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Light gluinos and precision tests at the CERN e^+e^- collider LEP

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A slight mismatch between the low and high energy α_s measurements has fueled speculation in recent times on the existence of light gluinos—a scenario not yet ruled out by direct experimental searches. We study the impact of light virtual gluinos (~ 3 GeV) on some electroweak observables measured at the CERN e^+e^- collider LEP 1 with unprecedented precision. We conclude that squark masses in the range 50–60 GeV are disfavored by the present data with the above choice of gluino mass.

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The assertion that the presence of a light colored neutral fermion improves the agreement between the low and high energy α_s measurements has received attention of late [1–5]. A light gluino is a strong candidate to satisfy such a requirement. In this Rapid Communication we examine the impact of such a supersymmetric scenario from a different perspective; namely, the loop effects of a light gluino on some electroweak observables precisely measured at the CERN e^+e^- collider LEP. We show that the agreement between those precise measurements and their standard model (SM) predictions are so good that not much space is left to accommodate large contributions generated by a light virtual gluino—a result suggesting that the prospect of a light gluino may not be promising as more statistics accumulate on the Z peak.

The nonobservation of any supersymmetric particle so far, mainly in the CERN e^+e^- machine LEP and the Fermilab $p\bar{p}$ collider Tevatron, leads to a general belief that superparticles are heavy. Lower bounds on squark and gluino masses are set from the Tevatron and they are significantly stringent, being $m_{\tilde{q}} \geq 141$ GeV and $m_{\tilde{g}} \geq 126$ GeV [6]. But there still seems to exist a possible exception to the above; that the gluinos are extremely light (weighing up to a few GeV). Although such a possibility has been examined by a number of experiments, particularly the CERN $p\bar{p}$ collider [7], in bottomonium decays and in fixed target experiments looking for missing energies [8,9], a region with $m_{\tilde{g}} \sim 3$–4 GeV with lifetimes around 10^{-13} s or $(10^{-8}$–$10^{-10})$ s has escaped detection [5]. In fact the lower bounds on the squark and gluino masses at the level of 100 GeV rely on the assumption that these particles, once produced, will lead to significant amount of missing transverse energy while decaying ultimately to the lightest supersymmetric particle (LSP), which is either the photino or some other weakly interacting stable neutralino. The hadronization Monte Carlo programs for gluino production leading to those bounds work reliably for $m_{\tilde{g}} \sim 100$ GeV or more and are not intended for light gluinos. A squark produced in hadronic collision, on the other hand, will immediately decay into a quark and a gluino. If that gluino is light, the LSP it decays into will carry off a very small amount of transverse energy, thus escaping detection, and no bound can be set on the squark mass [2]. However, the nonobservation of squark-antisquark pairs in Z decay sets a lower limit on the squark mass $\sim M_Z/2$. If, in particular, $m_{\tilde{q}}$ lies between $M_Z/2$ and M_Z and if the gluino is light enough, the channel $Z \to \overline{\tilde{q}} q \tilde{g} +$ c.c. opens up and the resultant contribution to the hadronic width is manifested through an overall change in the strong coupling constant α_s [2], whose central value is larger than the low energy α_s measurements (after naive extrapolation). Measurement of α_s from jet correlation also leads to an enhancement once the loop effects due to light gluinos are considered [5]. On the other hand, the low energy determinations of α_s, for example, in deep inelastic scattering, quarkonium [2], or τ decays, need to be extrapolated through the renormalization group equations for comparison with the high energy measurements. It turns out that α_s should run slower for better agreement with the high energy measurements, and that requires an excitation of a neutral light colored fermionic degree of freedom. However, one must admit at the same time that this improvement is not all that mandatory as the low and high energy determinations of α_s are not statistically inconsistent with each other without a light gluino.

