Status of Light Gaugino Scenarios

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I summarize recent devlopments in supersymmetry scenarios which leave some or all gauginos light. The emphasis is on experimental and phenomenological progress in the past year.

1. Introduction and Preliminaries

Since SUSY95 there has been considerable interest in the possibility of light gauginos. It would be impossible to review here all of the works on the subject, so I will limit myself to the following:

- Attractive new models with a richer spectrum of gaugino masses.
- Higher order pQCD results including light gluinos.
- Constraints on the gluino mass and condensate from properties of the η'.
- New constraints from cosmology.
- A direct search for a decaying "glueballino".
- A direct search for a decaying R-baryon.
- Limits from renormalization group running of α_s, extracted from the e^+e^- total hadronic cross section and R_τ.
- Limit from a combined fit to properties of hadronic final states in Z-decay.
- Proposal for a model independent test of the all-gauginos-light scenario at LEP2.
- Squark mass limits when gluinos are light.
- Some tantalizing observations which are readily explained with light gluinos, but have eluded satisfactory explanation without them.

For many years, views about the possible superpartner spectrum were based on models in which the fundamental interactions respect a GUT symmetry and SUSY breaking is transmitted to the observable sector by gravity. In such models, one expects the tree-level masses of standard model gauginos to be degenerate at short distance and diverge from one another at longer distance because of renormalization group running, just as the gauge couplings do. Depending on the SUSY breaking mechanism, R-invariance is strongly broken or not, leading to $m_{1/2} \approx M_{sq}$ or $m_{1/2} \approx \frac{M_{sq}^2}{M_{Pl}}$. In the latter case, the low-scale gaugino masses are predominantly due to stop-top and electroweak gauge-Higgs/ino loops[1]. The resultant gaugino masses are typically of order 1 GeV or less[2,3]. For most parameter choices the gluino has mass of order 100 MeV and the lightest neutralino (a photino) is somewhat heavier due to significant contributions of the electroweak loops[1][2,3]. Charginos and heavier neutralinos get their masses through the Higgs phenomenon and mixing. One chargino is always lighter than the W and three neutralinos lighter than the Z in this type of scenario, unless μ is very large.

In gauge-mediated models of SUSY breaking, gaugino masses arise from 1-loop interaction with messenger supermultiplets carrying the gauge charge. Superpartners of quarks and leptons get masses at two loops due to their coupling to gauginos. If the messengers form a complete GUT multiplet all gauginos are massive and their spectrum is like that in SUGRA models. However if the messengers are neutral under some

[1]This observation is crucial to the success of the light gaugino scenario. Otherwise, the glueballino lifetime would be so short as to have already been excluded.

gauge group, those gauginos are massless at leading order. Since quarks and leptons have both $SU(2)$ and $U(1)$ charges, it is enough for the messengers to have $SU(2)$ or $U(1)$ charges to make the squarks and sleptons massive. In this case, gluinos do not receive mass at 1-loop. Wino and bino are massive or not, depending on the messenger charges. One can also obtain models in which all the standard model gauginos are massless at one loop by introducing additional gauge interactions under which the messengers and quarks and leptons are charged, but the messengers are standard model singlets. Mohapatra and Nandi (also joined by Chacko and Dutta) and Raby have recently given models of these types[5]. One interesting feature of the Raby model is that for part of parameter space the gravitino is heavier than the gluino, as are the bino and wino, so the gluino is the LSP and is stable. Its mass can be adjusted over a large range, from ≈ 0 to hundreds of GeV.

The new models were constructed to have nice properties in their own right, such as solving the strong CP problem in the case of some of the Mohapatra-Nandi models. And as pointed out in [6], models with sufficiently small dimension-3 SUSY breaking automaticalloy solve the SUSYCP problem. Although it appears possible to generate essentially arbitrary combinations of gaugino masses, I will concentrate here on the following different light-gaugino phenomenologies:

- All gauginos are nearly massless and get masses of order 1 GeV or less from stop-top and electroweak loops.
- The gluino and the bino or wino is light.
- The gluino is the LSP.

The case of light wino and bino and heavy gluino is already excluded. This will be discussed below.

Besides these model building accomplishments, the last two years have seen advances in extending perturbative QCD in phenomenologically important ways. The tour-de-force 1-loop calculation of 4-jet matrix elements in e^+e^- annihilation has been completed[7] and applied to study of event-shape and 4-jet angular distributions by Dixon and Signer[8,9]. In addition, the 3-loop calculations of R_{had} and R_τ and the QCD beta-function have been extended to the case with light gluinos[10]. These successes give hope that the most daunting calculation of all, the 2-loop corrections to the 3-jet matrix elements, will also prove feasible. These results are necessary for theoretical predictions to be sufficiently accurate to discriminate the theory with and without light gluinos, as discussed in sec. 2.3.

