Original citation:
ATLAS Collaboration (Including: Jones, G. (Graham)). (2012) Hunt for new phenomena using large jet multiplicities and missing transverse momentum with ATLAS in 4.7 fb−1 of s√=7TeV proton-proton collisions. Journal of High Energy Physics, Volume 2012 (Number 7). Article Number 167.

Permanent WRAP url:
http://wrap.warwick.ac.uk/60045

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work of researchers of the University of Warwick available open access under the following conditions.

This article is made available under the Creative Commons Attribution 4.0 International license (CC BY 4.0) and may be reused according to the conditions of the license. For more details see: http://creativecommons.org/licenses/by/4.0/

A note on versions:
The version presented in WRAP is the published version, or, version of record, and may be cited as it appears here.

For more information, please contact the WRAP Team at: publications@warwick.ac.uk
Hunt for new phenomena using large jet multiplicities and missing transverse momentum with ATLAS in 4.7 fb$^{-1}$ of $\sqrt{s} = 7$ TeV proton-proton collisions

The ATLAS collaboration

ABSTRACT: Results are presented of a search for new particles decaying to large numbers of jets in association with missing transverse momentum, using 4.7 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV collected by the ATLAS experiment at the Large Hadron Collider in 2011. The event selection requires missing transverse momentum, no isolated electrons or muons, and from $\geq 6$ to $\geq 9$ jets. No evidence is found for physics beyond the Standard Model. The results are interpreted in the context of a MSUGRA/CMSSM supersymmetric model, where, for large universal scalar mass $m_0$, gluino masses smaller than 840 GeV are excluded at the 95% confidence level, extending previously published limits. Within a simplified model containing only a gluino octet and a neutralino, gluino masses smaller than 870 GeV are similarly excluded for neutralino masses below 100 GeV.

KEYWORDS: Hadron-Hadron Scattering
1 Introduction

Many extensions of the Standard Model of particle physics predict the presence of TeV-scale strongly interacting particles that decay to lighter, weakly interacting descendants. Any such weakly interacting particles that are massive and stable can contribute to the dark matter content of the universe. The strongly interacting parents would be produced in the proton-proton interactions at the Large Hadron Collider (LHC), and such events would be characterized by significant missing transverse momentum $E_T^{\text{miss}}$ from the unobserved weakly interacting daughters, and jets from emissions of quarks and/or gluons.

In the context of $R$-parity conserving [1–5] supersymmetry [5–10], the strongly interacting parent particles are the squarks $\tilde{q}$ and gluinos $\tilde{g}$, they are produced in pairs, and the lightest supersymmetric particles can provide the stable dark matter candidates [11, 12]. Jets are produced from a variety of sources: from quark emission in supersymmetric cascade decays, production of heavy Standard Model particles ($W$, $Z$ or $t$) which then decay hadronically, or from QCD radiation. Examples of particular phenomenological interest

---

---
include models where squarks are significantly heavier than gluinos. In such models the gluino pair production and decay process

\[ \tilde{g} + \tilde{g} \rightarrow (t + \overline{t} + \tilde{\chi}^0_1) + (t + \overline{t} + \tilde{\chi}^0_1) \]

can dominate, producing large jet multiplicities when the resulting top quarks decay hadronically. In the context of MSUGRA/CMSSM models, a variety of different cascade decays, including the \( \tilde{g}\tilde{g} \) initiated process above, can lead to large jet multiplicities.

A previous ATLAS search in high jet multiplicity final states [13] examined data taken during the first half of 2011, corresponding to an integrated luminosity of 1.34 fb\(^{-1}\). This paper extends the analysis to the complete ATLAS 2011 \( pp \) data set, corresponding to 4.7 fb\(^{-1}\), and includes improvements in the analysis and event selection that further increase sensitivity to models of interest.

Events are selected with large jet multiplicities ranging from \( \geq 6 \) to \( \geq 9 \) jets, in association with significant \( E_T^{\text{miss}} \). Events containing high transverse momentum \( (p_T) \) electrons or muons are vetoed in order to reduce backgrounds from (semi-leptonically) decaying top quarks or \( W \) bosons. Other complementary searches have been performed by the ATLAS collaboration in final states with \( E_T^{\text{miss}} \) and one or more leptons [14, 15]. Further searches have been carried out by ATLAS using events with at least two, three or four jets [16], or with at least two \( b \)-tagged jets [17]. Searches have also been performed by the CMS collaboration, including a recent analysis in fully hadronic final states [18].

2 The ATLAS detector and data samples

The ATLAS experiment [19] is a multi-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and nearly 4\( \pi \) coverage in solid angle.\(^1\) The layout of the detector is dominated by four superconducting magnet systems, which comprise a thin solenoid surrounding inner tracking detectors, and a barrel and two end-cap toroids supporting a large muon spectrometer. The calorimeters are of particular importance to this analysis. In the pseudorapidity region \( |\eta| < 3.2 \), high-granularity liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. An iron/scintillator-tile calorimeter provides hadronic coverage for \( |\eta| < 1.7 \). The end-cap and forward regions, spanning 1.5 \( < |\eta| < 4.9 \), are instrumented with LAr calorimetry for both EM and hadronic measurements.

The data sample used in this analysis was taken during April–October 2011 with the LHC operating at a proton-proton centre-of-mass energy of \( \sqrt{s} = 7 \) TeV. Application of beam, detector and data-quality requirements resulted in a corresponding integrated luminosity of 4.7\( \pm 0.2 \) fb\(^{-1}\) [20]. The analysis makes use of dedicated multi-jet triggers that required either at least four jets with \( p_T > 45 \) GeV or at least five jets with \( p_T > 30 \) GeV,\(^1\)

\(^1\)ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the \( z \)-axis along the beam pipe. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \( \phi \) being the azimuthal angle around the beam pipe. The pseudorapidity \( \eta \) is defined in terms of the polar angle \( \theta \) by \( \eta = -\ln \tan(\theta/2) \),
where the energy is measured at the electromagnetic scale\(^2\) and the jets must have \(|\eta| < 3.2\). In all cases the trigger efficiency was greater than 98% for events satisfying the offline jet multiplicity selections described in section 4.

## 3 Object reconstruction

The jet, lepton and missing transverse momentum definitions are based closely on those of ref. [13], with small updates to account for evolving accelerator and detector conditions.

Jet candidates are reconstructed using the anti-\(k_t\) jet clustering algorithm [21, 22] with radius parameter of 0.4. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the noise level. Jet momenta are reconstructed by performing a four-vector sum over these topological clusters of calorimeter cells, treating each as an \((E, \vec{p})\) four-vector with zero mass. The jet energies are corrected for the effects of calorimeter non-compensation and inhomogeneities by using \(p_T\) - and \(\eta\)-dependent calibration factors based on Monte Carlo (MC) simulations validated with extensive test-beam and collision-data studies [23]. Only jet candidates with \(p_T > 20\text{ GeV}\) and \(|\eta| < 4.9\) are retained. Further corrections are applied to any jet falling in problematic areas of the calorimeter. The event is rejected if, for any jet, this additional correction leads to a contribution to \(E_T^{\text{miss}}\) that is greater than both 10 GeV and 0.1 \(E_T^{\text{miss}}\). These criteria, along with selections against non-collision background and calorimeter noise, lead to a loss of signal efficiency of \(\sim 8\%\) for the models considered. When identification of jets containing heavy flavour quarks is required, either to make measurements in control regions or for cross checks, a tagging algorithm exploiting both impact parameter and secondary vertex information is used. Jets are tagged for \(|\eta| < 2.5\) and the parameters of the algorithm are chosen such that 70\% of \(b\)-jets and \(\sim 1\%\) of light flavour or gluon jets, are selected in \(t\bar{t}\) events in Monte Carlo simulation [24]. Jets initiated by charm quarks are tagged with about 20\% efficiency.

Electron candidates are required to have \(p_T > 20\text{ GeV}\) and \(|\eta| < 2.47\), and to satisfy the ‘medium’ electron shower shape and track selection criteria of ref. [14]. Muon candidates are required to have \(p_T > 10\text{ GeV}\) and \(|\eta| < 2.4\). Additional requirements are applied to muons when defining leptonic control regions. In this case muons must have longitudinal and transverse impact parameters within 1 mm and 0.2 mm of the primary vertex, respectively, and the sum of the transverse momenta of other tracks within a cone of \(\Delta R = 0.2\) around the muon must be less than 1.8 GeV, where \(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}\).

