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Search for Scalar Bottom Quark Pair Production with the ATLAS Detector in pp Collisions at $\sqrt{s} = 7$ TeV

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The results of a search for pair production of the scalar partners of bottom quarks in 2.05 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS experiment are reported. Scalar bottom quarks are searched for in events with large missing transverse momentum and two jets in the final state, where both jets are identified as originating from a bottom quark. In an R-parity conserving minimal supersymmetric scenario, assuming that the scalar bottom quark decays exclusively into a bottom quark and a neutralino, 95% confidence-level upper limits are obtained in the $\tilde{b}_1 - \tilde{\chi}_1^0$ mass plane such that for neutralino masses below 60 GeV scalar bottom masses up to 390 GeV are excluded.

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Supersymmetry (SUSY) [1–9] is a theory that provides an extension of the standard model (SM) and naturally resolves the hierarchy problem by introducing supersymmetric partners of the known bosons and fermions. In the framework of a generic R-parity conserving minimal supersymmetric extension of the SM, the MSSM, SUSY particles are produced in pairs and the lightest supersymmetric particle is stable, providing a possible candidate for dark matter. The scalar partners of right-handed and left-handed quarks (squarks) can mix to form two mass eigenstates. In a large variety of models, the lightest supersymmetric particle is the lightest neutralino ($\tilde{\chi}_1^0$) and the mass of the lightest scalar bottom quark eigenstate (sbottom, $\tilde{b}_1$) can be significantly lower than the other squark masses. Consequently, $\tilde{b}_1$ could be produced with large cross sections at the Large Hadron Collider (LHC). In this Letter, a search for direct sbottom pair production is presented, assuming a SUSY particle mass hierarchy such that the sbottom decays exclusively into a b quark and a $\tilde{\chi}_1^0$ ($\tilde{b}_1 \to b\tilde{\chi}_1^0$). The expected signal is characterized by the presence of two jets originating from the hadronization of the b quarks and missing transverse momentum—its magnitude is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$ in the following—resulting from the undetected neutralinos. Results of searches for direct sbottom production have been previously reported by the Tevatron [10,11] and LEP [12] experiments. The search described here extends these results using 2.05 fb^{-1} of 7 TeV pp collision data recorded by the ATLAS experiment at the LHC.

The ATLAS detector [13] consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with a toroidal magnetic field. The inner detector, in combination with the 2 T field from the solenoid, provides precision tracking of charged particles for $|\eta| < 2.5$ [14]. It consists of a silicon pixel detector, a silicon strip detector, and a straw tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. It is composed of sampling calorimeters with either liquid argon or scintillating tiles as the active media. The muon spectrometer has separate trigger and high-precision tracking chambers which provide muon identification and measurement for $|\eta| < 2.7$.

This search uses data recorded between March and August 2011 at the LHC. After the application of beam, detector, and data quality requirements, the data set corresponds to a total integrated luminosity of 2.05 ± 0.08 fb^{-1} [15,16]. The data are selected with a three-level trigger system that requires a high transverse momentum (p_{T}) jet and missing transverse momentum [17]. Events are required to have a reconstructed primary vertex associated with five or more tracks, consistent with the beam spot position.

Jets are reconstructed offline from three-dimensional topological calorimeter energy clusters by using the anti-k_t jet algorithm [18,19] with a radius parameter of 0.4. The measured jet energy is corrected for inhomogeneities and for the noncompensating nature of the calorimeter by using p_{T}- and η-dependent correction factors ([20] and references therein). Only jet candidates with $p_{\mathrm{T}} > 20$ GeV within $|\eta| < 2.8$ are retained. During the data-taking period, a localized electronics failure in the liquid argon barrel calorimeter created an inactive region in the second and third calorimeter layers ($\Delta\eta \times \Delta\phi \simeq 1.4 \times 0.2$) in which on average 30% of the incident jet energy is not measured. If either of the two selected leading jets fall in this region the event is rejected. The loss in signal acceptance is smaller than 10% for the models considered.

