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Aad, G.; et al., [Unknown]; Bentvelsen, S.; Bobbink, G.J.; Bos, K.; Boterenbrood, H.; Colijn, A.P.; Daum, C.; de Jong, P.; de Nooij, L.; Doxiadis, A.D.; Ferrari, P.; Garitaonandia, H.; Geerts, D.A.A.; Gosselink, M.; Hartjes, F.; Hessey, N.P.; Igonkina, O.; Kayl, M.S.; Klous, S.; Kluit, P.; Koffeman, E.; Koutsman, A.; Lee, H.; Lenz, T.; Linde, F.; Luijckx, G.; Massaro, G.; Mechnich, J.; Mussche, I.; Ottersbach, J.P.; Reichold, A.; Rijpstra, M.; Ruckstuhl, N.; Snuverink, J.; Ta, D.; Tsiakiris, M.; Turlay, E.; van der Graaf, H.; van der Kraaij, E.; van der Leeuw, R.; van der Poel, E.; van Kesteren, Z.; van Vulpen, I.; Verkerke, W.; Vermeulen, J.C.; Vranjes Milosavljevic, M.; Vreeswijk, M.

DOI
10.1103/PhysRevD.85.012006

Publication date
2012

Document Version
Final published version

Published in
Physical Review D. Particles, Fields, Gravitation, and Cosmology

Link to publication

Citation for published version (APA):
Aad, G., et al., U., Bentvelsen, S., Bobbink, G. J., Bos, K., Boterenbrood, H., Colijn, A. P., Daum, C., de Jong, P., de Nooij, L., Doxiadis, A. D., Ferrari, P., Garitaonandia, H., Geerts, D. A. A., Gosselink, M., Hartjes, F., Hessey, N. P., Igonkina, O., Kayl, M. S., ... Vreeswijk, M. (2012). Search for supersymmetry in final states with jets, missing transverse momentum and one isolated lepton in √s = 7 TeV pp collisions using 1 fb-1 of ATLAS data. *Physical Review D. Particles, Fields, Gravitation, and Cosmology*, *85*(1), Article 012006. https://doi.org/10.1103/PhysRevD.85.012006

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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

G. Aad *et al.**
(ATLAS Collaboration)

(Received 29 September 2011; published 18 January 2012)

We present an update of a search for supersymmetry in final states containing jets, missing transverse momentum, and one isolated electron or muon, using 1.04 fb^{-1} of proton-proton collision data at $\sqrt{s} = 7$ TeV recorded by the ATLAS experiment at the LHC in the first half of 2011. The analysis is carried out in four distinct signal regions with either three or four jets and variations on the (missing) transverse momentum cuts, resulting in optimized limits for various supersymmetry models. No excess above the standard model background expectation is observed. Limits are set on the visible cross section of new physics within the kinematic requirements of the search. The results are interpreted as limits on the parameters of the minimal supergravity framework, limits on cross sections of simplified models with specific squark and gluino decay modes, and limits on parameters of a model with bilinear R-parity violation.

DOI: 10.1103/PhysRevD.85.012006 PACS numbers: 12.60.Jv, 13.85.Rm, 14.80.Ly

I. INTRODUCTION AND ANALYSIS OVERVIEW

Many extensions of the standard model predict the existence of new colored particles, such as the squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) of supersymmetric (SUSY) theories [1], which could be accessible at the LHC. The dominant SUSY production channels are assumed to be squark-(anti)squark, squark-gluino, and gluino-gluino pair production. Squarks and gluinos are expected to decay to quarks and gluons and the SUSY partners of the gauge bosons (charginos, $\tilde{\chi}^{\pm}$, and neutralinos, $\tilde{\chi}^{0}$), leading to events with energetic jets. In R-parity-conserving SUSY models [2], the lightest supersymmetric particle (LSP) is stable and escapes detection, giving rise to events with significant missing transverse momentum. In decay chains with charginos ($\tilde{q}_{\mathrm{L}} \rightarrow q\tilde{\chi}^{\pm}$, $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}^{\pm}$), the chargino decay can produce a high-momentum lepton. LHC results of searches for SUSY with 35 pb^{-1} of data collected in 2010, in final states with zero, one, or two leptons (where leptons refer to either electrons or muons), can be found in Refs [3–18]. First results obtained with 1 fb^{-1} of data collected in 2011 have also been published for the no-lepton channel [19].

This paper reports on an update of a search for events with exactly one isolated high-transverse momentum (p_{T}, relative to the beam direction) electron or muon, at least three high-p_{T} jets, and significant missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$), using data collected by ATLAS in the first half of 2011. The analysis proceeds similarly to the analysis of the 2010 data [4], with a number of differences. To cover a broader range of signals, the analysis has been extended from one signal search region to four. The kinematic requirements on leptons and jets have been modified, to accommodate changing trigger requirements, minimize the overlap with searches in other final states, and optimize the sensitivity of the search.

As in the 2010 analysis, a combined fit to the observed number of events in signal and background control regions is used to search for an excess of events in the signal regions. The control regions normalize the backgrounds from W and $t\bar{t}$ production. To estimate these backgrounds in the signal regions, an extrapolation of the individual background components from the control to the signal regions is performed. This is done using transfer factors obtained from Monte Carlo (MC) simulations that represent the expected ratio of events in the signal and control regions for the various background processes.

The selection cuts are optimized based on samples of simulated events. The cut optimization was performed not only in the MSUGRA/CMSSM (minimal supergravity/constrained minimal supersymmetric standard model) framework [20,21], but also for simplified models characterizing specific SUSY production and decay modes. The results are interpreted in these MSUGRA/CMSSM and simplified model frameworks, as well as in a model with bilinear R-parity violation (bRPV) [22].

II. MODELS

In the MSUGRA/CMSSM model, supersymmetry is characterized by universal scalar and gaugino mass parameters m_0 and $m_{1/2}$ and a universal trilinear coupling

*Full author list given at the end of the article.

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parameter A_0, all expressed at the grand unified theory scale, the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, and the sign of the Higgs mixing parameter μ. In this paper, results are interpreted in terms of m_0 and $m_{1/2}$ for fixed values of $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$. The interpretation is given for $\tan\beta = 10$ rather than for $\tan\beta = 3$ as in our previous publication [4], since $\tan\beta = 3$ is increasingly disfavored by the results of direct Higgs boson searches. The influence of a variation of A_0 on the results is very small, whereas high values of $\tan\beta$ (> 30) mostly affect the behavior of the third generation of squarks and sleptons, for which dedicated analyses are developed. ISAJET [23] is used to calculate the SUSY particle mass spectrum at the electroweak scale. For illustration purposes, the expected signal distributions of the MSUGRA/CMSSM model point $m_0 = 500$ GeV, $m_{1/2} = 330$ GeV, which is close to the expected sensitivity limit, are shown in the figures of this paper.

Simplified models [24,25] are characterized by well-defined SUSY particle production and decay modes, and a minimal particle content for the final state under study. This can be achieved by assuming that all SUSY particles not of interest to a specific model are very massive and decouple. In order to achieve a final state with leptons, the simplified models considered here contain a chargino decaying to the lightest neutralino (LSP) and an on shell or off shell W boson: $\tilde{\chi}^{\pm} \rightarrow W^{(*)}\tilde{\chi}^0$. The chargino arises from the decay of a squark or a gluino, via one of the following two models considered:

(i) In the mass hierarchy corresponding to sequential squark-chargino-neutralino decay, hereafter called the squark model, the decay chain $\tilde{q} \rightarrow q'\tilde{\chi}^{\pm} \rightarrow q'W^{(*)}\tilde{\chi}^0$ is assumed to have a 100% branching fraction, and only first- and second-generation squark-squark and squark-antisquark production is considered. This is achieved by setting all other SUSY particle masses, including those of third-generation squarks, to multi-TeV values. This model is characterized by three free parameters: $m_{\tilde{q}}$, $m_{\tilde{\chi}^0}$, and $x = (m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}^0})/(m_{\tilde{q}} - m_{\tilde{\chi}^0})$.

(ii) In the gluino-chargino-neutralino model, hereafter called gluino model, the decay chain $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^{\pm} \rightarrow q\bar{q}W^{(*)}\tilde{\chi}^0$ is assumed to have a 100% branching fraction, and only gluino-gluino production is considered. This is achieved by setting all other SUSY particle masses, including those of all squarks, to multi-TeV values. This model is also characterized by three free parameters: $m_{\tilde{g}}$, $m_{\tilde{\chi}^0}$, and $x = (m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}^0})/(m_{\tilde{g}} - m_{\tilde{\chi}^0})$.

The assumption of massive third-generation squarks in the squark model is motivated by the fact that the phenomenology of light third-generation squarks (production of top and/or bottom squarks) is covered by a separate dedicated analysis [7]. For each choice of the three free parameters in the simplified models, the sparticle mass spectrum at the weak scale, and the sparticle decays are fully specified. Simplified models are used to identify the limits of the effectiveness of the search, characterize a possible excess in data, and derive limits. Constraints on a wide variety of models can be deduced from limits on simplified models [25].

The MSUGRA/CMSSM model and the simplified models assume R-parity conservation. Additionally, results are interpreted in a model that allows for bilinear R-parity-breaking terms in the superpotential [22]. Such terms lead to nonvanishing vacuum expectation values for the sneutrinos which in turn induce a mixing between neutrinos and neutralinos, thus providing a phenomenologically viable alternative to the origin of neutrino mass and mixing [26,27]. In the study presented here, the R-parity-violating couplings are embedded in an MSUGRA/CMSSM SUSY production model. For a chosen set of MSUGRA parameters, the bRPV parameters are unambiguously determined under the tree-level dominance scenario [28] by fitting them to the neutrino oscillations data as described in Ref. [29]. The neutralino LSP is unstable and decays within the detector through decay modes that predominantly include neutrinos [30]. Such decays along with the presence of neutrinos in SUSY decay chains such as $\tilde{\chi}^{\pm} \rightarrow \ell\nu\tilde{\chi}^0$ lead to significant missing transverse momentum. However, this model was not used to optimize the selection. Only the muon selection is considered in this analysis since in the leptonic decays of the LSP, the electron channels are highly suppressed in favor of the μ- and τ-producing modes. Scenarios leading to a long lifetime ($c\tau \gtrsim 15$ mm) of the LSP are not considered here.

III. THE ATLAS DETECTOR

ATLAS [31] is a particle physics detector with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle [32]. The inner detector consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT). The inner detector is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic (EM) calorimeters. Hadron calorimetry is provided by an iron-scintillator tile calorimeter in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer is based on three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters, and a system of three stations of chambers for the trigger and chambers for precise measurements.