The measurement of the missing transverse momentum two-vector \(\vec{p}_T^{\text{miss}}\) and its magnitude (conventionally denoted \(E_T^{\text{miss}}\)) is then based on the transverse momenta of all electron and muon candidates, all jets with \(|\eta| < 4.5\) which are not also electron candidates, and all calorimeter clusters with \(|\eta| < 4.5\) not associated to such objects [25].

Following the steps above, overlaps between candidate jets with \(|\eta| < 2.8\) and leptons are resolved as follows. First, any such jet candidate lying within a distance \(\Delta R = 0.2\) of an

\(^2\)The electromagnetic scale is the basic calorimeter signal scale for the ATLAS calorimeters. It has been established using test-beam measurements for electrons and muons to give the correct response for the energy deposited in electromagnetic showers, although it does not correct for the lower response of the calorimeter to hadrons.
electron is discarded, then any lepton candidate remaining within a distance $\Delta R = 0.4$ of such a jet candidate is discarded. Thereafter, all jet candidates with $|\eta| > 2.8$ are discarded, and the remaining electron, muon and jet candidates are retained as reconstructed objects.

### 4 Event selection

Following the object reconstruction described in section 3, events are discarded if they contain any jet failing quality criteria designed to suppress detector noise and non-collision backgrounds, or if they lack a reconstructed primary vertex with five or more associated tracks.

For events containing no isolated electrons or muons, six non-exclusive signal regions (SRs) are defined as shown in table 1. The first three require at least seven, eight or nine jets, respectively, with $p_T > 55$ GeV; the latter three require at least six, seven or eight jets, respectively, with $p_T > 80$ GeV. The final selection variable is $E_T^{\text{miss}}/\sqrt{H_T}$, the ratio of the magnitude of the missing transverse momentum to the square root of the scalar sum $H_T$ of the transverse momenta of all jets with $p_T > 40$ GeV and $|\eta| < 2.8$. This ratio is closely related to the significance of the missing transverse momentum relative to the resolution due to stochastic variations in the measured jet energies [25]. The value of $E_T^{\text{miss}}/\sqrt{H_T}$ is required to be larger than 4 GeV$^{1/2}$ for all signal regions.

A previous ATLAS analysis of similar final states [13] required jets to be separated by $\Delta R > 0.6$ to ensure that the trigger efficiency was on its plateau. It has since been demonstrated that the requirement of an offline jet multiplicity at least one larger than that used in the trigger is sufficient to achieve a 98% trigger efficiency. Investigations on the enlarged data sample, in comparison to the previous incarnation of the strategy used here, allow various improvements to be made; in particular, the requirement on jet-jet separation is modified so as to increase the acceptance for signal models of interest by a factor two to five, without introducing any significant trigger inefficiency.

The dominant backgrounds are multi-jet production, including purely strong interaction processes and fully hadronic decays of $t\bar{t}$; semi- and fully-leptonic decays of $t\bar{t}$; and leptonically decaying $W$ or $Z$ bosons produced in association with jets. Non-fully-hadronic $t\bar{t}$, and $W$ and $Z$ are collectively referred to as ‘leptonic’ backgrounds. Contributions from gauge boson pair and single top quark production are negligible. The determination of the multi-jet and ‘leptonic’ backgrounds is described in sections 6 and 7, respectively.

| Signal region | 7j55 | 8j55 | 9j55 | 6j80 | 7j80 | 8j80 |
|---------------|------|------|------|------|------|------|
| Number of isolated leptons ($e, \mu$) | = 0 |
| Jet $p_T$ | $> 55$ GeV | $> 80$ GeV |
| Jet $|\eta|$ | < 2.8 |
| Number of jets | $\geq 7$ | $\geq 8$ | $\geq 9$ | $\geq 6$ | $\geq 7$ | $\geq 8$ |
| $E_T^{\text{miss}}/\sqrt{H_T}$ | $> 4$ GeV$^{1/2}$ |

Table 1. Definitions of the six signal regions.
5 Monte Carlo simulations

Monte Carlo simulations are used as part of the ‘leptonic’ background determination process, and to assess sensitivity to specific SUSY signal models. The ‘leptonic’ backgrounds are generated using Alpgen2.13 [26] with the PDF set CTEQ6L1 [27]. Fully-leptonic $t\bar{t}$ events are generated with up to five additional partons in the matrix element, while semi-leptonic $t\bar{t}$ events are generated with up to three additional partons in the matrix element. $W + \text{jets}$ and $Z \to \nu\bar{\nu} + \text{jets}$ are generated with up to six additional partons, and the $Z \to \ell^+\ell^- + \text{jets}$ ($\ell \in \{e, \mu, \tau\}$) process is generated with up to five additional partons in the matrix element. In all cases, additional jets are generated via parton showering, which, together with fragmentation and hadronization, is performed by Herwig [28, 29]. Jimmy [30] is used to simulate the underlying event. The $W + \text{jets}$, $Z + \text{jets}$ and $t\bar{t}$ backgrounds are normalized according to their inclusive theoretical cross sections [31, 32].

The estimation of the ‘leptonic’ backgrounds in the signal regions is described in detail in section 7.

Supersymmetric production processes are generated using Herwig++2.4.2 [33]. Signal cross sections are calculated to next-to-leading order in the strong coupling constant $\alpha_S$, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [34–38]. An envelope of cross-section predictions is defined using the 68% confidence-level (CL) ranges of the CTEQ6.6 [39] (including the $\alpha_S$ uncertainty) and MSTW2008 NLO [40] PDF sets, together with independent variations of the factorization and renormalization scales by factors of two or one half. The nominal cross-section value is then taken to be the midpoint of the envelope, and the uncertainty assigned is half the full width of the envelope, following closely the PDF4LHC recommendations [41]. MSUGRA/CMSSM particle spectra and decay modes are calculated with ISAJET++7.75 [42]. For illustrative purposes, plots of kinematic quantities show the distribution expected for an example MSUGRA/CMSSM point that has not been excluded in previous searches. This reference point is defined by: $m_0 = 2960$ GeV, $m_{1/2} = 240$ GeV, $A_0 = 0$, $\tan \beta = 10$, and $\mu > 0$.

All Monte Carlo samples employ a detector simulation [43] based on GEANT4 [44] and are reconstructed with the same algorithms as the data.

6 Multi-jet backgrounds

The dominant background at intermediate values of $E_T^{miss}$ is multi-jet production including purely strong interaction processes and fully hadronic decays of $t\bar{t}$. These processes are not

---

3The NLL correction is used for squark and gluino production when the average of the squark masses in the first two generations and the gluino mass lie between 200 GeV and 2 TeV. In the case of gluino-pair (associated squark-gluino) production processes, the calculations were extended up to squark masses of 4.5 TeV (3.5 TeV). For masses outside this range and for other types of production processes (i.e. electroweak and associated strong and electroweak), cross sections at NLO accuracy obtained with Prospino2.1 [34] are used.

4A particular MSUGRA/CMSSM model point is 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 $\mu$. 
reliably predicted with existing Monte Carlo calculations, and so their contributions must be determined from collision data. Indeed, the selection cuts have been designed such that multi-jet processes can be determined reliably from supporting measurements.

The method for determining the multi-jet background from data is motivated by the following considerations. In events dominated by jet activity, including hadronic decays of top quarks and gauge bosons, the $E_T^{\text{miss}}$ resolution is approximately proportional to $\sqrt{H_T}$, and is almost independent of the jet multiplicity. The distribution of the ratio $E_T^{\text{miss}}/\sqrt{H_T}$ has a shape that is almost invariant under changes in the jet multiplicity, as shown in figure 1. The multi-jet backgrounds therefore can be determined using control regions with lower $E_T^{\text{miss}}/\sqrt{H_T}$ and/or lower jet multiplicity than the signal regions.\(^5\) The control regions are assumed to be dominated by Standard Model processes, an assumption that is corroborated by the agreement of multi-jet cross section measurements with up to six jets [45] with Standard Model predictions.

