Search for strong production of supersymmetric particles in final states with missing transverse momentum and at least three b-jets at $\sqrt{s} = 8$ TeV proton-proton collisions with the ATLAS detector


Published in: The Journal of High Energy Physics

DOI: 10.1007/JHEP05(2011)024
Search for strong production of supersymmetric particles in final states with missing transverse momentum and at least three \( b \)-jets at \( \sqrt{s} = 8 \) TeV proton-proton collisions with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: This paper reports the results of a search for strong production of supersymmetric particles in 20.1 fb\(^{-1}\) of proton-proton collisions at a centre-of-mass energy of 8 TeV using the ATLAS detector at the LHC. The search is performed separately in events with either zero or at least one high-\(p_T\) lepton (electron or muon), large missing transverse momentum, high jet multiplicity and at least three jets identified as originated from the fragmentation of a \( b \)-quark. No excess is observed with respect to the Standard Model predictions. The results are interpreted in the context of several supersymmetric models involving gluinos and scalar top and bottom quarks, as well as a mSUGRA/CMSSM model. Gluino masses up to 1340 GeV are excluded, depending on the model, significantly extending the previous ATLAS limits.

Keywords: Hadron-Hadron Scattering

ArXiv ePrint: 1407.0600
1 Introduction

Supersymmetry (SUSY) [1–9] provides an extension of the Standard Model (SM) which can solve the hierarchy problem by introducing supersymmetric partners for the SM bosons and fermions [10–15]. In the framework of the R-parity-conserving minimal supersymmetric extension of the SM (MSSM) [10, 16–19], SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. In a large fraction of the MSSM R-parity conserving models, the LSP is the lightest neutralino $(\tilde{\chi}_1^0)$\(^1\) which is weakly interacting, thus providing a possible candidate for dark matter. The coloured superpartners of quarks and gluons, the squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), if not too heavy, would be produced in strong interaction processes at the Large Hadron Collider (LHC) and decay via cascades ending

\(^1\)The SUSY partners of the electroweak gauge and Higgs bosons are called gauginos and higgsinos, respectively. The charged gauginos and higgsinos mix to form charginos $(\tilde{\chi}_1^\pm, i = 1, 2)$, and the neutral ones mix to form neutralinos $(\tilde{\chi}_j^0, j = 1, 2, 3, 4)$. 

---

1 The ATLAS collaboration

36
with the LSP. The undetected LSP results in missing transverse momentum — whose magnitude is referred to as $E_{\text{T}}^{\text{miss}}$ — while the rest of the cascade yields final states with multiple jets and possibly leptons. The scalar partners of the right-handed and left-handed quarks, $\tilde{q}_R$ and $\tilde{q}_L$, mix to form two mass eigenstates $\tilde{q}_1$ and $\tilde{q}_2$. A substantial mixing is expected between $\tilde{t}_R$ and $\tilde{t}_L$ because of the large Yukawa coupling of the top quark, leading to a large mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$.

SUSY can solve the hierarchy problem by preventing “unnatural” fine-tuning in the Higgs sector provided that the superpartners of the top quark have masses not too far above the weak scale $[20, 21]$. This condition requires that the gluino is not too heavy in order to limit its contribution to the radiative corrections to the stop masses. Besides, the mass of the left-handed sbottom ($\tilde{b}_L$) is tied to the stop mass because of the SM weak isospin symmetry. As a consequence, the lightest sbottom ($\tilde{b}_1$) and stop ($\tilde{t}_1$) could be produced via strong production with relatively large cross-sections at the LHC, mainly via direct pair production or through $\tilde{g}\tilde{g}$ production followed by $\tilde{g} \to \tilde{b}_1 b$ or $\tilde{g} \to \tilde{t}_1 t$ decays.

This paper presents new results of a search for supersymmetry in final states with large $E_{\text{T}}^{\text{miss}}$ and at least three jets identified as originated from the fragmentation of a $b$-quark ($b$-jets). The previous version of this analysis, using only events with no electrons or muons (0-lepton) in the final state, was performed with the full data set recorded by the ATLAS detector in 2011 at a centre-of-mass energy of 7 TeV $[22]$. The present analysis uses the dataset of 20.1 fb$^{-1}$ collected during 2012 at a centre-of-mass energy of 8 TeV, and extends the previous search by considering events with at least one high-$p_T$ electron or muon (1-lepton) in the final state.

The results are interpreted in the context of various SUSY models where top or bottom quarks are produced in gluino decay chains. Additional interpretations are provided for a direct sbottom pair production scenario where the sbottom decays into a bottom quark and the next-to-lightest neutralino, $\tilde{\chi}^0_2$, followed by the $\tilde{\chi}^0_2$ decay into a Higgs boson and the LSP, and for a mSUGRA/CMSSM model designed to accommodate a Higgs boson with a mass of about 125 GeV. Exclusion limits in similar SUSY models have been placed by other analyses carried out by the ATLAS $[23, 24]$ and CMS $[25–28]$ collaborations with the same integrated luminosity at a centre-of-mass energy of 8 TeV.

2 SUSY signals

In order to confront the experimental measurements with theoretical expectations, several classes of simplified models with $b$-quarks in the final state are considered. Results from the 0-lepton channel are used to explore all models considered, while the complementarity between the searches in the 0- and 1-lepton channels is used to maximise the sensitivity to models predicting top quarks in the decay chain.

In the first class of simplified models, the lightest stops and sbottoms are lighter than the gluino, such that $\tilde{b}_1$ and $\tilde{t}_1$ are produced either in pairs, or via gluino pair production followed by $\tilde{g} \to \tilde{b}_1 b$ or $\tilde{g} \to \tilde{t}_1 t$ decays. The mass of the $\tilde{\chi}^\pm_1$ is set at 60 GeV consistently for all models. The following models, also shown in figure 1, are considered:
Figure 1. This figure shows the diagrams for the (a) direct-sbottom, (b) gluino-sbottom and (c) gluino-stop scenarios studied in this paper. The different decay modes are discussed in the text.

- **Direct-sbottom model**: in this model, the $\tilde{b}_1$ is produced in pairs and is assumed to decay exclusively via $\tilde{b}_1 \rightarrow b + \tilde{\chi}^0_2$. The slepton masses are set above a few TeV and only the configuration $m_{\tilde{\chi}^0_2} > m_{\tilde{\chi}^0_1} + m_h$ with a branching ratio for $\tilde{\chi}^0_2 \rightarrow h + \tilde{\chi}^0_1$ of 100% is considered. The mass of the lightest neutral Higgs boson $h$ is set to 125 GeV, and its decay branching ratios are assumed to be those of the SM Higgs boson. The analysis is mainly sensitive to signal events where both Higgs bosons decay into a $b\bar{b}$ pair, yielding six $b$-quarks, two neutralinos and no leptons at the end of the decay chain.

- **Gluino-sbottom model**: in this model, the $\tilde{b}_1$ is the lightest squark, all other squarks are heavier than the gluino, and $m_{\tilde{g}} > m_{\tilde{b}_1} + m_h$ such that the branching ratio for $\tilde{g} \rightarrow \tilde{b}_1 b$ decays is 100%. Sbottoms are produced in pairs or via gluino pair production and are assumed to decay exclusively via $\tilde{b}_1 \rightarrow b\tilde{\chi}^0_1$. The analysis is sensitive to the gluino-mediated production, which has four bottom quarks, two neutralinos and no leptons at the end of the decay chain.

- **Gluino-stop models**: in these models, the $\tilde{t}_1$ is the lightest squark, all other squarks are heavier than the gluino, and $m_{\tilde{g}} > m_{\tilde{t}_1} + m_t$ such that the branching ratio for $\tilde{g} \rightarrow \tilde{t}_1 t$ decays is 100%. Stops are produced in pairs or via gluino pair production and are assumed to decay exclusively via $\tilde{t}_1 \rightarrow b\tilde{\chi}^\pm_1$ (model I), or via $\tilde{t}_1 \rightarrow t\tilde{\chi}^0_1$ (model II).
II). For the first model, the chargino mass is assumed to be twice the mass of the neutralino, such that the chargino decays into a neutralino and a virtual $W$ boson. The analysis is sensitive to the gluino-mediated production with two top quarks, two bottom quarks, two virtual $W$ bosons and two neutralinos (model I), or four top quarks and two neutralinos (model II) at the end of the SUSY decay chain, yielding signatures with or without leptons.

In the second class of simplified models, all sparticles, apart from the gluino and the neutralino, have masses well above the TeV scale such that the $\tilde{t}_1$ and the $\tilde{b}_1$ are only produced off-shell via prompt decay of the gluinos. Thus, the sbottom and stop masses have little impact on the kinematics of the final state. The following models, also shown in figure 2, are considered:

- **Gluino-sbottom off-shell (Gbb) model:** in this model, the $\tilde{b}_1$ is the lightest squark, but with $m_{\tilde{b}} < m_{\tilde{t}_1}$. A three-body decay $\tilde{g} \rightarrow \tilde{b}\bar{b}\tilde{\chi}^0_1$ via an off-shell sbottom is assumed for the gluino with a branching ratio of 100%. As for the gluino-sbottom model, four bottom quarks, two neutralinos and no leptons are expected at the end of the decay chain. Therefore, only the 0-lepton analysis is used for the interpretation.
• **Gluino-stop off-shell (Gtt) model**: in this model, the \( \tilde{t}_1 \) is the lightest squark, but \( m_{\tilde{g}} < m_{\tilde{t}_1} \). A three-body decay \( \tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0_1 \) via an off-shell stop is assumed for the gluino with a branching ratio of 100%. Four top quarks and two neutralinos are expected as decay products of the two gluinos, resulting in signatures with or without leptons.