I now turn to experimental and phenomenological constraints on the allowed mass range of gluinos. The lightest hadron containing a single gluino is expected to be the gluon-gluino bound state, usually denoted R^0 (glueballino). The relation between gluino current mass and the mass of the R^0 can only be estimated. A massless gluino would imply a degenerate chiral supermultiplet consisting of scalar, pseudoscalar and R^0, if mixing with $q\bar{q}$ states can be ignored. Quenched QCD predicts a 0^{++} glueball mass of 1.5-1.7 GeV and good candidates are the $f_0(1500)$ and $f_0(1700)$[2]. Thus a massless gluino suggests an R^0 mass of about $1\frac{1}{2}$ GeV. Its lifetime should be in the $10^{-5} - 10^{-10}$ sec range, or longer if the up and down squarks are very heavy[3].

If the R^0 lifetime is less than about 10^{-10} sec, the original missing energy[12] and beam dump[13] techniques are applicable. These methods have been used to establish $m_{\tilde{g}} \gtrsim 150$ GeV[14]. Ref. [15] compiled experimental limits relevant to gluinos for R^0 lifetimes longer than about 10^{-10} sec. The most important constraint is from the CUSB experiment[16] which did not find $\Upsilon \rightarrow \gamma\eta_{\tilde{g}}$ at the pQCD-predicted level. This result rules out gluinos in the mass range $\sim 1\frac{1}{2} - 3\frac{1}{2}$ GeV and hence R^0's between about $2\frac{1}{2} - 4$ GeV, for any lifetime[15]. As noted above, for $m(R^0)$ below the CUSB-excluded range and photinos in the expected mass range of $\sim \frac{1}{2} - 1$ GeV, the R^0 lifetime falls out of the range of applicability of beam-dump and missing energy experiments and previous limits were weak.

If the gluino is above the CUSB limit of about $3\frac{1}{2}$ GeV, the R^0 mass should exceed the gluino

[2] See [11] for a recent discussion and references.

mass by the constituent mass of a gluon, $\frac{1}{2}-1$ GeV, in analogy with heavy-light quark mesons. The spectator approximation is applicable and the R^0 lifetime is well-approximated by the free-gluino lifetime. For a light photino this is: $\tau \approx 2\ 10^{-14}(\frac{M_{sq}}{100\ \mathrm{GeV}})^4(\frac{4\ \mathrm{GeV}}{m_{\tilde{g}}})^5$ sec. Thus $m_{\tilde{g}} > 3\frac{1}{2}$ GeV is only viable if up and down squark masses are at least ~ 700 GeV, or if R^0 decay to a lighter neutralino is kinematically forbidden.

In the case that the gluino and lightest hadron containing it are stable, the most important consideration is whether any new hadrons bind to nucleons to produce new stable nuclei which accumulate near Earth. If so, limits on exotic isotopes give stringent limits[17,18,19,20]. In order to produce an interesting dark matter density, a heavy gluino must have a mass too large to be consistent with properties of our galaxy[19,20].

A very light gluino requires a corresponding pseudogoldstone boson. The η' suits this role well if $m_{\tilde{g}} = 80 - 140$ MeV and $<\lambda\lambda> = -(0.15-0.36)$ GeV^3[21]. This mass lies within the range estimated from the top-stop loop[3], and this condensate is consistent with the naive expectation $(<\lambda\lambda>)^{\frac{1}{3}} \approx \frac{9}{4}(<q\bar{q}>)^{\frac{1}{3}}$[15].

If the photino is the LSP and R-parity is exact, it can provide relic dark matter. For a radiatively-generated photino mass, i.e., of order 1 GeV or less, obtaining the correct dark matter abundance requires $r \equiv m(R^0)/m_{\tilde{\gamma}}$ to be in the range 1.3 - 1.55[22,23]. In this case, interconversion of photinos and R^0's keeps them in equilibrium until the appropriate epoch. Photinos would "overclose" the universe if $r > 1.8$ unless their mass is greater than about 10 GeV[22,23]. It is non-trivial that the predicted R^0 lifetime range $10^{-5}-10^{-10}$ sec, is consistent both with the experimental limits[15] and the lifetime as estimated from requiring the correct dark matter abundance[23].

2. New Experimental Constraints

To summarize the foregoing, SUSY breaking scenarios in which gaugino masses are mainly radiatively generated by known particles and their superpartners are naturally consistent with the requirements of dark matter, the η' mass, and direct experimental limits as of 1995. The glueballino mass should be in the range $\approx 1.4-2.2$ GeV on theoretical grounds; experiment requires it to be less than about $2\frac{1}{2}$ GeV. Dark matter is correct if $1.3 < r \equiv \frac{m(R^0)}{m_{\tilde{\gamma}}} < 1.55$; $r > 1.8$ is ruled out by cosmology unless $m_{\tilde{\gamma}} \gtrsim 10$ GeV. We now turn to constraints from new direct and indirect experimental searches.