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Electron candidates are required to have $p_T > 20$ GeV, $|\eta| < 2.47$, and satisfy the "medium" selection criteria reported in [21]. Muon candidates are required to have $p_T > 10$ GeV, $|\eta| < 2.4$ and are identified as a match between an extrapolated inner detector track and one or more track segments in the muon spectrometer. Additional requirements are applied to electron and muon candidates when defining lepton ($\ell = e, \mu$) control regions. In this case, electrons must have $p_T > 25$ GeV, pass the "tight" selection criteria in [21] and be isolated—the p_T sum of tracks within a cone in the (η, ϕ) plane of radius $\Delta R = 0.2$ around the candidate, Σp_T, must be less than 10% of the electron p_T. Muons must have $p_T > 25$ GeV, longitudinal and transverse impact parameter within 1 mm and 0.2 mm of the primary vertex, respectively, and $\Sigma p_T < 1.8$ GeV. Following the object reconstruction described above, overlaps between jet candidates and electrons or muons are resolved. Any jet within a distance $\Delta R = 0.2$ of a "medium" electron candidate is discarded. Any remaining lepton within $\Delta R = 0.4$ of a jet is discarded.

The calculation of E_T^{miss} is based on the magnitude of the vectorial sum of the p_T of the reconstructed jets (with $p_T > 20$ and $|\eta| < 4.5$), leptons—including nonisolated muons—and the calorimeter clusters not belonging to reconstructed objects [22].

Events must pass basic quality criteria against detector noise and noncollision backgrounds and are selected with at least one jet with $p_T > 130$ GeV and $E_T^{miss} > 130$ GeV to ensure full trigger efficiency, and one additional jet with $p_T > 50$ GeV. Both jets are required to be associated to the primary interaction and to originate from a b quark using a tagging algorithm that exploits both impact parameter and secondary vertex information. Jets are tagged for $|\eta| < 2.5$ and the parameters of the algorithm are chosen such that a tagging efficiency of 60%, 10%, and <1% is achieved for b jets, c jets, and light flavor or gluon jets, respectively, in $t\bar{t}$ events in Monte Carlo (MC) simulation [23]. Events with identified electron or muon candidates or additional jets with $p_T > 50$ GeV are vetoed to exploit the topology of the addressed signal. The multijet background contribution with large E_T^{miss}, due to the mismeasurement of the jet energies in the calorimeters or to neutrino production in heavy quark decays, is suppressed by requiring the smallest azimuthal separation between the E_T^{miss} direction and any of the two leading jets, $\Delta\phi_{min}$, to be above 0.4. If a third jet with $30 < p_T < 50$ GeV is found in the event, its azimuthal separation with the E_T^{miss} must be above 0.2, where jets with p_T below 30 GeV are not used due to the large expected contribution from multiple interactions. In addition, the ratio of E_T^{miss} to the scalar sum of E_T^{miss} and the transverse momenta of the two leading jets is required to be above 0.25.

A selection based on the boost-corrected contransverse mass [24], m_{CT}, is employed to further discriminate sbottom pair production from SM background processes. For two identical decays of heavy particles into two visible particles v_1 and v_2, and into invisible particles, the contransverse mass [25] is defined as $([E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2)^{1/2}$. The boost-corrected contransverse mass conservatively corrects to account for boosts in the transverse plane due to initial state radiation and hence protects the expected endpoint in the distribution. In the case of sbottom pair production with $\tilde{b}_1 \to b\tilde{\chi}_1^0$, m_{CT} is expected to have an endpoint at $[m(\tilde{b}_1)^2 - m(\tilde{\chi}_1^0)^2]/m(\tilde{b}_1)$. To maximize the sensitivity across the $\tilde{b}_1 - \tilde{\chi}_1^0$ mass plane, three signal regions (SRs) are defined as a function of the m_{CT} threshold, with $m_{CT} > 100$, 150 and 200 GeV.

