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Searching for Gluinos at the Tevatron

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This letter describes how to perform model-independent searches for new pair-produced color octet particles that each subsequently decay into two jets plus missing energy at the Tevatron. Current searches are not sensitive to all regions of parameter space because they employ CMSSM-motivated cuts. Optimizing the H_T and $\not\!\!E_T$ cuts expands the sensitivity of searches for all kinematically allowed decays.

I. INTRODUCTION

In many theories beyond the Standard Model, there is a new color octet particle that decays into jets plus a stable neutral singlet. This occurs, for example, in supersymmetry [1] and Universal Extra Dimensions [2], as well as Randall-Sundrum [3] and Little Higgs models [4]. As a result, jets plus missing transverse energy ($\not\!\!E_T$) is a promising experimental signature for new phenomena [5–8].

At present, the jets + $\not\!\!E_T$ searches at the Fermilab Tevatron are based upon the minimal supersymmetric standard model (MSSM) and look for production of gluinos ($\tilde{g}$) and squarks ($\tilde{q}$), the supersymmetric partners of gluons and quarks, respectively [6, 7]. Both gluinos and squarks can decay to jets and a bino ($\tilde{B}$), the supersymmetric partner of the photon. The bino is stable, protected by a discrete R-parity, and is manifest as missing energy in the detector. Different jet topologies are expected, depending on the relative masses of the gluinos and squarks.

There are many parameters in the MSSM and setting mass bounds in a multi-parameter space is difficult. This has lead to a great simplifying ansätz known as the CMSSM (or mSUGRA) parameterization of supersymmetry breaking [9]. This ansätz sets all the gaugino masses equal at the grand unified scale. As a result, the ratio between the mass of the gluino and bino is constant ($m_{\tilde{g}} : m_{\tilde{B}} = 6 : 1$). Thus, the mass ratio between the gluino and bino is never scanned when searching through CMSSM parameter space, which means that there is a large region of kinematically accessible gluinos where there are no known limits.

The CMSSM parametrization is not representative of all supersymmetric models. Other methods of supersymmetry breaking, such as anomaly [10], mirage [11], and non-Minimal gauge mediation [12], lead to different low-energy particle spectra where $m_{\tilde{g}} : m_{\tilde{B}}$ is not necessarily fixed. A more comprehensive search strategy should be sensitive to all values of $m_{\tilde{g}}$ and $m_{\tilde{B}}$.

In this paper, we describe how model-independent mass bounds can be placed on gluino and bino[1] masses. We will treat the gluino as the first new colored particle and will assume that it only decays to the the stable bino: $\tilde{g} \to \bar{q}_1 \tilde{q}^* \to \bar{q}_1 q_2 \tilde{B}$. We show how a set of optimized cuts for $\not\!\!E_T$ and $H_T = \sum_{\text{jets}} E_T$ can set much tighter mass bounds than current Tevatron searches. Our searches are closely based upon DØ 's searches for monojets [8], squarks and gluinos [6]. In doing so, we hope that our projected sensitivity is close to what is achievable and not swamped by unforeseen backgrounds.

II. EVENT GENERATION

A. Signal

The number of jets expected as a result of gluino production at the Tevatron depends on the relative mass difference between the gluino and bino, $m_{\tilde{g}} - m_{\tilde{B}}$. When the mass splitting is much larger than the bino mass, the search is not limited by phase space and four or more well-separated jets are produced, as well as large missing transverse energy. The situation is very different for light gluinos ($m_{\tilde{g}} \lesssim 200$ GeV) that are nearly degenerate with the bino. Such light gluinos can be copiously produced at the Tevatron, with cross sections $\mathcal{O}(10^2$ pb), as compared to $\mathcal{O}(10^{-2}$ pb) for their heavier counterparts ($m_{\tilde{g}} \gtrsim 400$ GeV). Despite their large production cross sections, these events are challenging to detect because the jets from the decay are soft, with modest amounts of missing transverse energy. Even if the gluinos are strongly boosted, the sum of the bino momenta will approximately cancel when reconstructing the missing transverse energy (Fig. 1A). To discover

[1] Throughout this note, we will call the color octet a "gluino" and the neutral singlet the "bino," though nothing more than the color and charge is denoted by these names.

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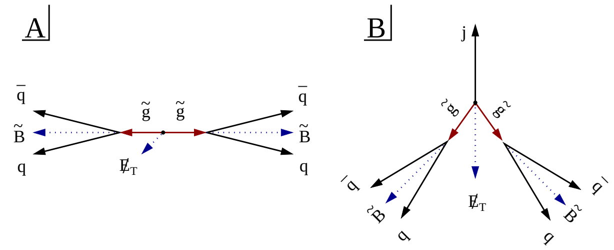

FIG. 1: Boosted gluinos that are degenerate with the bino do not enhance the missing transverse energy when there is no hard initial- or final-state radiation. (A) illustrates the cancellation of the bino's $\not{E}_T$. (B) shows how initial- or final-state radiation leads to a large amount of $\not{E}_T$ even if the gluino is degenerate with the bino.

a gluino degenerate with a bino, it is necessary to look at events where the gluino pair is boosted by the emission of hard QCD jets (Fig. 1B). Therefore, initial-state radiation (ISR) and final-state radiation (FSR) must be properly accounted for.

