Dijet Searches for Supersymmetry at the Large Hadron Collider

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We present several strategies for searching for supersymmetry in dijet channels, using the two leading jets' momenta alone rather than the full missing transverse energy. Preliminary investigations suggest that signal-to-background ratios of at least 4–5 should be achievable at the LHC, with discovery possible for squarks as heavy as ~1.7 TeV.

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The LHC is set to explore the physics of the weak scale, whatever it should turn out to be. Supersymmetry is one of the leading candidates, and enormous effort has been dedicated to studying missing energy signals that characterize almost any weak-scale supersymmetric model. However, supersymmetry searches will be challenging, and disentangling the supersymmetry parameters will be more difficult still.

In light of the above, it is imperative to study every possible channel in order to optimize our chances of discovering new physics and understanding the underlying theory. Although two-jet events with missing energy have been studied at the Tevatron [1], they have been less prominent in LHC studies. ATLAS has shown that two-jet events can be useful for certain SUSY models, both for discovery and for constraining superpartner masses [2], but recent ATLAS and CMS studies have focused more heavily on the more challenging cascade decays. In this Letter, we study one novel and two existing kinematic variables, constructed from the leading two jets' momenta alone. These provide search strategies that are complementary to ones using the full missing transverse energy calculated from all calorimeter deposits. We find that pairs of these variables can be used to give signal-to-background of at least 4–5, indicating that these variables are worth exploring with a full detector simulation. (Such a study has been started by CMS [3]. In addition, ATLAS is currently engaged in an updated dijet study [4].)

Dijet events are worthy of attention as a potentially clear window into parameter space. Studies along the lines explored here may usefully supplement recent analyses dedicated to distinguishing SUSY from other models using events with at least three jets [5].

The kinematic variables we consider should have different systematic uncertainties than missing transverse energy since they are based on different measurements and pick out slightly different events. At the very least, then, the searches we suggest should be worthwhile as cross checks of standard searches. The variables we use may also be useful for optimization when signal to background is relatively low.

The searches we describe will be most effective when the squarks are lighter than the gluino so that cascade decays through gluinos are absent. Because t-channel gluino exchange is an important source of squark pair production, the lighter the gluino, the more prominent the signal. For the parameter points considered below, the signal is cut by a factor of ~6–7 when the gluino decouples. Fortunately, comparable gluino and squark masses are a feature of a large class of models—most notably high-scale models where the heavier gluino mass feeds into the squark mass. We focus on such models in this study.

Before getting to the dijet properties that will be the focus of our study, we consider the effectiveness of $\not{E}_T$ and $\not{H}_T$ [1], the missing transverse energy obtained from the dijet system alone. After requiring the sum of the two jets' p_T's to be greater than 500 GeV, event rates and signal-to-background ratios for one particular SUSY point are presented in Table I (details regarding event generation and cuts are given below). Neither variable suffices for a clean search, but we observe that the S/B values obtained using $\not{H}_T$ are essentially identical to those obtained using $\not{E}_T$. This analysis suggests that, in the two-jet channel at high p_T, nothing is to be gained by using full $\not{E}_T$ rather than kinematic variables associated with the two jets alone.

We now present three dijet variables that can be used to separate signal and background, with ~1% of signal events passing all cuts.

α: which we define as the ratio of the p_T of the second hardest jet and the invariant mass formed from the two hardest jets, $\alpha \equiv p_{T2}/m_{jj}$. As far as we know, this variable has not been considered previously. (α's dependence on the jets' rapidities and on the ratio of their transverse momenta distinguishes it from other variables such as $\Delta\phi$ and $\not{H}_T$.) Background events generally trail off at $\alpha = 0.5$, whereas supersymmetry events with invisible decay products can easily have larger α. Large α tends to arise in events in which the jets are not back-to-back. As one extreme example, if the two jets are nearly aligned, their invariant mass can be quite small, leading to very large α. Because of the background's sharp dropoff around $\alpha = 0.5$, this variable is potentially useful as a diagnostic tool for ana-

TABLE I. The dependence of the signal cross section and signal to background (S/B) on a variable $\not{E}_T$ cut (top), and on a variable $\not{H}_T$ cut (bottom). All energies are in GeV. We take $M_{1/2} = 300$ GeV, $M_0 = 100$ GeV, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$.

