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Search for Physics Beyond the Standard Model in Opposite-sign Dilepton Events in pp Collisions at $\sqrt{s} = 7$ TeV

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Abstract

A search is presented for physics beyond the standard model (SM) in final states with opposite-sign isolated lepton pairs accompanied by hadronic jets and missing transverse energy. The search is performed using LHC data recorded with the CMS detector, corresponding to an integrated luminosity of 34 pb^{-1}. No evidence for an event yield beyond SM expectations is found. An upper limit on the non-SM contribution to the signal region is deduced from the results. This limit is interpreted in the context of the constrained minimal supersymmetric model. Additional information is provided to allow testing the exclusion of specific models of physics beyond the SM.

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1 Introduction

In this paper we describe a search for physics beyond the standard model (BSM) in a sample of proton-proton collisions at a centre-of-mass energy of 7 TeV. The data sample was collected with the Compact Muon Solenoid (CMS) detector [1] at the Large Hadron Collider (LHC) between March and November of 2010 and corresponds to an integrated luminosity of $34\,\mathrm{pb}^{-1}$.

The BSM signature in this search is motivated by three general considerations. First, new particles predicted by BSM physics scenarios are expected to be heavy, since they have so far eluded detection. Second, BSM physics signals with high enough cross sections to be observed in our current dataset are expected to be produced strongly, resulting in significant hadronic activity. Third, astrophysical evidence for dark matter suggests [2, 3] that the mass of weakly-interacting massive particles is of the order of the electroweak symmetry breaking scale. Such particles, if produced in pp collisions, could escape detection and give rise to an apparent imbalance in the event transverse energy. We therefore focus on the region of high missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). An example of a specific BSM scenario is provided by R-parity conserving supersymmetric (SUSY) models in which new, heavy particles are pair-produced and subsequently undergo cascade decays, producing hadronic jets and leptons [4–10]. These cascade decays may terminate in the production of weakly-interacting massive particles, resulting in large $E_{\mathrm{T}}^{\mathrm{miss}}$.

The results reported in this paper are part of a broad program of BSM searches in events with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$, characterized by the number and type of leptons in the final state. Here we describe a search for events containing opposite-sign isolated lepton pairs ($\mathrm{e}^+\mathrm{e}^-$, $\mathrm{e}^\pm\mu^\mp$, $\mu^+\mu^-$) in addition to the jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. Results from a complementary search with no electrons or muons in the final state have already been reported in Ref. [11].

Our analysis strategy is as follows. In order to select dilepton events, we use high-p_{T} lepton triggers and a preselection based on that of the $\mathrm{t\bar{t}}$ cross section measurement in the dilepton channel [12]. Good agreement is found between this data sample and predictions from SM Monte Carlo (MC) simulations in terms of the event yields and shapes of various kinematic distributions. Because BSM physics is expected to have large hadronic activity and $E_{\mathrm{T}}^{\mathrm{miss}}$ as discussed above, we define a signal region with requirements on these quantities to select about 1% of dilepton $\mathrm{t\bar{t}}$ events, as predicted by MC. The observed event yield in the signal region is compared with the predictions from two independent background estimation techniques based on data control samples, as well as with SM and BSM MC expectations. Finally, the robustness of the result is confirmed by an independent analysis based on hadronic activity triggers, different "physics object" reconstruction, and a complementary background estimation method.

No specific BSM physics scenario, e.g. a particular SUSY model, has been used to optimize the search. In order to illustrate the sensitivity of the search, a simplified and practical model of SUSY breaking, the constrained minimal supersymmetric extension of the standard model (CMSSM) [13, 14], is used. The CMSSM is described by five parameters: the universal scalar and gaugino mass parameters (m_0 and $m_{1/2}$, respectively), the universal trilinear soft SUSY breaking parameter A_0, the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$), and the sign of the Higgs mixing parameter μ. Throughout the paper, two CMSSM parameter sets, referred to as LM0 and LM1 [15], are used to illustrate possible CMSSM yields. The parameter values defining LM0 (LM1) are $m_0 = 200\ (60)\,\mathrm{GeV}/c^2$, $m_{1/2} = 160\ (250)\,\mathrm{GeV}/c^2$, $A_0 = -400\ (0)\,\mathrm{GeV}$; both LM0 and LM1 have $\tan\beta = 10$ and $\mu > 0$. These two scenarios are beyond the exclusion reach of previous searches performed at the Tevatron and LEP. They were recently excluded by a search performed at CMS in events with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ [11] based on the same data sample used for this search. In this analysis, the LM0 and LM1 scenarios serve as benchmarks which may be used to allow comparison of the sensitivity with other analyses.

2 CMS Detector

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. Within the field volume are several particle detection systems. Charged particle trajectories are measured by silicon pixel and silicon strip trackers, covering $0 \leq \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity, defined as $\eta = -\log[\tan\theta/2]$, where θ is the polar angle of the trajectory of the particle with respect to the counterclockwise proton beam direction. A crystal electromagnetic calorimeter and a brass/scintillator hadronic calorimeter surround the tracking volume, providing energy measurements of electrons and hadronic jets. Muons are identified and measured in gas-ionization detectors embedded in the steel return yoke outside the solenoid. The detector is nearly hermetic, allowing energy balance measurements in the plane transverse to the beam direction. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis. A more detailed description of the CMS detector can be found elsewhere [1].

3 Event Selection

Samples of MC events are used to guide the design of the analysis. These events are generated using either the PYTHIA 6.4.22 [16] or MADGRAPH 4.4.12 [17] event generators. They are then simulated using a GEANT4-based model [18] of the CMS detector, and finally reconstructed and analyzed using the same software as is used to process collision data.

