Top Quark Candidates and Light Gluinos*

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ABSTRACT
We discuss the case for a light gluino and the mutual impact of this possibility with the Fermilab top quark candidates.

In the last year or two, the Fermilab collider experiments, CDF and D0, have observed several dozen isolated, high transverse momentum leptons associated with significant jet activity and large missing transverse momentum. These events are highly improbable (likelihood $10^{-5}$) from the standpoint of previously known particles and hence constitute clear evidence for either the top quark or particles beyond the standard model. In the same period several anomalies at the Z scale and below have lent support to the idea that the gluino of supersymmetry (SUSY) lies in the low energy region. The strong mutual impact between this idea and the top quark interpretation of the Fermilab events is the subject of this talk.

It has long been known that there are one or more low energy windows [1] allowed by experiment for the gluino mass. In the last few years, however, many authors have gone beyond this to point out positive, though indirect, hints that this scenario may, in fact, be realized in nature. One can count at least seven such indications of a light gluino. These are:

1.) Consistency of SUSY grand unified theory (GUT) with low energy data on $\alpha_s(M_Z)$. The minimal SUSY GUT (MSSM) predicts [2, 3, 4] an $\alpha_s(M_Z)$ above 0.117 while most of the low energy data prefers a much smaller value. The $e^+e^-$ jet measures, whose energy dependence indicates absence of non-perturbative corrections, as well as a large body of quarkonium data interpreted in the standard model, predict $\alpha_s(M_Z) = .098 \pm .003$. [5] The QCD sum rules which provide a systematic way to control non-perturbative corrections predict $\alpha_s(M_Z) = .109 \pm .001$. The truth may be somewhere between these two predictions but, in any case, low energy analyses systematically prefer an anomalously low value of $\alpha_s(M_Z)$ compared to GUT predictions. The problem can be eliminated if the gluino lies at the Z scale or below [7, 8] while the other SUSY particles apart from the photino are much heavier. Unfortunately, this solution violates

* Talk presented at the Workshop on the Physics of the Top Quark, Iowa State University, May 1995
the supergravity inspired mass relations among the SUSY particles which we take for present purposes to be part of the MSSM assumption. Namely, a universal gaugino mass predicts in the light gluino case a simultaneously light ($\simeq M_W$) gaugino spectrum. This is important in the discussion to follow of the $b$ excess in $Z$ decay but causes the MSSM prediction of $\alpha_s(M_Z)$ to again become high even in the presence of the light gluino. [9] It now seems that if one wants to preserve the supergravity mass universality conditions one cannot unambiguously reach low values of $\alpha_s(M_Z)$ in the MSSM. This has lent support to the SUSY Missing Doublet Model (MDM) where low values of $\alpha_s(M_Z)$ are naturally predicted [4, 10]. Of course one can appeal to model-dependent non-renormalizable or gravitational effects [11] but it seems then that it would be as easy to destroy the good SUSY prediction of $\sin^2(\theta)$ as to achieve a lower $\alpha_s(M_Z)$.

2.) **Consistency of $\alpha_s(M_c)$ with $\alpha_s(M_b)$**. [5] In the non-relativistic color singlet model the values of the strong coupling at these two scales are inconsistent by many standard deviations. The situation is greatly alleviated if the gluino lies in the low mass window below 0.7 GeV. [5] Alternatively, the problem might be resolved by relativistic corrections but introducing an ad-hoc parameter to represent these corrections [12] implies a 70% reduction in the $J/\Psi$ decay rate due to this parameter, leads to several paradoxes, and only succeeds in raising $\alpha_s(M_Z)$ to about 0.113 even with this 70% model-dependent reduction.

3.) **Consistency of $\alpha_s(M_Z)$ from direct measurements at the $Z$ scale with that inferred from low energy measurements**. The LEP measurements of the $Z$ width interpreted in the standard model lead to an $\alpha_s(M_Z) = 0.125 \pm .005$. This is inconsistent with low energy measurements which, interpreted in the Standard Model as discussed above, imply a value near or below 0.11. A gluino in the $\Upsilon$ region or below causes $\alpha_s$ to run more slowly and alleviates the problem. [5, 13] However, in the non-relativistic quarkonium analysis, [5] even with the light gluino effect one only reaches an $\alpha_s(M_Z)$ of 0.113 implying there is some extra contribution to the $Z$ width to make the apparent $\alpha_s(M_Z)$ as great as 0.125. It has been suggested that this extra contribution is associated with the $b$ excess in $Z$ decay [14] which is also natural in the light gluino case. The problem has been known since 1992 when an attempt was made to explain the results in terms of $Z$ decays into $\bar{q}q\tilde{G}$ with a light gluino and a squark mass between $M_Z/2$ and $M_Z$. [15] This explanation is still viable but it would not explain the $b$ excess in $Z$ decay unless the $b$ squark is significantly lighter than the other squarks.