2.1. Direct search via decays

The predominant decay mode of R^0's in this scenario is to $\pi^+\pi^-\tilde{\gamma}$[4]. Thus it was proposed that the current generation of K_L^0 experiments search for evidence of R^0's in their beam, whose decays would result in $\pi^+\pi^-$ pairs with high invariant mass and unbalanced p_t[4]. KTeV has now completed such a study using a small fraction of their total data[24]. Their cut $m(\pi^+\pi^-) > 648$ MeV restricts them to the study of the kinematic region $m(R^0)(1-1/r) > 648$ MeV. However subject to this constraint their limits are extremely good. For the largest r allowed by cosmology, 1.8, they are therefore sensitive to $m(R^0) \gtrsim 1\frac{1}{2}$ GeV and considerably improve the previous limits[15]. Fig. 1 shows the mass-lifetime region excluded by KTeV[24], for two values of r. Unfortunately the sensitivity drops rapidly for lower r and they are completely blind to the R^0 mass region of primary interest, 1.4-2.2 GeV, for $r \leq 1.4$. The experimental challenge will be to reduce the invariant mass cut.

Another strategy to find a light gluino is to look in a charged hyperon beam for the R_p $(uud\tilde{g})$ decaying to the ground state R-baryon, the S^0 $(uds\tilde{g})$[4]. This weak decay, $R_p \to S^0 + \pi^+$, should have a lifetime $2\cdot 10^{-10} - 2\cdot 10^{-11}$ sec[4]. Assuming the gluino mass is $O(100$ MeV), the mass of the $uud\tilde{g}$ state is calculated to be about 200 MeV higher than the S^0[17]. The most interesting mass range for the R_p is $1.6-3.1$ GeV[4]. The lower end of this range is motivated by the speculation that the $\Lambda(1405)$ is actually a crypto-exotic flavor singlet $udsg$[25]. The upper end of this range is the mass above which the S^0 is likely to be strong interaction stable due to the decay $S^0 \to R^0\Lambda$. The kinematics of the charged particles in this decay is different from that of decays of known particles, so an upper limit on the pro-

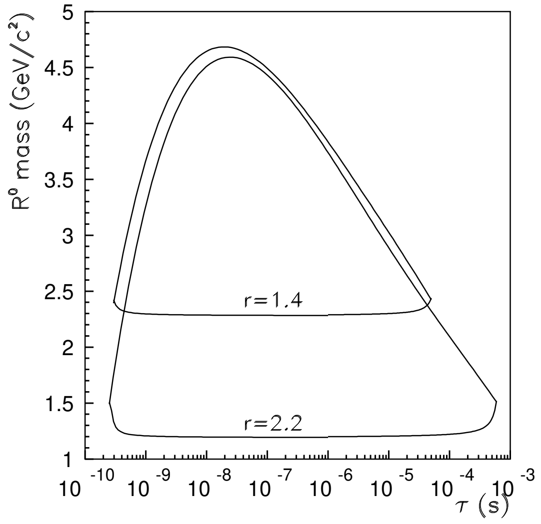

Figure 1. KTeV limits[24].

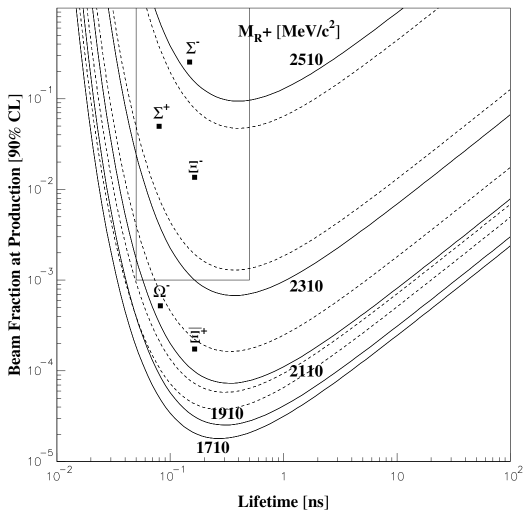

Figure 2. E761 limits vs. $\tau(R_p)$[26] .

duction rate of R_p's can be obtained.

Unfortunately, it is difficult to reliably estimate the production cross section. Perturbative QCD cannot be used, since the constitiuents of the relevant state are not heavy and the transverse momentum is not large. However one can use the measured D-meson differential cross section as a benchmark for R^0 production, since their masses are comparable. The larger color charge of the R^0's constituents probably is not relevant at low p_t due to color screening. On the other hand, no known hadron provides a good analogy for R_p production. One would expect the R_p production cross section to be significantly lower than that of Ω^- or $\bar{\Xi}$, since the R_p is heavier than these, is pair produced with another particle whose mass is at least $1\frac{1}{2}$ GeV, and in addition requires binding 4 quanta rather than 3. Hence upper bounds on the production fraction of order 10^{-4} or better are probably the minimum needed to hope to see a signal. To rule it out, much better limits would be needed.

The R_p search described above was performed by E761 at Fermilab and no evidence for anomalous decays was found[26]. The experiment's best sensitivity is at $m(R_p) = 1.7$ GeV and $\tau(R_p) = 3\ 10^{-10}$ sec. There, the sensitivity is about an order of magnitude lower than the production level of $\bar{\Xi}$. Given the suppression factors mentioned above, this is a marginal level of sensitivity for exclusion. However a more serious problem is that the sensitivity drops rapidly as lifetime decreases into the interesting range and as mass increases above about 2 GeV.

