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Beyond the Higgs boson at the Tevatron: Detecting gluinos from Yukawa-unified SUSY

Howard Baer [a,*], Sabine Kraml [b], Andre Lessa [a], Sezen Sekmen [c], Heaya Summy [a]

[a] Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
[b] Laboratoire de Physique Subatomique et de Cosmologie, UJF Grenoble 1, CNRS/IN2P3, INPG, 53 Avenue des Martyrs, F-38026 Grenoble, France
[c] Dept. of Physics, Florida State University, Tallahassee, FL 32306, USA

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ABSTRACT

Simple SUSY GUT models based on the gauge group $SO(10)$ require t–b–τ Yukawa coupling unification, in addition to gauge coupling and matter unification. The Yukawa coupling unification places strong constraints on the expected superparticle mass spectrum, with scalar masses ~ 10 TeV while gluino masses are much lighter: in the 300–500 GeV range. The very heavy squarks suppress negative interference in the $q\bar{q} \to \tilde{g}\tilde{g}$ cross section, leading to a large enhancement in production rates. The gluinos decay almost always via three-body modes into a pair of b-quarks, so we expect at least four b-jets per signal event. We investigate the capability of Fermilab Tevatron collider experiments to detect gluino pair production in Yukawa-unified SUSY. By requiring events with large missing E_T and $\geqslant 2$ or 3 tagged b-jets, we find a 5σ reach in excess of $m_{\tilde{g}} \sim 400$ GeV for 5 fb^{-1} of data. This range in $m_{\tilde{g}}$ is much further than the conventional Tevatron SUSY reach, and should cut a significant swath through the most favored region of parameter space for Yukawa-unified SUSY models.

1. Introduction

There is now an ongoing huge effort at the Fermilab Tevatron $p\bar{p}$ collider to extract a Standard Model Higgs boson signal from a daunting set of SM background processes. While such an effort is to be lauded—and if successful would complete the picture provided by the Standard Model (SM)—we note here that an even bigger prize may await in the form of the gluino of supersymmetric (SUSY) models [1]. Current searches from CDF and D0 Collaborations have explored values of $m_{\tilde{g}}$ up to ~ 300 GeV within the context of the minimal supergravity (mSUGRA or CMSSM) model [2,3]. Here, we show that Tevatron experiments should—with current data sets—be able to expand their gluino search much further: into the 400 GeV regime, in Yukawa-unified SUSY, which is a model with arguably much higher motivation than mSUGRA [4]. Since Yukawa-unified SUSY favors a light gluino in the mass range 300–500 GeV, with the lower portion of this range giving the most impressive Yukawa coupling unification [5–9], such a search would explore a huge swath of the expected model parameter space.

Supersymmetric grand unified theories (SUSY GUTs) based upon the gauge group $SO(10)$ are extremely compelling [10]. For one, they explain the ad-hoc anomaly cancellation within the SM and $SU(5)$ theories. Further, they unify all matter of a single generation into the 16-dimensional spinor representation $\hat{\psi}(16)$, provided one adds to the set of supermultiplets a SM gauge singlet superfield $\hat{N}_i^c$ ($i = 1$–3 is a generation index) containing a right-handed neutrino.[1] Upon breaking of $SO(10)$, a superpotential term $\hat{f} \ni \frac{1}{2} M_{N_i} \hat{N}_i^c \hat{N}_i^c$ is induced which allows for a Majorana neutrino mass M_{N_i} which is necessary for implementing the see-saw mechanism for neutrino masses [11]. In addition, in the simplest $SO(10)$ theories where the MSSM Higgs doublets reside in a 10 of $SO(10)$, one expects t–b–τ Yukawa coupling unification in addition to gauge coupling unification at scale $Q = M_{\rm GUT}$ [12,13]. In models with Yukawa coupling textures and family symmetries, one only expects Yukawa coupling unification for the third generation [14].

In spite of these impressive successes, GUTs and also SUSY GUTs have been beset with a variety of problems, most of them arising from implementing GUT gauge symmetry breaking via large, unwieldy Higgs representations. Happily, in recent years physicists have learned that GUT theories—as formulated in spacetime dimensions greater than four—can use extra-dimension compactification to break the GUT symmetry instead [15]. This is much in the spirit of string theory, where anyway one must pass from

* Corresponding author.
E-mail addresses: baer@nhn.ou.edu (H. Baer), sabine.kraml@lpsc.in2p3.fr (S. Kraml), lessa@nhn.ou.edu (A. Lessa), sezen.sekmen@cern.ch (S. Sekmen), heaya@nhn.ou.edu (H. Summy).

[1] Here, we adopt the superfield "hat" notation as presented in Ref. [1].

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a 10- or 11-dimensional theory to a 4-d theory via some sort of compactification.

Regarding Yukawa coupling unification in $SO(10)$, our calculation begins with stipulating the b and τ running masses at scale $Q = M_Z$ (for two-loop running, we adopt the $\overline{DR}$ regularization scheme) and the t-quark running mass at scale $Q = m_t$. The Yukawa couplings are evolved to scale $Q = M_{SUSY}$, where threshold corrections are implemented [16], as we pass from the SM effective theory to the Minimal Supersymmetric Standard Model (MSSM) effective theory. From M_{SUSY} on to M_{GUT}, Yukawa coupling evolution is performed using two-loop MSSM (or MSSM + RHN) RGEs. Thus, Yukawa coupling unification ends up depending on the complete SUSY mass spectrum via the t, b and τ self-energy corrections.