• **Gluino-stop/sbottom off-shell (Gtb) model**: in this model, the \( \tilde{b}_1 \) and \( \tilde{t}_1 \) are the lightest squarks, with \( m_{\tilde{g}} < m_{\tilde{b}_1}, \tilde{t}_1 \). Pair production of gluinos is the only process taken into account, with gluinos decaying via virtual stops or sbottoms, with a branching ratio of 100% assumed for both \( \tilde{t}_1 \rightarrow b + \tilde{\chi}^\pm_1 \) and \( \tilde{b}_1 \rightarrow t + \tilde{\chi}^\pm_1 \). The mass difference between charginos and neutralinos is set to 2 GeV, such that the fermions produced in \( \tilde{\chi}^\pm_1 \rightarrow \tilde{\chi}^0_1 + ff' \) do not contribute to the event selection, and gluino decays result in effectively three-body decays (\( bt\tilde{\chi}^0_1 \)). Two top quarks, two bottom quarks and two neutralinos are expected as decay products of the two gluinos, yielding signatures with or without leptons.

The results are also interpreted in the context of a minimal supergravity model mSUGRA/CMSSM \cite{29–34} specified by five parameters: the universal scalar mass \( m_0 \), the universal gaugino mass \( m_{1/2} \), the universal trilinear scalar coupling \( A_0 \), the ratio of the vacuum expectation values of the two Higgs fields \( \tan \beta \), and the sign of the higgsino mass parameter \( \mu \). The model used for interpretation has \( A_0 = -2m_0 \), \( \tan \beta = 30 \), \( \mu > 0 \) and is designed to accommodate a SM Higgs boson with a mass of around 125 GeV, in the \( m_0 - m_{1/2} \) range relevant for this analysis.

3 The ATLAS detector and data sample

The ATLAS detector \cite{35} is a multi-purpose particle physics detector with forward-backward symmetric cylindrical geometry. It consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters and a muon spectrometer with a magnetic field produced by three large superconducting toroids each with eight coils. The inner detector, in combination with the 2 T field from the solenoid, provides precision tracking of charged particles for \( |\eta| < 2.5 \). It consists of a silicon pixel detector, a silicon microstrip detector and a straw-tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range \( |\eta| < 4.9 \). A high-granularity liquid-argon (LAr) sampling calorimeter with lead absorber is used to measure the energy of electromagnetic (EM) showers within \( |\eta| < 3.2 \). Hadronic showers are measured by an iron/scintillator tile calorimeter in the central region \((|\eta| < 1.7)\) and by a LAr calorimeter in the end-cap \((1.5 < |\eta| < 3.2)\). The forward region \((3.1 < |\eta| < 4.9)\) is instrumented with a LAr calorimeter for both EM and hadronic showers.

\[ \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \]
measurements. The muon spectrometer has separate trigger and high-precision tracking chambers, which provide muon identification and momentum measurement for $|\eta| < 2.7$.

The data sample used in this analysis was recorded during the period from March 2012 to December 2012 with the LHC operating at a $pp$ centre-of-mass energy of 8 TeV. After the application of the data-quality requirements, the total integrated luminosity amounts to $20.1 \, \text{fb}^{-1}$, with an associated uncertainty of $\pm 2.8\%$ measured using techniques similar to those detailed in ref. [36], resulting from a preliminary calibration of the luminosity scale using beam-separation scans performed in November 2012. Events for the analysis are selected using a trigger based on a missing transverse momentum selection, which is found to be $> 99\%$ efficient after the offline requirements $E_{\text{T}}^{\text{miss}} > 150$ GeV and at least one reconstructed jet of transverse momentum $p_{\text{T}} > 90$ GeV and $|\eta| < 2.8$.

4 Simulated event samples

Samples of simulated Monte Carlo (MC) events are used to assess the sensitivity to specific SUSY models and aid in the prediction of the SM backgrounds. Jets are labelled as true $b$-jets in MC simulations if they satisfy the kinematic requirements applied to $b$-jets detailed in section 5 and if they are matched to a generator-level $b$-quark with $p_{\text{T}} > 5$ GeV within $\Delta R = 0.3$. The various background processes are then classified into two categories: those leading to final states with at least three true $b$-jets form the irreducible component while all other processes form the reducible component, the latter being the dominant source of background. Irreducible backgrounds arise mainly from $t\bar{t} + b$ and $t\bar{t} + b\bar{b}$ production, and to a minor extent from $t\bar{t} + Z/h$ followed by $Z/h \rightarrow b\bar{b}$. Their contributions are estimated from MC simulations that are generated inclusively, each event being classified at a later stage based on the number of true $b$-jets found. Contributions from background events in which at least one jet is misidentified as a $b$-jet arise mainly from $t\bar{t}$ production in association with light-parton- and $c$-jets. Sub-dominant contributions arise from $t\bar{t}$ production in association with $W/Z/h+\text{jets}$ (except events with $Z/h \rightarrow b\bar{b}$), single top quark production, $W/Z+\text{jets}$ production, and diboson ($WW$, $WZ$, $ZZ$) production. The contributions from all these reducible background processes are estimated simultaneously using a data-driven method described in section 7.1, and MC samples are only used for comparison. Details of the MC simulation samples used in this analysis, as well as the order of cross-section calculations in perturbative QCD (pQCD) used for yield normalisation, are shown in table 1. The background prediction calculated as the sum of the event yield predicted by the MC simulation for each SM process is referred as the MC-only prediction in the following.

The SUSY signal samples used in this analysis were generated with Herwig++ 2.5.2 [66]. For the Gbb model, in order to ensure an accurate treatment of the initial-state radiation (ISR), MadGraph-5.1.5.4 interfaced to PYTHIA-6.426 is used. All the signal samples were generated with the parton distribution function (PDF) set CTEQ6L1. They are normalised to the signal cross-sections calculated to next-to-leading order in the strong coupling constant, adding the re-summation of soft gluon emission at next-to-leading-logarithmic approximation (NLO+NLL) [67–71]. 


The nominal cross-section and the uncertainty $\sigma_{\text{SUSY}}^{\text{SUSY}}$ are taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalisation scales, as prescribed in ref. [72]. An additional source of systematic uncertainty is taken into account for the Gbb model, where the modelling of the ISR can significantly affect the signal acceptance in the region of the parameter space with small mass splitting $\Delta m$ between the $\tilde{t}$ and the $\tilde{\chi}_1^0$. The uncertainty on the signal acceptance is estimated by varying the value of $\alpha_s$, the renormalisation and factorisation scales, as well as the matching parameters in the MadGraph+PYTHIA-6 MC samples. This uncertainty amounts to 30% for the lowest mass splitting and decreases exponentially with increasing $\Delta m$. It is negligible in the region with $\Delta m > 200$ GeV, where the predictions from MadGraph+PYTHIA-6 and Herwig++ are consistent within statistical uncertainties. This systematic uncertainty is negligible for all other signal models considered in this paper.

All the MC samples are processed either through a full simulation of the ATLAS detector [73] based on GEANT4 [74] or a fast simulation [75] that uses a parameterisation of the performance of the ATLAS electromagnetic and hadronic calorimeters and GEANT4 elsewhere. Potential differences between the full and fast simulations were found negligible for this analysis. The effect of multiple $pp$ interactions in the same or neighbouring bunch crossings (pile-up) is incorporated into the simulation by overlaying additional minimum-
bias events generated with PYTHIA-8 onto the hard-scattering process. Simulated events are then weighted to match the observed distribution of the number of pp interactions, and are reconstructed in exactly the same way as the data otherwise.

5 Object reconstruction and identification

Jets are reconstructed from three-dimensional calorimeter energy clusters with the anti-\( k_t \) jet algorithm [76] with a radius parameter \( R = 0.4 \). The measured jet energy is corrected for inhomogeneities and for the non-compensating response of the calorimeter by differently weighting energy deposits arising from electromagnetic and hadronic showers with correction factors derived from MC simulations and in situ measurement in data [77]. Jets are corrected for pile-up using a method proposed in ref. [78]. Finally, additional corrections are applied to calibrate the jet energy to the energy of the corresponding jet of stable particles. Only jets with \( |\eta| < 4.5 \) and \( p_T > 20 \) GeV after calibration are retained.

To remove events with jets from detector noise and non-collision backgrounds, events are rejected if they include jets failing to satisfy the loose quality criteria described in ref. [77]. Additional cleaning cuts based on the fraction of the transverse momentum of the jet carried by reconstructed charged particle tracks and the fraction of the jet energy in the EM calorimeter are applied to reject events containing spurious jet signals. Except for the \( E_T^{\text{miss}} \) computation, only jets with \( |\eta| < 2.8 \) are further considered.

A neural-network-based algorithm [79] is used to identify jets originated from the fragmentation of a \( b \)-quark. It uses as inputs the output weights of different algorithms exploiting the impact parameter of the inner detector tracks, the secondary vertex reconstruction and the topology of \( b \)- and \( c \)-hadron decays inside the jet. The algorithm used has an efficiency of 70% for tagging \( b \)-jets in a MC sample of \( t \bar{t} \) events with rejection factors of 137, 5 and 13 against light-quarks, \( c \)-quarks and \( \tau \) leptons respectively. The \( b \)-jets are identified within the acceptance of the inner detector (\( |\eta| < 2.5 \)). To compensate for the small differences between the \( b \)-tagging efficiencies and the misidentification (mistag) rates in data and MC simulations, correction factors are applied to each jet in the simulations, as described in refs. [79–82]. These corrections are of the order of a few per cent.

