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Long-lived Staus from Cosmic Rays

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The collision of a high energy cosmic ray with a nucleon in the upper atmosphere could produce long-lived heavy particles. Such particles would be very *penetrating*, since the energy loss in matter scales as the inverse mass, and could reach a neutrino telescope like IceCube from large zenith angles. Here we study this possibility and focus on the long-lived stau of SUSY models with a gravitino LSP. The signal would be a pair of muon-like parallel tracks separated by 50 meters along the detector. We evaluate the background of muon pairs and show that any events from zenith angles above 80° could be explained by the production of these heavy particles by cosmic rays.

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I. INTRODUCTION

The *hierarchy problem* has motivated an intense search for new physics during the past 20 years. Colliders like LEP, the Tevatron, or the B factories have explored the standard model (SM) at the quantum level but have not reached the energy or the sensitivity necessary to detect new physics. There is experimental evidence for neutrino masses, whereas cosmological data strongly suggest the presence of a stable weakly-interacting massive particle (WIMP) as the origin of the dark matter of the universe. However, these features could be easily *added* to the SM without changing its structure. Therefore, as we approach the search for extensions like supersymmetry (SUSY), technicolor or extra dimensions at the LHC, it is clear that we should never underestimate the SM.

On the other hand, cosmic rays are another source of elementary particles of very high energy with the potential to explore the physics beyond the SM. When a proton of 10^8 GeV from outer space hits an atmospheric nucleon it provides a center of mass energy $\sqrt{s} = \sqrt{2 m_N E}$ around 14 TeV. A small fraction of these protons (or of the secondary particles with still enough energy) may then produce exotic massive particles. Of course, the question is whether such an event could give any observable signal. In this paper we argue that this is the case, the long-lived charged particles present in some extensions of the SM could provide a distinct signature when they cross a neutrino telescope from large zenith angles.

The process that we propose could take place in SUSY models with an exact R-parity, a gravitino lightest SUSY particle (LSP) working as dark matter, and a charged next-to-LSP (NLSP) [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. The collision of the cosmic proton with the nucleon could produce any pair of SUSY particles, which would then decay promptly into the NLSP. Since the NLSP couples very weakly to the LSP gravitino, it will be long-lived and able to cross a kilometer-long detector like IceCube. The generic features of this framework could be also found in other extensions of the SM, like Little Higgs models [11]. These models may incorporate a T-parity [12] *separating* the standard and the exotic particles. The T-parity would forbid unobserved mixing between both sectors, tree-level four fermion operators, and would also make the lightest particle in the odd sector stable. If this particle (constituting the dark matter) is very weakly coupled with the rest, the next-to-lightest one will be long-lived.

The possibility to observe quasi-stable gluinos in IceCube [13] has been considered in [14, 15] in the framework of split-SUSY models with very heavy sfermions [16]. Here we will focus on non-colored particles, which present some remarkable differences with the gluinos. In particular, as one of these particles propagates in matter it loses energy at a much smaller rate than an R-hadron [17, 18]. This fact makes it easier to confuse it with a muon, but it also lets the particle reach IceCube form larger zenith angles. To be definite we will consider a long-lived stau $\widetilde{\tau}_R$[1], although our arguments would be analogous for any massive charged particle: charginos, other sleptons, or vectorlike leptons that may appear in Little Higgs models.

Other analyses of the production of exotic particles by cosmic rays refer to primary neutrinos [20, 21, 22, 23]. Being weakly interacting, the relative effect of new physics on the neutrino-nucleon cross section may be larger (see below), however, it is difficult to make precise predictions until the flux of cosmic neutrinos is determined. In contrast, our analysis here relies on a flux of primary cosmic rays that is well-known in the relevant

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[1] We will assume in the following that the $\widetilde{\tau}_R$ life-time is much larger than the propagation time through the Earth (see *e.g.* [19]).

