Long-Lived Gluinos and Stable Axinos

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In this Letter we present a novel version of "long-lived" gluinos in supersymmetric models with the gluino lightest ordinary supersymmetric particle (LOSP) and the axino lightest supersymmetric particle. Within certain ranges of the axion decay constant $f_a < 1 \times 10^{10}$ GeV, the gluino mass bounds are reduced to less than 1000 GeV. The best limits can be obtained by looking for decaying R hadrons in the detector where the gluino decays to a gluon and axino in the calorimeters. Supersymmetry (SUSY) models with a gluino LOSP can occur over a significant region of parameter space in either *mirage mediation* or general gauge-mediated SUSY breaking models. The gluino LOSP is not constrained by cosmology, but in this scenario the axion or axino may be a good dark matter candidate.

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Introduction.—Supersymmetric models with nonuniversal gaugino masses are well defined even in the range of parameters for which gluinos are the lightest supersymmetric particle (LSP) [1–5]. The most stringent constraint in this case comes from cosmology. Although gluinos are Majorana particles and annihilate with a strong interaction rate, there are still too many of them left over in the early Universe. They form stable, hadronic bound states and searches for heavy hydrogen essentially rule out this possibility [6–8]. In this Letter we show that when gluinos are the lightest ordinary supersymmetric particle with an axino LSP we clearly evade these cosmological bounds. Moreover, we show that collider bounds on the gluino mass can be significantly reduced for an axion decay constant in the allowed region with $f_a < 1 \times 10^{10}$ GeV.

There are presently strong limits on gluino masses coming from the first run of the LHC. In particular, we are interested in the bounds for long-lived gluinos. We consider recent CMS results. These come from searches for R hadrons which travel through the detector [9] or for R hadrons which stop in the detector and then decay [10]. For long-lived gluinos the bounds depend on the fraction, f, which initially hadronizes as a gluino-gluon bound state [9]. For $f = 0.1$, the bounds require $m_{\tilde{g}} > 1233$ GeV or even greater, depending on the model for propagation. These bounds only require data from the central tracker. The track that the charged R hadron leaves in the central tracker must satisfy $|\eta| < 2.1$, $p_T > 45$ GeV$/c$ and must have significant dE/dx. The track must also be isolated in both the tracker and the calorimeter with $\sum p_T < 50$ GeV$/c$ where the sum is over all tracks (except the candidate track) within a cone $\Delta R < 0.3$ rad. Thus if the R hadron should decay in the tracker or calorimeter it will not pass these cuts. However, if the lifetime is long enough such that the gluino decays outside the window of the collision region, it will be counted in this event sample. Therefore, in order to evade these bounds, the gluino must decay fast enough so that it leaves energy in the calorimeters. Thus, we need $\langle\beta\rangle c\tau_{\tilde{g}} \lesssim 2.5$ m or $\tau_{\tilde{g}} \lesssim 8.3(\langle\beta\rangle)^{-1} \times 10^{-9}$ s. If the gluino does live long enough to make it to the muon system, then it will be constrained by other data sets which give just as strong bounds on the gluino mass. The limits are slightly less strong for gluinos which are long lived and stop in the detector [10]. In this case the most stringent bound is $m_{\tilde{g}} \geq 1000$ GeV for gluino lifetimes in the range, 10^{-6} s $< \tau_{\tilde{g}} < 10^3$ s. However, any event which satisfies the latter stopped bounds was already constrained by the former long-lived bounds.

These limits can be applied to any theory where the gluino is the next-to-lightest supersymmetric particle which decays into a gluon and a neutral LSP. It has applications to gauge-mediated supersymmetry (SUSY) breaking models where the gluino decays to a gluon and a Goldstino [11] or to split SUSY models where the gluino decays to a quark-antiquark pair and a neutralino LSP [12].

In this Letter we consider another scenario where the gluino is the lightest ordinary supersymmetric particle (LOSP) with an axino LSP. The strong CP problem has a natural solution in terms of the Peccei-Quinn-Weinberg-Wilczek axion [13–15]. Its modern form is in terms of an invisible axion of the Kim-Shifman-Vainshtein-Zakharov type [16,17] or the Dine-Fischler-Srednicki-Zhitnisky type [18,19]. In a supersymmetric theory the axion has a scalar partner, the saxion, and a fermionic partner, the axino [20,21]. The saxion typically has a mass of the order of the gravitino mass, while the axino can be much lighter [22–25].

