

Sensitivity of Extensive Air Showers to Features of Hadronic Interactions at Ultra-High Energies

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Abstract. We study the dependence of extensive air shower development on the first hadronic interactions at ultra-high energies occurring in the startup phase of the air shower cascade. The interpretation of standard air shower observables depends on the characteristics of these interactions. Thus, it is currently difficult to draw firm conclusions for example on the primary cosmic ray mass composition from the analysis of air shower data. On the other hand, a known primary mass composition would allow us to study hadronic interactions at center of mass energies well above the range that is accessible to accelerators measurements.

Keywords: Hadronic interactions, extensive air showers, ultra-high energies

I. INTRODUCTION

Currently, the interpretation of existing high quality air shower data in terms of important properties as e.g. the primary mass composition, is complicated by the poorly constraint hadronic interaction physics at ultra-high energies (e.g. Ref. [1]). For an unambiguous analysis of air shower data reduced uncertainties of interaction characteristics are needed.

The longitudinal development of extensive air showers is very sensitive to hadronic interaction in the startup phase of the air shower cascade. These few interactions at ultra-high energies are subject to particularly large uncertainties; Their characteristics must be inferred from extrapolations of accelerator data at much lower energies to cosmic-ray energies and secondary particle production phase space. These extrapolations are not well constraint by theory nor experiment [2]. To explore the importance of these extrapolations to ultra-high energies on the final resulting air shower observables, we modified these extrapolations during air shower simulations.

If, with the help of astrophysical arguments, the composition of cosmic rays of a specific energy can be constraint, then it is possible to learn about the physics of hadronic interactions at energies far above the LHC from the analysis of air shower data. This would allow one to use ultra-high energy cosmic ray observatories as fixed target particle physics experiments at energies up to $\sqrt{s} \sim 450$ TeV, which is far above the reach of any Earth-based particle accelerator.

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II. MODIFIED AIR SHOWER SIMULATIONS

For our studies we implemented a modified version of the CONEX [4] air shower simulation program that can modify the characteristics of hadronic interactions during the simulation. We adapt the following factor to re-scale specific properties of hadronic interactions:

$$f(E) = 1 + (f_{19} - 1) F(E) \quad (1)$$

with

$$F(E) = \begin{cases} 0 & E \leq 1 \text{ PeV} \\ \frac{\ln(E/1 \text{ PeV})}{\ln(10 \text{ EeV}/1 \text{ PeV})} & E > 1 \text{ PeV} \end{cases}, \quad (2)$$

where E is the energy of the projectile of the interaction. The factor $F(E)$ is 0 below 10^{15} eV, and thus $f(E) = 1$, where accelerator data is available to constrain the models (the Tevatron corresponds to $\sim 2 \times 10^{15}$ eV). At higher energies $F(E)$ is increasing logarithmically with energy, reflecting the growing uncertainty of the extrapolation with energy. The resulting impact of $f(E)$ on the extrapolation of the production cross section is shown in Fig. 1. By using Eq. (1) for all interactions during the simulated air shower development with energies above 10^{15} eV, the effect of the modified extrapolation to ultra-high energies affects not only the primary cosmic ray-air interaction, but also the high energy interactions in the startup phase of the air shower, until the energy of the particles drops below 10^{15} eV.

The interactions of hadrons, and thus in particular of primary proton cosmic ray particles, are directly

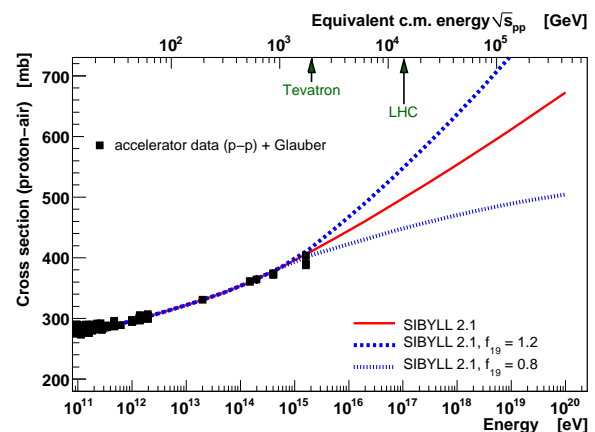


Fig. 1. Example of a modified hadronic production cross section for SIBYLL for a 20% increase and decrease of f_{19} [8].

