Investigating the influence of diffractive interactions on ultra-high energy extensive air showers

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**Abstract**

The understanding of the basic properties of the ultra-high energy extensive air showers is strongly dependent on the description of the hadronic interactions in a energy range beyond that probed by the LHC. One of the uncertainties present in the modeling of the air showers is the treatment of diffractive interactions, which are dominated by non-perturbative physics and usually described by phenomenological models. These interactions are expect to affect the development of the air showers, since they provide a way of transporting substantial amounts of energy deep in the atmosphere, modifying the global characteristics of the shower profile. In this paper we investigate the impact of the diffractive interactions in the observables that can be measured in hadronic collisions at high energies and ultra-high energy cosmic ray interactions. We consider three distinct phenomenological models for the treatment of diffractive physics and estimate the influence of these interactions on the elasticity, number of secondaries, longitudinal air shower profiles and muon densities for proton-air and iron-air collisions at different primary energies. Our results demonstrate that the diffractive events has a non-negligible effect on the observables and that the distinct approaches for these interactions, present in the phenomenological models, are an important source of theoretical uncertainty for the description of the extensive air showers.

PACS numbers:
I. INTRODUCTION

Understanding the behaviour of high energy hadron reactions from a fundamental perspective within Quantum Chromodynamics (QCD) is an important goal of particle physics. One of the main open questions is the treatment of the diffractive processes, which are characterized by the presence of an intact hadron and large rapidity gaps in the final state (For a recent review see Ref. [1]). These processes are in general described in terms of a color singlet object: the Pomeron ($I^P$). This object, with the vacuum quantum numbers, was introduced phenomenologically in the Regge theory as a simple moving pole in the complex angular momentum plane, to describe the high-energy behaviour of the total and elastic cross-sections of the hadronic reactions [2]. The diffractive events are dominated by low transverse momentum processes, i.e. processes in which the strong running coupling constant is large and the useful perturbative methods are not valid. These processes are in general described by phenomenological models based on first principles of the Quantum Field Theory and basic properties of QCD [3]. It implies a large theoretical uncertainty, with a strong impact on the predictions for the magnitude and energy dependence of the diffractive cross section. For example, while some models [4] predict that $\sigma_{\text{diff}} \propto \ln^2 s$ at asymptotic energies, other models [5] predict $\sigma_{\text{diff}} \propto \ln s$. As a consequence, the contribution of the diffractive events for the total cross sections at very high energies still is an open question. Recent experimental results from the Run 1 of the LHC have shed some light on the energy behaviour of the single and double diffractive cross sections [6] and more precise results are expected in the Run 2 [1]. The expectation is that these data could be used to constrain the basic assumptions present in the phenomenological models, decreasing the uncertainty in its predictions at larger energies.

The understanding of the hadronic interactions also is fundamental for the description of the ultra-high energy cosmic ray (UHECR) air showers [7, 8], with the reconstruction of the primary UHECR properties being strongly dependent on the treatment of the diffractive and non-diffractive events present in the hadron–air interactions. Due to the dominance of soft physics, the models of hadronic interactions in the generator models used in the simulation of extensive air showers (EAS) are largely phenomenological and have to be extrapolated from accelerator energies, where they are calibrated, to the UHECR energies. In recent years, the underlying theoretical framework present in these generators have been improved and the
LHC data have been used to tuning the basic cross sections \cite{4, 9, 10}. However, the available collider data do not cover the full kinematic region of interest in UHECR interactions \cite{11}. In particular, experimental data for the particle production at very forward rapidities still are scarce, with its theoretical description still being an open question (For a recent study see, e.g. Ref. \cite{12}). As a consequence of the theoretical uncertainty present in the description of the hadronic interactions present in the EAS, the air shower simulations still are one of the main source of systematic uncertainty in the interpretation of cosmic ray data \cite{13–15}.

