Relation between hadronic interactions and ultra-high energy extensive air showers

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Abstract. The simulation of hadronic interactions is of fundamental importance for the analysis of extensive air showers. The details of the relation between the measurement of hadronic interactions at accelerators and the impact on the air shower development is very difficult to evaluate. Several possibilities to study this relation are presented here.

1. Introduction

The most difficult observable to simulate in extensive air showers at this moment is the muon content. There are indications from ultra-high energy cosmic ray experiments that the muon content in data is significantly higher than any simulation can reproduce [1,2]. Various possibilities have been suggested to increase the number of muons in air shower simulations, however, so far no consistent description could be identified that yields muon numbers as large or even larger than found in nature.

Thus, there must be a so far unidentified mechanism in extensive air showers to yield these large fraction of muons. Since muons are produced mainly by decays of hadrons, the source of the problem will be related to the production of hadrons in the showers at very high energies. Many such possible scenarios have been tested using air shower simulations in the past [3–6]. It is found that it is possible to modify the muon production, however, the quest for a consistent model, or parameter-set for a model, is still open.

2. Sensitivity of air shower observables to hadronic interactions

It is important to understand the relevance of the fact that we cannot simulate the correct muon content of air showers. Does it mean that we just do not understand air showers to do any interpretation of the data, or can other aspects of air showers be understood much better? It is found that we can predict the longitudinal shower development and in particular the depth of the shower maximum much more precisely compared to the muon content.

This is illustrated in Fig. 1, where one particular air shower simulation of a vertical proton at 10 EeV is analysed. The longitudinal development in terms of energy deposit but also in terms of the muon number is shown for the complete air shower (blue line), but also for each of the 100 highest energy subshowers (dashed lines).

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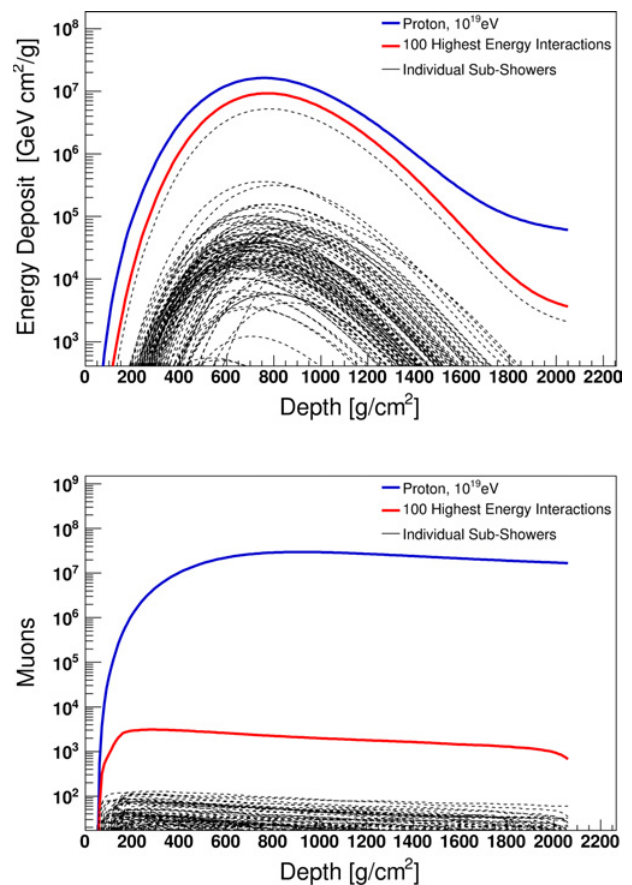
Figure 1. Simulated air shower of a proton primary at 10 EeV. The contributions of the 100 highest energy subshowers are shown explicitly. Top panel: longitudinal energy deposit profile. Bottom panel: longitudinal muon profile.