The correct inclusion of ISR/FSR with parton showering requires generating gluino events with matrix elements. We used MadGraph/MadEvent [13] to compute processes of the form

$$p\bar{p} \to \tilde{g}\tilde{g} + Nj, \tag{1}$$

where $N = 0, 1, 2$ is the multiplicity of QCD jets. The decay of the gluino into a bino plus a quark and an antiquark, as well as parton showering and hadronization of the final-state partons, was done in PYTHIA 6.4 [14].

To ensure that no double counting of events occurs between the matrix-element multi-parton events and the parton showers, a version of the MLM matching procedure was used [15]. In this procedure, the matrix element multi-parton events and the parton showers are constrained to occupy different kinematical regions, separated using the $k_\perp$ jet measure:

$$\begin{aligned} d^2(i,j) &= \Delta R_{ij}^2 \min(p_{Ti}^2, p_{Tj}^2) \\ d^2(i,\text{beam}) &= p_{Ti}^2, \end{aligned} \tag{2}$$

where $\Delta R_{ij}^2 = 2(\cosh\Delta\eta - \cos\Delta\phi)$ [16]. Matrix-element events are generated with some minimum cut-off $d(i,j) = Q_{\text{min}}^{\text{ME}}$. After showering, the partons are clustered into jets using the k_T jet algorithm with a $Q_{\text{min}}^{\text{PS}} > Q_{\text{min}}^{\text{ME}}$. The event is then discarded unless all resulting jets are matched to partons in the matrix-element event, $d(\text{parton}, \text{jet}) < Q_{\text{min}}^{\text{PS}}$. For events from the highest multiplicity sample, extra jets softer than the softest matrix-element parton are allowed. This procedure avoids double-counting jets, and results in continuous and smooth differential distributions for all jet observables.

The matching parameters ($Q_{\text{min}}^{\text{ME}}$ and $Q_{\text{min}}^{\text{PS}}$) should be chosen resonably far below the factorization scale of the process. For gluino production, the parameters were:

$$Q_{\text{min}}^{\text{ME}} = 20 \text{ GeV and } Q_{\text{min}}^{\text{PS}} = 30 \text{ GeV}. \tag{3}$$

The simulations were done using the CTEQ6L1 PDF [17] and with the renormalization and factorization scales set to the gluino mass. The matched cross sections were rescaled to the next-to-leading-order (NLO) cross sections obtained using Prospino 2.0 [18].

Finally, we used PGS [19] for detector simulation, with a cone jet algorithm with $\Delta R = 0.5$. As a check on this procedure, we compared our results to the signal point given in [6] and found that they agreed to within 10%.

B. Backgrounds

The three dominant Standard Model backgrounds that contribute to the jets plus missing energy searches are: $W^\pm/Z^0$ + jets, $t\bar{t}$, and QCD. There are several smaller sources of missing energy that include single top and di-boson production, but these make up a very small fraction of the background and are not included in this study.

The $W^\pm/Z^0 + nj$ and $t\bar{t}$ backgrounds were generated using MadGraph/MadEvent and then showered and hadronized using PYTHIA. PGS was used to reconstruct the jets. MLM matching was applied up to three jets for the $W^\pm/Z^0$ background, with the parameters $Q_{\text{min}}^{\text{ME}} = 10$ GeV and $Q_{\text{min}}^{\text{PS}} = 15$ GeV. The top background was matched up to two jets with $Q_{\text{min}}^{\text{ME}} = 14$ GeV and $Q_{\text{min}}^{\text{PS}} = 20$ GeV. Events containing isolated leptons with $p_T \geq 10$ GeV were vetoed to reduce background contributions from leptonically decaying $W^\pm$ bosons. To reject cases of $\not{E}_T$ from jet energy mismeasurement, a lower bound of 90° and 50° was placed on the azimuthal angle between $\not{E}_T$ and the first and second hardest jets, respectively. An acoplanarity cut of $< 165°$ was applied to the two hardest jets. Because the DØ analysis did not veto hadronically decaying tau leptons, all taus were treated as jets in this study.