Electrons are reconstructed from energy clusters in the electromagnetic calorimeter associated with tracks in the inner detector. Electron candidates are required to have \( p_T > 20 \) GeV and \( |\eta| < 2.47 \), and must satisfy the medium shower shape and track selection criteria based upon those described in ref. [83], adapted for 2012 data conditions. Muon candidates are identified using a match between an extrapolated inner detector track and one or more track segments in the muon spectrometer [84], and are required to have \( p_T > 10 \) GeV and \( |\eta| < 2.5 \). In order to reduce the contributions from semileptonic decays of hadrons, lepton candidates found within \( \Delta R = 0.4 \) of a jet are discarded. Events containing one or more muon candidates that have a transverse (longitudinal) impact parameter \( d_0 \) (\( z_0 \)) with respect to the primary vertex larger than 0.2 (1) mm are rejected to suppress cosmic rays. Signal electrons (muons) are required to be isolated, i.e. the sum of the extra transverse energy deposits in the calorimeter, corrected for pile-up effects, within a cone of \( \Delta R = 0.3 \) around the lepton candidate must be less than 18% (23%) of the lepton \( p_T \),
and the scalar sum of the transverse momenta of tracks within a cone of $\Delta R = 0.3$ around the lepton candidate must be less than 16% (12%) of the lepton $p_T$. Energy deposits and tracks of the leptons themselves are not included. In addition, to further suppress leptons originating from secondary vertices, signal electrons (muons) must have $|z_0 \sin \theta| < 0.4$ mm and $d_0/\sigma_{d_0} < 5(3)$. Signal electrons must also satisfy tighter quality requirements based upon the criteria denoted by $tight$ in ref. [83]. Correction factors are applied to MC events to match the lepton identification and reconstruction efficiencies observed in data.

The measurement of the missing transverse momentum vector (and its magnitude $E_T^{\text{miss}}$) is based on the transverse momenta of all jets, electron and muon candidates, and all calorimeter clusters not associated with such objects. Clusters associated with either electrons or photons with $p_T > 10$ GeV, and those associated with jets with $p_T > 20$ GeV, make use of the calibrations of these respective objects. Clusters not associated with these objects are calibrated using both calorimeter and tracker information [85].

6 Event selection

Following the trigger and object selection requirements described in sections 3 and 5, events are discarded if they fail to satisfy basic quality criteria designed to reject detector noise and non-collision backgrounds. Candidate events are required to have a reconstructed primary vertex associated with five or more tracks with $p_T > 0.4$ GeV [86]; when more than one such vertex is found, the vertex with the largest summed $p_T^2$ of the associated tracks is chosen as the primary vertex. Events must have $E_T^{\text{miss}} > 150$ GeV and at least four jets with $p_T > 30$ GeV. The leading jet is required to have $p_T > 90$ GeV and at least three of the jets with $p_T > 30$ GeV must be $b$-tagged. The events selected at this stage are then divided into two complementary channels based on the number of leptons: i) 0-lepton channel, formed by events with no reconstructed electron or muon candidates; and ii) 1-lepton channel, formed by events with at least one signal lepton with $p_T > 25$ GeV. After this basic selection, events are classified into several signal regions (SR), designed to provide sensitivity to the different kinematic topologies associated with the various SUSY models under study. Each SR is defined by a set of selection criteria using additional event-level variables calculated from the reconstructed objects.

For the 0-lepton channel, four additional variables are used:

- The inclusive effective mass $m^{\text{incl}}_\text{eff}$, defined as the scalar sum of the $E_T^{\text{miss}}$ and the $p_T$ of all jets with $p_T > 30$ GeV. It is correlated with the overall mass scale of the hard-scatter interaction and provides good discrimination against SM background.

- The exclusive effective mass $m^{4j}_\text{eff}$, defined as the scalar sum of the $E_T^{\text{miss}}$ and the $p_T$ of the four leading jets. It is used to suppress the multi-jet background and to define the SRs targeting SUSY signals where exactly four $b$-jets and large $E_T^{\text{miss}}$ are expected in the final state.

- $\Delta \phi^{4j}_{\text{min}}$, defined as the minimum azimuthal separation between any of the four leading jets and the missing transverse momentum direction. To remove multi-jet events
where $E_{\text{T}}^{\text{miss}}$ results from poorly reconstructed jets or from neutrinos emitted close to the direction of the jet axis, events are required to have $\Delta \phi_{\text{min}}^{4j} > 0.5$ and $E_{\text{T}}^{\text{miss}}/m_\text{eff}^{4j} > 0.2$. The combination of these two requirements reduces the contribution of the multi-jet background to a negligible amount.

- The missing transverse momentum significance, defined as $E_{\text{T}}^{\text{miss}}/\sqrt{H_T^{4j}}$, where $H_T^{4j}$ is the scalar sum of the transverse momenta of the four leading jets, is used to define the SRs aiming at SUSY signals with four jets in the final state.

For the 1-lepton channel, event selections are defined using the following variables:

- $n_{\text{incl}}^{\text{eff}}$, defined as for the 0-lepton channel with the addition of the $p_T$ of all signal leptons with $p_T > 20$ GeV.

- The transverse mass $m_T$ computed from the leading lepton and the missing transverse momentum as $m_T = \sqrt{2p_L^T E_{\text{T}}^{\text{miss}} (1 - \cos \Delta \phi (\ell, E_{\text{T}}^{\text{miss}}))}$. It is used to reject the main background from $t\bar{t}$ events where one of the $W$ bosons decays leptonically. After the $m_T$ requirement, the dominant contribution to the $t\bar{t}$ background in the 1-lepton channel arises from dileptonic $t\bar{t}$ events.

The baseline event selections for each channel and the nine resulting SRs are summarised in table 2. Three sets of SRs, two for the 0-lepton channel and one for the 1-lepton channel, each denoted by ‘0$\ell$’ or ‘1$\ell$’, respectively, are defined to enhance the sensitivity to the various models considered. They are characterised by having relatively hard $E_{\text{T}}^{\text{miss}}$ requirements and at least four (SR-0$\ell$-4j), six (SR-1$\ell$-6j) or seven (SR-0$\ell$-7j) jets, amongst which at least three are $b$-jets. Signal regions with zero leptons and at least four jets target SUSY models with sbottoms in the decay chain, while the 1-lepton and the 0-lepton-7-jets SRs aim to probe SUSY models predicting top quarks in the decay chain. All SRs are further classified as A/B/C depending on the thresholds applied to the various kinematic variables previously defined, designed to target different mass hierarchies in the various scenarios considered. In particular, a dedicated SR aiming to increase the sensitivity at low mass splitting between the gluino and the $\tilde{\chi}_1^0$ in the Gbb model is defined. This SR (denoted by SR-0$\ell$-4j-C* in table 2) exploits the recoil against an ISR jet by requiring the leading jet to fail the $b$-tagging requirements.

7 Background estimation

The main source of reducible background is the production of $t\bar{t}$ events where a $c$-jet or a hadronically decaying $\tau$ lepton is mistagged as a $b$-jet, the contribution from $t\bar{t}$ events with a light-quark or gluon jet mistagged as a $b$-jet being relatively small. In the 0-lepton channel, most of these $t\bar{t}$ events have a $W$ boson decaying leptonically where the lepton is not reconstructed, is outside the acceptance, is misidentified as a jet, or is a $\tau$ lepton which decays hadronically. In the 1-lepton channel, the high $m_T$ requirement used to define the SRs enhances the contribution from dileptonic $t\bar{t}$ events, where one of the two leptons is
Baseline 0-lepton selection: lepton veto, \( p_{T}^{l_{1}} > 90 \) GeV, \( E_{T}^{\text{miss}} > 150 \) GeV,
\( \geq 4 \) jets with \( p_{T} > 30 \) GeV, \( \Delta \phi_{\text{min}}^{ij} > 0.5, E_{T}^{\text{miss}}/m_{\text{eff}}^{ij} > 0.2, \geq 3 \) b-jets with \( p_{T} > 30 \) GeV

\[
\begin{array}{|c|c|c|c|c|}
\hline
& N \text{ jets} (p_{T} \,[\text{GeV}]) & E_{T}^{\text{miss}} \,[\text{GeV}] & m_{\text{eff}} \,[\text{GeV}] & E_{T}^{\text{miss}}/\sqrt{H_{T}^{4j}} \,[\text{GeV}] \\
\hline
\text{SR-0f-4j-A} & \geq 4 \,(50) & > 250 & m_{\text{eff}}^{ij} > 1300 & - \\
\text{SR-0f-4j-B} & \geq 4 \,(50) & > 350 & m_{\text{eff}}^{ij} > 1100 & - \\
\text{SR-0f-4j-C^{*}} & \geq 4 \,(30) & > 400 & m_{\text{eff}}^{ij} > 1000 & > 16 \\
\hline
\text{SR-0f-7j-A} & \geq 7 \,(30) & > 200 & m_{\text{incl}}^{\text{eff}} > 1000 & - \\
\text{SR-0f-7j-B} & \geq 7 \,(30) & > 350 & m_{\text{incl}}^{\text{eff}} > 1000 & - \\
\text{SR-0f-7j-C} & \geq 7 \,(30) & > 250 & m_{\text{incl}}^{\text{eff}} > 1500 & - \\
\hline
\end{array}
\]

Baseline 1-lepton selection: \( \geq 1 \) signal lepton (e,\( \mu \)), \( p_{T}^{l_{1}} > 90 \) GeV, \( E_{T}^{\text{miss}} > 150 \) GeV,
\( \geq 4 \) jets with \( p_{T} > 30 \) GeV, \( \geq 3 \) b-jets with \( p_{T} > 30 \) GeV

\[
\begin{array}{|c|c|c|c|c|}
\hline
& N \text{ jets} (p_{T} \,[\text{GeV}]) & E_{T}^{\text{miss}} \,[\text{GeV}] & m_{T} \,[\text{GeV}] & m_{\text{incl}}^{\text{eff}} \,[\text{GeV}] \\
\hline
\text{SR-1f-6j-A} & \geq 6 \,(30) & > 175 & > 140 & > 700 \\
\text{SR-1f-6j-B} & \geq 6 \,(30) & > 225 & > 140 & > 800 \\
\text{SR-1f-6j-C} & \geq 6 \,(30) & > 275 & > 160 & > 900 \\
\hline
\end{array}
\]

| Table 2. | Definition of the signal regions used in the 0-lepton and 1-lepton selections. The jet \( p_{T}^{j} \) threshold requirements are also applied to b-jets. The notation SR-0f-4j-C^{*} means that the leading jet is required to fail the b-tagging requirements to target the region close to the kinematic boundary in the Gbb model. |

a hadronically decaying \( \tau \) lepton. Additional minor sources of reducible background are single-top production, \( t\bar{t}+W/Z/h \) (except events with \( Z/h \rightarrow b\bar{b} \)), \( W/Z+\text{heavy-flavour} \) jets, and diboson events. The irreducible backgrounds with at least three true b-jets in the final state arise predominantly from \( t\bar{t}+b/b\bar{b} \) events, and to a minor extent from \( t\bar{t}+Z/h \) production with a subsequent decay of the \( Z \) or Higgs boson into a pair of b-quarks.