Our main goal in this paper is to give a quantitative estimate of the uncertainty associated to the treatment of the diffractive interactions on the shower observables. These interactions are expect to affect the development of the air showers, since diffractive interactions have direct impact on the inelasticity – the relative energy loss of the leading secondary particle – providing a way of transporting substantial amounts of energy deep in the atmosphere. Consequently, they modify the global characteristics of the shower profile. In particular, a higher diffraction rate implies a slower EAS development, modifying the position of the shower maximum \(X_{\text{max}}\), and a smaller number of secondaries in each interaction. In what follows we will study the impact of the diffractive interactions on ultra-high energy extensive air showers through the comparative analysis of the predictions for the EAS observables from the standard versions of the Sibyll \cite{5}, QGSJET \cite{4} and EPOS \cite{10} hadronic models, which are available in the framework of the CORSIKA air shower simulation package \cite{16}. Our study is strongly motivated by the analysis performed thirteen years ago in Ref. \cite{17}, where the authors have studied the same problem using the pre-LHC hadronic models and the AIRES program \cite{18} for the simulation of the EAS development. In what follows we will update that analysis by considering the current hadronic models and include new results for Fe-Air collisions which were not considered in that reference. In order to investigate the contribution of these interactions, we will present, for each hadronic model, a comparison between predictions obtained using the full simulations, i.e. including the non-diffractive and diffractive events, with those derived excluding the diffractive events of the EAS development. In particular, in Section \ref{sec:II} we will compare the predictions of the different hadronic models for the distribution of number of secondaries, fraction of diffractive events, average fraction of pions and elasticity distributions, considering individual p-Air and Fe-Air collisions at different values for the primary energy. The impact on the EAS observables is studied in Section \ref{sec:III} where we will analyse the impact of the diffractive interactions on the
longitudinal profiles of charged particles and muons as well as on the position of the shower maximum. Finally, in Section IV we summarize our main conclusions.

II. IMPACT OF THE DIFFRACTIVE INTERACTIONS IN HADRONIC COLLISIONS

As discussed in the Introduction, the treatment of the hadronic interactions in the air shower simulation codes is based on phenomenological models. In what follows we will consider the Sibyll 2.1, QGSJET – II 04 and EPOS LHC models, present in the CORSIKA package, and compare its predictions for distinct observables in \( p \)-Air and \( Fe \)-Air collisions at different center-of-mass energies. Before to present our results, lets present a brief review of the main assumptions of the different phenomenological models (For a more detailed review see, e.g., Ref. [13]).

Most current hadronic interaction models are based on basic quantum field theory principles, such as unitarity and analyticity of scattering amplitudes, and use Gribov - Regge theory [19] of multi - Pomeron exchange between nucleons as the basis for the treatment of high energy, soft interactions. Perturbative QCD is considered to describe hard interactions with high transverse momentum, which becomes important at high energies. In general, simplifications are made in the implementation of the hard processes if they are not directly relevant to the production of high energy secondaries. QGSJET and Sibyll consider the eikonal model and assume unitarized cross sections with the real eikonal function being given by a sum of soft and hard contributions. EPOS also is based on Gribov - Regge theory and provides a energy - conserving quantum mechanical multiple scattering approach in terms of parton ladders. At high energies, nonlinear effects associated to the high partonic density becomes important and should be taken into account [20, 21]. QGSJET provides a microscopic treatment of nonlinear interaction effects in hadronic and nuclear collisions in terms of Pomeron - Pomeron interaction diagrams. On the other hand, in Sibyll these effects are modelled by means of an energy - dependent cutoff for the minijet production. In contrast, EPOS employs a phenomenological approach for nonlinear interaction effects and address the energy - momentum correlations between multiple scattering processes at the amplitude level. The generalization from \( pp \) to \( pA \) and \( AA \) collisions is usually performed via Glauber - Gribov formalism [22, 23], taking into account inelastic screening and
low mass diffraction effects. Finally, diffractive interactions are treated differently in the distinct models. In Sibyll and QGSJET models, the diffraction dissociation is described in terms of the Good - Walker formalism [24], where the colliding hadrons are represented by superpositions of elastic scattering eigenstates which undergo different absorption during the collision. In Sibyll, high mass diffraction is described in terms of a 2 - channel eikonal approach. On the other hand, the description of this process in QGSJET is based on all - order resummation of cut enhanced $\Pi$ - diagrams. In contrast, a particular kind of Pomeron is used to define a diffractive event in EPOS. Depending of each event configuration it can be classified as non - diffractive, low mass diffraction without central particle production, or high mass diffraction.