In this work, we adopt the ISAJET 7.79 program for calculation of the SUSY mass spectrum and mixings [17]. ISAJET uses full two-loop RG running for all gauge and Yukawa couplings and soft SUSY breaking (SSB) terms. In running from M_{GUT} down to M_{weak}, the RG-improved 1-loop effective potential is minimized at an optimized scale choice $Q = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$, which accounts for leading two-loop terms. Once a tree-level SUSY/Higgs spectrum is calculated, the complete 1-loop corrections are calculated for all SUSY/Higgs particle masses. Since the SUSY spectrum is not known at the beginning of the calculation, an iterative approach must be implemented, which stops when an appropriate convergence criterion is satisfied.

Yukawa coupling unification has been examined in a number of previous papers [12,5–9,13,18–20]. The parameter space to be considered is given by

$$m_{16},\ m_{10},\ M_D^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu) \tag{1}$$

along with the top quark mass, which we take to be $m_t = 172.6$ GeV [21]. Here, m_{16} is the common mass of all matter scalars at M_{GUT}, m_{10} is the common Higgs soft mass at M_{GUT} and M_D^2 parameterizes either D-term splitting (DT) [19,5,9] or "just-so" Higgs-only soft mass splitting (HS) [20,5,6]. The latter is given by $m^2_{H_{u,d}} = m^2_{10} \mp 2M_D^2$. As in the minimal supergravity (mSUGRA) model, $m_{1/2}$ is a common GUT scale gaugino mass, A_0 is a common GUT scale trilinear soft term, and the bilinear SSB term B has been traded for the weak scale value of $\tan\beta$ via the EWSB minimization conditions. The latter also determine the magnitude (but not the sign) of the superpotential Higgs mass term μ.

What has been learned is that t–b–τ Yukawa coupling unification *does* occur in the MSSM for $\mu > 0$ (as preferred by the $(g-2)_\mu$ anomaly), but *only if certain conditions* are satisfied.

- $\tan\beta \sim 50$.
- The gaugino mass parameter $m_{1/2}$ should be as small as possible.
- The scalar mass parameter m_{16} should be very heavy: in the range 8–20 TeV.
- The SSB terms should be related as $A_0^2 = 2m_{10}^2 = 4m_{16}^2$, with $A_0 < 0$ (we use SLHA [22] conventions). This combination was found to yield a radiatively induced inverted scalar mass hierarchy (IMH) by Bagger et al. [23] for MSSM + right-hand neutrino (RHN) models with Yukawa coupling unification.
- EWSB can be reconciled with Yukawa unification only if the Higgs SSB masses are split at M_{GUT} such that $m^2_{H_u} < m^2_{H_d}$.[2] The HS prescription ends up working better than DT splitting [20,19].

In the case where the above conditions are satisfied, Yukawa coupling unification to within a few percent can be achieved. The resulting sparticle mass spectrum has some notable features.

- First and second generation matter scalars have masses of order $m_{16} \sim 8$–20 TeV.
- Third generation scalars, m_A and μ are suppressed relative to m_{16} by the IMH mechanism: they have masses on the 1–2 TeV scale. This reduces the amount of fine-tuning one might otherwise expect in such models.
- Gaugino masses are quite light, with $m_{\tilde{g}} \sim 300$–500 GeV, $m_{\tilde{\chi}_1^0} \sim 50$–80 GeV and $m_{\tilde{\chi}_1^\pm} \sim 100$–160 GeV.

Since the lightest neutralino of $SO(10)$ SUSY GUTs is nearly a pure bino state, it turns out that its relic density $\Omega_{\tilde{\chi}_1^0} h^2$ would be extremely high, of order 10^2–10^4 (unless it annihilates resonantly through the light Higgs [6], which is the case only in a very narrow strip of the parameter space). Such high values conflict with the WMAP observation [25], which gives

$$\Omega_{CDM} h^2 \equiv \rho_{CDM}/\rho_c = 0.1099 \pm 0.0124 \quad (2\sigma), \tag{2}$$

where $h = 0.74 \pm 0.03$ is the scaled Hubble constant. Several solutions to the $SO(10)$ SUSY GUT dark matter problem have been proposed in Refs. [26,6,8]. The arguably most attractive one is that the dark matter particle is in fact not the neutralino, but instead a mixture of *axions* a and thermally and non-thermally produced *axinos* $\tilde{a}$. Mixed axion/axino dark matter occurs in models where the MSSM is extended via the Peccei–Quinn (PQ) solution to the strong *CP* problem [27]. The PQ solution introduces a spin-0 axion field into the model; if the model is supersymmetric, then a spin-$\frac{1}{2}$ axino is also required. The $SO(10)$ SUSY GUT models with mixed axion/axino DM can [8]: 1. yield the correct abundance of CDM in the universe (where a dominant *axion* abundance is most favorable), 2. avoid the gravitino/BBN problem via $m(\mathit{gravitino}) \sim m_{16} \sim 10$ TeV and 3. have a compelling mechanism for generating the matter–antimatter asymmetry of the universe via non-thermal leptogenesis [28]. A consequence of the mixed axion/axino CDM scenario with an axino as LSP is that WIMP search experiments will find null results, while a possible positive result might be found at relic axion search experiments [29].