In this paper we explore the consequences of a supersymmetric scenario with $m_{\tilde{g}} \sim 3$ GeV and $m_{\tilde{q}} \sim M_Z/2$ (or more) contributing through loops to the vertices $Zq\bar{q}$. The effects of heavy squarks and gluinos satisfying the Tevatron bounds have been investigated in a previous work [10]. Here we carry out the same investigation in the light gluino case in view of the recent interest. As in our earlier work, we take the parameter $R = \Gamma_{\rm had}/\Gamma_{l\bar{l}}$, which, being a precisely measured observable at LEP and being free of the top quark uncertainties, provides a sensible hunting ground for new physics. Just for the sake of making this note self-contained, we bring out in what follows the essence of the formalism of our earlier work [10]. The quark-squark-gluino Lagrangian is given by

$$\mathcal{L}_{q\tilde{q}\tilde{g}} = i\sqrt{2} g_s \tilde{q}_i^{\dagger a} \bar{\tilde{g}}_\alpha (\lambda_\alpha/2)_{ab} \left[\Gamma_L^{ip} \frac{1-\gamma_5}{2} + \Gamma_R^{ip} \frac{1+\gamma_5}{2} \right] q_p^b , \tag{1}$$

where for three generations of quarks $p=1-3, i=1-6$ (for each quark flavor there are two squark states), the color indices $a,b=1-3$ and $\alpha=1-8$. The 6×3 matrices Γ_L and Γ_R are determined by the quark and squark mass matrices (see below).

Each quark flavor has two chiralities, left and right, which correspond to two different squark states. Hence, for three generations of quarks there are six up-type and six down-type squarks. We note that the quark and squark mass matrices are not diagonal in the same basis. The $\tilde{d}$ mass squared matrix (in a basis in which the d-quark mass matrix is diagonal) is

$$M_{\tilde{d}}^2=\begin{bmatrix} \mu_L^2 1+\hat{M}_d^2+cK\hat{M}_u^2K^\dagger & Am_{3/2}\hat{M}_d \\ Am_{3/2}\hat{M}_d & \mu_R^2 1+\hat{M}_d^2 \end{bmatrix} \quad (2)$$

where μ_L and μ_R are flavor-blind supersymmetry-breaking parameters for the left- and right-type squarks, respectively. K is the standard Cabibbo-Kobayashi-Maskawa matrix. $\hat{M}_u$ and $\hat{M}_d$ are diagonal up- and down-quark mass matrices respectively. The c term corresponds to the quantum mass correction due to Higgsino exchange for a d-type left squark, c is a phenomenological input in our treatment. The off-diagonal element is the left-right mixing term which is proportional to the corresponding quark mass matrix (d type for this case). $\tilde{U}$ is the matrix which diagonalizes $M_{\tilde{d}}^2$. Γ_L and Γ_R in Eq. (1) are each 6×3 matrices and are given by

$$\Gamma_L=\tilde{U}\begin{bmatrix}1\\0\end{bmatrix}, \quad \Gamma_R=\tilde{U}\begin{bmatrix}0\\1\end{bmatrix} .$$

$m_{3/2}$ is the gravitino mass and 1 is the (3×3) identity matrix. It should be mentioned that the above mass matrix follows from $N=1$ supergravity models.

The other ingredient necessary for this calculation are the couplings of squarks to the Z boson. For d-type squarks,

$$\mathcal{L}_{Z\text{-}\tilde{d}\text{-}\tilde{d}}=i\frac{g}{4\cos\theta_W}S_{ij}\tilde{d}_i\overleftrightarrow{\partial}_\mu\tilde{d}_jZ^\mu . \quad (3)$$

Here $i,j=1-6$ and

$$S=\tilde{U}^\dagger\begin{bmatrix}(v_d+a_d)1 & 0\\ 0 & (v_d-a_d)1\end{bmatrix}\tilde{U} ; \quad (4)$$

v_d and a_d are the vector and axial-vector couplings of Z to the d-type quarks, which for arbitrary fermions v_f and a_f are given by

$$v_f=\sqrt{\rho}(2t_3^f-4Q_f\sin^2\bar{\theta}_W) , \quad (5)$$

$$a_f=\sqrt{\rho}2t_3^f . \quad (6)$$

The expression of the partial width of Z into a massless fermion-antifermion pair $(f\bar{f})$ within the framework of the SM is given by

$$\Gamma_f=N_c^f\frac{G_\mu M_Z^3}{24\pi\sqrt{2}}(v_f^2+a_f^2) \quad (7)$$

where N_c^f is the color factor.

