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Search for supersymmetry in events with b jets and missing transverse momentum at the LHC

The CMS Collaboration

Abstract: A search for supersymmetry is presented using a sample of events with b jets and missing transverse momentum. The search uses a data sample of proton-proton collisions at a centre-of-mass energy of 7 TeV, corresponding to an integrated luminosity of 35 pb^{-1}, collected with the CMS detector. A total of $0.33\ ^{+0.43}_{-0.33}$ (stat.) $\pm$ 0.13 (syst.) events is predicted, using control samples in the data, to arise from standard model processes, and one event is observed in the data. Upper limits are set at the 95% confidence level on the cross sections of benchmark supersymmetric models.

Keywords: Hadron-Hadron Scattering

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Contents

1 Introduction

Supersymmetry (SUSY) [1–5] is an extension of the standard model (SM) of particle physics, which can solve the "hierarchy problem" [6, 7] and provide a candidate for cold dark matter [8]. For a large class of supersymmetric parameter sets, squarks ($\tilde{\mathrm{q}}$), the SUSY partners of quarks, are relatively light. In this case, significant event yields at the Large Hadron Collider (LHC) can result from strong production of squarks, which subsequently decay giving a weakly interacting lightest supersymmetric particle (LSP). If bottom and top squarks, which can decay to b quarks, are relatively light, there may be an abundance of events with one or more b-quark jets and momentum imbalance transverse to the beam line due to the undetectable LSPs.

This Letter describes a search for events with two or more hadronic jets, at least one of which must be b tagged [9], and significant transverse momentum imbalance. It extends a similar search without a b-tag requirement [10]. The momentum imbalance is characterized [11] by the ratio of the p_{T} of the second-highest-p_{T} jet and the invariant mass formed from the two highest-p_{T} jets. This ratio can be estimated by $\alpha_{\mathrm{T}} = \frac{1}{2}\frac{H_{\mathrm{T}}-\Delta H_{\mathrm{T}}}{\sqrt{H_{\mathrm{T}}^2-\not{H}_{\mathrm{T}}^2}}$, where $\not{H}_{\mathrm{T}} = |\sum_i \vec{p}_{\mathrm{T}}^{\,\mathrm{jet}_i}|$, $H_{\mathrm{T}} = \sum_i p_{\mathrm{T}}^{\mathrm{jet}_i}$, and $p_{\mathrm{T}}^{\mathrm{jet}_i}$ is the momentum transverse to the beam line for jet i in an event. The jets in an event are grouped into two pseudo-jets and ΔH_{T} is the minimal value of $|p_{\mathrm{T}}^{\mathrm{pseudojet1}} - p_{\mathrm{T}}^{\mathrm{pseudojet2}}|$ over all combinations; this approach optimizes rejection of backgrounds with apparent $\not{H}_{\mathrm{T}}$ from instrumental effects and other sources.

The main backgrounds are due to standard model multijet production (hereafter denoted "QCD background"), electroweak W and Z boson production (EWK), and top quark pair production ($t\bar{t}$). Owing to low average $\not{H}_{\mathrm{T}}$, the QCD background is effectively rejected by a requirement on α_{T}. The b-tag requirement further suppresses the QCD and EWK backgrounds.

The results of the search are characterized in terms of the mSUGRA/CMSSM [12, 13] scenario of SUSY. These models are described by four parameters and one sign: the universal scalar and gaugino mass parameters, m_0 and $m_{1/2}$, respectively; the universal trilinear coupling, A_0; the ratio of the two Higgs doublet vacuum expectation values, $\tan\beta$; and the sign of the Higgs mixing parameter, sign(μ). Three signal points are considered as benchmarks: LM0, LM1, both discussed in ref. [10], and LMB (corresponding to $m_0 = 400\,\mathrm{GeV}$, $m_{1/2} = 200\,\mathrm{GeV}$, $A_0 = 0\,\mathrm{GeV}$, $\tan\beta = 50$, and $\mathrm{sign}(\mu) > 0$), chosen to be near the edge of sensitivity of this search in mSUGRA/CMSSM parameter space.

