of protons, helium and carbon. By calculating Λ for all possible combinations we arrive to the following lower limits on the fraction of protons in the three-component mixture:

$$\begin{aligned} &\mathrm{p/(p + He + C)} > 0.20\ (68\%\ \mathrm{CL}) \quad \text{QGSJET II-04},\\ &\mathrm{p/(p + He + C)} > 0.23\ (68\%\ \mathrm{CL}) \quad \text{EPOS-LHC}, \end{aligned} \tag{2}$$

The following 95% CL limits may be obtained repeating the analysis done for Equation (2):

$$\begin{aligned} &\mathrm{p/(p + He + C)} > 0.09\ (95\%\ \mathrm{CL}) \quad \text{QGSJET II-04},\\ &\mathrm{p/(p + He + C)} > 0.11\ (95\%\ \mathrm{CL}) \quad \text{EPOS-LHC}. \end{aligned} \tag{3}$$

Conclusions

The present limits constrain the models with helium domination in the energy range under study, e.g. the helium version of the disappointing model [9]. These models generally include the preferential acceleration of helium or an excessive helium abundance at the acceleration region. At the same time, the result is fully compatible with the original pure proton dip model [10, 11, 12] and with the modification of the dip model with $\mathrm{p/He} = 5$ [13] as long as with the standard disappointing model [9] with $\mathrm{p/He} \sim 1$.

The results are also in favor of the safe operation of the future colliders [6]. Still the importance of issue demand higher confidence which may be achieved with the future precision measurements of the attenuation length.

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