As an example, the estimation of the background expected in the 8j55 signal region is obtained as follows. A template describing the shape of the $E_T^{\text{miss}}/\sqrt{H_T}$ distribution is obtained from those events that contain exactly six jets, using the same 55 GeV $p_T$ threshold as the target signal region. That six-jet $E_T^{\text{miss}}/\sqrt{H_T}$ template is normalized to the number

\(^5\)Residual variations in the shape of the $E_T^{\text{miss}}/\sqrt{H_T}$ are later used to quantify the systematic uncertainty associated with the method, as described in section 6.1.
of eight-jet events observed in the region \( \frac{E_T^{\text{miss}}}{\sqrt{H_T}} < 1.5 \text{ GeV}^{1/2} \) after subtraction of the ‘leptonic’ background expectation. The normalized template then provides a prediction for the multi-jet background for the 8j55 signal region for which \( \frac{E_T^{\text{miss}}}{\sqrt{H_T}} > 4 \text{ GeV}^{1/2} \).

A similar procedure is used for each of the signal regions, and can be summarized as follows. For each jet \( p_T \) threshold \( p_\text{<} \in \{55 \text{ GeV}, 80 \text{ GeV} \} \), control regions are defined for different numbers \( n_{\text{jet}} \) of jets found above \( p_\text{<} \). The number of events \( N_{p_\text{<}, n_{\text{jet}}} (s_{\text{min}}, s_{\text{max}}) \) for which \( E_T^{\text{miss}}/\sqrt{H_T} \) (in units of \( \text{ GeV}^{1/2} \)) lies between \( s_{\text{min}} \) and \( s_{\text{max}} \) is determined, and the predicted ‘leptonic’ contributions \( L_{p_\text{<}, n_{\text{jet}}} (s_{\text{min}}, s_{\text{max}}) \) subtracted

\[
N_{p_\text{<}, n_{\text{jet}}}^L (s_{\text{min}}, s_{\text{max}}) = N_{p_\text{<}, n_{\text{jet}}} (s_{\text{min}}, s_{\text{max}}) - L_{p_\text{<}, n_{\text{jet}}} (s_{\text{min}}, s_{\text{max}}).
\]

Transfer factors

\[
T_{p_\text{<}, n_{\text{jet}}} = \frac{N_{p_\text{<}, n_{\text{jet}}}^L (4, \infty)}{N_{p_\text{<}, n_{\text{jet}}}^L (0, 1.5)}
\]

connect regions with the same \( p_\text{<} \) and \( n_{\text{jet}} \) with different \( E_T^{\text{miss}}/\sqrt{H_T} \). The multi-jet prediction for the signal region is found from the product of the \( T_{p_\text{<}, n_{\text{jet}}} \), with the same \( p_\text{<} \) as the signal region and \( n_{\text{jet}} = 6 \) when \( p_\text{<} = 55 \text{ GeV} \) (\( n_{\text{jet}} = 5 \) when \( p_\text{<} = 80 \text{ GeV} \)) times the number of events (after subtracting the expected contribution from ‘leptonic’ background sources) satisfying signal region jet multiplicity requirements but with \( E_T^{\text{miss}}/\sqrt{H_T} < 1.5 \text{ GeV}^{1/2} \).

### 6.1 Systematic uncertainties on multi-jet backgrounds

The method is validated by determining the accuracy of predictions for regions with jet multiplicities and/or \( E_T^{\text{miss}}/\sqrt{H_T} \) smaller than those chosen for the signal regions. Figure 1 shows that the shape of the \( E_T^{\text{miss}}/\sqrt{H_T} \) distribution for \( p_\text{<} = 55 \text{ GeV} \) and \( n_{\text{jet}} = 6 \) is predicted to an accuracy of better than 20% from that measured using a template with the same value of \( p_\text{<} \) and \( n_{\text{jet}} = 5 \). Similarly, the distribution for \( p_\text{<} = 80 \text{ GeV} \) and \( n_{\text{jet}} = 5 \) can be predicted for all \( E_T^{\text{miss}}/\sqrt{H_T} \) using a template with \( n_{\text{jet}} = 4 \). The templates are normalized for \( E_T^{\text{miss}}/\sqrt{H_T} < 1.5 \text{ GeV}^{1/2} \), and continue to provide a good prediction of the distribution out to values of \( E_T^{\text{miss}}/\sqrt{H_T} \) of \( 4 \text{ GeV}^{1/2} \) and beyond. Additional validation regions are defined for each \( p_\text{<} \) and for jet multiplicity requirements equal to those of the signal regions, but for the intermediate values of \( (s_{\text{min}}, s_{\text{max}}) \) of \( (1.5, 2) \), \( (2, 2.5) \) and \( (2.5, 3.5) \). Residual inaccuracies in the predictions are used to quantify the systematic uncertainty from the closure of the method. Those uncertainties are in the range 15%–25%, depending on \( p_\text{<} \) and \( E_T^{\text{miss}}/\sqrt{H_T} \).

The mean number of proton-proton interactions per bunch crossing \( \langle \mu \rangle \) increased during the 2011 run, reaching \( \langle \mu \rangle = 16 \) at the start of proton fills for runs late in the year. Sensitivity to those additional interactions is studied by considering the jet multiplicity as a function of \( \langle \mu \rangle \), and of the number of reconstructed primary vertices. The consistency of the high-\( p_T \) tracks within the selected jets with a common primary vertex is also investigated. The effect of additional jets from pile-up interactions is found to be significant for low-\( p_T \) jets but small for jets with \( p_T > 45 \text{ GeV} \), and negligible for the jet selection used for the SRs.
The presence of multiple in-time and out-of-time pp interactions also leads to a small but significant deterioration of the $E_T^{\text{miss}}$ resolution. The effectiveness of the $E_T^{\text{miss}}/\sqrt{H_T}$ template method described above is tested separately for subsets of the data with different values of the instantaneous luminosity, and hence of $\langle \mu \rangle$. Good agreement is found separately for each subset of the data. Since the data set used to form the template has the same pile-up conditions as that used to form the signal regions, the changing shape of the $E_T^{\text{miss}}$ resolution is included in the data-driven determination and does not lead to any additional systematic uncertainty.

Due to the presence of neutrinos produced in the decay of hadrons containing bottom or charm quarks, events with heavy-flavour jets exhibit a different $E_T^{\text{miss}}$ distribution. To quantify the systematic uncertainty associated with this difference, separate templates are defined for events with at least one $b$-tagged jet and for those with none. The sum of the predictions for events with and without $b$-tagged jets is compared to the flavour-blind approach, and the difference is used to characterize the systematic uncertainty from heavy flavour (10%–20%). Other systematic uncertainties account for imperfect knowledge of: the subtracted ‘leptonic’ contributions (10%), the potential trigger inefficiency (2%), and imperfect response of the calorimeter in problematic areas (1%).

The backgrounds from multi-jet processes are cross checked using another data-driven technique [16] which smears the energies of individual jets from low-$E_T^{\text{miss}}$ multi-jet ‘seed’ events in data. Separate smearing functions are defined for $b$-tagged and non-$b$-tagged jets, with each modelling both the Gaussian core and the non-Gaussian tail of the jet response, including the loss of energy from unobserved neutrinos. The jet smearing functions are derived from GEANT4 [44] simulations [43]. The Gaussian core of the function is tuned to di-jet data, and the non-Gaussian tails are verified with data in three-jet control regions in which the $p_T^{\text{miss}}$ can be associated with the fluctuation of a particular jet. There is agreement within uncertainties between the background predicted by this jet-smearing method and the primary method based on the shape invariance of $E_T^{\text{miss}}/\sqrt{H_T}$.

### 7 ‘Leptonic’ backgrounds

Non-fully-hadronic (i.e. semi-leptonic or di-leptonic) $t\bar{t}$, and $W$ and $Z$ production are collectively referred to as ‘leptonic’ backgrounds. The process $Z \rightarrow \nu\nu + \text{jets}$ contributes to the signal regions since it produces jets in association with $E_T^{\text{miss}}$. Leptonic $t\bar{t}$ and $W$ decays contribute to the signal regions when hadronic $\tau$ decays allow them to evade the lepton veto, with smaller contributions from events in which electrons or muons are produced but are not reconstructed.

The ‘leptonic’ background predictions employ the Monte Carlo simulations described in section 5. To reduce uncertainties from Monte Carlo modelling and detector response, it is desirable to normalize the background predictions to data using control regions (CR) and cross-check them against data in other validation regions (VR). These control regions and validation regions are designed to be distinct from, but kinematically close to, the signal regions. Each is designed to provide enhanced sensitivity to a particular background process.