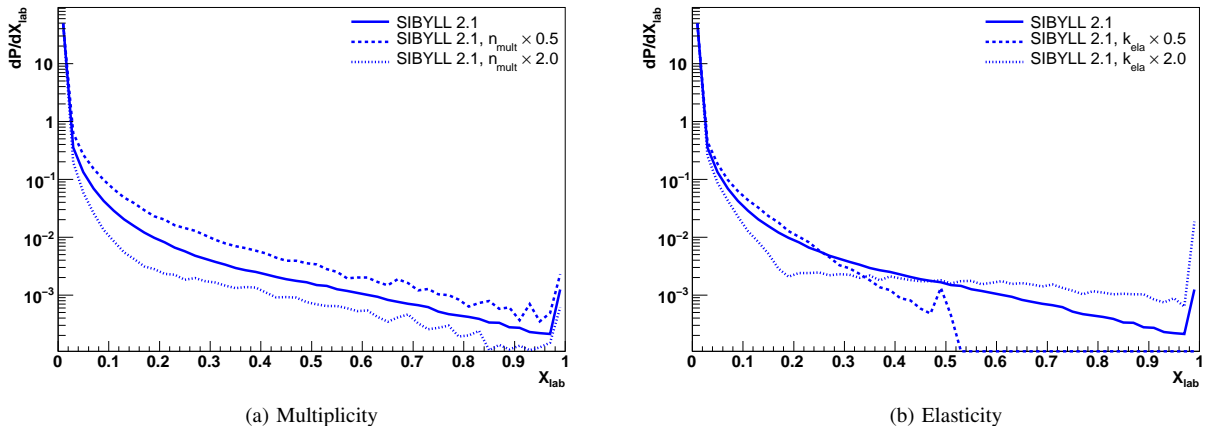


Fig. 2. Impact of secondary particle resampling on X_{lab} -distributions [3].

modified by using the factor Eq. (1). For nuclei, however, the semi-superposition model [5, 6] is applied in order to describe the interactions of nuclei based on the fundamental hadronic interactions of the individual nucleons of the nucleus. Since this model is implemented within the SIBYLL event generator [7], the handling of primary nucleons is straightforward and all results presented here are based on the SIBYLL model.

To change characteristics of the secondary particle production, like e.g. the multiplicity or the elasticity, we developed a secondary particle re-sampling algorithm that, by deletion or duplication of existing particles and re-distributing of kinetic energy between secondary particles, can achieve to modify these characteristic properties. At the same time great care is invested to conserve all relevant physical quantities such as the total energy, leading particles, charge, particle types and energy fractions in particle type groups as far as possible. Also the momentum of all particles is consistently recalculated. A detailed description of the algorithm can be found in Ref. [3]. In Fig. 2 the impact of the resampling algorithm for multiplicity and elasticity on secondary particle X_{lab} -distributions is displayed. For the modified multiplicity the number of particles is rescaled, while leaving the shape of the X_{lab} -distribution almost untouched, in particular the leading particle is conserved. In the case of a modified elasticity kinetic energy is re-distributed between the leading particle and the rest of the secondaries. For an increased elasticity the leading particle inherits energy from the other particles, so these particles are accumulating at lower energies. For the decreasing elasticity the leading particle loses significance by a reduction of its energy. This leads to a generally more uniform distribution of the total energy on all the secondaries, and in the limiting case to the equal distribution of energy on all secondaries.

For our study we simulated 1000 air showers for each value of f_{19} . All simulations were performed at primary energies of $10^{19.5}$ eV for proton and iron primaries.

III. RESULTS

We are concentrating on three features of hadronic interactions, that can be easily attributed a direct impact on air shower development. These are the hadronic production cross section σ , secondary multiplicity n_{mult} and the elasticity $k_{ela} = E/E_{tot}$. Extended Heitler models (e.g. Ref. [9]) exhibit the relation between these quantities to air shower observable as X_{max}

$$X_{max} \approx \lambda_{int} + \lambda_r \cdot \ln \frac{E_0(1 - k_{ela})}{n_{mult} \cdot E_{crit}^{e.m.}}, \quad (3)$$

where λ_r is the electromagnetic radiation length and $E_{crit}^{e.m.}$ the critical energy in air.

To demonstrate the impact of these interaction features on the air shower development we simulate the effect on the depth of the shower maximum, X_{max} , and on the total number of electrons above 1 MeV, N_e , and muons above 1 GeV, N_μ , after 1000 g/cm² of shower development.

The quantity that is affected most directly is X_{max} , see Eq. (3); The effects on N_e and N_μ can be mostly understood relative to X_{max} - as the consequence of a changing distance from the shower maximum to the observation level.

The results for proton primaries are summarized in Fig. 3 and for iron primaries in Fig. 4.