The choice of $\tan\beta = 50$ for the LMB point is appropriate because of its b-quark enrichment. However, this choice of parameter space is merely a benchmark; light bottom and top squarks are in fact a generic feature of many supersymmetiric models. This analysis extends the sensitivity beyond ref. [10] for such b-quark enriched models because of the reduced backgrounds.

The analysis presented here uses a data sample of proton-proton collisions at 7 TeV, corresponding to an integrated luminosity of 35 pb^{-1}, collected with the Compact Muon Solenoid (CMS) detector, at the LHC. The main components of CMS are a silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass/scintillator hadron calorimeter, all placed in a 3.8 T axial magnetic field, complemented by gas-ionization detectors embedded in the steel return yoke, to measure muons. A detailed description of the detector and its performance can be found in ref. [14]. In the cylindrical coordinate system of CMS, ϕ is the azimuthal angle and the pseudo-rapidity (η) is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the counterclockwise beam direction.

2 Event selection

The event selection requirements are mostly identical to those in ref. [10]. Events in the search sample are collected with triggers based on H_{T} computed from jets reconstructed at trigger level. A muon-enriched control sample is collected with triggers requiring a muon. Events must have a good reconstructed pp collision vertex [15]. Jets are reconstructed as clusters of energy in the calorimeters by the anti-k_{T} algorithm [16] with a distance parameter of 0.5, and are required to have energy transverse to the beam, E_{T}, in excess of 50 GeV and $|\eta|$ less than 3.

To perform a fully hadronic final state search and to reduce the backgrounds, events with an isolated lepton (electron or muon) or photon are vetoed, and events consistent with having apparent $\not{H}_{\mathrm{T}}$ [10] are rejected. Selected events are required to have at least two jets, both with $E_{\mathrm{T}} > 100\,\mathrm{GeV}$, $|\eta| < 2.5$ for the highest-E_{T} jet, $H_{\mathrm{T}} > 350\,\mathrm{GeV}$, at least one jet tagged as originating from a b quark, and $\alpha_{\mathrm{T}} > 0.55$.

Jets are b tagged using a discriminator based on the impact parameter significance of tracks in a jet (Track Counting High Purity discriminator, TCHP [9]), with a "tight" selection (TCHP > 3.41) designed to have a light-flavour contamination of less than 0.1%.

Looser b-tagging selections are used to produce various control samples. An event is said to be anti-tagged if it contains no jets with a loose b tag (TCHP > 1.19). To remain within the acceptance of the pixel tracker, only jets with a central axis of $|\eta| < 2.4$ are considered for b tagging.

3 Background estimation

The backgrounds for this search can be categorized into three main groups: namely QCD, EWK, and $t\bar{t}$. The contamination from $t\bar{t}$ is mainly in the tau decay mode. The vast majority of events from the QCD background do not feature large transverse momentum imbalance and are therefore rejected by the $\alpha_{\mathrm{T}} > 0.55$ requirement. The EWK backgrounds consist of W and Z boson production, with genuine missing energy due to decay neutrinos. The requirement of at least one b jet greatly reduces the EWK and QCD backgrounds. The dominant background for the analysis arises from $t\bar{t}$ production, in which b jets and genuine missing energy due to neutrinos can arise from the top quark decay chains.

A procedure based on control data samples, described in section 3.1, is employed to estimate all backgrounds simultaneously. In this method, the fraction of all events with $\alpha_{\mathrm{T}} > 0.55$, denoted $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55)$, is measured in a lower-H_{T} control region and applied in the signal region.

The $\mathrm{Z} \to \nu\bar{\nu}$ and $t\bar{t}$ background yields are cross-checked separately, as discussed in section 3.2. The $t\bar{t}$ cross-check uses muons to emulate the hadronic decays of taus. The cross-check of $\mathrm{Z} \to \nu\bar{\nu}$ utilizes $\mathrm{Z} \to \mu^+\mu^-$ events for which α_{T} is determined after excluding the muons.