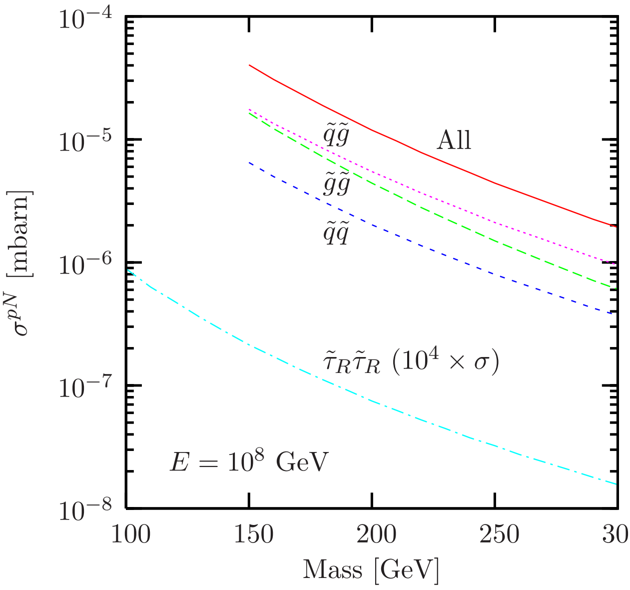

FIG. 1: pN cross section to produce SUSY particles for different values of the stau and the (common) squark/gluino mass and a proton energy of 10^8 GeV.

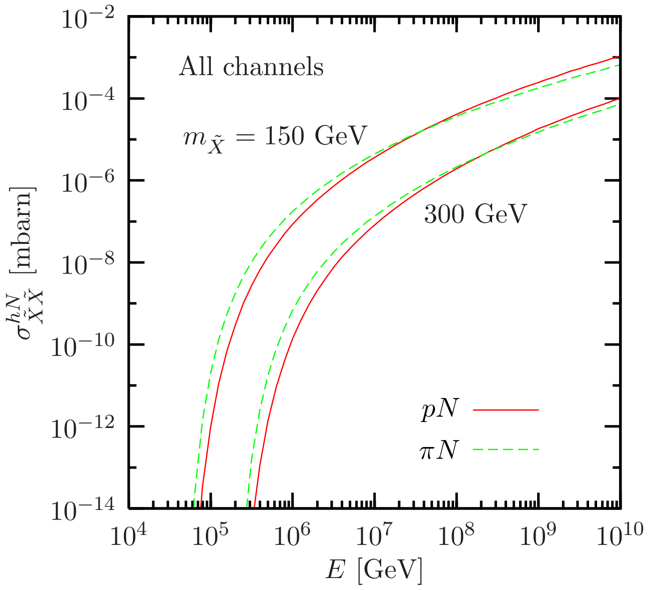

FIG. 2: Cross section to produce any pair of colored SUSY particles in a pN and a πN collision for different incident energies and a squark/gluino mass $m_{\tilde{X}} = 150$, 300 GeV.

energy region 10^5–10^8 GeV.

The outline of the paper is as follows. In Sec. II, we calculate the rate of long-lived stau pairs produced by collisions of primary and secondary cosmic rays in the atmosphere. We discuss then in Sec. III the signal of these pairs at IceCube and the background from muon pairs. Section IV includes a summary of our results.

II. PRODUCTION OF STAU PAIRS

At energies above 10^4 GeV the decay length of nucleons, charged pions and kaons is much larger than their interaction length in the air. Therefore, as they propagate in the atmosphere the probability that one of these hadrons (h) collides with a nucleon (N) to produce new physics is just [24]

$$\mathcal{P}^h_X(E) \approx \frac{A\, \sigma^{hN}_X}{\sigma^{ha}_T}\,. \tag{1}$$

In this expression σ^{hN}_X is the cross section to produce the exotic particle(s) X and σ^{ha}_T the total cross section of the hadron with the air (we assume $A = 14.6$ nucleons in a nucleus of air and neglect nuclear effects). The (default) cross sections with the air used by CORSIKA [25] above 10^4 GeV can be approximated by $\sigma^{ha}_T \approx C^h_0 + C^h_1 \ln(E/\mathrm{GeV}) + C^h_2 \ln^2(E/\mathrm{GeV})$, with the constants given in Table I. Since σ^{ha}_T is above 100 mb, it is apparent that this probability will be very small and that it would be much larger for a neutrino propagating in matter.