We apply a preselection based on that of the $\mathrm{t\bar{t}}$ cross section measurement in the dilepton channel [12]. Events with two opposite-sign, isolated leptons ($\mathrm{e^+e^-}$, $\mathrm{e^\pm}\mu^\mp$, or $\mu^+\mu^-$) are selected. At least one of the leptons must have $p_\mathrm{T} > 20\,\mathrm{GeV}/c$ and both must have $p_\mathrm{T} > 10\,\mathrm{GeV}/c$, and the electrons (muons) must have $|\eta| < 2.5$ ($|\eta| < 2.4$). In events with more than two such leptons, the two leptons with the highest p_T are selected. Events with an $\mathrm{e^+e^-}$ or $\mu^+\mu^-$ pair with invariant mass between $76\,\mathrm{GeV}/c^2$ and $106\,\mathrm{GeV}/c^2$ or below $10\,\mathrm{GeV}/c^2$ are removed, in order to suppress Drell–Yan (DY) $\mathrm{Z}/\gamma^* \to \ell\ell$ events, as well as low mass dilepton resonances.

Events are required to pass at least one of a set of single-lepton or double-lepton triggers. The efficiency for events containing two leptons passing the analysis selection to pass at least one of these triggers is very high, in excess of 99% for dilepton $t\bar{t}$ events.

Because leptons produced in the decays of low-mass particles, such as hadrons containing b and c quarks, are nearly always inside jets, they can be suppressed by requiring the leptons to be isolated in space from other particles that carry a substantial amount of transverse momentum. The details of the lepton isolation measurement are given in Ref. [12]. In brief, a cone is constructed of size $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the lepton momentum direction. The lepton relative isolation is then quantified by summing the transverse energy (as measured in the calorimeters) and the transverse momentum (as measured in the silicon tracker) of all objects within this cone, excluding the lepton, and dividing by the lepton transverse momentum. The resulting quantity is required to be less than 0.15, rejecting the large background arising from QCD production of jets.

We require the presence of at least two jets with $p_\mathrm{T} > 30\,\mathrm{GeV}/c$ and $|\eta| < 2.5$, separated by $\Delta R > 0.4$ from leptons passing the analysis selection with $p_\mathrm{T} > 10\,\mathrm{GeV}/c$. The anti-$k_T$ clustering algorithm [19] with $\Delta R = 0.5$ is used for jet clustering. Jets are reconstructed using calorimeter information and their energies are corrected using reconstructed tracks [20]. The event is required to satisfy $H_\mathrm{T} > 100\,\mathrm{GeV}$, where H_T is defined as the scalar sum of the transverse energies of the selected jets. In addition, the $E_\mathrm{T}^\mathrm{miss}$ in the event is required to exceed $50\,\mathrm{GeV}$.

Several techniques are used in CMS for calculating $E_{\mathrm{T}}^{\mathrm{miss}}$ [21]. Here, the raw $E_{\mathrm{T}}^{\mathrm{miss}}$, calculated from calorimeter signals in the range $|\eta| < 5.0$, is corrected by taking into account the contributions from minimally interacting muons. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is further corrected on a track-by-track basis for the expected response of the calorimeter derived from simulation, resulting in an improved $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution.

The data yields and corresponding MC predictions after this event preselection are given in Table 1. The MC yields are normalized to $34\,\mathrm{pb}^{-1}$ using next-to-leading order (NLO) cross sections. As expected, the MC predicts that the sample passing the preselection is dominated by dilepton $\mathrm{t\bar{t}}$. The data yield is in good agreement with the prediction. We also quote the yields for the LM0 and LM1 benchmark scenarios.

Table 1: Data yields and MC predictions after preselection, using the quoted NLO production cross sections σ. The $\mathrm{t\bar{t}} \to \ell^+\ell^-$ corrresponds to dilepton $\mathrm{t\bar{t}}$, including $\mathrm{t} \to \mathrm{W} \to \tau \to \ell$; $\mathrm{t\bar{t}} \to$ other includes all other $\mathrm{t\bar{t}}$ decay modes. The samples of MC $\mathrm{t\bar{t}}$, $\mathrm{W}^{\pm}$ + jets, and single-top events were generated with MADGRAPH. The Drell–Yan sample (which includes events with invariant masses as low as $10\,\mathrm{GeV}/c^2$) was generated using a mixture of MADGRAPH and PYTHIA. All other samples were generated with PYTHIA. The LM0 and LM1 benchmark scenarios are defined in the text. Uncertainties are statistical only.

Sample	σ (pb)	ee	$\mu\mu$	eμ	Total
$\mathrm{t\bar{t}} \to \ell^+\ell^-$	16.9	14.50 ± 0.24	17.52 ± 0.26	41.34 ± 0.40	73.36 ± 0.53
$\mathrm{t\bar{t}} \to$ other	140.6	0.49 ± 0.04	0.21 ± 0.03	1.02 ± 0.06	1.72 ± 0.08
Drell–Yan	18417	1.02 ± 0.21	1.16 ± 0.22	1.20 ± 0.22	3.38 ± 0.37
$\mathrm{W}^{\pm}$ + jets	28049	0.19 ± 0.13	0.00 ± 0.00	0.09 ± 0.09	0.28 ± 0.16
$\mathrm{W^+W^-}$	2.9	0.15 ± 0.01	0.16 ± 0.01	0.37 ± 0.02	0.68 ± 0.03
$\mathrm{W^{\pm}Z}$	0.3	0.02 ± 0.00	0.02 ± 0.00	0.04 ± 0.00	0.09 ± 0.00
ZZ	4.3	0.01 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.05 ± 0.00
Single top	33.0	0.46 ± 0.02	0.55 ± 0.02	1.24 ± 0.03	2.25 ± 0.04
Total SM MC		16.85 ± 0.34	19.63 ± 0.34	45.33 ± 0.47	81.81 ± 0.67
Data		15	22	45	82
LM0	52.9	10.67 ± 0.31	12.63 ± 0.34	17.81 ± 0.41	41.11 ± 0.62
LM1	6.7	2.35 ± 0.05	2.83 ± 0.06	1.51 ± 0.04	6.69 ± 0.09

Figure 1 compares several kinematic distributions in data and SM MC for events passing the preselection. As an illustration, we also show the MC distributions for the LM1 benchmark point. We find that the SM MC reproduces the properties of the bulk of dilepton $\mathrm{t\bar{t}}$ events. We therefore turn our attention to the tails of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and H_{T} distributions of the $\mathrm{t\bar{t}}$ sample.

