



# Search for physics beyond the standard model using multilepton signatures in pp collisions at $\sqrt{s} = 7$ TeV <sup>☆</sup>

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## ABSTRACT

A search for physics beyond the standard model in events with at least three leptons and any number of jets is presented. The data sample corresponds to  $35 \text{ pb}^{-1}$  of integrated luminosity in pp collisions at  $\sqrt{s} = 7$  TeV collected by the CMS experiment at the LHC. A number of exclusive multileptonic channels are investigated and standard model backgrounds are suppressed by requiring sufficient missing transverse energy, invariant mass inconsistent with that of the Z boson, or high jet activity. Control samples in data are used to ascertain the robustness of background evaluation techniques and to minimise the reliance on simulation. The observations are consistent with background expectations. These results constrain previously unexplored regions of supersymmetric parameter space.

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## 1. Introduction

Supersymmetry (SUSY) is a preferred candidate for a theory beyond the standard model (SM) because it solves the hierarchy problem, allows the unification of the gauge couplings, and may provide a candidate particle for dark matter [1–3]. The 7 TeV centre-of-mass energy of the Large Hadron Collider (LHC) makes it possible to search for squark and gluino production in previously unexplored regions of supersymmetric parameter space with the integrated luminosity delivered in the first few months of operation. Hadronic collisions yielding three or more electrons, muons, or taus (“multileptons”) serve as an ideal hunting ground for physics beyond the SM, as leptonic SM processes are relatively rare at hadron colliders and multilepton events particularly so.

We report results from a search with broad sensitivity to the potentially large multilepton signals from SUSY particle production. Our strategy takes advantage of the strong background suppression obtained when requiring three or more leptons; this allows us to relax requirements for SM background reduction relative to other searches with fewer leptons or purely hadronic searches at the LHC [4,5].

The multilepton search presented here is not tailored for any particular SUSY scenario. Nonetheless, it probes multiple new regions of the supersymmetric parameter space beyond previous multilepton searches at the Tevatron [6–12]. Overall, this search complements the Tevatron searches, which are mostly sensitive to electroweak gaugino production, while this search is mostly sensitive to squark–gluino production. As in the case of Tevatron searches, we interpret results in the mSUGRA/CMSSM [13,14] scenario of supersymmetry in which the superpartner masses and gauge couplings become unified at the grand unification scale, resulting in common masses  $m_0$  ( $m_{1/2}$ ) for all spin 0 (1/2) superpartners at this scale. The remaining CMSSM parameters are  $A_0$ ,  $\tan\beta$ , and  $\mu$ . For illustration, we define a CMSSM benchmark point called “TeV3”, characterised by  $m_0 = 60 \text{ GeV}/c^2$ ,  $m_{1/2} = 230 \text{ GeV}/c^2$ ,  $A_0 = 0$ ,  $\tan\beta = 3$ ,  $\mu > 0$ , and a next-to-leading order (NLO) cross section of 10 pb for all supersymmetric processes.

In this Letter we also study scenarios with gravitinos as the lightest supersymmetric particle (LSP) and sleptons as the next-to-lightest supersymmetric particles (NLSPs). Scenarios of this type arise in a wide class of theories of gauge mediation with split messengers (GMSM) [15,16]. Multilepton final states arise naturally in the subset of the GMSM parameter space where the right-handed sleptons are flavour-degenerate, the so-called slepton co-NLSP scenario [8,15–17]. We define a slepton co-NLSP benchmark point, called ML01, characterised by a chargino mass  $m_{\chi^\pm} = 385 \text{ GeV}/c^2$

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and gluino mass  $m_{\tilde{g}} = 450 \text{ GeV}/c^2$ . The other superpartner masses are then given by the generic relationships  $m_{\tilde{e}_R} = 0.3m_{\chi^\pm}$ ,  $m_{\chi_1^0} = 0.5m_{\chi^\pm}$ ,  $m_{\tilde{t}_L} = 0.8m_{\chi^\pm}$ , and  $m_{\tilde{q}_L} = 0.8m_{\tilde{g}}$ . ML01 has an estimated 45 pb NLO cross section for all supersymmetric processes. Finally, we also consider the possibility that the LSP is unstable.

## 2. Detector

The data sample used in this search corresponds to the integrated luminosity of  $35 \text{ pb}^{-1}$  recorded in 2010 with the Compact Muon Solenoid (CMS) detector at the LHC, running at 7 TeV centre-of-mass energy. The CMS detector has cylindrical symmetry around the pp beam axis with tracking and muon detector pseudorapidity coverage to  $|\eta| < 2.4$ , where  $\eta = -\ln \tan(\theta/2)$  and  $\theta$  is the polar angle with respect to the counterclockwise beam. The azimuthal angle  $\phi$  is measured in the plane perpendicular to the beam direction. Charged particle tracks are identified with a  $200 \text{ m}^2$ , fully silicon-based tracking system composed of a pixel detector with three barrel layers at radii between 4.4 cm and 10.2 cm and a silicon strip tracker with 10 barrel detection layers, of which four are double sided, extending outwards to a radius of 1.1 m. Each system is completed by endcaps extending the acceptance of the tracker up to a pseudorapidity of  $|\eta| < 2.5$ . The lead-tungstate scintillating crystal electromagnetic calorimeter (ECAL) and brass/scintillator hadron calorimeter hermetically surrounding the tracking system measure the energy of showering particles with  $|\eta| < 3.0$ . These subdetectors are placed inside a 13 m long and 6 m diameter superconducting solenoid with a central field of 3.8 T. Outside the magnet is the tail-catcher of the hadronic calorimeter followed by the instrumented iron return yoke, which serves as a multilayered muon detection system in the range  $|\eta| < 2.4$ . The CMS detector has extensive forward calorimetry, extending the pseudorapidity coverage to  $|\eta| < 5.0$ . The performance of all detector components as measured with cosmic rays has been reported in Ref. [18] and references therein. A much more detailed description of CMS can be found elsewhere [19].

## 3. Event trigger

The data used for this search came from single- and double-lepton triggers. The Level-1 (L1) and High Level Trigger (HLT) configurations of the CMS trigger were adapted to changing beam conditions and increasing LHC luminosities during data collection. For example, the transverse momentum ( $p_T$ ) threshold for the unrescaled single muon trigger was raised from 9 GeV/c to 15 GeV/c near the end of data taking. The analogous single electron trigger went from a transverse energy ( $E_T$ ) threshold of 10 GeV in the early part of data taking to 17 GeV. Double-lepton trigger thresholds were set at  $p_T > 5 \text{ GeV}/c$  for muons and  $E_T > 10 \text{ GeV}$  for electrons.