A basic feature of the diffractive interactions is that there is a leading particle whose energy is much larger than the energies of the other particles and the total number of secondaries is generally small. The resulting final states have a high elasticity. In previous studies, these characteristics were used to tag the diffractive events [17, 25]. In contrast, in our study the classification of the diffractive and non - diffractive events was made using internal variables of the respective hadronic generators. In particular, in the EPOS LHC and QGSJET-II 04 generators, the events were classified according to the variable typevt, which define the collision type: if typevt = 1, the event is classified as non-diffractive; otherwise, the event is considered a diffractive one. As this variable is read after the event is generated, it allows to reject diffractive events when generating samples of non-diffractive events. In contrast, in Sibyll 2.1, a hadron-air interaction is classified as diffractive requiring that there is only one wounded nucleon in the target (NW = 1) and that the interaction with this nucleon is diffractive (JDIFF(0) > 0). Again, variables are read after the event have been generated. For nucleus-nucleus interactions, we implemented a distinct scheme for this model. As Sibyll 2.1 treats nucleus-nucleus collisions in a semisuperposition model, where the A projectile nucleons are considered independent particles, it generates A superposed interactions. We found reasonable to classify as diffractive the collisions whose all superposed interactions were diffractive. Otherwise, if at least one interaction is non-diffractive, the event is labelled as non-diffractive.

In order to illustrate the classification between diffractive and non - diffractive events, in Fig. we present our results for the elasticity-multiplicity plane considering $10^4 p - Air$ collisions at $\sqrt{s} = 10$ TeV. The elasticity is characterized by the leading energy fraction $f_L$,
FIG. 1: Predictions of the different hadronic generators for diffractive and non-diffractive events in the elasticity – multiplicity ($f_L \times N_{sec}$) plane considering $10^4$ p - Air collisions at $\sqrt{s} = 10$ TeV. Diffractive events are represented by red squares and the non-diffractive one by light blue circles.

which is defined by the ratio between the energy of the secondary with maximum energy $E_{\text{lead}}$ (leading particle) and the primary energy $E_{\text{prim}}$, i.e. $f_L \equiv E_{\text{lead}}/E_{\text{prim}}$. The predictions of the three different hadronic generators are presented separately, with the diffractive events being represented by red squares and the non-diffractive one by light blue circles. We have that the most of the diffractive events appear on the region of low multiplicity and elasticity close to 1, in agreement with the theoretical expectation. However, the distribution is different for the distinct hadronic models. In what follows, we will analyse the phenomenological implications of these differences.

We have generated samples of $10^4$ p - Air and Fe - Air collisions at different center of mass energies for each event generator model: QGSJET-II 04, EPOS LHC and Sibyll 2.1. We assume that the target is a mixture of nitrogen, oxygen and argon, exactly as it is implemented in the CORSIKA package [16]. After the events have been generated, we register all secondaries, imposing a cutoff on the kinetic energy of the secondary particle. Basically, we excluded from the secondary list all particles with kinetic energy smaller than 40 MeV. It is assumed to eliminate from the secondary list, the fragments of the target nucleus, which are included in the EPOS LHC case, but not in the others models. Such cutoff is expected to have no influence in the air shower development [25], since particles with such low values of kinetic energy should not be able to propagate in the atmosphere. As we are interested in the particular case of diffractive collisions, we generated separately samples without diffractive events and full samples including non-diffractive and diffractive events.
FIG. 2: Comparison between the Sybill, QGSJET and EPOS LHC predictions for the number of secondaries considering $p$-Air (upper panels) and Fe-Air (lower panels) collisions at three different values for the primary energy.