A more direct consequence of the Yukawa-unified SUSY models is that the color-octet gluino particles are quite light, and possibly accessible to Fermilab Tevatron searches. Under the assumption of gaugino mass unification, the LEP2 chargino mass limit that $m_{\tilde{\chi}_1^\pm} > 103.5$ GeV normally implies that $m_{\tilde{g}} \gtrsim 430$ GeV, quite beyond the Tevatron reach. However, in Yukawa-unified SUSY, the trilinear soft breaking term is large: $A_0 \sim 10$–20 TeV. Such a large trilinear term actually causes a large effect on gaugino mass evolution through two-loop RGE terms, as illustrated in Fig. 1. Here the left frame shows the gaugino mass evolution for the mSUGRA model point with $(m_0, m_{1/2}, A_0, \tan\beta, \mu) = (500\ \text{GeV}, 157\ \text{GeV}, 0, 10, +)$, which has $m_{\tilde{\chi}_1^\pm} = 103.5$ GeV, with $m_{\tilde{g}} = 426.1$ GeV. In the right frame, we show the gaugino mass evolution for Point B of Table 2 of Ref. [8], but with a slightly lower $m_{1/2}$ value. This point has the following GUT scale input parameters: $m_{16} = 10\,000$ GeV, $m_{10} = 12\,053.5$ GeV, $M_D = 3287.12$ GeV, $m_{1/2} = 34$ GeV, $A_0 = -19\,947.3$ GeV, $\tan\beta = 50.398$ and $\mu > 0$. ($\tan\beta$ is input as a weak scale value.) In this case, the gaugino mass evolution is strongly affected by the large two-loop terms, resulting in a much smaller splitting between gaugino masses M_2 and M_3. Here, we find (after computing physical masses including one-loop sparticle mass corrections) that while $m_{\tilde{\chi}_1^\pm} = 108.2$ GeV, the gluino mass is only $m_{\tilde{g}} = 322.8$ GeV. This value of $m_{\tilde{g}}$ may well be within range of Tevatron discovery, even while respecting chargino mass bounds from LEP2.

[2] An exception is the case of highly split trilinears [24].

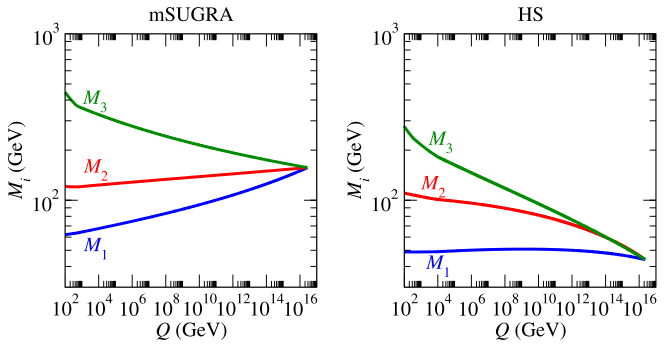

Fig. 1. Evolution of soft SUSY breaking gaugino mass parameters using two-loop RG evolution in the case of mSUGRA and in the case of the HS model with parameters as listed in the text.

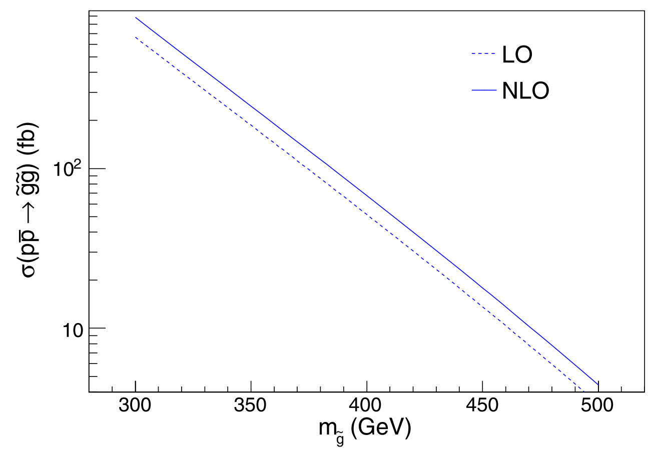

Fig. 2. Production cross section $\sigma(p\bar{p} \to \tilde{g}\tilde{g}X)$ in fb at the $\sqrt{s} = 1.96$ TeV Fermilab Tevatron collider versus $m_{\tilde{g}}$, for $m_{\tilde{q}} = 10$ TeV.

In Yukawa-unified models, the b and τ Yukawa couplings are large, while the top and bottom squark masses are much lighter than their first/second generation counterparts. As a consequence, gluino decays to third generation particles—in particular decays to b quarks—are enhanced. In addition, gluino pair production via $q\bar{q}$ fusion is normally suppressed by t- and s-channel interferences in the production cross section. For $m_{\tilde{q}} \sim 10$ TeV, the negative interference is suppressed, leading to greatly enhanced gluino pair cross sections. Use may be made of the large gluino pair production cross section, and the fact that each $\tilde{g}\tilde{g}$ production event is expected to have four or more identifiable b-jets, along with large E_T^{miss}, to reject SM backgrounds.

In this Letter, we examine gluino pair production at the Fermilab Tevatron collider. While negative searches for gluino pair production have been made, and currently require (under an analysis with ~ 2 fb^{-1} of integrated luminosity) $m_{\tilde{g}} \gtrsim 308$ GeV [2,3] in mSUGRA-like models, use has not yet been made of the large gluino pair production cross section and high b-jet multiplicity expected from Yukawa-unified models.[3] Here, we point out the importance of exploiting the b-jet multiplicity to maximize the reach. By requiring Tevatron events with $\geqslant 4$ jets plus large E_T^{miss}, along with $\geqslant 2$ or 3 tagged b-jets, QCD and electroweak backgrounds can be substantially reduced relative to expected signal rates. We find that the CDF and D0 experiments should be sensitive to $m_{\tilde{g}} \sim 400$–440 GeV with 5–10 fb^{-1} of integrated luminosity. Thus, Tevatron experiments are sensitive to much higher values of gluino mass than otherwise expected from conventional searches. With 5–10 fb^{-1} of data, Tevatron experiments can indeed begin to explore a large swath of Yukawa-unified SUSY model parameter space.