The control and validation regions are defined as shown in table 2. By using control regions that are kinematically similar to the signal regions, theoretical uncertainties, includ-
Figure 2. Jet multiplicity distributions for the $\bar{t}t + \text{jets}$ validation regions (left) and control regions (right) before any jet multiplicity requirements, for a jet $p_T$ threshold of 45 GeV (top), 55 GeV (middle) and 80 GeV (bottom).
### Table 2. Definitions of the validation regions and control regions for the 'leptonic' backgrounds: $t\bar{t} + \text{jets}$, $W + \text{jets}$ and $Z + \text{jets}$. The validation regions VR are defined by the first five selection requirements. A long dash ‘—’ indicates that no requirement is made. The control regions CR differ from the VR in their treatment of the muons, and by having additional requirements on jets and $E_T^{\text{miss}}/\sqrt{H_T}$, as shown in the final two rows.

| Requirement                        | $t\bar{t} + \text{jets}$ | $W + \text{jets}$ | $Z + \text{jets}$ |
|------------------------------------|---------------------------|-------------------|-------------------|
| **Muon kinematics**                | $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$ |                   |                   |
| **Muon multiplicity**              | $= 1$                     | $= 2$             |                   |
| **Electron multiplicity**          |                           |                   |                   |
| **$b$-tagged jet multiplicity**    | $\geq 1$                  | $= 0$             | $—$               |
| **$m_T$ or $m_{\mu\mu}$**         | $50 \text{ GeV} < m_T < 100 \text{ GeV}$ | $80 \text{ GeV} < m_{\mu\mu} < 100 \text{ GeV}$ |                   |
| **VR $\rightarrow$ CR transform** | $\mu \rightarrow \text{jet}$ | $\mu \rightarrow \nu$ |                   |
| **Jet $p_T$, $|\eta|$, multiplicity (CR)** |                           |                   | As in table 1. |
| $E_T^{\text{miss}}/\sqrt{H_T}$ (CR) |                           |                   |                   |

In detail, for those control regions where the Monte Carlo simulations predict at least one event for $4.7 \text{ fb}^{-1}$, the leptonic background prediction $s_i$ for each signal region from each background is calculated by multiplying the number of data events $c_i^{\text{data}}$ found in the corresponding control region by a Monte Carlo-based factor $t_i^{\text{MC}}$

$$s_i = c_i^{\text{data}} \times t_i^{\text{MC}}.$$  

This transfer factor is defined to be the ratio of the number of MC events found in the signal region to the number of MC events found in the control region

$$t_i^{\text{MC}} = \frac{s_i^{\text{MC}}}{c_i^{\text{MC}}}.$$  

In each case, the event counts are corrected for the expected contamination by the other background processes. Whenever less than one event is predicted in the control region,

---

---

6 The procedure is also sensitive to those di-leptonic $t\bar{t}$ decays in which one lepton was not observed in the VR. After the VR $\rightarrow$ CR replacement ($\mu \rightarrow \text{jet}$), the procedure captures the leading di-leptonic $t\bar{t}$ contributions to the SR.
the Monte Carlo prediction for the corresponding signal region is used directly, without invoking a transfer factor.

For the $t\bar{t} +$ jets background, the validation region requires exactly one isolated muon, at least one $b$-tagged jet, and no selected electrons. The transverse mass for the muon transverse momentum $p_T^\mu$ and the missing transverse momentum two-vector $\vec{p}_{T}^{\text{miss}}$ is calculated using massless two-vectors

$$m_T^2 = 2|\vec{p}_T^\mu||\vec{p}_{T}^{\text{miss}}| - 2\vec{p}_T^\mu \cdot \vec{p}_{T}^{\text{miss}},$$

and must satisfy $50 \text{ GeV} < m_T < 100 \text{ GeV}$. Figure 2 shows the jet multiplicity in the $t\bar{t}$ validation regions, and it is demonstrated that the Monte Carlo provides a good description of the data.

The $t\bar{t}$ control regions used to calculate the background expectation differ from the validation regions as follows. Since the dominant source of background is from hadronic $\tau$ decays in the control regions, the muon is used to mimic a jet, as follows. If the muon has sufficient $p_T$ to pass the jet selection threshold $p_{<}$, the jet multiplicity is incremented by one. If the muon $p_T$ is larger than 40 GeV it is added to $H_T$. The selection variable $E_{T}^{\text{miss}}/\sqrt{H_{T}}$ is then recalculated, and required to be larger than the threshold value of 4 GeV$^{1/2}$. Distributions of the jet multiplicity in the $t\bar{t}$ control regions may also be found in figure 2.

The $W +$ jets validation regions and control regions are defined in a similar manner to those for $t\bar{t} +$ jets, except that a $b$-jet veto is used rather than a $b$-jet requirement (see table 2). Figure 3 shows that the resulting jet multiplicity distributions are well described by the Monte Carlo simulations.

The $Z +$ jets validation regions are defined (as shown in table 2) requiring precisely two muons with invariant mass $m_{\mu\mu}$ consistent with $m_Z$. The dominant backgrounds from $Z +$ jets arise from decays to neutrinos, so in forming the $Z +$ jets control regions from the validation regions, the vector sum of the $p_T$ of the muons is added to the measured $\vec{p}_{T}^{\text{miss}}$, to model the $E_{T}^{\text{miss}}$ expected from $Z \rightarrow \nu\nu$ events. The selection variable $E_{T}^{\text{miss}}/\sqrt{H_{T}}$ is then recalculated and required to be greater than 4 GeV$^{1/2}$ for events in the control region. Figure 4 shows that the resulting jet multiplicity distributions in both validation and control regions are well described by the Monte Carlo simulations.

For each of the ‘leptonic’ backgrounds further comparisons are made between Monte Carlo and data using the lower jet $p_T$ threshold of 45 GeV, showing agreement within uncertainties for all multiplicities (up to nine jets for $t\bar{t}$, see figures 2(a) and 2(b). The Alpgen Monte Carlo predictions for $Z +$ jets and $W +$ jets were determined with six additional partons in the matrix element calculation, and cross checked with a calculation in which only five additional partons were produced in the matrix element — in each case with additional jets being produced in the parton shower. The two predictions are consistent with each other and with the data, providing further supporting evidence that the parton shower offers a sufficiently accurate description of the additional jets.

7.1 Systematic uncertainties on ‘leptonic’ backgrounds

The use of control regions is effective in reducing uncertainties from Monte Carlo modelling and detector response. When predictions are taken directly from the Monte Carlo, the
Figure 3. Jet multiplicity distributions for the \( W^\pm + \) jets validation regions (left) and control regions (right) before any jet multiplicity requirements, and for a jet \( p_T \) threshold of 55 GeV (top) and 80 GeV (bottom).

‘leptonic’ background determinations are subject to systematic uncertainties from Monte Carlo modelling of: the jet energy scale (JES, 40%), the jet energy resolution (JER, 4%), the number of multiple proton-proton interactions (3%), the \( b \)-tagging efficiency (5% for \( t\bar{t} \)), the muon trigger and reconstruction efficiency and the muon momentum scale. The numbers in parentheses indicate the typical values of the SR event yield uncertainties prior to the partial cancellations that result from the use of control regions.

The JES and JER uncertainties are calculated using a combination of data-driven and Monte Carlo techniques [23], using the complete 2011 ATLAS data set. The calculation accounts for the variation in the uncertainty with jet \( p_T \) and \( \eta \), and that due to nearby jets. The Monte Carlo simulations model the multiple proton-proton interactions with a
ep 

\text{thresholds} \approx \frac{Z}{E_T} > \text{final}

\text{prior to the final} + \text{jets validation regions and control regions.}

\text{shows the jet multiplicity distributions for the two different jet}

\text{requirements. It should be noted that the signal regions are}

\text{shows the distributions after applying the jet selections for the six}

\text{requirements.}

\text{but for the} \langle H_T \rangle \text{requirement.}

\text{scale uncertainty is reduced to} \approx 6%.

\text{When transfer factors are used to connect control regions to signal regions, the effects}

\text{of these uncertainties largely cancel in the ratio. For example, the impact of the jet energy}

\text{scale uncertainty is reduced to} \approx 6%.