In what follows we will compare the predictions from these two configurations, which allow us to estimate the impact of diffraction on the average properties of the hadronic collisions as well as to investigate the theoretical uncertainty associated to the distinct treatment of diffraction present in the hadronic generators considered in our study.

Initially, in Fig. 2 (upper panels) we present the predictions for the distributions of number of secondaries $N_{sec}$ produced in $p$-Air collisions considering three different values for the primary energy: $E_{prim} = 100$ GeV, 1 TeV and 100 PeV. We have that for $E_{prim} = 100$ GeV, the distinct predictions are similar. One the other hand, for $E_{prim} = 1$ TeV, these distributions are different, with the presence of two peaks: one at small values of $N_{sec}$, associated to diffractive events and other at larger values of $N_{sec}$, related to non-diffractive events. Finally, for $E_{prim} = 100$ PeV ($\sqrt{s_{NN}} \approx 14$ TeV) the distributions extend up to thousands of secondary particles, and the peaks become more evident. In the case
FIG. 3: Predictions of the different hadronic generators for the primary energy dependence of the average number of secondaries produced in $p$-Air (left panel) and $Fe$-Air (right panel) collisions. The solid (open) symbols represent simulations including diffractive interactions (non-diffractive events only).

of Sibyll 2.1, the peak at low $N_{sec}$ is suppressed. In Fig. 2 (lower panels) we shown the $N_{sec}$ distributions for $Fe$-Air collisions. In this case we have that the predictions of the different models for the peak at low - $N_{sec}$ are very distinct, being enhanced in the Sibyll case and suppressed for both QGSJET-II 04 and EPOS LHC with the increasing of the primary energy.

The predictions of the different hadronic generators for the dependence of the average number of secondaries produced in $p$-Air collisions on the primary energy are presented in Fig. 3 (left panel). The full simulations, including diffractive and non - diffractive events, are represented by solid symbols. On the other hand, the simulations including only non - diffractive events are represented by open symbols. Initially, lets compare the predictions of the different hadronic generators for the full simulations. In this case we have that for $E_{prim} \approx 10$ PeV, the EPOS LHC and QGSJET-II 04 generators predict, on average, very similar values for the number of secondaries. As the energy increases, differences become significant, with the QGSJET-II 04 predicting the largest number of secondaries at the highest energies, while Sibyll 2.1 predicts the smaller value. One have that the relative difference between the hadronic generators is smaller after the LHC tuning. In particular, the QGSJET prediction for the number of secondaries produced at ultra - high energies in $p$-Air collisions was substantially reduced after the LHC tune. Our predictions for $Fe$ - Air collisions are presented in Fig. 3 (right panel). In this case, Sibyll 2.1 predicts the largest
number of secondaries for primary energies smaller than 10 EeV. At higher energies, the QGSJET-II 04 predictions are slightly larger than Sibyll 2.1, with the EPOS LHC predicting the lowest number of secondaries in the whole considered energy range. As already observed in \( p \)-Air collisions, the QGSJET-II 04 and EPOS LHC results are very similar at energies lower than 10 PeV and become very distinct at higher energies.

Let's now analyse the impact of the diffractive events on the average number of secondaries. As can be observed in Fig. 3 (left panel) by the comparison between the solid and dashed lines, one have that for \( p \)-Air collisions the contribution of the diffractive events is small for the Sibyll 2.1. One the other hand, these events have a non-negligible impact on the QGSJET-II 04 and EPOS LHC predictions, with the contribution of diffraction increasing with the primary energy. In contrast, in the case of the predictions for \( Fe \)-Air collisions, presented in Fig. 3 (right panel), Sibyll 2.1 receives the most significant influence of diffractive interactions on the mean secondary multiplicity, while QGSJET-II 04 one is almost not influenced by diffraction. One have that in \( p \)-Air and \( Fe \)-Air collisions, the presence of the diffractive interactions reduces the average number of secondaries produced in the collisions. It is expected, since diffractive interactions produce less secondaries than non-diffractive collisions. Consequently, it is expected that the sample of collisions without diffraction has more secondaries on the average.