The cross section to produce SUSY particles in a hadronic collision depends basically on their mass and on whether they have strong interactions. All the cross sections at the parton level can be found in Ref. [26]. Collider bounds on SUSY particles with prompt decay into a neutral LSP are around 250 GeV for gluinos and squarks, and 100 GeV for the stop, the sbottom, charginos, and charged sleptons [27]. These bounds, however, may not apply if the particles decay instead into a long-lived charged or colored SUSY particle. For example, in order to minimize the SM background a recent analysis [28] of jets plus missing momentum at the run II of the Tevatron imposes a veto on events with an isolated electron or muon with large transverse momentum. However, gluino or squark events will include here final staus (instead of neutralinos) that could be taken by isolated muons. We are not aware of specific bounds on the colored SUSY spectrum in stau NLSP models. Notice that bounds based on the delay in the time of flight versus a muon or the anomalous ionization of the staus should also be specific, as they are based on the absence of slow-moving ($\beta \lesssim 0.6$) charged particles, but here the staus get an extra boost from the decay of the parent squark or gluino. Through the paper we will then consider slepton,

TABLE I: Constants defining the total cross section with the air $\sigma^{ha}_T \approx C^h_0 + C^h_1 \ln(E/\mathrm{GeV}) + C^h_2 \ln^2(E/\mathrm{GeV})$.

h	C^h_0 [mb]	C^h_1 [mb]	C^h_2 [mb]
N	185.7	13.3	0.08
π	100.5	16.9	0.00
K	79.7	13.9	0.05

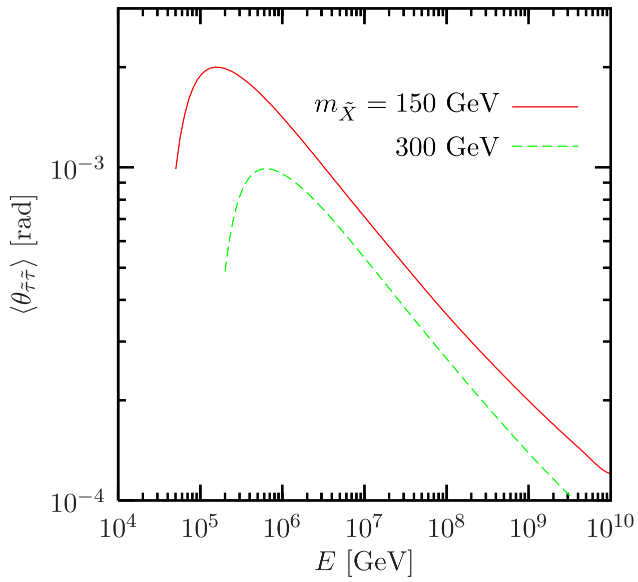

FIG. 3: Average angle between the two staus (in the laboratory frame) for $m_{\tilde X} = 150$, 300 GeV.

chargino and neutralino masses as low as 100 GeV and colored SUSY particles above 150 GeV.

In Fig. 1 and 2 we plot the total hN ($h = p$, π) cross sections to produce pairs of these SUSY particles for different SUSY masses (left panel) and for values of the hadron energy between 10^4 and 10^{11} GeV (right panel). We have used the CTEQ6M [29] (MRSS [30]) parton distribution functions for baryonic (mesonic) interactions, with the renormalization scale $\mu = 0.2 m_{\tilde X}$ suggested by a NLO calculation [31]. We observe that the cross section to produce *directly* a pair of long-lived staus of 100 GeV is much smaller than via the production and prompt decay of colored particles of mass around 200 GeV. In the latter case, we estimate that the final stau will carry a fraction η

$$\eta \approx \frac{m_{\tilde X}^2 + m_{\tilde\tau}^2}{2 m_{\tilde X}^2} \qquad (\tilde X = \tilde g, \tilde q) \tag{2}$$

of the energy of the parent gluino or squark. The average angle of the stau pair (in the lab frame) for different energies of an incident proton are given in Fig. 3.

