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Search for physics beyond the standard model in events with two leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV

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Abstract: A search is presented for physics beyond the standard model in final states with two opposite-sign same-flavor leptons, jets, and missing transverse momentum. The data sample corresponds to an integrated luminosity of 19.4 fb^{-1} of proton-proton collisions at $\sqrt{s} = 8$ TeV collected with the CMS detector at the CERN LHC in 2012. The analysis focuses on searches for a kinematic edge in the invariant mass distribution of the opposite-sign same-flavor lepton pair and for final states with an on-shell Z boson. The observations are consistent with expectations from standard model processes and are interpreted in terms of upper limits on the production of supersymmetric particles.

Keywords: Supersymmetry, Hadron-Hadron Scattering

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1 Introduction

This paper presents a search for physics beyond the standard model (SM) in events containing a pair of opposite-sign same-flavor (SF) electrons or muons, jets, and an imbalance in transverse momentum. The analysis is based on a sample of proton-proton (pp) collisions collected at a center-of-mass energy of 8 TeV with the CMS detector [1] at the CERN LHC in 2012 and corresponds to an integrated luminosity of 19.4 fb^{-1}.

The invariant mass distribution of the two-lepton system can exhibit an excess that increases with the dilepton mass, followed by a sharp decrease and thus an "edge", if the two leptons originate from the decay of an on-shell heavy neutral particle. This kind of signature is fairly generic for models of physics beyond the SM (BSM), assumes an isotropic decay, and is purely kinematic in origin. In models of supersymmetry (SUSY) [2], an edge with a triangular shape is expected in the cascade process $\widetilde{\chi}_2^0 \to \ell\widetilde{\ell} \to \widetilde{\chi}_1^0\ell^+\ell^-$ [3], where $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$ are respectively the next-to-lightest and lightest neutralino, with $\widetilde{\ell}$ a selectron or smuon, the SUSY partners of an electron or muon. Alternatively, the $\widetilde{\chi}_2^0$ can undergo a three-body decay to $\widetilde{\chi}_1^0\ell^+\ell^-$ through a virtual Z^* boson, also yielding an edge in the dilepton

mass spectrum but with a more rounded shape. Another possibility is the decay of a $\widetilde{\chi}_2^0$ to an on-shell Z boson, $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0 \mathrm{Z}$. This latter process does not produce an edge but rather a dilepton mass peak near 91 GeV. These processes arise as a consequence of the gauge-coupling structure of SUSY and are a characteristic feature of SUSY decay chains. Their relative importance depends on the SUSY mass hierarchy and is thus model dependent.

This search is therefore motivated by the possible existence of the fairly generic signal shape of an edge, or of a peak at the Z boson mass, that would be visible in the invariant mass distribution of the two leptons. The position of the edge would give an indication of the unknown BSM mass hierarchy. The dilepton invariant mass provides a search variable that is unaffected by uncertainties in the jet energy scale and resolution, and the search for an edge is therefore complementary to searches based solely on hadronic quantities.

The CMS Collaboration previously presented two searches for BSM physics based on events with an opposite-sign SF lepton pair: a search for an edge in the dilepton mass spectrum outside the Z boson mass region [4], and a search for events containing on-shell Z bosons [5]. Both these studies were conducted using the 7 TeV CMS data sample collected in 2011. The present study updates and combines these two analyses, using the 8 TeV data sample. Searches for SUSY in opposite-sign dilepton final states, but targeting different production and/or decay mechanisms, are presented by the ATLAS Collaboration in refs. [6, 7].

A brief description of the CMS detector is given in section 2. Signal models studied in this analysis are described in section 3. Section 4 outlines the event selection and simulation. The background estimation methods are presented in section 5. A fitting procedure used to search for an edge is described in section 6. The results of the search are presented in section 7. Systematic uncertainties associated with the signal modeling are discussed in section 8 and the results of the search are interpreted in the context of the signal models in section 9. A summary is presented in section 10.

2 Detector and trigger

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter that produces an axial magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/plastic-scintillator hadron calorimeter are positioned within the field volume. Iron and quartz-fiber hadron calorimeters are located outside the magnetic field volume, within each endcap region of the detector. Muons are measured using gas-ionization detectors embedded in the steel flux-return yoke outside of the solenoid. A detailed description of the CMS detector, its coordinate system, and the main kinematic variables used in the analysis can be found in ref. [1].

Events must satisfy at least one of a set of ee, $\mu\mu$, and eμ triggers. The ee and $\mu\mu$ triggers collect signal candidate data while the eμ trigger collects data used in the background-determination procedure, as described below. These triggers require at least one electron or muon with transverse momentum $p_{\mathrm{T}} > 17$ GeV, and another with $p_{\mathrm{T}} > 8$ GeV. Their efficiencies after event selection (>90%) are measured in data and are accounted for in the analysis. The efficiencies of the ee, $\mu\mu$, and eμ triggers differ by only a few percent in the kinematic range of this search.

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3 Signal scenarios

Two classes of signal events are considered, as explained below. Both classes are implemented in the framework of simplified models [8], in which only the targeted production and decay schemes are examined, with all non-participating BSM particles assumed to be too heavy to be relevant.

The first class of signal events targets the production of an edge in the invariant mass spectrum of opposite-sign SF lepton pairs, as expected from the correlated production of these leptons in cascade decays. This class of scenarios is based on the production of a bottom squark-antisquark pair. Each bottom squark $\widetilde{\mathrm{b}}$ decays to a bottom quark b and the $\widetilde{\chi}_2^0$ neutralino. Two specific possibilities are considered. In the first scenario (figure 1 left), the $\widetilde{\chi}_2^0$ decays to an off-shell Z boson Z^* and the $\widetilde{\chi}_1^0$ neutralino, where the $\widetilde{\chi}_1^0$ is a stable, weakly interacting, lightest SUSY particle (LSP). The Z^* boson decays according to its SM branching fractions, sometimes producing a charged lepton pair $\ell^+\ell^-$ ($\ell = \mathrm{e}, \mu$). The mass difference between the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$, which determines the location of the edge, is fixed to 70 GeV. This scenario is referred to as the "fixed-edge" scenario. In the second scenario (figure 1 right), the $\widetilde{\chi}_2^0$ decays to an on- or off-shell Z boson and the $\widetilde{\chi}_1^0$ LSP or according to $\widetilde{\chi}_2^0 \to \ell\widetilde{\ell}$, with a 50% probability for each decay. The slepton $\widetilde{\ell}$, i.e., the SUSY partner of the lepton, then decays according to $\widetilde{\ell} \to \ell\widetilde{\chi}_1^0$. The considered sleptons are mass-degenerate selectrons and smuons. The mass of the slepton is chosen to lie halfway between the masses of the two neutralinos: $m_{\widetilde{\ell}} = m_{\widetilde{\chi}_1^0} + 0.5(m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0})$. The mass of the $\widetilde{\chi}_1^0$ is set to 100 GeV, with the position of the edge a free parameter in a scan of the mass spectrum. This scenario is referred to as the "slepton-edge" scenario.

