Ultra High Energy Cosmic Rays and Air Shower Simulations: a top-bottom view *

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Abstract

Stable Superstring Relics (SSR) provide some of the candidates for the possible origin of the Ultra High Energy Cosmic Rays (UHECR). After a brief overview of the motivations for introducing such relics, we address the question whether statistical fluctuations in the formation of the air showers generated by the primary spectrum of protons can be separated from a possible signal of new physics hidden in the first impact with the atmosphere. Our results are generated by using minimal modifications in the cross section of the primaries, and using available simulation codes used by the experimental collaborations. The results indicate that substantial increases in the cross section of the first impact, possibly due to new interactions, are unlikely to be detected in geometrical and/or variations of multiplicities in the cascade.

1 Introduction

Superstring theories represent the most advanced theories to probe the unification of gravity and gauge interactions. Over the past decade our understanding of the theory has improved considerably with the realization that the

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disparate string theories in ten dimensions, together with eleven dimensional supergravity, are limits of a more fundamental theory, dubbed M–theory. The question remains however how to connect these advances to experimental data. In this respect we may regard the ten dimensional string limits, as well as the eleven dimensional limit, as effective limits of the more fundamental theory. We should therefore anticipate that non of these effective theories fully characterizes the true nonperturbative vacuum, but can merely probe some of its properties. Thus, for example, the heterotic limit is the one that reveals the grand unification structures that underly the Standard Model data, whereas the type I limit may, perhaps, be more suited to study the dilaton stabilization issue. In this context it may also be that the confrontation of the fundamental theory with experimental data will be achieved via its effective limits and its abstract formulation will only be needed for conceptual consistency.

In this context one of the remarkable properties of the observed Standard Model spectrum is the embedding of its matter multiplets in spinorial representations of $SO(10)$. It is therefore sensible to seek an effective string limit that preserves this embedding. The only limit that realizes the $SO(10)$ embedding is the heterotic limit as it is the only limit that gives rise to spinorial representations in the perturbative spectrum. Indeed, while a highly non–trivial task, phenomenological three generation string models that preserve the $SO(10)$ embedding have been constructed [1].

2  Wilson-line Breaking Mechanism

The prevalent method in string theory to break the non–Abelian GUT symmetry is by utilizing Wilson line breaking. In turn, breaking of the non–Abelian gauge symmetries in string vacua compactified on non–simply connected manifolds results in massless states that do not fall into representations of the original unbroken GUT gauge group. The spectra thus contain states that carry fractional charge with respect to the Abelian Cartan generators of the original GUT gauge group [2]. Such states may carry fractional electric charge, or in models in which the GUT symmetry is broken to $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Z'}$, the non–GUT states may carry the standard charges under the Standard Model gauge group, but a “fractional” non–GUT charge with respect to to the additional $U(1)_{Z'}$. This phenomena is of primary importance for superstring phenomenology. The main consequence is that it generically results in super–massive states that are meta–stable. In the case of fractionally charged states this is obvious. The states are protected from decaying by electric charge conservation. In the case of fractional $U(1)_{Z'}$ charge the meta–stability of the exotic state depends on the charges
of the Higgs spectrum that breaks the $U(1)_{Z'}$ symmetry. Such states are therefore endemic in string GUT models that utilize the Wilson–line symmetry breaking mechanism.

The typical mass scale of the exotic states will exceed the energy range accessible to future collider experiments by several order of magnitude. This general expectation follows from the fact that the exotic states appear in vector-like representation and therefore we in general expect that unsuppressed mass terms are generated. In some cases the exotics mass scale arises from a confinement scale of a hidden sector non–Abelian gauge group. The question is therefore whether the physics of the exotic states can be probed experimentally, as it is unlikely to be accessible to collider experiments.

In this respect one of the most intriguing experimental observations of the past several decades is the observation of Ultra–High Energy Cosmic Rays (UHECR) in excess of the so–called GZK cutoff. Cosmic rays in excess of this bound are not expected experimentally due to their scattering on the microwave background, and consequent constraints on their mean free path. Primaries with energy in excess of the GZK bound could not have reached the earth from cosmological distances, whereas there are no local astrophysical sources that can accelerate them to the required energies. The meta–stable super–heavy string relics suggest an appealing explanation for the observed events in the form of so–called top–down models. If the relics are sufficiently abundant in our local neighborhood, and provided that their mass scale is of the right order, then they can account for the observed events by their rare decay into quarks and leptons. Thus, while the observation of primaries with energies in excess of the GZK bound is still an hotly debated experimental issue, this is clearly one of the exciting possible experimental probes into the physics far beyond that which is accessible to collider experiments. The vital issue is therefore how to connect between the data which is collected by the UHECR experiments and the theoretical expectation of the heavy–relics from the string models. The string models predict specific states and quantum charges under the four dimensional gauge group that can be modeled further by using an effective field theory parameterization. Examples of such states in concrete string models are provided by the so called free fermionic heterotic string models.