Before we quantitatively analyze the contribution to the parameter R from the supersymmetric sector of our concern we stress again the virtue of this parameter: that it is free of the large uncertainties coming from the ambiguity of m_t. A sizable δR can therefore be considered as a significant hint of new physics. Apart from the masses there are two important parameters c and A which appear in the mass matrix. A is responsible for the mixing of the left and right blocks of the squark mass matrix. We have checked that changes in A do not alter our results to any degree of significance. As a consequence we have set $A=0$ throughout our calculation. The parameter c induces flavor mixings in the mass matrix through radiative corrections and is of negative sign. While dealing with squark masses ~ 50 GeV, one has to be careful that, given m_t, c is small enough to ensure that none of the mass eigenvalues is pulled down below $M_Z/2$ violating the LEP bounds. For the sake of definiteness, we take the simplifying scenario $A=0$ and $c=0$. Although such assumptions amount to a loss of generality, nevertheless, within the present texture they do not materially affect any observable consequence.

In our previous work [10] we calculated δR by expanding in powers of the ratio of the Z mass ($\simeq 91.2$ GeV) to the minimum of the squark and the gluino masses which respect the Tevatron bounds (~ 150 GeV). We had also cross-checked this calculation by performing an exact analysis using the standard two-point and three-point functions (B and C functions of Passarino and Veltman [11]) with the heaviest quarks (b and c) in the external legs. In this work we have improved upon the precision of this latter method so that it can be reliably applied to lighter quarks in the external lines. The expressions of the amplitudes look exactly as in Eqs. (17) and (18) of Ref. [10]. In Fig. 1 we present the variation of δR with the average squark mass $\mu_L=\mu_R=\mu$ varying between 50 to 100 GeV for a gluino mass fixed at $m_{\tilde{g}}=3$ GeV. In all regions of the parameter space, δR is positive. We observe that, for $\mu=50$ GeV, δR is as high as 0.27, and, as

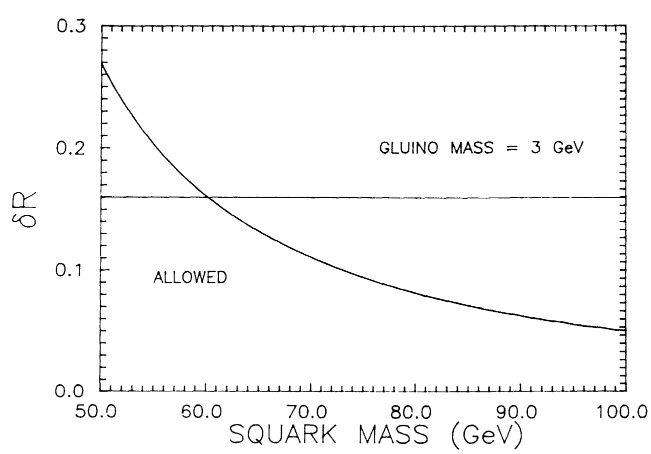

FIG. 1. The supersymmetric correction δR as a function of the average squark mass ($\simeq\mu$) for gluino mass $=3$ GeV. The horizontal line indicates the upper limit of contribution from any extension beyond the SM at the 90% C.L. of the experimental measurement of R.

μ is pushed up to 100 GeV, δR falls smoothly down to 0.05. Effects of varying $m_{\tilde{g}}$ by a few GeV do not show up within the scale of the graph. Next, one should verify how much leeway is left to accommodate new physics through δR in view of the present status of the LEP measurements. At the moment, according to the combined results [12] of the four LEP experimental groups, $R=20.77\pm0.05$, the SM expectation is 20.69–20.81. Thus at 90% C.L. of the experimental measurement and taking care of the SM uncertainties, the extent of new physics should be constrained by $\delta R=0.16$. We notice that for $\mu=50$ GeV the size of the supersymmetric correction is large and the net result (SM + supersymmetry) is inconsistent with the experimental observation up to 4σ, which indicates that the region of parameter space comprising of $m_{\tilde{g}}=3$ GeV and $m_{\tilde{q}}=50$ GeV is disfavored. However, as we increase the squark mass, δR gets diminished monotonically as a result of propagator suppression, and for $m_{\tilde{q}}$ beyond 60 GeV the contribution to δR falls significantly; such an extension can be accommodated comfortably within the present experimental uncertainties.