The second class of signal events targets the production of an opposite-sign SF lepton pair from the decay of an on-shell Z boson. This class of scenarios, illustrated in figure 2, is based on gluino pair production in the context of gauge mediated supersymmetry breaking (GMSB) models [9–11]. Each gluino decays to a quark-antiquark pair and the $\widetilde{\chi}_1^0$ neutralino. The $\widetilde{\chi}_1^0$ decays to an on-shell Z boson and a stable, massless, weakly interacting gravitino LSP. We refer to this scenario as the "GMSB" scenario.

The production of squark and gluino pairs is simulated with the MadGraph 5.1.3.30 [12, 13] Monte Carlo (MC) leading-order event generator, including up to two additional partons at the matrix element level. The decays of the squarks, gluinos, and other particles are simulated with the pythia 6.4.22 [14] event generator. The MadGraph events are subsequently processed with the pythia program to generate parton showers and account for hadronization. The decay of the Z boson is handled in pythia. In all the aforementioned scenarios (fixed-edge, slepton-edge, GMSB), the Z boson decays according to its SM branching fractions. To reduce computational requirements, the detector response is simulated using the CMS fast simulation [15]. Differences in the lepton reconstruction and identification efficiencies between the fast and a "full" simulation, where the full simulation is based on processing through the Geant4 [16] programs, are corrected using scale factors. The expected signal event rates are normalized to cross sections calculated at the next-to-leading order (NLO) in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic (NLO+NLL) accuracy [17–22].

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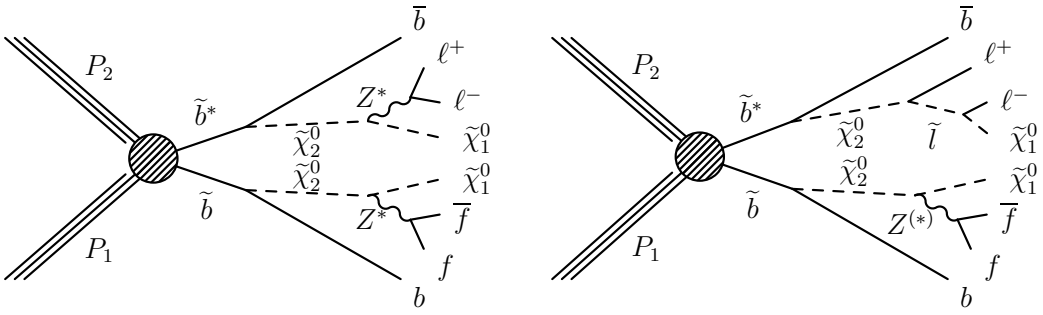

Figure 1. Event diagrams for the (left) "fixed-edge", and (right) "slepton-edge" scenarios, with $\widetilde{\mathrm{b}}$ a bottom squark, $\widetilde{\chi}_2^0$ the second lightest neutralino, $\widetilde{\chi}_1^0$ a massive neutralino LSP, and $\widetilde{\ell}$ an electron- or muon-type slepton. For the slepton-edge scenario, the Z boson can be either on- or off-shell, while for the fixed-edge scenario it is off-shell.

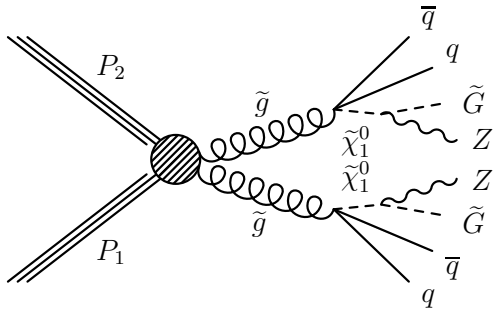

Figure 2. Event diagram for the "GMSB" scenario, with $\widetilde{\mathrm{g}}$ a gluino, $\widetilde{\chi}_1^0$ the lightest neutralino, and $\widetilde{\mathrm{G}}$ a massless gravitino LSP.

4 Event selection, reconstruction, and search strategy

We select events with an oppositely charged lepton pair ($\mathrm{e^+e^-}$, $\mathrm{e^\pm}\mu^\mp$, or $\mu^+\mu^-$). The leptons are required to have $p_\mathrm{T} > 20\,\mathrm{GeV}$ and $|\eta| < 2.4$, where η is the pseudorapidity [1]. In events with more than two selected leptons, we choose the two oppositely charged leptons with highest p_T. The background estimation techniques employed in this analysis rely, in part, on a symmetry between lepton pairs with the same flavor compared to those with opposite flavor (OF), where OF refers to $\mathrm{e^\pm}\mu^\mp$ combinations. It is therefore desirable that the reconstruction efficiencies of electrons [23] and muons [24] be as similar as possible. For this reason, we exclude leptons in the intervals $1.4 < |\eta| < 1.6$ between the barrel and endcap regions of the detector [1], where the electron and muon reconstruction efficiencies differ significantly. For the SF signal candidate sample, only events with an $\mathrm{e^+e^-}$ or $\mu^+\mu^-$ pair are used.

Leptons produced in the decays of low-mass particles, such as hadrons containing b and c quarks, almost always lie in or near jets. The background from these low-mass processes can be suppressed by requiring the leptons to be isolated in space from other particles. A cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ is constructed around the lepton momentum direction, where ϕ is the azimuthal angle. The lepton relative isolation is then quantified

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by the scalar p_{T} sum of all particle candidates within this cone, excluding the lepton, divided by the lepton p_{T}. The resulting quantity is required to be less than 0.15. The sum includes a correction to the total energy to account for contributions from extraneous pp interactions within the same or a nearby bunch crossing (pileup). For electrons, the pileup correction is based on the effective area method [25], while for muons it is based on the number of charged hadrons not associated with the primary vertex. The performance of the electron and muon isolation criteria is discussed in refs. [23, 24].

The primary vertex is taken to be the reconstructed vertex with the largest p_{T}^2 sum of associated tracks. Leptons with impact parameters larger than 0.2 mm in the transverse plane or 1 mm along the beam direction are rejected. As an additional requirement, the two selected leptons must be separated by $\Delta R > 0.3$ to avoid systematic effects that arise for isolation requirements in very collinear topologies.

