Superstring theory predicts the existence of relic metastable particles whose average lifetime is longer than the age of the universe and which could, in principle, be good dark matter candidates. At the same time, these states would be responsible for the Ultra High Energy Cosmic Rays (UHECR) events which will be searched for by various experimental collaborations in the near future. We describe a possible phenomenological path which could be followed in order to search for new physics in their detection.

1. Introduction

Strings are with no doubt the richest and most fascinating theoretical constructs of the last decades, but, at this time, no experimental signal has emerged pointing toward a validation/ falsification of the theory. This is the main motivation for studying string model building.

On the other hand, the success of the Standard Model has its own unescapable limitations, since the origin of the mass in the model is still under question and issues of naturalness indicate that new physics might be at the door at forthcoming collider experiments. In the meanwhile, we have also seen that important new results from the astroparticle side -such as neutrino oscillations- are getting more and more entangled with “traditional” collider studies to give us a broader perspective of what may lay beyond the high energy frontier.
2. Cosmic Rays

Particle Astrophysics, in particular cosmic rays astrophysics, may not be able to reach the level of accuracy that we expect from other kinds of experiments, such as collider experiments, but the technology is rapidly changing and we may hope for serious improvements within a decade or even less.

It is to be remarked that theoretical methods and tools of analysis which are common in collider phenomenology are not immediately applicable to astroparticle physics, since the scales entering in the dynamics, for instance in the UHECR dynamics, are in practice much larger that those we are used to in collider studies. Nevertheless, it is still interesting to see what we can say about processes at the Greisen-Zatsepin-Kuzmin (GZK) (∼ 10^{19} eV) cutoff in terms of standard QCD tools based on perturbation theory.

Recently, it has been shown that the renormalization group can be used to describe the dynamics of the UHECR in the so called “top-down” approach to their origin. In particular, the impact of supersymmetry in the re-organization of the spectrum of heavy relics fragmenting into ordinary hadrons has been quantified. The re-adjustment of the spectrum obtained is, of course, dependent on the type of evolution model used to generate supersymmetric fragmentation functions from the high scale, down to the low energy scale where ordinary hadronization takes place. In the model analized is based on the mixing of supersymmetric anomalous dimensions with the corresponding QCD ones with vanishing initial conditions at the susy threshold(s).

We have to mention that the analysis presented in can be also applied to other mechanisms held responsible for the origin of the UHECR, such as Z-bursts and others, since it is the first impact (the interaction of the protons of the primary ray with the atmosphere) to affect the evolution of the cascade and to arrange the multiplicity distributions and the associated shape variables. We recall that for GZK energies, the center of mass energy of the incoming nucleon with the nucleon in the atmosphere is of the order of several hundreds of TeV’s.

3. Wilson Lines Breaking and Fractionally Charged States

One of the solution to the problem of the origin of the UHECR, as we have mentioned above, comes from the decay of long-lived super-heavy states whose mass is in the 10^{12−15} GeV range. The primaries, according to this hypothesis, would be generated in the galactic halo, and the GZK cutoff would not apply. The mass required for the meta-stable state, whose
lifetime is between $10^{17} - 10^{27}$ sec, is about $10^{12-13}$ GeV. Their abundancy ($\sim 5 \times 10^{-11}$) is constrained by the observed flux of the UHECR events.

Superstring theory can naturally account for the meta-stable states, through a stabilization mechanism due to the breaking of the non-abelian gauge symmetries by Wilson lines. This mechanism gives rise to states in the string spectrum which carry standard charge under the Standard Model, but fractional charge under an additional $U(1)_Z'$ gauge group. The existence of fractionally charged states can be regarded as a standard consequence of string unification.

4. Detecting UHECR and the Case for New Physics

The Auger experiment is constructing two 300 Km² grids of detectors spaced at 1.5 km intervals, one in the northern hemisphere and a second one in the southern hemisphere. The possibility to detect fluorescence radiation along the slanted path of the incoming primary has also been taken into account and implemented through fly’s eye detector arrays, beside the usual Cerenkov detectors, laid on the ground.

In the top-down approach to the formation of UHECR

1) a relic decays and generates a given initial distribution of primaries;
2) primary particles propagate and mostly protons survive;
3) primary protons collide with the atmosphere thereby generating atmospheric showers;
4) multiplicity of distributions and their deposited energy are detected on the ground.

If we aim at unveiling new physics from UHECR experiments, we should
1) allow in the analysis of the first impact of the primary the possibility of new interactions;
2) allow a modification of the fragmentation region due to the new interactions (from angular ordering to small $p_T$ exchanges, now with susy).

In standard cosmic rays applications, the simulations of cosmic rays events are performed using monte carlo event generators whose purpose is
1) to generate a first collision with the nuclei in the atmosphere and
2) track down each secondary ray produced to some selected observation levels.

The type of interaction processes implemented in the existing simulation programs do not, at the moment, include any new physics yet.
5. New Models of Interaction and their Simulations

It is possible to introduce new models of interactions, (in our case, specifically, supersymmetric models) and interface them with the traditional monte carlo generators which generate the profile of the final shower and see the enhanced/modified effects on the multiplicities at various observation levels in the atmosphere. This study is on the way and results will be presented elsewhere. However, to illustrate the shape of the distribution of multiplicities that one expects from the simulations of this type, we have included 3 Figs., which we have generated using the simulation program CORSIKA\(^7\), interfaced with the program SYBILL\(^8\) for the generation of the hadronic interactions. The Figs. show separate multiplicities for various particles plotted against rapidities and/or radial distances, the latter measured respect to an axis running perpendicular to the plane of the detector. The geometry is simplified here for a zero zenith angle of impact of the ray, as measured by an observer on the ground of the detector.