To look for possible BSM contributions, we define a signal region that preserves about 1% of the dilepton $\mathrm{t\bar{t}}$ events, by adding the following two requirements to the preselection described above:

$$H_{\mathrm{T}} > 300\,\mathrm{GeV} \text{ and } y > 8.5\,\mathrm{GeV}^{1/2}, \tag{1}$$

where $y \equiv E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$. The requirement is on y rather than $E_{\mathrm{T}}^{\mathrm{miss}}$ because the variables H_{T} and y are found to be almost uncorrelated in dilepton $\mathrm{t\bar{t}}$ MC, with a correlation coefficient of $\sim 5\%$. This facilitates the use of a background estimation method based on data, as discussed in Section 4.

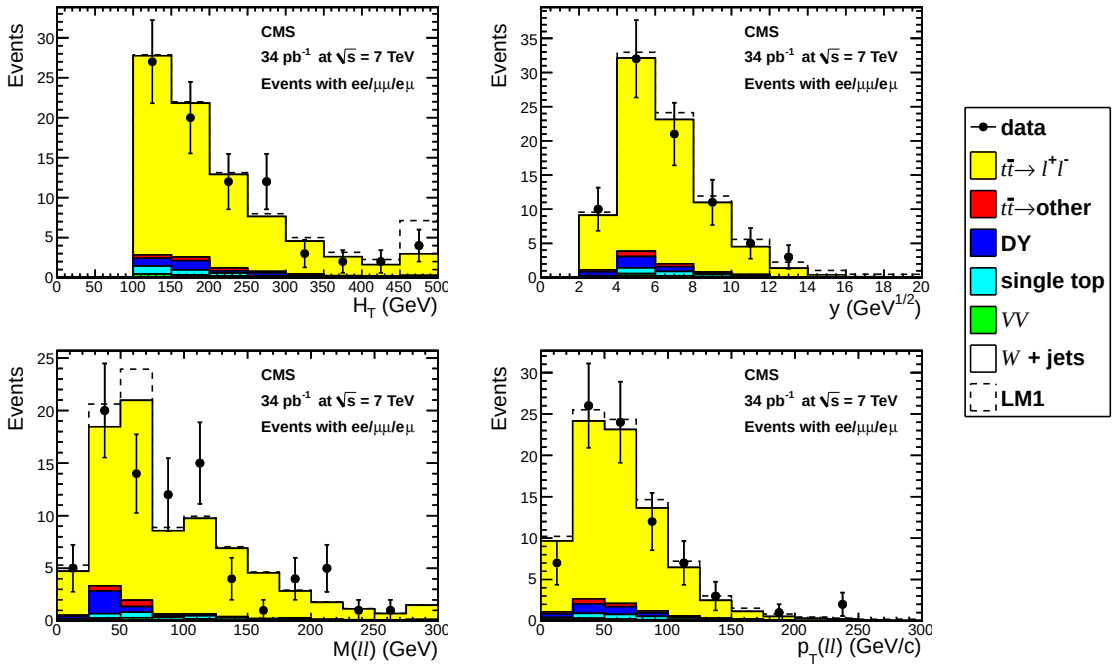

Figure 1: Distributions of (top left) scalar sum of jet transverse energies (H_T), (top right) $y \equiv E_T^{miss}/\sqrt{H_T}$, (bottom left) dilepton invariant mass $M(\ell\ell)$, and (bottom right) dilepton transverse momentum $p_T(\ell\ell)$ for SM MC and data after preselection. The last bin contains the overflow. Here $t\bar{t} \to \ell^+\ell^-$ corresponds to dilepton $t\bar{t}$, including $t \to W \to \tau \to \ell$; $t\bar{t} \to$ other includes all other $t\bar{t}$ decay modes, and VV indicates the sum of WW, WZ, and ZZ. The MC distributions for the LM1 benchmark points are also shown.

The MC predicts 1.3 SM events, dominated by dilepton $t\bar{t}$, in the signal region. The expectations for the LM0 and LM1 points are 8.6 and 3.6 events, respectively.

4 Background Estimates from Data

We have developed two independent methods to estimate from data the background in the signal region. The first method exploits the fact that H_T and y are nearly uncorrelated for the $t\bar{t}$ background. Four regions (A, B, C, and D) are defined in the y vs. H_T plane, as indicated in Figure 2, where region D is the signal region defined in Eq. 1. In the absence of a signal, the yields in the regions A, B, and C can be used to estimate the yield in the signal region D as $N_D = N_A \times N_C/N_B$; this method is referred to as the "ABCD method".

The expected event yields in the four regions for the SM MC, as well as the background prediction $N_A \times N_C/N_B$, are given in Table 2. We observe good agreement between the total SM MC predicted and observed yields. A 20% systematic uncertainty is assigned to the predicted yield of the ABCD method to take into account uncertainties from contributions of backgrounds other than dilepton $t\bar{t}$ (16%), finite MC statistics in the closure test (8%), and variation of the boundaries between the ABCD regions based on the uncertainty in the hadronic energy scale (8%).