IV. MONTE CARLO SIMULATION

MC simulations are used to develop the analysis, extrapolate backgrounds from the control to the signal regions, and to assess sensitivity to specific SUSY signal models. Samples of W and Z/γ^* production with accompanying jets are simulated with ALPGEN [33], using the CTEQ6L1 [34] parton density functions (PDFs). Top quark pair production is simulated with MC@NLO [35] and the next-to-leading-order (NLO) PDF set CTEQ66 [36], which is used for all NLO MC. Single top production is simulated with MC@NLO. Fragmentation and hadronization for the ALPGEN and MC@NLO samples is performed with HERWIG [37], using JIMMY [38] for the underlying event. Diboson production is simulated with HERWIG, using the MRST2007LO* [39] modified leading-order PDFs. SUSY signal samples in the MSUGRA/CMSSM model and for the simplified models are generated with HERWIG ++ [40], normalized using NLO cross sections determined by PROSPINO [41]. The bRPV sparticle spectrum is calculated with SPHENO 3.1 [42,43], the event generation is carried out by PYTHIA6 [44] and the NLO cross sections are also provided by PROSPINO. The MC samples are produced using an ATLAS parameter tune of PYTHIA and HERWIG/JIMMY [45] and a GEANT4 [46] based detector simulation [47]. Detailed comparisons of MC-predicted lepton reconstruction and identification efficiencies to the corresponding measurements from data are used to determine scale factors. These scale factors obtained from specifically selected event samples, such as $Z \to \ell\ell$, are then used to correct the MC prediction of efficiencies and acceptances for both signal and background events. The MC samples are produced with a simulation of multiple interactions per LHC bunch crossing (pileup). Differing pileup conditions as a function of the instantaneous luminosity of the LHC machine are taken into account by reweighting MC events according to the mean number of interactions expected.

V. OBJECT RECONSTRUCTION

Collision events are selected by requiring a reconstructed primary vertex with at least five associated tracks, consistent with the beam spot position.

Electrons are reconstructed from clusters in the EM calorimeter matched to a track in the inner detector [48]. Several requirements on the track and clusters are imposed to select true electrons. The ''medium'' electron selection, used in this analysis to estimate the contribution from nonisolated and misidentified electrons and to veto on dileptonic events, is based on calorimeter shower shape, inner-detector track quality, and track-to-calorimeter-cluster matching. Electrons in the final selection are required to pass the ''tight'' electron definition, which adds a requirement on the ratio E/p, where E is the calorimeter cluster energy and p is the track momentum, and detection of transition radiation in the TRT. Furthermore, the electron is required to be isolated: the p_{T} sum of tracks within a cone of $\Delta R < 0.2$ around the electron candidate (excluding the electron candidate itself) is required to be less than 10% of the electron p_{T}. All electrons are required to pass kinematic cuts of $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.47$. In addition, electrons with a distance to the closest jet of $0.2 < \Delta R < 0.4$ are discarded, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. For tight electrons, the p_{T} requirement is raised to 25 GeV.

Preselected muons are either the result of a combined track in the muon spectrometer and in the inner detector, or a muon spectrometer segment matching with an extrapolated inner detector track [49]. The matched inner detector track must have ≥ 1 hit in the pixel detector, ≥ 1 hit in the inner layer of the pixel detector if the pixel detector module at that location is operational, ≥ 6 hits in the SCT, and fewer than two missing hits on the track in pixel and SCT detectors. For $|\eta| < 1.9$, at least 6 TRT hits are required, and the number of TRT hits that are classified as ''outliers'' must be less than 90% of the total number of TRT hits on the track. The latter cut is also applied if $|\eta| \geq 1.9$ and at least 6 TRT hits are on the track. TRT outliers appear in two forms in the track reconstruction, as a straw tube with a signal but not crossed by the nearby track, or as a set of TRT measurements in the prolongation of a track which, however, failed to form a smooth trajectory together with the pixel and SCT measurements. These quality cuts are put in place to suppress fake tracks and discriminate against muons from hadron decays. Muons with a distance to the closest jet of $\Delta R < 0.4$ are discarded. In order to reject muons resulting from cosmic rays, tight cuts are applied on the proximity of the muon trajectories to the primary vertex (PV): $|z_\mu - z_{\mathrm{PV}}| < 5$ mm and $d_0 < 2$ mm, where z_μ is the z coordinate of the extrapolated muon track at the point of closest approach to the primary vertex, z_{PV} is the z coordinate of the primary vertex, and d_0 is the magnitude of the impact parameter of the muon in the transverse plane. These preselected muons, similar to the electron case, are used to quantify the contribution from nonisolated muons and to reject events with additional muons, and are required to have $p_{\mathrm{T}} > 10$ GeV, and $|\eta| < 2.4$. For muons in the final selection, the p_{T} requirement is raised to 20 GeV, and the muon is required to be isolated: the p_{T} sum of tracks within a cone of $\Delta R < 0.2$ around the muon candidate (excluding the muon candidate itself) is required to be less than 1.8 GeV.

Jets are reconstructed using the anti-k_t jet clustering algorithm [50] with a radius parameter of 0.4. The inputs to the jet algorithm are three-dimensional clusters formed from energy deposits in the calorimeter. The jets are calibrated using p_{T}- and η-dependent correction factors based on MC simulation and validated by test beam and

collision data studies [51]. Preselected jets are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.8$. Events with jets not passing jet quality criteria against noise and noncollision backgrounds [52] are rejected. Jets within a distance $\Delta R < 0.2$ of a preselected electron are rejected, since these jets are likely to be electrons also reconstructed as jets. For jets in the signal regions, the p_{T} requirement is tightened to 25 GeV and to remove jets that are not associated with the hard scattering of interest, jets with associated tracks are required to pass the selection that at least 75% of the summed p_{T} of all associated tracks must come from tracks associated to the selected primary vertex.

The occurrence of a b-tagged jet in the final state is used to distinguish between $t\bar{t}$ and W events. The reconstruction of b-tagged jets proceeds as for other jets, apart from the requirement that $|\eta| < 2.5$, and that a b-tagging algorithm exploiting both impact parameter and secondary vertex information [53] tags the jet. This algorithm has a 60% efficiency for tagging b-jets in a Monte Carlo sample of $t\bar{t}$ events, with a mistag rate for light quarks and gluons of less than 1%.

The missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ in this analysis is the opposite of the vectorial p_{T} sum of reconstructed objects in the event, comprised of the jets with $p_{\mathrm{T}} > 20$ GeV, the selected lepton, any additional identified nonisolated muons, and three-dimensional calorimeter clusters with $|\eta| < 4.5$ not belonging to any of the aforementioned object types.

During a part of the data-taking period, an electronics failure in the LAr barrel EM calorimeter created a dead region in the second and third layers, corresponding to approximately 1.4×0.2 in $\Delta\eta \times \Delta\phi$. Events with an electron in this region are vetoed, leading to loss of signal efficiency of about 1%. The energy measurement for jets in the data in the problematic region is underestimated. A correction to the jet energy is made using the energy depositions in the cells neighboring the dead region, and this is also propagated to $E_{\mathrm{T}}^{\mathrm{miss}}$. The correction to the jet energy amounts to a few percent for jets just touching the dead region and reaches 40% for jets in the center of the dead region. The contribution of jets in the dead region to $E_{\mathrm{T}}^{\mathrm{miss}}$ can be estimated and is denoted as $E_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{hole})$. Projecting this quantity on the direction of $E_{\mathrm{T}}^{\mathrm{miss}}$ gives the quantity $\Delta E_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{hole}) = E_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{hole}) \cdot \cos\Delta\phi(\mathrm{jet}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})$. Events with $\Delta E_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{hole}) > 10$ GeV and $\Delta E_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{hole})/E_{\mathrm{T}}^{\mathrm{miss}} > 0.1$ are rejected. This requirement rejects less than 0.5% of the events in the signal regions, and up to 2% of the events in the control regions.

In the event selection, a number of variables derived from the reconstructed objects are used. The transverse mass m_{T} formed by $E_{\mathrm{T}}^{\mathrm{miss}}$ and the p_{T} of the lepton (ℓ) is defined as

$$m_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos(\Delta\phi(\vec{\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})))}.$$

The effective mass m_{eff} is obtained from objects in the event as the scalar sum

$$m_{\mathrm{eff}} = p_{\mathrm{T}}^{\ell} + \sum_{i=1}^{3(4)} p_{\mathrm{T}}^{\mathrm{jet}_i} + E_{\mathrm{T}}^{\mathrm{miss}},$$

where $p_{\mathrm{T}}^{\mathrm{jet}_i}$ are the transverse momenta of the three (four) leading jets.

VI. TRIGGER AND DATA SELECTION

The data were collected between March and July 2011. The trigger system selects events online by requiring an electron or muon trigger to fire. The electron trigger selects electrons that deposit an amount of energy corresponding to $E_{\mathrm{T}} = E\sin\theta > 20$ GeV in the calorimeter. The muon trigger requirement determines a logical OR between a trigger that requires a muon with $p_{\mathrm{T}} > 18$ GeV and a trigger that requires a muon of looser quality with $p_{\mathrm{T}} > 40$ GeV in the barrel; the OR of these two triggers increases the trigger acceptance in the barrel. The trigger efficiency is measured in the data. To assure good data quality, only runs in which all subdetectors perform well are used, resulting in a data set corresponding to an integrated luminosity of 1.04 fb^{-1}, with an estimated uncertainty of 3.7% [54].

VII. EVENT SELECTION

The kinematic selections start by requiring the presence of exactly one lepton (electron or muon) with $p_{\mathrm{T}} > 25$ GeV in case of an electron and $p_{\mathrm{T}} > 20$ GeV for muons. If another lepton is reconstructed with $p_{\mathrm{T}} > 20$ GeV (medium electrons) or $p_{\mathrm{T}} > 10$ GeV (preselected muons), the event is rejected in order to minimize overlap with other analyses aimed at final states with higher lepton multiplicities.

At least three or four good jets with pseudorapidity $|\eta| < 2.8$ are required, depending on the selection, as outlined below. Large mismeasurement of the jet transverse momenta are avoided by requiring that $E_{\mathrm{T}}^{\mathrm{miss}}$ is not aligned with any of the three or four selected jets ($\Delta\phi(\mathrm{jet}_i, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.2$). Kinematic distributions after application of the lepton and jet selection requirements are shown in Fig. 1 for at least three jets and Fig. 2 for at least four jets.