Different techniques are used to estimate the contribution from the reducible and the irreducible backgrounds in the SRs, explained in detail in the following sections.

### 7.1 Reducible background

All reducible backgrounds are estimated simultaneously using a data-driven method which predicts the contribution from events with at least one mistagged jet amongst the three selected b-jets. This estimate is based on a matrix method (MM) similar to that used in ref. [87] to predict the contribution from background events with fake and non-prompt leptons. It consists of solving a system of equations relating the number of events with \( N_{j} \) jets and \( N_{b} \) b-jets to the number of events with \( N_{T}^{T} \) true b-jets and \( (N_{j} - N_{T}^{T}) \) non-true b-jets, prior to any b-tagging requirement. This method is applied on an event-by-event basis, such that for a given event containing \( N_{j} \) jets satisfying the \( \eta \) and \( p_{T} \) requirements applied to b-jets, \( 2^{N_{j}} \) linear equations are necessary to take into account the possibility for each of the \( N_{j} \) jets to be a true b-jet or not. These linear equations are written in the form of a matrix of dimension \( 2^{N_{j}} \times 2^{N_{j}} \), the elements of which are functions of the probabilities for each jet in the event to be tagged or mistagged as a b-jet. The system of \( 2^{N_{j}} \) equations
is solved by inverting the matrix, and an event weight is calculated from the combinations containing zero, one or two true $b$-jets. The weights obtained for each event satisfying all selection criteria except the $b$-tagging requirements are then summed to obtain the predicted number of events with at least one mistagged $b$-jet amongst the selected $b$-jets.

The $b$-tagging efficiencies used in the MM are measured in data for each jet-flavour using different techniques \cite{Higgs2011, Higgs2012, Higgs2013}. They are labelled as $\epsilon_b$, $\epsilon_c$, $\epsilon_\tau$ and $\epsilon_l$ for $b$-, $c$-, $\tau$- and light-parton-jets respectively. However, since the origin of a jet candidate is unknown in data, a mistag rate based on MC simulations which takes into account the relative contribution of each source of non-true $b$-jets is derived. The average mistag rate $\epsilon_f$ is defined in terms of the various jet-flavour efficiencies as $\epsilon_f = f_\tau \epsilon_\tau + f_c \epsilon_c + f_l \epsilon_l$, where $f_\tau$, $f_c$ and $f_l$ are the relative fractions of each jet-flavour prior to any $b$-tagging requirement.

Since the reducible background is dominated by $t\bar{t}$ events, the relative jet-flavour fractions are extracted from the $t\bar{t}$ MC sample described in section 4, separately for each lepton multiplicity. In events containing zero or one lepton, they are obtained as a function of the jet $p_T$ and $|\eta|$, and as a function of the jet multiplicity to take into account the dependence with the number of additional partons produced in the hard-scattering or in the radiations. In events with exactly one lepton, the contribution from hadronic $\tau$-jets arising from the second $W$ boson decay increases in events with $m_T > m(W)$ and therefore the relative fractions of each jet-flavour are additionally binned as a function of the transverse mass. Events with two leptons are present in the inclusive 1-lepton SRs and in a 2-lepton control region (CR) used for the determination of the dominant irreducible background contribution. This CR is obtained by requiring $m_T < 140$ GeV to prevent overlap with the 1-lepton SRs as detailed in section 7.2. In dileptonic $t\bar{t}$ events, both $W$ bosons decay into an electron, a muon or a leptonically decaying $\tau$ and mistagged $b$-jets can only come from additional $c$- or light-parton-jets. Consequently, the jet-flavour fractions are only parameterised as a function of the jet $p_T$ and $\eta$ in events with two leptons.

Alternatively, the average mistag rates are determined in data using 0, 1 and 2-lepton regions enriched in $t\bar{t}$ events. These regions are defined following the same requirements as for the baseline event selection for all channels, except that events are required to have at least two $b$-jets and $E_T^{\text{miss}}$ between 100 GeV and 200 GeV in order to minimise any possible contribution from signal events in the data. To estimate the mistag rate, the contribution from events with at least three true $b$-jets is subtracted using MC simulations. The mistag rate is measured as the probability to have a third $b$-jet in bins of $p_T$ and $|\eta|$, and an additional parameterisation as a function of $m_T$ is used in the 1-lepton channel. The results obtained with this method are consistent with the ones based on MC simulations. Because of the low number of events in data, the mistag rate estimated from MC simulations using the jet-flavour fractions method is taken as baseline, and the difference with the measurement in data is treated as a systematic uncertainty.

This procedure was validated using the inclusive sample of simulated $t\bar{t}$ events described in section 4 as follows. The MM is applied to the entire MC sample to predict the number of events with at least one mistagged $b$-jet. The contribution from the irreducible $t\bar{t} + b/b\bar{b}$ background is extracted from the same sample as detailed in section 4, and the sum of the two components is compared to the inclusive event yield of the MC sample. Good agreement is found, at preselection level and also at various steps in the event selection chain.
7.2 Irreducible background

The estimate of the minor contribution from $t\bar{t} + Z/h$ production followed by $Z/h \rightarrow b\bar{b}$ relies on MC predictions normalised to their theoretical cross-sections, while the dominant irreducible background from $t\bar{t} + b/\bar{b}$ events is estimated by normalising the MC predictions to the observed data in a CR. The CR, common to all SRs in both the 0- and 1-lepton channels, is defined using events with exactly two signal leptons and at least four jets with $p_T > 30$ GeV, at least one of them being required to have $p_T > 90$ GeV and three of them to be $b$-tagged. The $E_T^{\text{miss}}$ threshold is relaxed to 100 GeV to increase the sample size, and the transverse mass is required to be less than 140 GeV to remove the overlap with the 1-lepton SRs and to reduce the potential contamination from signal events to below a few per cent. The trigger efficiency is above 90% in the CR and a systematic uncertainty of 2% is added to account for a small difference between the trigger turn-on curves in data and MC simulations in the 100–150 GeV $E_T^{\text{miss}}$ range. Figure 3 shows the $m_T$ distribution in the CR, before the requirement of $m_T < 140$ GeV; the jet multiplicity, the $E_T^{\text{miss}}$, and the $m_{\text{incl}}^{\text{eff}}$ distributions with $m_T < 140$ GeV are also shown.

The expected number of $t\bar{t} + b/\bar{b}$ events in the various SRs is estimated via a profile likelihood fit [88] to the events in the 2-lepton CR. The expected and observed numbers of events in the CR are described by Poisson probability functions. The statistical and systematic uncertainties on the expected values described in section 8 are treated as nuisance parameters and are constrained by a Gaussian function with a width corresponding to the size of the uncertainty considered, taking into account the correlations between these parameters. The likelihood function is built as the product of the Poisson probability functions and the constraints on the nuisance parameters. The free parameter is the overall normalisation of the $t\bar{t} + b/\bar{b}$ background, while the normalisations of the remaining irreducible and reducible backgrounds are initially set to their predictions and allowed to vary within their systematic uncertainties. The result of the fit in the CR is summarised in table 3. Given the good agreement between the expected and observed yields, the fit gives a negligible correction to the normalisation of the $t\bar{t} + b/\bar{b}$ background. The uncertainty on the total background estimate is smaller than the largest individual uncertainty due to anticorrelations between the uncertainties on the reducible and irreducible backgrounds.

8 Systematic uncertainties

The dominant detector-related systematic uncertainties on the amount of irreducible background are due to the jet energy scale (JES) and resolution (JER) uncertainties; they range respectively from 16% to 37% and from 1% to 32% in the various SRs before the fit. The JES uncertainty is derived from a combination of simulations, test beam data and in situ measurements [77, 89]. Additional contributions accounting for the jet-flavour composition, the calorimeter response to different jet-flavours, pile-up and $b$-jet calibration uncertainties are also taken into account. Uncertainties on the JER are obtained with an in situ measurement of the jet response asymmetry in dijet events. Uncertainties in jet measurements are propagated to the $E_T^{\text{miss}}$, and additional subdominant uncertainties on $E_T^{\text{miss}}$ arising from energy deposits not associated with any reconstructed objects are
Figure 3. Expected distributions of SM background events and observed data distributions in the 2-lepton control region. The distributions of (a) $m_T$ prior to the requirement on this variable, and (b) the number of jets with $p_T > 30$ GeV, (c) $E_T^{miss}$ and (d) $m^{\text{incl}}_{\text{eff}}$ are shown. Also displayed are the respective contributions of the backgrounds described in the legend and the ratio between the expected and observed event yields. The shaded bands include all experimental systematic uncertainties on the MC and MM predictions. The normalisation of the irreducible background $t\bar{t} + b/\bar{b}$ is as predicted by its theoretical cross-section scaled to the same luminosity as the data, prior to the fit in the control region.


