Light Gluino and Tevatron Data

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ABSTRACT

A very light gluino ($m_{\tilde{g}} \lesssim 2\text{GeV}$) is still consistent with experimental data and is attractive from a theoretical standpoint. This has been shown to lead to a small gluino content of the proton. We use this effect to demonstrate that such a light gluino could lead to a striking enhancement, at Tevatron, of monojets accompanied by large missing momentum. A reanalysis of the existing data may thus rule out a light gluino for a common squark mass of upto $\sim 600\text{GeV}$. 
As supersymmetry provides one of the best theoretically motivated scenarios going beyond the Standard Model (SM), the search for superparticles has, understandably, constituted one of the main areas of interest in recent experimental endeavours. Negative results at both the Tevatron [1] and LEP [2] have, however, significantly constrained the parameter space available to the (R-parity conserving) minimal supersymmetric standard model (MSSM). Somewhat surprisingly though, a very light gluino (mass less than a few GeV) may still be allowed [3, 4, 5]. Since the existence of such a light gluino will drastically alter the signal for supersymmetry, considerable effort has been directed towards a close examination of this scenario, both from a theoretical standpoint [6] as well as a phenomenological one [7]. Additional incentive was provided by an assertion [3, 8] that such a particle helps explain the apparent discrepancy between the value of $\alpha_s$ determined by high energy experiments and that expected from an application of QCD evolution (with the SM quark content) to the same quantity measured at low energy experiments. While this claim has been contested [9], like much else associated with this scenario, it points to the need of a closer examination of the phenomenological consequences associated with the existence of a light gluino. In this Letter we shall undertake this task from the point of view of existing Tevatron data on monojets with large missing momenta. We demonstrate that a reanalysis of the existing can lead to either an evidence for a light gluino, or in the negative case, to strong constraints on the scenario.

To appreciate the peculiarities of the scenario, let us, first, briefly recapitulate the essential features and the existing constraints. (i) As the Tevatron limits [1] on the squark masses no longer apply, the latter need to be consistent only with the lower bounds from LEP1. Note, however, that precision electroweak tests disfavour $m_{\tilde{q}} \lesssim 60$ GeV for a light gluino [10]. (ii) Gluino decay: though light, the gluino is not necessarily the lightest supersymmetric particle (LSP). The lightest neutralino (in most cases, the photino) is often the LSP instead (and, thus, a viable dark matter candidate [11]). In such a case, the gluino would decay into a quark-antiquark pair and the LSP, the rate depending on the relevant squark mass. Negative search results at beam dump experiments [12] suggests that a light gluino that decays within the detector volume is ruled out. This would require that the squark mass be larger than a few hundred GeV [13]. However, unlike its heavy counterpart, the gluino can now form a relatively stable and light bound neutral state [14, 4]. The lifetime of the bound state is longer than that of the free gluino [7] and, furthermore, the photino from the decay interacts too weakly with the detector to trigger a signal. It has been argued though that, for $m_{\tilde{g}} \gtrsim 4$ GeV, the lifetime is short enough for a missing energy signal to be viable and that UA1 data can effectively rule this out [15]. What if the gluino is indeed the LSP? Even then, the photino is the lightest colour-singlet supersymmetric particle [16] and hence stable. The lightest bound state still decays into the photino and all of the above arguments hold.

Constraints on lighter gluinos are obtained from quarkonia decay. The window $1.5$ GeV $\lesssim m_{\tilde{g}} \lesssim 4$ GeV can be ruled out [17] by considering the decay $\Upsilon \rightarrow \tilde{\eta}\gamma$ where $\tilde{\eta}$ is the pseudoscalar $\tilde{g}\tilde{g}$ bound state. Extending this analysis to lower masses is difficult as the applicability of perturbative QCD becomes questionable [17]. While some constraints on $m_{\tilde{g}} \lesssim 1.5$ GeV have been discussed in the literature, most of these turn out to be
weak or model dependent. A case in point are the constraints [18] from the $b \to s\gamma$ process which depends strongly on squark mixing. The exception are the constraints [19] deduced from final state correlations in $e^+e^- \to Z \to 4\text{jets}$. Indeed, a claim [20] has been made recently that LEP data [21, 22] can be used to rule out this window at 90% C.L. This claim has however been criticized [23] on the grounds that the jet angular distributions are sensitive to, as yet uncalculated, higher order QCD effects.