The efficiencies of the single-lepton triggers are determined with the tag-and-probe technique. Events with Z boson decays into two electrons or muons are selected by requiring one lepton and another track as a lepton candidate, with an invariant mass in the Z-mass window of 80 to 100 GeV/c<sup>2</sup>. The fraction of probed tracks that are reconstructed correctly as leptons including the trigger requirements determines the lepton efficiency. The average trigger efficiency determined for  $p_T > 15 \text{ GeV}/c$  is  $97.5 \pm 1.5\%$  for the electrons and  $89.1 \pm 0.9\%$  for the muons.

## 4. Lepton identification

Leptons in this search can be either electrons, muons, or taus. Electrons and muons are selected with  $p_T \geq 8 \text{ GeV}/c$  and  $|\eta| < 2.1$  as reconstructed from measured quantities from the tracker,

calorimeter, and muon system. Since a large fraction of the data set was collected with the highest trigger threshold implemented at high luminosity, we require at least one identified muon with  $p_T > 15 \text{ GeV}/c$  or an electron with  $E_T > 20 \text{ GeV}$ . The matching candidate tracks must satisfy quality requirements and spatially match with the energy deposits in the ECAL and the tracks in the muon detectors, as appropriate. Details of reconstruction and identification can be found in Ref. [20] for electrons and in Ref. [21] for muons. Jets are reconstructed using particles with  $|\eta| \leq 2.5$  via the particle-flow (PF) algorithm, as described in Ref. [22].

Although the reconstruction of taus presents challenges, we include these because there are regions of parameter space where signatures that include taus are enhanced. Taus decay either leptonically or hadronically. The electrons or muons from the leptonic decays are identified as above. The hadronic decays yield either a single charged track (one-prong decays) or three charged tracks (three-prong decays) with or without additional electromagnetic energy from neutral pion decays. We explore two strategies for hadronic decay reconstruction in this search and combine the results in the end. In the first selection, the one-prong hadronic decays are reconstructed as isolated tracks with  $p_T > 8 \text{ GeV}/c$ . In the second selection, hadronic decays are reconstructed with the PF algorithm [23,24], which also includes the three-prong decays and decays with associated ECAL activity. This algorithm defines an energy-dependent signal cone in the  $\eta$ - $\phi$  region around the candidate track with an angular radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  of  $5 \text{ GeV}/E_T(\text{jet})$ . This “shrinking cone” is limited to the range  $0.07 \leq \Delta R \leq 0.15$ . Inside the signal cone one or three charged tracks are required. PF tau candidates that are also electron or muon candidates are explicitly rejected.

These two algorithms have complementary benefits. Isolated tracks originating from one-prong decays make up only about 18% of hadronic tau decays, but have relatively low backgrounds. Additionally, some electrons and muons that fail normal requirements described above are accepted with the isolated track reconstruction. The PF algorithm reconstructs all hadronic tau decays including the larger-background three-prong decays, necessitating tighter kinematic requirements for some event topologies. After event selection, the tau channel efficiencies are similar for both selections.

Sources of background leptons include genuine leptons occurring inside or near jets, hadrons simulating leptons by punch-through into the muon system, hadronic showers with large electromagnetic fractions, or photon conversions. An isolation requirement strongly reduces the background from misidentified leptons, since most of them occur inside jets. We define the relative isolation  $I_{\text{rel}}$  as the ratio of the sum of calorimeter energy and  $p_T$  of any other tracks in the cone defined by  $\Delta R < 0.3$  around the lepton to the  $p_T$  of the lepton. For electrons, muons, and isolated tracks, we require  $I_{\text{rel}} < 0.15$ . For PF taus, tracking and ECAL isolation requirements are applied [24] in the annular region between the signal cone and an isolation cone with  $\Delta R = 0.5$ .

Leptons from SUSY decays considered in this search originate from the collision point (“prompt” leptons). After the isolation selection, the most significant background sources are residual non-prompt leptons from heavy quark decays, where the lepton tends to be more isolated because of the high  $p_T$  with respect to the jet axis. This background is reduced by requiring that the leptons originate from within one centimeter of the primary vertex in  $z$  and that the impact parameter  $d_{xy}$  between the track and the event vertex in the plane transverse to the beam axis be small. For electrons, muons, and isolated tracks, the impact parameter requirement is  $d_{xy} \leq 0.02 \text{ cm}$ , while  $d_{xy} \leq 0.03 \text{ cm}$  is required for PF taus. The isolation and promptness criteria are

efficient for the SUSY signal but almost eliminate misidentified leptons.

## 5. Search strategy

### 5.1. Multilepton channels

Candidate events in this search must have at least three leptons, of which at least one must be an electron or a muon, and may contain two or fewer hadronic tau candidates. We classify multilepton events into search channels on the basis of the number of leptons, lepton flavour, and relative charges as well as charge and flavour combinations and other kinematic quantities described below.

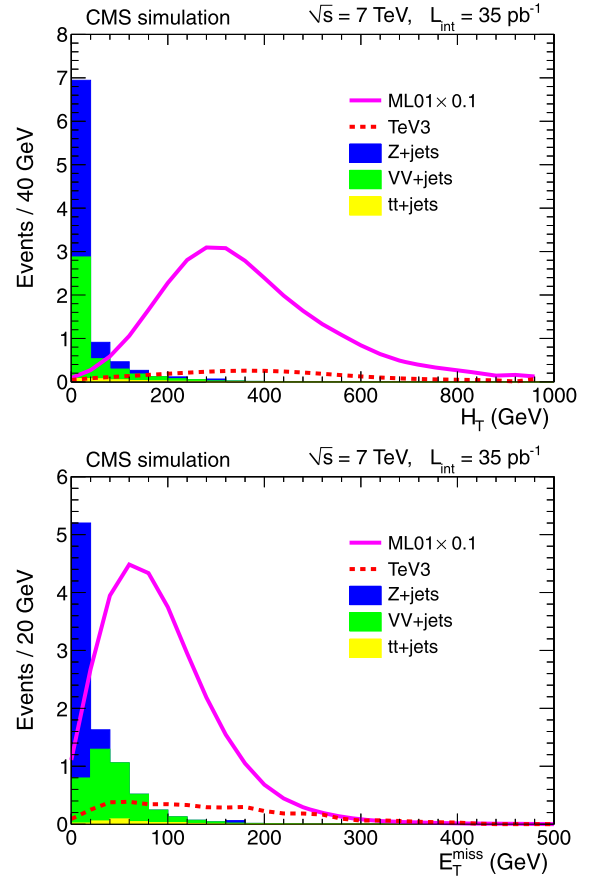
We use the following symbols and conventions in describing the search. The symbol  $\ell$  stands for an electron or a muon, including those from tau decays. In describing pairs of leptons, OS stands for opposite-sign, SS for same-sign, and SF for same (lepton) flavour. To explicitly denote differing lepton flavours in a pair, we use the symbol  $\ell\ell'$ . The symbol  $\tau$  refers to hadronic tau decays reconstructed using the PF tau algorithm and  $T$  refers to decays reconstructed as isolated tracks.