	$\not{E}_T/\not{H}_T$ cut	300	350	400	450	500	550	600	650	700
$\not{E}_T$	σ_{susy} (fb)	864.0	759.0	645.0	526.0	397.0	257.0	143.0	81.9	51.1
	S/B	0.7	1.0	1.3	1.7	1.8	2.0	1.8	1.5	1.4
$\not{H}_T$	σ_{susy} (fb)	862.0	757.0	639.0	521.0	379.0	229.0	128.0	74.5	47.4
	S/B	0.7	1.0	1.3	1.7	1.9	1.8	1.7	1.5	1.3

lyzing two-jet events and cleanly separating signal events from QCD.

$\Delta\phi$: the azimuthal angle between the two hardest jets. Azimuthal angle is often used in conjunction with missing transverse energy, and $\Delta\phi$ was among the variables used in the dijet SUSY search at D0 [1].

M_{T2} [6]: which depends on the momenta of the two jets and an assumed value χ of the invisible particle's mass. In calculating $M_{T2}(\chi)$, we use the missing transverse momentum as determined by the dijet system alone. If χ is set to the mass of the invisible particle, the M_{T2} distribution will have an endpoint at the mass of the decaying particle. Not knowing this mass, M_{T2} end points still constrain the masses of the decaying and invisible particles, as emphasized in [6] and used below.

We consider these variables singly and in tandem. We find the first two variables are useful in that one can choose parameter-independent cuts that give sizable S/B, whereas the last variable, though more parameter-dependent in its optimization, might ultimately maximize S/B. Since the advantage is not overwhelming, we expect all the variables could prove useful, either at the trigger or analysis level. Because they are dimensionless, the first two variables might have the further advantage of being less sensitive to absolute energy scale, and might therefore have lower systematic errors.

For all our analyses, we select events in which exactly two jets have $p_T > 50$ GeV, with no isolated leptons, photons, or τ jets. One could attempt to achieve better background rejection by an additional veto on extra jets with lower p_T. In general, we have chosen felicitous cuts but have not pursued a careful optimization, which will be more appropriate at the full-detector-simulation level.

We specify parameters at the high scale and use the SUSY-HIT package [7] to calculate superpartner masses and decay branching ratios. In the relevant parameter regions, the signal depends strongly on $M_{1/2}$, the unified gaugino mass at the high scale, and is less sensitive to M_0, the unified scalar mass, because the squark mass is dominated by gauge-loop contributions. We set the other SUSY parameters to be $\tan\beta = 10$, $A_0 = 0$, and $\mu > 0$.

The backgrounds included in our analyses are QCD, $(W \to l\bar{\nu})/(Z \to \nu\bar{\nu})$ + jets, and $t\bar{t}$. The QCD and $t\bar{t}$ samples were generated with PYTHIA 6.4 [8], and Z/W + jets with ALPGEN 2.12 [9]. Fully showered and hadronized events were then passed to the PGS 4.0 detector simulator [10], with the energy smearing in the hadronic calorimeter given by $\Delta E/E = 0.8/\sqrt{E/\text{GeV}}$ and the calorimeter granularity set to $(\Delta\phi \times \Delta\eta) = (0.1 \times 0.1)$. Jets were defined using a cone algorithm with $\Delta R = 0.4$.

A K-factor of 2 is applied to the QCD sample, but no K-factor is used for W/Z production because the most important contributions come from W/Z + 2 jets, which are not enhanced at NLO [11]. For $t\bar{t}$, we use $\sigma = 830$ pb as the NLO production cross section [12]. Including the K factors, our samples sizes are $\sim 0.8\ \text{fb}^{-1}$ for QCD, $\sim 20\ \text{fb}^{-1}$ for $t\bar{t}$, and $\sim 100\ \text{fb}^{-1}$ for W/Z. Appropriate generator-level kinematic cuts were imposed to obtain the QCD and W/Z samples.