3 Can we detect new physics at Auger?

There are various issues that can be addressed, both at theoretical and at experimental level, on this point, one of them being an eventual confirmation of the real existence of events above the cutoff. However, even if these measure-
ment will confirm their existence, remain yet to be seen whether any additional new physics can be inferred just from an analysis of the air shower. A possibility might be supersymmetry \( \mathcal{M} \) or any new underlying interaction, given the large energy available in the first impact. We recall that the spectrum of the decaying X-particle (whatever its origin may be), prior to the atmospheric impact of the UHECR is of secondary relevance, since the impact is always due to a single proton.

What is relevant, instead, is the dynamics in the evolution of the air shower and it is in the first collision that most of the new channels may become available. One important point to keep into consideration is that the new physical signal carried by the primaries in these collisions is strongly “diluted” by their interaction with the atmosphere and that large statistical fluctuations are immediately generated both by the randomness of the first impact, the variability in the zenith angle of the impact, and the extremely large phase space available at those energies in terms of fragmentation channels.

Figure 1: Multiplicities of \( e^\pm \) for various values of the correction factors modifying the cross section of the first primary impact.
4 A simple test

The simplest way to test whether a new interaction at the first proton-proton impact can have any effect on the shower is to modify the cross section at the first atmospheric impact using CORSIKA [5] in combination with some of the current hadronization models which are supposed to work at and around the GZK cutoff. There are obvious limitations in this approach, since none of the existing codes incorporates any new physics beyond the standard model, but this is possibly one of the simplest ways to proceed. Therefore we take our results with some caution.

![Figure 2: Averaged geometric (radial) distributions of $e^\pm$ measured with respect to the center of the detector (here located at 0 cm) for a zero zenith impact of the primary proton versus the correction factors](image)

We show in two figures results on the multiplicities, obtained at zero zenith angle, of some selected particles (electrons and positrons, in our case, but similar results hold for all the dominant components of the final shower) obtained from a large scale simulation of air showers at and around the GZK cutoff. We have used the simulation code CORSIKA [5] for this purpose.

In Fig. 1 we show a plot obtained simulating an artificial first proton impact in which we have modified the first interaction cross section by a nominal factor ranging from 0.7 to 2. We plot on the y-axis the corresponding fluctuations in the multiplicities both for electrons and positrons. Statistical fluctuations
have been estimated using bins of 60 runs. The so-developed showers have been thinned using the Hillas algorithm \[6\], as usually done in order to make the results of these simulations manageable, given the size of the showers at those energies. As one can immediately see, the artificial corrections on the cross section are compatible with ordinary fluctuations of the air-shower. The result is a negative one: a modified first impact, at least for such correction factors 0.7-2 in the cross section of the first impact, is unlikely to modify the multiplicities in any appreciable way.

A second test is illustrated in Fig. 2. Here we plot the same correction factors on the x-axis as in Fig. 1 but we show on the y-axis (for the same particles) the average point of impact on the detector and its corresponding statistical fluctuations.

As we increase the correction factor statistical fluctuations in the formation of the air shower seem to be compatible with the modifications induced by the “new physics” of the first impact and no special new effect is observed.

5 Summary

Fluctuations of these type, generated by a minimal modification of the existing codes only at the first impact may look simplistic, and can possibly be equivalent to ordinary simulations with a simple rescale of the atmospheric height at which the first collision occurs, since the remaining interactions are, in our approach, unmodified. The effects we have been looking for, therefore, appear subleading compared to other standard fluctuations which take place in the formation of the cascade. On the other hand, drastic changes in the structure of the air shower should possibly depend mostly on the physics of the first impact and only in a less relevant way on the modifications affecting the cascade that follows up. We have chosen to work at an energy of $10^{20}$ GeV but we do not observe any substantial modifications of our results at lower energies ($10^{19}$ GeV), except for the multiplicities which are down by a factor of 10. Our brief analysis, though simple, has the purpose to illustrate one of the many issues which we believe should be analyzed with great care in the near future: the physics of the first impact and substantial modifications to the existing codes in order to see whether any new physics can be extracted from these measurements from the multiplicities of the shower and its geometrical shape. We have pointed out that it might be very difficult to disentangle any new physics from the large fluctuations of the air showers and set a warning over enthusiastic claims such as detecting supersymmetry or other “new” interaction from these

\[1\] we keep the height of the first proton impact with the atmosphere arbitrary for each selected correction factor (x-axis)
types of studies. However, we do hope for the best, and clearly improving our ability to extract viable information from cosmic ray experiments continues to pose a vital challenge [7].

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