The level of SM background varies considerably across the channels. Channels with hadronic tau decays or containing OS-SF ( $\ell^\pm\ell^\mp$ ) pairs suffer from large backgrounds, but channels such as  $\ell^\pm\ell^\pm\ell'$  have smaller backgrounds because they do not contain OS-SF pairs. High-background channels play two distinct roles in this search, depending on the scenario of new physics. For models that predict a small signal yield in these channels, they act as “control” samples that give confidence in predictions for the “discovery” channels that have small background. But it is also possible that new physics may preferentially manifest itself in the high-background channels. For example, taus can greatly outnumber electrons and muons in the case of supersymmetry with large  $\tan\beta$  values. Therefore, we retain channels such as those with two hadronic tau decays although they contribute only modestly to scenarios of new physics which we discuss later. In comparison, dilepton searches have higher backgrounds and are thus less sensitive to tau-rich signals because of additional requirements necessary to reduce these backgrounds to a manageable level. We avoid using kinematic quantities such as  $E_T^{\text{miss}}$  or  $H_T$  in defining datasets used in background determination. Such loose selection criteria minimize signal contamination between high and low background channels. Even for tau-rich mSUGRA scenarios, the signal contamination is below 5%.

### 5.2. Background reduction

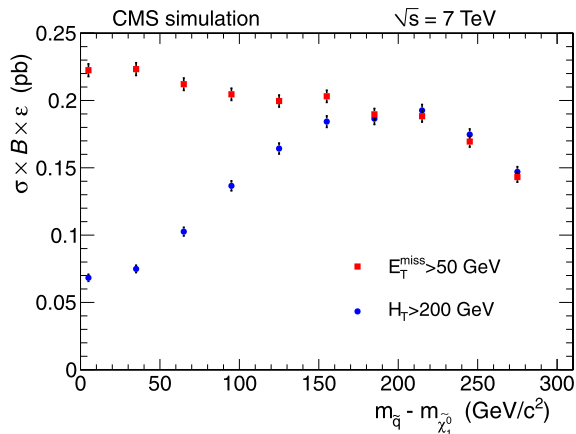
Other searches for new physics such as those requiring dileptons or single leptons suffer from large SM backgrounds and are hence forced to require substantial jet activity as well as missing transverse energy. For the multilepton search described here, the presence of a third lepton results in lower SM backgrounds, thus reducing reliance on other requirements and increasing sensitivity to diverse signatures of new physics. The presence of hadronic activity in an event is characterised by the variable  $H_T$ , defined as the scalar sum of the transverse jet energies for all jets with  $E_T > 30$  GeV and  $|\eta| < 2.4$ . Jets used for the  $H_T$  determination must be well separated from any identified leptons; jets are required to have no lepton in a cone  $\Delta R < 0.3$  around the jet axis. The missing transverse energy  $E_T^{\text{miss}}$  is defined as the magnitude of the vectorial sum of the momenta of all lepton candidates and jets with  $E_T > 20$  GeV and  $|\eta| < 5.0$ . Comparison between data and simulation [25,26] shows good modelling of  $E_T^{\text{miss}}$ .

Both  $H_T$  and  $E_T^{\text{miss}}$  are good discriminating observables for physics beyond the SM, as demonstrated in Fig. 1. In specific re-



**Fig. 1.** The  $H_T$  (top) and  $E_T^{\text{miss}}$  (bottom) distributions for SM background channels  $Z + \text{jets}$ ,  $t\bar{t}$ , and  $VV + \text{jets}$ , where  $V = W, Z$  and two SUSY benchmark points for the simulation events that pass all other requirements for the three-lepton events. The ML01 and TeV3 benchmark points are defined in Section 1 and details of the simulation are given in Section 6.

gions of parameter space one observable may be more effective than the other. Fig. 1 suggests that  $H_T$  has slightly superior discriminating power for the models we happen to consider here. On the other hand,  $H_T$  would be suppressed if the supersymmetric production were dominated by electroweak processes, as would be the case at the Tevatron [6]. Another possibility is that the sparticle mass ordering in the supersymmetric particle spectrum may result in reduced participation of hadronic sparticles in the decay chain despite strong production, resulting in negligible jet activity. Fig. 2 illustrates this situation, showing the product of cross section, branching fraction, and efficiency, i.e., event yield per unit integrated luminosity, as a function of the mass difference between the squark and lightest neutralino. The slepton co-NLSP supersymmetric topology illustrated here has degenerate squarks with vanishing left–right mixing and right-handed sleptons with masses of 500 and 185 GeV/ $c^2$ , respectively, with a variable lightest neutralino mass, and other superpartners decoupled. The figure shows that the  $H_T$  requirement suppresses sensitivity when neutralino and squark masses are similar because squarks and gluinos fail to participate in the decay chain, resulting in minimal hadronic activity. By comparison,  $E_T^{\text{miss}}$  is an appropriate discriminant in a multilepton search because neutrino production generally accompanies  $e$ ,  $\mu$ , and  $\tau$  production. Nonetheless, in order to retain search sensitivity beyond that of dilepton searches, both  $E_T^{\text{miss}}$  and  $H_T$  selections should be used as sparingly as possible. The flexibility of the multichannel approach allows us to selectively impose the  $E_T^{\text{miss}}$  or  $H_T$  requirements in specific channels. Doing so maximises sensitivity to new physics.



**Fig. 2.** Effect of mass difference between squark and lightest neutralino on cross section times branching fraction times efficiency for an  $E_T^{\text{miss}} > 50$  GeV requirement (red squares) or for an  $H_T > 200$  GeV requirement (blue circles). Less hadronic energy is released if this difference becomes small, so the  $H_T$  requirement loses sensitivity in this region of parameter space. The example is for channels containing two muons plus at least one electron or a tau. The slepton co-NLSP topology used here is described in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

We exploit the background reduction ability of both  $E_T^{\text{miss}}$  and  $H_T$  as follows. Events with  $E_T^{\text{miss}} > 50$  GeV ( $H_T > 200$  GeV) are said to satisfy the  $E_T^{\text{miss}}$  ( $H_T$ ) requirement. The justification for the values chosen is evident from Fig. 1. Another criterion for background reduction is the “Z veto”, in which the invariant mass of the OS–SF lepton pairs is required to be outside the 75–105 GeV/ $c^2$  window. A possible source of background is from the final state radiation in  $Z \rightarrow 2\ell$  ( $\ell = e, \mu$ ) events undergoing a  $\gamma \rightarrow 2\ell$  conversion. Therefore, the Z veto requirement is also applied to the invariant mass  $M(3\ell)$  of three leptons for  $3e$  and  $\mu\mu e$  events which have low  $E_T^{\text{miss}}$  and  $H_T$ . As described below, these kinematic selection criteria are applied together or separately as warranted by the background level of the channel under consideration.