SUSY samples, with all subprocesses included, were also generated with PYTHIA. For each parameter point, we use PROSPINO 2.0 [13] to calculate a K-factor from the NLO cross section for $\tilde{q}\tilde{q}$ production [14]. For the parameters we consider, this is the smallest squark/gluino K-factor and should give a conservative estimate.

Figure 1 shows that appropriate cuts on α, $\Delta\phi$, and/or M_{T2} can suppress both the QCD background and the dominant background after cuts, $(Z \to \nu\bar{\nu})$ + jets. Here and below, we impose a hard cut on the sum of the two hard jets' transverse momenta, $p_{T1} + p_{T2} > 500$ GeV.

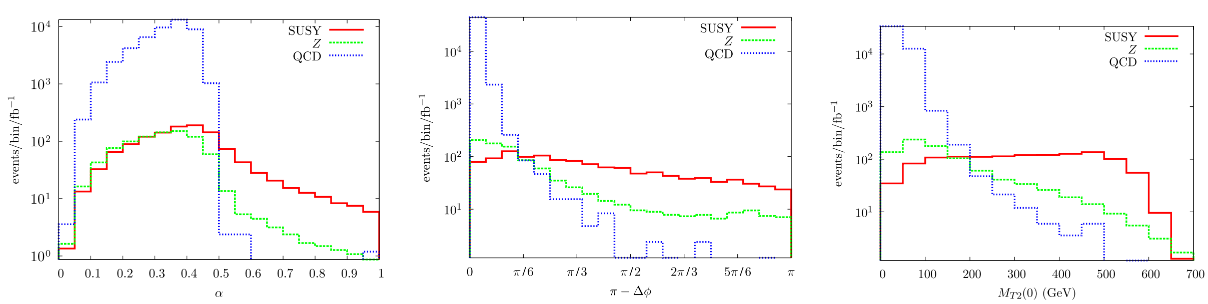

FIG. 1 (color online). Rates for events passing the cuts described in the text, as functions of α, $\Delta\phi$, and $M_{T2}(0)$. To streamline the analysis, events were required to have $\not{E}_T > 100\ \text{GeV}^3$. We take $M_{1/2} = 300$ GeV, $M_0 = 100$ GeV, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$.

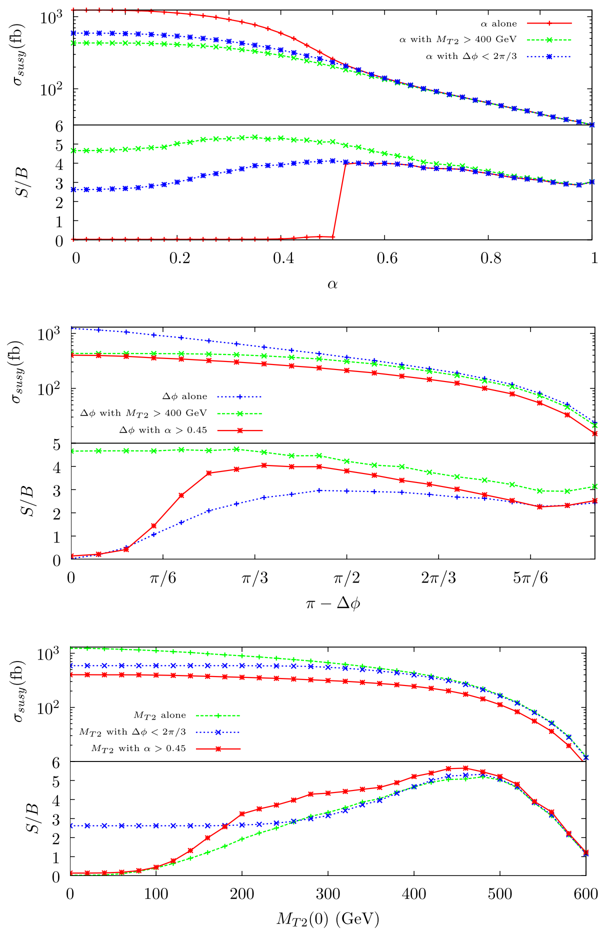

FIG. 2 (color online). For events with at least one of $\alpha > 0.5$, $\Delta\phi < 2\pi/3$, and $\not{E}_T > 100$ GeV[3], the signal cross section and S/B for variable cuts on α (top), $\Delta\phi$ (middle), and M_{T2} (bottom).