Simulated event samples are used to aid in the description of the background and to model the SUSY signal. Top quark pair and single top production are simulated with MC@NLO [26], fixing the top quark mass at 172.5 GeV, and the next-to-leading-order (NLO) parton density function (PDF) set CTEQ6.6 [27]. Samples of W + jets, Z + jets with light and heavy flavor jets, and $t\bar{t}$ with additional b jets, $t\bar{t}b\bar{b}$, are generated with ALPGEN [28] and PDF set CTEQ6L1 [29]. The fragmentation and hadronization for the ALPGEN and MC@NLO samples are performed with HERWIG [30], using JIMMY [31] for the underlying event. Samples of $Zt\bar{t}$ and $Wt\bar{t}$ are generated with MADGRAPH [32] interfaced to PYTHIA [33]. Diboson (WW, WZ, ZZ) samples are generated with HERWIG. All background cross sections are normalized to the results of higher order calculations [34]. The signal samples are generated in the MSSM framework at fixed $\tilde{b}_1$ and $\tilde{\chi}_1^0$ masses, with BR$(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 100\%$, using the HERWIG++ [30] v2.4.2 Monte Carlo program. The SUSY sample yields are normalized to the results of NLO calculations, as obtained using the PROSPINO [35] v2.1 program. The CTEQ6.6M [36] parameterization of the PDFs is used and the renormalization and factorization scales, $\mu_{R,F} = \mu$, are set to the sbottom mass. NLO cross sections vary between 12 pb and 0.05 pb for sbottom masses in the range 200–500 GeV. The MC samples are produced using parameters tuned as described in [37,38] and are processed through a detector simulation [39] based on GEANT4 [40]. Effects of multiple proton-proton interactions per bunch crossing are included in the simulation.

The signal efficiencies vary across the $\tilde{b}_1 - \tilde{\chi}_1^0$ mass plane. As an example, for the SR with $m_{CT} > 150$ GeV the efficiencies are found to be between 1% and 6% as the sbottom mass increases from 200 GeV to 500 GeV, and between 6% and 2% as $\Delta m = m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$ decreases. The sensitivity for Δm below 130 GeV is limited by the selection in m_{CT} and the trigger-driven requirements on the leading jet p_T and E_T^{miss}.

The main SM processes contributing to the background are top quark pair and single top production as well as associated production of W/Z bosons with heavy flavor jets—referred to as Z + hfand W + hf, respectively. In particular, the signal region with $m_{CT} > 100$ GeV is dominated by semileptonic $t\bar{t}$ events as a consequence of the $m_{\rm CT}$ endpoint at 135 GeV in top pair production, while the signal regions with $m_{\rm CT} > 150$, 200 GeV are dominated by the irreducible $Z + {\rm hf}$ production with $Z \rightarrow \nu\nu$ decay, followed by $W + {\rm hf}$ production with $W \rightarrow \tau\nu$. Contributions from multijet, diboson, and associated production of $t\bar{t}$ with W, Z or additional b jets are subdominant. Noncollision backgrounds were found to be negligible.

The estimation of the main background processes is carried out by defining data control regions where each background component is dominant. The background estimate in each SR is derived through "transfer factors" equivalent to the ratio of expected event yields in the signal and control regions estimated using the MC simulation. The contributions from top and $W + {\rm hf}$ production are estimated using a transfer factor from a control region where events have exactly one electron or muon, $E_{\rm T}^{\rm miss} > 80$ GeV, and at least two b jets with $p_{\rm T} >$ 130 GeV and 50 GeV. The transverse mass of the $(\ell, E_{\rm T}^{\rm miss})$ system is required to be between 40 GeV and 100 GeV to select events containing $W \rightarrow \ell\nu$. The contribution to this control region from other SM processes accounts for less than 10% of the total and is estimated from simulation. The $Z + {\rm hf}$ contribution is estimated using a transfer factor from a control region where events have two opposite-sign same-flavor leptons $(\ell^+\ell^-)$, at least two b jets with $p_{\rm T} > 80$ GeV and 50 GeV, and invariant mass of the two leptons $m_{\ell\ell}$ between 81 GeV and 101 GeV (Z-mass interval). In addition, the transverse momentum of the $(\ell^+, \ell^-, E_{\rm T}^{\rm miss})$ system is required to be greater than 50 GeV. The contribution from top quark production in this control region accounts for about 50% of the total and is subtracted using a sideband estimate in two 40 GeV mass windows above and below the Z-mass interval.

The subdominant background contribution from dibosons, $Zt\bar{t}$, $Wt\bar{t}$, and $t\bar{t}b\bar{b}$ is estimated using MC simulation and increases from 1% to 10% of the total SM prediction as the selection cut on $m_{\rm CT}$ increases from 100 GeV to 200 GeV. Finally, the residual multijet background is estimated using data. A sample of multijet events with large $E_{\rm T}^{\rm miss}$ is constructed starting from multijet events with low $E_{\rm T}^{\rm miss}$ and smearing the momenta of jets with response functions. This prediction is tuned in a multijet dominated control region where the requirement on $\Delta\phi_{\rm min}$ is inverted [41]. The contribution is found to be less than 5% across the SRs.