In order to estimate how the contribution of the diffractive events change with the energy, let's consider the relative probability of diffraction, which is related to the ratio of the diffractive to the total cross sections and determines how many diffractive events are expected in a sample of collisions. The relative probabilities of diffraction predicted by the
different hadronic generators for $p$-Air and $Fe$-Air collisions at different primary energies are presented in Fig. 4. For $p$-Air collisions (left panel), the EPOS LHC predicts the largest fraction of diffractive events in the whole energy range, being $\approx 40\%$ at 100 GeV and 18\% for 100 EeV. On the other hand, Sibyll 2.1 predicts that the contribution of the diffractive events is of the order of 20\% at 100 GeV, decreasing at larger energies. In particular, Sibyll 2.1 predicts the smaller contribution of these events at ultra-high energies. Finally, QGSJET-II 04 shows a different behaviour, increasing from 10\% at 100 GeV to 17\% at 100 TeV and then decreasing for 12\% at 100 EeV. The results for $Fe$-Air collisions are presented in Fig. 4 (right panel). As observed in $p$-Air collisions, EPOS LHC predicts the largest fraction of diffractive events at all primary energies. However, the magnitude of this contribution is smaller, with values around 13\% in the energy range considered. The Sibyll 2.1 and QGSJET-II 04 predictions also are smaller in comparison to the $p$-Air collisions, with the Sibyll 2.1 one increasing with the energy and predicting similar values to the EPOS LHC at ultra-high energies.

In Fig. 5 we present the predictions of the different hadronic generators for the energy dependence of the fraction of pions produced in $p$-Air (left panel) and $Fe$-Air (right panel) collisions, which is given by the ratio between the number of pions produced and the total number of secondaries. We have that EPOS LHC predicts the largest fraction of pions for all primary energies, with the diffractive events decreasing the fraction. On the other hand, as expected from the Fig. 4, the fraction of pions predicted by the Sibyll 2.1 is almost not influenced by the diffractive events. The predictions for $Fe$-Air collisions are presented.
in Fig. 5 (right panel). In this case, we have that the fraction of pions predicted by the three hadronic generators is smaller than in $p$-Air collisions and the QGSJET-II 04 predicts the largest fraction in the energy range considered. Moreover, we have that the Sibyll 2.1 prediction at large energies is strongly influenced by the diffractive events.

In Fig. 6 we present the predictions for the elasticity distribution considering $p$-Air collisions and three representative primary energies: 1 TeV, 100 PeV and 100 EeV. The large $f_L$ region is detailed in the small plots on the right. We can verify the presence of a peak for $f_L \approx 1$, which is related to the diffractive interactions, where the leading particle carry most of the primary energy. At small energies ($E_{prim} = 1$ TeV), the predictions of the different models are similar, except by the fact that the diffractive peak predicted by the QGSJET - II 04 is smaller in comparison to the other models. As the energy increases, the
distributions starts to be different, with the QGSJET - II 04 predicting the largest fraction of non-diffractive events at small $f_L$, which is associated to the fact that this model predicts the largest number of secondaries at high energies [See Fig. 3 (left panel)]. We have that the EPOS LHC and QGSJET - II 04 predict the increasing of the peak for $f_L \approx 1$. In contrast, Sibyll 2.1 predicts that it becomes smaller at large energies, in agreement with the results presented in Fig. 4. Finally, in order to investigate the influence of the diffractive interactions in the average elasticity $\langle f_L \rangle$ in p-Air collisions, in Fig. 7 we present the predictions for the energy dependence of $\langle f_L \rangle$. We have that the presence of the diffractive events implies a higher average elasticity, since these events populate the region of large $\langle f_L \rangle$. Moreover, the largest impact is in the EPOS LHC predictions, which is associated to the fact that this model predicts the largest peak for $f_L \approx 1$.