### 5.3. Final kinematic selections

In order to maximise sensitivity to diverse new physics scenarios, we group the final selections into two broadly complementary domains. As the name suggests, the *hadronic* selection makes a uniform  $H_T$  requirement ( $H_T > 200$  GeV). It reduces backgrounds to practically negligible values for channels with electrons and muons. Both one- and three-prong hadronic tau decays are reconstructed using the PF technique. For channels with OS–SF  $\ell\ell$  pairs plus  $\tau$ 's, the residual background from Z + jets is further reduced with the  $E_T^{\text{miss}}$  requirement ( $E_T^{\text{miss}} > 50$  GeV). Only the  $t\bar{t}$  background then remains nonnegligible; about one event is expected in  $35 \text{ pb}^{-1}$  after the full selection.

The *inclusive* selection is based on the combined  $E_T^{\text{miss}} > 50$  GeV and Z-veto requirements for events with an OS–SF lepton pair. These events also must satisfy  $M(2\ell) > 12 \text{ GeV}/c^2$  to reject low mass Drell–Yan production and the  $J/\psi(1S)$  and  $\Upsilon$  resonances. In addition, candidate events are binned in exclusive channels characterised by total charge, number of lepton candidates, lepton flavours, high or low  $E_T^{\text{miss}}$ , and whether the Z veto described above is satisfied or not. Isolated tracks are used to reconstruct the single-prong tau decays.

## 6. Background estimation

The main SM backgrounds in multilepton plus jet events originate from Z + jets, double vector boson production (VV + jets),  $t\bar{t}$

production, and QCD multijets. Leptons associated with jets can be from heavy quark decays, or with a lower probability, can be misidentified hadrons. Leptons from heavy quark decays are suppressed by the isolation requirement. The probability that a QCD event includes three misidentified leptons is negligible. Backgrounds from cosmic rays are also found to be negligible. Backgrounds from beam-halo muons are included in the background estimate discussed below.

The largest background remaining after the basic three-lepton reconstruction originates from the Z + jets process, which in our nomenclature includes the Drell–Yan process as well. The dileptons resulting from these processes, together with misidentified isolated tracks give rise to a trilepton background. The probability that such an isolated track is misidentified as a lepton is measured in control samples where no signal should be present, such as in dijet samples. We measure the probability for an isolated track to produce a misidentified muon (electron) to be  $2.2 \pm 0.6\%$  ( $1.3_{-0.3}^{+1.8}\%$ ). The misidentification SM background for the three-lepton sample is then obtained by multiplying the number of isolated tracks in the two-lepton sample by this probability. In a similar way we estimate the misidentified background for four-lepton events by examining two-lepton events with two additional isolated tracks. The large systematic uncertainty on this rate is due to the difference in jet environment in QCD and Z + jets control samples. Such differences are expected due to the variation of heavy quark content across the control samples.

For channels with isolated tracks, we measure the SM background by using the isolation sideband  $0.2 < I_{\text{rel}} < 1.0$  to extrapolate to the signal region  $I_{\text{rel}} < 0.15$ . In order to improve the statistical error as well as to gain a systematic understanding of the extrapolation process, we study the isolation distribution in various QCD samples with different levels of jet activity and then evaluate the ratio of events in the two isolation regions in the QCD sample that most resembles the dilepton sample where the ratio is eventually applied. The ratio of the numbers of isolated tracks in the two regions is measured to be  $15 \pm 3\%$ . The 3% systematic uncertainty is derived from the extent of variation of the ratio in these QCD control samples. The ratio is then applied to the  $2\ell$  event sample. Because the number of events after the  $E_T^{\text{miss}}$  selection is too small to be useful, we derive the SM background in these channels by applying the isolation probability ratio as well as the probability of a  $2\ell$  event to pass the  $E_T^{\text{miss}}$  selection to the full sample.

Understanding of SM backgrounds at the three-lepton selection level as above is essential before implementing the final kinematic selections. We perform a detailed simulation of the detector response using GEANT4 [27] for  $Z/\gamma^* + \text{jets}$ ,  $t\bar{t}$  quark pairs, and double vector boson production events generated using MADGRAPH [28], and QCD events generated with PYTHIA 8.1 [29]. We use CTEQ6.6 parton distribution functions [30]. Already at the dilepton level, comparisons between data and simulation for distributions of the opposite-sign pair mass and for  $H_T$  show good agreement for both muons and electrons. Fig. 3 shows the mass spectrum for dimuon events and the  $H_T$  distribution for dielectron events. After requiring a third lepton, the kinematic selections efficiently eliminate the Z + jets background. The  $t\bar{t}$  and double vector boson backgrounds then come to the fore.

There is not sufficient data yet for a data-based estimate of the  $t\bar{t}$  background, so we use simulation, with the contribution scaled to the measured  $t\bar{t}$  cross section [31]. The  $t\bar{t}$  background comes primarily from leptonic decays of both W bosons accompanied by a lepton from the b jets. In order to verify the adequacy of simulation for background estimation, we examine the  $e\mu$  dilepton distribution since  $t\bar{t}$  contributes dominantly to it. In particular, the spectrum of muons in this sample which fail isolation re-

quirements is described well by the simulation whether the muon originated promptly or not. The same is true of nonisolated tracks. Agreement of these distributions with the simulation gives confidence that the semileptonic branching fractions of the  $b$  quark and semileptonic form factors are reproduced correctly by the simulation. The  $VV + \text{jets}$  channels include the irreducible background from  $WZ + \text{jets}$  with both vector bosons decaying leptonically and the neutrino yielding missing energy, as well as from  $ZZ + \text{jets}$ . The simulation is used as these processes do include prompt leptons, which are reasonably well described by simulation [32].

The lepton charge misidentification probability is generally less than 1% for the lepton momenta typical for this search. The data-based background estimation techniques described above automatically account for charge misidentification background associated with the  $Z + \text{jets}$  processes because the dilepton data sample used for multilepton background estimation contains events with charge misidentification. The probability of acquiring  $WZ$  trilepton events with total charge of three units because of charge misidentification is too small for the quantity of data considered here.