Thus the E761 search must be considered a first step which demonstrates the feasibility of this technique. I particularly want to stress that the $R_p \to S^0\pi^+$ search is complementary to the $R^0 \to \pi^+\pi^-\tilde{\gamma}$ search and both need to be pursued. Since the former is a weak decay, the superparticle spectrum is essentially irrelevant to the R_p lifetime. The lifetime is unaffected by whether the gluino (R^0) is the LSP or whether the u- and d-squarks are light. The search relies only on the mass of the gluino being low enough that R_p production is at an experimentally accessible level. On the other hand, the R^0 search can be very sensitive to small production cross sections because of the cleanliness and intensity of this generation of kaon experiments. However it depends in three crucial ways on the superparticle spectrum: i) If the u- and d-squarks are heavier than ~ 130 GeV, they must be heavier than ~ 600 GeV as discussed in sec. 4. In this case the lifetime, $(10^{-7}-10^{-10})(\frac{M_{\tilde{q}}}{100\text{ GeV}})^4$ sec[4], may be inaccessibly long for KTeV[3]. ii) If the gravitino and lightest neutralino are heavier than the R^0 it won't decay at all, assuming R-parity is good. iii) If the Q value of the decay is too small, because R^0 and $\tilde{\gamma}$ are too close in mass, it will be difficult to discriminate signal from background.

Besides looking forward to improvements in the KTeV and E761 type searches, the next couple of years may see other advances in direct searches. T. LeCompte and collaborators have been preparing a parasitic search at Fermilab for states with anomalously long lifetimes, which may be relevant for long-lived R-hadrons. Also Nussinov has made several suggestions on how to enhance the signal to noise in searching for long-lived R^0's[20].

2.2. Running of α_s

Csikor and Fodor[28] (CF) fit the Q^2 evolution of α_s to the 3-loop beta function prediction, with and without light gluinos. The problem with previous attempts in this direction has been the difficulty of determining α_s without reliance on models of non-perturbative physics. For instance a model or parameterization of higher twist effects is required if deep inelastic scattering is used. CF employ R_{had}, the hadronic total cross section in e^+e^- annihilation. This is the theoretically cleanest way to determine α_s, on the assumption that we know the particle content of the theory. Since it is a total cross section it is insensitive to hadronization and does not require resummation of large logarithms of the jet definition parameter y_{cut}. Since it is known to 3-loops, it is insensitive to the arbitrary renormalization scale, μ.

The drawback to using R_{had} is that it is not very sensitive to α_s, being proportional to $1+\frac{\alpha_s}{\pi}+O(\alpha_s)^2$. Thus the statistical error in its determination is larger than in other methods. At the Z^0 peak CF quote $\alpha_s = 0.123 \pm 0.006$ and at lower vales of $\sqrt{s}$ the errors are very large. Therefore CF also use α_s obtained from the hadronic width of the τ, which has a smaller statistical error. The perturbative contributions to R_τ are also known to 3-loops. However the error on $\alpha_s(m_\tau)$ which should be associated with modeling non-perturbative effects is controversial. CF take $\alpha_s(m_\tau) = 0.335 \pm 0.08$, but Shifman and collaborators argue that due to finite-size singularities in the Operator Product Expansion (e.g., instantons) the actual error may be twice as large as this[29]. The need for a more conservative error estimate is confirmed by Jan Fischer[4].

CF consider two mass regions for the gluino. For $m_{\tilde{g}} < 1\frac{1}{2}$ GeV they do not use R_τ in the fit and obtain a 70 % cl exclusion limit. For $m_{\tilde{g}} = 3(5)$ GeV they do include $\alpha_s(m_\tau) = 0.335 \pm 0.08$ in the fit and obtain 95(90)% cl exclusion limits. However had they used the larger error advocated in [29], these limits would also be degraded to ≤ 70 % cl. Thus unless the theoretical uncertainty on $\alpha_s(m_\tau)$ can be reduced, or other sources of high-precicion, model-independent information on α_s at low Q^2 can be found, the approach of using the running of α_s to exclude light gluinos is inconclusive.

2.3. Hadronic Event Shapes in Z^0 Decay

The other new effort to exclude light gluinos is due to ALEPH[31]. Their strategy is to determine the effective number of quark flavors, n_f, from a combined fit to several different 4-jet angular distributions and D_2, the differential 2-jet rate. At leading order, adding gluinos to ordinary QCD increases n_f determined via the running of α_s or 4-jet angular correlations by 3 units.

The differential 2-jet rate is the number of events as a function of y_3. The variable y_3 is the value of y_{cut} for a given event at which it changes from being a 3-jet to a 2-jet event. D_2 is statistically powerful, since every hadronic Z decay is used, but is quite sensitive to the arbitrary renormalization scale, μ, since it is only known to 1 loop (NLO) accuracy. Furthermore, the shape of the D_2 distribution is distorted in

[3]The reaction $\tilde{\gamma}\pi \leftrightarrow R^0\pi$ can still serve its crucial cosmological catalysis function due to the R_π resonance[27].