A particle-flow (PF) technique [26] is used to reconstruct jets and missing transverse momentum. All objects reconstructed with the PF algorithm serve as input for jet reconstruction, based on the anti-k_{T} clustering algorithm [27] with a distance parameter of 0.5, as implemented in the FastJet package [25, 28]. We apply p_{T}- and η-dependent corrections to account for residual effects of nonuniform detector response. The contribution to the jet energy from pileup is estimated on an event-by-event basis using the jet area method described in ref. [29], and is subtracted from the overall jet p_{T}. Jets are required to have $p_{\mathrm{T}} > 40\,\mathrm{GeV}$, $|\eta| < 3.0$, and to be separated by $\Delta R > 0.4$ from all selected leptons. The missing transverse momentum $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is defined as the projection on the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed PF objects in an event. The magnitude of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions of events in the SF and OF samples for dilepton invariant mass $m_{\ell\ell} > 20\,\mathrm{GeV}$ and number of jets $N_{\mathrm{jets}} \geq 2$ are shown in figure 3.

The event selection criteria are motivated by the expectation that BSM signal events, involving the production of new heavy particles, generally have larger jet multiplicity and $E_{\mathrm{T}}^{\mathrm{miss}}$ than background events, which primarily arise from top quark-antiquark ($\mathrm{t\bar{t}}$) and Drell-Yan (DY) processes. The large value of $E_{\mathrm{T}}^{\mathrm{miss}}$ expected in signal events is due to the weakly interacting LSP particles, which escape without detection.

In the search for an edge, we define two signal regions: either $N_{\mathrm{jets}} \geq 2$ and $E_{\mathrm{T}}^{\mathrm{miss}} > 150\,\mathrm{GeV}$, or $N_{\mathrm{jets}} \geq 3$ and $E_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$. For both regions, we separately consider events in which both leptons satisfy $|\eta_{\mathrm{lep}}| < 1.4$ ("central" signal region) and events in which at least one lepton satisfies $1.6 < |\eta_{\mathrm{lep}}| < 2.4$ ("forward" signal region). The motivation for the distinction between the central and forward regions is that for BSM production through the decay of heavy resonances, the final-state leptons and jets are expected to be more centrally distributed than for the SM backgrounds. Two methods are used to search for an edge signature. In the first method, a search for an edge is performed in the range $20 < m_{\ell\ell} < 300\,\mathrm{GeV}$ by fitting the signal and background hypotheses to data, as described in section 6. In the second method, based on a direct comparison of event counts, with no assumption about the shapes of the signal and background distributions, we select three regions, $20 < m_{\ell\ell} < 70\,\mathrm{GeV}$, $81 < m_{\ell\ell} < 101\,\mathrm{GeV}$, and $m_{\ell\ell} > 120\,\mathrm{GeV}$, denoted the "low-mass", "on-Z", and "high-mass" regions, respectively. For this "counting experiment", the integrated yield in each region is compared to the corresponding background prediction.

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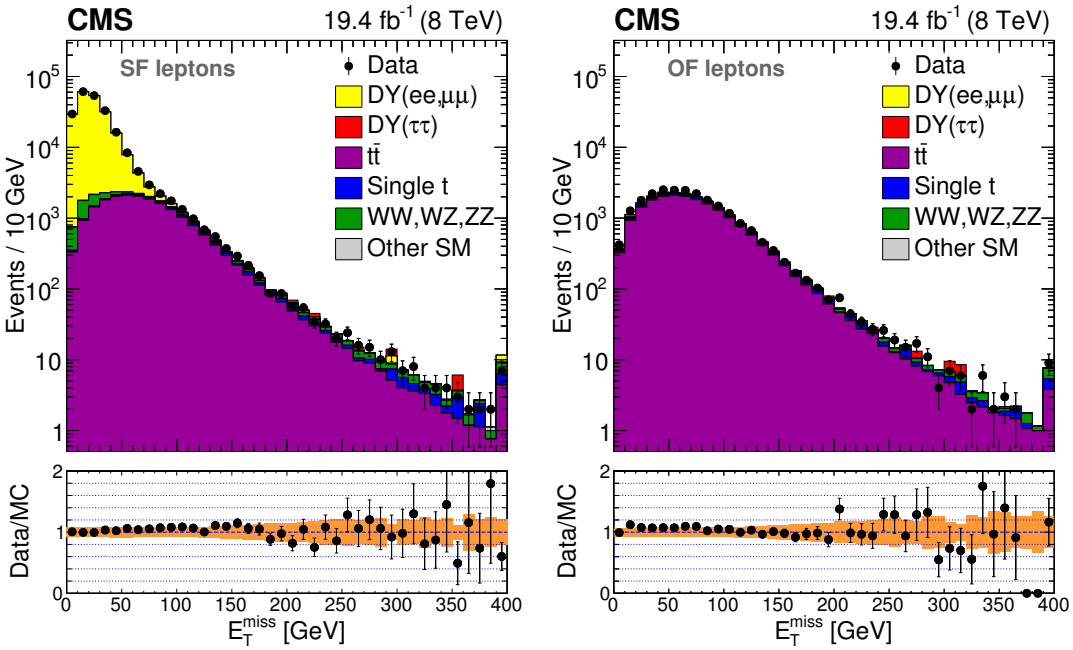

Figure 3. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions of events in the SF (left) and OF (right) samples for $m_{\ell\ell} > 20\,\mathrm{GeV}$ and $N_{\mathrm{jets}} \geq 2$ in comparison with predictions for the SM background from the MC generators described in section 4. In the ratio panel below each plot, the error bars on the black points show the statistical uncertainties of the data and MC samples, while the shaded band indicates the MC statistical and systematic uncertainties added in quadrature. The rightmost bins contain the overflow.

In the search for BSM events with an on-shell Z boson, we perform a dedicated counting experiment in the region $81 < m_{\ell\ell} < 101\,\mathrm{GeV}$, based on the distribution of $E_{\mathrm{T}}^{\mathrm{miss}}$. For this study, two inclusive bins in the number of jets are defined: $N_{\mathrm{jets}} \geq 2$ and $N_{\mathrm{jets}} \geq 3$. Events are examined in exclusive bins of $E_{\mathrm{T}}^{\mathrm{miss}}$ as described in section 7.