As a cross-check, the SM background events are binned in the two-dimensional isolation versus impact parameter plane. The background in the signal region, characterised by small isolation ( $I_{\text{rel}} < 0.15$ ) and impact parameters ( $d_{xy} < 0.02$  cm), is extrapolated from the three outside regions (“sidebands”) in this two-dimensional plot by assuming the two variables  $I_{\text{rel}}$  and  $d_{xy}$  to be uncorrelated, so both can be independently extrapolated. This cross-check technique presently suffers from large statistical uncertainties, but the resulting background estimates are consistent with those described above.

In summary, the nonprompt backgrounds from  $Z + \text{jets}$  are measured from data, and the methods described above successfully predict the number of events in data samples dominated by SM processes. The irreducible/prompt backgrounds from  $t\bar{t}$  and  $VV + \text{jets}$  are then obtained from simulation with high confidence.

## 7. Observations

Table 1 shows the expected and observed numbers of three- and four-lepton events in this search before and after the final kinematic selections. A tau candidate is indicated by  $T$  for an isolated track as proxy for a hadronic tau decay and  $\tau$  for the PF tau selection. Channels containing OS-SF lepton pairs are listed separately because they suffer from a larger SM background expectation. The main SM backgrounds are given in the first three columns followed by the total SM background, which can be slightly larger than the sum of the previous columns, since it includes less significant backgrounds such as those involving initial and final state radiation. Columns for the inclusive and hadronic kinematic selections show the number of events surviving all requirements. For the inclusive selection only the signal channels are shown, which require  $E_{\text{T}}^{\text{miss}} > 50$  GeV,  $Z$ -veto, and  $M(2\ell) > 12$  GeV/ $c^2$  for events with an OS-SF pair as discussed in Section 5.3. The control channels used in the limit setting are discussed in Section 7.1. For the hadronic selection the background reduction comes from the  $H_{\text{T}} > 200$  GeV requirement. The sum of the SM backgrounds, mainly from  $t\bar{t}$  and the irreducible  $VV + \text{jets}$  backgrounds, is given as well.

Table 1 also shows signal expectations for the slepton co-NLSP benchmark point ML01 described earlier. All cross sections for the benchmark point and those used in the following exclusion plots include next-to-leading-order corrections calculated using PROSPINO [33], which yields  $K$  factors in the range 1.3–1.5.

Observations and SM expectations agree reasonably well. We observe five three-lepton events worth noting. An  $e^+e^-\tau^+$  event with  $H_{\text{T}} = 246$  GeV satisfies both the  $H_{\text{T}} > 200$  GeV and  $E_{\text{T}}^{\text{miss}} >$

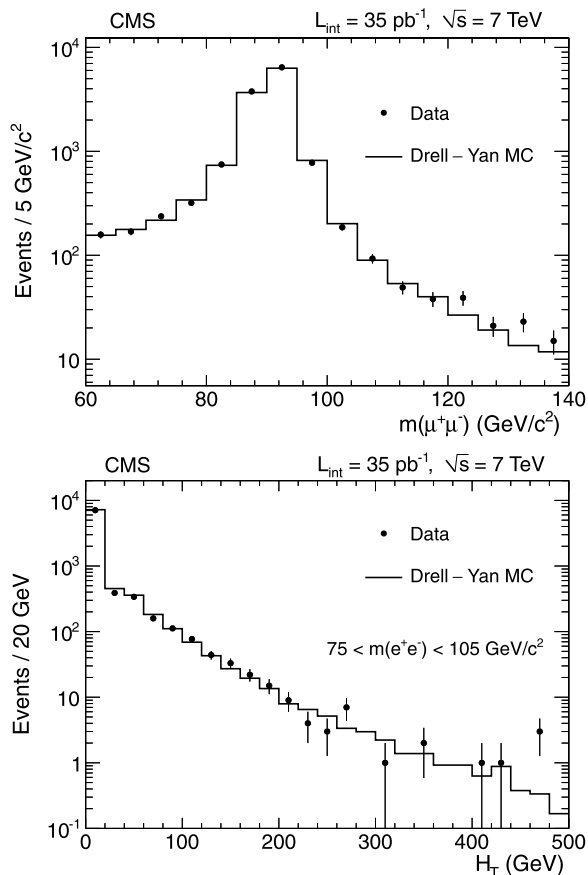


Fig. 3. Two-lepton events in data, compared with the SM simulation. Top: mass spectrum for  $Z \rightarrow \mu\mu$ . Bottom:  $H_{\text{T}}$  distribution for  $Z \rightarrow ee$ . Processes other than Drell-Yan are too rare to be visible in these distributions.

50 GeV requirements. So does an  $e^+\mu^+\tau^+$  event with  $H_{\text{T}} = 384$  GeV. A  $\mu^+\mu^-e^+$  event satisfies the  $H_{\text{T}} > 200$  GeV requirement but not  $E_{\text{T}}^{\text{miss}}$ . Two  $e^+\mu^-T^-$  events with  $E_{\text{T}}^{\text{miss}}$  of 70 and 101 GeV fail the  $H_{\text{T}}$  requirement. The largest background in the  $e\mu T$  channel is expected from  $t\bar{t}$  events, and one event is indeed selected as a  $t\bar{t}$  event in the CMS top selection [31], but the other fails the lepton  $p_{\text{T}}$  requirement.

The four-lepton  $\ell\ell\ell\ell$  row in Table 1 also merits discussion since we observe two  $\mu^+\mu^-\mu^+\mu^-$  events despite the SM expectation of only 0.21 events. One of the events is completely consistent with the  $ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$  hypothesis. The  $ZZ$  invariant mass for this event is 212 GeV/ $c^2$  and it has negligible  $E_{\text{T}}^{\text{miss}}$ . The second event is unlikely to be a  $ZZ$  event, but it contains a  $\mu^+\mu^-$  pair with an invariant mass of 80 GeV/ $c^2$  which is too close to the  $Z$  mass to pass the  $Z$  veto criterion. Both events have small  $E_{\text{T}}^{\text{miss}}$ , leptons originating from the same vertex, and minimal other activity.