\text{results, interpretation and limits}

\text{Figure 5 shows the} E_T^{\text{miss}} / \sqrt{H_T} \text{distributions after applying the jet selections for the six}

\text{different signal regions (see table 1) prior to the final} E_T^{\text{miss}} / \sqrt{H_T} > 4 \text{ GeV}^{1/2} \text{ requirement.}

\text{Figure 6 shows the jet multiplicity distributions for the two different jet} p_T \text{ thresholds}

\text{after the final} E_T^{\text{miss}} / \sqrt{H_T} \text{ requirement. It should be noted that the signal regions are}
for each of the six different signal regions, prior to the final requirement.

\[
\frac{E_T^\text{miss}}{\sqrt{H_T}} > 55 \text{ GeV}
\]

\[
\frac{E_T^\text{miss}}{\sqrt{H_T}} > 80 \text{ GeV}
\]

\[
\frac{E_T^\text{miss}}{\sqrt{H_T}} > 4 \text{ GeV}^{1/2}
\]

\[
\frac{E_T^\text{miss}}{\sqrt{H_T}} > 4 \text{ GeV}^{1/2}
\]

**Figure 5.** The distribution of the variable \(\frac{E_T^\text{miss}}{\sqrt{H_T}}\) for each of the six different signal regions defined in table 1, prior to the final \(\frac{E_T^\text{miss}}{\sqrt{H_T}} > 4 \text{ GeV}^{1/2}\) requirement.
Figure 6. The distribution of jet multiplicity for jets with $p_T > 55$ GeV (a) and those with $p_T > 80$ GeV (b). Only events with $E_T^{\text{miss}}/\sqrt{H_T} > 4$ GeV$^{1/2}$ are shown.
Table 3. Results for each of the six signal regions for an integrated luminosity of 4.7 fb$^{-1}$. The expected numbers of Standard Model events are given for each of the following sources: multi-jet (including fully hadronic $t\bar{t}$), semi- and fully-leptonic $t\bar{t}$ decays combined, and $W$ and $Z$ bosons (separately) in association with jets, as well as the total Standard Model expectation. The uncertainties on the predictions show the combination of the statistical and systematic components. Where small event counts in control regions have not made it possible to determine a central value for the expectation, an asymmetric bound is given instead. The numbers of observed events are also shown. The final five rows show the statistical quantities described in the text. Both the expected (exp) and the observed (obs) values are shown for $N^{95\%}_{BSM,max}$ and $\sigma^{95\%}_{BSM,max} \times A \times \epsilon$.

Table 3.

| Signal region | 7j55    | 8j55    | 9j55    | 6j80    | 7j80    | 8j80    |
|---------------|---------|---------|---------|---------|---------|---------|
| Multi-jets    | 91±20   | 10±3    | 1.2±0.4 | 67±12   | 5.4±1.7 | 0.42±0.16 |
| $t\bar{t} \rightarrow q\ell, \ell\ell$ | 55±18   | 5.7±6.0 | 0.70±0.72 | 24±13   | 2.8±1.8 | 0.38±0.40 |
| $W + \text{jets}$ | 18±11   | 0.81±0.72 | 0±0.13  | 13±10   | 0.34±0.21 | 0±0.06  |
| $Z + \text{jets}$ | 2.7±1.6 | 0.05±0.19 | 0±0.12  | 2.7±2.9 | 0.10±0.17 | 0±0.13  |
| **Total Standard Model** | **167±34** | **17±7** | **1.9±0.8** | **107±21** | **8.6±2.5** | **0.80±0.45** |
| **Data** | 154 | 22 | 3 | 106 | 15 | 1 |
| $N^{95\%}_{BSM,max}$ (exp) | 72 | 16 | 4.5 | 46 | 8.4 | 3.5 |
| $N^{95\%}_{BSM,max}$ (obs) | 64 | 20 | 5.7 | 46 | 15 | 3.8 |
| $\sigma^{95\%}_{BSM,max} \times A \times \epsilon$ (exp) [fb] | 15 | 3.4 | 0.96 | 9.8 | 1.8 | 0.74 |
| $\sigma^{95\%}_{BSM,max} \times A \times \epsilon$ (obs) [fb] | 14 | 4.2 | 1.2 | 9.8 | 3.2 | 0.81 |
| $p_{SM}$ | 0.64 | 0.27 | 0.28 | 0.52 | 0.07 | 0.43 |

not exclusive. For example, in figure 5, all plots contain the same event at $E_T^{\text{miss}}/\sqrt{H_T} \sim 11$ GeV$^{1/2}$. The ‘leptonic’ backgrounds shown in the figures are those calculated from the Monte Carlo simulation, using the MC calculation of the cross section and normalized to 4.7 fb$^{-1}$. The number of events observed in each of the six signal regions, as well as their Standard Model background expectations are shown in table 3. Good agreement is observed between SM expectations and the data for all six signal regions. Table 3 also shows the 95% confidence-level upper bound $A^{95\%}_{BSM,max}$ on the number of events originating from sources other than the Standard Model, the corresponding upper limit $\sigma^{95\%}_{BSM,max} \times A \times \epsilon$ on the cross section times efficiency within acceptance (which equals the limit on the observed number of signal events divided by the luminosity) and the $p$-value for the Standard-Model-only hypothesis ($p_{SM}$).

In the absence of significant discrepancies, limits are set in the context of two supersymmetric (SUSY) models. The first is the $\tan \beta = 10$, $A_0 = 0$ and $\mu > 0$ slice of the MSUGRA/CMSSM parameter space. The second is a simplified SUSY model with only a gluino octet and a neutralino $\tilde{\chi}_1^0$ within kinematic reach. Theoretical uncertainties on the SUSY signals are estimated as described in section 5. Combined experimental systematic uncertainties on the signal yield from jet energy scale, resolution, and event cleaning are approximately 25%. Acceptance times efficiency values are tabulated elsewhere [50].

The limit for each signal region is obtained by comparing the observed event count with that expected from Standard Model background plus SUSY signal processes, taking into
**Figure 7.** Combined 95% CL exclusion curves for the $\tan \beta = 10$, $A_0 = 0$ and $\mu > 0$ slice of MSUGRA/CMSSM (a) and for the simplified gluino-neutralino model (b). The dashed grey and solid red lines show the 95% CL expected and observed limits respectively, including all uncertainties except the theoretical signal cross section uncertainty (PDF and scale). The shaded yellow band around the expected limit shows its $\pm 1\sigma$ range. The $\pm 1\sigma$ lines around the observed limit represent the result produced when moving the signal cross section by $\pm 1\sigma$ (as defined by the PDF and scale uncertainties). The contours on the MSUGRA/CMSSM model show values of the mass of the gluino and the mean mass of the squarks in the first two generations. Exclusion limits are also shown from previous ATLAS searches with $\geq 2$, 3 or 4 jets plus $E_T^{miss}$ [16], multi-jets plus $E_T^{miss}$ [13] or with same-sign dileptons [46] and from LEP [47, 48] in (a). The lower plot shows limits from ATLAS searches with same-sign dileptons [46] or with one-lepton plus $b$-jet [49].
account all uncertainties on the Standard Model expectation, including those which are correlated between signal and background (for instance jet energy scale uncertainties) and all but theoretical cross section uncertainties (PDF and scale) on the signal expectation. The combined exclusion regions are obtained using the \( CL_s \) prescription \cite{51}, taking the signal region with the best expected limit at each point in parameter space. The 95\% confidence level (CL) exclusion in the \( \tan \beta = 10, A_0 = 0 \) and \( \mu > 0 \) slice of MSUGRA/CMSSM is shown in figure 7. The ±1\( \sigma \) band surrounding the expected limit shows the variation anticipated from statistical fluctuations and systematic uncertainties on SM and signal processes. The uncertainties on the supersymmetric signal cross section from PDFs and higher-order terms are calculated as described in section 5, and the resulting signal cross section uncertainty is represented by ±1\( \sigma \) lines on either side of the observed limit.\(^7\)

The analysis substantially extends the previous exclusion limits \cite{13, 16, 17} for \( m_0 > 500 \) GeV. For large \( m_0 \), the analysis becomes independent of the squark mass, and the lower bound on the gluino mass is extended to almost 840 GeV for large \( m_0 \).\(^8\) In the simplified model gluinos are pair-produced and decay with unit probability to \( t\bar{t} + \tilde{\chi}_1^0 \). In this context, the 95\% CL exclusion bound on the gluino mass is 870 GeV for neutralino masses up to 100 GeV.

## 9 Summary

A search for new physics is presented using final states containing large jet multiplicities in association with missing transverse momentum. The search uses the full 2011 \( pp \) LHC data set taken at \( \sqrt{s} = 7 \) TeV, collected with the ATLAS detector, which corresponds to an integrated luminosity of 4.7 fb\(^{-1}\).