It is to be remarked that the experiments will be measuring only the energy deposited and other measurements, such as of rapidities or \(p_T\) distributions on the final showers will not be possible at any of these experiments. Neutrinos are also not detected and therefore these plots are mostly of theoretical interests.

As one can see, multiplicity distributions of the 3 main particles are clearly separated, the photon showing higher statistics compared to the other particles. In the simulations we have kept the depth of the first impact to be random, at an energy below the GZK cutoff (\(10^5\) TeV). We remark that current hadronic interaction models may not be appropriate at the GZK cutoff. The results show a fast increase in the number of the secondaries as we raise the collision energy. To allow comparisons, the multiplicities have been normalized in such a way that the area under each distribution is set to be one.

6. Astro QCD/ SUSY-QCD: Perspectives

Among the issues that need to be analyzed in the context of Ultra High Energy QCD (Astro-QCD) is the role played by supersymmetry in the fragmentation, the role of mini-jet cross sections and of vacuum exchanges (with and without supersymmetry) near the cutoff, where theory is still lagging compared to the planned experiments.

Numerical solutions of the Renormalization Group Equations\(^5\) have been obtained recently and indicate that - at least at large momentum transfers- the impact of supersymmetry on the evolution of the cascades
is small and comparable to other hadronic background \(^1\). To support this point, in Fig. 4 \(^1\) we show results obtained by solving the Renormalization Group Equations for the following inclusive observables,

\[
R_h^{QCD}(Q^2) = \sum_{i=1}^{n_f} e_i^2 \int_{z_{min}^h}^{1} dz \left( D_{hq_i}^h(z, Q^2) + D_{h\bar{q}_i}^h(z, Q^2) \right) \quad (1)
\]

and

\[
R_{SQCD}^{h}(Q^2) = \sum_{i=1}^{n_f} e_i^2 \int_{z_{min}^h}^{1} dz \left( D_{hq_i}^h(z, Q^2) + D_{h\bar{q}_i}^h(z, Q^2) + D_{h\tilde{q}_i}^h(z, Q^2) + D_{h\bar{\tilde{q}}_i}^h(z, Q^2) \right) \quad (2)
\]

with \(D_{hq_i}^h(z, Q^2)\) being the fragmentation of function of quark flavour \(i\) into hadrons \(h\), and with \(z_{min}^h = m_h/(Q/2)\) being the minimum fractional energy required for the fragmentation to take place. \(e_i\) are the charges of the \(n_f\) quark and squark flavours. This result has been obtained solving approximately 100 coupled equations of DGLAP-type, as described in \(^1\). Fig. 4 describes the fragmentation into final protons and compares the QCD case (curve above) to the Susy QCD (SQCD) one (curve below). Again, we see that there are indications that sussy effects, linked to the mixing of super-symmetric operators to QCD light-cone operators, are at the few percent level. These differences, although small, can’t be discarded, since in monte carlo simulations of showers these effects change sensitively the hadronization process. If they combine to give variations in the total cross sections at the 10 percent level, they may affect the profile of the showers \(^9\).

Although these results are encouraging, and theorists have shown a great deal of interest on the matter \(^4\), more work in this direction, however, is needed.

Acknowledgement

We thank Alon Faraggi for collaboration on related work and Subir Sarkar for discussions. The work of A.C., C.C. and M.G. is partly supported by INFN (iniziativa specifica BA21).

References

1. C. Corianò and A. Faraggi, *Phys. Rev.* **D65**, 075001, (2002); *AIP Conf. Proc.* **602** 145 (2001) (ed. P. Colangelo and G. Nardulli); hep-ph/0201129. Contributed to 4th Meeting of the RTN Network and Workshop on Across the Present Energy Frontiers: Probing the Origin of Mass, Corfu, Greece, 10-13 Sep 2001.

2. A. Faraggi hep-th/9910042

3. S. Sarkar hep-ph/0202013 and references therein;

4. S. Sarkar and R. Toldra, *Nucl.Phys.* **B621** 495, (2002); C. Barbot and M. Drees, *Phys. Lett.* **B533** 107 (2002).
Figure 1. Plot of the normalized occurrences of $\gamma$, $\nu_{\mu}$, and $e^{-}$ assuming an impact energy of $10^{5}$ TeV as a function of distance on a logarithmic scale.

Figure 2. Distributions of rapidities of $\gamma$, $\nu_{\mu}$, and $e^{-}$ at the same energy as in Fig. 1.

5. C. Corianò, Nucl.Phys. B627 94, 2002; hep-ph/0102164.
6. S. Chang, C. Corianò and A. Faraggi, Nucl.Phys.B477:65-104, 1996, Phys. Lett. B397 76,(1997); C. Corianò, A. Faraggi and M. Plumacher Nucl.Phys. B614 253, (2001).
7. D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz and T. Thouw, Report FZKA 6019, Karlsruhe;
Figure 3. Plot of the normalized occurrences of \( \gamma \), \( \nu_\mu \) and \( e^- \) assuming an impact energy of \( 10^5 \) TeV as a function of transverse momentum \( p_T \).

Figure 4. Plot of the R-function describing the fragmentation of quarks into final protons with supersymmetry (curve above) and without supersymmetry (curve below) versus \( Q \), the initial fragmentation energy.

8. R. S. Fletcher, T.K. Glasser, P. Lipari and T. Stanev, Phys. Rev. D50, 5710 (1994); R. Engel, T.K. Glasser, P. Lipari and T. Stanev, Phys. Rev. D46, 5013 (1992).

9. A. Cafarella et al., in preparation.