### 7.1. Systematic uncertainties and statistical procedures

We discuss the sources of systematic uncertainty and how they impact the search sensitivity before extracting upper limits on the contributions from physics outside the SM. All channels share systematic uncertainties for luminosity (11%), renormalization scales (10%), parton distribution functions ( $\leq 14\%$ ), and trigger efficiency ( $\sim 5\%$ ). (Note that the luminosity uncertainty subsequently decreased to 4%, but the improvement does not have significant implications for this result.) The precision of lepton selection efficiencies increases with lepton  $p_{\text{T}}$ . For a typical slepton co-NLSP

**Table 1**  
Summary of numbers of events in the various search channels (rows). Channels with electrons and muons have been combined as  $\ell\ell$ , with  $\ell = e$  or  $\mu$ , or  $\ell\ell'$ , if the flavours are different. For the  $\ell\ell\ell$  channels different flavour combinations are implied. For the inclusive selection (upper table) isolated tracks are used as proxy for the hadronic tau decays ( $T$  channels), while for the hadronic selection (lower table) PF tau reconstruction ( $\tau$  channels) is used. The rows for inclusive selection are aggregations of selected subsets of channels used in the search. The first three columns give the expected SM background events for the dominant backgrounds after requiring the corresponding number of leptons for each channel. The comparison with data at this stage is given in the next two columns. The SM backgrounds are further reduced using either inclusive or hadronic selection (see text) and compared with data and signal expectations from the ML01 benchmark point in the last columns. Uncertainties are a combination of statistics plus systematics relevant for SM background expectations.

Channel	After lepton ID requirements					Inclusive selection		
	Z + jets	$t\bar{t}$	VV + jets	$\sum$ SM	Data	$\sum$ SM	Data	ML01
Channel	three-lepton channels							
OS( $\ell\ell$ ) e	1.7	0.1	1.2	$4.4 \pm 1.5$	6	$0.1 \pm 0.1$	0	121
OS( $\ell\ell$ ) $\mu$	2.8	0.2	1.7	$4.7 \pm 0.5$	6	$0.1 \pm 0.1$	0	124
OS( $\ell\ell$ ) $T$	122	0.5	0.7	$123 \pm 16$	127	$0.4 \pm 0.1$	0	80
$\ell\ell'T$	0.7	0.5	0.2	$1.7 \pm 0.7$	3	$0.4 \pm 0.2$	2	18.6
SS( $\ell\ell$ ) $\ell'$	0.13	0.1	0.0	$0.2 \pm 0.1$	0	$0.2 \pm 0.1$	0	2.8
SS( $\ell\ell$ ) $T$	0.25	0.0	0.1	$0.7 \pm 0.4$	3	$0.1 \pm 0.1$	0	9.0
$\ell TT$	47	0.3	0.1	$48 \pm 9$	30	$0.4 \pm 0.1$	0	8.0
$\sum \ell\ell(\ell/T)$	127	1.4	3.8	$135 \pm 16$	145	$1.3 \pm 0.2$	2	356
Channel	four-lepton channels							
$\ell\ell\ell\ell$	0	0	0.2	$0.2 \pm 0.1$	2	0	0	164
$\ell\ell\ell T$	0	0	0.1	$0.1 \pm 0.1$	0	0	0	62
$\ell\ell TT$	0	0	0	$0.0 \pm 0.1$	0	0	0	21
$\sum \ell\ell(\ell/T)(\ell/T)$	0	0	0.3	$0.3 \pm 0.1$	2	0	0	247

Channel	After lepton ID requirements					Hadronic selection		
	Z + jets	$t\bar{t}$	VV + jets	$\sum$ SM	Data	$\sum$ SM	Data	ML01
Channel	three-lepton channels							
OS( $\ell\ell$ ) e	1.7	0.1	1.2	$4.4 \pm 1.5$	6	$0.2 \pm 0.1$	1	142
OS( $\ell\ell$ ) $\mu$	2.8	0.2	1.7	$4.7 \pm 0.5$	6	$0.1 \pm 0.1$	0	121
OS( $\ell\ell$ ) $\tau$	476	2.7	3.9	$484 \pm 77$	442	$0.6 \pm 0.2$	1	68
$\ell\ell'\tau$	4.7	2.9	0.6	$11.2 \pm 2.5$	10	$0.4 \pm 0.1$	1	12.3
SS( $\ell\ell$ ) $\ell'$	0.13	0.1	0.0	$0.2 \pm 0.1$	0	$0.1 \pm 0.1$	0	2.8
SS( $\ell\ell$ ) $\tau$	1.4	0.0	0.1	$3.0 \pm 1.1$	3	$0.0 \pm 0.1$	0	6.9
$\sum \ell\ell(\ell/\tau)$	487	6.0	7.5	$507 \pm 77$	467	$1.3 \pm 0.3$	3	350
Channel	four-lepton channels							
$\ell\ell\ell\ell$	0	0	0.2	$0.2 \pm 0.1$	2	0	0	149
$\ell\ell\ell\tau$	0	0	0.1	$0.1 \pm 0.1$	0	0	0	33
$\ell\ell\tau\tau$	3.1	0.1	0.1	$3.2 \pm 0.7$	5	0	0	17
$\sum \ell\ell(\ell/\tau)(\ell/\tau)$	3.1	0.1	0.4	$3.5 \pm 0.7$	5	0	0	199

signal scenario which has leptons with  $p_T$  in excess of 20 GeV/ $c$ , the lepton identification and isolation efficiency systematic uncertainty is  $\sim 1.5\%$  per lepton for muons and electrons, as well as for isolated tracks. However, CMSSM signals result in lower  $p_T$  leptons, leading to a higher systematic uncertainty on efficiency of  $\sim 3\%$  per lepton for muons and for isolated tracks. For low-energy electrons the systematic uncertainty on the isolation efficiency can be as large as  $\sim 10\%$  because of effects of synchrotron radiation in the high CMS solenoidal magnetic field. The uncertainty on the efficiency of PF tau identification is studied using a comparison of  $Z \rightarrow \tau\tau$  events in data and simulation. For this study, events with a muon plus hadronic tau decay are analysed, yielding a 30% systematic uncertainty [34].

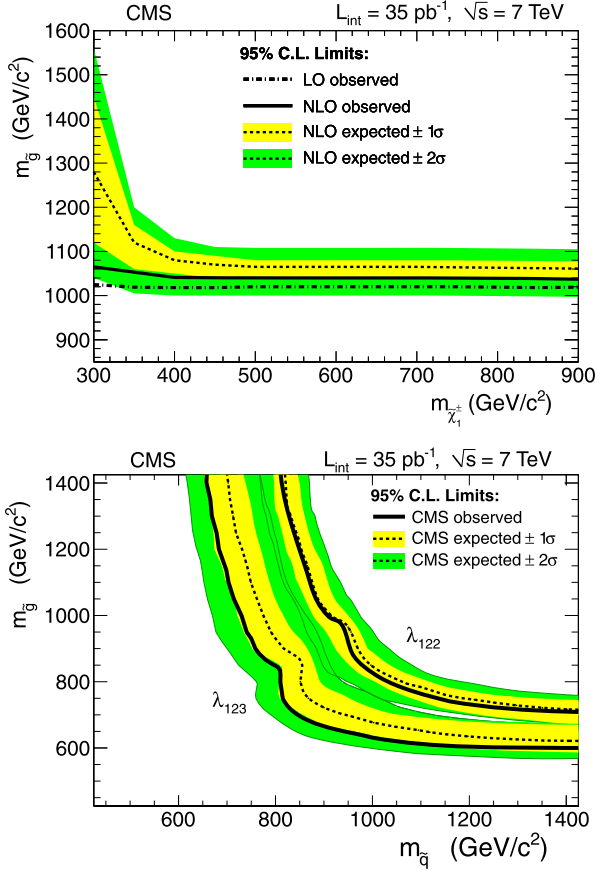
The impact of uncertainty from the jet energy scale for the  $H_T$  selection is  $\leq 14\%$  as determined by varying the  $H_T$  requirement by  $\pm 5\%$ . The jet-energy scale uncertainty [35] has a small effect on the signal, since the signal efficiency is high given the jet energy requirements; it varies in the range of 2–4%, where the larger number is for the tau modes.