Our results for $p$-Air and $Fe$-Air collisions demonstrated that the diffractive interactions modify the magnitude of the number of secondaries and the inelasticity of these collisions. Moreover, our results indicated that the distinct treatment of these interactions, present in the different hadronic generators, implies a non-negligible theoretical uncertainty in the predictions. In the next Section, we will expand our analysis for air shower observables.

III. IMPACT OF THE DIFFRACTIVE INTERACTIONS ON SHOWER OBSERVABLES

In order to investigate the impact of the diffractive interactions on the air shower observables we will use the software CORSIKA (Version 7.4.005) to simulate air showers generated
by primary protons and iron nuclei with energies of $10^{17}$ and $10^{20}$ eV, reaching the atmosphere with a zenith angle of 60°. The simulations have been performed considering two distinct configurations: (a) full simulations, which include diffractive and non-diffractive interactions in the shower development, and (b) non-diffractive (ND) simulations generated removing the diffractive interactions of the shower development. For the description of the hadronic interactions we will consider the same models discussed in the previous Section.

In Fig. 8 we present the predictions for the mean longitudinal profiles of charged particles for showers generated by protons and iron nuclei at $10^{17}$ eV (upper panels) and $10^{20}$ eV (lower panels). The solid lines represent showers generated including the non-diffractive and diffractive interactions (full simulations), while the dashed lines represent showers where the diffractive interactions were removed of the shower development (non-diffractive simulations). The impact of the diffractive interactions is very clear: the presence of the
TABLE I: Predictions for the shift in $\langle X_{\text{max}} \rangle$ due to the presence of the diffractive events.

| $E_{\text{prim}}$ | Primary | QGSJET-II 04 | EPOS LHC | Sibyll 2.1 |
|-------------------|---------|--------------|----------|-------------|
| $10^{17}$ eV      | p       | 24.5 $g/cm^2$ | 23.3 $g/cm^2$ | 8.3 $g/cm^2$ |
|                   | Fe      | 17.0 $g/cm^2$ | 20.0 $g/cm^2$ | 11.2 $g/cm^2$ |
| $10^{20}$ eV      | p       | 19.6 $g/cm^2$ | 26.0 $g/cm^2$ | 10.9 $g/cm^2$ |
|                   | Fe      | 16.5 $g/cm^2$ | 22.5 $g/cm^2$ | 8.3 $g/cm^2$ |

The influence of the diffractive interactions also can be estimated by the analysis of the shift in the depth of maximum $\langle X_{\text{max}} \rangle$, given by $\langle X_{\text{max}}^{(\text{full})} \rangle - \langle X_{\text{max}}^{(\text{ND})} \rangle$. In Table I we present our results for this quantity. We can see that the influence of the diffractive interactions on the profiles is smaller in the case of Sibyll 2.1, for both primaries. This is related to the fact that Sibyll 2.1 usually produces less diffractive events (See Fig. 4) in hadron-nucleus collisions than the other models. Additionally, we have that the showers generated using the EPOS LHC are more influenced by diffraction than those generated by the other models. This also can be verified in Fig. 9 where the energy dependence of $\langle X_{\text{max}} \rangle$ is presented.
FIG. 10: Predictions for the average longitudinal profiles of muons for air showers generated by protons and iron nuclei with primary energies of $10^{17}$ eV (upper panels) and $10^{20}$ eV (lower panels). Solid (dashed) lines represent the full (non-diffractive) simulations.

Moreover, we have that the impact of the diffractive interactions on this observable is almost energy-independent for the three considered models of hadronic interactions. We have that the impact of the diffractive interactions in the shower maximum position depends of the treatment of the diffractive physics and it is of the order of the typical experimental precision for the $\langle X_{\text{max}} \rangle$ measurements. Such uncertainty has as consequence the degradation of the accuracy of other quantities, as for example, the composition of the UHECR \cite{26}.