The second background estimate, henceforth referred to as the dilepton transverse momentum ($p_T(\ell\ell)$) method, is based on the idea [22] that in dilepton $t\bar{t}$ events the p_T distributions of the charged leptons and neutrinos from W decays are related, because of the common boosts

from the top and W decays. This relation is governed by the polarization of the W's, which is well understood in top decays in the SM [23, 24] and can therefore be reliably accounted for. We then use the observed $p_{\mathrm{T}}(\ell\ell)$ distribution to model the $p_{\mathrm{T}}(\nu\nu)$ distribution, which is identified with $E_{\mathrm{T}}^{\mathrm{miss}}$. Thus, we use the number of observed events with $H_{\mathrm{T}} > 300\,\mathrm{GeV}$ and $p_{\mathrm{T}}(\ell\ell)/\sqrt{H_{\mathrm{T}}} > 8.5\,\mathrm{GeV}^{1/2}$ to predict the number of background events with $H_{\mathrm{T}} > 300\,\mathrm{GeV}$ and $y = E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 8.5\,\mathrm{GeV}^{1/2}$. In practice, two corrections must be applied to this prediction, as described below.

The first correction accounts for the $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$ requirement in the preselection, which is needed to reduce the DY background. We rescale the prediction by a factor equal to the inverse of the fraction of events passing the preselection which also satisfy the requirement $p_{\mathrm{T}}(\ell\ell) > 50\,\mathrm{GeV}/c$. This correction factor is determined from MC and is $K_{50} = 1.5$. The second correction (K_C) is associated with the known polarization of the W, which introduces a difference between the $p_{\mathrm{T}}(\ell\ell)$ and $p_{\mathrm{T}}(\nu\nu)$ distributions. The correction K_C also takes into account detector effects such as the hadronic energy scale and resolution which affect the $E_{\mathrm{T}}^{\mathrm{miss}}$ but not $p_{\mathrm{T}}(\ell\ell)$. The total correction factor is $K_{50} \times K_C = 2.1 \pm 0.6$, where the uncertainty is dominated by the 5% uncertainty in the hadronic energy scale [25].

All background estimation methods based on data are in principle subject to signal contamination in the control regions, which tends to decrease the significance of a signal which may be present in the data by increasing the background prediction. In general, it is difficult to quantify these effects because we do not know what signal may be present in the data. Having two independent methods (in addition to expectations from MC) adds redundancy because signal contamination can have different effects in the different control regions for the two methods. For example, in the extreme case of a BSM signal with identical distributions of $p_{\mathrm{T}}(\ell\ell)$ and $E_{\mathrm{T}}^{\mathrm{miss}}$, an excess of events might be seen in the ABCD method but not in the $p_{\mathrm{T}}(\ell\ell)$ method.

Backgrounds in which one or both leptons do not originate from electroweak decays (non-W/Z leptons) are assessed using the method of Ref. [12]. A non-W/Z lepton is a lepton candidate originating from within a jet, such as a lepton from semileptonic b or c decays, a muon decay-in-flight, a pion misidentified as an electron, or an unidentified photon conversion. Estimates of the contributions to the signal region from pure multijet QCD, with two non-W/Z leptons, and in W + jets, with one non-W/Z lepton in addition to the lepton from the decay of the W, are derived separately. We find $0.00^{+0.04}_{-0.00}$ and $0.0^{+0.4}_{-0.0}$ for the multijet QCD and W+jets contributions respectively, and thus consider these backgrounds to be negligible.

Backgrounds from DY and from processes with two vector bosons and single top are negligible compared to dilepton $\mathrm{t\bar{t}}$.

5 Results

We find one event in the signal region D. The event is in the eμ channel and contains 3 jets. The SM MC expectation is 1.3 events.

Table 2 summarizes the event yields obtained for each of the four ABCD regions in the data and in the MC samples. The prediction of the ABCD method is given by $N_{\mathrm{A}} \times N_{\mathrm{C}}/N_{\mathrm{B}} = 1.3 \pm 0.8\ (\mathrm{stat.}) \pm 0.3\ (\mathrm{syst.})$ events. The data, together with SM expectations, are presented in Figure 2.

The ABCD prediction is then compared with that of the $p_{\mathrm{T}}(\ell\ell)$ method. We find 1 event passing the requirements $H_{\mathrm{T}} > 300\,\mathrm{GeV}$ and $p_{\mathrm{T}}(\ell\ell)/\sqrt{H_{\mathrm{T}}} > 8.5\,\mathrm{GeV}^{1/2}$. This leads to a predicted background of $2.1 \pm 2.1\ (\mathrm{stat.}) \pm 0.6\ (\mathrm{syst.})$ after applying the correction factor $K_{50} \times K_C =$

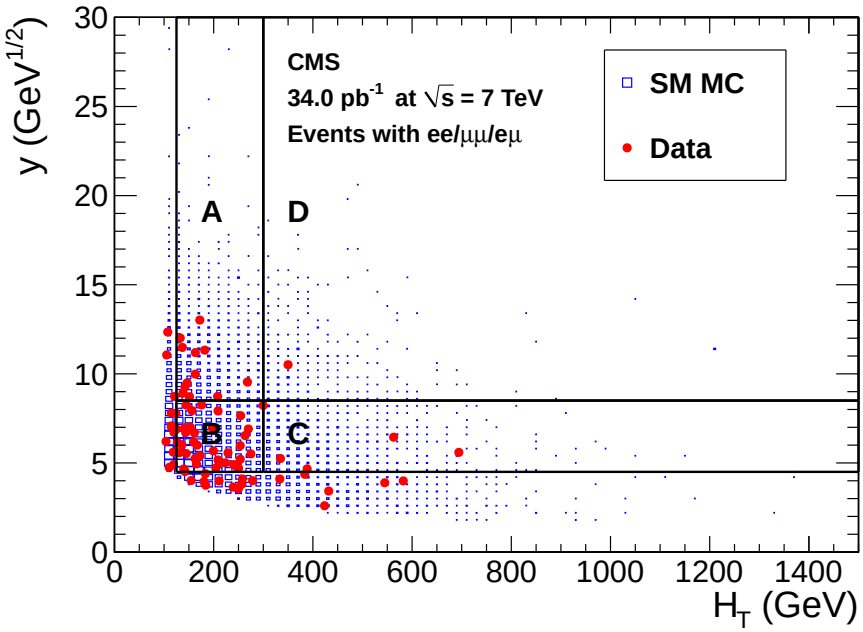

Figure 2: Distributions of y vs. H_T for SM MC (2-dimensional histogram) and data (scatter plot). Here our choice of the ABCD regions is also shown.