While the main SM backgrounds are estimated using data control samples, simulated MC events are used to evaluate smaller sources of background. The simulation is also used to estimate uncertainties. Simulated samples of DY + jets, $\mathrm{t\bar{t}}$, W + jets, VV, and $\mathrm{t\bar{t}V}$ (V = W, Z) events are generated with the MadGraph 5.1.3.30 event generator. The DY + jets sample considers events with dilepton invariant masses as low as 10 GeV, as well as decays to the $\tau\tau$ channel. The matrix element calculation performed with MadGraph 5.1.3.30 is then interfaced to the pythia 6.4.22 program for the description of parton showering and hadronization, analogous to the procedure used for the signal samples. The detector response in these samples is simulated with a Geant4 model [16] of the CMS detector. The simulated events are reconstructed and analyzed with the same software used to process data. In the simulation, multiple pp interactions are superimposed on the hard collision, and the simulated samples are reweighted to reflect the beam conditions, taking into account the total inelastic pp cross section at the LHC. Corrections are applied to account for the differences between simulation and data in the trigger and reconstruction efficiencies. The simulated sample yields are normalized to an integrated luminosity

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of $19.4\,\mathrm{fb}^{-1}$ using NLO inclusive cross sections, except for the DY + jets and W + jets samples, where next-to-next-to-leading order calculations [30] are used.

5 Background estimates

The principal SM backgrounds are divided into two categories. Backgrounds that produce OF pairs ($\mathrm{e}^+\mu^-, \mathrm{e}^-\mu^+$) as often as SF pairs ($\mathrm{e}^+\mathrm{e}^-, \mu^+\mu^-$) are referred to as flavor-symmetric (FS) backgrounds. This category is dominated by $\mathrm{t\bar{t}}$ processes. Drell-Yan events form the second principal background category. The FS background estimate accounts also for WW, $\mathrm{Z}/\gamma^*(\to\tau\tau)$, and tW single-top quark production, as well as for backgrounds due to leptons from hadron decays and from hadrons misidentified as leptons. Contributions from $\mathrm{t\bar{t}}+\mathrm{X}$, with X a W, Z, or Higgs boson, have been studied in the simulation and found to be negligible.

The missing transverse momentum in DY + jets events arises primarily from jet energy resolution and reconstruction effects. Contributions from SM WZ and ZZ processes, which might include genuine $E_{\mathrm{T}}^{\mathrm{miss}}$, are incorporated into the DY + jets background estimates.

5.1 Flavor-symmetric backgrounds

The contribution of FS background events to the signal regions is determined using a control sample defined by OF events that satisfy the full event selection. The OF yields are multiplied by a factor $R_{\mathrm{SF/OF}}$ to account for efficiency differences in the selection of dilepton pairs in the SF and OF samples. Two methods are used to evaluate the $R_{\mathrm{SF/OF}}$ factor, as explained below. We also determine corresponding factors $R_{\mathrm{ee/OF}}$ and $R_{\mu\mu/\mathrm{OF}}$ for the individual SF terms.

The first method, referred to as the "factorization" method, uses a data control sample to determine the SF-to-OF ratio of reconstruction efficiencies, and a second data control sample to determine the corresponding ratio of trigger efficiencies. The reconstruction efficiency ratio is evaluated using a large DY + jets data control sample selected by requiring $60 < m_{\ell\ell} < 120\,\mathrm{GeV}$, $N_{\mathrm{jets}} \geq 2$, and $E_{\mathrm{T}}^{\mathrm{miss}} < 50\,\mathrm{GeV}$. The measured quantity is $r_{\mu\mathrm{e}} = \sqrt{N_{\mu\mu}/N_{\mathrm{ee}}}$, which represents a ratio of the muon-to-electron reconstruction efficiency uncorrected for trigger efficiencies. The extrapolation of $r_{\mu\mathrm{e}}$ into the central (forward) signal region is studied using data. A 10% (20%) systematic uncertainty is assigned to account for the observed dependencies. The ratio R_{T} of the trigger efficiencies in SF and OF events is determined using a data control sample selected with a trigger based on H_{T}, which is the scalar sum of jet p_{T} values for jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$. The sample is selected by requiring $H_{\mathrm{T}} > 200\,\mathrm{GeV}$, $m_{\ell\ell} > 20\,\mathrm{GeV}$, and excluding events with $N_{\mathrm{jets}} = 2$ and $E_{\mathrm{T}}^{\mathrm{miss}} > 100\,\mathrm{GeV}$. The latter two requirements ensure that this control sample is uncorrelated with the control sample used to determine the reconstruction efficiencies. A 5% uncertainty is assigned to the efficiency of each dilepton trigger ($\mathrm{e}^+\mathrm{e}^-$, $\mu^+\mu^-$, $\mathrm{e}^\pm\mu^\mp$) to account for the observed dependence of these efficiencies on $m_{\ell\ell}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, and N_{jets}. The full correction to the OF event rate is $R_{\mathrm{SF/OF}} = 0.5(r_{\mu\mathrm{e}} + r_{\mu\mathrm{e}}^{-1})R_{\mathrm{T}}$, with $R_{\mathrm{T}} = \sqrt{\epsilon_{\mathrm{ee}}^{\mathrm{trig}}\epsilon_{\mu\mu}^{\mathrm{trig}}}/\epsilon_{\mathrm{e}\mu}^{\mathrm{trig}}$.

The second method, referred to as the "control-region" method, directly measures the $R_{\mathrm{SF/OF}}$ factors from the ratio of the $\mathrm{e}^+\mathrm{e}^-$, $\mu^+\mu^-$, or combined SF yields with the OF

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	Central	Forward
Factorization method		
$R_{\mathrm{SF/OF}}$	$1.03 \pm 0.01 \pm 0.06$	$1.11 \pm 0.04 \pm 0.08$
$R_{\mathrm{ee/OF}}$	$0.47 \pm 0.01 \pm 0.06$	$0.46 \pm 0.02 \pm 0.10$
$R_{\mu\mu/\mathrm{OF}}$	$0.56 \pm 0.01 \pm 0.07$	$0.65 \pm 0.03 \pm 0.14$
$r_{\mu\mathrm{e}}$	$1.09 \pm 0.00 \pm 0.11$	$1.18 \pm 0.00 \pm 0.24$
R_{T}	$1.03 \pm 0.01 \pm 0.06$	$1.10 \pm 0.04 \pm 0.07$
Control-region method		
$R_{\mathrm{SF/OF}}$	$0.99 \pm 0.05 \pm 0.02$	$1.11 \pm 0.11 \pm 0.03$
$R_{\mathrm{ee/OF}}$	$0.44 \pm 0.03 \pm 0.01$	$0.49 \pm 0.06 \pm 0.02$
$R_{\mu\mu/\mathrm{OF}}$	$0.55 \pm 0.03 \pm 0.01$	$0.62 \pm 0.07 \pm 0.02$
$r_{\mu\mathrm{e}}$	$1.12 \pm 0.04\,(\mathrm{stat})$	$1.12 \pm 0.08\,(\mathrm{stat})$
R_{T}	$0.98 \pm 0.05\,(\mathrm{stat})$	$1.11 \pm 0.11\,(\mathrm{stat})$
Combined		
$R_{\mathrm{SF/OF}}$	1.00 ± 0.04	1.11 ± 0.07
$R_{\mathrm{ee/OF}}$	0.45 ± 0.03	0.48 ± 0.05
$R_{\mu\mu/\mathrm{OF}}$	0.55 ± 0.03	0.63 ± 0.07