<table>
<thead>
<tr>
<th></th>
<th>Before the fit</th>
<th>After the fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Total background events</td>
<td>48 ± 7</td>
<td></td>
</tr>
<tr>
<td>Reducible background events</td>
<td>27 ± 7</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} + b/\bar{b}$ events</td>
<td>20 ± 10</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} + (Z \rightarrow b\bar{b})$ events</td>
<td>0.5 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} + (h \rightarrow b\bar{b})$ events</td>
<td>0.9 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>MC-only prediction</td>
<td>50</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3. Background fit result in the $t\bar{t} + b/\bar{b}$ CR. Uncertainties quoted include statistical and detector-related systematic effects. The MC-only prediction is given for comparison.

also included. The uncertainty associated with $b$-jets is evaluated by varying the $p_T$- and flavour-dependent correction factors applied to each jet in the simulation within a range that reflects the systematic uncertainty on the measured tagging efficiencies and mistag rates. It varies between 10% and 16% in the different SRs for the irreducible background, but it largely cancels for the $t\bar{t} + b/\bar{b}$ background because of the normalisation in the CR. Uncertainties in lepton reconstruction and momentum scales are negligible. All these experimental systematic uncertainties are treated as fully correlated between the signal and the irreducible backgrounds extracted from MC simulations.

Additional theoretical systematic uncertainties are considered for the irreducible backgrounds. The uncertainty on the $t\bar{t} + b/\bar{b}$ cross-section cancels in the normalisation of the MC simulation in the CR, and only the theoretical uncertainties on the MC prediction used to extrapolate from the CR to the SRs are considered. The uncertainty due to the choice of the factorisation ($\mu_F$) and renormalisation ($\mu_R$) scales in POWHEG are estimated by comparing the baseline sample to POWHEG+PYTHIA-6 samples generated with $\mu_F$ and $\mu_R$ varied separately up and down by a factor of two, giving an uncertainty of up to 13%. The uncertainty due to the choice of MC generator is estimated by comparing the estimate from the nominal POWHEG+PYTHIA-6 sample to the MadGraph+PYTHIA-6 sample generated with up to three additional partons at the matrix-element level, yielding an uncertainty of up to 30%. The parton shower uncertainty is assessed by comparing POWHEG interfaced to PYTHIA-6 with POWHEG interfaced to HERWIG and JIMMY, and amounts up to 65% in the SRs where at least seven jets are required. The PDF uncertainties are derived following the Hessian method [90], resulting in an uncertainty of less than 2% for all SRs.

The theoretical uncertainty on the $t\bar{t} + Z$ cross-section is 22% [59]. The systematic uncertainties associated with the modelling of $t\bar{t} + Z$ events are estimated by using different MadGraph+PYTHIA-6 samples: variations up and down of the $\mu_R$ and $\mu_F$ by a factor of two result in an uncertainty of up to 50%; variations of the ISR/FSR parameters within ranges validated by measurements in data yield an uncertainty of up to 50% for each variation; variations up and down of the matrix-element to parton-shower matching parameter $xqcut$ by 5 GeV around the central value of 20 GeV result in an uncertainty of up
to 30%. For the small contribution from the $t\bar{t} + h(\rightarrow b\bar{b})$ background, a total uncertainty of 100% is assumed to account for large uncertainties on the acceptance, while the inclusive cross-section is known to better precision.

Systematic uncertainties on the MM prediction of the reducible backgrounds include the uncertainties on the measurement of the $b$-tagging efficiency for the different jet-flavours. They vary in the range between 4% and 14% and are treated as fully correlated with the irreducible background and the signal. The statistical uncertainty of the $t\bar{t}$ MC sample used to extract the jet-flavour fractions is also taken into account and is of the order of 1%. The difference between the baseline prediction obtained with the mistag rate from simulated $t\bar{t}$ events and the prediction obtained using the mistag rate measured in data is assigned as a systematic uncertainty. This uncertainty ranges from 9% to 45% in the different SRs. Finally, the statistical uncertainty on the number of observed events for each $b$-jet multiplicity is propagated to the MM prediction. This latter uncertainty is the dominant source of uncertainty on the background estimation in most SRs.

9 Results

The data are compared to the background predictions in figures 4–10. Figure 4 shows the observed distributions of the number of jets with $p_T > 30$ GeV, $m_{4j}^{\text{eff}}$ and $E_T^{\text{miss}}$ after the 0-lepton baseline selection detailed in table 2, together with the background prediction from the MM for the reducible background and from MC simulations for the irreducible background. Figure 5 shows the same distributions for events with at least four jets with $p_T > 50$ GeV and three $b$-jets with $p_T > 50$ GeV after the 0-lepton baseline selection. The $m_{\text{incl}}^{\text{eff}}$ and $E_T^{\text{miss}}$ distributions with a requirement of at least seven jets with $p_T > 30$ GeV after the 0-lepton baseline selection are shown in figure 6. Figure 7 shows the number of jets with $p_T > 30$ GeV after the 1-lepton baseline selection, as well as the distributions of $m_T$, $E_T^{\text{miss}}$ and $m_{\text{incl}}^{\text{eff}}$ after requiring at least six jets with $p_T > 30$ GeV in addition to the 1-lepton baseline selection. The $m_{4j}^{\text{eff}}$, $m_{\text{incl}}^{\text{eff}}$ and $E_T^{\text{miss}}$ distributions obtained before the final requirement on these quantities are shown in figures 8–10, representing each SR. Also shown in all figures are the predictions of two benchmark signal models.

The background prediction in each SR is obtained by adding the Poisson probability function describing the expected number of events in the SR and the corresponding nuisance parameters in the likelihood fit. The results of the fits and the observed data in each SR are reported in tables 4 and 5 for the 0-lepton and 1-lepton channels, respectively. No significant deviation from the SM expectation is observed in any of the 0-lepton SRs. In the 1-lepton channel, a deficit in data is observed in all overlapping SRs. In addition to the event yields, the $CL_{b}$-values [91], which quantify the observed level of agreement with the expected yield, and the $p_0$-values, which represent the probability of the SM background alone to fluctuate to the observed number of events or higher, are also reported. The $p_0$-values are truncated at 0.5 if the number of observed events is below the number of expected events. Upper limits at 95% confidence level (CL) on the number of beyond-the-SM (BSM) events are derived in each SR using the $CL_s$ prescription [91] and neglecting any possible signal contamination in the CR. These are obtained with a fit in each SR.
which proceeds in the same way as the fit used to predict the background, except that the number of events observed in the SR is added as an input to the fit, and an additional parameter for the non-SM signal strength, constrained to be non-negative, is fit. The upper limits are derived with pseudo-experiments, and the results obtained with an asymptotic approximation [88] are given in parentheses for comparison. These limits, after being normalised by the integrated luminosity of the data sample, can be interpreted in terms of upper limits on the visible cross-section for hypothetical BSM contributions, defined in terms of the kinematic acceptance $A$ and the experimental efficiency $\epsilon$ as $\sigma_{\text{vis}} = \sigma \times A \times \epsilon$.

10 Interpretations

The results are used to derive exclusion limits in the context of several SUSY models (see section 2) including bottom quarks or top quarks in the decay chain. The expected and observed exclusion limits are calculated using the asymptotic approximation for each SUSY model, treating the systematic uncertainties as fully correlated between the signal and the background and between the 0- and 1-lepton channels where appropriate, and including the expected signal contamination in the CR. Theoretical uncertainties on the SUSY signals are estimated as described in section 4. Limits are calculated for the nominal cross-section, and for the $\pm 1\sigma_{\text{theory}}$ cross-sections. All limits quoted in the text correspond to the $-1\sigma_{\text{theory}}$ hypothesis.

Limits are derived using the SR yielding the best expected sensitivity for each point in the parameter space, derived prior to having considered the data in the SR. For signal models where both the 0- and 1-lepton channels contribute to the sensitivity, these are combined in a simultaneous fit to enhance the sensitivity of the analysis. In this case, all possible permutations between the three 1-lepton and the six 0-lepton SRs are considered for each point of the parameter space, and the best expected combination is used. The SR-0$\ell$-4j signal regions are mostly sensitive to the gluino decays $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_0^1$ via on-shell or off-shell sbottoms, whilst the SR-0$\ell$-7j and SR-1$\ell$-6j signal regions are used to set exclusion limits in models where top quark enriched final states are expected.

The expected and observed 95% CL exclusion limits obtained with the 0-lepton channel for the direct-sbottom model are presented in the $(m_{\tilde{b}_1}, m_{\tilde{\chi}_2^0})$ plane in figure 11. Sbottom masses between 340 GeV and 600 GeV are excluded for $m_{\tilde{\chi}_2^0} = 300$ GeV. No sensitivity is obtained for low $m_{\tilde{\chi}_2^0}$ due to the soft $E_T^{\text{miss}}$ expected for these signal events. The sensitivity of this analysis to $\tilde{b}_1$ pair production processes where $\tilde{b}_1 \rightarrow b + \tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \rightarrow h + \tilde{\chi}_1^0$, depends on $m_{\tilde{\chi}_1^0}$. For higher neutralino masses, the sensitivity decreases because of the tight $E_T^{\text{miss}}$ and jet $p_T$ selections applied in this analysis.