3.1 Background prediction using α_{T} vs H_{T} extrapolation

In SM simulation studies [10], $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55)$ has no H_{T} dependence in events with large genuine missing transverse energy, i.e., the $t\bar{t}$ and EWK backgrounds. In the QCD background, however, $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55)$ is expected to be a decreasing function of H_{T} because of the H_{T} dependence of the factors contributing to apparent $\not{H}_{\mathrm{T}}$, such as jet energy resolution and jet E_{T} threshold effects.

In data control samples, $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55)$ is consistent with having no H_{T} dependence, which indicates that the $t\bar{t}$ and EWK backgrounds dominate. The larger anti-tagged data sample is also consistent with having no H_{T} dependence. Because a tight b-tag requirement further suppresses the QCD background, the tight tagged data sample is expected to have a negligible QCD contribution and therefore $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55)$ independent of H_{T}.

The total background is estimated by measuring $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55) = 1.48\,^{+1.93}_{-1.48} \times 10^{-5}$ in a control region with $250 < H_{\mathrm{T}} < 350\,\mathrm{GeV}$ and multiplying this fraction by the number of events in the signal region before the $\alpha_{\mathrm{T}} > 0.55$ requirement. In data, this procedure yields a prediction of $0.33\,^{+0.43}_{-0.33}$ (stat.) $\pm\,0.13$ (syst.) events. The statistical uncertainty is dominated by the presence of one event with $\alpha_{\mathrm{T}} > 0.55$ in the control sample. The systematic uncertainty on the prediction is given by the difference in $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55)$ measured in the tight and loose tagged control samples. Table 1 lists this background prediction, the observation in data, and the expected contribution of SUSY signal for points LM0, LM1, and LMB.

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N-jets	Background Prediction	Data	LM0	LM1	LMB
≥ 2	$0.33\ ^{+0.43}_{-0.33}$ (stat.) $\pm\, 0.13$ (syst.)	1	14	2	5

Table 1. Predicted and observed numbers of events for 35 pb^{-1}. The prediction comes from the α_{T} vs H_{T} extrapolation described in section 3.1.

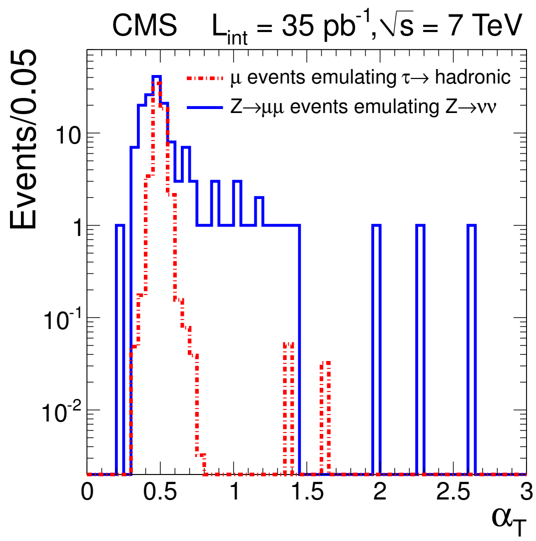

Figure 1. The α_{T} distributions for $\mathrm{Z} \rightarrow \mu^+\mu^-$ emulation of $\mathrm{Z} \rightarrow \nu\bar{\nu}$ (solid blue) and muon emulation of hadronic tau decays (dashed red).

3.2 Cross-checks of $\mathrm{Z} \rightarrow \nu\bar{\nu}$ and $t\bar{t}$ background contributions

While the above background estimate is the one used in this search, we perform auxiliary measurements to cross-check the $\mathrm{Z} \rightarrow \nu\bar{\nu}$ and $t\bar{t}$ background components, which together are expected to comprise the majority of the background. As would be crucial in case of an observed excess, these cross-checks provide an overestimate of the $\mathrm{Z} \rightarrow \nu\bar{\nu}$ and $t\bar{t}$ background components.