In Section 2, we review gluino pair production total cross sections and expected branching fractions, and introduce a special Yukawa-unified SUSY model line. In Section 3, we provide details of our event simulation program, and show how the requirement of events with $\geqslant 4$ jets plus large E_T^{miss}, along with $\geqslant 2$ or 3 identified b-jets, rejects much SM background, at little cost to signal. We provide our reach results versus $m_{\tilde{g}}$. In Section 4, we present a summary and conclusions.

2. Production and decay of gluinos at the Tevatron

2.1. Gluino pair production

Recent studies of squark and gluino pair production at the Fermilab Tevatron collider, using data corresponding to 2 fb^{-1} of integrated luminosity and a beam energy of $\sqrt{s} = 1.96$ TeV, have produced limits at the 95% CL that $m_{\tilde{g}} > 280$ GeV (in the case of CDF [2]), and $m_{\tilde{g}} > 308$ GeV (in the case of D0 [3]). These studies—in the parts focused on gluino pair production—essentially asked for the presence of events with $\geqslant 4$ hard jets, plus large E_T^{miss} and large H_T, where H_T is the scalar sum of the E_Ts of all identified jets in the event, beyond an expected SM background level. These studies do not use some of the unique characteristics common to gluino pair production in Yukawa-unified SUSY, so we expect Tevatron experiments to be able to do much better in this case.

First, we present the expected total cross section rates for gluino pair production in Fig. 2, displaying leading order (LO) and next-to-leading order (NLO) cross sections as given by Prospino [31]. We adopt a common first/second generation squark mass of $m_{\tilde{q}} = 10$ TeV, and take the Tevatron energy as $\sqrt{s} = 1.96$ TeV. We see from the figure that for $m_{\tilde{g}} = 300$ GeV, the cross section is about 900 fb, dropping to about 65 fb for $m_{\tilde{g}} \simeq 400$ GeV. Moreover, it remains at the level of several fb even for $m_{\tilde{g}}$ as high as 500 GeV.

These cross sections are well in excess of those which enter the CDF and D0 search for gluino pair production. To understand why, we first note that gluino pair production for $m_{\tilde{g}} \sim 300$–500 GeV is dominated by valence quark annihilation via $q\bar{q}$ fusion at the Tevatron. The gg fusion subprocess is dominant at much lower gluino masses, where the gluon PDFs have their peak magnitude at small parton fractional momentum x. The $q\bar{q} \to \tilde{g}\tilde{g}$ subprocess cross section receives contributions from s-channel gluon exchange, along with t- and u-channel squark exchange diagrams [32]. The st- and su-channel interference terms contribute *negatively* to the total production cross section, thereby leading to an actual suppression of $\sigma(p\bar{p} \to \tilde{g}\tilde{g}X)$ for $m_{\tilde{q}} \sim m_{\tilde{g}}$. For $m_{\tilde{q}} \gg m_{\tilde{g}}$ on the other hand, the t-channel, u-channel and interference terms are all highly suppressed, leaving the s-channel gluon exchange contribution unsuppressed and dominant. The situation is illustrated in Fig. 3, where we plot the LO and NLO gluino pair production cross section for $m_{\tilde{g}} = 300$, 400 and 500 GeV versus $m_{\tilde{q}}$ (since the gluino mass ranges between 300 and 500 GeV in Yukawa-unified SUSY, as noted in Section 1). We see that as $m_{\tilde{q}}$ grows, the total production cross section *increases*, and by a large factor: for $m_{\tilde{g}} = 400$ GeV, as $m_{\tilde{q}}$ varies from 400 GeV to 10 TeV, we see a factor of ~ 10 increase in total rate!

At the present time—Fall 2009—CDF and D0 have amassed over 5 fb^{-1} of integrated luminosity.[4] Thus, if $m_{\tilde{g}} \sim 400$ GeV, there

[3] The utility of b-jet tagging for extracting SUSY signals at the LHC has been examined in Ref. [30].

[4] It is expected that CDF and D0 will reach the ~ 10 fb^{-1} level during 2010.

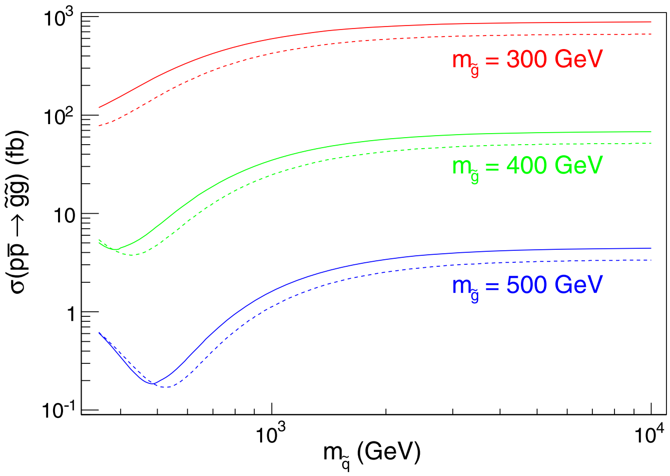

Fig. 3. Cross section of gluino pair production (in fb) at the Fermilab Tevatron collider as a function of $m_{\tilde{q}}$, for $m_{\tilde{g}} = 300$, 400 and 500 GeV. Dashed line is LO QCD, while solid line is NLO, as given by Prospino.