These subshowers are generated from the highest energy collisions in the sample of all hadronic interactions taking place in the shower. The summed profile of the 100 highest energy subshowers is shown as a red line. It indicates the relevance of these subshowers for the total shower development.
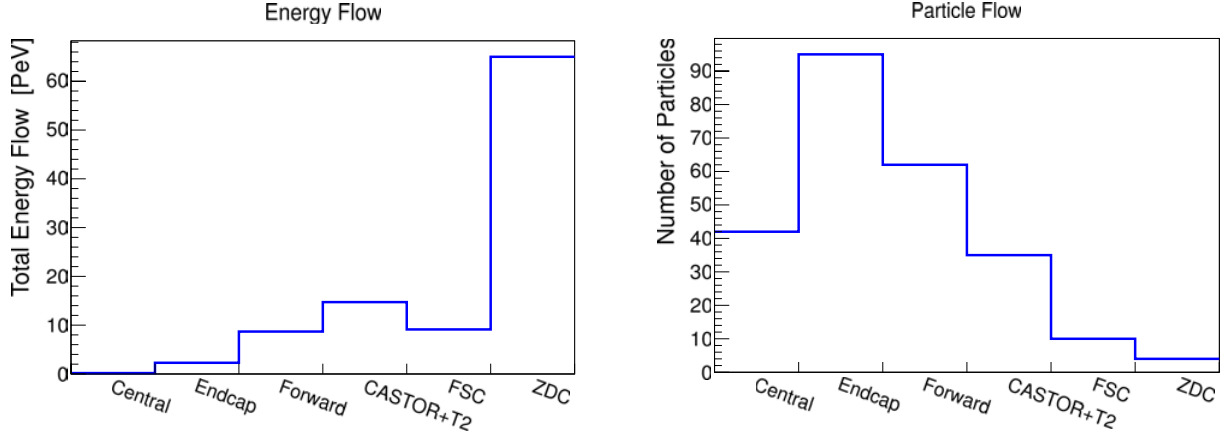
Figure 2. Distribution of secondary particle energy (left panel) and charged particle multiplicity (right panel) in the different acceptance regions as defined in the text. The particles are for one particular proton-air collisison at a center-of-mass energy per nucleon of $\sqrt{s_{\mathrm{NN}}} = 14\,\mathrm{TeV}$. Charged particles are counted for electromagnetic particles above 3 MeV and hadrons+muons above 300 MeV.

While for the energy deposit it is found that only the very first few highest-energy subshowers dominate the total longitudinal development, for the muon number these subshowers contribute only marginally to the final muon content. In order to simulate the muon content, basically all hadronic interactions from ultra-high energies down to the level of $\sim 10\,\mathrm{GeV}$ are relevant.

3. Acceptance of LHC experiments as a limitation to understand extensive air showers

The experimental acceptance of LHC experiments is limited. The most precise measurements are performed only in the most central region of particle production. In terms of pseudorapidity, $\eta = -\log \tan \theta/2$, this corresponds roughly to $|\eta| < 1$. The central region is typically followed by the endcap detectors up to $|\eta| < 3$. Some experiment provide additional information beyond that, e.g. forward calorimeters at $|\eta| < 5$, TOTEM/T2+CMS/CASTOR at $|\eta| < 6.6$, Forward Shower Counters (CMS) at $|\eta| < 8$ and zero-degree calorimeters at $|\eta| > 8$. These numbers are not accurate, but they are similar for all the experiments. In general, the precision of detectors rapidly decreases with increasing pseudorapidity.

So far Monte Carlo event generators are almost entirely tuned to the particle production in the more central particle production region at $|\eta| < 3$. Thus, to find out what fraction of the extensive air shower cascades is described by this limited acceptance of LHC experiments, and how large is the missing part, we performed a dedicated simulation study.

Several individual proton-air collisions at a center-of-mass energy per nucleon of $\sqrt{s_{NN}} = 14\,\mathrm{TeV}$ are generated. This corresponds to extensive air shower cascades initiated by protons hitting the atmosphere at an energy of $E_0 = 10^{17}\,\mathrm{eV}$. The secondary particles produced in these collisions are sorted according to their pseudorapidity and assigned to groups corresponding to one of the above mentioned typical acceptance regions. In Fig. 2 the distribution in these groups is shown.

After this sorting step, the air shower is simulated with the CORSIKA air shower simulation program for each of these acceptance regions individually. The total air shower is finally summed up over all these individually simulated regions. Finally, the response generated by the individual acceptance regions can be indicated explicitly.

It can be seen from Fig. 3 that so far about 10% of the total air showers are described by the region of particle production that was used for model tuning at LHC. About 90% of the shower development is related to particle production into the forward phase-space and is so far only poorly constrained by collider data. One particular fact must be considered: while the very forward particles in the acceptance of the zero-degree calorimeters are the most relevant, the calorimeters can in fact only observe neutral particles. Unfortunately, there is another acceptance limitation, namely, the fact that zero-degree calorimeters can only observe neutral secondary particles.