For $\mathrm{Z} \rightarrow \nu\bar{\nu}$, a sample of $\mathrm{Z} \rightarrow \mu^+\mu^-$ events is selected with two or more jets but no α_{T}, H_{T}, or b-tagging requirements. The solid blue line in figure 1 shows the α_{T} distribution for the resulting events. The fraction of these events containing a b-tagged jet is measured. Then, a sample is selected with no b-tag requirement, jet $E_{\mathrm{T}} = 75\,\text{GeV}$ thresholds on the two highest-E_{T} jets, $H_{\mathrm{T}} > 275\,\text{GeV}$, and $\alpha_{\mathrm{T}} > 0.52$. The number of events in this sample is scaled by the measured b-tag fraction in the other sample, corrected for the muon identification efficiency and acceptance, and multiplied by the ratio of branching fractions $\frac{\mathrm{BR}(\mathrm{Z} \rightarrow \nu\bar{\nu})}{\mathrm{BR}(\mathrm{Z} \rightarrow \mu^+\mu^-)} \approx 6$. This procedure gives an overestimate of the number of $\mathrm{Z} \rightarrow \nu\bar{\nu}$ events in the signal region owing to less stringent requirements than in the final selection, and yields 0.48 ± 0.39 events.

Simulation studies indicate that most of the $t\bar{t}$ background comes from events with hadronic tau decays. To estimate the hadronic tau decay yield, $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55)$ is first

Requirement	LM0		LM1		LMB	
Pre-selection	98%	98%	98%	98%	98%	98%
Lepton/Photon Veto	57%	56%	55%	54%	61%	60%
Jet Requirements	51%	28%	63%	34%	54%	33%
$H_{\mathrm{T}} > 350\,\mathrm{GeV}$	90%	25%	94%	32%	97%	32%
Trigger	99%	25%	99%	32%	99%	31%
Apparent $\not{H}_{\mathrm{T}}$ Veto	68%	17%	81%	26%	65%	20%
Tight b-tag	31%	5.3%	12%	3.0%	54%	11%
$\alpha_{\mathrm{T}} > 0.55$	14%	0.7%	29%	0.9%	12%	1.3%

Table 2. Cumulative and individual efficiencies for the selection in three SUSY benchmark points. For each point, the left and right columns represent the individual and cumulative efficiencies, respectively. Different benchmarks have different b-tag efficiencies due to different average numbers of b quarks per event. The fraction of events containing at least one b quark before the b-tag selection is 66% in LM0, 18% in LM1, and 91% in LMB.

measured in a sample with $E_{\mathrm{T}} = 80\,\mathrm{GeV}$ thresholds on the two leading jets, $H_{\mathrm{T}} > 280\,\mathrm{GeV}$, at least one medium b-tagged jet (TCHP > 1.91), and one or two muons. These selection requirements are chosen to be less strict than the signal selection in order to increase the number of events in this sample. The muons are used to emulate the hadronic decays of taus. To do so, for each muon the presence of a tau jet is emulated with an E_{T} value set to a fraction of the muon p_{T}, using a distribution taken from simulation. The dashed red line in figure 1 displays the resulting α_{T} distribution. The measured value of $\mathrm{F}(\alpha_{\mathrm{T}} > 0.55)$ in this sample is multiplied by the number of emulated events in the signal region before the α_{T} requirement. This value is corrected for the muon selection efficiency, acceptance and the hadronic tau decay branching ratio to obtain the hadronic tau decay yield. The predicted hadronic tau decay yield is increased by 38%, as determined in simulation, in order to account for the entire $t\bar{t}$ background. The procedure yields a 25% overestimate of the total $t\bar{t}$ background in simulation. In data, 1.4 ± 0.5 events are predicted.