[4]Private communication. See also [30].

comparison to the fixed order PQCD predictions due to logarithms of y_3 which are large when y_3 is small. These logs must be resummed, and the final prediction is dependent on the procedure used to match the resummed and fixed order formulae. The 4-jet angular distribution is statistically weaker and is subject to large hadronization errors but is insensitive to μ[8]. ALEPH's hope was that by performing a combined fit to both distributions, their strengths might be complementary and their deficiencies less important.

ALEPH reports $n_f = 4.24 \pm 0.29(stat) \pm 1.15(syst)$ and concludes that they rule out a gluino with mass less than 6.3 GeV at 95 % cl. The precision of the ALEPH result is governed by their systematic errors, specifically the uncertainty in the theoretical prediction, since their statistical errors are small. Thus determining their systematic errors is the critical issue. A detailed discussion can be found in refs. [31,32]. Here I give a brief synopsis of the main problems.

The most important contribution to the systematic error is the uncertainty in the predicted D_2 distribution due to truncation of the perturbation series. This is manifested by the sensitivity of the fit to renormalization scale, μ, and to the resummation scheme. The conventional treatment of the uncertainty due to renormalization scale is to vary μ between $\sqrt{s}/2$ and $2\sqrt{s}$, and treat the spread of results as a $\pm 1\sigma$ error. Such a procedure leads to a $\pm 2\frac{1}{2}$ unit uncertainty on n_f (see Fig. 3, from [31]). With such a large uncertainty, no useful constraint on light gluinos can be obtained.

To reduce the uncertainty coming from scale sensitivity, ALEPH assumed that there is a value of μ at which the resummed NLO prediction for D_2 agrees with the all-orders prediction. If this hypothesis is correct, μ should be fixed to the value which gives the best fit, and the associated uncertainty is essentially the statistical uncertainty in finding μ. Thus the scale uncertainty in n_f would be the range in the n_f obtained by varying μ to increase χ^2 by 1 unit above its minimum.

Using the log R-matching scheme and varying μ to get the best fit, ALEPH finds $n_f = 3.68$, with $\chi^2 = 78.5$ for 73 dof. Increasing χ^2 by one unit gives the range $n_f = 3.09 - 4.08$. A similar exercise for the R-matching scheme gives the best fit $n_f = 4.88$, with $\chi^2 = 81.6$, and the range $n_f = 3.57 - 5.81$ as μ's variation raises χ^2 to 83. The other systematic errors they estimate are ± 0.45 from hadronization modeling and ± 0.27 for the detector simulation. Combining errors in quadrature and averaging the results of the two matching schemes then gives their final result quoted above.

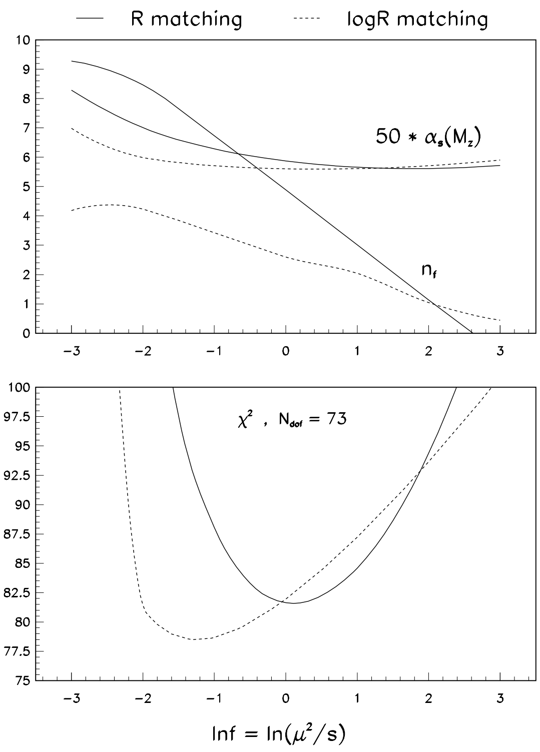

Figure 3. ALEPH's n_f, α_s, and χ^2 vs μ[31].

Unfortunately, the "experimental optimization" procedure employed by ALEPH to reduce their scale sensitivity is known to be invalid. Burrows[33] examined the proposition that a judicious choice of scale can improve the accuracy of the theoretical prediction for hadronic event shape distributions. He found that none of the

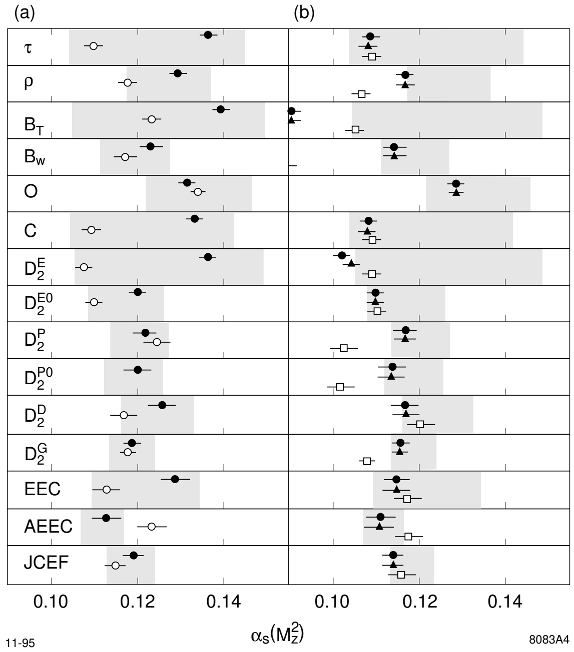

Figure 4. (a) α_s from various event shape distributions using $\mu = M_Z$ (solid circles) and experimental-optimization (open circles). (b) Using other schemes[33].