4.) **Self-consistency of $Z$ data (width vs jet measures)**. [16] The light gluino affects the jet measures differently than the total width and improves consistency.

5.) **Deep inelastic vs $Z$ scale measurement of $\alpha_s(M_Z)$**. [17] In this analysis, however, the conclusion that a light gluino is favored depends on the apparent high value of $\alpha_s(M_Z)$ being correct.

6.) **$b$ excess in $Z$ decay**. The observed $b$ excess in $Z$ decay can be fit in SUSY models if the chargino and/or charged Higgs and the stop quark are light (in the 50 GeV
mass region). This cannot be achieved in the supergravity inspired MSSM if the gluino is heavy. However in the model with a light gluino, the charginos and neutralinos are necessarily in this region and the stop is also naturally light if the universal scalar mass is below several hundred GeV. The $b$ excess can be quantitatively correlated with the apparently large value of $\alpha_s(M_Z)$ at LEP but even if the $b$ excess disappears with more data, the large apparent $\alpha_s(M_Z)$ at LEP is an independent indication that there are non-standard contributions to the $Z$ width strongly suggesting low mass SUSY particles.

7.) **Anomaly in the $B$ semi-leptonic branching ratio.** There is a $2 \sim 3 \sigma$ discrepancy in the $B$ semi-leptonic branching ratio which hints of non-standard model contributions to $B$ non-leptonic decay. It has been suggested that the $B \to sG$ decay can be enhanced without unduly enhancing $B \to s\gamma$ if the gluino is light.

Returning to indication 6 above, we note that the squared squark masses in the MSSM, although dominantly determined by the squared universal scalar mass, $m_0^2$, receive a positive contribution proportional to the squared universal gaugino mass, $m_1^2/2$. Unless this parameter is negligible it is impossible to achieve a sufficiently light stop quark mass to explain the $b$ excess. Although abandoning the supergravity inspired mass relations has been suggested, these relations are worth defending and still viable in the light gluino case where $m_{1/2} = 0$ (minimal gauge-kinetic coupling). To illustrate this viability we put $m_{1/2} = 0$ and run a Monte-Carlo choosing random values of the five parameters $m_0$, $\mu$, $m_t$, $\tilde{A}_t$, and $\tan\beta$. Here $m_t$ is the top mass, $\mu$ is the Higgs mixing parameter, $\tilde{A}_t$ is the dimensionless top trilinear coupling, and $\tan\beta$ is the ratio of the Higgs vacuum expectation values. We reject solutions with chargino or neutralino masses too low for the LEP data. We impose the $\rho$ parameter result $\rho = 1.009 \pm .002$ and if $m_t < 158$ GeV we require that $m_\chi + m_b < m_t < m_t$. This latter constraint is used since it allows prominent top decays into light gluinos thus evading the Fermilab high $P_T$ lepton trigger. In this case, of course, one has to find an alternate (SUSY) explanation for the top quark candidates. We find experimental consistency with the MSSM and light gluinos if $45$ GeV $< m_\chi < 52$ GeV, $1.5 < \tan\beta < 1.74$, $52$ GeV $< |\mu| < 78$ GeV, and $124$ GeV $< m_t < 182$ GeV. In fig. 1 we show the Monte-Carlo solutions projected into the $m_t, m_\tilde{t}$ plane where $\tilde{t}$ is the lightest stop mass. Solutions with a sufficient $b$ excess in $Z$ decay due to stop-chargino loops lie below and to the left of the dashed line. In the heavy gluino case solutions below $M_t = 158$ GeV are excluded by the Fermilab results and the $\tilde{t}$ mass is raised due to the contribution from $m_{1/2}$ so no solutions remain below the dashed line.

The $\mu$ parameter is severely constrained by the gaugino masses. If radiative breaking of the electroweak symmetry holds, its square must be equal to

$$\mu_{rad}^2 = -M_Z^2/2 - m_0^2[1 + \frac{(m_t/205\text{GeV})^2}{2\cos(2\beta)}(3 + \tilde{A}_t^2\{1 - \frac{(m_t/205\text{GeV})^2}{\sin^2\beta}\})].$$  

(1)
Since this is a perturbation theory result we might require only that

$$-0.15 < \frac{|\mu_{\text{rad}}| - |\mu|}{|\mu_{\text{rad}}| + |\mu|} < 0.15.$$ \hspace{1cm} (2)