2.1 ± 0.6, as shown in Figure 3 (left).

As a validation of the $p_T(\ell\ell)$ method in a region with higher statistics, we also apply the $p_T(\ell\ell)$ method in control region A by restricting H_T to be in the range 125–300 GeV. Here the prediction is 9.0 ± 6.0 (stat.) background events, in good agreement with the observed yield of 12 events, as shown in Figure 3 (right).

In summary, for the signal region defined as $H_T > 300\,\text{GeV}$ and $y > 8.5\,\text{GeV}^{1/2}$: we observe one event in the data, SM MC predicts 1.3 events, the ABCD method predicts 1.3 ± 0.8 (stat.) $\pm$ 0.3 (syst.) events, and the $p_T(\ell\ell)$ method predicts 2.1 ± 2.1 (stat.) ± 0.6 (syst.) events.

All three background predictions are consistent within their uncertainties. We thus take as our best estimate of the SM yield in the signal region the error-weighted average of the two background estimates based on data and find a number of predicted background events $N_{BG} = 1.4 \pm 0.8$, in good agreement with the observed signal yield. We therefore conclude that no evidence for a non-SM contribution to the signal region is observed.

6 Acceptance and Efficiency Systematic Uncertainties

The acceptance and efficiency, as well as the systematic uncertainties in these quantities, depend on the signal model. For some of the individual uncertainties, it is reasonable to quote values based on SM control samples with kinematic properties similar to the SUSY benchmark models. For others that depend strongly on the kinematic properties of the event, the systematic uncertainties must be quoted model by model.

The systematic uncertainty in the lepton acceptance consists of two parts: the trigger efficiency uncertainty and the identification and isolation uncertainty. The trigger efficiency for two leptons of $p_T > 10\,\text{GeV}/c$, with one lepton of $p_T > 20\,\text{GeV}/c$ is close to 100%. We estimate the efficiency uncertainty to be a few percent, mostly in the low p_T region, using samples of $Z \to \ell\ell$.

Table 2: Data yields in the four regions of Figure 2, as well as the predicted yield in region D given by $N_A \times N_C / N_B$. The SM and BSM MC expectations are also shown. The quoted uncertainties are statistical only.

Sample	N_A	N_B	N_C	N_D	$N_A \times N_C / N_B$
$t\bar{t} \to \ell^+\ell^-$	8.44 ± 0.18	32.83 ± 0.35	4.78 ± 0.14	1.07 ± 0.06	1.23 ± 0.05
$t\bar{t} \to$ other	0.12 ± 0.02	0.78 ± 0.05	0.16 ± 0.02	0.02 ± 0.01	0.02 ± 0.01
Drell–Yan	0.17 ± 0.08	1.18 ± 0.22	0.04 ± 0.04	0.12 ± 0.07	0.01 ± 0.01
$W^\pm$ + jets	0.00 ± 0.00	0.09 ± 0.09	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
W^+W^-	0.11 ± 0.01	0.29 ± 0.02	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0.00
$W^\pm Z$	0.01 ± 0.00	0.04 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
ZZ	0.01 ± 0.00	0.02 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Single top	0.29 ± 0.01	1.04 ± 0.03	0.04 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
Total SM MC	9.14 ± 0.20	36.26 ± 0.43	5.05 ± 0.14	1.27 ± 0.10	1.27 ± 0.05
Data	12	37	4	1	1.30 ± 0.78
LM0	4.04 ± 0.19	4.45 ± 0.20	13.92 ± 0.36	8.63 ± 0.27	12.63 ± 0.88
LM1	0.52 ± 0.02	0.26 ± 0.02	1.64 ± 0.04	3.56 ± 0.06	3.33 ± 0.27

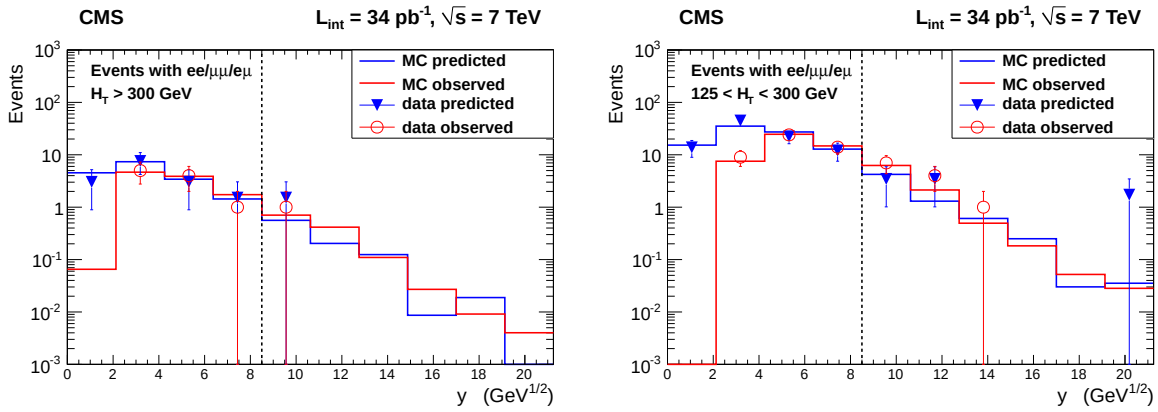

Figure 3: Distributions of y (observed) and $p_T(\ell\ell)/\sqrt{H_T}$ scaled by the correction factor K_{50} (predicted) for (left) the signal region and (right) the control region A, for both MC and data. The vertical dashed line indicates the search region defined by $y > 8.5\,\mathrm{GeV}^{1/2}$. The deficit at low y is due to the $E_T^{miss} > 50\,\mathrm{GeV}$ preselection requirement.