A. Signal regions

Four different signal regions are defined to maximize the sensitivity to different kinematic configurations of supersymmetric event topologies

(1) *"Loose" 3-jet selection* (3JL). The loose 3-jet selection is nearly identical to the selection used in the analysis of the 2010 data [4]. At least three jets, with $p_{\mathrm{T}} > 60$ GeV for the leading jet, and $p_{\mathrm{T}} > 25$ GeV for the other jets, are required. The transverse mass

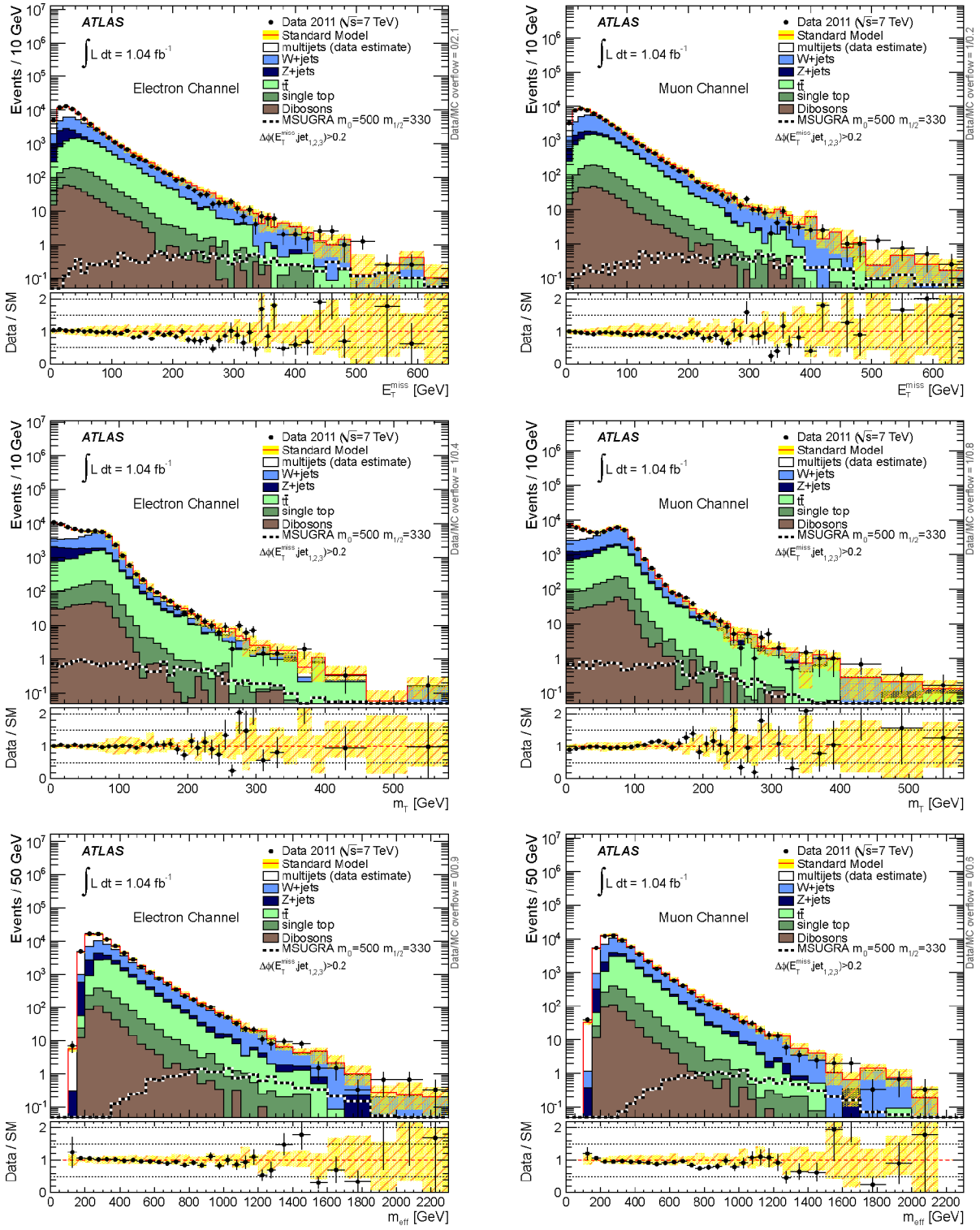

FIG. 1 (color online). Distributions after requiring one electron with $p_{\mathrm{T}} > 25$ GeV or one muon with $p_{\mathrm{T}} > 20$ GeV, and at least three jets with $p_{\mathrm{T}} > 60, 25, 25$ GeV and $\Delta\phi(\mathrm{jet}_i, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.2$. The top row shows the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, the middle row shows the transverse mass, m_{T}, and the bottom row displays the effective mass, m_{eff}. The electron channel is shown in the left column, the muon channel is shown in the right column. The "Data/SM" plots show the ratio between data and the summed standard model expectation. In these plots, the standard model expectation is derived from Monte Carlo simulations only, normalized to the theoretical cross sections. The uncertainty band on the standard model expectation combines the MC statistical uncertainty and systematic uncertainties on the jet energy scale and resolution, the lepton resolution and identification efficiencies, pileup and luminosity. For illustration, the expected signal distributions of the MSUGRA/CMSSM model point $m_0 = 500$ GeV, $m_{1/2} = 330$ GeV are also showmn.

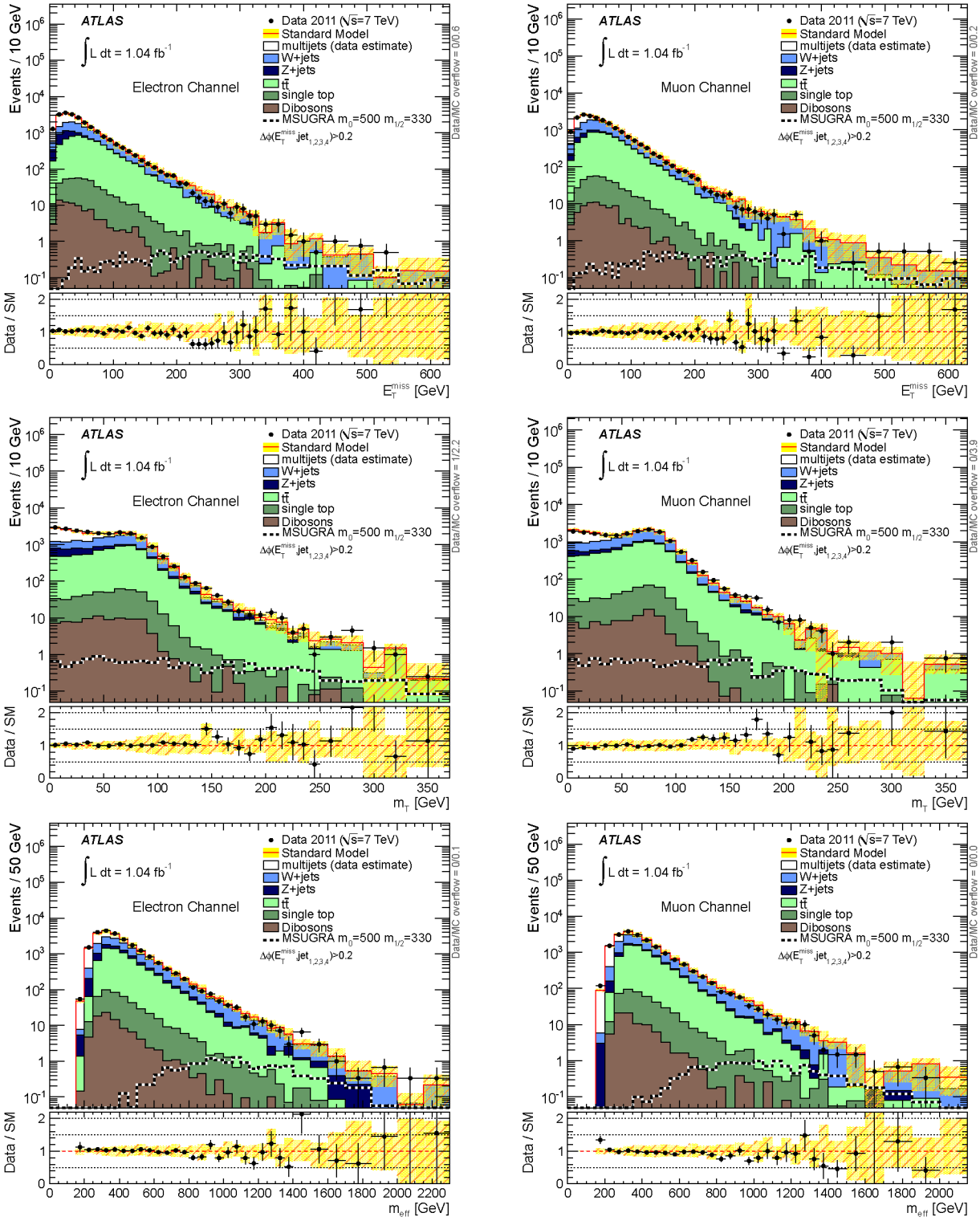

FIG. 2 (color online). Distributions after requiring one electron with $p_{\mathrm{T}} > 25$ GeV or one muon with $p_{\mathrm{T}} > 20$ GeV, and at least four jets with $p_{\mathrm{T}} > 60, 25, 25, 25$ GeV and $\Delta\phi(\mathrm{jet}_i, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.2$. The top row shows the missing transverse momentum, the middle row shows the transverse mass, and the bottom row displays the effective mass. The electron channel is shown in the left column, the muon channel is shown in the right column. The "Data/SM" plots show the ratio between data and the summed standard model expectation. In these plots, the standard model expectation is derived from Monte Carlo simulations only, normalized to the theoretical cross sections. The uncertainty band on the standard model expectation combines the MC statistical uncertainty and systematic uncertainties on the jet energy scale and resolution, the lepton resolution and identification efficiencies, pileup and luminosity. For illustration, the expected signal distributions of the MSUGRA/CMSSM model point $m_0 = 500$ GeV, $m_{1/2} = 330$ GeV are also shown.

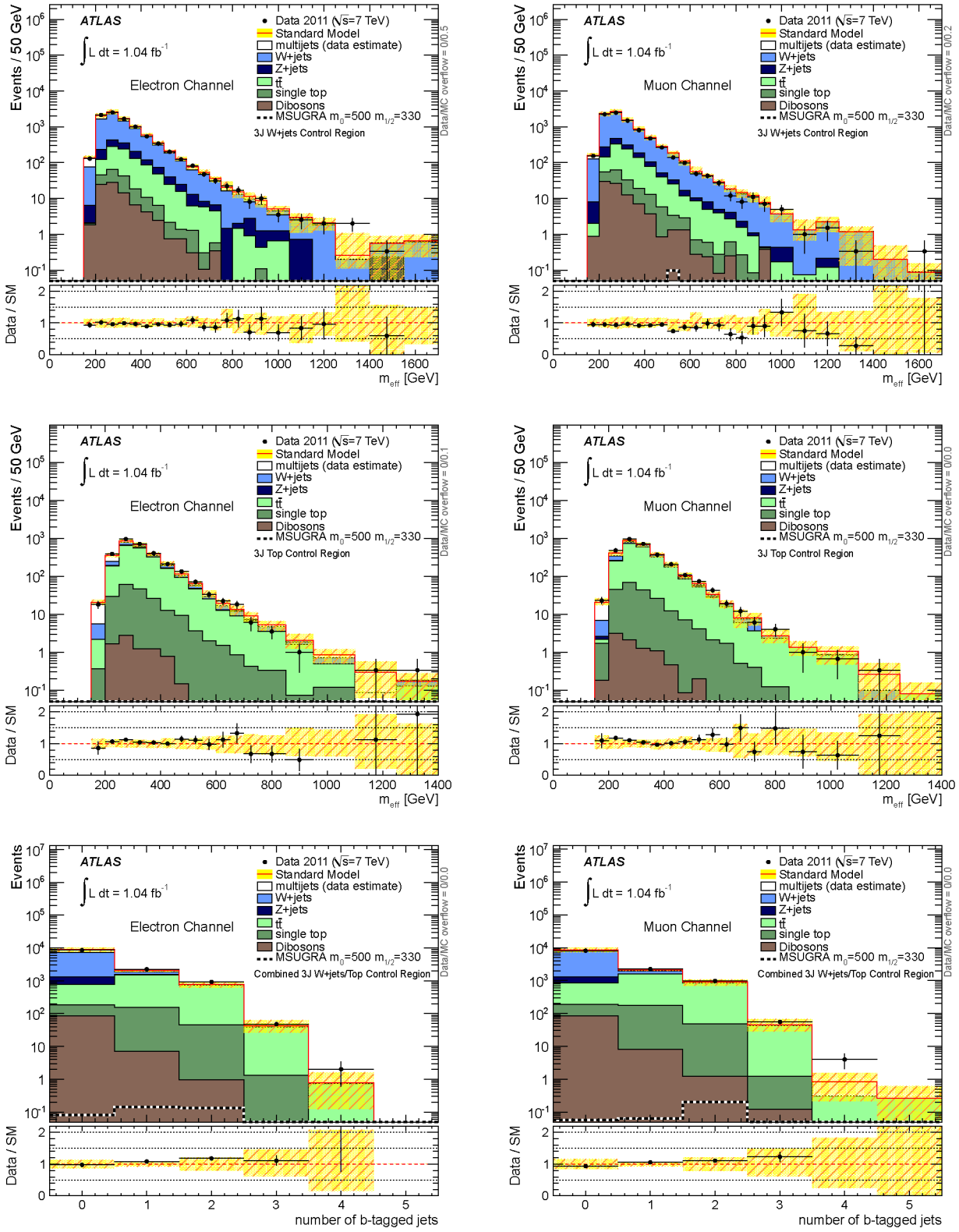

FIG. 3 (color online). Distributions for events in the lepton plus three jets control regions for the electron channel (left column) and muon channel (right column). Top row: effective mass in the W + jets control region. Middle row: effective mass in the top control region. Bottom row: number of b-tagged jets in the combined W + jets and top control regions. The "Data/SM" plots show the ratio between data and the summed standard model expectation. The uncertainty band on the standard model expectation combines the MC statistical uncertainty and systematic uncertainties on the jet energy scale and resolution, b-tagging, the lepton resolution and identification efficiencies, pileup and luminosity.