To evaluate the production rate of stau pairs by cosmic rays we need the total flux of hadrons: primary plus secondary nucleons, pions and kaons produced at any depth in the atmosphere and with enough energy to create staus in the collision with an air nucleon. This analysis has been carried out in [14] assuming a flux of primary nucleons

$$\frac{\mathrm{d}\Phi_N}{\mathrm{d}E} \approx 1.8 \left(\frac{E}{1\,\mathrm{GeV}}\right)^{-2.7} \frac{\text{nucleons}}{\text{cm}^2\ \text{s sr GeV}}\,, \tag{3}$$

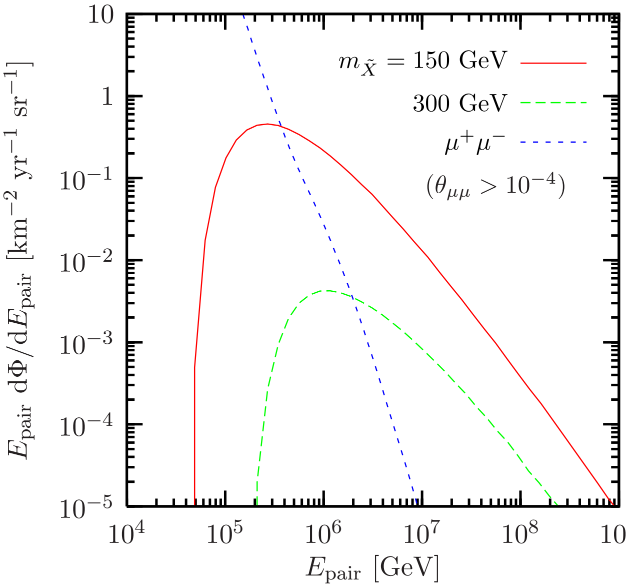

FIG. 4: Flux of stau pairs produced by cosmic rays in terms of the (total) stau energy $E_{\tilde\tau\tilde\tau}$ on production for $m_{\tilde X} = 150$, 300 GeV and $\eta = 1$. We include the flux of muon pairs produced with an opening angle above 10^{-4} rad.

for energies up to 10^6 GeV, with a spectral index that changes to 3 in the interval 10^6–10^9 GeV and goes back to 2.7 at higher energies (*e.g.* [32]). We will use in the following the results on the flux of secondary hadrons (nucleons, pions, and kaons) derived there.

The flux of quasi-stable staus produced via the prompt decay of a pair $\tilde X \tilde X'$ of SUSY particles is then

$$\Phi_{\tilde\tau\tilde\tau} = \sum_{h=N,\pi,K} \int_{E_{\min}}^{\infty} \mathrm{d}E\, \frac{\mathrm{d}\Phi_h}{\mathrm{d}E}\, \mathcal{P}^h_{\tilde X \tilde X'}(E)\,. \tag{4}$$

In Fig. 4 we plot the differential flux ($\mathrm{d}\Phi/\mathrm{d}E_{\tilde\tau\tilde\tau}$) of stau pairs produced by cosmic rays for squarks and gluinos masses of 150 and 300 GeV and $\eta = 1$.

III. BACKGROUND OF MUON PAIRS AND SIGNAL AT ICECUBE

The flux of stau pairs produced high in the atmosphere needs to propagate down to the core of IceCube, about two kilometers under the antarctic ice, to be observed. In addition, the possible signal faces a strong background of muon pairs crossing the detector. We plot in Fig. 4 the flux ($\mathrm{d}\Phi/\mathrm{d}E_{\mu\mu}$) of muon pairs[2] produced by cosmic rays of energy $E_h > 10^4$ GeV. We include only the events where the two muons are produced with an opening angle

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[2] We neglect the muons from tau decays as they are a ≈ 1% correction to this flux.