Simulation of the missing energy background from QCD is beyond the scope of PYTHIA and PGS, and was therefore not done in this work. However, to avoid the regions where hadronically produced missing energy becomes the dominant background, a lower limit of $\not{E}_T > 100$ GeV was imposed. Additionally, in the dijet analysis, the azimuthal angle between the $\not{E}_T$ and any jet with $p_T \geq 15$ GeV and $|\eta| \leq 2.5$ was bounded from below by 40°. This cut was not placed on the threejet or multijet samples because of the large jet multiplicities in these cases.

For each of the $W^\pm/Z^0 + nj$ and $t\bar{t}$ backgrounds, 500K events were generated. The results reproduce the shape and scale of the $\not{E}_T$ and H_T distributions published by the DØ collaboration in [6] for 1fb^{-1}. For

	$1j + \not{E}_T$	$2j + \not{E}_T$	$3j + \not{E}_T$	$4^+j + \not{E}_T$
$E_{T\,j_1}$	≥ 150	≥ 35	≥ 35	≥ 35
$E_{T\,j_2}$	< 35	≥ 35	≥ 35	≥ 35
$E_{T\,j_3}$	< 35	< 35	≥ 35	≥ 35
$E_{T\,j_4}$	< 20	< 20	< 20	≥ 20

TABLE I: Summary of the selection criteria for the four non-overlapping searches. The two hardest jets are required to be central ($|\eta| \leq 0.8$). All other jets must have $|\eta| \leq 2.5$.

the dijet case, where the most statistics are available, the correspondence with the DØ result is ±20%. With the threejet and multijet cuts, the result for the $t\bar{t}$ background is similar, while the $W^\pm/Z^0 + nj$ backgrounds reproduce the DØ result to within $30 - 40\%$ for the threejet and multijet cases. The increased uncertainty may result from insufficient statistics to fully populate the tails of the $\not{E}_T$ and H_T distributions. The PGS probability of losing a lepton may also contribute to the relative uncertainties for the $W^\pm + nj$ background. Heavy flavor jet contributions were found to contribute 2% to the $W^\pm/Z^0$ backgrounds, which is well below the uncertainties that arise from not having NLO calculations for these processes and from using PGS.

III. PROJECTED REACH OF SEARCHES

The goal of a model-independent gluino search is to have broad acceptances over a wide range of kinematical parameter space. The searches should be sensitive to cases where the gluino and bino are nearly degenerate, as well as cases where the gluino is far heavier than the bino. As already discussed, the number of jets and $\not{E}_T$ depend strongly on both $m_{\tilde{g}}$ and $m_{\tilde{g}} : m_{\tilde{B}}$. Because the signal changes dramatically as the masses of the gluino and bino are varied, it is necessary to design searches that are general, but not closely tied to the kinematics. We divided events into four mutually exclusive searches for $\not{E}_T$ plus $1j$, $2j$, $3j$ and 4^+j, respectively. For convenience, we keep the $nj + \not{E}_T$ classification fixed for all gluino and bino masses (see Table I). These selection criteria were modeled after those used in DØ 's existing search [6].[2] These exclusive searches can be statistically combined to provide stronger constraints.

Two cuts are placed on each search: $H_T^{\min}$ and $\not{E}_T{}^{\min}$. In the DØ analysis, the H_T and $\not{E}_T$ cuts are constant for each search. The signal (as a function of the gluino and bino masses) and Standard Model background are very sensitive to these cuts. To maximize the discovery potential, these two cuts should be optimized for all gluino and bino masses. For a given gluino and bino mass, the significance ($S/\sqrt{S+B}$) is maximized over $H_T^{\min}$ and $\not{E}_T{}^{\min}$ in each $nj + \not{E}_T$ search. Due to the uncertainty in the background calculations, the S/B was not allowed to drop beneath a minimal value. A conservative limit of $S/B > 1$ was placed and compared to the more aggressive lower limit of $S/B > 0.3$. The resulting 95% sensitivity plot using the optimized H_T and $\not{E}_T$ cuts is shown in Fig. 2.

For light and degenerate gluinos, the $1j + \not{E}_T$ and $2j + \not{E}_T$ searches both have good sensitivity. In an intermediate region, the $2j + \not{E}_T$, $3j + \not{E}_T$ and $4^+j + \not{E}_T$ all cover with some success, but there appears to be a coverage gap where no search does particularly well. If one does not impose a S/B requirement, a lot of the gap can be covered, but background calculations are probably not sufficiently precise to probe small S/B. For massive, non-degenerate gluinos, the $3j + \not{E}_T$ and $4^+j + \not{E}_T$ both give good sensitivity, with the $4^+j + \not{E}_T$ giving slightly larger statistical significance.