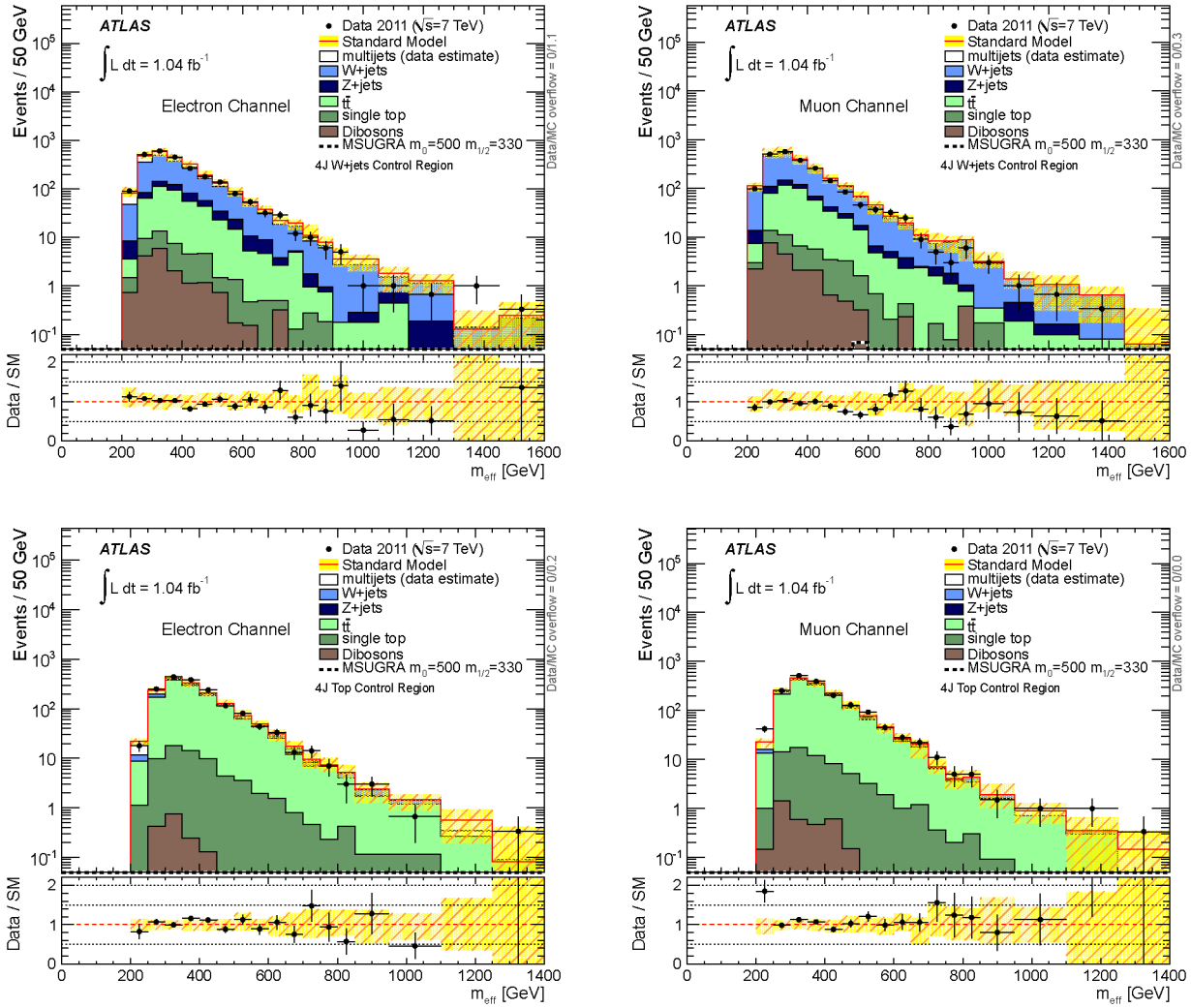

FIG. 4 (color online). Distributions for events in the lepton plus four jets control regions for the electron channel (left column) and muon channel (right column). Top row: effective mass in the W + jets control region. Bottom row: effective mass in the top control region. The "Data/SM" plots show the ratio between data and the summed standard model expectation. The uncertainty band on the standard model expectation combines the MC statistical uncertainty and systematic uncertainties on the jet energy scale and resolution, b-tagging, the lepton resolution and identification efficiencies, pileup and luminosity.

m_{T} must exceed 100 GeV, and $E_{\mathrm{T}}^{\mathrm{miss}}$ must be larger than 125 GeV. Two final cuts, $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.25$ and $m_{\mathrm{eff}} > 500$ GeV, define this signal region.

(2) *Tight 3-jet selection* (3JT). In the tight 3-jet selection, the requirement on the leading jet p_{T} is raised to 80 GeV. In addition to these cuts, the following criteria are applied: $m_{\mathrm{T}} > 100$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 240$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.15$ and $m_{\mathrm{eff}} > 600$ GeV.

(3) *"Loose" 4-jet selection* (4JL). Four jets with $p_{\mathrm{T}} > 25$ GeV are required, with at least one of them exceeding 60 GeV. In addition to the jet cuts, the selection requires: $m_{\mathrm{T}} > 100$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 140$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.30$ and $m_{\mathrm{eff}} > 300$ GeV.

(4) *Tight 4-jet selection* (4JT). A tight selection with at least four jets is defined. The p_{T} requirement on the nonleading jets is raised to 40 GeV, whereas the leading jet is still required to pass $p_{\mathrm{T}} > 60$ GeV. To define this signal region, three more criteria are imposed: $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.15$ and $m_{\mathrm{eff}} > 500$ GeV.

The tight signal regions are optimized for the MSUGRA/CMSSM model, which is characterized by energetic jets and large missing transverse momentum. The loose signal regions perform better for the simplified models with compressed particle spectra, i.e., when the LSP mass approaches the squark or gluino mass. The 3-jet selection is optimized for squark-squark and squark-antisquark production, the 4-jet selection is better suited for squark-gluino and gluino-gluino production.

B. Control regions

Two classes of control regions are defined, i.e., separate control regions for the 3-jet and the 4-jet selections. The requirements on the lepton and the jets in the control regions are identical to those in the signal regions.

(1) W + jets *control regions* (WR). W + jets control regions are defined by requiring $30\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 80$ GeV, $40\,\text{GeV} < m_{\text{T}} < 80$ GeV, and that none of the three or four jets with the highest p_{T} is tagged as a b-jet.

(2) *Top control regions* (TR). Top control regions are defined by identical cuts on $E_{\text{T}}^{\text{miss}}$ and m_{T} as for the W + jets control regions, but requiring at least one b-tagged jet among the three or four jets with the highest p_{T}.

The jet requirements are identical to the ones of the loose signal regions. In addition, a cut on m_{eff} is applied to both classes of control regions, again corresponding to the cut of the loose signal regions: $m_{\text{eff}} > 500$ GeV for the 3-jet selection, and $m_{\text{eff}} > 300$ GeV for the 4-jet selection. Fig. 3 shows distributions of m_{eff} and the number of b-tagged jets for events in the W + jets and top control regions for the electron and muon channel applying the 3-jet selection. The distributions of m_{eff} in the 4-jet control regions are shown in Fig. 4. The MC simulation describes the data well.

VIII. BACKGROUND ESTIMATION

The multijet background is estimated from the data in the signal regions and in the W + jets and top control regions, using a matrix method. This background originates from jets misidentified as leptons, but also from nonisolated real leptons, for example, from heavy flavor decay. In this paper, both components are collectively called misidentified leptons. For all regions, multijet-dominated samples are defined by loosening the lepton identification criteria: for electrons the medium criteria are used instead of the tight criteria [48], and for both electrons and muons the isolation criterion is dropped. Defining N_{pass} and N_{fail} as the number of events in such a loose sample passing or failing the final lepton selection criteria, and defining N_{real} and N_{misid} as the number of real and the number of misidentified leptons, the following equations hold:

$$N_{\text{pass}} = \epsilon_{\text{real}} N_{\text{real}} + \epsilon_{\text{misid}} N_{\text{misid}},$$

$$N_{\text{fail}} = (1 - \epsilon_{\text{real}}) N_{\text{real}} + (1 - \epsilon_{\text{misid}}) N_{\text{misid}},$$

where ϵ_{real} is the relative identification efficiency for real leptons, and ϵ_{misid} is the misidentification efficiency for misidentified leptons. Solving the equations leads to:

$$N_{\text{misid}}^{\text{pass}} = \epsilon_{\text{misid}} N_{\text{misid}} = \frac{N_{\text{fail}} - (1/\epsilon_{\text{real}} - 1) N_{\text{pass}}}{1/\epsilon_{\text{misid}} - 1/\epsilon_{\text{real}}}.$$

The efficiency ϵ_{real} is taken from simulated $Z \to ee$ events (electron channel) or $t\bar{t}$ and W + jets events (muon channel). The efficiency ϵ_{misid} is determined from data control samples enriched in multijet events, selected as follows. For the electron channel medium electrons with $p_{\text{T}} > 20$ GeV are required. In addition, one jet with $p_{\text{T}} > 30$ GeV needs to be present in the event. To suppress W and $t\bar{t}$ contributions, an upper cut of 30 GeV is imposed on $E_{\text{T}}^{\text{miss}}$. For the determination of the multijet background in the top control region, a b-tag is required for at least one of the selected jets. For the muon final state, the multijet control region is defined by one preselected muon with $p_{\text{T}} > 20$ GeV, one jet with $p_{\text{T}} > 60$ GeV and $E_{\text{T}}^{\text{miss}} < 30$ GeV. These control samples are corrected for contamination by real leptons, which amounts to about 9% for muons, and less than 3% for electrons. The misidentification efficiency ϵ_{misid} is measured as function of p_{T} and η and this dependence is considered in the determination of the multijet contribution in both the signal and control regions. Typical values for ϵ_{real} and ϵ_{misid} are 88% and 10%, respectively, for the electron channel, and 98% and 35%, respectively, for the muon channel.