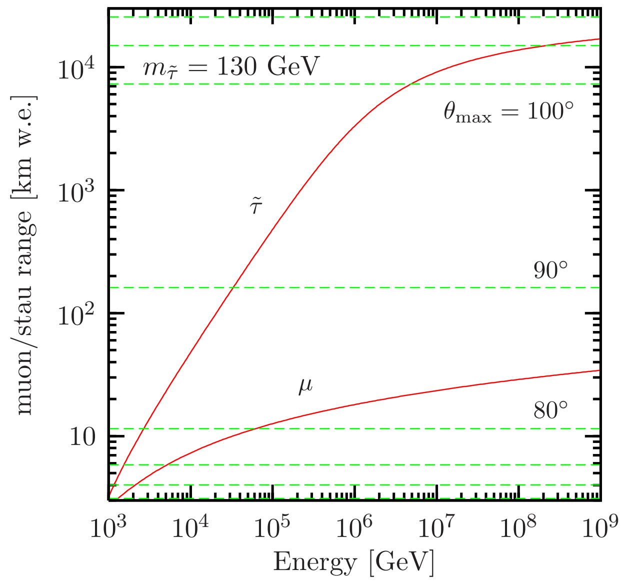

FIG. 5: Range of staus and muons of different energy. The dashed lines show the integrated column depth of the Earth from the center of IceCube for increasing zenith angles ($\Delta\theta_{\max} = 10°$).

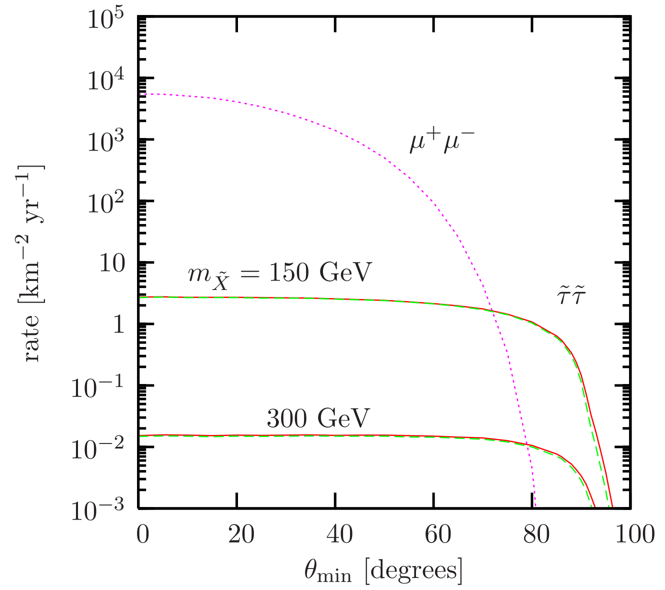

FIG. 6: Integrated number of stau and muon pairs with a minimal separation of 50 meters at the detector for different values of a minimal zenith angle.

above 10^{-4} rad, since smaller angles imply a separation between the two muon tracks that can not be resolved at IceCube (see below). Notice that this requirement cuts off muon pairs with an invariant mass near threshold, $\sqrt{\hat{s}} \leq 1$ GeV, where the PDFs are mostly unknown and the process would be better described in terms of hadronic resonances.

The propagation of muons and heavy charged particles in matter is well understood. For a muon of energy $E_\mu > 2m_\mu$ the mean energy loss per column density (measured in g/cm^2) can be approximated as

$$-\frac{\mathrm{d}E_\mu}{\mathrm{d}z} = \alpha_\mu + \beta_\mu E_\mu \; , \qquad (5)$$

where $\alpha_\mu \approx 2 \times 10^{-3}$ GeV cm^2/g describes ionization effects and $\beta_\mu \approx 4 \times 10^{-6}$ cm^2/g accounts for bremsstrahlung, pair production and photohadronic processes. The solution of Eq. (5) provides an approximation of the total range of (initially) very relativistic muons, which we consider in the following.[3]

For a stau, at the lowest order ionization effects coincide ($\alpha_{\tilde{\tau}} \approx \alpha_\mu$) whereas the other effects depend mainly on the velocity of the particle, which implies $\beta_{\tilde{\tau}} \approx \beta_\mu m_\mu / m_{\tilde{\tau}}$. For $m_{\tilde{\tau}} \approx 100$ GeV, this means that a stau of energy above 10^5 GeV losses 10^3 times less energy than a muon of the same energy, but below 500 GeV they deposit energy at a similar rate. In our analysis we will use the approximation for the range of a stau provided in [17] and will neglect losses through electroweak interactions [18], as they are not important for the stau energies that we obtain.