scale fixing schemes, including exerimental optimization, successfully improves perturbation theory. His procedure was to extract $\alpha_s(m_Z)$ from 15 different event-shape distributions, such as D_2, thrust, etc., using various scale fixing schemes, such as experimental optimization, minimal sensitivity, etc. If a scheme provided a systemtic improvement, this procedure would lead to a consistent set of α_s values, within the errors from other sources. What Burrows found (see Fig. 4) is that the dispersion in values is essentially the same in all schemes, and comparable to the one found using the conventional procedure[33].

Thus ALEPH's method of fixing μ and estimating the theoretical systematic error associated with the scale depedence is not valid. In the absence of a better way to estimate this uncertainty, the conservative approach is to adopt the traditional procedure used by other experiments, which gives ± 2.5. At least this allows a direct comparison between the sensitivities of previous analyses employing just 4-jet angular distributions and the ALEPH procedure which also uses D_2. This will be done below.

Another problem with the ALEPH analysis is the estimation of the hadronization error. That is in principle done by repeating the analysis using several hadronization MC's which perform equally well for other purposes. A fit using Herwig instead of Jetset gave $n_f = 6.21$ with $\chi^2 = 91.6$, instead of $n_f = 4.88$ and $\chi^2 = 81.6$ (see Table 3 of [31]). However μ was optimized only for the Jetset fit and that value was used for all the different MC's, so there is no way of knowing what the Herwig result would have been, or how small its χ^2 would have been, had the μ optimization been systematically applied. Because the χ^2 of this Herwig fit is enough larger than for the Jetset best fit, the ALEPH error-assignment procedure discards it entirely[31].

It is also difficult to know what error to assign to the resummation matching-scheme dependence of D_2. ALEPH used the dispersion between log-R and R matching. But since the log-R matching scheme gives $n_f < 5$ for any value of μ, we can infer it is NOT the correct matching scheme.

Even adopting the ALEPH hadronization error estimate and neglecting matching scheme uncertainty altogether, one can see that employing D_2 with its strong μ sensitivity leads to a worse determination of n_f than using the angular distributions alone. If one uses the R-matching scheme result and takes the $\pm 1\sigma$ scale error to be given by the $1/2 < \mu/\sqrt{s} < 2$ variation, the ALEPH result becomes $n_f = 4.88 \pm 0.29(stat) \pm 2.57(syst)$ which is considerably worse than the limits obtained by the other LEP groups using just the 4-jet angular distributions[34].

3. Model Independent Proposal for a LEPII Search

To summarize the previous section: direct searches for decaying R-hadrons have not yet explored the interesting regions of $m_{\pi\pi}$[24] or R_p

lifetime[26]. Indirect searches for light gluinos via α_s running[28] and Z^0 event shapes[31] are stymied by theoretical uncertainties. In this section I describe a complementary search technique[27] which is theoretically very clean. It is relevant to the case that the gluino and either wino or bino is light; it relies on the high energy and integrated luminosity of LEP2.

When electroweak gaugino masses are negligible, the chargino and neutralino masses depend only on[5] μ and $tan\beta$. When m_2 vanishes, one chargino is lighter than the $W^{\pm}$. Its mass decreases as μ or $tan\beta$ are increased, so large μ and $tan\beta$ are excluded by the Z^0 width[6]. However for small μ, three neutralinos have masses below the Z^0 if m_1 and m_2 are both small. Considering the neutralino contribution to the Z^0 width further restricts μ and $tan\beta$ but does not exclude the scenario.

At energies above the Z^0, production of inos in e^+e^- collisions depends on μ and $tan\beta$, and $m(\tilde{\nu}_e)$ in the case of charginos. Varying $m(\tilde{\nu}_e)$ over the allowed range, one can compute the minimum total cross section for ino production, as a function of E_{cm}, μ and $tan\beta$. Even this lower limit is quite substantial: 2 pb at 173 GeV and 184 GeV, summing over chargino and neutralino production.