A normalization of the W + jets and top backgrounds to the data is performed in the W + jets and top control regions. Assuming that the shape of the distributions is described correctly by the Monte Carlo simulation, transfer factors $C_{i\text{R}\to\text{SR}}^{j}$ from control region iR ($i = \text{W}, \text{T}$) to signal region SR for background type j ($j = W$ + jets, top) can be defined as

$$C_{i\text{R}\to\text{SR}}^{j} = \frac{N_{\text{MC},j}^{\text{SR}}}{N_{\text{MC},j}^{i\text{R}}}.$$

Thus the predicted contribution for background type j in the signal region is given by

$$N_{\text{pred.}\,j}^{\text{SR}} = \sum_{i=\text{W,T}} (N_{\text{data}}^{i\text{R}} \times C_{i\text{R}\to\text{SR}}^{j}).$$

Typical values for the transfer factors are $C_{\text{WR}\to\text{SR}}^{\text{W}} = 0.023\,(0.007)$ and $C_{\text{TR}\to\text{SR}}^{t\bar{t}} = 0.040\,(0.023)$ for the electron channel and the 3JT (4JL) selection. The control regions are not 100% pure, and cross-contamination of backgrounds in the various control regions is taken into account. The solution of the coupled equations is performed in a combined fit to each signal region and the corresponding WR and TR control regions. The estimated backgrounds include contributions from dileptonic events with an undetected lepton as well as top quark or W + jets production with leptonic tau decays.

The assumption that the MC simulation is able to predict the backgrounds in the signal regions from the control regions is validated by checking additional control regions

at low m_{T} and high $E_{\mathrm{T}}^{\mathrm{miss}}$, or at low $E_{\mathrm{T}}^{\mathrm{miss}}$ and high m_{T}. Since these additional control regions have different kinematics and composition than the nominal ones, these regions are susceptible to reacting differently to any mismodeling of the data. In each region, the observed number of events is compared to the prediction of the nominal background fit. In these 28 additional control regions, only one is found where the difference between expected and observed events exceeds 2σ.

Possible contamination from events originating from cosmic ray muons is estimated by loosening the $|z_\mu - z_{\mathrm{PV}}| < 5$ mm requirement and studying the z_μ distribution, and is found to be negligible. Remaining backgrounds from single top and diboson production are estimated with MC simulation, and are also found to be negligible.

IX. SYSTEMATIC UNCERTAINTIES

In this analysis systematic uncertainties arise on the estimates of the background in the signal regions, as well as on the estimate of the SUSY signal itself. The primary sources of systematic uncertainty are the jet energy scale (JES) calibration, the jet energy resolution (JER) uncertainty, theory and MC modeling uncertainties, and uncertainties on object reconstruction and identification.

The JES uncertainty has been measured from the complete 2010 data set using the techniques described in Ref. [55]. Additional contributions to the JES uncertainty are added to account for the effect of pileup at the relatively high luminosity delivered by the LHC in the 2011 run. The JES and JER calibrations are applied to MC-simulated jets, and their uncertainties are propagated throughout the analysis, including to $E_{\mathrm{T}}^{\mathrm{miss}}$.

The JER measured with 2010 data [56] is applied to all MC-simulated jets. The difference in the JER between the recalibrated and nominal MC simulation is taken as the systematic uncertainty. Additional contributions are added to account for pileup in 2011.

MC modeling uncertainties, affecting the transfer factors, are derived from alternative MC samples with different generators, or with different generator parameters.

Apart from jet energy scale, jet energy resolution and MC modeling uncertainties, further uncertainties on the background estimates originate from finite MC statistics of top and W + jets events, from lepton energy/momentum scale and resolution uncertainties, from uncertainty in the lepton misidentification rates, from the identification efficiencies for real leptons, and from b-tagging uncertainties. The uncertainties on the background estimates are summarized in Table I.

Systematic uncertainties on the SUSY signal are estimated through variation of the factorization and renormalization scales in PROSPINO between half and twice their default values, by considering variations in α_s, and by considering the PDF uncertainties provided by CTEQ6. Uncertainties are calculated for individual SUSY production processes. In the relevant regions of parameter space in the MSUGRA/CMSSM model, these theoretical uncertainties on the signal cross sections are typically 20–30%. Further uncertainties on the number of predicted signal events arise from the JES uncertainty (1–10%), the JER uncertainty (1–10%), pileup uncertainties (1–10%), lepton trigger and identification uncertainties (1–4%), the uncertainty on the luminosity (3.7%), and finite statistics of the signal Monte Carlo samples ($\sim$ 15%). Uncertainties in the modeling of initial state radiation in signal events affect the uncertainty of the acceptance for low values of squark and/or gluino masses, and for small mass differences in the simplified models. These uncertainties are estimated from

TABLE I. Breakdown, in number of events, of the dominant systematic uncertainties on background estimates in the various signal regions. Note that the nuisance parameters of individual uncertainties can be correlated in the fit, and therefore their uncertainties do not necessarily add quadratically to the total background uncertainty.

Electron channel	3JL	3JT	4JL	4JT
Total statistical ($\sqrt{N_{\mathrm{obs}}}$)	$\pm$8.4	$\pm$3.7	$\pm$6.4	$\pm$3.0
Total background systematic	$\pm$30.2	$\pm$7.4	$\pm$17.9	$\pm$3.7
jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ energy resolution	$\pm$5.9	$\pm$0.5	$\pm$4.2	$\pm$0.8
jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale	$\pm$18.6	$\pm$4.1	$\pm$13.6	$\pm$2.4
Lepton energy resolution	$\pm$0.5	$\pm$0.3	$\pm$0.1	$\pm$0.3
Lepton energy scale	$\pm$1.1	$\pm$0.3	$\pm$0.4	$\pm$0.5
b-tagging	$\pm$1.2	$\pm$0.2	$\pm$0.7	$\pm$0.1
MC stat top	$\pm$5.8	$\pm$2.0	$\pm$3.8	$\pm$1.4
MC stat W	$\pm$4.4	$\pm$2.3	$\pm$2.2	$\pm$1.3
Lepton misidentification rate	$\pm$1.4	$\pm$0.1	$\pm$0.2	$<$0.1
Real lepton rate	$\pm$1.5	$\pm$0.3	$\pm$0.8	$\pm$0.1
Top background modeling	$\pm$15.9	$\pm$2.1	$\pm$9.8	$\pm$1.2
W background modeling	$\pm$19.0	$\pm$5.6	$\pm$5.1	$\pm$1.9
Pileup	$\pm$5.1	$\pm$1.0	$\pm$2.5	$\pm$0.4
Muon channel	**3JL**	**3JT**	**4JL**	**4JT**
Total statistical ($\sqrt{N_{\mathrm{obs}}}$)	$\pm$7.6	$\pm$3.3	$\pm$7.1	$\pm$2.7
Total background systematic	$\pm$19.3	$\pm$4.3	$\pm$15.8	$\pm$2.7
jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ energy resolution	$\pm$9.0	$\pm$1.1	$\pm$0.9	$\pm$0.5
jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale	$\pm$7.0	$\pm$0.2	$\pm$9.1	$\pm$1.6
Lepton energy resolution	$<$0.1	$<$0.1	$<$0.1	$<$0.1
Lepton energy scale	$\pm$0.8	$\pm$0.3	$\pm$1.4	$\pm$0.5
b-tagging	$\pm$1.0	$\pm$0.2	$\pm$0.9	$\pm$0.1
MC stat top	$\pm$5.4	$\pm$2.1	$\pm$4.0	$\pm$1.4
MC stat W	$\pm$2.5	$\pm$1.4	$\pm$2.6	$\pm$0.7
Lepton misidentification rate	$<$0.1	$<$0.1	$<$0.1	$<$0.1
Real lepton rate	$\pm$0.5	$\pm$0.1	$\pm$0.4	$<$0.1
Top background modeling	$\pm$12.9	$\pm$2.4	$\pm$10.0	$\pm$1.2
W background modeling	$\pm$8.8	$\pm$2.7	$\pm$7.3	$\pm$0.7
Pileup	$\pm$3.5	$\pm$0.8	$\pm$2.7	$\pm$0.3

variations of MC generator parameters as well as by explicitly generating $\tilde{g}\,\tilde{g}$ +jet and $\tilde{q}\,\tilde{q}$ +jet events with a matrix element approach as implemented in MadGraph 5 [57]. Resulting uncertainties vary from negligible at high masses and high mass splittings, to ~30% at low masses and low mass splittings.

X. RESULTS AND INTERPRETATION

Figs. 5 and 6 show the distributions of the effective mass in the 3-jet and 4-jet signal regions, respectively, after application of the final selection criteria described in Sec. VII A, except for the cut on m_{eff} itself.

As discussed in Sec. VIII, a combined fit to the number of observed events in the signal and control regions is performed. The fit is performed for the four signal regions individually. The likelihood function of the fit is written as

$$L(\mathbf{n}|s, \mathbf{b}, \boldsymbol{\theta}) = P_{\text{S}} \times P_{\text{W}} \times P_{\text{T}} \times C_{\text{Syst}}, \tag{1}$$

where $\mathbf{n}$ represents the number of observed events in data, s is the SUSY signal to be tested, $\mathbf{b}$ is the background, and $\boldsymbol{\theta}$ represents the systematic uncertainties, which are treated as nuisance parameters with a Gaussian probability density function. The three P functions in the right-hand side are Poisson probability distributions for event counts in the defined signal (S) and control regions (W and T, for W and top pair, respectively) and C_{Syst} represents the constraints on systematic