In Fig. 5 we plot the range of staus and muons of energy between 10^3 and 10^9 GeV. We give the correspondence between integrated column depth of the Earth (see *e.g.* [33]) and zenith angle for several trajectories ending at the center of IceCube. We observe, for example, that whereas a muon of $E = 10^7$ GeV has a range of about 25 km water equivalent (w.e.) and can reach IceCube from a zenith angle $\theta_{\max} \approx 86°$, the range of a stau of the same energy is 360 times larger, which makes it able to reach IceCube from zenith angles of up to $\theta_{\max} \approx 105°$.

Another relevant observable is the separation of the two particles when they cross IceCube. This depends on their angle at the creation point (see Fig. 3) and the distance from that point to the telescope. The interaction length of a 10^7 GeV proton in air is around 4 g/cm^2 (its cross section is $\sigma_T^{ha} \approx 400$ mb), which corresponds to an altitude of about 20 km in the atmosphere. Therefore, if a primary proton creates a stau pair it will do it around that altitude. The production of a stau pair by a secondary hadron will typically occur along the second interaction length, finishing at around 15 km, and so on. To estimate the distance between the parallel stau tracks at IceCube we will assume that they are created at a height $H \approx 15$ km. This implies that stau pairs coming from zenith angles of 60°, 80°, and 100° fly an approximate distance of about 30, 90, and 2300 km, respectively, to reach the center of IceCube.

In Fig. 6 we compare the number of stau and muon

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[3] Below $E \approx 2m$ the ionization energy loss grows like $1/\beta^2$ (see *e.g.* [27]).

pairs reaching IceCube with a separation larger than 50 meters, so that the two tracks can be resolved [34]. We plot the flux of these particles coming from zenith angles larger than the value given in the x-axis (*e.g.* $\theta_{\rm min} = 0$ corresponds to pairs coming from any direction). We show the cases $m_{\tilde{X}} = 150$, 300 GeV and $\eta = 1$, 0.7. We observe that from zenith angles between 80° and 95° there is a possible signal with no background from muon pairs.

IV. SUMMARY AND DISCUSSION

Cosmic rays may be continuously producing massive particles when they collide with nucleons in the upper atmosphere. If these particles are long-lived they will be able to reach a detector like IceCube, about two kilometers under the ice. To have a sizeable production rate (order 1 per year and square kilometer) the particles should be produced through strong interactions. This would be the case for a quasi-stable stau resulting from the prompt decay of a gluino or a squark. We have studied in some detail the possibility to observe such an event.

The heavy staus would be produced in pairs at altitudes around 15 km, and as they approach IceCube the two staus would separate. In principle, they could be confused with a muon pair: a muon and a stau of 500 GeV would give in IceCube a very similar signature. We have shown, however, that it is possible to reduce the dimuon background below the signal. Above $E \approx 500$ GeV muons lose energy in ice much faster than the staus. As a consequence, while muons will never reach IceCube from directions close to the horizon, staus can come from zenith angles of up to 110°. In addition, larger zenith angles mean also larger distance of flight and, in turn, larger separation between the two tracks at IceCube.

We obtain that any events with two muon-like tracks separated by more than 50 meters coming from zenith angles of 80°–100° would be a clear signal of heavy charged particles produced by cosmic rays high in the atmosphere (see Fig. 6).

One may wonder if this signal could also be distinguished from possible stau pairs produced by primary neutrinos, which have been extensively considered in the literature. We find two main differences with such an event. Suppose that the primary comes horizontally ($\theta = 90°$). In our case the staus will be created high in the atmosphere, whereas in a neutrino event the interaction to produce them will typically take place deep inside the ice. This implies a smaller distance between the two stau tracks along IceCube. A second important difference is that while neutrino events could come basically from any direction, the staus produced by primary protons vanish at zenith angles above about 115°.

We think that the study of inclined ($\theta \geq 60°$) two-muon events at IceCube would be interesting by itself. For example, it can be used as an indirect measure of the total (primary plus secondary) flux of hadrons of 10^4–10^9 GeV and, thus, as a test for the different codes that simulate extensive air showers. Going to zenith angles below the horizon the SM background vanishes, leaving some room for exotic physics.

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