The results are shown for one particular simulated vertical proton-induced air shower. The overall conclusion is very similar for the longitudinal electron number profile, the muon density at ground level but also e.g. the typical energy estimator used by the Pierre Auger Observatory, S1000 (see Fig. 4). The overall simulation process described here was repeated for many air showers, always giving qualitatively identical results.

## 4. Hadronic particle production in extensive air showers

Concerning the deficit of muons in air shower simulations, it is possible to investigate how modifications of the hadronic multiparticle production in the shower cascades influence the final muon content. This was suggested several times, and interesting effects have been identified/proposed.

4.1. Forward ρ^0 production in charge exchange reactions

In particular the very important charge exchange reaction in air showers, where high-energy charged pions collide
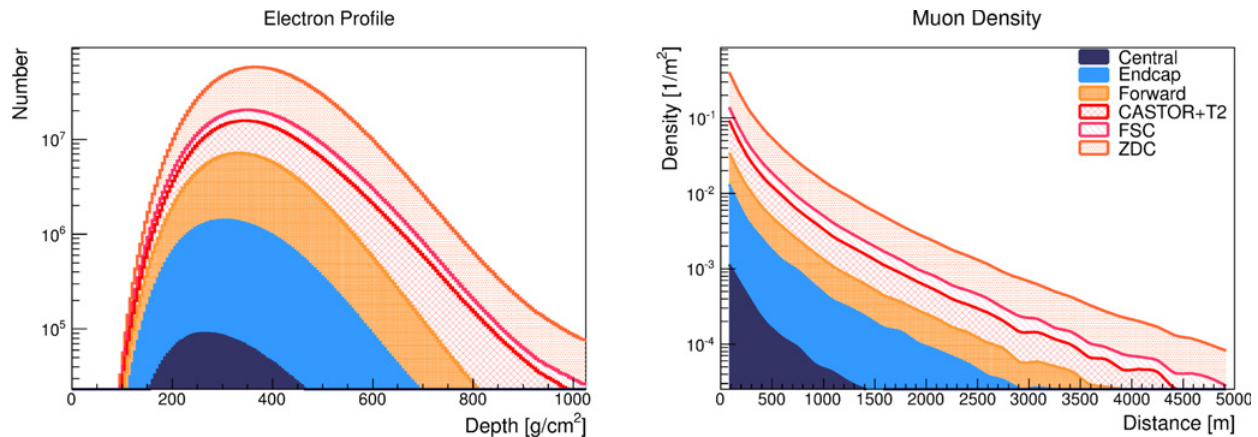
Figure 3. The fractions of the total air shower signal produced by secondary particles of the first collision in the various acceptance regions of LHC. The air shower is a vertical proton-induced shower at 10^{17} eV. Left panel: the longitudianl development of the number of electrons. Right panel: the radial density of muons.
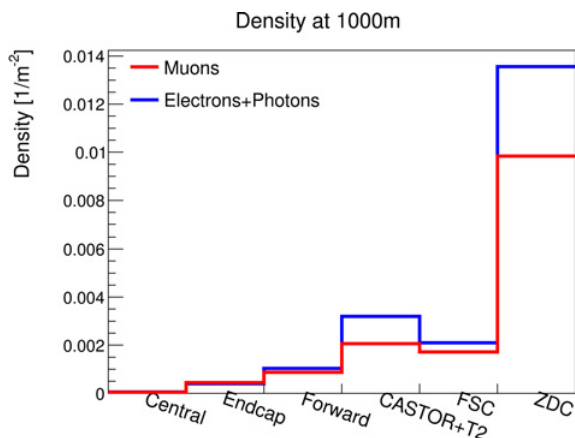
Figure 4. The fractions of the typical energy estimator of the Pierre Auger Observatory, S1000, for surface detector events produced by secondary particles of the first collision in the various acceptance regions of LHC. The air shower is a vertical proton-induced shower at 10^{17} eV.

with nuclei and produce forward leading π^0 or ρ^0 mesons, is a very interesting candidate to influence the muon number. This is mainly since the π^0 decay into photons, thus, to the electromagnetic part of the cascade, while ρ^0 decay into charged pions, thus, keeping the energy in the hadronic cascade. The muon number is in the end proportional to the number-size of the hadronic cascade at particle energies of several 10 GeVs. From simulations it is found, that by far most muons are generated from decaying pions produced in collisions of pions with air at energies of 20 to 30 GeV [7].