4 Signal selection efficiency

To interpret the results of this search in terms of a given signal model, the selection efficiency for that model must be determined. Table 2 lists the cumulative and individual efficiencies for the event selection in the three SUSY benchmark models LM0, LM1, and LMB, from which events are generated at leading order (LO) via PYTHIA 6.4, tune Z2 [17] using parton distribution functions provided by CTEQ6.6 [18]. Without b tagging, the cumulative efficiencies for LM0 and LM1 are about 85% of those in ref. [10], because of a more stringent lepton and photon veto. Table 3 lists the relative systematic uncertainties on the signal yield, which are dominated by the uncertainty on the b-tagging efficiency, described below. The other uncertainties and the methods used to obtain them are similar to ref. [10].

Source	Uncertainty (%)
Luminosity	4
JES	3.5
Jet Energy Resolution	1
Trigger Efficiency	1
Apparent $\not{H}_{\mathrm{T}}$ Veto	4
Lepton/Photon Veto	4
b-tag Efficiency (LMB)	20
Total	22

Table 3. Relative systematic uncertainties on the signal yield.

The b-tagging efficiency is measured from inclusive dijet events in which one jet has an associated muon and another "away" jet has a TCHP value of at least 1.0. The relative fraction of jets from b quarks in a data sample is determined by a fit to the distribution of transverse momentum of muons relative to their associated jet axis, $p_{\mathrm{T}}^{\mathrm{rel}}$ [9, 19], which is larger for jets from b quarks than from other flavours. This fit is to a linear combination of simulation-derived $p_{\mathrm{T}}^{\mathrm{rel}}$ expected distributions from different flavours. The fitted b fractions for jets passing and failing the analysis b-tagging requirement are used in the b-tagging efficiency calculation. This efficiency is measured separately for jets with $|\eta| > 1.4$ and $|\eta| \leq 1.4$, in four ranges of jet E_{T}. The ratio between the b-tagging efficiency measured in data and in simulation is taken as the efficiency scale factor for a particular range in E_{T} and $|\eta|$.

Systematic uncertainties on the scale factors arise from potential biases in the $p_{\mathrm{T}}^{\mathrm{rel}}$ fitting procedure. These uncertainties are measured by varying the muon-to-jet matching and muon p_{T} thresholds, fraction of gluon splitting to $b\bar{b}$, jet energy scale and resolution, jet angular resolution, and b-tagging requirement on the away jet. The effect of measuring the scale factors using only semi-leptonic b decays is also accounted for. The scale factors are used to correct the expected event yield at each signal point for differences between the efficiencies in data and simulation. For example, for LMB the application of the scale factors translates into a change in the yield by a factor 0.87 ± 0.18. The systematic and statistical uncertainties give a total relative uncertainty of 20% in LMB, with a similar uncertainty of 23% in LM1.

5 Results

The observation of one data event in the signal region is consistent with background expectations. Combining the expected signal and background prediction from section 3.1 and using frequentist statistical methods in the manner of ref. [20] with the Profile Likelihood ratio [21] to handle nuisance parameters, we derive 95% confidence level (CL) cross-section upper limits ($\sigma_{95}^{\mathrm{obs}}$) of 18.9, 15.4, and 10.2 pb for LM0, LM1, and LMB, respectively. The effect of possibly overestimating the background due to signal contamination in the control regions increases the $\sigma_{95}^{\mathrm{obs}}$ value to 22.1 pb for LM0, 16.7 pb for LM1, but is negligible