The expected and observed exclusion limits for the gluino-sbottom scenario are shown in figure 12 (a). Exclusion limits are presented in the $(m_{\tilde{g}}, m_{\tilde{b}_1})$ plane for the 0-lepton channel. Gluino masses below 1250 GeV are excluded for sbottom masses up to about 900 GeV. The result is complementary to the ATLAS search for direct sbottom pair production also carried out with 20.1 fb$^{-1}$ of data at 8 TeV [92].

A combination of the 0- and 1-lepton results is used to derive the limit contours for the gluino-stop I and II models, presented in the $(m_{\tilde{g}}, m_{\tilde{t}_1})$ plane in figure 12 (b) and
Figure 4. The observed distributions of (a) the number of jets with \( p_T > 30 \) GeV, (b) \( m_{4j} \) and (c) \( E^{\text{miss}}_T \) after the 0-lepton baseline selection, together with the background prediction. Also displayed are the respective contributions of the backgrounds described in the legend and the ratio between the expected and observed event yields. The shaded bands include all experimental systematic uncertainties on the background prediction. The prediction for two signal points from the Gtt (\( \tilde{g} \to t\tilde{\chi}_1^0 \)) and Gbb (\( \tilde{g} \to b\bar{b}\tilde{\chi}_1^0 \)) models are overlaid. The normalisation of the irreducible background \( t\bar{t} + b/b\bar{b} \) is as predicted by its theoretical cross-section scaled to the same luminosity as the data, prior to the fit in the control region.
Figure 5. The observed distributions of (a) the number of jets with $p_T > 50$ GeV, (b) $m_{4j}^{\text{eff}}$ and (c) $E_T^{\text{miss}}$ after requiring at least four jets with $p_T > 50$ GeV and at least three $b$-jets with $p_T > 50$ GeV in addition to the 0-lepton baseline selection, together with the background prediction. Also displayed are the respective contributions of the backgrounds described in the legend and the ratio between the expected and observed event yields. The shaded bands include all experimental systematic uncertainties on the background prediction. The prediction for two signal points from the Gtt ($\tilde{g} \rightarrow t\tilde{\chi}_1^0$) and Gbb ($\tilde{g} \rightarrow b\tilde{\chi}_1^0$) models are overlaid. The normalisation of the irreducible background $t\bar{t} + b/b\bar{b}$ is as predicted by its theoretical cross-section scaled to the same luminosity as the data, prior to the fit in the control region.
Results of the likelihood fit in all 0-lepton signal regions. The errors shown include all systematic uncertainties. The data in the signal regions are not included in the fit. The MC-only predictions are given for comparison. The $CL_b$-values, which quantify the observed level of agreement with the expected yield, and the $p_0$-values, which represent the probability of the SM background alone to fluctuate to the observed number of events or higher, are also reported. The $p_0$-values are truncated at 0.5 if the number of observed events is below the number of expected events. Also shown are the expected and observed upper limits (UL) at 95% CL on the number of beyond-the-SM events $N_{BSM}$ in each SR. These limits are derived with pseudo-experiments, and the results obtained with an asymptotic approximation are given in parentheses for comparison. They are used to derive upper limits on the visible cross-section $\sigma_{vis} = \sigma \times A \times \epsilon$ for hypothetical non-SM contributions.

<table>
<thead>
<tr>
<th></th>
<th>SR-0(\ell)-4j-A</th>
<th>SR-0(\ell)-4j-B</th>
<th>SR-0(\ell)-4j-C*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Fitted background events</td>
<td>1.6 ± 0.9</td>
<td>1.3 ± 0.9</td>
<td>1.6 ± 0.7</td>
</tr>
<tr>
<td>Reducible background events</td>
<td>1.1 ± 0.8</td>
<td>0.7$^{+0.8}_{-0.7}$</td>
<td>1.1 ± 0.5</td>
</tr>
<tr>
<td>$tt + b/b\bar{b}$ events</td>
<td>0.4 ± 0.3</td>
<td>0.4 ± 0.3</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>$tt + (Z \rightarrow b\bar{b})$ events</td>
<td>0.03 ± 0.02</td>
<td>0.04 ± 0.03</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>$tt + (h \rightarrow b\bar{b})$ events</td>
<td>0.05 ± 0.05</td>
<td>0.07 ± 0.07</td>
<td>0.03 ± 0.03</td>
</tr>
<tr>
<td>MC-only prediction</td>
<td>2.6</td>
<td>3.7</td>
<td>2.3</td>
</tr>
<tr>
<td>$CL_b$</td>
<td>0.65</td>
<td>0.87</td>
<td>0.39</td>
</tr>
<tr>
<td>$p_0$</td>
<td>0.40</td>
<td>0.15</td>
<td>0.5</td>
</tr>
<tr>
<td>Expected UL on $N_{BSM}$</td>
<td>$4.5^{+1.7}<em>{-0.5} \times (4.3^{+2.6}</em>{-0.9})$</td>
<td>$4.5^{+1.7}<em>{-0.6} \times (4.3^{+2.6}</em>{-1.0})$</td>
<td>$4.1^{+1.7}<em>{-0.3} \times (4.1^{+2.2}</em>{-1.0})$</td>
</tr>
<tr>
<td>Observed UL on $N_{BSM}$</td>
<td>5.2 (5.0)</td>
<td>6.5 (6.2)</td>
<td>3.9 (3.8)</td>
</tr>
<tr>
<td>Observed (expected) UL on $\sigma_{vis}$ [fb]</td>
<td>0.26 (0.22)</td>
<td>0.32 (0.22)</td>
<td>0.19 (0.20)</td>
</tr>
<tr>
<td>Observed events</td>
<td>21</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Fitted background events</td>
<td>21.2 ± 4.6</td>
<td>3.2 ± 1.6</td>
<td>0.9$^{+1.0}_{-0.9}$</td>
</tr>
<tr>
<td>Reducible background events</td>
<td>13.6 ± 4.0</td>
<td>1.7 ± 1.2</td>
<td>&lt; 0.65</td>
</tr>
<tr>
<td>$tt + b/b\bar{b}$ events</td>
<td>6.7 ± 3.9</td>
<td>1.3 ± 1.1</td>
<td>0.8 ± 0.7</td>
</tr>
<tr>
<td>$tt + (Z \rightarrow b\bar{b})$ events</td>
<td>0.3 ± 0.1</td>
<td>0.07 ± 0.03</td>
<td>0.03 ± 0.03</td>
</tr>
<tr>
<td>$tt + (h \rightarrow b\bar{b})$ events</td>
<td>0.5 ± 0.5</td>
<td>0.1 ± 0.1</td>
<td>0.06 ± 0.06</td>
</tr>
<tr>
<td>MC-only prediction</td>
<td>31.4</td>
<td>6.8</td>
<td>3.1</td>
</tr>
<tr>
<td>$CL_b$</td>
<td>0.51</td>
<td>0.53</td>
<td>0.59</td>
</tr>
<tr>
<td>$p_0$</td>
<td>0.50</td>
<td>0.50</td>
<td>0.46</td>
</tr>
<tr>
<td>Expected UL on $N_{BSM}$</td>
<td>$13.8^{+4.7}<em>{-3.4} \times (13.5^{+5.3}</em>{-3.7})$</td>
<td>$6.0^{+2.2}<em>{-1.3} \times (5.9^{+2.5}</em>{-1.8})$</td>
<td>$4.1^{+1.6}<em>{-0.8} \times (4.1^{+2.1}</em>{-1.0})$</td>
</tr>
<tr>
<td>Observed UL on $N_{BSM}$</td>
<td>13.9 (13.4)</td>
<td>6.1 (5.8)</td>
<td>4.2 (4.1)</td>
</tr>
<tr>
<td>Observed (expected) UL on $\sigma_{vis}$ [fb]</td>
<td>0.69 (0.69)</td>
<td>0.30 (0.30)</td>
<td>0.21 (0.20)</td>
</tr>
</tbody>
</table>

**Table 4.** Results of the likelihood fit in all 0-lepton signal regions. The errors shown include all systematic uncertainties. The data in the signal regions are not included in the fit. The MC-only predictions are given for comparison. The $CL_b$-values, which quantify the observed level of agreement with the expected yield, and the $p_0$-values, which represent the probability of the SM background alone to fluctuate to the observed number of events or higher, are also reported. The $p_0$-values are truncated at 0.5 if the number of observed events is below the number of expected events. Also shown are the expected and observed upper limits (UL) at 95% CL on the number of beyond-the-SM events $N_{BSM}$ in each SR. These limits are derived with pseudo-experiments, and the results obtained with an asymptotic approximation are given in parentheses for comparison. They are used to derive upper limits on the visible cross-section $\sigma_{vis} = \sigma \times A \times \epsilon$ for hypothetical non-SM contributions.
(c). Gluino masses below 1180 GeV are excluded for stop masses up to 1000 GeV in the gluino-stop I model, while gluino masses below 1190 GeV are excluded for stop masses up to 1000 GeV in the gluino-stop II model. The sensitivity is lower in the gluino-stop I model for most of the parameter space where soft $E_T^{\text{miss}}$ and jets are expected from the chargino decay $\tilde{\chi}^\pm_1 \rightarrow W^* \tilde{\chi}^0_1$. The result is complementary to the ATLAS searches for direct stop pair production performed in the 0-lepton channel with 20.1 fb$^{-1}$ of data at 8 TeV [93] and in the 1-lepton channel with 4.7 fb$^{-1}$ of data at 7 TeV [94].