Six non-exclusive signal regions are defined. The first three require at least seven, eight or nine jets, with \( p_T > 55 \) GeV; the latter three require at least six, seven or eight jets, with \( p_T > 80 \) GeV. In all cases the events are required to satisfy \( E_T^{\text{miss}}/\sqrt{H_T} > 4 \) GeV\(^{1/2}\), and to contain no isolated high-\( p_T \) electrons or muons. Investigations on the enlarged data sample have resulted in improvements compared to a previous measurement using a similar strategy. In particular, inclusion of events with smaller jet-jet separation increases the acceptance for signal models of interest by a factor two to five, without significantly increasing the systematic uncertainty.

The Standard Model multi-jet background is determined using a template-based method that exploits the invariance of \( E_T^{\text{miss}}/\sqrt{H_T} \) under changes in jet multiplicity, cross-checked with a jet-smearing method that uses well reconstructed multi-jet seed events from data. The other significant backgrounds — \( t\bar{t} + \text{jets} \), \( W + \text{jets} \) and \( Z + \text{jets} \) — are determined using a combination of data-driven and Monte Carlo-based methods.

In each of the six signal regions, agreement is found between the Standard Model prediction and the data. In the absence of significant discrepancies, the results are interpreted

\(^7\)Previous analyses have a slightly different presentation of the effect of the signal cross section uncertainty. In refs. \cite{13, 16, 17} the effect of the signal cross section uncertainty was folded into the displayed limits and so was not shown separately.

\(^8\)Limits on sparticle masses quoted in the text are those from the lower edge of the 1\( \sigma \) signal cross section band rather than the central value of the observed limit, so can be considered conservative.
as limits in the context of $R$-parity conserving supersymmetry. Exclusion limits are shown for MSUGRA/CMSSM, for which, for large $m_0$, gluino masses smaller than 840 GeV are excluded at the 95% confidence level. For a simplified supersymmetric model in which both of the pair-produced gluinos decay via the process $\tilde{g} \to t + \bar{t} + \tilde{\chi}_1^0$, gluino masses smaller than about 870 GeV are similarly excluded for $\tilde{\chi}_1^0$ masses up to 100 GeV.

A Event displays

A display of an event that passes the 9j55 and 7j80 signal region selections can be found in figure 8. A display of an event that passes all signal region selections can be found in figure 9.
Figure 9. A display of an event which passes all signal region selections. The event has $E_T^{\text{miss}}/\sqrt{H_T}$ of 11.6 GeV$^{1/2}$, $H_T$ of 1.17 TeV and $E_T^{\text{miss}}$ of 397 GeV. One of the jets, with $p_T$ of 107 GeV is $b$ tagged. The event also contains a muon with $p_T$ of 90 GeV, overlapping with a jet.

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, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CIF, Canada; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; 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 and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and
Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, 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 (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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

References

[1] P. Fayet, Supersymmetry and weak, electromagnetic and strong interactions, Phys. Lett. B 64 (1976) 159 [nsSPIRE].

[2] P. Fayet, Spontaneously broken supersymmetric theories of weak, electromagnetic and strong interactions, Phys. Lett. B 69 (1977) 489 [nsSPIRE].

[3] G.R. Farrar and P. Fayet, Phenomenology of the production, decay and detection of new hadronic states associated with supersymmetry, Phys. Lett. B 76 (1978) 575 [nsSPIRE].

[4] P. Fayet, Relations between the masses of the superpartners of leptons and quarks, the goldstino couplings and the neutral currents, Phys. Lett. B 84 (1979) 416 [nsSPIRE].

[5] S. Dimopoulos and H. Georgi, Softly broken supersymmetry and SU(5), Nucl. Phys. B 193 (1981) 150 [nsSPIRE].

[6] E. Witten, Dynamical breaking of supersymmetry, Nucl. Phys. B 188 (1981) 513 [nsSPIRE].

[7] M. Dine, W. Fischler and M. Srednicki, Supersymmetric technicolor, Nucl. Phys. B 189 (1981) 575 [nsSPIRE].

[8] S. Dimopoulos and S. Raby, Supercolor, Nucl. Phys. B 192 (1981) 353 [nsSPIRE].

[9] N. Sakai, Naturalness in supersymmetric GUTs, Z. Phys. C 11 (1981) 153 [nsSPIRE].

[10] R.K. Kaul and P. Majumdar, Cancellation of quadratically divergent mass corrections in globally supersymmetric spontaneously broken gauge theories, Nucl. Phys. B 199 (1982) 36 [nsSPIRE].

[11] H. Goldberg, Constraint on the photino mass from cosmology, Phys. Rev. Lett. 50 (1983) 1419 [Erratum ibid. 103 (2009) 099905] [nsSPIRE].

[12] J.R. Ellis, J. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, Supersymmetric relics from the Big Bang, Nucl. Phys. B 238 (1984) 453 [nsSPIRE].

[13] ATLAS collaboration, Search for new phenomena in final states with large jet multiplicities and missing transverse momentum using \( \sqrt{s} = 7 \) TeV pp collisions with the ATLAS detector, JHEP 11 (2011) 099 [arXiv:1110.2299] [nsSPIRE].
ATLAS collaboration, Search for supersymmetry in final states with jets, missing transverse momentum and one isolated lepton in $\sqrt{s} = 7$ TeV pp collisions using 1 fb$^{-1}$ of ATLAS data, Phys. Rev. D 85 (2012) 012006 [arXiv:1109.6606] [SPIRE].

ATLAS collaboration, Searches for supersymmetry with the ATLAS detector using final states with two leptons and missing transverse momentum in $\sqrt{s} = 7$ TeV proton-proton collisions, Phys. Lett. B 709 (2012) 137 [arXiv:1110.6189] [SPIRE].

ATLAS collaboration, Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions, Phys. Lett. B 710 (2012) 67 [arXiv:1109.6572] [SPIRE].

ATLAS collaboration, Search for scalar bottom pair production with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. Lett. 108 (2012) 181802 [arXiv:1112.3832] [SPIRE].

CMS collaboration, Search for supersymmetry at the LHC in events with jets and missing transverse energy, Phys. Rev. Lett. 107 (2011) 221804 [arXiv:1109.2352] [SPIRE].

ATLAS collaboration, The ATLAS experiment at the CERN Large Hadron Collider, 2008 JINST 3 S08003 [SPIRE].

ATLAS collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector in 2011, ATLAS-CONF-2011-116 (2011).

M. Cacciari, G.P. Salam and G. Soyez, The anti-$k_t$ jet clustering algorithm, JHEP 04 (2008) 063 [arXiv:0802.1189] [SPIRE].

M. Cacciari and G.P. Salam, Dispelling the $N^3$ myth for the $k_t$ jet-finder, Phys. Lett. B 641 (2006) 57 [hep-ph/0512210] [SPIRE].

ATLAS collaboration, Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV, arXiv:1112.6426 [SPIRE].

ATLAS collaboration, Commissioning of the ATLAS high-performance b-tagging algorithms in the 7 TeV collision data, ATLAS-CONF-2011-102 (2011).

M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A.D. Polosa, ALPGEN, a generator for hard multiparton processes in hadronic collisions, JHEP 07 (2003) 001 [hep-ph/0206293] [SPIRE].

J. Pumplin et al., New generation of parton distributions with uncertainties from global QCD analysis, JHEP 07 (2002) 012 [hep-ph/0201195] [SPIRE].

G. Corella et al., HERWIG 6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes), JHEP 01 (2001) 010 [hep-ph/0011363] [SPIRE].

G. Corella et al., HERWIG 6.5 release note, hep-ph/0210213 [SPIRE].

J. Butterworth, J.R. Forshaw and M. Seymour, Multiparton interactions in photoproduction at HERA, Z. Phys. C 72 (1996) 637 [hep-ph/9601371] [SPIRE].

M. Aliev et al., HATHOR: HAdronic Top and Heavy quarks crOss section calculatoR, Comput. Phys. Commun. 182 (2011) 1034 [arXiv:1007.1327] [SPIRE].

K. Melnikov and F. Petriello, Electroweak gauge boson production at hadron colliders through $O(\alpha_s^2)$, Phys. Rev. D 74 (2006) 114017 [hep-ph/0609070] [SPIRE].
[33] M. Bahr et al., HERWIG++ physics and manual, *Eur. Phys. J. C* 58 (2008) 639 [arXiv:0803.0883] [inSPIRE].