For dilepton $t\bar{t}$, LM0, and LM1, the trigger efficiency uncertainties are found to be less than 1%. We verify that the MC reproduces the lepton identification and isolation efficiencies in data using samples of $Z \to \ell\ell$; the data and MC efficiencies are found to be consistent within 2%.

Another significant source of systematic uncertainty is associated with the jet and E_T^{miss} energy scale. The impact of this uncertainty is final-state dependent. Final states characterized by very large hadronic activity and E_T^{miss} are less sensitive than final states where the E_T^{miss} and H_T are typically close to the minimum requirements applied to these quantities. To be more quantitative, we have used the method of Ref. [12] to evaluate the systematic uncertainties in the acceptance for $t\bar{t}$ and for the two benchmark SUSY points using a 5% uncertainty in the hadronic energy scale [25]. For $t\bar{t}$ the uncertainty is 27%; for LM0 and LM1 the uncertainties are 14% and 6%, respectively.

The uncertainty in the integrated luminosity is 11% [26].

7 Same-flavour Dilepton Search

The result of Section 5 is cross-checked in a similar kinematic region with an independent search relying on a different trigger path, different methods for "physics object" reconstruction, and a different background estimation method. This search is directed at BSM scenarios in which decay chains of a pair of new heavy particles produce an excess of same-flavour (e^+e^- and $\mu^+\mu^-$) events over opposite-flavour ($e^\pm\mu^\mp$) events. For example, in the context of the CMSSM, this excess may be caused by decays of neutralinos and Z bosons to same-flavour lepton pairs. For the benchmark scenario LM0 (LM1), the fraction of same-flavour events in the signal region discussed below is 0.67 (0.86).

The dominant background in this search is also dilepton $t\bar{t}$, for which such an excess does not exist because the flavours of the two leptons are uncorrelated. Therefore, the rate of $t\bar{t}$ decays with two same-flavour leptons may be estimated from the number of opposite-flavour events, after correcting for the ratio of muon to electron selection efficiencies, $r_{\mu e}$. This method actually estimates the contribution of any uncorrelated pair of leptons, including e.g. $Z \to \tau\tau$ events where the two τ leptons decay leptonically. This method will also subtract any BSM signal producing lepton pairs of uncorrelated flavour.

Events with two leptons with $p_T > 10\,\text{GeV}/c$ are selected. Because the lepton triggers are not fully efficient for events with two leptons of $p_T > 10\,\text{GeV}/c$, the data sample for this analysis is selected with hadronic triggers based on the scalar sum of the transverse energies of all jets reconstructed from calorimeter signals with $p_T > 20\,\text{GeV}/c$. The event is required to pass at least one of a set of hadronic triggers with transverse energy thresholds ranging from 100 to 150 GeV. The efficiency of this set of triggers with respect to the analysis selection is greater than 99%. In addition to the trigger, we require $H_T > 350\,\text{GeV}$, where H_T in this analysis is defined as the scalar sum of the transverse energies of all selected jets with $p_T > 30\,\text{GeV}/c$ and within an increased pseudorapidity range $|\eta| < 3$, in line with the trigger requirement. The jets, E_T^{miss}, and leptons are reconstructed with the Particle Flow technique [27]. The resulting performance of the selection of leptons and jets does not differ significantly from the selection discussed in Section 3.

The signal region is defined by additionally requiring $E_T^{miss} > 150\,\text{GeV}$. This signal region is chosen such that approximately one SM event is expected in our current data sample.

The lepton selection efficiencies are measured using the Z resonance. As discussed in Section 6, these efficiencies are known with a systematic uncertainty of 2%. The selection efficiencies of isolated leptons are different in the $t\bar{t}$ and $Z + \text{jets}$ samples. The ratio of muon to electron efficiencies $r_{\mu e}$, however, is found to differ by less than 5% in the MC simulations, and a corresponding systematic uncertainty is assigned to this ratio. This procedure gives $r_{\mu e} = 1.07 \pm 0.06$.

The $W + \text{jets}$ and QCD multijet contributions, where at least one of the two leptons is a secondary lepton from a heavy flavour decay or a jet misidentified as a lepton (non-W/Z leptons) are estimated from a fit to the lepton isolation distribution, after relaxing the isolation requirement on the leptons. Contributions from other SM backgrounds, such as DY or processes with two gauge bosons, are strongly suppressed by the E_T^{miss} requirement and are expected to be negligible.

We first estimate the number of SM events in a $t\bar{t}$-dominated region with $100 < H_T < 350\,\text{GeV}$ and $E_T^{miss} > 80\,\text{GeV}$. In order to cope with the lower H_T requirement, we use the same high-p_T lepton trigger sample as described in Section 3. In this region we observe 26 opposite-flavour candidates and predict 1.0 ± 0.5 non-W/Z lepton events from the fit to the lepton isolation

distribution. This results in an estimate of 25.0 ± 5.0 $t\bar{t}$ events in the eμ channel. Using the efficiency ratio $r_{\mu e}$ this estimate is then converted into a prediction for the number of same-flavour events in the ee and $\mu\mu$ channels.

Table 3: Number of predicted and observed ee and $\mu\mu$ events in the control region, defined as $100 < H_T < 350\,\text{GeV}$ and $E_T^{miss} > 80\,\text{GeV}$. "SM MC" indicates the sum of all MC samples ($t\bar{t}$, DY, W + jets, and WW/WZ/ZZ) and includes statistical uncertainties only.