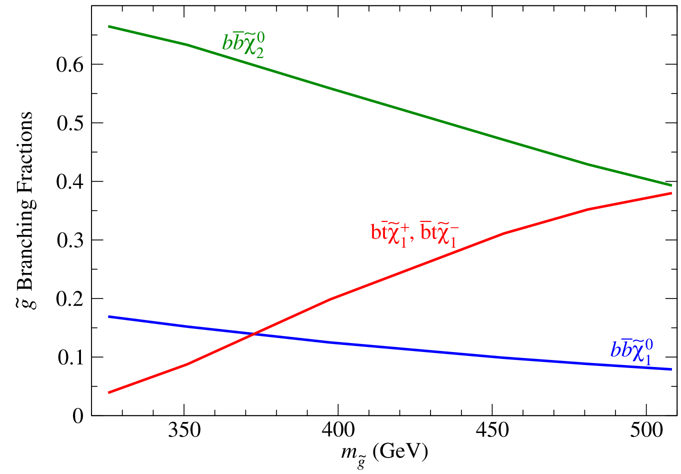

Fig. 4. Dominant gluino branching fractions versus $m_{\tilde{g}}$ for the Yukawa-unified SUSY HS model line.

could be ~ 300 gluino pair events in each group's data. Such a large event sample may well be visible if appropriate background rejection cuts can be found. The exact collider signatures depend on the dominant gluino decay modes, which we discuss in the next section.

2.2. Gluino decays in Yukawa-unified SUSY

To examine the gluino decay modes in Yukawa-unified SUSY, we will adopt a model line which allows us to generate typical Yukawa-unified models over the entire range of $m_{\tilde{g}}$ which is expected. First, we note in passing that Yukawa unification is not possible in the mSUGRA model, since the large t–b–τ Yukawa couplings tend to drive the $m_{H_d}^2$ soft SUSY breaking term more negative than $m_{H_u}^2$, in contradiction to what is needed for an appropriate breakdown of electroweak symmetry. Yukawa-unified models can be found if one instead moves to models with non-universal Higgs masses, where $m_{H_u}^2 < m_{H_d}^2$ already at the GUT scale [33,18]. In this case, $m_{H_u}^2$ gets a head start in its running towards negative values. Detailed scans over the parameter space in Ref. [6] using the parameter space in (1) found a variety of solutions in the Higgs splitting (HS) model. We will adopt Point B of Table 2 of Ref. [8] as a template model. This point has the following GUT scale input parameters: $m_{16} = 10000$ GeV, $m_{10} = 12053.5$ GeV, $M_D = 3287.12$ GeV, $m_{1/2} = 43.9442$ GeV, $A_0 = -19947.3$ GeV, $\tan\beta = 50.398$ and $\mu > 0$ (where $\tan\beta$ is again at the weak scale). The Yukawa couplings at M_{GUT} are found to be $f_t = 0.557$, $f_b = 0.557$ and $f_\tau = 0.571$, so unification is good at the 2% level. The gluino mass which is generated is $m_{\tilde{g}} = 351$ GeV.

If we now allow $m_{1/2}$ to vary, we still maintain valid Yukawa-unified solutions over the range of $m_{1/2}$: 35–100 GeV, corresponding to a variation in $m_{\tilde{g}}$: 325–508 GeV. (The Yukawa unification gets worse as $m_{1/2}$ increases, and at $m_{1/2} = 100$ GeV diminishes to 7.3%.) The value of the chargino mass at $m_{1/2} = 35$ GeV is $m_{\tilde{\chi}_1^\pm} = 108$ GeV, i.e. slightly above the LEP2 limit. We will label Point B with variable $m_{1/2}$ as the Higgs splitting, or HS, model line. The value of the light Higgs boson is $m_h \simeq 127$ GeV all along the HS model line.

Armed with a Yukawa-unified SUSY model line, we can now examine how the gluino decays as a function of gluino mass. The gluino decay branching fractions as calculated by ISAJET are shown in Fig. 4. Here, we see that at low $m_{\tilde{g}} \sim 325$ GeV, the mode $\tilde{g} \to b\bar{b}\tilde{\chi}_2^0$ occurs at over 60%, and dominates the $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$ branching fraction, which occurs at typically 10–20% [34]. As $m_{\tilde{g}}$ increases, the decay modes $\tilde{g} \to t\bar{b}\tilde{\chi}_1^- +$ c.c. grows from the kinematically suppressed value of below 10% at $m_{\tilde{g}} \sim 325$ GeV, to $\sim 40\%$ at $m_{\tilde{g}} \sim 500$ GeV. All these dominant decay modes lead to two bs per gluino in the final state, so that for gluino pair production at the Tevatron, we expect collider events containing almost always $\geqslant 4$ jets $+ E_T^{miss}$, with $\geqslant 4$ b-jets. Even more b-jets can come from $\tilde{\chi}_2^0$ decays, since $\tilde{\chi}_2^0 \to b\bar{b}\tilde{\chi}_1^0$ at around 20% all across the HS model line. Only a very small fraction of gluino decays, less than 10%, lead to first/second generation quarks in the final state.