[This preselection cut is made to reduce the number of events to be analyzed. Once we impose hard cuts on α and/or $\Delta\phi$ (see below), there is effectively no $\not{E}_T$ cut.]

Evidently, signal dominates over background for $\alpha \gtrsim 0.5$, $\Delta\phi \lesssim 2\pi/3$, and $M_{T2} \gtrsim 300$ GeV. We will soon see that α, $\Delta\phi$, and M_{T2} can be used to discriminate signal from background by themselves, but first we point out that cuts on these variables can improve an analysis based on $\not{E}_T$ or $\not{H}_T$. For example, the combination ($\alpha > 0.45$, $\not{H}_T > 300$ GeV) selects 315 signal events per fb^{-1}, with $S/B = 4.3$. The combination ($\Delta\phi < 2\pi/3$, $\not{H}_T > 450$ GeV) gives a somewhat lower S/B (3.1), but with more events (429). An M_{T2} cut of 450 GeV gives the largest S/B of all (5.0, with 304 events), and in fact there appears to be no benefit in supplementing the M_{T2} cut with the $\not{H}_T$ cut.

Figure 2 shows that each of α, $\Delta\phi$, and M_{T2} can be used independently to observe a clear signal, without employing $\not{H}_T$. Well-chosen cuts give ~afew $\times 10^2$ signal events after 1 fb^{-1}, with $S/B \sim 3$–5.

Figure 2 also shows how the variables can be used in pairs to improve S/B in conjunction with the signal rate.

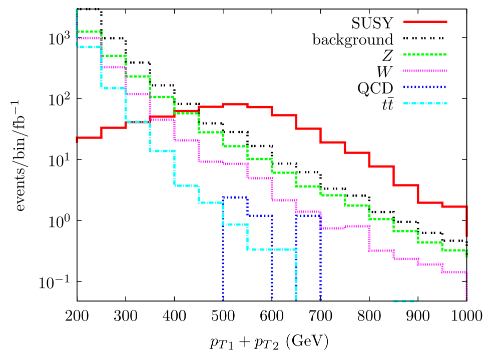

FIG. 3 (color online). Event rates after the cuts $\Delta\phi < 2\pi/3$ and $\alpha > 0.45$. QCD is not included for $p_{1T} + p_{2T} < 500$ GeV.

We again find that M_{T2} seems to dominate a little, but since we do not know if this is the cleanest variable to use in practice, which can be determined only after a full detector simulation, we present all combinations. Any two on their own can potentially give a robust signal.

As an example, we consider the combination $\Delta\phi < 2\pi/3$ and $\alpha > 0.45$, which gives a good S/B and a decent event rate. As stated earlier, we do not optimize cuts, but we use this combination that works rather well.

With those cuts in place, Fig. 3 shows signal and background events binned in the sum of the two hardest jets' transverse momenta. We see that Z + jets is the dominant background, followed by W + jets. A total of four QCD events with $p_{1T} + p_{2T} < 500$ GeV passed the cuts, out of a sample corresponding to over 1.5 fb^{-1} of integrated luminosity, divided by the K factor. A higher luminosity sample would be needed to get a better estimate of the QCD background, but it seems safe to say that the W and Z backgrounds are more important.

Cutting above $p_{1T} + p_{2T} = 550$ GeV gives $S/B = 4.9$, with an average of 205 signal events after 1 fb^{-1}. Table II shows the efficiencies with which the SUSY events pass the successive jet multiplicity, $p_{T1} + p_{T2}$, $\Delta\phi$, and α cuts. The final efficiency is lower than that for SUSY searches with additional jets, and so SUSY might well be discovered in other channels first [15]. On the other hand, this analysis picks out particularly simple events, and if these events do occur, it would certainly be worthwhile to study them in isolation.