If the gluino is heavy, the charginos and heavier neutralinos decay mainly into the lightest neutralino and products of $W^{\pm}$ or Z^0 decay. This possibility is already completely excluded by LEP[35,36]. However if the gluino is light as well, inos can decay via a real or virtual squark, to $q\bar{q}\tilde{g}$. Indeed, this is the dominant decay mode for squark masses up to $m_{sq} \sim 100$ GeV[37]. Then the sensitivity of the usual ino searches is reduced by the factor $(1-b)^2$, where b is the suitablly averaged branching fraction of an ino into $q\bar{q}\tilde{g}$. However when both inos decay to $q\bar{q}\tilde{g}$, the event contributes to the hadronic cross section. The total hadronic cross section is well-enough measured that $b = 1$ is excluded for any value of μ, $tan\beta$, and $m(\tilde{\nu}_e)$ by OPAL's recent analysis[36,27]. For the moment, the integrated luminosity is too small to extend the analysis away from $b = 1$ and $b = 0$, but with the integrated luminosity planned at 183 GeV, LEP should be able to probe all values of b. This method should also permit the discovery or complete elimination of models such as Mohapatra and Nandi's [5] in which only m_2 and m_3 are small, while m_1 and μ may be large. The possiblilty of putting interesting constraints on other combinations is presently under investigation.

A notable feature of this search is that it is theoretically very clean[27]. There is essentially no sensitivity to μ. The sensitivity to parameters of the standard model such as α_s and m_W is weak and introduces an uncertainty which is small compared to present statistical errors. Most important, since it employs the total cross section the details of hadronization are insignificant and there is no small parameter such as y_{cut} to introduce large logarithms which need resummation.

4. Constraints on squarks if the gluino is light

Lower bounds on squark masses are much weaker when the gluino is light than when missing energy is a signature. Early Z^0 width measurements gave $m_{\tilde{q}} > 50-60$ GeV for degenerate squarks[38]. If only one flavor of squark is light the limit becomes 30 GeV for a L-type squark and there is practically no constraint for an R-type squark[25]. Data on the Z^0 has improved enormously in the intervening period, inconsistencies with the SM such as R_b have disappeared, and higher energy data is now available. Therefore the analysis of refs. [38] should be redone – it would surely yield significantly better limits now.

A stop more than a little lighter than the top would dominate top decay because of $t \to \tilde{t} + \tilde{g}$. This is probably excluded, but the possibility that the stop decay products can "fake" the final states observed by D0 and CDF deserves investigation.

There have been a number of papers on the effect of associated squark-gluino production on the dijet invariant mass distribution in $p\bar{p}$ collisions, starting with Terekov and Clavelli[39]. More recently, using the full $106 pb^{-1}$ of Tevatron dijet

[5] In this context, μ is the higgsino mass parameter in SUSY models, not the renormalization scale!

[6] These statements ignore radiative corrections, which is not strictly correct for extremely large μ[2].

data, Hewett et al[40] and Terekov[41] have extended the analysis also to dijet angular distributions. They are able to exclude the mass ranges $150 < M(\tilde{u}) < 620$ GeV and $170 < M(\tilde{d}) < 620$ GeV[41] and $130 < M \lesssim 600$ GeV[40]. At lower squark mass, QCD background swamps the SUSY dijets; at larger mass the production rate is too low.

Choudhury[42] suggested that a monojet analysis might allow Tevatron data to be used to exclude all squark masses below 240 GeV. The dijet-pair analysis proposed in [25], which should be useful for lower squark masses and less model dependent than the monojet analysis, has not yet been carried out.

5. Hints of a light gluino?

There are several well-established phenomena, which have so far eluded satisfactory explanation within the framework of standard model physics, but which are readily explained with a light gluino.

5.1. The $\eta(1410)$

The $\eta(1410)$ meson is a flavor singlet pseudoscalar. All nearby pseudoscalar nonets are filled, so that it must be a glueball or some other exotic state[7]. The relationship between its width and production in J/ψ radiative decay are apparently inconsistent with its being a $q\bar{q}$ state[11]. It cannot be identified with a KK^* "molecule" because no corresponding spin-1 state is observed so KK^* binding would have to occur only in the p-wave and not in the s-wave which would be unprecedented. Its coupling to glue-rich channels is strong[11] and it would naturally be interpreted as a glueball, except that:

- For a 2-gluon state to have $J^{PC} = 0^{-+}$ requires one unit of orbital angular momentum. This suggests $m(0^{-+}) - m(0^{++}) \approx 500 - 600$ MeV, the splitting between ^3P and ^1S mesons.
- Lattice gauge calculations predict the mass of the lightest 0^{-+} glueball to be 2.2 ± 0.3 GeV; similar calculations for the 0^{++} and 2^{++} sectors are within about 100 MeV or better of good candidate states.
- Models such as the bag and instanton gas calculations corroborate the lattice result that $m(0^{-+}) >> m(0^{++})$.
- There is some evidence for a suitable glueball candidate in the mass range of the lattice prediction[8].

Overall, accounting for the $\eta(1410)$ and its strong affinity for glue is difficult within QCD. However the very-light gluino scenario *predicts*[15] the existance of a flavor singlet pseudoscalar not present in conventional QCD, with mass about equal to the unmixed scalar glueball, i.e., 1.4-1.8 GeV according to lattice gauge theory. The predicted properties of the $\eta_{\tilde{g}}$ fit the observed $\eta(1410)$ properties[11].