3. Reach of the Fermilab Tevatron for gluinos in Yukawa-unified SUSY

Next, we examine whether experiments at the Fermilab Tevatron can detect gluino pair production in the HS model line assuming 5–10 fb^{-1} of integrated luminosity. We generate signal and background events using ISAJET 7.79, with a toy detector simulation containing hadronic calorimetry ranging out to $|\eta| < 4$, with cell size $\Delta\eta \times \Delta\phi = 0.1 \times 0.262$. We adopt hadronic smearing of $\Delta E = 0.7/\sqrt{E}$ and EM smearing of $\Delta E = 0.15/\sqrt{E}$. We adopt the ISAJET GETJET jet finding algorithm, requiring jets in a cone size of $\Delta R = 0.5$ with $E_T^{jet} > 15$ GeV. Jets are ordered from highest $E_T(j1)$ to lowest E_T. Leptons within $|\eta_\ell| < 2.5$ ($\ell = e, \mu$) are classified as isolated if $p_T(\ell) > 10$ GeV and a cone of $\Delta R = 0.4$ about the lepton direction contains $E_T < 2$ GeV. Finally, if a jet with $|\eta_j| \leqslant 2$ has a B-hadron with $E_T \geqslant 15$ GeV within $\Delta R \leqslant 0.5$, it is tagged as a b-jet with an efficiency of 50%. Ordinary QCD jets are mis-tagged as b-jets at a 0.4% rate [35].

We also generate SM background (BG) event samples from $W+$jets production, $Z + b\bar{b}$ production, $t\bar{t}$ production, vector boson pair production, hadronic $b\bar{b}$ production, $b\bar{b}b\bar{b}$ production, $t\bar{t}b\bar{b}$ production and $Zb\bar{b}b\bar{b}$ (followed by $Z \to \nu\bar{\nu}$) production.[5] The $W+$jets sample uses QCD matrix elements for the primary parton emission, while subsequent emissions (including $g \to b\bar{b}$ splitting) are generated from the parton shower. For $Z+b\bar{b}$, we use the exact $2 \to 3$ matrix element, which is pre-programmed into ISAJET using Madgraph [36]. We use AlpGen [37] plus Pythia [38] for $b\bar{b}b\bar{b}$ and $t\bar{t}b\bar{b}$ production, and Madgraph plus Pythia for $Zb\bar{b}b\bar{b}$ production [36].

[5] We do not take into account the QCD dijet backgrounds which turn out to be negligible after the cuts described below.

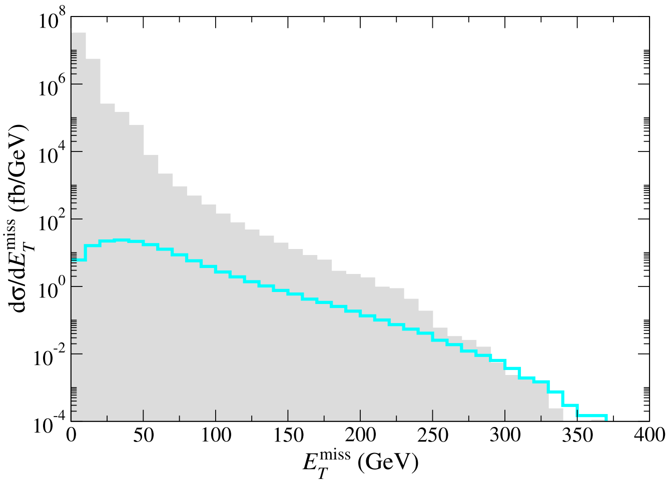

Fig. 5. Distribution in missing E_T from gluino pair production in Yukawa-unified SUSY Pt. B, along with summed SM backgrounds (gray histogram), with minimal cuts listed in text.

Table 1
Sets of cuts from Refs. [39,2,3] used in this analysis. In addition we require throughout $\geqslant 4$ jets, *no* isolated leptons, at least one jet with $|\eta_j| < 0.8$ and $\Delta\phi(j1, j2) < 160°$.

Cuts	$E_T^{\rm miss}$	H_T	$E_T(j1)$	$E_T(j2)$	$E_T(j3)$	$E_T(j4)$
BMPT	$\geqslant 75$ GeV	–	15	15	15	15
CDF	$\geqslant 90$ GeV	280	95	55	55	25
D0	$\geqslant 100$ GeV	400	35	35	35	20

For our first results, we exhibit the distribution in $E_T^{\rm miss}$ in Fig. 5 as generated for the HS model line Pt. B (with $m_{\tilde g} = 350$ GeV) as the blue histogram, along with the summed SM backgrounds (gray histogram). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.) While the signal histogram is harder than the BG histogram, the BG level is so high that signal doesn't exceed BG until $E_T^{\rm miss} \gtrsim 300$ GeV. Of course, this Pt. B gluino mass is well beyond the current Tevatron gluino mass limits, so this is easy to understand.

To do better, we must adopt a set of cuts that selects out canonical gluino pair production events. Here, we will follow the recent papers BMPT [39], CDF [2] and D0 [3], and require the cuts listed in Table 1.

We have yet to make use of the high b-jet multiplicity which is expected from Yukawa-unified SUSY. In Fig. 6, we plot the multiplicity of b-jets expected from SM background (brown histogram), and the summed BG plus signal from HS Pt. B. (The BG in the $n_b = 0$ channel is very under-estimated, since we leave off QCD multi-jet production.) We see that the BG distribution has a sharp drop-off as n_b increases. Especially, there is a very sharp drop-off in BG in going from the $n_b = 2$ to the $n_b = 3$ bin. When we add in the signal distribution, we see the histogram expanding out to large values of n_b due to the presence of 4–6 b-jets per SUSY event. For the softer BMPT cuts, the signal hardly influences the $n_b = 0, 1, 2$ bins. However, in the $n_b = 3$ bin, there is a huge jump in rate, reflecting the presence of a strong source of $\geqslant 3$ b-jet events. In the case of the CDF and D0 cuts, which are much harder, the total BG is much diminished. In this case, the summed signal plus BG distribution actually becomes rounded, and is again much harder than just BG alone. For the CDF (D0) cuts, signal exceeds BG in the $n_b = 2$ bin by a factor of 2 (3). By the time we move to the $n_b = 3$ bin, then for both CDF and D0 cuts, signal exceeds BG by over an order of magnitude. Using soft cuts and low b-jet multiplicity, one should gain a good normalization of total BG rates. Then, as one moves towards large b-jet multiplicity $n_b \geqslant 2$ or 3, there should be much higher rates than expected from SM BG.