SM backgrounds derived from data suffer from large systematic uncertainties because of the limited quantity of data in hand; uncertainties on the misidentification rates are 30% for the PF taus, 20% for tracks,  $\sim 30\%$  for muons, and  $\sim 80\%$  for electrons. These uncertainties are derived from extensive studies in which misidentification rates are factorised into contributing components such

as isolation efficiency and the factorised pieces are studied in different data sets. Although these uncertainties appear to be large, they do not affect the results significantly as the backgrounds are small. The uncertainties on backgrounds derived from simulation are dominated by the  $\sim 30\%$  uncertainty on the measured SM cross sections.

We utilise the agreement between the expected SM backgrounds and observations shown in Table 1 to constrain new physics scenarios. While being complementary in their approach, the two kinematic selections overlap substantially. This overlap must be removed in the combination of the two selections to evaluate the search sensitivity for new physics. For this purpose, we retain all events from the inclusive selection that satisfy the additional requirement of  $H_T < 200$  GeV and all events from the hadronic selection, which have by definition  $H_T > 200$  GeV.

There are 55 channels in the combination used for limit setting. We include both  $H_T > 200$  GeV and  $H_T < 200$  GeV versions of the following 24 three- and four-lepton channels: 2 OS( $\ell\ell$ )e; 2 OS( $\ell\ell$ ) $\mu$ ; 2 OS( $\ell\ell$ ) $\tau$ ; 2  $\ell\ell'\tau$ ; 2 SS( $\ell\ell$ ) $\ell'$ ; 2 SS( $\ell\ell$ ) $\tau$ ; 5  $\ell\ell\ell$ ; 4  $\ell\ell\ell\tau$ ; and 3  $\ell\ell\tau\tau$ , where  $\tau$  refers to either tau algorithm. For the remaining seven channels, three require  $H_T < 200$  GeV and more than four leptons, with up to two taus, and four require three leptons with two taus:  $\sum Q = \pm 3$ ;  $E_T^{\text{miss}} > 50$  GeV and  $H_T > 200$  GeV;  $E_T^{\text{miss}} > 50$  GeV and on-Z; and  $E_T^{\text{miss}} < 50$  GeV and on-Z.



**Fig. 4.** Top: Limits on the slepton co-NLSP model as a function of the gluino and wino-like chargino masses obtained by comparing with leading order (LO) or next to leading order (NLO) cross sections. Bottom: Limits for the R-parity violating scenario as a function of the gluino and degenerate squark masses with either  $\lambda_{122} \neq 0$  or  $\lambda_{123} \neq 0$ . For both exclusions, squark and slepton universality is enforced with vanishing left–right mixing; mass relationships for other superpartner masses are described in the text.

The statistical model uses a Poisson distribution for the number of events in each channel, while the nuisance parameters are modeled with a Gaussian, truncated to be always positive. The significant nuisance parameters are the luminosity uncertainty, trigger efficiency, and lepton identification efficiencies. The expected value in the model is the sum of the signal and the expected backgrounds. We set 95% confidence level (CL) upper limits on the signal parameters and cross sections using a Bayesian method with a flat prior. We check the stability of the result with respect to nuisance constraints selection by substituting log-normal constraints for the Gaussian ones, and find the upper limit results to be stable within 3%. The statistical model is implemented in the program package RooStats [36]. We apply these upper limits on the contribution of new physics for the following SUSY scenarios.

## 7.2. Slepton co-NLSP

In supersymmetry, multilepton final states arise naturally in the subset of GMSM parameter space where the right-handed sleptons are flavour-degenerate and at the bottom of the Minimal Supersymmetric Standard Model (MSSM) mass spectrum. The Higgsinos are decoupled. Supersymmetric production proceeds mainly through pairs of squarks and/or gluinos. Cascade decays of these states eventually pass sequentially through the lightest neutralino ( $\tilde{g}, \tilde{q} \rightarrow \chi^0 + X$ ), which decays into a slepton and a lepton ( $\chi^0 \rightarrow$

$\tilde{\ell} \pm \ell^\mp$ ). Each of the essentially degenerate right-handed sleptons promptly decays to the Goldstino component of the almost massless and non-interacting gravitino and a lepton ( $\tilde{\ell} \rightarrow \tilde{G} \ell$ ) thus yielding events with four or more hard leptons and missing energy. Such scenarios have a high cross section with little background [17].

The 95% CL exclusion limits for the slepton co-NLSP model is shown in the top panel of Fig. 4. Deviation from the expected limit is due to a modest data excess. The result corresponds to a limit of  $\approx 6$  events on the signal yield, and a slepton co-NLSP benchmark 95% CL upper limit on the cross section of  $\sigma_{95} = 0.2\text{--}0.4$  pb. Squark and gluino masses of up to  $830$   $\text{GeV}/c^2$  and  $1040$   $\text{GeV}/c^2$  are excluded.