5.2. Anomalies in jet production

Shortly after the announcement by CDF of an excess in very high E_T jets[43], several papers addressed the question of whether light gluinos could account for the effect[44]. The excitement abated after CTEQ announced[45] that a slight generalization of the functional form taken for the pdf's would allow the gluon pdf to be increased enough to accomodate the new high E_T jet data. While the light gluino hypothesis improved the overall fit, it was not essential.

However the most problematic anomaly in $p\bar{p}$ jet physics is the strong violation of scaling observed by both CDF and D0 in the ratio of x_T distributions at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1800$ GeV. Modifications in pdf's change the inclusive x_T distribution but do not significantly affect the *ratio* of the scaled x_T distributions. As of the CTEQ workshop in Nov. 1996, no explanation for the scaling violation had been found within standard model physics. Clavelli and Terekov[46] point out that the observed breakdown of scaling may result from associated production of a light gluino and squark, with $M_{\tilde{q}} \approx 100 - 140$ GeV.

5.3. Ultra High Energy Cosmic Rays

Several cosmic rays of extremely high energy ($> 10^{20}$ eV) have been detected. Their shower

[7] For a review and primary references see [11].

[8] W. Dunwoodie, private communication.

properties are consistent with those expected for a proton or nucleus primary, but not with a photon or neutrino primary. On the other hand, protons and nuclei of such high energy interact strongly with the cosmic microwave background radiation via the Δ resonance or nuclear breakup, leading to an upper bound on their energies if they are to come from cosmological distances. This is known as the GZK bound[47]. Thus if the highest energy cosmic ray 3 10^{20} eV were a proton, its source would have to be closer than about 50 Mpc[48]. The problem is that in order to produce such extremely high energy projectiles, the source is expected to be remarkable in other observable ways. In particular it should be an exceptionally strong x-ray source[49]. There are no plausible candidates with appropriate features in the relevant angular region, closer than 50 Mpc[48]. However the two highest energy cosmic rays point toward a good source at about 240 Mpc, and an excellent one beyond 1000 Mpc[48]. It was suggested that these UHECR's might be the lightest R-baryon, the S^0 $(uds\tilde{g})$ mentioned above[4]. Its interaction length in the CMBR is much longer than a nucleon's, and can accomodate even a Gpc source[50]. Because its interactions with atmospheric nuclei is similar to a nucleon's, its shower development would be consistent with observations. For further details, references, and discussion of alternative "uhecrons" see [50].

6. Summary

The past two years have seen subtantial effort on many fronts to explore the various light gaugino possibilities. KTeV and E761 searches for evidence of decaying R-hadrons have yielded null results, but they have not yet investigated the most plausible regions of parameter space (see sec. 2.1).

Indirect searches are still either theoretically or statistically inadequate. The running of α_s as determined by R_{had} in $e^+e^- \rightarrow$ hadrons is theoretically clean but only gives a 70 % cl exclusion of light gluinos[28]. Analysis of Z^0 event shapes is statistically powerful but the theoretical predictions are not known to high enough order, so that the renormalization scale and resummation matching-scheme ambiguity is large. In particular, ALEPH's claimed limit on light gluinos ($m_{\tilde{g}} > 6.3$ GeV at 95% cl) must be set aside because it relies on an ansatz for reducing the scale sensitivity which has been shown to be invalid (see sec. 2.3). Using a more realistic estimate of the intrinsic theoretical uncertainty leads to the conclusion that the ALEPH analysis is actually less sensitive than earlier experiments employing only 4-jet angular distributions, for which systematic uncertainties were also too large to make a definitive statement. In order to reduce the theoretical error in the ALEPH analysis to a useful level, the two-loop correction to three-jet matrix elements is needed.

It is still possible that all gauginos are massless, aside from radiative corrections due to known particles and their superpartners. This gives a gluino mass is of order 100 MeV and is consistent with properties of the η'. Such a scenario provides an explanation for dark matter, predicts the "extra" flavor singlet pseudoscalar ($\eta(1410)$), and accounts for the apparent violation of the GZK bound by ultra-high energy cosmic rays. This scenario should be completely excluded, or suggestive evidence for it found, in the next year of LEP running, using a combination of conventional signatures and limits on an excess in the hadronic total cross section[27,36]. With planned increases in integrated luminosity, the case that only the wino and gluino are light can be fully investigated in the same way. The possibility that the wino and/or bino are light, but the gluino is heavy, is already excluded by LEP.

The most difficult case to study experimentally is when the gluino is the only light gaugino. With a significant improvement on the determination of the e^+e^- total cross section at $Q^2 \neq m_Z^2$, the beta function can be determined with sufficient accuracy to unambiguously infer or exclude some gluino mass ranges. The requisite 3-loop calculations have been done and the method does not require knowledge of non-perturbative physics. When the 3-jet differential cross section in Z^0 decay has been calculated to 2-loop accuracy, it will probably be possible to use Z^0 event shapes to obtain a consitent set of determinations of $\alpha_s(m_Z)$ and n_f. However further control of hadronization and resummation uncertainties may also prove necessary. A final strategy if the gluino is not too heavy is to extend the search for the weak decay $R_p \to S^0 + \pi^+$ in the fashion of E761[4,26] to shorter lifetimes and much lower production levels.

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