A. Cross section

A changing cross section has a strong impact on X_{max} . Both the mean as well as the fluctuations are affected. Especially for the fluctuation, the cross section is much more important than any other hadronic interaction feature. The effect on the electron number is related to the changing distance from the shower maximum to the observation level. Muon are only weakly affected.

For iron primaries the effects are very much reduced. Interestingly the impact on the mean X_{max} is still very notable, while it changes the fluctuations only by up to a few g/cm².

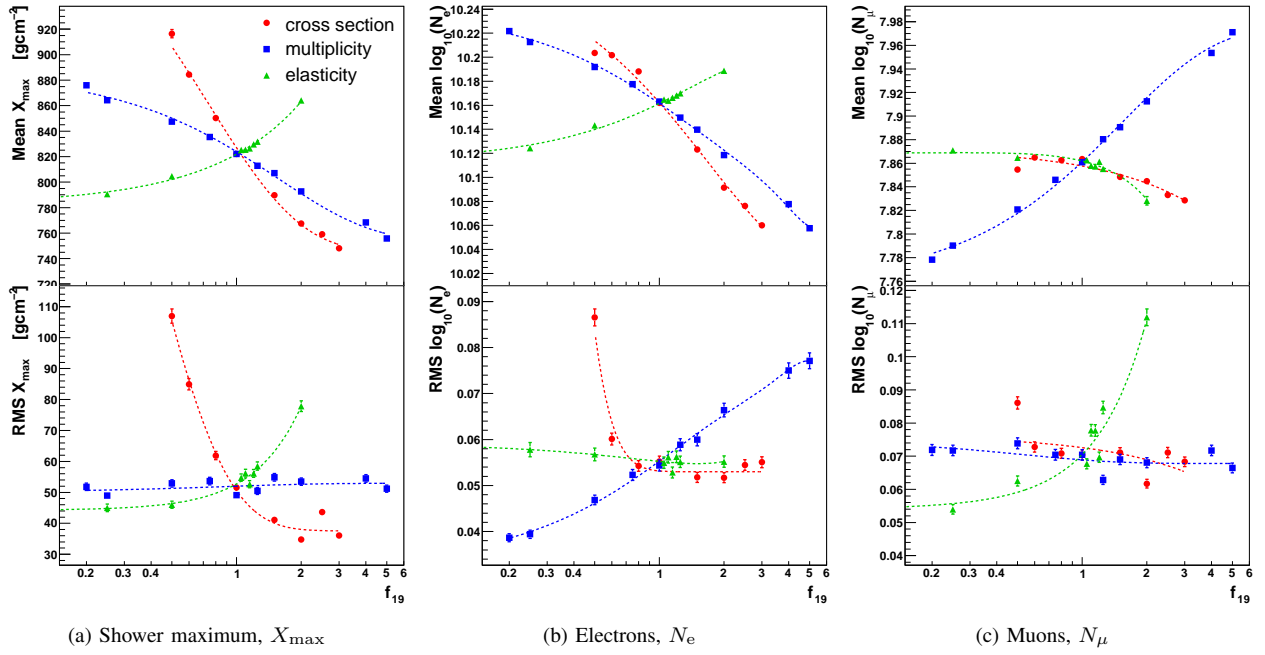


Fig. 3. Effect of changing interaction characteristics on proton induced air showers. Shown is the impact on the observables X_{\max} , N_e and N_μ . Each data point is the mean value for 1000 simulated air showers at a primary energy of $10^{19.5}$ eV. The lines are just to guide the eye.