In this Letter, we adopt an approach complementary to that of de Gouvêa and Murayama [20] and seek to point out that a reanalysis of existing Tevatron data can provide important constraints. It has been recognized [24, 25] that the presence of light gluinos alters the Altarelli-Parisi evolution of the nucleon structure functions in an essential way. While it has been argued that this effect is numerically too small to be of any relevance to present experiments, we shall demonstrate that this is not the case. The important aspect is that the proton now has a small but non-zero gluino content. In fact, ref. [24] (which we shall use for the rest of the analysis) explicitly shows that, for the mass range in question, the gluino content of the proton is roughly 2–5 times that of the strange-quark sea. The ratio is only weakly dependent on $Q^2$, but depends significantly on the momentum fraction carried by the parton (see Fig.1).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The ratio of the gluino and strange quark densities [24] in the proton as a function of the momentum fraction. (a) $m_{\tilde{g}} = 0.4$ GeV, and (b) $m_{\tilde{g}} = 1.3$ GeV.}
\end{figure}

This immediately leads to the possibility of a resonant squark production at the Tevatron. Once produced, the squark would obviously tend to decay into the corresponding quark and the gluino. This channel is uninteresting though. We rather focus
on the suppressed decay channel $\tilde{q} \rightarrow q \tilde{\gamma}$. Our process thus is

$$q + \tilde{g} \rightarrow q + \tilde{\gamma}$$

(1)

This will obviously lead to a monojet accompanied by missing transverse momentum (equal to the transverse momentum of the jet). The distribution in the latter would thus have a peak close to $m_{\tilde{q}}/2$ and thus could be identified. Although the s-channel contribution is the dominant one (on account of the resonance), for completeness we include the t-channel contribution as well [26].

The SM background to this process arises from two different sources, the straightforward one being $Z + \text{jet}$ ($gg \rightarrow qZ$ and $qq \rightarrow gZ$) production with the $Z$ decaying invisibly [27]. Also to be considered are the processes $qq \rightarrow q'\tau\nu$ and $qq' \rightarrow g\tau\nu$. Of course, if the $\tau$ is far away from the jet, it would be recognised as a thin jet by itself and such configurations can be vetoed. On the other hand, if the difference in their azimuthal separation ($\delta \phi$) and pseudorapidity separation ($\delta \eta$) be such that the jet and tau fall within the cone defined by, say, $\Delta R \equiv \sqrt{(\delta \phi)^2 + (\delta \eta)^2} \leq 0.7$, then these might not be separable and have to be merged to form a single jet.

![Figure 2: The $p\bar{p} \rightarrow q + \tilde{\gamma} + X$ cross-section (at the Tevatron) as a function of the jet $p_T$ for various values of $m_{\tilde{q}}$. All squarks have been assumed to be degenerate and the cut of eq.(2) imposed. Also shown is the SM cross section for (monojet + missing energy).](image)

In Fig. 2, we show the $p_T$ distribution of the process in eq.(1) for various values of squark masses. We have assumed here that all squarks are degenerate. A minimum of $p_T(\text{jet})$ of 40 GeV is demanded so that it may constitute a clear signal [28]. To be consistent with detector coverage, we have also imposed a cut on jet rapidity:

$$|\eta_{\text{jet}}| < 3.$$ (2)
We have used here the distributions \[24\] for \(m_\tilde{g} = 1.3\text{ GeV}\) as these lead to the weakest constraints. To stay on the conservative side, we have further imposed an \textit{ad hoc} upper bound of \(\tilde{g}(x)/s(x) \leq 3\). The latter, though, weakens only the bound on the \(\tilde{b}_{L,R}\) mass.

As expected, the peaks lie close to \(p_T \sim m_\tilde{q}/2\). Also shown in the figure is the SM background. Thus, with a judicious choice of the \(p_T\) window, a signal to noise ratio larger than unity can be obtained for a wide range of squark masses. In Table 1 we list the number of events in the optimum \(p_T\) window for different squark masses. As can be seen from the table, even with an integrated luminosity of 100 pb\(^{-1}\), a significant signal/\(\sqrt{\text{background}}\) \((S/\sqrt{B})\) ratio can be achieved. A strong statement about the existence of such a gluino would, then, is thus not out of place.