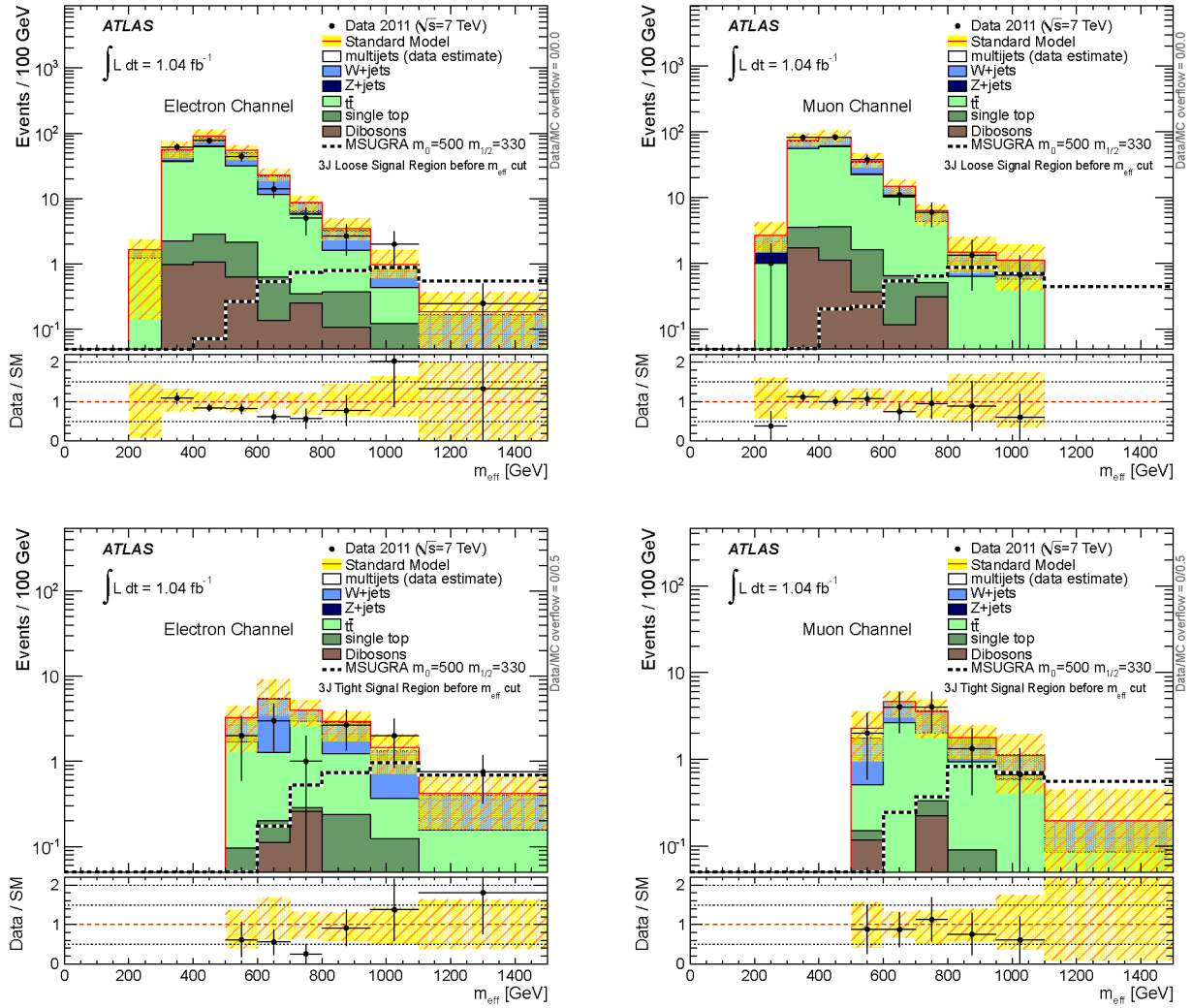

FIG. 5 (color online). Distributions of the effective mass for events in the 3-jet signal regions 3JL (top) and 3JT (bottom) for the electron channel (left) and the muon channel (right), after application of the final selection criteria described in Sec. VII A, except for the cut on m_{eff} itself. The "Data/SM" plots show the ratio between data and the summed standard model expectation. The uncertainty band on the standard model expectation combines the MC statistical uncertainty and systematic uncertainties on the jet energy scale and resolution, the lepton resolution and identification efficiencies, pileup and luminosity. For illustration, the expected signal distributions of the MSUGRA/CMSSM model point $m_0 = 500$ GeV, $m_{1/2} = 330$ GeV are also shown.

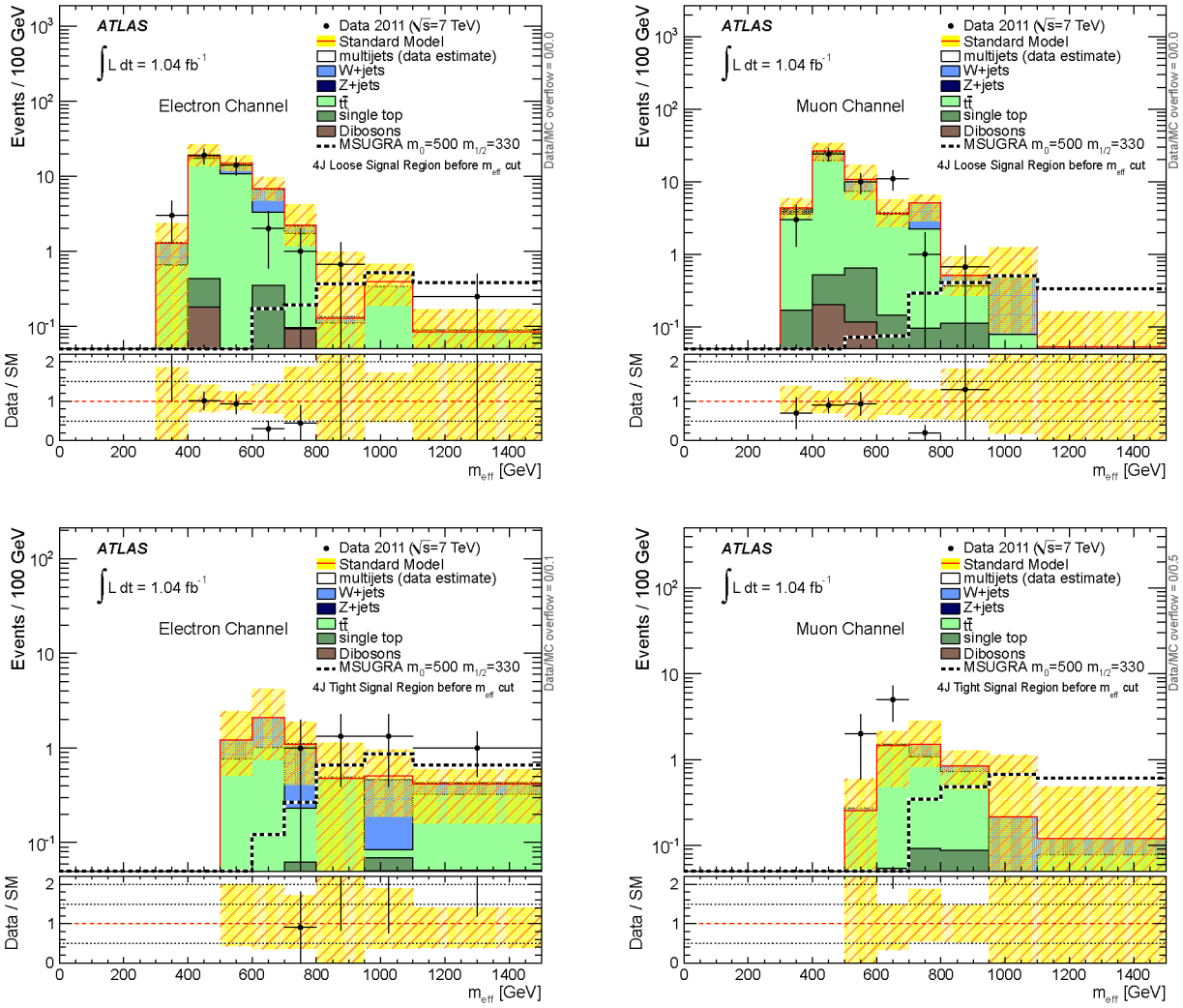

FIG. 6 (color online). Distributions of the effective mass for events in the 4-jet signal regions 4JL (top) and 4JT (bottom) for the electron channel (left) and the muon channel (right), after application of the final selection criteria described in Sec. VII A, except for the cut on m_{eff} itself. The "Data/SM" plots show the ratio between data and the summed standard model expectation. The uncertainty band on the standard model expectation combines the MC statistical uncertainty and systematic uncertainties on the jet energy scale and resolution, the lepton resolution and identification efficiencies, pileup and luminosity. For illustration, the expected signal distributions of the MSUGRA/CMSSM model point $m_0 = 500$ GeV, $m_{1/2} = 330$ GeV are also shown.

uncertainties. Systematic uncertainties can be correlated between the signal and control regions. The determination of the multijet contribution to the various regions, with the method described in Sec. VIII, is performed as part of the fit procedure.

In "discovery mode," the number of SUSY signal events in the signal regions is left free in the fit, as well as the background normalizations and nuisance parameters. Possible signal contamination in the control regions is ignored. This fit tests the standard model hypothesis in the signal regions, and quantifies any possible excess of events above the background-only expectation in the signal regions. The results of the "discovery fit" are shown in Tables II and III. Note that for the control regions, by construction, the number of "fitted" background events equals the number of observed events. The observed number of events in data is consistent with the standard model expectation. The last column in Table IV shows the $p-$values of the discovery fit to data [$p(s = 0)$ for the no-signal hypothesis] for the individual electron and muon channels.

Model-independent upper limits on new physics contributions to (only) the signal regions can be derived from the discovery fit results. The ignorance of possible signal contamination in the control regions in the discovery fit leads to conservative upper limits on non-standard model contributions. The limits are derived using the CL_s method [58] based on the profile

TABLE II. Fit results for the electron (top part) and muon (bottom part) channels in the loose 3-jet (3JL) and tight 3-jet (3JT) signal regions. The results are obtained from the control regions using the "discovery fit" (see text for details). Nominal MC expectations (normalized to MC cross sections) are given between parentheses for comparison.

Observed events	71	14	162	565
Fitted top events	56 ± 20 (51)	7.6 ± 3.0 (6.8)	125 ± 16 (112)	64 ± 8 (58)
Fitted W/Z events	35 ± 20 (34)	10.5 ± 6.5 (10.1)	30.1 ± 9.1 (29.3)	425 ± 36 (413)
Fitted multijet events	$6.0^{+2.3}_{-1.4}$	$0.46^{+0.37}_{-0.22}$	7.2 ± 2.6	76 ± 24
Fitted sum of background events	97 ± 30	18.5 ± 7.4	162 ± 13	565 ± 24

Muon channel	3JL Signal region	3JT Signal region	Top region	W region
Observed events	58	11	166	413
Fitted top events	47 ± 16 (38)	8.9 ± 3.2 (7.3)	142 ± 14 (115)	70 ± 7 (57)
Fitted W/Z events	16.6 ± 9.4 (20.1)	5.0 ± 3.2 (61)	19.0 ± 4.8 (232)	322 ± 23 (393)
Fitted multijet events	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.6}_{-0.0}$	5.4 ± 2.2	21.6 ± 5.7
Fitted sum of background events	64 ± 19	13.9 ± 4.3	166 ± 13	413 ± 20

TABLE III. Fit results for the electron (top part) and muon (bottom part) channels in the loose 4-jet (4JL) and tight 4-jet (4JT) signal regions. The results are obtained from the control regions using the "discovery fit" (see text for details). Nominal MC expectations (normalized to MC cross sections) are given between parentheses for comparison.