In the exclusion plot, the $\not{E}_T$ and H_T cuts were optimized for each point in gluino-bino parameter space. However, for gluino masses 200 GeV $\lesssim m_{\tilde{g}} \lesssim$ 350 GeV, where the monojet search gives no contribution, we found that the exclusion region does not markedly change if the following set of generic cuts are placed:

$$(H_T, \not{E}_T) \geq (150,100)_{2j+\not{E}_T}, (150,100)_{3j+\not{E}_T}, (200,100)_{4^+j+\not{E}_T}. \quad (4)$$

As a comparison, the cuts used in the DØ analysis are

$$(H_T, \not{E}_T) \geq (300,225)_{2j+\not{E}_T}, (400,150)_{3j+\not{E}_T}, (300,100)_{4^+j+\not{E}_T}. \quad (5)$$

The lowered cuts provide better coverage for intermediate mass gluinos, as indicated in Fig. 2. For larger gluino masses, the generic cuts are no longer effective and it is necessary to use the optimized cuts, which are tighter than DØ 's. While DØ technically has statistical significance in this high-mass region with their existing cuts, their signal-to-background ratio is less than unity. Because of the admitted difficulties in calculating the Standard Model backgrounds, setting exclusions with a low signal-to-background should not be done and fortunately can be avoided by tightening the H_T and $\not{E}_T$ cuts. Similarly, for $m_{\tilde{g}} \lesssim 200$ GeV, we place tighter cuts on the monojet and dijet samples than DØ does. This increases our sensitivity while keeping $S/B > 1$.

IV. CONCLUSIONS AND OUTLOOK

In this paper, we describe the sensitivity that DØ has in searching for gluinos away from the CMSSM hy-

[2] It should be noted, however, that the DØ searches are inclusive because each is designed to look for separate gluino/squark production modes (i.e., $pp \to \tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$).

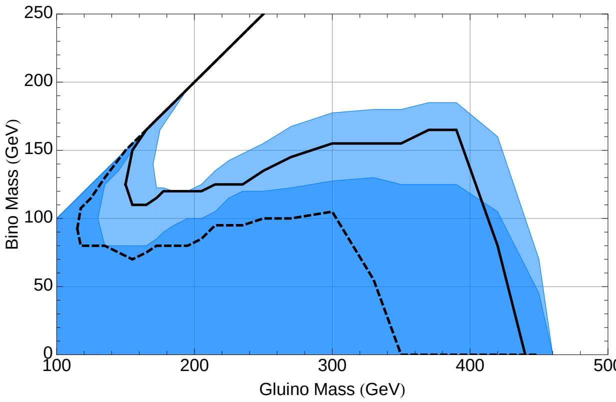

FIG. 2: The 95% sensitivity of DØ to discover gluinos at 4 fb^{-1}. The dark blue region corresponds to $S/B > 1$, while the light blue shows the reach for $S/B > 0.3$. The dashed and solid lines show the corresponding exclusion regions using DØ 's non-optimized H_T and $\not{E}_T$ cuts.

pothesis in jets + $\not{E}_T$ searches. It was assumed that the gluino only decayed to two jets and a stable bino. However, many variants of this decay are possible and the search presented here can be generalized accordingly.

One might, for example, consider the case where the gluino decays dominantly to bottom quarks and heavy flavor tagging can be used advantageously. Cascade decays are another important possibility. Decay chains have a significant effect upon the searches because they convert missing energy into visible energy. In this case, additional parameters, such as the intermediate particle masses and the relevant branching ratios, must be considered. In the CMSSM, the branching ratio of the gluino into the wino is roughly 80%. While this cascade decay may be representative of many models that have gluino-like objects, the fixed mass ratio and branching ratio are again artifacts of the CMSSM. A more thorough examination of cascade decays should be considered.

In addition to alternate decay routes for the gluino, alternate production modes are important when there are additional particles that are kinematically accessible. In this paper, it was assumed that the squarks are kinematically inaccessible at the Tevatron; however, if the squarks are accessible, $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ production channels could lead to additional discovery possibilities. For instance, a gluino that is degenerate with the bino could be produced with a significantly heavier squark. The squark's subsequent cascade decay to the bino will produce a great deal of visible energy in the event and may be more visible than gluino pair production.[3]

Ultimately, a model-independent search for jets plus missing energy would be ideal. We believe that our exclusive $nj + \not{E}_T$ searches, with results presented in an exclusion plot as a function of H_T and $\not{E}_T$, would provide significant coverage for these alternate channels. This analysis should be carried forward to the LHC to ensure that the searches discover all possible supersymmetric spectra. The general philosophy of parameterizing the kinematics of the decay can be easily carried over. The main changes are in redefining the H_T and $\not{E}_T$ cuts, as well as the hard jet energy scale. We expect a similar shape to the sensitivity curve seen in Fig. 2, but at higher values for the gluino and bino masses. Therefore, it is unlikely that there will be a gap in gluino-bino masses where neither the Tevatron nor the LHC has sensitivity.

[3] We thank M. Ibe and R. Harnik for this observation.

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