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Cosmic Ray Mass Composition Problem: towards model-independent evaluation based on the analysis of the spatial and temporal structure of EAS charged components

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The determination of the mass composition of primary cosmic rays is at present stage the crucial issue for understanding their origin and propagation through the interstellar medium. The mass composition above 10^{14} eV is inferred from the extensive air shower (EAS) observations by comparisons with simulations results, which rely on accurate description of air shower physics including hadronic interaction models uncertain in the relevant energy range. Numerous methods and techniques are implemented, including analysis of mean values, fluctuations, correlations or even particular features of distributions of different observables characterized both longitudinal and spatial shower development (depth of maximum, muon production depth, total number of electrons and muons at the observation level and their local densities at various distances from the shower axis, particles arrival time profiles, spatial distributions of radio emission and Cherenkov light etc.). Large efforts have been made recently in both gaining experimental data with increased resolution in detection of various EAS components and developing improved methods for physical interpretation of the data along with evolving hadronic interaction models after the LHC results. Nevertheless, the composition results still remain ambiguous in the entire energy range available for EAS studies.

The discrepancies between estimates of mass composition derived by various methods from the data of different experiments, in addition to insufficiency in statistics, are apparently caused by complex of instrumental and methodological systematic biases of different nature, as well as by strong model dependence of the observables, mostly in case of muon component characteristics (so-called "Muon Puzzle"), disadvantages in taking into account meteorological effects etc.

A possible solution might be achieved with refined (multi-)hybrid measurements together with generalizations of the analysis by revealing universal features, based on the intrinsic physic properties of air showers, evaluation of new parameters and functionals, which are weakly sensitive to the hadronic interaction model being good primary mass indicators.

In this paper we present the updated analysis of spatial distributions of electrons and muons with respect to the scale invariance in lateral distribution (LD) functions (the extended scaling formalism). We demonstrate that this formalism enables accurate description of lateral distributions of electrons and muons by one-parametric scale-invariant functions in wide primary energy and radial distance ranges. The scale-invariance of LD and air shower universality manifesting through the functional dependence between radial scale factors and longitudinal shower age are both insensitive to hadronic interaction models. An additional composition sensitive observable, which can be included in the multicomponent analysis of experimental data obtained by 100% duty cycle ground-based detectors, is time profile of charged particles measured by surface scintillation counters at different ranges of radial distances.

Thus, integrated spatial and temporal characteristics of the charged EAS component can be effectively used as a source of the improved cosmic ray mass composition results when interpreting the experimental data of the ground-based EAS arrays. The proposed approach could be implemented for the present and future (multi-)hybrid air shower observations by TAIGA, Yakutsk Complex Air Shower Array, Auger and Telescope Array observatories taking into account their upcoming upgrades, as well as for re-analysis and cross-calibration of the data collected from different air shower arrays within the single method in a broad primary energy range.

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