Table 1. Results for $R_{\mathrm{SF/OF}}$ in the signal regions. The results of the two methods are shown with statistical and systematic uncertainties, while the uncertainties for the combined values are a combination of the statistical and systematic terms. The values of $r_{\mu\mathrm{e}}$ and R_{T} listed for the control-region method are not used directly in the analysis and are listed for purposes of comparison only.

yields in a $\mathrm{t\bar{t}}$-dominated control region with $N_{\mathrm{jets}} \geq 2$, $100 < E_{\mathrm{T}}^{\mathrm{miss}} < 150\,\mathrm{GeV}$, and $20 < m_{\ell\ell} < 70\,\mathrm{GeV}$. Differences between the factors obtained in this control region and in the signal regions are studied with the $\mathrm{t\bar{t}}$ simulation. No difference is observed within the MC statistical uncertainty, which is used to define the corresponding systematic uncertainty. The size of this uncertainty is found to be 2% (3–4%) in the central (forward) region.

As the two methods rely on uncorrelated control samples, and the results agree within their uncertainties, the final results for $R_{\mathrm{SF/OF}}$ are obtained by taking the weighted average of the results from the two methods, propagating the uncertainties. The results are shown in table 1. The FS background is then given by the number of events in the OF control samples multiplied by the corresponding $R_{\mathrm{SF/OF}}$ factor. It is seen that the values of the $R_{\mathrm{SF/OF}}$ ratios are consistent with unity within the uncertainties. We find that the variation of $R_{\mathrm{SF/OF}}$ for increasing $m_{\ell\ell}$, N_{jets}, and $E_{\mathrm{T}}^{\mathrm{miss}}$ lies within the assigned uncertainty. We thus use the same value of $R_{\mathrm{SF/OF}}$ for all signal regions.

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5.2 SM Drell-Yan background

In the search for an edge based on a fit, the DY+jets background is determined as described in section 6. For the counting experiment method, the DY background is determined using the jet-Z balance (JZB) and $E_{\mathrm{T}}^{\mathrm{miss}}$-template methods [5], as described in this section.

The JZB is a measure of the imbalance between the p_{T} of the Z/γ^* boson and the p_{T} of the recoiling hadronic system in DY + jets. The JZB is defined as the scalar difference between the p_{T} of the Z/γ^* and the net p_{T} of the recoiling hadronic system. Standard model DY + jets events equally populate negative and positive values of JZB, because non-zero JZB in these events arises from jet energy resolution effects, whereas in BSM and $\mathrm{t\bar{t}}$ events, which contain genuine $E_{\mathrm{T}}^{\mathrm{miss}}$, JZB can be very asymmetric towards positive values because of the correlated production of the lepton pair and the undetected particles. Events with negative values of JZB mainly arise from DY + jets processes, with a small contribution from $\mathrm{t\bar{t}}$ production. The number of $\mathrm{t\bar{t}}$ events that contribute negative JZB values is determined using the corresponding results for OF events. The $\mathrm{t\bar{t}}$ contribution is then subtracted from the number of negative JZB events in the SF sample to estimate the DY+jets background. Uncertainties arising from imperfect knowledge of the $R_{\mathrm{SF/OF}}$ factor (table 1) when subtracting the $\mathrm{t\bar{t}}$ contribution are propagated to the final DY + jets estimate. This method also accounts for processes with DY$\to \ell^{\pm}\ell^{\mp} + X$, where X denotes other particles that might be present in the final state. The systematic uncertainty in the assumption that DY + jets events equally populate positive and negative values of JZB is evaluated in simulation by comparing the $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions of events with JZB < 0 and >0. A systematic uncertainty of 20% is assigned to account for possible differences, dominated by the limited statistical precision of the MC sample.

The $E_{\mathrm{T}}^{\mathrm{miss}}$-template method relies on a data control sample consisting of events with photons and jets to evaluate the DY + jets background in a high $E_{\mathrm{T}}^{\mathrm{miss}}$ signal region. For both DY + jets and γ + jets events, large values of $E_{\mathrm{T}}^{\mathrm{miss}}$ arise from the mismeasurement of jet p_{T} values. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for DY + jets events can thus be evaluated using γ + jets events selected with similar kinematic requirements. After selection, the N_{jets}, H_{T}, and boson p_{T} distributions of the γ + jets sample are reweighted to match those of the DY + jets sample. The systematic uncertainty is determined in simulation by applying this reweighting to a γ + jets MC sample and comparing the reweighted $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum to that in a DY + jets MC sample. The uncertainty is taken as the larger of the difference between the two samples or the MC statistical uncertainty. The assigned uncertainty is 4% for $E_{\mathrm{T}}^{\mathrm{miss}} < 60\,\mathrm{GeV}$, 15% for $60 < E_{\mathrm{T}}^{\mathrm{miss}} < 200\,\mathrm{GeV}$, 34% for $200 < E_{\mathrm{T}}^{\mathrm{miss}} < 300\,\mathrm{GeV}$, and 100% for $E_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$. The uncertainty in the last two $E_{\mathrm{T}}^{\mathrm{miss}}$ bins is mostly due to the MC statistical uncertainty. Uncertainties are also assigned to account for the difference in the number of pileup interactions in the triggered DY + jets and γ + jets events (1–3%, increasing with $E_{\mathrm{T}}^{\mathrm{miss}}$) and the purity of the photon selection (1–5%, increasing with $E_{\mathrm{T}}^{\mathrm{miss}}$).

With the $E_{\mathrm{T}}^{\mathrm{miss}}$-template method, the backgrounds from WZ, ZZ, and other rare SM processes are estimated using simulation. An uncertainty of 50% is assigned to the WZ and ZZ backgrounds based on comparisons with data in orthogonal control samples selected by requiring $N_{\mathrm{jets}} \geq 2$ and either exactly three leptons (WZ control sample) or exactly four

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leptons (ZZ control sample). For the other rare backgrounds, which include events with $\mathrm{t\bar{t}Z}$, ZZZ, ZZW, and ZWW production, an uncertainty of 50% is similarly assigned.