[34] W. Beenakker, R. Hopker, M. Spira and P. Zerwas, Squark and gluino production at hadron colliders, *Nucl. Phys. B* 492 (1997) 51 [hep-ph/9610490] [inSPIRE].

[35] A. Kulesza and L. Motyka, Threshold resummation for squark-antisquark and gluino-pair production at the LHC, *Phys. Rev. Lett.* 102 (2009) 111802 [arXiv:0807.2405] [inSPIRE].

[36] A. Kulesza and L. Motyka, Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC, *Phys. Rev. D* 80 (2009) 095004 [arXiv:0905.4749] [inSPIRE].

[37] W. Beenakker et al., Soft-gluon resummation for squark and gluino hadroproduction, *JHEP* 12 (2009) 041 [arXiv:0909.4418] [inSPIRE].

[38] W. Beenakker et al., Squark and gluino hadroproduction, *Int. J. Mod. Phys. A* 26 (2011) 2637 [arXiv:1105.1110] [inSPIRE].

[39] P.M. Nadolsky et al., Implications of CTEQ global analysis for collider observables, *Phys. Rev. D* 78 (2008) 013004 [arXiv:0802.0007] [inSPIRE].

[40] A. Martin, W. Stirling, R. Thorne and G. Watt, Parton distributions for the LHC, *Eur. Phys. J. C* 63 (2009) 189 [arXiv:0901.0002] [inSPIRE].

[41] M. Botje et al., The PDF4LHC working group interim recommendations, arXiv:1101.0538 [inSPIRE].

[42] F.E. Paige, S.D. Protopopescu, H. Baer and X. Tata, ISAJET 7.69: a Monte Carlo event generator for pp, p\bar{p} and e^+e^- reactions, hep-ph/0312045 [inSPIRE].

[43] ATLAS collaboration, The ATLAS simulation infrastructure, *Eur. Phys. J. C* 70 (2010) 823 [arXiv:1006.4568] [inSPIRE].

[44] GEANT4 collaboration, S. Agostinelli et al., GEANT4: a simulation toolkit, *Nucl. Instrum. Meth. A* 506 (2003) 250 [inSPIRE].

[45] ATLAS collaboration, Measurement of multi-jet cross sections in proton-proton collisions at a 7 TeV center-of-mass energy, *Eur. Phys. J. C* 71 (2011) 1763 [arXiv:1107.2092] [inSPIRE].

[46] ATLAS collaboration, Search for gluinos in events with two same-sign leptons, jets and missing transverse momentum with the ATLAS detector in pp collisions at $\sqrt{s}=7$ TeV, ATLAS-CONF-2012-004 (2012).

[47] LEP SUSY WORKING GROUP, ALEPH, DELPHI, L3 and OPAL collaboration, Combined LEP chargino results, up to 208 GeV for large $m_0$, LEPSUSYWG/01-03.1.

[48] LEP SUSY WORKING GROUP, ALEPH, DELPHI, L3 and OPAL collaboration, Combined LEP selectron/smuon/stau results, 183–208 GeV, LEPSUSYWG/04-01.1.

[49] ATLAS collaboration, Search for supersymmetry in pp collisions at $\sqrt{s}=7$ TeV in final states with missing transverse momentum and b-jets with the ATLAS detector, ATLAS-CONF-2012-003 (2012).

[50] HepData, http://hepdata.cedar.ac.uk/view/red4991.

[51] A. Read, Presentation of search results: the CL_s technique, *J. Phys. G* 28 (2002) 2693 [inSPIRE].
The ATLAS collaboration

G. Aad48, B. Abbott111, J. Abdallah11, S. Abdel Khalek115, A.A. Abdelalim49, O. Abdirinov40, B. Abi112, M. Abolins88, O.S. AboutZeid158, H. Abramowicz153, H. Abreu116, E. Acerbi89a,89b, B.S. Achaarya164a,164b, L. Adamczyk37, D.L. Adams24, T.N. Addy56, J. Adelman176, S. Adomeit38, P. Adragna79, T. Adye129, S. Afeshky22, J.A. Aguilar-Saavedra124a, M. Aharrache81, S.P. Ahlen21, F. Ahles48, A. Ahmad148, M. Ahsan40, G. Aielli133a,133b, T. Akdogan18a, T.P.A. Akesson9, G. Akimoto155, A.V. Akimov94, A. Akiyama66, M.S. Alam1, M.A. Alam76, J. Albert169, S. Albrand55, M. Aleksa49, I.N. Aleksandrov64, F. Alessandria89a, C. Alexa25a, G. Alexander153, G. Alexandre49, T. Alexopoulos69, M. Alhroob164a,164c, M. Aliev15, G. Alimonti89a, J. Alison120, B.M.M. Allbrooke17, P.P. Allport73, S.E. Allwood-Spiers53, J. Almond82, A. Aloisio102a,102b, R. Alon172, A. Alonso79, B. Alvarez Gonzalez88, M.G. Alvigg102a,102b, K. Anako65, C. Anelund22, V.V. Anmossov129, A. Amorim124a,b, N. Amrani153, C. Anastopoulos29, L.S. Ancu16, N. Andari115, T. Anderson34, C.F. Anderson40, G. Anderson88a, K.J. Anderson30, A. Andreae89a,89b, V. Andrei58a, X.S. Anduaga70, A. Angerami34, F. Anghinolfi29, A. Anisenkov107, N. Anjos124a, A. Anovii47, A. Antonaki87, M. Antonoff47, J. Antonov96, J. Antos144b, F. Anulli32a, S. Aoun83, L. APEEDis70, R. Apolle118, G. Arabidze88, I. Aracena143, Y. Araï65, A.T.H. Arce44, S. Arfaoui148, J-F. Arguin14, E. Arik18a, M. Arik18a, A.J. Armbruster87, O. Arnaez81, V. Arnal30, C. Arnau115, A. Artamonov95, G. Artomo132a,132b, D. Artunov20, S. Asai55, R. Asfandiyarov173, S. Ask27, B. Asman146a,146b, L. Asquith5, K. Assamagan24, A. Astbury169, B. Aubert4, E. Auger115, K. Augsten127, M. Aurousseau145a, G. Avolio163, R. Avramidin9, D. Axen168, G. Azuelos93d, Y. Azuma155, M.A. Baak29, G. Baccaglini89a, C. Bacci134a,134b, A.M. Bach4, H. Baccacou136, K. Bachas29, M. Backes49, M. Backhaus120, E. Badesca25a, P. Bagnaia132a,132b, S. Bahnipati6, Y. Bai32a, D.C. Bailey158, T. Bain158, J.T. Baines129, O.K. Bakes176, M.D. Baker24, S. Baker77, E. Banas38, P. Banerjee83w, S. Banerjee173, D. Banfi29, A. Banger150, V. Bansal169, H.S. Bansil17, L. Barak172, S.P. Baranov94, A. Barbaro Galtieri14, T. Barber8, E.L. Barberis86, D. Barberis50a,50b, M. Barbero39, D.Y. Bardin64, T. Barillari99, M. Barisonz175, T. Barklow143, N. Barlov27, B.M. Barnett129, R.M. Barnett14, A. Baroncelli134a, G. Barone49, A.J. Barr118, F. Barreiro80, J. Barreiro Guimaraes da Costa37, P. Barrillon115, R. Bartold4, A.E. Barton71, V. Bartsch149, R.L. Bates53, L. Batkova144a, J.R. Batley27, A. Battaglia16, M. Battistin29, F. Bauer36, H.S. Bawa143c, S. Beale89, T. Beau78, P.H. Beauchemin161, R. Beccherle50a, P. Bechtel20, H.P. Beck16, S. Becker98, M. Beckingham138, K.H. Beck175, A.J. Beddall18c, A. Beddall18c, S. Beddian176, V.A. Bednyakov64, C.P. Beo81, M. Begel24, S. Behar152, M. Beimford99, C. Belanger-Champagne85, P.J. Bell49, W.H. Bell19, G. Bella135, L. Bellagamba9a, F. Bellina29, M. Bellomo29, A. Belloni57, O. Beloborodova107f,k, M. Belotsky96, O. Beltrame194, O. Benay153, D. Bencek135a, K. Bendtzz146a,146b, N. Benekos165, Y. Benhammou152, E. Benhar Noccioli49, J.A. Benitez Garcia159b, D.P. Benjamin44, M. Benoi115, J.R. Bensinger22, K. Benslamam130, S. Bentvelsen105, D. Berge9, E. Begaesas Kuutmann11, N. Berger1, F. Berghaus169, E. Berglund1105, J. Beringer14, P. Bernat77, R. Bernhard48, C. Bernius24, T. Berry76, C. Bertella83, A. Bertin9a,19b, F. Bertolucci122a,122b, M.I. Besana89a,89b, G.J. Besjes104, N. Besson136, S. Bethke99, W. Bihimi45, R.M. Bianchi29, M. Bianco72a,72b, O. Biebel98, S.P. Bieniek77, K. Bierwagen54, J. Biesia44, M. Biglietti134a, H. Bilokon47, M. Bindl18a,19b, S. Bines115, A. Bingu18c, C. Bini132a,132b, C. Biscarat178, U. Bitenc84, K.M. Black21, R.E. Blair5, J-B. Blanchard136, G. Blanchot29, T. Blazek144a, C. Blockey22, J. Blocki38, A. Blondel29, W. Blum81, U. Blumenschein54, G.J. Bobbink105, V.B. Bobrovnikov117, S.S. Bocchetta29, A. Bocci44, C.R. Boddy118, M. Boehler41, J. Boek75, N. Boelaer35, J.A. Boggers95, A. Boganich107, A. Bogouc190, C. Bohn163a, J. Bohm125, V. Boisvert76, T. Bold17, V. Boldr125a, N.M. Bolnet136, M. Bomben75, M. Bona75, M. Bondioli193, M. Boonekamp136.
R. Zimmermann\textsuperscript{20}, S. Zimmermann\textsuperscript{20}, S. Zimmermann\textsuperscript{48}, M. Ziolkowski\textsuperscript{141}, R. Zitoun\textsuperscript{4}, L. Živković\textsuperscript{34}, V.V. Zmouchko\textsuperscript{128}, G. Zobernig\textsuperscript{173}, A. Zoccoli\textsuperscript{19a,19b}, M. zur Nedden\textsuperscript{15}, V. Zutshi\textsuperscript{106} and L. Zwalinski\textsuperscript{29}.