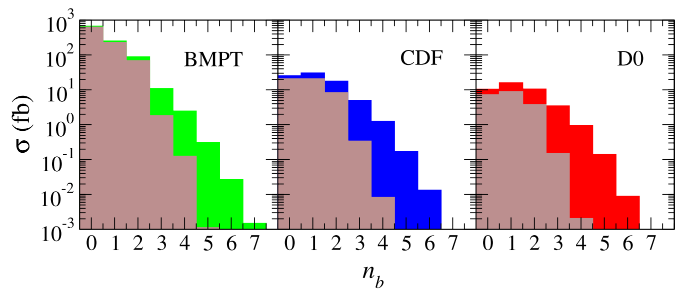

Fig. 6. Distribution in tagged b-jet multiplicity for gluino pair production in Yukawa-unified SUSY Pt. B, along with summed SM backgrounds (brown histogram), after cut sets BMPT, CDF, and D0 given in Table 1. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

Table 2 shows a listing of expected contamination from each BG source after the different sets of cuts. The hard $E_T^{\rm miss}$ and H_T cuts largely eliminate the $b\bar b$ BG. The isolated lepton veto combined with large $E_T^{\rm miss}$ requirement cuts much of $W +$ jets. The remaining large BGs come from $t\bar t$ production and $Z + b\bar b$ production, where $Z \to \nu\bar\nu$. Requiring $\geqslant 4$ jets along with large H_T for the CDF and D0 cuts largely reduces $Zb\bar b$ to small levels, leaving $t\bar t$ as the dominant BG.

In light of these results, we proceed by requiring BMPT, CDF or D0 cuts, along with

- $n_b \geqslant 2$ or 3.

In Fig. 7 we plot the resultant SM background (blue dashed lines), along with expected signal rates for the HS model line (full lines) for the three sets of cuts with $n_b \geqslant 2$ (upper row) as well as $n_b \geqslant 3$ (lower row). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.) The SM background comes almost entirely from $t\bar t$ production. The third b-jet in $t\bar t$ production can come from additional $g \to b\bar b$ radiation, or from QCD jet mis-tags. Since the dominant BG comes from $t\bar t$ production, and the $\sigma(p\bar p \to t\bar t X)$ cross section is well known from standard top search channels, the background should be rather well understood.

We see from Fig. 7 that signal actually exceeds BG for a substantial range of $m_{\tilde g}$ for all cases except the BMPT cuts with $n_b \geqslant 2$. We also compute the signal cross sections required for a 5σ discovery for each selection assuming 5 and 10 fb^{-1} of integrated luminosity, shown as the dot-dashed and dotted lines, respectively. The significance in σs is derived from the p-value corresponding to the number of S + B events in a Poisson distribution with a mean that equals to the number of background events. The best reach is achieved with the hard D0 cuts. In this case, requiring $n_b \geqslant 2$, we find that signal exceeds the 5σ level for 5 (10) fb^{-1} of integrated luminosity for $m_{\tilde g} < 395$ (410) GeV. Requiring $n_b \geqslant 3$, the 5σ reach for 5 (10) fb^{-1} increases to $m_{\tilde g} = 405$ (430) GeV. Thus, in the case of Yukawa-unified SUSY where an abundance of b-jets are expected to accompany gluino pair production, *we expect Fermilab Tevatron experiments to be able to probe values of $m_{\tilde g}$ to much higher values than have previously been found.*

Since the value of $m_{\tilde g}$ is expected to lie in the range 300–500 GeV for Yukawa-unified models, and in fact the Yukawa unification is best on the lower range of $m_{\tilde g}$ values, it appears to us that CDF and D0, using current data samples, stand a good chance of either discovering Yukawa-unified SUSY, or excluding a huge portion of the allowed parameter space.

Table 2
SM backgrounds in fb before and after cuts BMPT, CDF and D0 for $n_b \geqslant 2$ and $\geqslant 3$. The p_T range for $b\bar{b}$ subprocess generation is 15–200 GeV. The p_T range for $t\bar{t}$ subprocess generation is 10–300 GeV. The $\sqrt{\hat{s}}$ range for $Zb\bar{b}$ subprocess generation is 100–400 GeV. In the above, $V = W$ or Z.