Lets now analyse the impact on the muonic content of the air showers, which is known to be related to the primary composition and also to the properties of the hadronic interactions on the shower development. In particular, Auger collaboration has recently measured the depth of maximum production of muons $X_{\mu \text{max}}$ in high energy air showers and has verified that QGSJET-II 04 bracketed the data with simulations of proton and iron induced showers, while EPOS LHC underestimates values of $X_{\mu \text{max}}$ \cite{27}. Auger collaboration also showed that both
FIG. 11: Ratio between the predictions for muon densities obtained considering only non-diffractive interactions and those derived including diffractive and non-diffractive interactions as a function of the distance to the shower core. Showers initiated by protons (iron nuclei) are represented by blue circles (red triangles). Solid (open) symbols denote showers initiated by primary reaching the atmosphere with a zenithal angle of 60° (30°).

models underestimate the muon content that reach the ground [28], with the discrepancies being larger for the QGSJET-II 04 predictions than those from the EPOS LHC model. In Fig. 10 we present the predictions of the different hadronic generators for the longitudinal profiles of the muonic component for air showers generated at $10^{17}$ eV (upper panels) and $10^{20}$ eV (lower panels). Qualitatively, the influence of diffraction is the same observed for the profiles of charged particles: simulations without diffractive processes produce more muons and the profiles are shifted towards lower atmospheric depths. It is worth note that EPOS LHC predicts more muons than the other models and that its predictions for the profiles are more dependent on the diffractive interactions.

Finally, let’s analyse the influence of the diffractive interactions on the density of muons that hit the ground ($\rho_\mu$). In particular, we estimate the ratio between the predictions for $\rho_\mu$ obtained considering only non-diffractive interactions and those derived including diffractive and non-diffractive interactions. In Fig. 11 we present our results for the ratio $\rho_\mu^{(ND)}/\rho_\mu^{(full)}$ as a function of distance to the core shower, assuming a primary energy of $10^{17}$ eV and an observation level of 1400 m (Pierre Auger Observatory), which corresponds to an atmospheric depth of 1760 g/cm$^2$ for a zenith angle of 60°. For showers generated with a zenith angle of 30° degrees, such altitude corresponds to an atmospheric depth of $\approx$ 16.
1000 g/cm². We present results assuming both values for the zenith angle. We have that the ratio increases with distance to the shower core and that the influence of the diffractive interactions becomes non-negligible at large distances, specially for small values of the zenith angle.

A final comment is in order. After the completion of our study, a new version of the event generator Sibyll have been released [9]. One of the implications of the modifications implemented in Sibyll 2.3 is the enhancement of the diffractive interactions. As a consequence, the new version predicts, on average, less secondaries in the whole energy range considered for both primaries. One have verified that our results are not strongly modified. The main modification is that the differences between non-diffractive and full simulations of the distinct observables are enhanced by a factor smaller than 1.25 (∼25%) in comparison with the former version Sibyll 2.1, for all energies and primaries. Therefore, our main conclusions about the impact of the diffractive interactions remain valid using the Sibyll 2.3.

IV. SUMMARY

In this paper we investigated the impact of the diffractive interactions on distinct observables for p-Air and Fe-Air collisions as well as in ultra-high energy cosmic ray interactions. Our results demonstrated that the distinct phenomenological models, present in the CORSIKA package, predict a different magnitude for the fraction of diffractive events and for its energy dependence. As a consequence, the influence of these interactions on the number of secondaries and fraction of pions is strongly model dependent. We demonstrated that the predictions of these models for the elasticity are distinct, which directly modifies the air shower development. Our results for ⟨X_{max}⟩ indicated that the impact of the diffractive interactions on this observable is almost energy-independent for the three considered models of hadronic interactions and it is of the order of the typical experimental precision for the ⟨X_{max}⟩ measurements. Moreover, we shown that the average longitudinal profile of muons is sensitive to the diffractive interactions, in particular for small zenithal angles. Our results indicated that the diffractive interactions has a non-negligible influence on the observables and that the treatment of the diffractive physics is an important source of uncertainty in the description of the extensive air showers.
Acknowledgments

This work was financed by the Brazilian funding agencies CAPES, CNPq and FAPERGS.

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