Electron channel	4JL Signal region	4JT Signal region	Top region	W region
Observed events	41	9	1382	1872
Fitted top events	38 ± 15 (34)	4.5 ± 2.6 (4.1)	1258 ± 44 (1138)	391 ± 14 (354)
Fitted W/Z events	9.5 ± 7.5 (9.2)	3.5 ± 2.2 (3.4)	88 ± 21 (86)	1242 ± 89 (1202)
Fitted multijet events	$0.90^{+0.54}_{-0.37}$	$0.00^{+0.02}_{-0.00}$	35 ± 13	239 ± 78
Fitted sum of background events	48 ± 18	8.0 ± 3.7	1382 ± 37	1872 ± 43

Muon channel	4JL Signal region	4JT Signal region	Top region	W region
Observed events	50	7	1448	1623
Fitted top events	39 ± 13 (36)	4.7 ± 2.2 (4.3)	1319 ± 45 (1231)	382 ± 13 (357)
Fitted W/Z events	14.1 ± 8.5 (14.2)	1.4 ± 1.1 (1.4)	91 ± 19 (92)	1169 ± 46 (1185)
Fitted multijet events	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.6}_{-0.0}$	38 ± 10	71 ± 16
Fitted sum of background events	53 ± 16	6.0 ± 2.7	1448 ± 38	1623 ± 40

likelihood ratio test statistic [59], $\Lambda(s) = -2(\ln L(\mathbf{n}|s, \hat{\hat{\mathbf{b}}}, \hat{\hat{\boldsymbol{\theta}}}) - \ln L(\mathbf{n}|\hat{s}, \hat{\mathbf{b}}, \hat{\boldsymbol{\theta}}))$, where $\hat{s}$, $\hat{\mathbf{b}}$ and $\hat{\boldsymbol{\theta}}$ maximize the likelihood function and $\hat{\hat{\mathbf{b}}}$ and $\hat{\hat{\boldsymbol{\theta}}}$ maximize the likelihood for a given choice of s. In the fit, s and $\hat{s}$ are constrained to be non-negative. The resulting 95% confidence level (CL) limits are shown in Table IV as observed and expected upper limits on the number of non-SM events in the signal regions, as well as upper limits on the visible cross section (which equals the limit on the observed number of signal events divided by the integrated luminosity).

Limits within the MSUGRA/CMSSM framework are derived from a second fit to signal and control regions, in "exclusion mode." This fit mode tests for a specific new physics model, 3 to 10, the limits are to a good approximation independent of $\tan\beta$. For higher values of $\tan\beta$, up to $\tan\beta = 40$, the effect on the limits depends on m_0 and $m_{1/2}$; for regions in the $(m_0, m_{1/2})$ plane with $m_{\tilde{q}} \approx m_{\tilde{g}}$, mass limits deteriorate by up to 10%.

The results for the interpretation in terms of the simplified models are shown in Fig. 8. Again, the selection

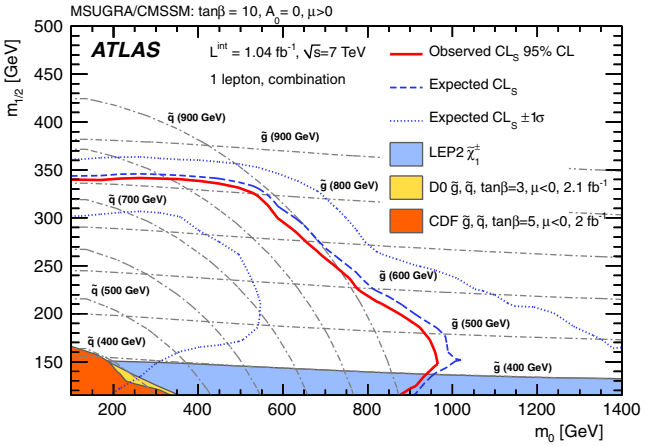

FIG. 7 (color online). Observed and expected 95% CL exclusion limits, as well as the $\pm 1\sigma$ variation on the median expected limit, in the combined electron and muon channels. The plots also show the published limits from CDF [60], D0 [61], and the results from the LEP experiments [62].

TABLE IV. 95% CL upper limits on the visible cross section ($\langle \epsilon\sigma \rangle^{95}_{\rm obs}$) and on the observed ($S^{95}_{\rm obs}$) and expected ($S^{95}_{\rm exp}$) number of signal events for the various signal regions. The last two columns indicate the CL_B value and discovery p-value ($p(s = 0)$). All numbers are given for the individual electron and muon channels.

Electron channel	$\langle \epsilon\sigma \rangle^{95}_{\rm obs}$ [fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$	CL_B	$p(s=0)$
3JL	50	52	63^{+23}_{-11}	0.21	0.79
3JT	14	14.3	$16.5^{+6.7}_{-3.0}$	0.30	0.71
4JL	33	34	38^{+15}_{-7}	0.35	0.65
4JT	10	10.6	$9.5^{+4.3}_{-1.6}$	0.61	0.42
Muon channel	$\langle \epsilon\sigma \rangle^{95}_{\rm obs}$ [fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$	CL_B	$p(s=0)$
3JL	36	38	41^{+16}_{-7}	0.39	0.60
3JT	10	9.9	$11.4^{+4.5}_{-2.0}$	0.31	0.70
4JL	31	32	34^{+14}_{-7}	0.42	0.58
4JT	9	8.9	$8.0^{+3.0}_{-1.6}$	0.63	0.39

yielding the best expected limit for a given parameter point is used for the combination of the four signal regions. The plots of Fig. 8 show an upper limit on the cross section for new physics, at 95% CL, as a function of neutralino (LSP) and gluino or squark mass, for three different values of the third free parameter, corresponding to the ratio of the mass differences in the relevant SUSY decay mode, $x = (m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0})/(m_{\tilde{g}} - m_{\tilde{\chi}^0})$ (for the gluino models) or $x = (m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0})/(m_{\tilde{q}} - m_{\tilde{\chi}^0})$ (for the squark models). To obtain these upper limits, identical cross sections are assumed for the electron and muon channels, and no theoretical uncertainties are considered. The plots of Fig. 8 show that the limits on the cross section for new physics deteriorate when the LSP mass approaches the squark or gluino mass, i.e., when the mass spectrum is compressed. Also indicated on the plots are the observed exclusion regions, assuming production cross sections as calculated with PROSPINO for the MSSM, and a 100% branching fraction into the assumed decay modes. In the gluino model, all squark masses are set to 4.5 TeV and only gluino pair production is considered. In the squark model, the masses of the gluino and of the third-generation squarks are set to 4.5 TeV. The masses of the left- and right-handed squarks of the first- and second-generation are set to be equal. By setting the gluino mass to 4.5 TeV, the t-channel (gluino exchange) production of $\tilde{q}_{\rm L}\tilde{q}_R$ is effectively suppressed. In supersymmetric theories such as the MSSM only the left-handed squarks decay to charginos with 100% wino content, which is implied by this particular simplified model. Therefore the PROSPINO squark pair production cross section is divided by a factor of 2 to obtain the $\tilde{q}_{\rm L}\tilde{q}_{\rm L}$ cross section. Note that reducing the gluino mass to 1.2 TeV would increase this cross section by a few percent for $m_{\tilde{q}} = 200$ GeV, but by a factor two for $m_{\tilde{q}} = 400$ GeV. For the calculation of the exclusion regions, theoretical uncertainties on the cross sections, as discussed in Sec. IX, are taken into account. In the gluino model at high x, gluino masses up to 650 GeV are excluded for massless LSPs, but for LSP masses above 280 GeV no exclusion can be made. In this model, LSP masses below 200 GeV are excluded for gluino masses below 600 GeV and $x > 1/2$. The best exclusion limits are obtained for $x = 3/4$, which gives rise to higher $p_{\rm T}$ leptons than the $x = 1/4$ case. In the squark model, no exclusion in the $x = 1/4$ and $x = 1/2$ planes can be made. These results are the first simplified model results in the one-lepton channel, and complement earlier simplified model results for the zero-lepton channel [16,17].

For the bilinear R-parity-violating model, among the four signal regions considered, the tight selection criteria provide wider reach than the loose ones. The most stringent exclusion limits are set by the 4JT signal region as shown in Fig. 9. The model is not tested for regions of parameter space where $c\tau$ of the LSP exceeds about 15 mm, which is approximately the case for $m_{1/2} <$ 240 GeV. Within the context of this model, and for equal squark and gluino masses, masses below 760 GeV are excluded.

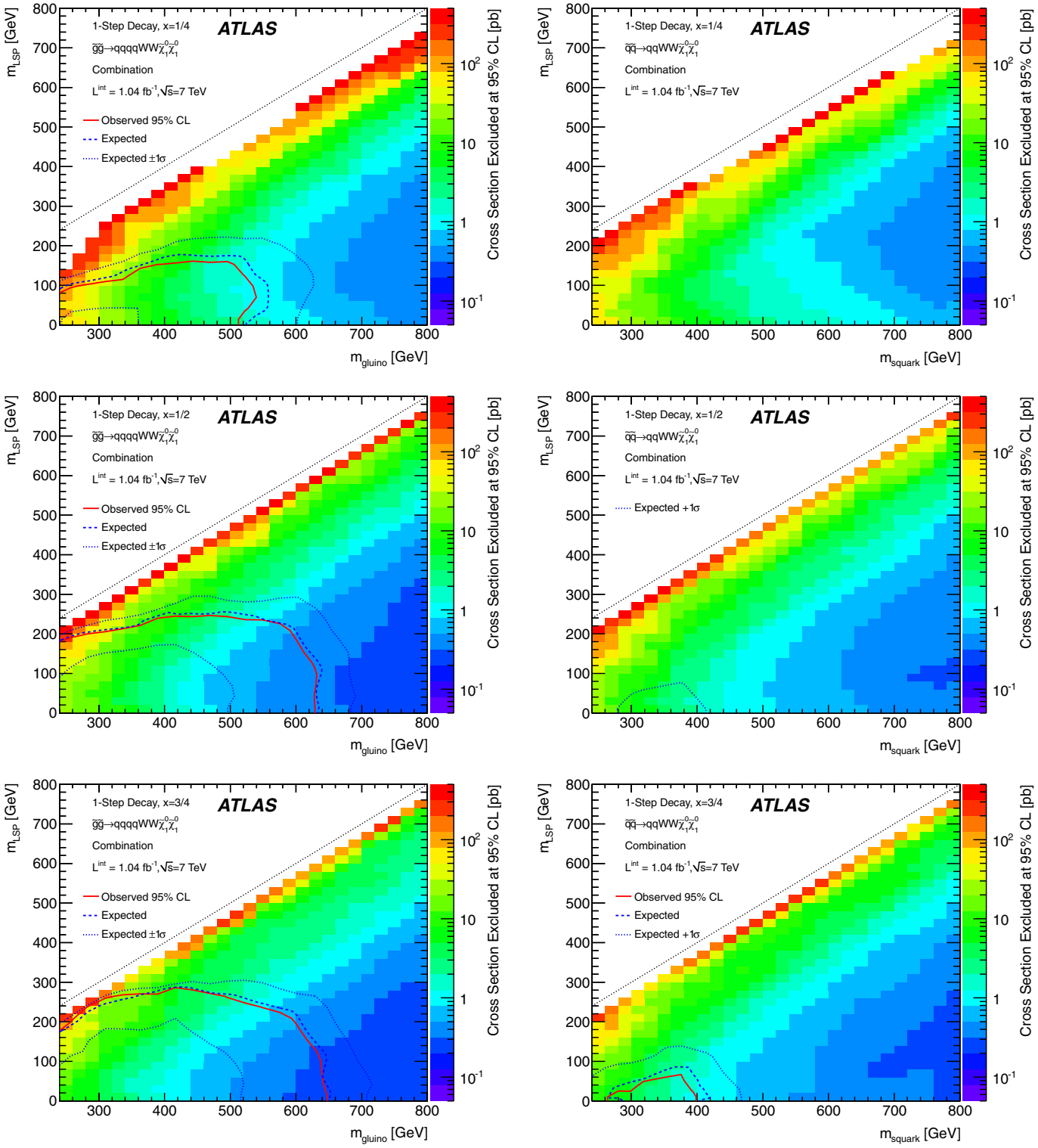

FIG. 8 (color online). Excluded cross sections at 95% confidence level for the simplified models. The left column shows the results for the gluino models, the right column shows the results for the squark models. The top row plots represent the case $x = 1/4$, the middle row $x = 1/2$, and the bottom row $x = 3/4$. The color coding (right axis) represents the model-independent cross section limit. Full lines indicate the observed exclusion regions in the shown plane assuming production cross sections as calculated with PROSPINO for the MSSM, and a 100% branching fraction into the assumed decay modes. The dashed line shows the corresponding median expected limit and the dotted lines show the $\pm 1\sigma$ variation on the expected limit.