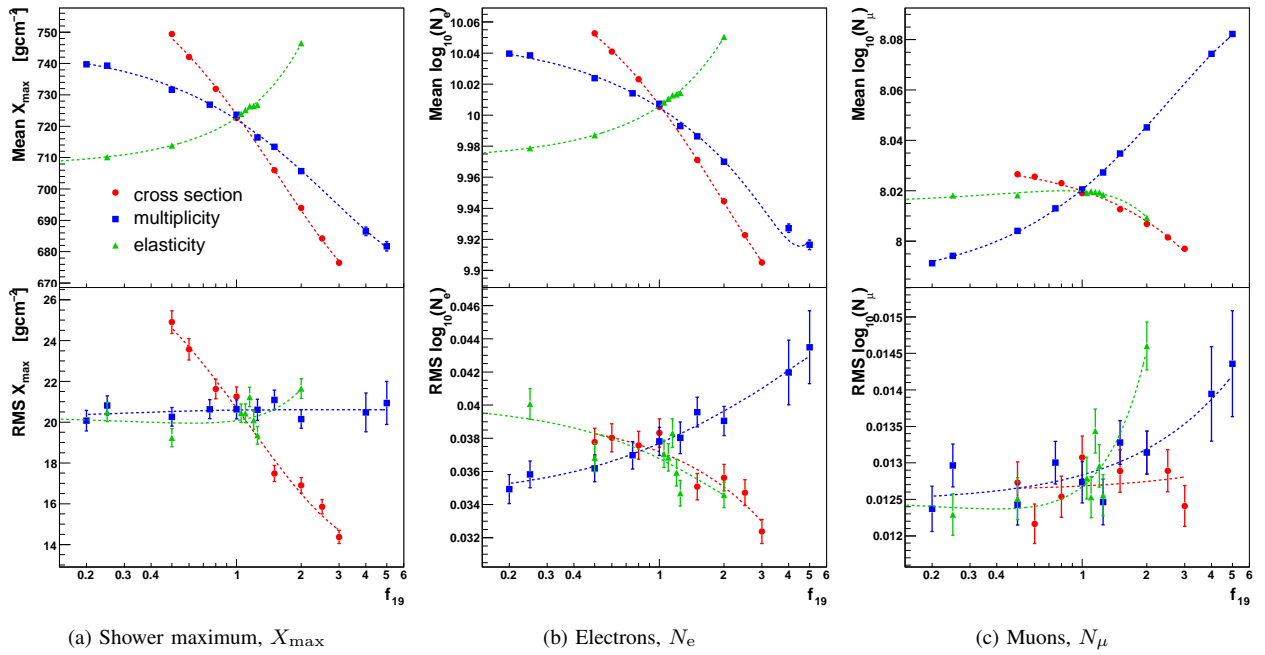


Fig. 4. Effect of changing interaction characteristics on iron induced air showers. Shown is the impact on the observables X_{\max} , N_e and N_μ . Each data point is the mean value for 1000 simulated air showers at a primary energy of $10^{19.5}$ eV. The lines are just to guide the eye.

B. Multiplicity

The multiplicity shifts the mean value of X_{\max} while leaving its fluctuations almost untouched. The electron number is reduced for a growing multiplicity, since the shower maximum moves further away from the detector level. This is also why the fluctuations are increasing at the same time. The muon number, on the other hand, grows since it does not depend strongly on the distance to the shower maximum. This inverse reaction of electron and muon numbers on a changing multiplicity certainly has interesting implications on N_e/N_μ unfolding technique, as practiced e.g. by the KASCADE Collaboration [1]; By changing the multiplicity, the model predictions move on diagonal lines in the N_e/N_μ -plane.

The same effects are observed on a reduced scale for iron primaries.

C. Elasticity

The elasticity has an influence on the mean as well as RMS of the X_{\max} distribution. The case of an increased elasticity by $f_{19} = 2$, as we included it in our results, is the most extreme modification of hadronic interactions that we present; The elasticity is not expected to rise at ultra-high energies. Again, the electron number reacts to the shifting X_{\max} . A surprisingly strong effect is observed in the fluctuations of the muon signal.

The latter effect disappears for iron primaries. The impact on X_{\max} and N_e is comparable to the one induced by multiplicity and cross section.

IV. SUMMARY

We demonstrate the importance of the extrapolation of hadronic interaction features from accelerator data to ultra-high energies for air shower development. For this purpose hadronic interactions are modified during the air shower simulation process within a customized version of the CONEX program.

It is found that the resulting impact on air shower observables is much larger than by just considering the properties of the single first interaction of the primary cosmic ray particle in the atmosphere. For example the predicted value of $\langle X_{\max} \rangle$ for primary iron nuclei changes by up to $> 30 \text{ g/cm}^2$ while changing the cross section by a factor of 2; Since the mean free path of iron in air itself is only $\sim 8 \text{ g/cm}^2$ a change by a factor of 2 can only explain 4 respectively 16 g/cm^2 of the total impact. The remaining shift of $\langle X_{\max} \rangle$ is in fact originating from a different air shower development after the first interaction.

Currently, the existing uncertainties in interaction physics at cosmic ray energies prevent an unambiguous interpretation of air shower data in terms of e.g. the primary cosmic ray mass composition.

The demonstrated sensitivity of standard air shower observables on hadronic interactions characteristics can be exploited to put constraints on hadronic interaction physics at energies far above the LHC. Furthermore, if the composition of the cosmic ray flux in a specific energy region can be inferred from astrophysical considerations, existing and future high quality air experiments [10-13] can be used in order to explore particle physics up to $\sqrt{s} \sim 450 \text{ TeV}$. This is possible for proton cosmic ray primaries but, with somewhat limited sensitivity, also for primary iron nuclei.

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