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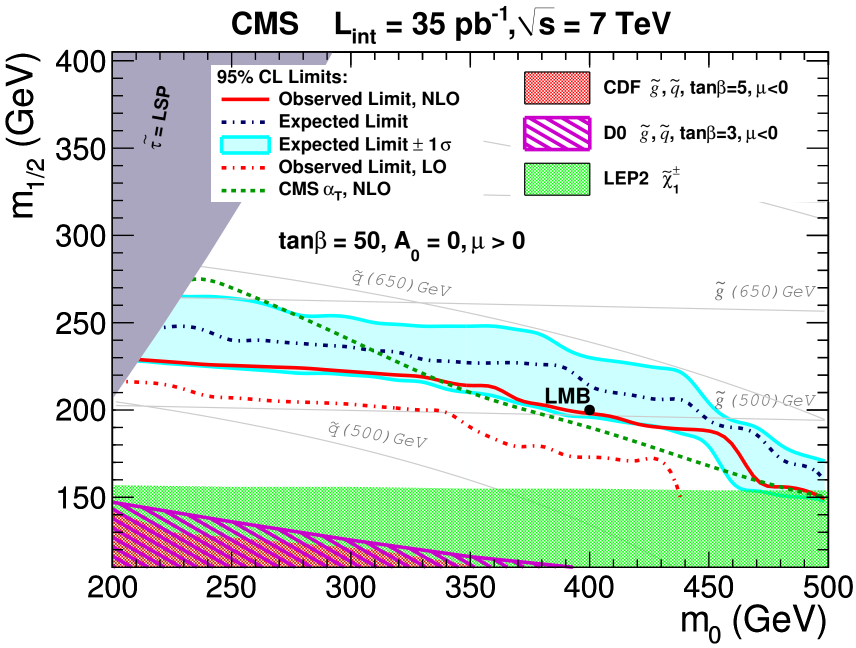

Figure 2. Exclusion regions in the $(m_0,\ m_{1/2})$ plane for one set of CMSSM parameters, for this analysis (solid red), and the non-b tagged version [10] (dashed green).

for LMB. To quantify the sensitivity with reduced dependence on the amount of b-quark production, a 95% CL upper limit on the cross section times branching ratio to at least one b quark of 4.0 pb is determined in LM1.

The resulting excluded region in the $(m_0,\ m_{1/2})$ plane for a reference model with CMSSM parameters $A_0 = 0\,\text{GeV}$, $\tan\beta = 50$, and $\mu > 0$ is shown in figure 2. The expected and observed exclusion regions are calculated using next-to-leading-order (NLO) cross sections, obtained with the program Prospino [22]. The excluded region is extended with respect to that of ref. [10] without b tagging, also shown, for scenarios with increased b production, such as those with m_0 above 350 GeV.

6 Summary

A search for events with multiple jets, at least one of which is b tagged, and significant transverse momentum imbalance has been presented. One event is observed, which is consistent with background expectations. The dominant background comes from $t\bar{t}$ production. The results of the search are characterized as an exclusion region in CMSSM parameter space and 95% CL upper limits on representative scenarios with expected cross section of approximately 15 pb. The sensitivity of this search surpasses that of the Tevatron experiments [23, 24] and is comparable to a recent fully hadronic, b-tagged search from ATLAS [25].

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22: Also at Università degli studi di Siena, Siena, Italy
23: Also at California Institute of Technology, Pasadena, USA
24: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
25: Also at University of California, Los Angeles, Los Angeles, USA
26: Also at University of Florida, Gainesville, USA
27: Also at Université de Genève, Geneva, Switzerland
28: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
29: Also at University of Athens, Athens, Greece
30: Also at The University of Kansas, Lawrence, USA
31: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
32: Also at Paul Scherrer Institut, Villigen, Switzerland
33: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
34: Also at Gaziosmanpasa University, Tokat, Turkey
35: Also at Adiyaman University, Adiyaman, Turkey
36: Also at The University of Iowa, Iowa City, USA
37: Also at Mersin University, Mersin, Turkey
38: Also at Izmir Institute of Technology, Izmir, Turkey
39: Also at Kafkas University, Kars, Turkey
40: Also at Suleyman Demirel University, Isparta, Turkey
41: Also at Ege University, Izmir, Turkey
42: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
43: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
44: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
45: Also at Utah Valley University, Orem, USA
46: Also at Institute for Nuclear Research, Moscow, Russia
47: Also at Los Alamos National Laboratory, Los Alamos, USA
48: Also at Erzincan University, Erzincan, Turkey

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