The total systematic uncertainty on the background expectations varies from 21% to 44%, increasing with the $m_{\rm CT}$ selection applied, and is dominated by the uncertainty due to finite data statistics in the control regions. The next dominant uncertainty on the SM estimates derives from the residual uncertainties on the theoretical modeling of the top background. It varies between 10% and 15% depending on the SR and is evaluated using additional MC samples: ACERMC [42,43], for the impact of initial and final state radiation, PYTHIA and POWHEG [44] for choice of fragmentation model and generator. The residual uncertainties on the $W + {\rm hf}$ and $Z + {\rm hf}$ theoretical modeling account for less than 5% of the total uncertainty. Finally, the experimental uncertainties on the b-tagging efficiency and jet energy scale and resolution are also considered; across the SRs they vary between 5% and 8% and between 6% and 9%, respectively.

For the SUSY signal processes, uncertainties on renormalization and factorization scales and on the PDF affect the theoretical cross section. PDF uncertainties are estimated using the CTEQ6.6M PDF error eigenvector set and are between 7% and 16% depending on the sbottom mass. The variation of renormalization and factorization scales by a factor of 2 changes the nominal signal cross section, $\sigma_{\rm nom}$, by $\pm 15\%$, independently of $m_{\tilde{b}_1}$. In the following, the cross sections calculated with scale settings $2 \times \mu$ and $\mu/2$ are referred to as $\sigma_{\rm min}$ and $\sigma_{\rm max}$, respectively. The impact of detector-related uncertainties, such as the jet energy scale and b-tagging, on the signal event yields varies between 35% and 45% and is dominated by the uncertainties on the b-tagging efficiency.

Table I reports the observed number of events and the SM predictions before the $m_{\rm CT}$ selection and for each SR. Both transfer factor and MC estimates are given. The data are in good agreement with the SM background expectations within uncertainties in all cases. Figure 1 shows the measured $m_{\rm CT}$ and $E_{\rm T}^{\rm miss}$ distributions before $m_{\rm CT}$ selection compared to the SM predictions. MC estimates are rescaled to match the total integral predicted by the transfer factor estimates for $Z + {\rm hf}$ and the sum of top and $W + {\rm hf}$, respectively. For illustrative purposes, the distributions expected for the MSSM scenario with sbottom and neutralino masses of 300 GeV and 100 GeV, respectively, are added to the SM predictions. The results are translated into 95% confidence-level (C.L.) upper limits on contributions from new physics using the CL_s prescription [45]. The SR with the best expected sensitivity at each point in parameter space is adopted as the nominal result. Figure 2 shows the observed and expected exclusion limits at 95% C.L. in the $\tilde{b}_1 - \tilde{\chi}_1^0$ mass plane, assuming $\mathrm{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) =$ 100%. Systematic uncertainties are treated as nuisance parameters and their correlations are taken into account. For the MSSM scenarios considered, the upper limit at 95% C.L. on the sbottom masses obtained in the most conservative hypothesis, $\sigma_{\rm min}$, is 390 GeV for $m_{\tilde{\chi}_1^0} = 0$. The limit becomes 405 GeV for $\sigma_{\rm nom}$ and 420 GeV for $\sigma_{\rm max}$. Neutralino masses of 120 GeV are excluded for $275 < m_{\tilde{b}_1} < 350$ GeV. The three signal regions are used to set limits on the effective cross section of new physics models, $\sigma_{\rm eff}$, including the effects of experimental acceptance and efficiency. The observed (expected)

TABLE I. Expected and measured number of events for an integrated luminosity of 2.05 fb^{-1}. Z + hf and the sum of top and W + hf are estimated using a transfer factor estimate (TF). The column labeled as "Others" reports multijet background predictions as estimated with a jet smearing (JS) method, and subdominant SM backgrounds estimated from MC simulations. For comparison the numbers obtained using MC samples are shown in parenthesis. The total systematic uncertainties are also reported.