The expected and observed exclusion limits for the Gbb model are shown in figure 13 (a). As for the gluino-sbottom model, four $b$-jets and $E_T^{\text{miss}}$ are expected in the final state and only the 0-lepton channel is used for the interpretation. Gluino masses below 1250 GeV are excluded for $m_{\tilde{\chi}^0_1} < 400$ GeV while neutralino masses below 600 GeV are excluded for $m_{\tilde{g}} = 1000$ GeV. Lower sensitivity is achieved at very low mass splitting between the gluino and the neutralino because of the presence of soft $b$-jets and the low $E_T^{\text{miss}}$ expected in signal events.

The combination of the 0-lepton and 1-lepton channels is used to obtain the exclusion contours for the Gtt model, displayed in figure 13 (b). Gluino masses below 1340 GeV are excluded for $m_{\tilde{\chi}^0_1} < 400$ GeV while neutralino masses below 620 GeV are excluded for $m_{\tilde{g}} = 1000$ GeV. The SR-0$\ell$-7j signal regions have the best sensitivity at large mass splitting.
Figure 7. The distribution of (a) the number of jets with $p_T > 30$ GeV observed in data after the 1-lepton baseline selection, together with the background prediction. The (b) $m_T$, (c) $E_{T}^{\text{miss}}$ and (d) $m_{\text{incl}}$ distributions after requiring at least six jets $p_T > 30$ GeV in addition to the 1-lepton baseline selection are also shown. Also displayed are the respective contributions of the backgrounds described in the legend and the ratio between the expected and observed event yields. The shaded bands include all experimental systematic uncertainties on the background prediction. The prediction for one signal point from the Gtt ($\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$) model is overlaid. The normalisation of the irreducible background $t\bar{t} + b/b\bar{b}$ is as predicted by its theoretical cross-section scaled to the same luminosity as the data, prior to the fit in the control region.
between the gluino and the neutralino, where hard jets and large $E_T^{\text{miss}}$ are expected, while the 1-lepton SRs have a better sensitivity close to the kinematic boundary.

Figure 13 (c) shows the expected and observed exclusion limits for the Gtb scenario. The combination of the two channels is used to set the excluded area. Gluino masses below 1300 GeV are excluded for $m_{\tilde{\chi}_0^1} < 300$ GeV while neutralino masses below 600 GeV are excluded for $m_{\tilde{g}} = 1100$ GeV.

Finally, expected and observed 95% CL limits for the mSUGRA/CMSSM scenario discussed in section 2 are presented in the $(m_0, m_{1/2})$ plane in figure 14. Gluino masses smaller than 1280 GeV are excluded. This analysis is especially sensitive to the high $m_0$ region, where final states with four top quarks dominate.
Figure 9. The (a)-(c) $m_{\text{eff}}^{\text{incl}}$ and (b) $E_T^{\text{miss}}$ distributions observed in data for SR-0l-7j-A, SR-0l-7j-B and SR-0l-7j-C, respectively, after all requirements applied but the one indicated by the arrow, together with the background prediction. The shaded bands include all experimental systematic uncertainties on the background prediction. The prediction for two signal points from the Gtt ($\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_0^1$) and Gbb ($\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_0^1$) models are overlaid. The normalisation of the irreducible background $t\bar{t} + b/b\bar{b}$ is as predicted by its theoretical cross-section scaled to the same luminosity as the data, prior to the fit in the control region.

11 Conclusions

A search is presented in this paper for pair production of gluinos and sbottoms decaying into final states with multi-$b$-jets and missing transverse momentum. This analysis uses 20.1 fb$^{-1}$ of $pp$ collisions at a centre-of-mass energy of 8 TeV collected by the ATLAS experiment at the LHC. Events with large missing transverse momentum, at least four to at least seven jets, and at least three $b$-jets are considered. The analysis is carried out separately for events with and without leptons in the final state, and the two channels are combined to enhance the sensitivity to SUSY scenarios with top quarks in the decay chain. No significant excess of events above SM expectations is found in data and the results are interpreted in the context of various simplified models involving gluinos, sbottoms and stops. In particular, gluino masses up to about 1340 GeV are excluded at 95% CL in some models.
Figure 10. The (a) $m_{\text{eff}}^{\text{incl}}$ and (b)-(c) $E_T^{\text{miss}}$ distribution observed in data for SR-$1\ell$-6j-A, SR-$1\ell$-6j-B and SR-$1\ell$-6j-C, respectively, after all requirements applied but the one indicated by the arrow, together with the background prediction. The shaded bands include all experimental systematic uncertainties on the background prediction. The prediction for one signal point from the Gtt ($\tilde{g} \to t\tilde{t}\chi^0_1$) model is overlaid. The normalisation of the irreducible background $tt + b/bb$ is as predicted by its theoretical cross-section scaled to the same luminosity as the data, prior to the fit in the control region.
Table 5. Results of the likelihood fit in all 1-lepton signal regions. The errors shown include all systematic uncertainties. The data in the signal regions are not included in the fit. The MC-only predictions are given for comparison. The $C L_b$-values, which quantify the observed level of agreement with the expected yield, and the $p_0$-values, which represent the probability of the SM background alone to fluctuate to the observed number of events or higher, are also reported. The $p_0$-values are truncated at 0.5 if the number of observed events is below the number of expected events. Also shown are the expected and observed upper limits (UL) at 95% CL on the number of beyond-the-SM events $N_{\text{BSM}}$ in each SR. These limits are derived with pseudo-experiments and the results obtained with an asymptotic approximation are given in parentheses for comparison. They are used to derive upper limits on the visible cross-section $\sigma_{\text{vis}} = \sigma \times A \times \epsilon$ for hypothetical non-SM contributions.

Figure 11. Exclusion limits in the $(m_{\tilde{b}_1}, m_{\tilde{t}_2})$ plane for the direct-sbottom model. The dashed blue and solid bold red lines show the 95% CL expected and observed limits respectively, including all uncertainties except the theoretical signal cross-section uncertainty. The shaded (yellow) bands around the expected limits show the impact of the experimental and background theoretical uncertainties while the dotted red lines show the impact on the observed limit of the variation of the nominal signal cross-section by 1$\sigma$ of its theoretical uncertainty.
Figure 12. Exclusion limits in the \((m_{\tilde{g}}, m_{\tilde{b}_1})\) plane for the (a) gluino-sbottom model, and in the \((m_{\tilde{g}}, m_{\tilde{t}_1})\) plane for the gluino-stop (b) I and (c) II models. The dashed blue and solid bold red lines show the 95% CL expected and observed limits respectively, including all uncertainties except the theoretical signal cross-section uncertainty. The shaded (yellow) bands around the expected limits show the impact of the experimental and background theoretical uncertainties while the dotted red lines show the impact on the observed limit of the variation of the nominal signal cross-section by 1\(\sigma\) of its theoretical uncertainty. Also shown for reference are the results from the ATLAS sbottom and stop searches [92–94] derived using the nominal cross section.
Figure 13. Exclusion limits in the \((m_{\tilde{g}}, m_{\tilde{\chi}^0})\) plane for the (a) Gbb, (b) Gtt and (c) Gtb models. The dashed blue and solid bold red lines show the 95% CL expected and observed limits respectively, including all uncertainties except the theoretical signal cross-section uncertainty. The shaded (yellow) bands around the expected limits show the impact of the experimental and background theoretical uncertainties while the dotted red lines show the impact on the observed limit of the variation of the nominal signal cross-section by 1\(\sigma\) of its theoretical uncertainty.
Figure 14. Exclusion limits in the \((m_0, m_{1/2})\) plane for the mSUGRA/CMSSM model. The dashed blue and solid bold red lines show the 95% CL expected and observed limits respectively, including all uncertainties except the theoretical signal cross-section uncertainty. The shaded (yellow) bands around the expected limits show the impact of the experimental and background theoretical uncertainties while the dotted red lines show the impact on the observed limit of the variation of the nominal signal cross-section by 1\(\sigma\) of its theoretical uncertainty.
Acknowledgments

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEAS-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINE-ERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.) and BNL (U.S.A.) and in the Tier-2 facilities worldwide.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References


[41] P. Bärrreuther, M. Czakon and A. Mitov, *Percent level precision physics at the Tevatron: first genuine NNLO QCD corrections to $q\bar{q} \to t\bar{t} + X$*, Phys. Rev. Lett. 109 (2012) 132001 [arXiv:1204.5201] [inspire].


M. Krämer et al., Supersymmetry production cross sections in pp collisions at \( \sqrt{s} = 7 \text{ TeV} \), arXiv:1206.2892 [nSPIRE].


ATLAS collaboration, Measurement of the mistag rate with 5 fb\(^{-1}\) of data collected by the ATLAS detector, ATLAS-CONF-2012-040, CERN, Geneva Switzerland (2012).