We perform a special set of air shower simulations, using the CONEX [8] air shower simulation package, where we modify the probability to produce forward π^0 or ρ^0 particles in charge exchange reactions in the SIBYLL [9] interaction model. The probability for the production of ρ^0 instead of π^0 is modified in an energy-dependent way using the parameter f_{19}. For technical details on this procedure, please read Ref. [6]. This is an

ad-hoc model modification, which only investigates the sensitivity of the air shower muon content to this process. In our simulations, pion interactions at energies above 10^{15} eV are affected. In real air showers also collisions at significantly smaller energy may be affected, yielding a larger effect than what we describe here. In Fig. 5 (top) it is shown that indeed the muon content is strongly affected in this way.

4.2. Baryon production in air showers

Also the increased production of baryons with respect to mesons is investigated. Due to baryon-number conservation the production of baryons leads to more energy in the hadronic cascade of the air shower. Mesons, however, can also decay and transfer energy from the hadronic to the muonic or electromagnetic cascade.

This was investigated with air shower simulations by converting individual baryons/mesons into mesons/baryons, while conserving the total energy and charge.

The impact is shown in Fig. 5 (middle). The average muon number indeed increases with a higher fraction of baryons. However, the effect is much less pronounces compared to increasing the fraction of ρ^0s. Also, the average depth of the shower maximum is not affected.

4.3. Probability for diffractive collisions

Diffractive interactions naturally produce final states with high-energy leading particles, thus, they have a high elasticity. At the same time the probability for diffraction reactions is around 20–30% of all inelastic collisions at LHC energies. By modifying the probability for diffractive reactions in air shower simulations (see Fig. 5 (bottom)) mainly the depth of the average shower maximum is affected. More diffraction leads to a higher elasticity and, thus, more penetrating air showers. On the other hand, the muon number is basically not influenced.
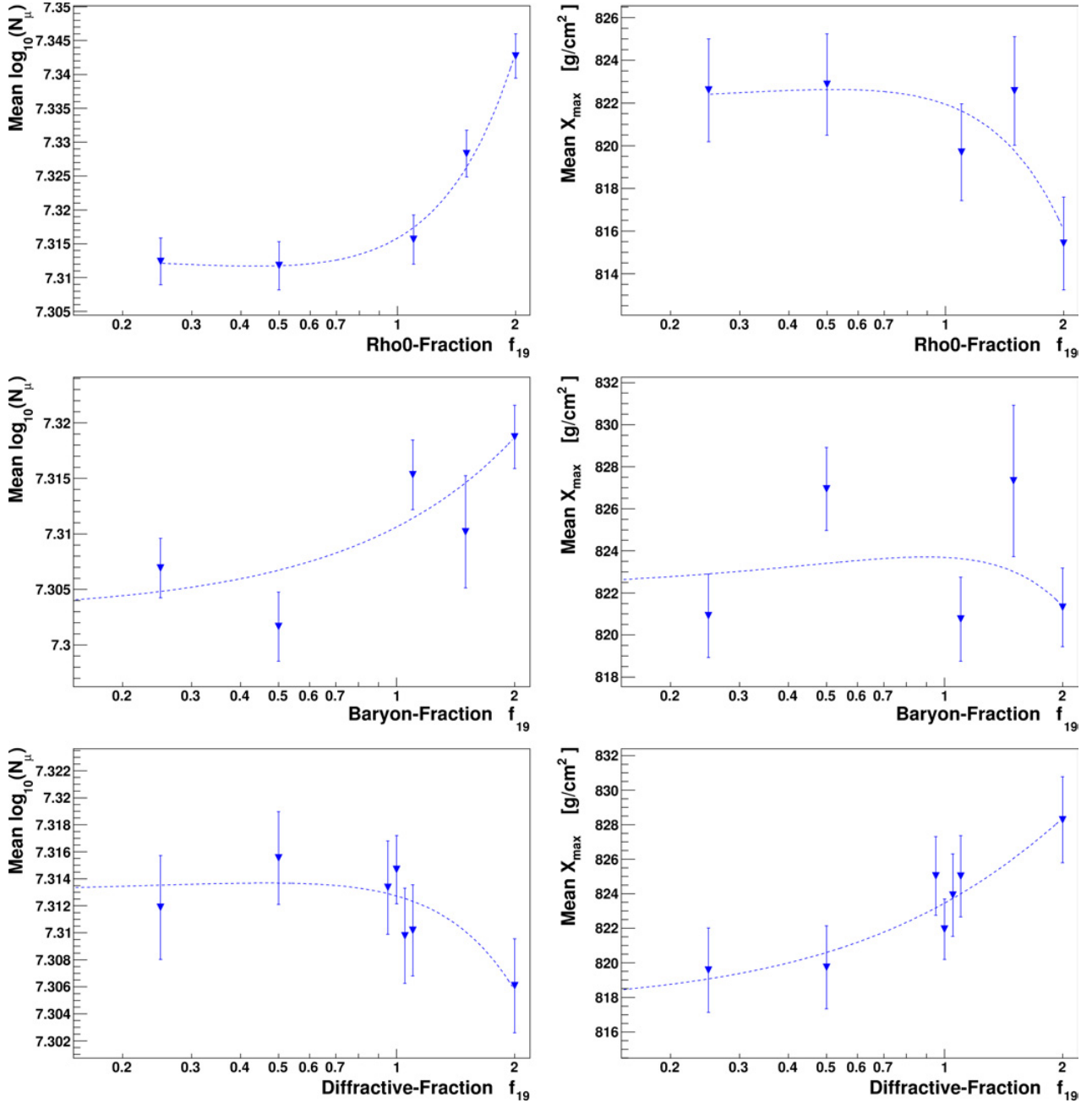
Figure 5. Impact of modified ρ^0 fraction (Top), Baryon production (Middle) and Diffraction (Bottom) on the Average muon number (left) and the average depth of the shower maximum (right). All simulations performed with the SIBYLL model at a primary energy of $10^{19.5}$ eV. The dashed lines are just to guide the eye.