Solutions that satisfy this inequality are indicated by $x$’s in fig. 1. If the two loop contributions to the light Higgs mass are negligible, this radiative breaking constraint may disfavor the light gluino scenario by predicting too low a Higgs mass (in the 50 GeV region) \[21\]. However, a new understanding of dominant light Higgs decay modes into gluinos \[22\] might affect those conclusions. The top quark mass upper limits in fig. 1 are driven by the $\rho$ parameter constraint. Top masses above 182 are inconsistent with the measured value of the $\rho$ parameter in the SUSY case with or without light gluinos. If the top quark is above 160 GeV and decays into $Wb$ with a branching ratio near unity then either the light gluino hypothesis or that of radiative breaking with a universal GUT scale Higgs mass is ruled out. If the gluino is heavy the explanation of the $b$ excess through stop-chargino or stop-charged-Higgs is wrong unless the supergravity related mass relations are broken. The radiative breaking prediction as currently derived is dependent on a universal scalar mass. However, it might be considered less problematic to disturb the universality of Higgs masses at the GUT scale than that of the gaugino or sfermion masses due to the fact that some of these latter lie in the same $SU(5)$ multiplets. \[9\]

It can also be seen from the $x$’s in fig. 1 that the radiative breaking constraint prefers solutions that lie below the dashed line giving therefore a $b$ excess in $Z$ decay. However,
in this case we must seek an alternate (SUSY) explanation for the FNAL events and explain how a lower mass top could have been missed. Such an explanation might run as follows.

1) The background from $W^+$ jets could be substantially increased in the light gluino scenario due to the extra light color octet. The $W^+4$ jets sample would include $WGG\tilde{G}$ and $WGG\tilde{G}$ closely related to the $WGG\tilde{G}$ final state of the standard model. To what extent the kinematics of these final states would mimic the CDF and D0 top quark candidates is at present unknown. The CDF collaboration proposes to limit any ‘non-standard’ $W^+$ multi-jet background by studying the measured $Z^+\, multi-jet$ events which are not expected to have a contribution from top decay. In its 1994 paper CDF found, however, a $Z^+ \geq 3$ jet signal with $b$ tagging $3.1 \pm 0.3$ times the expected background. Although this is reduced in its 1995 paper, it is still consistent with twice the expected background. Thus, the published CDF results on $Z^+ \, multi-jets$ do not exclude a $W^+ \, multi-jet$ background at a level of twice the standard model background. D0 also notes an anomalously large $W^+ \, jet$ production manifested by a fit value of $\alpha_s$ significantly greater than expected. If there are larger than expected $W^+ \, jet$ backgrounds, the likelihood that the top candidates are statistical fluctuations from non-top backgrounds is very much greater than the quoted $10^{-5}$ but there still may be a need for some leptonic decays of new particles perhaps as follows.

2) In the light gluino case, it is possible to produce heavy squarks in association with a light gluino rather than with another heavy sparticle. This enhances the cross section for a number of processes which could enter the CDF and D0 samples. A prime example is the process \( p\bar{p} \rightarrow \bar{t}\tilde{b}G \). This could be important even if the $\bar{b}$ is above 200 GeV since it is produced singly. The $\bar{b}$ could have a large branching ratio into $\bar{t}W$ with the $\bar{t}$ subsequently decaying into $b\ell\nu\gamma$ through a virtual (or real) chargino. Another process which could affect the top mass determination is the production of $\tilde{t}\tilde{t}$ or $\tilde{t}\tilde{G}$. The first of these has been already considered recently. The presence of the extra (gluino) jet in the latter process raises the question whether the CDF analysis has a bias toward large top quark mass due to their using only the four jets of highest energy.

A lower mass top could have been missed if its non-$W$ decays such as $\tilde{t}\tilde{G}$ have a significant branching ratio. In fact one would expect

\[
\frac{\Gamma(t \rightarrow \tilde{t}\tilde{G})}{\Gamma(t \rightarrow bW)} = \frac{2\alpha_s}{3\alpha} \sin^2(\theta) \left( \frac{M_W}{M_t} \right)^2 \left( 1 - \frac{M_t^2}{M_W^2} \right)^2 \left( 1 + 2\frac{M_W^2}{M_t^2} \right)^{-1}. \quad (3)
\]

Thus these modes could be comparable in the light gluino, light stop case. In the events where both tops decay to $bW$, there is a two-fold ambiguity in top mass due to the choice of which $b$ jet to associate with which $W$. There should be a low mass solution and a high mass solution both of which would lead to approximately equal masses of the two tops if the tops are produced with significant transverse momentum as is likely.

In conclusion it seems that the published top quark analyses, using Monte Carlos which are heavily dependent on the standard model, might not adequately treat the
possibility that a low mass top could be hiding under the $W^+$ multi-jet background in this light gluino scenario.

This work was supported in part by the DOE under grant DE-FG05-84ER40141.

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