m_{CT}	Top, W + hf TF (MC)	Z + hf TF (MC)	Others MC + JS	Total SM	Data
0	67 ± 10	23 ± 8	3.6 ± 1.5	94 ± 16	96
	(60 ± 25)	(16 ± 9)		(80 ± 35)	
100	36 ± 10	23 ± 9	3.1 ± 1.6	62 ± 13	56
	(34 ± 16)	(12 ± 7)		(49 ± 25)	
150	12 ± 5	12 ± 6	2.7 ± 0.9	27 ± 8	28
	(13 ± 8)	(8.3 ± 4.7)		(24 ± 13)	
200	3.2 ± 1.6	3.9 ± 3.2	1.0 ± 0.9	8.1 ± 3.5	10
	(4.1 ± 3.4)	(2.8 ± 1.5)		(8.0 ± 4.9)	

excluded values of σ_{eff} at 95% C.L. are 13.4 fb, 9.6 fb, and 5.6 fb (15.2 fb, 9.2 fb, and 4.7 fb), respectively, for $m_{CT} > 100$, 150, and 200 GeV.

In summary, we report results of a search for sbottom pair production in pp collisions at $\sqrt{s} = 7$ TeV, based on 2.05 fb^{-1} of ATLAS data. The events are selected with large E_T^{miss} and two jets consistent with originating from b quarks in the final state. The results are in agreement with SM predictions for backgrounds and translate into 95% C.L. upper limits on sbottom and neutralino masses in a given MSSM scenario for which the exclusive decay $\tilde{b}_1 \to b\tilde{\chi}_1^0$ is assumed. For neutralino masses below 60 GeV, sbottom masses up to 390 GeV are excluded, significantly extending previous results.

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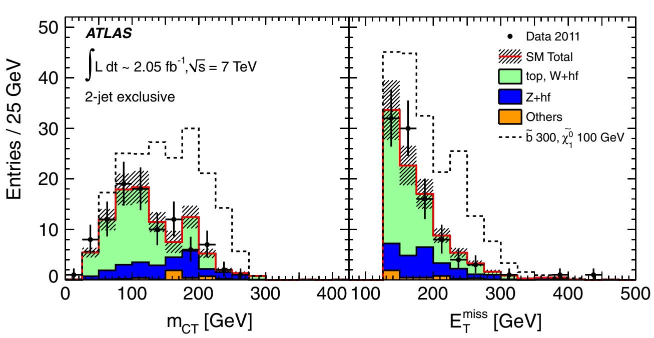

FIG. 1 (color online). Measured m_{CT} (left) and E_T^{miss} (right) distributions before the m_{CT} selection compared to the SM predictions (solid line) and SM+MSSM predictions (dashed lines). The dashed grey band represents the total systematic uncertainties.

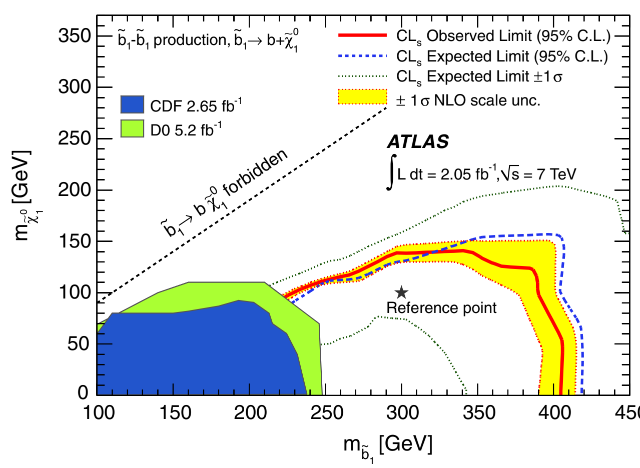

FIG. 2 (color online). Expected and observed exclusion limits, as well as $\pm 1\sigma$ variation on the expected limit, in the $\tilde{b}_1 - \tilde{\chi}_1^0$ mass plane. The band around the observed limit delimited by the two dashed lines shows the effect of renormalization and factorization scale variation. The reference point indicated on the plane corresponds to the MSSM scenario with sbottom and neutralino masses of 300 GeV and 100 GeV, respectively. Results are compared to previous exclusion limits from Tevatron experiments. Results from LEP cover the region with sbottom mass below 100 GeV.

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