The two methods are used to estimate the yield of SM DY events in the on-Z region, with all other selection criteria the same as for signal events. Since the two methods use uncorrelated samples to describe the high-$E_{\mathrm{T}}^{\mathrm{miss}}$ tail of SM DY + jets production, the DY background estimate in the on-Z region is taken to be the weighted average of the two estimates. The individual results are consistent with the weighted average within their uncertainties.

This estimate of the DY+jets background is extrapolated outside on-Z region using the ratio $R_{\mathrm{out/in}}$. It is measured in data as the event yield outside the on-Z region divided by the yield in the on-Z region, for the dilepton invariant mass distribution in SF events with $E_{\mathrm{T}}^{\mathrm{miss}} < 50\,\mathrm{GeV}$ and $N_{\mathrm{jets}} \geq 2$, after subtraction of the FS backgrounds. This distribution is almost entirely composed of lepton pairs from DY processes, making it suitable for the determination of $R_{\mathrm{out/in}}$. A systematic uncertainty of 25% is assigned to $R_{\mathrm{out/in}}$ to account for possible biases introduced by the different selection criteria used for the signal and control regions, and for differences in the value of $R_{\mathrm{out/in}}$ between electrons and muons.

6 Kinematic fit

The search for an edge based on the fit method is performed using a simultaneous extended unbinned maximum likelihood fit to the dilepton mass distributions of $\mathrm{e^+e^-}$, $\mu^+\mu^-$, and $\mathrm{e^\pm}\mu^\mp$ events. The likelihood model contains three components: (a) an FS background component, (b) a DY background component, and (c) a signal component.

The FS background is described using a model with three regions: a low-mass region modeling the rising distribution shaped by lepton acceptance requirements, a transition region, and a high-mass region in which the distribution falls exponentially. The probability density functions describing the three regions are:

$$\mathcal{P}_{FS}(m_{\ell\ell}) = \begin{cases} \mathcal{P}_{FS,1}(m_{\ell\ell}) = c_1\, m_{\ell\ell}^{\alpha} & \text{if} \quad 20\,\mathrm{GeV} < m_{\ell\ell} < m_{\ell\ell}^{(1)}, \\ \mathcal{P}_{FS,2}(m_{\ell\ell}) = \sum_{i=1}^{4} c_{2,i}\, m_{\ell\ell}^{i-1} & \text{if} \quad m_{\ell\ell}^{(1)} < m_{\ell\ell} < m_{\ell\ell}^{(2)}, \\ \mathcal{P}_{FS,3}(m_{\ell\ell}) = c_3\, \mathrm{e}^{-\beta m_{\ell\ell}} & \text{if} \quad m_{\ell\ell}^{(2)} < m_{\ell\ell} < 300\,\mathrm{GeV}, \end{cases} \tag{6.1}$$

where $m_{\ell\ell}^{(1)}$ and $m_{\ell\ell}^{(2)}$ define the boundaries between the regions. Because of the requirement that the function and its derivative both be continuous, the FS model is left with five independent parameters plus the normalization.

The DY background is modeled with the sum of an exponential function, which describes the low-mass rise, and a Breit-Wigner function with a mean and width set to the nominal Z boson values [31], which accounts for the on-Z lineshape. To account for the experimental resolution, the Breit-Wigner function is convolved with a double-sided

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Crystal-Ball [32] function $\mathcal{P}_{\mathrm{DSCB}}(m_{\ell\ell})$:

$$\mathcal{P}_{\mathrm{DSCB}}(m_{\ell\ell}) = \begin{cases} A_1\left(B_1 - \dfrac{m_{ll}-\mu_{\mathrm{CB}}}{\sigma_{\mathrm{CB}}}\right)^{-n_1} & \text{if} \quad \frac{m_{ll}-\mu_{\mathrm{CB}}}{\sigma_{\mathrm{CB}}} < -\alpha_1, \\ \exp\left(-\dfrac{(m_{ll}-\mu_{\mathrm{CB}})^2}{2\sigma_{\mathrm{CB}}^2}\right) & \text{if} \quad -\alpha_1 < \frac{m_{ll}-\mu_{\mathrm{CB}}}{\sigma_{\mathrm{CB}}} < \alpha_2, \\ A_2\left(B_2 + \dfrac{m_{ll}-\mu_{\mathrm{CB}}}{\sigma_{\mathrm{CB}}}\right)^{-n_2} & \text{if} \quad \frac{m_{ll}-\mu_{\mathrm{CB}}}{\sigma_{\mathrm{CB}}} > \alpha_2, \end{cases} \tag{6.2}$$

where

$$A_i = \left(\frac{n_i}{|\alpha_i|}\right)^{n_i} \exp\left(-\frac{|\alpha_i|^2}{2}\right) \quad \text{and} \quad B_i = \frac{n_i}{|\alpha_i|} - |\alpha_i|. \tag{6.3}$$

The full model for the on-Z DY lineshape is thus:

$$\mathcal{P}_{\mathrm{DY,\ on\text{-}Z}}(m_{\ell\ell}) = \int \mathcal{P}_{\mathrm{DSCB}}(m_{\ell\ell})\mathcal{P}_{\mathrm{BW}}(m_{\ell\ell} - m')\,\mathrm{d}m'. \tag{6.4}$$

The signal component is described by a triangular shape, convolved with a Gaussian distribution to account for the experimental resolution:

$$\mathcal{P}_S(m_{\ell\ell}) = \frac{1}{\sqrt{2\pi}\sigma_{\ell\ell}} \int_0^{m_{\ell\ell}^{\mathrm{edge}}} y \exp\left(-\frac{(m_{\ell\ell}-y)^2}{2\sigma_{\ell\ell}^2}\right) \mathrm{d}y. \tag{6.5}$$

As a preliminary step, a fit is performed separately for electrons and muons in the DY-enriched control region (the same control region as described for $R_{\mathrm{out/in}}$ in section 5.2) to determine the shape of backgrounds containing a Z boson. In systematic studies of the fit, the DY shape parameter that models the exponentially falling spectrum of the virtual photon is varied by ±25%. The total effect on the fitted signal yield is found to be negligible. The parameters of the DY shape are then fixed and only the normalizations of these backgrounds are free parameters in the fit. The nominal fit is applied simultaneously in the signal region to the dilepton invariant mass distributions in the $\mathrm{e^+e^-}$, $\mu^+\mu^-$, and $\mathrm{e}^{\pm}\mu^{\mp}$ samples. Therefore the model for the FS background is the same for the SF and OF events. The $R_{\mathrm{SF/OF}}$ factors, in the central and forward regions, are treated as nuisance parameters, parametrized by Gaussian distributions with a mean value and standard deviation given by the values of $R_{\mathrm{SF/OF}}$ and their uncertainties (table 1). The fit is carried out in the central and forward regions simultaneously, with the position of the edge as the only shared parameter. Therefore the signal model has three free parameters: the fitted signal yield in the central and forward regions separately, and the position of the edge.