	Control region	
Process	*ee*	$\mu\mu$
$t\bar{t}$ predicted from eμ	11.7 ± 2.4	13.4 ± 2.8
Non-W/Z leptons	0.5 ± 0.3	0.4 ± 0.2
Total predicted	12.2 ± 2.4	13.8 ± 2.8
Total observed	10	15
SM MC	8.4 ± 0.2	10.5 ± 0.3

Table 3 shows the number of expected SM background same-flavour events in the control region for the MC, as well as the prediction from the background estimation techniques based on data. There are a total of 25 same-flavour events, in good agreement with the prediction of 25.9 ± 5.2 events. We thus proceed to the signal region selection.

The SM background predictions in the signal region from the opposite-flavour and non-W/Z lepton methods are summarized in Table 4. We find one event in the signal region in the eμ channel with a prediction of non-W/Z leptons of 0.1 ± 0.1, and thus predict $0.9^{+2.2}_{-0.8}$ same-flavour events using Poisson statistical uncertainties. In the data we find no same-flavour events, in agreement with the prediction, in contrast with 7.3 ± 1.6 and 3.6 ± 0.7 expected events for the benchmark points LM0 and LM1, respectively. The predicted background from non-W/Z leptons is negligible.

Table 4: Number of predicted and observed events in the signal region, defined as $H_T > 350\,\text{GeV}$ and $E_T^{miss} > 150\,\text{GeV}$. "SM MC" indicates the sum of all MC samples ($t\bar{t}$, DY, W + jets, and WW/WZ/ZZ) and includes statistical uncertainties only.

	Signal region	
Process	ee	$\mu\mu$
$t\bar{t}$ predicted from eμ	$0.4^{+1.0}_{-0.4}$	$0.5^{+1.2}_{-0.4}$
Non-W/Z	0	0
Total predicted	$0.4^{+1.0}_{-0.4}$	$0.5^{+1.2}_{-0.4}$
Total observed	0	0
SM MC	0.38 ± 0.08	0.56 ± 0.07
LM0	3.4 ± 0.2	3.9 ± 0.2
LM1	1.6 ± 0.1	2.0 ± 0.1

Table 4 demonstrates the sensitivity of this approach. We observe comparable yields of the same benchmark points as for the high-p_T lepton trigger search, where 35–60% of the events are common to both searches for LM0 and LM1. Either approach would have given an excess in the presence of a signal.

8 Limits on New Physics

The three background predictions for the high-p_T lepton trigger search discussed in Section 5 are in good agreement with each other and with the observation of one event in the signal region. A Bayesian 95% confidence level (CL) upper limit [28] on the number of non-SM events in the signal region is determined to be 4.0, using a background prediction of $N_{BG} = 1.4 \pm 0.8$ events and a log-normal model of nuisance parameter integration. The upper limit is not very sensitive to N_{BG} and its uncertainty. This generic upper limit is not corrected for the possibility of signal contamination in the control regions. This is justified because the two independent background estimation methods based on data agree and are also consistent with the SM MC prediction. Moreover, no evidence for non-SM contributions in the control regions is observed (Table 2 and Figure 3). This bound rules out the benchmark SUSY scenario LM0, for which the number of expected signal events is 8.6 ± 1.6, while the LM1 scenario predicts 3.6 ± 0.5 events. The uncertainties in the LM0 and LM1 event yields arise from energy scale, luminosity, and lepton efficiency, as discussed in Section 6.

For the same-flavour search using hadronic activity triggers discussed in Section 7, no same-flavour events are observed and the corresponding Bayesian 95% CL upper limit on the non-SM yield is 3.0 events. This bound rules out the benchmark SUSY scenarios LM0 and LM1, for which the numbers of expected signal events are 7.3 ± 1.6 and 3.6 ± 0.7, respectively.

We also quote the result more generally in the context of the CMSSM. The Bayesian 95% CL limit in the $(m_0, m_{1/2})$ plane, for $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$ is shown in Figure 4. The high-p_T lepton and hadronic trigger searches have similar sensitivity to the CMSSM; here we choose to show results based on the high-p_T lepton trigger search. The SUSY particle spectrum is calculated using SoftSUSY [29], and the signal events are generated at leading order (LO) with PYTHIA 6.4.22. NLO cross sections, obtained with the program Prospino [30], are used to calculate the observed exclusion contour. At each point in the $(m_0, m_{1/2})$ plane, the acceptance uncertainty is calculated by summing in quadrature the uncertainties from jet and E_T^{miss} energy scale using the procedure discussed in Section 6, the uncertainty in the NLO cross section due to the choice of factorization and renormalization scale, and the uncertainty from the parton distribution function (PDF) for CTEQ6.6 [31], estimated from the envelope provided by the CTEQ6.6 error sets. The luminosity uncertainty and dilepton selection efficiency uncertainty are also included, giving a total relative acceptance uncertainty which varies in the range 0.2–0.3. A point is considered to be excluded if the NLO yield exceeds the 95% CL Bayesian upper limit calculated with this acceptance uncertainty, using a log-normal model for the nuisance parameter integration. The limit curves do not include the effect of signal contamination in the control regions. We have verified that this has a negligible impact on the excluded regions in Figure 4.

The excluded regions for the CDF search for jets + missing energy final states [32] were obtained for $\tan\beta = 5$, while those from D0 [33] were obtained for $\tan\beta = 3$, each with approximately 2 fb^{-1} of data and for $\mu < 0$. The LEP-excluded regions are based on searches for sleptons and charginos [34]. The D0 exclusion limit, valid for $\tan\beta = 3$ and obtained from a search for associated production of charginos $\chi_1^{\pm}$ and neutralinos χ_2^0 in trilepton final states [35], is also included in Figure 4. In contrast to the other limits presented in Figure 4, the results of our search and of the trilepton search are strongly dependent on the choice of $\tan\beta$ and they reach the highest sensitivity in the CMSSM for $\tan\beta$ values below 10.