One must indeed keep in mind that this is not the only sector of supersymmetry that contributes to the $Zq\bar{q}$ vertices. Boulware and Finnell [13] have shown that the gaugino and Higgs mediated contributions to the $Zb\bar{b}$ vertex are detectable at the 1% level of experimental accuracy. The lower bounds on the gaugino masses originate from their nonobservation at LEP1 and hence are $\sim M_Z/2$. The authors of Ref. [13] have examined the effects of the gauginos and the Higgs bosons on $R_b=\Gamma_b/\Gamma_{\rm had}$— a parameter which is free of the QCD uncertainties, although not free from the top-quark ambiguities. They have observed that the contribution is positive, i.e., adds to the SM value. Recent measurements [12] show that $R_b=0.220\pm0.0027$ while the SM predicts $R_b=0.218$ (0.215) for $m_t=100$ (180) GeV [14]. We have calculated the shift in R_b induced by the gauge-invariant subset of our interest consisting of the squarks and gluinos, and found that, for $m_{\tilde{g}}=3$ GeV and $m_{\tilde{q}}=50$ GeV, $\delta R_b=0.2\times10^{-3}$. In Fig. 2 we have plotted δR_b against $m_{\tilde{q}}$ for the same region of parameter space as in Fig. 1. As expected, and also as seen from Fig. 2, the contribution falls with increasing squark masses but remains positive everywhere, which means that the contribution to R_b induced by the squark-gluino subset is of the same sign as the one from the gauginos and the Higgs bosons. The most optimistic value of δR_b from the sector we study is still found to be one order of magnitude down compared to the error in the measurement of R_b. Further improvement in the b-quark tagging efficiency is therefore required to use R_b as an effective parameter for our purpose.

With the gluino masses of our interest, the channel $Z\to\tilde{g}\tilde{g}$ opens up through loop level processes with internal squark and quark lines. (Recall that at the tree-level Z does not couple with the gluinos.) So if δv and δa denote the loop-induced vector and axial-vector couplings of the Z to the gluinos, the width $\Gamma(Z\to\tilde{g}\tilde{g})$ is proportional to $(\delta v^2+\delta a^2)$. The sizes of δv and δa in this case are expected to be of the same order of magnitude as δv and δa for the gluino and squark mediated $Z\to q\bar{q}$ processes. But considering the fact that Z has tree-level couplings with the quarks, the leading additional contribution to the widths for the squarks and gluino mediated $Z\to q\bar{q}$ processes goes like $v\delta v+a\delta a$, originating from the interference terms of the tree- and loop-level amplitudes. $\Gamma(Z\to\tilde{g}\tilde{g})$ is therefore suppressed compared to $\delta\Gamma(Z\to q\bar{q})$ by $O(\delta v(\delta a)/v(a))$ and we do not take this into account. In any case, the process $Z\to\tilde{g}\tilde{g}$ contributes to the hadronic events and eventually increases the hadronic width as do the loop induced $\delta\Gamma(Z\to q\bar{q})$ processes and so we need not worry about the possibilities of cancellation.

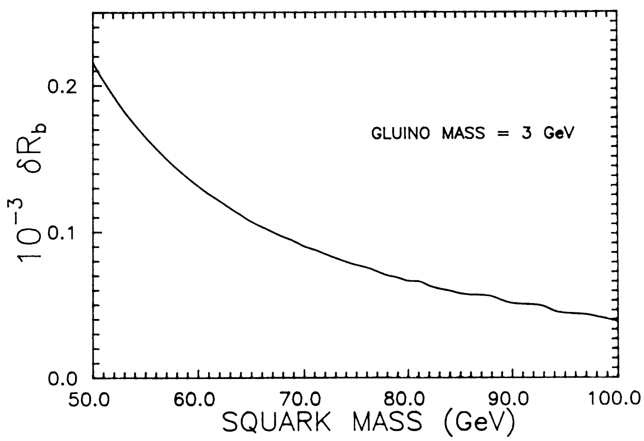

FIG. 2. The supersymmetric correction δR_b as a function of the average squark mass ($\simeq\mu$) for gluino mass $=3$ GeV.

In summary, we have examined the viability of the light gluino scenario and have put constraints on the parameter space in the light of the precision tests on the Z peak. Although one must admit that "better" agreement of α_s measurements at low and high energies in presence of a light gluino is after all not that pressing a motivation to confirm its existence, nevertheless, such a window has not yet been ruled out from direct searches and, therefore, needs a closer scrutiny from different perspectives. Direct search of a light gluino from four-jet events at LEP may tell something important. But, as we see in this work, further improvement in the measurement of R, as more data accumulate on the Z peak, might pose a serious threat to such a notion.

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