7 Results

The dilepton mass distributions and the results of the fit in the central and forward signal regions are shown in figure 4. Table 2 presents a summary of the fit results. A signal yield of 126 ± 41 (22 ± 20) events is obtained when evaluating the signal hypothesis in the central (forward) region, with an edge located at $78.7 \pm 1.4\,\mathrm{GeV}$. The p-value, evaluated using $-2\ln Q$, is 0.009, where Q denotes the ratio of the fitted likelihood value for the

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	Central	Forward
Drell-Yan	158 ± 23	71 ± 15
OF yield	2270 ± 44	745 ± 25
$R_{\mathrm{SF/OF}}$	1.03 ± 0.03	1.02 ± 0.05
Signal events	126 ± 41	22 ± 20
$m_{\ell\ell}^{\mathrm{edge}}$	$78.7 \pm 1.4\,\mathrm{GeV}$	
Local significance	$2.4\,\sigma$	

Table 2. Results of the unbinned maximum likelihood fit for event yields in the signal regions. The quoted uncertainties are calculated using the MINOS [33] program and account for both statistical and systematic sources.

signal-plus-background hypothesis to the background-only hypothesis for the case where the edge position is fixed to the observed value. This p-value is interpreted as the one-sided tail probability of a Gaussian distribution and corresponds to an excess in the observed number of events compared to the SM background estimate of 2.4 standard deviations.

As cross-checks, we tested alternative shapes for the FS background, specifically the sum of three Gaussian distributions, and binned and smoothed histograms taken from the OF events. In all cases, the results were found to be consistent with the nominal results.

Besides the fit described in section 6, we perform a counting experiment in the mass windows $20 < m_{\ell\ell} < 70\,\mathrm{GeV}$, $81 < m_{\ell\ell} < 101\,\mathrm{GeV}$, and $m_{\ell\ell} > 120\,\mathrm{GeV}$, with no assumption about a particular signal shape, as mentioned in section 4. Figure 5 shows the invariant mass distributions for the signal candidate sample and the estimated background. For the background prediction, the OF yield in the signal mass window is multiplied by the $R_{\mathrm{SF/OF}}$ factor, and the background prediction for backgrounds containing a Z boson in the on-Z region by the $R_{\mathrm{out/in}}$ factor, as described in sections 5.1 and 5.2.

The results are summarized in table 3. The significance of the excess in the observed number of events with respect to the estimated number of SM background events is evaluated using a profile likelihood asymptotic approximation [34]. The local significance of the excess in the central low-mass region, where the largest deviation is found, is 2.6 standard deviations. Note that the signal regions were defined before the data sample was examined, and that the low-mass region ($20 < m_{\ell\ell} < 70\,\mathrm{GeV}$) does not include events between 70 GeV and the best-fit value for the location of the edge ($m_{\ell\ell} = 78.7\,\mathrm{GeV}$). The flavor of the $\ell^+\ell^-$ pair was studied in the counting experiment. Within the statistical uncertainty and accounting for differences in the reconstruction efficiencies, the electron and the muon channels are found to contribute evenly to the excess. Further studies of the excess in the low-mass region do not yield evidence for a neglected systematic term. The excess is observed predominantly in events with at least one identified bottom quark jet (b jet) and diminishes if a veto on the presence of a b jet is applied. To identify b jets, we use the CSV algorithm at the medium working point [35].

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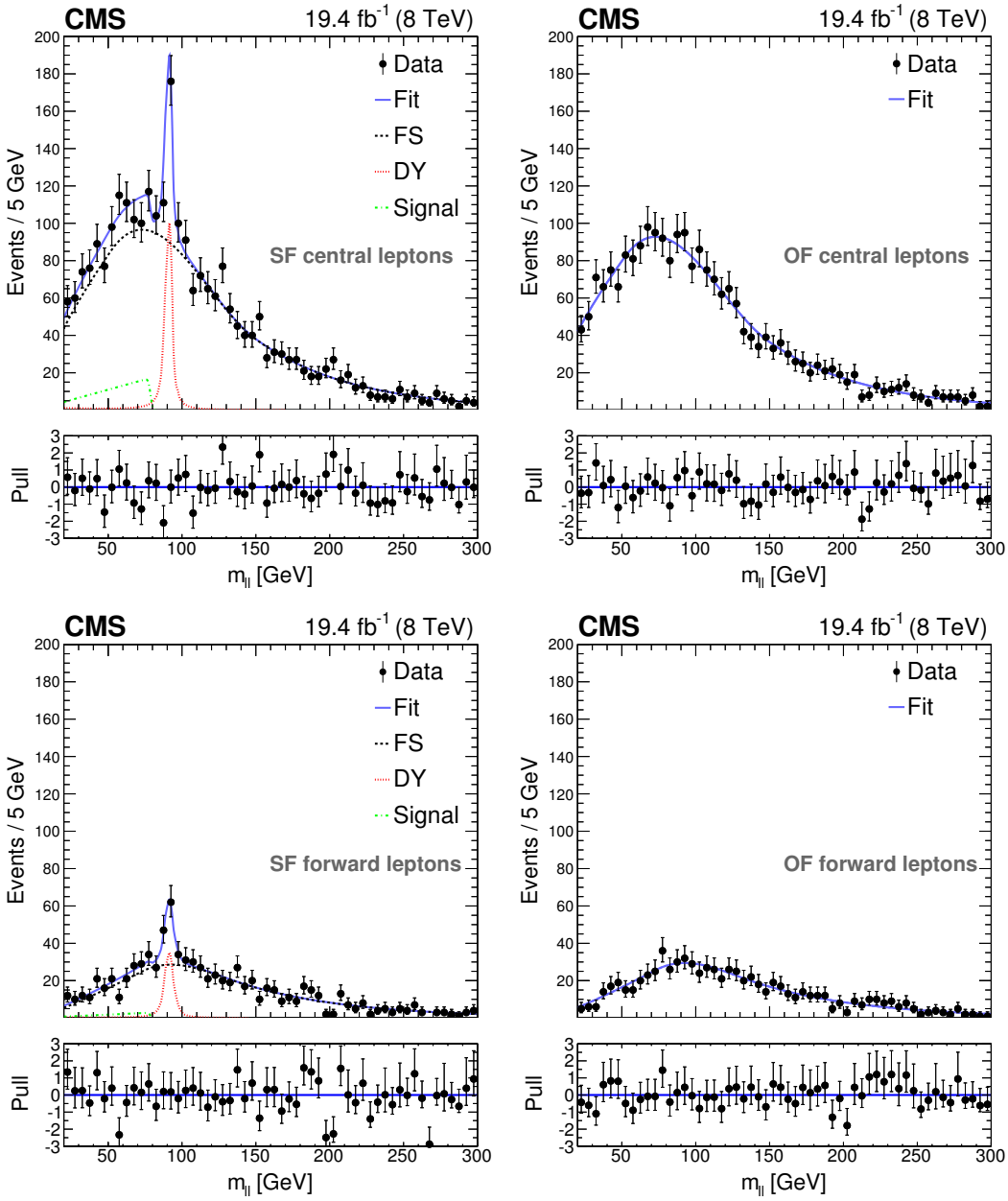