Supersymmetric models with nonuniversal gaugino masses, such as *mirage mediation* SUSY breaking or general gauge mediation have significant ranges of parameters where the gluino is the LSP. For example, in a recent study of mirage mediation in an SO(10) grand unified theory (GUT) [5], the gaugino mass formula at the GUT scale is given by

$$M_i = \left[1 + \frac{g_G^2 b_i \alpha}{16\pi^2} \log\left(\frac{M_{Pl}}{m_{16}}\right)\right] M_{1/2}, \tag{1}$$

where $b_i = (33/5, 1, -3)$ for $i = 1, 2, 3$, $M_{1/2}$ is the overall mass scale, and α is the ratio of the anomaly mediation to gravity mediation contributions. For an α in the range $3 \leq \alpha \leq 4$, we find that the gluino is the LSP. Also, in the case of general gauge mediation (see Ref. [3]), for messenger scales of the order of the GUT scale, the gravitino is heavy and we find that it is quite natural to have a gluino LSP. We note that these models have the very interesting property of precision gauge coupling unification [4,26]; i.e., the gauge couplings unify at the GUT scale to high accuracy, thus requiring little or no threshold corrections at M_{GUT}. However, as was discussed earlier, such theories are unacceptable cosmologically. Therefore, it becomes advantageous to combine these models with the axion solution to the strong *CP* problem. The gluino is then the LOSP with an axino LSP.

Gluino-axino coupling and gluino lifetime.—We consider the supersymmetrized axion multiplet coupling to the SU(3) gauge sector. We have [27,28]

$$\mathcal{L}^{\mathrm{eff}} = -\frac{\alpha_s}{2\sqrt{2}\pi f_a}\int d^2\theta A W^{a\alpha} W^a_\alpha + \mathrm{H.c.}, \tag{2}$$

where the axion superfield,

$$A = \frac{s + ia}{\sqrt{2}} + \sqrt{2}(\theta\psi_a) + (\theta)^2 F_A, \tag{3}$$

and the gauge superfield strength is given by

$$W^a_\alpha = -i\lambda^a_\alpha + \left[\delta^\beta_\alpha D^a - \frac{i}{2}(\sigma^\mu\bar{\sigma}^\nu)^\beta_\alpha G^a_{\mu\nu}\right]\theta_\beta + (\theta)^2 \sigma^\mu_{\alpha\dot{\alpha}} D^\mu \bar{\lambda}^{\dot{\alpha}}. \tag{4}$$

We define the four component Majorana spinors for the gluino and axino fields by

$$\tilde{g} = \begin{pmatrix} -i\lambda \\ i\bar{\lambda} \end{pmatrix}, \qquad \tilde{a} = \begin{pmatrix} \psi_a \\ \bar{\psi}_a \end{pmatrix}. \tag{5}$$

With this notation, we have

$$\begin{aligned}\mathcal{L}^{\mathrm{eff}} = \frac{\alpha_s}{8\pi f_a}&[a(G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + D_\mu(\bar{\tilde{g}}\gamma^\mu\gamma_5\tilde{g}))\\ &+ s(G^{a\mu\nu}G^a_{\mu\nu} - 2D^a D^a + 2\bar{\tilde{i}}g\gamma^\mu D_\mu\tilde{g})\\ &+ i\bar{\tilde{a}}G^a_{\mu\nu}\frac{[\gamma^\mu,\gamma^\nu]}{2}\gamma_5\tilde{g}^a - 2\bar{\tilde{a}}\tilde{g}^a D^a].\end{aligned} \tag{6}$$

We then find the gluino decay rate (neglecting the axino mass) given by

$$\Gamma_{\tilde{g}\to\tilde{a}g} = \frac{\alpha_s^2 m_{\tilde{g}}^3}{128\pi^3 f_a^2}. \tag{7}$$

Thus, the gluino lifetime for particular values of f_a and the gluino mass is given by

$$\tau_{\tilde{g}\to\tilde{a}g} = 3\times 10^{-8}\ \mathrm{s}\frac{(f_a/10^{10}\ \mathrm{GeV})^2}{(m_{\tilde{g}}/850\ \mathrm{GeV})^3}. \tag{8}$$

Therefore, as an example, for values of $f_a \leq 0.7\times 10^{10}$ GeV and an average gluino velocity, $\beta \sim \frac{1}{2}$, the gluino mass bound may reduce to $m_{\tilde{g}} \gtrsim 850$ GeV.

Conclusion.—We have presented a novel version of gluino LOSPs in supersymmetric models with an axino LSP. Within certain ranges of the axion decay constant $f_a < 1\times 10^{10}$ GeV, the gluino mass bounds are reduced to less than 1000 GeV. The best limits can be obtained by looking for decaying *R* hadrons in the hadronic calorimeters. Such decays will produce jets deep in the calorimeter. SUSY models with a gluino LOSP can occur over a significant region of parameter space in either mirage mediation or general gauge-mediated SUSY breaking models. Since the gluino LOSP is no longer constrained by cosmology, it would now be interesting to analyze the possibility of axion or axino dark matter in this scenario.

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