For example, with enough luminosity, these events alone can be used to obtain a simple constraint on the squark and neutralino masses, using the M_{T2} event function [6] introduced above. If one can ignore all visible particles in the event except those in the two jets, one expects the endpoint $M_{T2}(0)_{max} = (m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{q}}$. For the parameter point

TABLE II. The cut efficiencies ϵ, for SUSY events.

	$N_{jets} = 2$	$p_{T1} + p_{T2} > 550$	$\Delta\phi < 2\pi/3$	$\alpha > 0.45$
ϵ	1.08×10^{-1}	5.04×10^{-2}	2.05×10^{-2}	9.48×10^{-3}
σ_{susy} (fb)	2.33×10^3	1.09×10^3	443.0	205.0

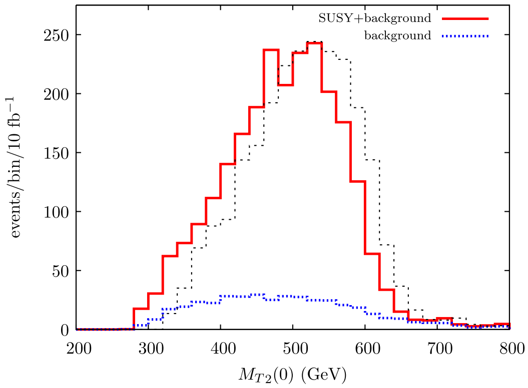

FIG. 4 (color online). The $M_{T2}(0)$ distribution, after the cuts described in the text. Also shown, as the lighter dashed line, is the full $M_{T2}(m_{\tilde{\chi}_1^0})$ distribution.

under study, this turns out to be 619 GeV if we use the mass of $\tilde{q}_R$, the one that decays predominantly to $\tilde{\chi}_1^0 q$. Figure 4 shows the $M_{T2}(0)$ distribution for 10/fb of data, with the cuts of Table II imposed. A sharp dropoff leading up to ~620 GeV is evident, consistent with expectations. The spillover to larger values is mostly due to the effects of extra jets not included in the calculation of the missing transverse energy from the dijet system.

The $(\alpha, \Delta\phi)$ analysis can be effective for higher-mass searches as well, with the cut on $p_{1T} + p_{2T}$ increased appropriately. Table III gives results for other parameter points. A significance $S/\sqrt{B} > 5$ should be possible for squark masses up to about ~1700 GeV after 100 fb^{-1} of integrated luminosity. Discovery for lighter squark masses, ~600 GeV, should be possible after ~ a few $\times 10^2$ pb^{-1} or less. Using $S/\sqrt{B}$ optimistically assumes that the background is fully understood. However, events with leptonic Z decays will provide some experimental handle on the dominant background, Z + jets, and the shapes of the $p_{T1} + p_{T2}$ distributions for signal and background events passing the α and $\Delta\phi$ cuts are quite different (see Fig. 3).

We have studied several kinematic variables that can be used for dijet SUSY searches and found that they give reasonable signal-to-background ratios. Dijet events can be used to constrain SUSY mass parameters should the type of supersymmetry model we have considered be correct. Studies of Z + jet events with leptonic Z decays will give a better understanding of the background and a more reliable extraction of signal from background. For the future, it would be useful to see how well the lessons here can be applied to develop multijet searches that do not rely on full missing energy.

TABLE III. Efficiencies, event rates, and signal-to-background ratios for various SUSY parameters, using the cuts described in the text. All masses are in GeV.

$(M_{1/2}, M_0)$	$(m_{\tilde{g}}, m_{\tilde{q}_R})$	$\sum p_T$ cut	ϵ	$\sigma_{\rm susy}$ (fb)	S/B
(300, 100)	(716, 640)	550	9.5×10^{-3}	205.0	4.9
(450, 100)	(1040, 918)	800	7.9×10^{-3}	21.3	4.7
(600, 150)	(1358, 1195)	1050	8.1×10^{-3}	4.07	5.0
(750, 200)	(1669, 1465)	1250	9.6×10^{-3}	1.17	4.8
(900, 200)	(1965, 1726)	1450	1.0×10^{-2}	0.37	3.5

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