5. Summary

The relation between hadronic particle production and extensive air shower observables is very indirect and difficult to investigate. We illustrated some of the very important aspects of this relation in this paper.

Different air shower observables are affected in a very different way by hadronic interaction in the shower cascade. While the longitudinal development is determined by the few highest energy collisions, the muon content, on the other hand, requires the complete understanding of the hadronic cascades from the highest energies down to GeV level. Thus, the muon number is naturally much more difficult to predict compared to e.g. the depth of the shower maximum. And, fortunately, it is possible to analyse the longitudinal development of air showers independently of the problem to simulate the muons. In this way studies of the cosmic ray mass composition [10] but also the measurement of the proton-air cross section [11] can in fact be performed.

It is estimated with a simulation study that the tuning of hadronic event generators to LHC measurements at central pseudorapidities does constrain about 10% of the total air shower cascade. In order to significantly improve this it is necessary to consider more forward data for the tuning, too.

There are several aspects of hadronic particle production that can indirectly lead to an increased muon content of air showers. It is shown that the forward ρ^0 production, in contrast to π^0 production, in charge exchange reactions does have a very strong impact on the muon content. However, it is already known that by itself this is not sufficient to potentially explain the observed muon number in air shower data. Even the QGSJetII.4 [12] model, which has maximal ρ^0 production, in contrast to QGSJETII.3, which does have no ρ^0 production, cannot produce a sufficient number of muons to explain the air shower data.

References

[1] A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. **D90**, 012012 (2014)

[2] A. Aab et al. (Pierre Auger Collaboration), Phys. Rev.D (2014)

[3] H.J. Drescher, Phys. Rev. **D77**, 056003 (2008)

[4] S. Ostapchenko, EPJ Web Conf. **52**, 02001 (2013)

[5] T. Pierog, K. Werner, Phys. Rev. Lett. **101**, 171101 (2008)

[6] R. Ulrich, R. Engel, M. Unger, Phys. Rev. **D83**, 054026 (2011)

[7] C. Meurer, J. Bluemer, R. Engel, A. Haungs, M. Roth, Czech. J. Phys. **56**, A211 (2006)

[8] T. Bergmann, R. Engel, D. Heck, N. Kalmykov, S. Ostapchenko et al., Astropart. Phys. **26**, 420 (2007)

[9] E.J. Ahn, R. Engel, T.K. Gaisser, P. Lipari, T. Stanev, Phys. Rev. **D80**, 094003 (2009)

[10] A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. **D90**, 122006 (2014)

[11] P. Abreu et al. (Pierre Auger Collaboration), Phys. Rev. Lett. **109**, 062002 (2012)

[12] S. Ostapchenko, Phys. Rev. **D83**, 014018 (2011)