| \(m_\tilde{q}\) (GeV) | \(p_T\) window | Gluino events | SM events |
|-------------------|----------------|--------------|-----------|
| 50                | (40, 65)       | 8665         | 5246      |
| 100               | (45, 55)       | 118004       | 2093      |
| 200               | (85, 105)      | 8600         | 450       |
| 300               | (125, 155)     | 1301         | 123       |
| 400               | (175, 210)     | 190          | 33        |
| 500               | (215, 265)     | 37.5         | 9.8       |
| 600               | (260, 310)     | 8.1          | 3.1       |
| 700               | (305, 365)     | 1.9          | 1.0       |

Table 1: The number of events expected solely from the process of eq.\([1]\) within the \(p_T\) window appropriate for a given squark mass. (All squarks are assumed to be degenerate.) Also shown are the number of events expected within the SM. An integrated luminosity of 100 pb\(^{-1}\) has been assumed.

We must, at this stage, point out the potential drawbacks in this analysis. As the LSP is mostly photino, its coupling to a quark is proportional to the charge of the latter. Furthermore, the quark content of the proton is dominated by the \(u\). Consequently, the supersymmetric contributions shown in Fig.\([2]\) are dominated by the \(\tilde{u}_{L,R}\). Thus one may seek to escape the bound by postulating the \(u\)-type squarks to be heavy. Such a solution is, however, problematic on more than one count. For one, apart from introducing an undesirable hierarchy amongst the squark masses, a large splitting between isodoublet partners is strongly disfavoured from considerations of the \(\rho\)-parameter. Thus, not only the \(\tilde{u}_{L,R}\), but the \(\tilde{d}_{L,R}\) will have to be heavy. Still, this will not solve all problems. As Table 2 illustrates, the bounds for the second generation squarks are also quite significant. For example, even if only the \(\tilde{c}_{L,R}\) were light, \(S/\sqrt{B} > 5\) can still be obtained for \(m_\tilde{c} \lesssim 265\ \text{GeV}\). Thus, if the proposed reanalysis of Tevatron data fails to produce any evidence for such a \((m_\tilde{g}, m_\tilde{q})\) pair, it would effectively rule out, for example, the light gluino solutions \([29, 23]\) to the 4-jet excess reported by ALEPH \([30]\). As for \(\tilde{b}_{L,R}\), the relatively weak bounds of Table 2 could be significantly improved if \(b\)-identification is used. The second potential drawback to our analysis is our deliberate ignoring of
Table 2: The mass limits that can be reached with 100 pb$^{-1}$ integrated luminosity if only one flavour of squarks were light. The last line represents the case when all the five flavours are degenerate and corresponds to Fig.4.

| Light Squark | Mass Limit |
|--------------|------------|
|               | $S/\sqrt{B} = 5$ | $S/\sqrt{B} = 10$ |
| $\tilde{u}_{L,R}$ | 590 | 510 |
| $\tilde{d}_{L,R}$ | 350 | 300 |
| $\tilde{c}_{L,R}$ | 265 | 225 |
| $\tilde{s}_{L,R}$ | 240 | 200 |
| $\tilde{b}_{L,R}$ | 155 | 125 |
| All           | 600 | 520 |

experimental efficiency factors. This, however, is unlikely to be a major factor. On the other hand, partial improvement might be possible if a more detailed fitting of the event distribution is attempted. These issues, though, can be addressed only in a full simulation.

With the ten-fold increase in luminosity that the main injector is expected to deliver, the $S/\sqrt{B}$ ratios would essentially increase by a factor of $\sqrt{10}$ and thus the reach can be extended to even higher masses. For $\tilde{u}_{L,R}$, for example, the bounds would be close to 800 GeV. With the advent of LHC, the bounds for each squark flavour (and chirality) would tend to be well above 1 TeV, thus destroying all motivation for a light gluino.

To summarize, we have examined a particularly striking consequence of the light gluino scenario. While most of the mass range of interest has already been ruled out, existing analyses have found it difficult to close the $m_{\tilde{g}} \lesssim 1.5$ GeV window. We aver that a reanalysis of existing Tevatron data on monojets accompanied by large missing momentum can severely constrain this window too. As such a small mass for the gluino results in a small, but nonnegligible, gluino content in the proton, resonant production of squarks becomes possible. The subsequent decay of the squark into a quark and the LSP results in the signature described above. We have performed a parton level simulation for both the signal and the SM backgrounds. For a properly chosen $p_T$ window, the signal is visible over the background for a considerably wide range of squark mass. The suggested reexamination of the existing Tevatron data can thus either establish this scenario or, in the case of a negative result, severely constrain it.

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