BG	σ (fb)	Events	BMPT		CDF		D0	
			$\geqslant 2bs$	$\geqslant 3bs$	$\geqslant 2bs$	$\geqslant 3bs$	$\geqslant 2bs$	$\geqslant 3bs$
$b\bar{b}$	3.8×10^8	10^6	–	–	–	–	–	–
$t\bar{t}$	5.9×10^3	10^6	51.9	1.3	8.6	0.3	3.9	0.14
$b\bar{b} + (Z \to \nu\bar{\nu})$	1.3×10^4	10^6	15.7	0.4	–	–	–	–
W + jets	4.8×10^6	5×10^6	1.9	–	–	–	–	–
VV	9.7×10^3	10^6	0.6	0.01	–	–	–	–
$b\bar{b}b\bar{b}$	6.3×10^4	9.7×10^5	0.39	0.13	0.065	0.065	–	–
$t\bar{t}b\bar{b}$	11	4.1×10^5	0.39	0.13	0.066	0.019	0.037	0.013
$b\bar{b}b\bar{b} + (Z \to \nu\bar{\nu})$	0.54	6.6×10^3	0.03	0.01	$< 10^{-2}$	$< 10^{-2}$	$< 10^{-3}$	$< 10^{-3}$
Total			70.9	1.98	8.7	0.38	3.94	0.15

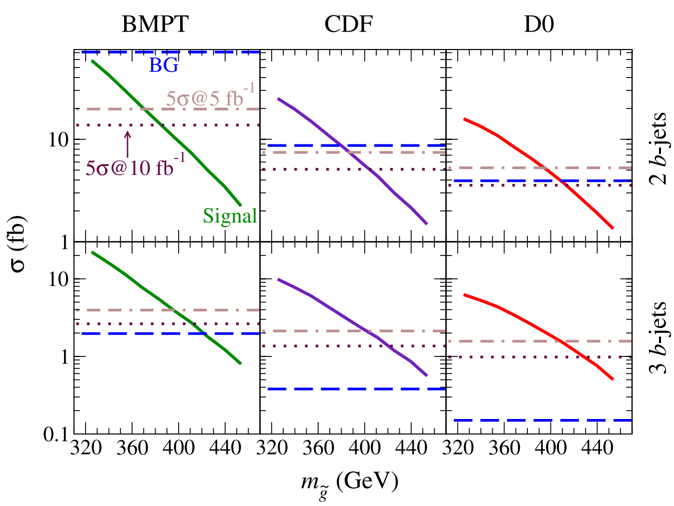

Fig. 7. Reach of the Fermilab Tevatron collider for gluino pair production in Yukawa-unified SUSY HS model line, versus $m_{\tilde{g}}$. We show the reach for 5 and 10 fb^{-1} of integrated luminosity.

4. Conclusions

In this Letter, we explored the capability of the CDF and D0 experiments to search for gluinos with properties as predicted by supersymmetic models with t–b–τ Yukawa coupling unification. While a vast effort is rightfully being placed by CDF and D0 to search for the SM Higgs boson, a potentially bigger prize—the gluinos from supersymmetric models—could be lurking in their data. The Yukawa-unified SUSY model is extremely compelling, in part because it combines four of the most profound ideas in physics beyond the SM: $SO(10)$ grand unification (which unifies matter as well as gauge couplings), weak scale supersymmetry, see-saw neutrino masses and the Peccei–Quinn–Weinberg–Wilczek solution to the strong CP problem. While we do not present a specific model which incorporates all these ideas into a single framework, a wide array of low energy, collider and astrophysical data give some indirect and also direct support to each of these ideas. The requirement of Yukawa coupling unification forces upon us a very specific and compelling sparticle mass spectrum, including first/second generation scalars at the ~ 10 TeV scale, while gluinos are quite light: in the ~ 300–500 GeV range. We investigated here whether these light gluinos are accessible to Tevatron searches for supersymmetry.

Our main result is that the CDF and D0 experiments should be already sensitive to gluino masses far beyond currently published bounds (which lie around the 300 GeV scale). This is due to three main factors:

1. Two-loop RGE effects allow for gluinos as light as 320 GeV in the Yukawa-unified model with multi-TeV trilinear soft terms, even while respecting LEP2 limits on the chargino mass. In the case of generic SUSY models with TeV scale soft parameters, the LEP2 chargino mass limit usually implies $m_{\tilde{g}} \gtrsim 425$ GeV.
2. Gluino pair production cross sections with $m_{\tilde{g}} \sim 300$–500 GeV are enhanced at the Tevatron due to the extremely high squark masses expected in Yukawa-unified SUSY. The huge value of $m_{\tilde{q}}$ acts to suppress negative interference effects in the $q\bar{q} \to \tilde{g}\tilde{g}$ subprocess cross section, leading to elevated production rates.
3. Gluinos of Yukawa-unified SUSY decay through cascade decays to final states almost always containing four b-jets, and sometimes six or eight b-jets, depending if $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 b\bar{b}$ occurs. By searching for collider events with $\geqslant 4$ jets plus large E_T^{miss}, along with $\geqslant 2$ or 3 b-jets which are tagged through the micro-vertex detector, SM backgrounds can be reduced by large factors, at only a small cost to signal.

This may allow Tevatron experiments to search for gluinos with mass in excess of 400 GeV. Such gluino masses are far beyond currently published bounds, and would allow exploration of a huge swath of parameter space of Yukawa-unified SUSY models.

In addition, in the case of the HS model where $\tilde{g} \to b\bar{b}\tilde{\chi}_2^0$ at a large rate, followed by $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+\ell^-$ (typically at $\sim 3\%$ branching ratio for each of $\ell = e$ or μ), there may be a corroborating signal at much lower rates in the multi-b-jet $+ E_T^{\mathrm{miss}} + \ell^+\ell^-$ mode, where $m(\ell^+\ell^-) < m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$.

We note finally that the results presented here in the context of Yukawa-unified models are more generally applicable to any model with very heavy scalars, and large enough $\tan\beta$ such that gluinos dominantly decay via three-body modes into b-quarks. They are also applicable to models with hierarchical soft terms, where first/second generation scalars are extremely heavy, and third generation scalars are much lighter; some references for such models are located in [40].

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