1: University at Albany, Albany NY, U.S.A.
2: Department of Physics, University of Alberta, Edmonton AB, Canada
3: (a)Department of Physics, Ankara University, Ankara; (b)Department of Physics, Dumlupinar University, Kutahya; (c)Department of Physics, Gazi University, Ankara; (d)Division of Physics, TOBB University of Economics and Technology, Ankara; (e)Turkish Atomic Energy Authority, Ankara, Turkey
4: LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5: High Energy Physics Division, Argonne National Laboratory, Argonne IL, U.S.A.
6: Department of Physics, University of Arizona, Tucson AZ, U.S.A.
7: Department of Physics, The University of Texas at Arlington, Arlington TX, U.S.A.
8: Physics Department, University of Athens, Athens, Greece
9: Physics Department, National Technical University of Athens, Zografou, Greece
10: Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11: Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12: (a)Institute of Physics, University of Belgrade, Belgrade; (b)Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
13: Department for Physics and Technology, University of Bergen, Bergen, Norway
14: Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, U.S.A.
15: Department of Physics, Humboldt University, Berlin, Germany
16: Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17: School of Physics and Astronomy, University of Birmingham, Birmingham, U.K.
18: (a)Department of Physics, Bogazici University, Istanbul; (b)Division of Physics, Doğus University, Istanbul; (c)Department of Physics Engineering, Gaziantep University, Gaziantep; (d)Department of Physics, Istanbul Technical University, Istanbul, Turkey
19: (a)INFN Sezione di Bologna; (b)Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20: Physikalisches Institut, University of Bonn, Bonn, Germany
21: Department of Physics, Boston University, Boston MA, U.S.A.
22: Department of Physics, Brandeis University, Waltham MA, U.S.A.
23: (a)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 Rei (UFSJ), Sao Joao del Rei; (d)Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
24: Physics Department, Brookhaven National Laboratory, Upton NY, U.S.A.
25: (a)National Institute of Physics and Nuclear Engineering, Bucharest; (b)University Politehnica Bucharest, Bucharest; (c)West University in Timisoara, Timisoara, Romania
26: Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27: Cavendish Laboratory, University of Cambridge, Cambridge, U.K.
28: Department of Physics, Carleton University, Ottawa ON, Canada
29: CERN, Geneva, Switzerland
30: Enrico Fermi Institute, University of Chicago, Chicago IL, U.S.A.
31: (a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France

Nevis Laboratory, Columbia University, Irvington NY, U.S.A.

Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

INFN Gruppo Collegato di Cosenza; Dipartimento di Fisica, Università della Calabria, Aracava di Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

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

Physics Department, Southern Methodist University, Dallas TX, U.S.A.

Physics Department, University of Texas at Dallas, Richardson TX, U.S.A.

DESY, Hamburg and Zeuthen, Germany

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

Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany

Department of Physics, Duke University, Durham NC, U.S.A.

SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, U.K.

Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 32700 Wiener Neustadt, Austria

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

Section de Physique, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova; Dipartimento di Fisica, Università di Genova, Genova, Italy

E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; 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, U.K.

II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France

Department of Physics, Hampton University, Hampton VA, U.S.A.

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, U.S.A.

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; 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, U.S.A.

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

University of Iowa, Iowa City IA, U.S.A.

Department of Physics and Astronomy, Iowa State University, Ames IA, U.S.A.

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, U.K.

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

Oliver Lodge Laboratory, University of Liverpool, Liverpool, U.K.

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

School of Physics and Astronomy, Queen Mary University of London, London, U.K.

Department of Physics, Royal Holloway University of London, Surrey, U.K.

Department of Physics and Astronomy, University College London, London, U.K.

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

Fysiska institutionen, Lunds universitet, Lund, Sweden

Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, U.K.

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

Department of Physics, University of Massachusetts, Amherst MA, U.S.A.

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, U.S.A.

Department of Physics and Astronomy, Michigan State University, East Lansing MI, U.S.A.

(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, U.S.A.

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

P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

(a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, U.S.A.

Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
(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

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

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

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, U.S.A.

Department of Physics and Astronomy, University of Sussex, Brighton, U.K.

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

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

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

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

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

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

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

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

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

Institute of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan

Science and Technology Center, Tufts University, Medford MA, U.S.A.

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine CA, U.S.A.

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

Department of Physics, University of Illinois, Urbana IL, U.S.A.

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

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-CNMT), University of Valencia and CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

Department of Physics, University of Warwick, Coventry, U.K.

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison WI, U.S.A.

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven CT, U.S.A.

Yerevan Physics Institute, Yerevan, Armenia

Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
a: Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
b: Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
c: Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, U.K.
d: Also at TRIUMF, Vancouver BC, Canada
e: Also at Department of Physics, California State University, Fresno CA, U.S.A.
f: Also at Novosibirsk State University, Novosibirsk, Russia
g: Also at Fermilab, Batavia IL, U.S.A.
h: Also at Department of Physics, University of Coimbra, Coimbra, Portugal
i: Also at Department of Physics, UASLP, San Luis Potosi, Mexico
j: Also at Università di Napoli Parthenope, Napoli, Italy
k: Also at Institute of Particle Physics (IPP), Canada
l: Also at Department of Physics, Middle East Technical University, Ankara, Turkey
m: Also at Louisiana Tech University, Ruston LA, U.S.A.
n: Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
o: Also at Department of Physics and Astronomy, University College London, London, U.K.
p: Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
q: Also at Department of Physics, University of Cape Town, Cape Town, South Africa
r: Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
s: Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
t: Also at Manhattan College, New York NY, U.S.A.
u: Also at School of Physics, Shandong University, Shandong, China
v: Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
w: Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
x: Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
y: Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
z: Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
aa: Also at Section de Physique, Université de Genève, Geneva, Switzerland
ab: Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
ac: Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, U.S.A.
ad: Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
ae: Also at California Institute of Technology, Pasadena CA, U.S.A.
af: Also at Institute of Physics, Jagiellonian University, Krakow, Poland
ag: Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
ah: Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, U.K.
aia: Also at Department of Physics, Oxford University, Oxford, U.K.
aaj: Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
ak: Also at Department of Physics, The University of Michigan, Ann Arbor MI, U.S.A.
*: Deceased