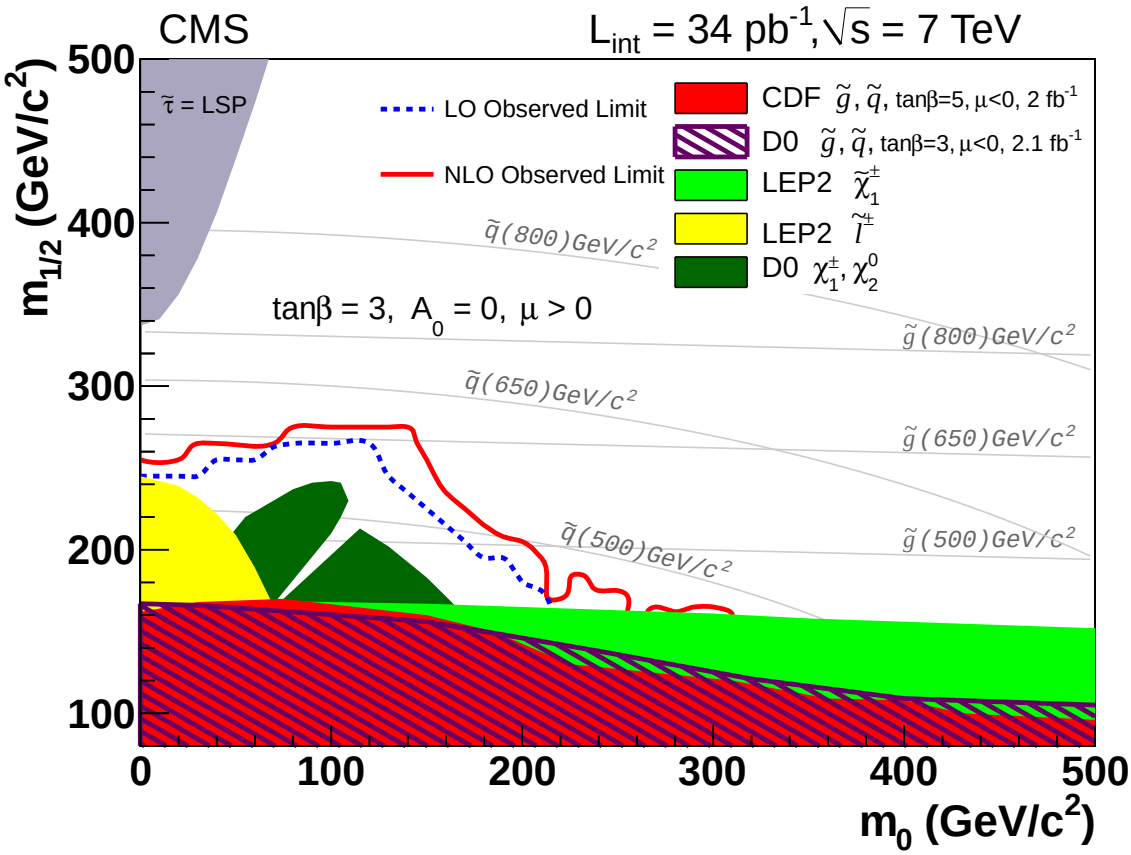

Figure 4: The observed 95% CL exclusion contour at NLO (solid red line) and LO (dashed blue line) in the CMSSM $(m_0, m_{1/2})$ plane for $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$. The area below the curve is excluded by this measurement. Exclusion limits obtained from previous experiments are presented as filled areas in the plot. Thin grey lines correspond to constant squark and gluino masses.

9 Additional Information for Model Testing

Other models of new physics in the dilepton final state can be confronted in an approximate way by simple generator-level studies that compare the expected number of events in 34 pb^{-1} with the upper limits from Section 8. The key ingredients of such studies are the kinematic requirements described in this paper, the lepton efficiencies, and the detector responses for H_T, y, and E_T^{miss}. The muon identification efficiency is $\approx$ 95%; the electron identification efficiency varies approximately linearly from $\approx$ 63% at $p_T = 10$ GeV/c to 91% for $p_T > 30$ GeV/c. The lepton isolation efficiency depends on the lepton momentum, as well as on the jet activity in the event. In $t\bar{t}$ events, it varies approximately linearly from $\approx$ 83% (muons) and $\approx$ 89% (electrons) at $p_T = 10$ GeV/c to $\approx$ 95% for $p_T > 60$ GeV/c. In LM0 events, this efficiency is decreased by $\approx$ 5–10% over the whole momentum spectrum. Electrons and muons from LM1 events have the same isolation efficiency as in $t\bar{t}$ events at low p_T and $\approx$ 90% efficiency for $p_T >$ 60 GeV/c. The average detector responses (the reconstructed quantity divided by the generated quantity) for H_T, y and E_T^{miss} are consistent with 1 within the 5% jet energy scale uncertainty. The experimental resolutions on these quantities are 10%, 14% and 16%, respectively.

10 Summary

We have presented a search for BSM physics in the opposite-sign dilepton final state using a data sample of proton-proton collisions at 7 TeV centre-of-mass energy corresponding to an integrated luminosity of $34\,\mathrm{pb}^{-1}$, recorded by the CMS detector in 2010. The search focused on dilepton events with large missing transverse energy and significant hadronic activity, motivated by many models of BSM physics, such as supersymmetric models. Good agreement with standard model predictions was found, both in terms of event yields and shapes of various relevant kinematic distributions. In the absence of evidence for BSM physics, we have set upper limits on the non-SM contributions to the signal regions. The result was interpreted in the context of the CMSSM parameter space and the excluded region was found to exceed those set by previous searches at the Tevatron and LEP experiments. Information on the acceptance and efficiency of the search was also provided to allow testing the exclusion of specific models of BSM physics.

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