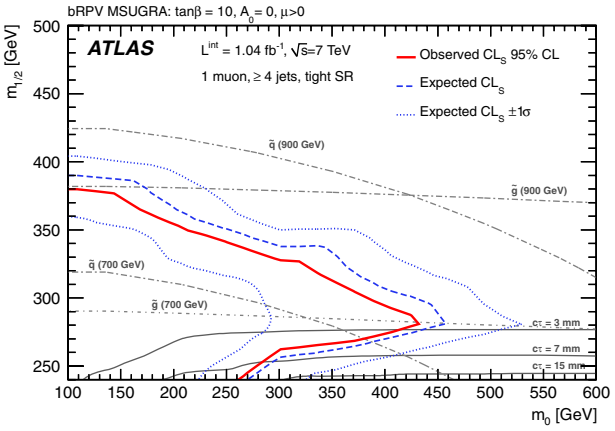

FIG. 9 (color online). Observed and expected 95% CL exclusion limits, as well as the $\pm 1\sigma$ variation on the expected limit, for the bilinear R-parity violation model in MSUGRA parameter space using the 4JT selection in the muon channel. The region with LSP lifetimes $c\tau > 15$ mm is not shown.

XI. SUMMARY AND CONCLUSION

In this paper, an update of the search for supersymmetry is presented, in final states containing one isolated electron or muon, jets, and missing transverse momentum. Good agreement is seen between the observed number of events in the signal regions and the standard model expectation, and limits are set on contributions of new physics to the signal regions. These limits significantly improve on the results from 2010 data and are applied to a wider range of SUSY models. Model-independent limits on the cross section of new physics contributions to the signal regions are set, varying between 9 fb and 50 fb depending on the channel and the signal region. In the MSUGRA/CMSSM model and for equal squark and gluino masses, gluino masses below 820 GeV are excluded. Limits are set on simplified models for gluino production and decay and squark production and decay via an intermediate chargino. For the gluino model and for the decay ratio $x > 1/2$, LSP masses below 200 GeV are excluded for gluino masses below 600 GeV. For the first time at the LHC, limits are set on supersymmetric models with bilinear R-parity violation.

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 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; ARTEMIS, 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; MERYS (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.

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(ATLAS Collaboration)

[1]*University at Albany, Albany New York, USA*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Turkey*
[3b]*Department of Physics, Dumlupinar University, Kutahya, Turkey*
[3c]*Department of Physics, Gazi University, Ankara, Turkey*
[3d]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[3e]*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, Illinois, USA*
[6]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[7]*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*
[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*
[12a]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[12b]*Vinca Institute of Nuclear Sciences, 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, California, USA*
[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, United Kingdom*
[18a]*Department of Physics, Bogazici University, Istanbul, Turkey*
[18b]*Division of Physics, Dogus University, Istanbul, Turkey*
[18c]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[18d]*Department of Physics, Istanbul Technical University, Istanbul, Turkey*
[19a]*INFN Sezione di Bologna, Italy*
[19b]*Dipartimento di Fisica, Università di Bologna, Bologna, Italy*
[20]*Physikalisches Institut, University of Bonn, Bonn, Germany*
[21]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[22]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[23a]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[23b]*Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[23c]*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*
[23d]*Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[24]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[25a]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[25b]*University Politehnica Bucharest, Bucharest, Romania*
[25c]*West University in Timisoara, Timisoara, Romania*
[26]*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[27]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[28]*Department of Physics, Carleton University, Ottawa, Ontario, Canada*

[29]CERN, Geneva, Switzerland
[30]Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
[31a]Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago, Chile
[31b]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[32a]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[32b]Department of Modern Physics, University of Science and Technology, of China, Anhui, China
[32c]Department of Physics, Nanjing University, Jiangsu, China
[32d]High Energy Physics Group, Shandong University, Shandong, China
[33]Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
[34]Nevis Laboratory, Columbia University, Irvington, New York, USA
[35]Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[36a]INFN Gruppo Collegato di Cosenza, Italy
[36b]Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
[37]Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
[38]The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[39]Physics Department, Southern Methodist University, Dallas, Texas, USA
[40]Physics Department, University of Texas at Dallas, Richardson, Texas, USA
[41]DESY, Hamburg and Zeuthen, Germany
[42]Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[43]Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
[44]Department of Physics, Duke University, Durham, North Carolina, USA
[45]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[46]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[47]Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
[48]Section de Physique, Université de Genève, Geneva, Switzerland
[49a]INFN Sezione di Genova, Italy
[49b]Dipartimento di Fisica, Università di Genova, Genova, Italy
[50a]E.Andronikashvili Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia
[50b]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[51]II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[52]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[53]II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[54]Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[55]Department of Physics, Hampton University, Hampton, Virginia, USA
[56]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[57a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[57b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[57c]ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[58]Faculty of Science, Hiroshima University, Hiroshima, Japan
[59]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60]Department of Physics, Indiana University, Bloomington, Indiana, USA
[61]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62]University of Iowa, Iowa City, Iowa, USA
[63]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[64]Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[65]KEK,High Energy Accelerator Research Organization, Tsukuba, Japan
[66]Graduate School of Science, Kobe University, Kobe, Japan
[67]Faculty of Science, Kyoto University, Kyoto, Japan
[68]Kyoto University of Education, Kyoto, Japan
[69]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[70]Physics Department, Lancaster University, Lancaster, United Kingdom
[71a]INFN Sezione di Lecce, Italy
[71b]Dipartimento di Fisica, Università del Salento, Lecce, Italy
[72]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[73]Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[74]Department of Physics, Queen Mary University of London, London, United Kingdom
[75]Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[76]Department of Physics and Astronomy, University College London, London, United Kingdom
[77]Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

[78]*Fysiska institutionen, Lunds universitet, Lund, Sweden*
[79]*Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain*
[80]*Institut für Physik, Universität Mainz, Mainz, Germany*
[81]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[82]*CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
[83]*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
[84]*Department of Physics, McGill University, Montreal, Quebec, Canada*
[85]*School of Physics, University of Melbourne, Victoria, Australia*
[86]*Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA*
[87]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
[88a]*INFN Sezione di Milano, Italy*
[88b]*Dipartimento di Fisica, Università di Milano, Milano, Italy*
[89]*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
[90]*National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus*
[91]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[92]*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
[93]*P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
[94]*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[95]*Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
[96]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[97]*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[98]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[99]*Nagasaki Institute of Applied Science, Nagasaki, Japan*
[100]*Graduate School of Science, Nagoya University, Nagoya, Japan*
[101a]*INFN Sezione di Napoli, Italy*
[101b]*Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
[102]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
[103]*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
[104]*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[105]*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
[106]*Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia*
[107]*Department of Physics, New York University, New York, New York, USA*
[108]*Ohio State University, Columbus, Ohio, USA*
[109]*Faculty of Science, Okayama University, Okayama, Japan*
[110]*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
[111]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
[112]*Palacký University, RCPTM, Olomouc, Czech Republic*
[113]*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
[114]*LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France*
[115]*Graduate School of Science, Osaka University, Osaka, Japan*
[116]*Department of Physics, University of Oslo, Oslo, Norway*
[117]*Department of Physics, Oxford University, Oxford, United Kingdom*
[118a]*INFN Sezione di Pavia, Italy*
[118b]*Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy*
[119]*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[120]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[121a]*INFN Sezione di Pisa, Italy*
[121b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[122]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
[123a]*Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal*
[123b]*Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
[124]*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
[125]*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
[126]*Czech Technical University in Prague, Praha, Czech Republic*
[127]*State Research Center Institute for High Energy Physics, Protvino, Russia*
[128]*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[129]*Physics Department, University of Regina, Regina, Saskatchewan, Canada*
[130]*Ritsumeikan University, Kusatsu, Shiga, Japan*
[131a]*INFN Sezione di Roma I, Italy*
[131b]*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
[132a]*INFN Sezione di Roma Tor Vergata, Italy*

[132b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[133a]INFN Sezione di Roma Tre, Italy
[133b]Dipartimento di Fisica, Università Roma Tre, Roma, Italy
[134a]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
[134b]Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco
[134c]Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000, Morocco
[134d]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
[134e]Faculté des Sciences, Université Mohammed V, Rabat, Morocco
[135]DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[136]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[137]Department of Physics, University of Washington, Seattle, Washington, USA
[138]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[139]Department of Physics, Shinshu University, Nagano, Japan
[140]Fachbereich Physik, Universität Siegen, Siegen, Germany
[141]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
[142]SLAC National Accelerator Laboratory, Stanford, California, USA
[143a]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
[143b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[144a]Department of Physics, University of Johannesburg, Johannesburg, South Africa
[144b]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[145a]Department of Physics, Stockholm University, Sweden
[145b]The Oskar Klein Centre, Stockholm, Sweden
[146]Physics Department, Royal Institute of Technology, Stockholm, Sweden
[147]Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
[148]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[149]School of Physics, University of Sydney, Sydney, Australia
[150]Institute of Physics, Academia Sinica, Taipei, Taiwan
[151]Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
[152]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[153]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[154]International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[155]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[156]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[157]Department of Physics, University of Toronto, Toronto, Ontario, Canada
[158a]TRIUMF, Vancouver, British Columbia, Canada
[158b]Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
[159]Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
[160]Science and Technology Center, Tufts University, Medford, Massachusetts, USA
[161]Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[162]Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
[163a]INFN Gruppo Collegato di Udine, Italy
[163b]ICTP, Trieste, Italy
[163c]Dipartimento di Fisica, Università di Udine, Udine, Italy
[164]Department of Physics, University of Illinois, Urbana, Illinois, USA
[165]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[166]Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingenierá Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[167]Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
[168]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
[169]Waseda University, Tokyo, Japan
[170]Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[171]Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
[172]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[173]Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[174]Department of Physics, Yale University, New Haven, Connecticut, USA
[175]Yerevan Physics Institute, Yerevan, Armenia
[176]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, United Kingdom.
[d]Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[e]Deceased.
[f]Also at TRIUMF, Vancouver, BC, Canada.
[g]Also at Department of Physics, California State University, Fresno, CA, USA.
[h]Also at Fermilab, Batavia, IL, USA.
[i]Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[j]Also at Universitá 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, USA.
[n]Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland.
[o]Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
[p]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[q]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[r]Also at Manhattan College, New York, NY, USA.
[s]Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[t]Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[u]Also at High Energy Physics Group, Shandong University, Shandong, China.
[y]Also at Section de Physique, Université de Genéve, Geneva, Switzerland.
[w]Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[x]Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
[y]Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[z]Also at California Institute of Technology, Pasadena, CA, USA.
[aa]Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[bb]Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[cc]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[dd]Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
[ee]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.
[ff]Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[gg]Also at Department of Physics, Nanjing University, Jiangsu, China.