## 7.3. R-parity violation

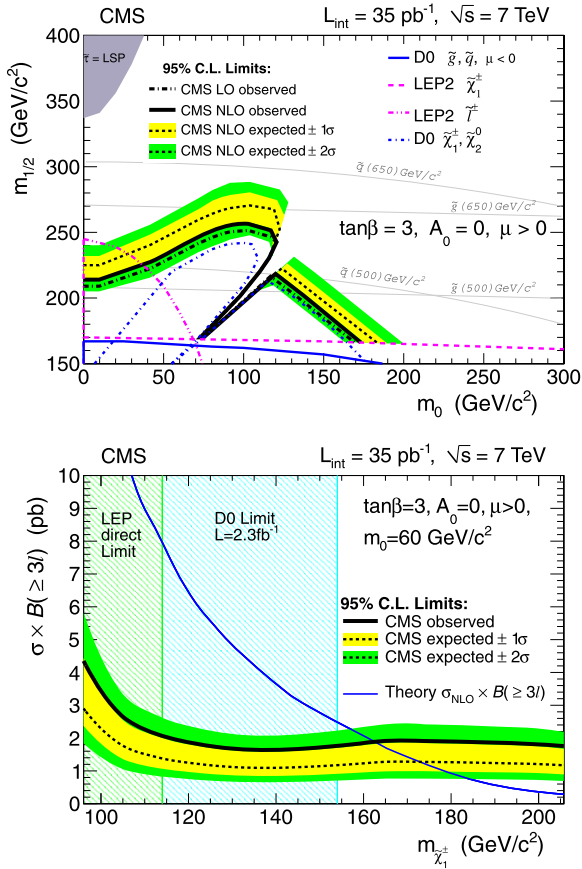
Although R-parity is often assumed to be conserved, the most general formulation of the MSSM superpotential contains R-parity violating couplings  $\lambda_{ijk}$ , where  $i, j$ , and  $k$  are generation indices. We study models in which lepton-number-violating decays are allowed, but baryon number is conserved, so these models are not constrained by limits on proton lifetime which require both  $B$  and  $L$  violation.

Events with four or more charged leptons in the final state originate from the production of pairs of squarks or gluinos, each of which cascade decays down to the LSP, which in the model considered here is the neutralino. Each neutralino decays to two charged leptons and a neutrino. Any nonzero value of  $\lambda_{ijk}$  causes the neutralino to decay, yielding multilepton final states. The actual value of  $\lambda_{ijk}$  simply determines the lifetime and hence the decay length of the neutralino. We consider  $\lambda_{ijk}$  to be sufficiently large so that the decay is prompt, the exclusion limits are independent of  $\lambda_{ijk}$  value, and thus the search is sensitive only to the sparticle masses. We consider the cases of nonzero  $\lambda_{122}$  and nonzero  $\lambda_{123}$  separately. For the  $\lambda_{122}$  coupling, the two charged leptons in each neutralino decay are electron and/or muon, while for  $\lambda_{123}$ , one of the charged leptons is a tau, and the other an electron or muon [37].

The 95% exclusion limits in the squark–gluino mass plane obtained using the inclusive kinematic selection are shown in the bottom panel of Fig. 4 for a topology with fixed  $m_{\chi^0_1} = 300$   $\text{GeV}/c^2$ ,  $m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R} = 1000$   $\text{GeV}/c^2$ , and with the wino and the Higgsino decoupled. The bumps in the contour plot are due to the fact that when the squark mass is larger than the gluino mass there are two additional jets in the event. This lowers the efficiency of the lepton isolation requirement and therefore decreases the signal acceptance. The limits for the  $\lambda_{123}$  coupling are lower because of the lower acceptance for taus. These results substantially extend previous exclusion limits from CDF and D0 based on integrated luminosities of  $350$   $\text{pb}^{-1}$  [11,12].

## 7.4. mSUGRA/CMSSM scenario

For the mSUGRA/CMSSM [13,14] scenario, limits in the  $m_0$ – $m_{1/2}$  plane are shown in Fig. 5 for  $A_0 = 0$ ,  $\tan \beta = 3$ , and  $\mu > 0$ . The TeV3 benchmark point defined above is close to the excluded limit from the Tevatron data; the total number of expected events after all cuts is  $\approx 7$  for the  $35$   $\text{pb}^{-1}$  data sample. As can be seen, our results extend the excluded region in comparison with previous results from LEP and the Tevatron. For small values of  $m_0$  the sleptons can become lighter than the gauginos, so the gauginos will decay into slepton and lepton (two-body decay), although for larger values of  $m_0$  three-body decays will dominate. While for two-body decays the branching fraction into leptons is 100%, it decreases rapidly for three-body decays. In the transition region from



**Fig. 5.** Top: excluded region for the mSUGRA/CMSM scenario along with the limits from the multilepton searches from the Tevatron [9] and the exclusion derived from slepton and chargino limits from LEP [38–43]. The region below the lines is excluded at 95% CL. Bottom: the expected and observed upper limits on the cross section times branching ratio  $\sigma \times B(\geq 3l)$  as a function of the chargino mass. The theoretical curve crosses the observed 95% CL upper limit on the cross section at  $163 \text{ GeV}/c^2$ , thus excluding charginos below this mass for the values of  $m_0$ ,  $A_0$ , and  $\tan\beta$  indicated in the figure. For comparison the regions excluded by LEP (from slepton limits [38–43]), Tevatron chargino–neutralino production [9], and Tevatron squark–gluino production [44] are indicated as well. This and other results have the other MSSM parameters fixed at  $\tan\beta = 3$ ,  $A_0 = 0$ , and  $\mu > 0$  except [44], which uses  $\mu < 0$ .

two- to three-body decays the leptons become soft and fail the  $p_T$  requirement [6]. Exclusion is therefore not possible, as shown by the non-excluded region between the two- and three-body decay regions. We exclude gluino masses up to  $628 \text{ GeV}/c^2$  for this choice of parameters. The 95% CL upper limit on the cross section times branching fraction into  $3l$  varies from  $\sigma_{95} = 0.8$  to 2 pb. The sensitivity to the chargino mass can be seen in the bottom panel of Fig. 5, where the NLO cross section for  $m_0 = 60 \text{ GeV}/c^2$  equals the 95% CL experimental limit of  $\sigma_{95} = 2 \text{ pb}$  for chargino mass of  $163 \text{ GeV}/c^2$ . Therefore, chargino masses above this value cannot be excluded.

## 8. Conclusion

We have performed a search for physics beyond the SM using multilepton final states. Taking advantage of the high centre-of-mass energy at the LHC, we were able to probe new regions of the MSSM parameter space. Our search complements those at the Tevatron, which are mostly sensitive to electroweak gaugino production via quark–antiquark interaction, while the result presented here is mostly sensitive to gluino and squark production via quark–gluon or gluon–gluon interactions.

The results of this search are consistent with SM expectations. In the CMSSM parameter space, gluino masses up to  $628 \text{ GeV}/c^2$  are thus excluded for specific SUSY parameters. This result is better than the prior multilepton results from the Tevatron, but is in the region already ruled out by other hadronic searches at the LHC [4, 5]. However, the following two regions of MSSM are not accessible to hadronic searches. With gravitinos as LSP and sleptons as co-NLSP, we are able to exclude squark and gluino masses of up to  $830 \text{ GeV}/c^2$  and  $1040 \text{ GeV}/c^2$ , respectively. We are also able to exclude models with leptonic R-parity violation for gluino masses up to  $600\text{--}700 \text{ GeV}/c^2$  depending on the choice of parameters. In both cases our search significantly extends into the regions of SUSY parameter space not accessible to multilepton searches at the Tevatron.

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