A. White\textsuperscript{5}, M.J. White\textsuperscript{1}, R. White\textsuperscript{1,2,3}, S. White\textsuperscript{1,2,3,4}, D. Whiteson\textsuperscript{14}, D. Wicke\textsuperscript{16}, F.J. Wickens\textsuperscript{13}, W. Wiedemann\textsuperscript{17}, M. Wiemers\textsuperscript{13}, P. Wienemann\textsuperscript{21}, C. Wiglesworth\textsuperscript{36}, L.A.M. Wiik-Fuchs\textsuperscript{2}, P.A. Wijeratne\textsuperscript{23}, A. Wildauer\textsuperscript{100}, M.A. Wildt\textsuperscript{42,47}, H.G. Wilkens\textsuperscript{30}, J.Z. Will\textsuperscript{99}, H.H. Williams\textsuperscript{121}, S. Williams\textsuperscript{28}, C. Willis\textsuperscript{89}, S. Willcock\textsuperscript{85}, A. Wilson\textsuperscript{88}, J.A. Wilson\textsuperscript{18}, I. Wingenter-Soez\textsuperscript{2}, F. Winklmeier\textsuperscript{115}, B.T. Winter\textsuperscript{15}, M. Wittgen\textsuperscript{144}, T. Wittig\textsuperscript{43}, J. Wittkowsk\textsuperscript{39}, S.J. Wolle\textsuperscript{82}, M.W. Wolters\textsuperscript{39}, H. Wolters\textsuperscript{125a,125c}, B.K. Wosiek\textsuperscript{39}, J. Wotschack\textsuperscript{30}, M.J. Woudstra\textsuperscript{83}, K.W. Wozniak\textsuperscript{39}, M. Wright\textsuperscript{53}, M. Wu\textsuperscript{55}, S.L. Wu\textsuperscript{174}, X. Wu\textsuperscript{49}, Y. Wu\textsuperscript{48}, E. Wulf\textsuperscript{35}, T.R. Wyatt\textsuperscript{83}, B.M. Wynne\textsuperscript{46}, S. Xella\textsuperscript{36}, M. Xiao\textsuperscript{137}, D. Xu\textsuperscript{33}, L. Xu\textsuperscript{33b,aa}, B. Yabsley\textsuperscript{151}, S. Yacoob\textsuperscript{146b,an}, M. Yamada\textsuperscript{65}, H. Yamaguchi\textsuperscript{156}, Y. Yamaguchi\textsuperscript{117}, A. Yamamoto\textsuperscript{65}, K. Yamamoto\textsuperscript{63}, S. Yamamoto\textsuperscript{156}, T. Yamamura\textsuperscript{156}, T. Yamakawa\textsuperscript{156}, K. Yamauchi\textsuperscript{102}, Y. Yamazaki\textsuperscript{116}, Z. Yan\textsuperscript{22}, H. Yang\textsuperscript{33c,4}, H. Yang\textsuperscript{174}, U.K. Yang\textsuperscript{83}, Y. Yang\textsuperscript{110}, S. Yanush\textsuperscript{92}, L. Yao\textsuperscript{33a}, W-M. Yao\textsuperscript{15}, Y. Yasu\textsuperscript{65}, E. Yatsenko\textsuperscript{42}, K.H. Yau Wong\textsuperscript{21}, J. Ye\textsuperscript{40}, S. Ye\textsuperscript{25}, A.L. Yen\textsuperscript{57}, E. Yildirim\textsuperscript{42}, M. Yilmaz\textsuperscript{4b}, R. Yoosooftimiai\textsuperscript{124}, K. Yorita\textsuperscript{172}, R. Yoshida\textsuperscript{6}, K. Yoshihara\textsuperscript{164}, C. Young\textsuperscript{144}, C.J. Young\textsuperscript{30}, S. Youssef\textsuperscript{22}, D.R. Yu\textsuperscript{15}, J. Yu\textsuperscript{8}, J.M. Yu\textsuperscript{88}, J. Yu\textsuperscript{113}, L. Yuan\textsuperscript{66}, A. Yurkewicz\textsuperscript{107}, I. Yusuff\textsuperscript{28,an}, B. Zabinski\textsuperscript{39}, R. Zaidan\textsuperscript{62}, A.M. Zaitev\textsuperscript{129,ae}, A. Zaman\textsuperscript{49}, S. Zambito\textsuperscript{24}, L. Zanello\textsuperscript{133a,133b}, D. Zanin\textsuperscript{100}, C. Zeitnitz\textsuperscript{176}, M. Zenati\textsuperscript{127}, A. Zeni\textsuperscript{38a}, K. Zengel\textsuperscript{23}, O. Zenin\textsuperscript{129}, T. Zenitis\textsuperscript{145a}, D. Zerwas\textsuperscript{116}, G. Zevi della Porta\textsuperscript{67}, D. Zhang\textsuperscript{88}, F. Zhang\textsuperscript{174}, H. Zhang\textsuperscript{89}, J. Zhang\textsuperscript{9}, L. Zhang\textsuperscript{152}, X. Zhang\textsuperscript{33d}, Z. Zhang\textsuperscript{116}, Z. Zhao\textsuperscript{33b}, A. Zhemchugov\textsuperscript{64}, J. Zhong\textsuperscript{119}, B. Zhou\textsuperscript{88}, L. Zhou\textsuperscript{35}, N. Zhou\textsuperscript{164}, C.G. Zhu\textsuperscript{33d}, H. Zhu\textsuperscript{33}, J. Zhu\textsuperscript{88}, Y. Zhu\textsuperscript{33b}, X. Zhuang\textsuperscript{133a}, K. Zhukov\textsuperscript{90}, A. Zibell\textsuperscript{175}, D. Zieminska\textsuperscript{60}, N.I. Zimine\textsuperscript{64}, C. Zimmermann\textsuperscript{82}, R. Zimmermann\textsuperscript{21}, S. Zimmermann\textsuperscript{48}, Z. Zinonos\textsuperscript{94}, M. Ziolkowski\textsuperscript{142}, G. Zobernig\textsuperscript{174}, A. Zoccoli\textsuperscript{20a,20b}, M. zur Nedden\textsuperscript{16}, G. Zurzolo\textsuperscript{103a,103b}, V. Zutshi\textsuperscript{107} and L. Zwalinski\textsuperscript{30}. 

\textsuperscript{1 Department of Physics, University of Adelaide, Australia, Australia}
\textsuperscript{2 Department, Physics Department, SUNY Albany, Albany NY, United States of America}
\textsuperscript{3 Department of Physics, University of Alberta, Edmonton AB, Canada}
\textsuperscript{4 (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Division of Physics, TOBB University of Economics and Technology, Ankara; (d) Turkish Atomic Energy Authority, Ankara, Turkey}
\textsuperscript{5 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France}
\textsuperscript{6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America}
\textsuperscript{7 Department of Physics, University of Arizona, Tucson AZ, United States of America}
\textsuperscript{8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America}
\textsuperscript{9 Physics Department, University of Athens, Athens, Greece}
\textsuperscript{10 Physics Department, National Technical University of Athens, Zografou, Greece}
\textsuperscript{11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan}
\textsuperscript{12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain}
\textsuperscript{13 (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia}
\textsuperscript{14 Department for Physics and Technology, University of Bergen, Bergen, Norway}
\textsuperscript{15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America}
\textsuperscript{16 Department of Physics, Humboldt University, Berlin, Germany}
\textsuperscript{17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland}
\textsuperscript{18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom;
Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

Physikalisches Institut, University of Bonn, Bonn, Germany

Department of Physics, Boston University, Boston MA, United States of America

Department of Physics, Brandeis University, Waltham MA, United States of America

Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rey (UFSJ), Sao Joao del Rey; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

(a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania

Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa ON, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China

Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

Nexis Laboratory, Columbia University, Irvington NY, United States of America

Niels Bohr Institute, University of Copenhagen, København, Denmark

(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas TX, United States of America

Physics Department, University of Texas at Dallas, Richardson TX, United States of America

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham NC, United States of America

SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

INFN Laboratori Nazionali di Frascati, Frascati, Italy

Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

Section de Physique, Université de Genève, Geneva, Switzerland

(a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy

(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

Department of Physics, Hampton University, Hampton VA, United States of America

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Physics, Indiana University, Bloomington IN, United States of America

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City IA, United States of America

Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America

Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

Department of Physics, Kyushu University, Fukuoka, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, United Kingdom

(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

Louisiana Tech University, Ruston LA, United States of America

Laboratoire de Physique Nucléaire et de Hautes Énergies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst MA, United States of America

Department of Physics, McGill University, Montreal QC, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

Group of Particle Physics, University of Montreal, Montreal QC, Canada

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
97 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
98 D.V.Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
101 Nagasaki Institute of Applied Science, Nagasaki, Japan
102 Graduate School of Science and Kobayashi-Maskava Institute, Nagoya University, Nagoya, Japan
103 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
106 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
107 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
108 Department of Physics, New York University, New York NY, United States of America
109 Ohio State University, Columbus OH, United States of America
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
112 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
113 Palacký University, RCPTM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
115 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
117 Department of Physics, University of Oslo, Oslo, Norway
118 Department of Physics, Oxford University, Oxford, United Kingdom
119 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
120 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica E. Fermi, Università di Roma, Roma, Italy
123 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
124 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
125 Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
127 Czech Technical University in Prague, Praha, Czech Republic
128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
129 State Research Center Institute for High Energy Physics, Protvino, Russia
130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
131 Department of Physics, University of Regina, Regina SK, Canada
132 Ritsumeikan University, Kusatsu, Shiga, Japan
133 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
134 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre,
Roma, Italy

136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPTPM, Oujda; (d) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco

137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France

138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

139 Department of Physics, University of Washington, Seattle WA, United States of America

140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

141 Department of Physics, Shinshu University, Nagano, Japan

142 Fachbereich Physik, Universität Siegen, Siegen, Germany

143 Department of Physics, Simon Fraser University, Burnaby BC, Canada

144 SLAC National Accelerator Laboratory, Stanford CA, United States of America

145 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

146 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

147 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

148 Physics Department, Royal Institute of Technology, Stockholm, Sweden

149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

151 School of Physics, University of Sydney, Sydney, Australia

152 Institute of Physics, Academia Sinica, Taipei, Taiwan

153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

159 Department of Physics, University of Toronto, Toronto ON, Canada

160 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada

161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

165 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

166 Department of Physics, University of Illinois, Urbana IL, United States of America

167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

168 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMM), University of Valencia and CSIC, Valencia, Spain
Hungary

ai Also at Department of Physics, Oxford University, Oxford, United Kingdom
aj Also at Department of Physics, Nanjing University, Jiangsu, China
ak Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
al Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
am Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
an Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

* Deceased