Figure 4. Fit results for the signal-plus-background hypothesis in comparison with the measured dilepton mass distributions, in the central (top) and forward (bottom) regions, projected on the same-flavor (left) and opposite-flavor (right) event samples. The combined fit shape is shown as a blue, solid line. The individual fit components are indicated by dashed lines. The flavor-symmetric (FS) background is displayed with a black dashed line. The Drell-Yan (DY) background is displayed with a red dashed line. The extracted signal component is displayed with a green dashed line. The lower plots show the pull distributions, defined as $(N_{\text{data}} - N_{\text{fit}})/\sigma_{\text{data}}$.

Figure 6 presents a comparison of the data and the SM simulation in the central region. Expectations for the fixed-edge bottom-squark pair-production scenario of figure 1 (left), with mass combinations $(m_{\tilde{b}}, m_{\tilde{\chi}_2^0}) = (225, 150)$ GeV, $(350, 275)$ GeV, and $(400, 150)$ GeV

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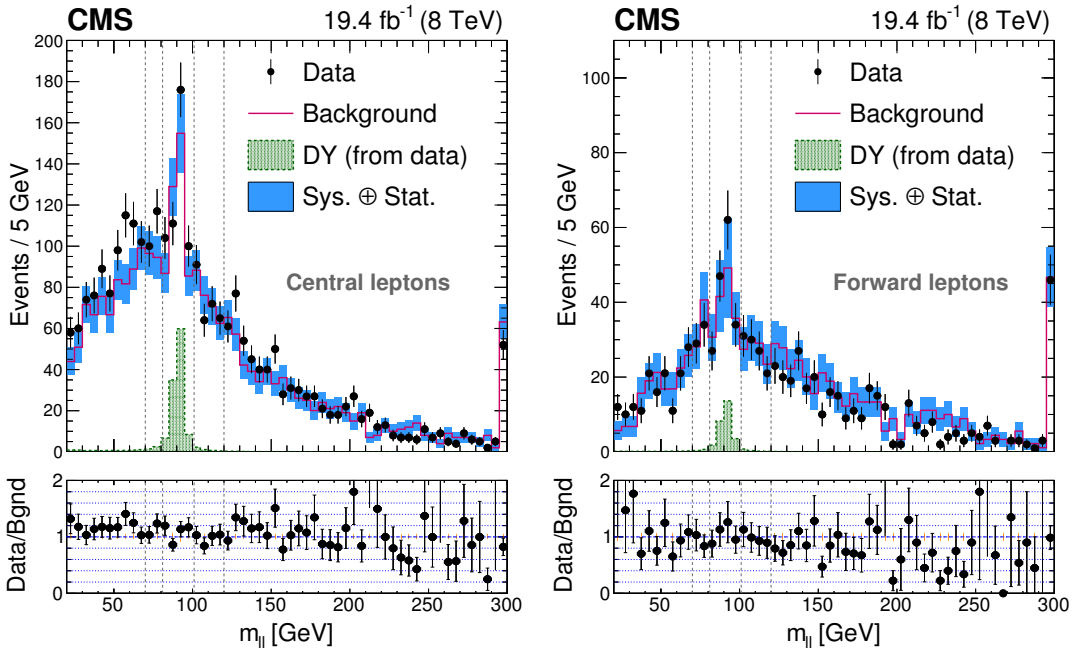

Figure 5. Comparison between the observed and estimated SM background dilepton mass distributions in the (left) central and (right) forward regions, where the SM backgrounds are evaluated from control samples (see text) rather than from a fit. The rightmost bins contain the overflow. The vertical dashed lines denote the boundaries of the low-mass, on-Z, and high-mass regions. The lower plots show the ratio of the data to the predicted background. The error bars for both the main and lower plots include both statistical and systematic uncertainties.

	Low-mass		On-Z		High-mass	
	Central	Forward	Central	Forward	Central	Forward
Observed	860	163	487	170	818	368
Flavor-symmetric	$722 \pm 27 \pm 29$	$155 \pm 13 \pm 10$	$355 \pm 19 \pm 14$	$131 \pm 12 \pm 8$	$768 \pm 28 \pm 31$	$430 \pm 22 \pm 27$
Drell-Yan	8.2 ± 2.6	2.5 ± 1.0	116 ± 21	42 ± 9	2.5 ± 0.8	1.1 ± 0.4
Total estimated	730 ± 40	158 ± 16	471 ± 32	173 ± 17	771 ± 42	431 ± 35
Observed−estimated	130^{+48}_{-49}	5^{+20}_{-20}	16^{+37}_{-38}	-3^{+20}_{-21}	47^{+49}_{-50}	-62^{+37}_{-39}
Significance	$2.6\,\sigma$	$0.3\,\sigma$	$0.4\,\sigma$	$<0.1\,\sigma$	$0.9\,\sigma$	$<0.1\,\sigma$

Table 3. Results of the edge-search counting experiment for event yields in the signal regions. The statistical and systematic uncertainties are added in quadrature, except for the flavor-symmetric backgrounds. Low-mass refers to $20 < m_{\ell\ell} < 70\,\text{GeV}$, on-Z to $81 < m_{\ell\ell} < 101\,\text{GeV}$, and high-mass to $m_{\ell\ell} > 120\,\text{GeV}$.

for the bottom squark and $\widetilde{\chi}_2^0$, are also shown. The first scenario presents the illustration of a model that can easily be excluded, while the other two present examples of models that are consistent with our data.

The results from the dedicated on-Z counting experiment mentioned in section 4 are presented in tables 4 and 5 for events with $N_{\text{jets}} \geq 2$ and $N_{\text{jets}} \geq 3$, respectively. The corresponding $E_{\text{T}}^{\text{miss}}$ distributions are shown in figure 7. The data are seen to agree with the SM predictions across the full $E_{\text{T}}^{\text{miss}}$ spectrum.

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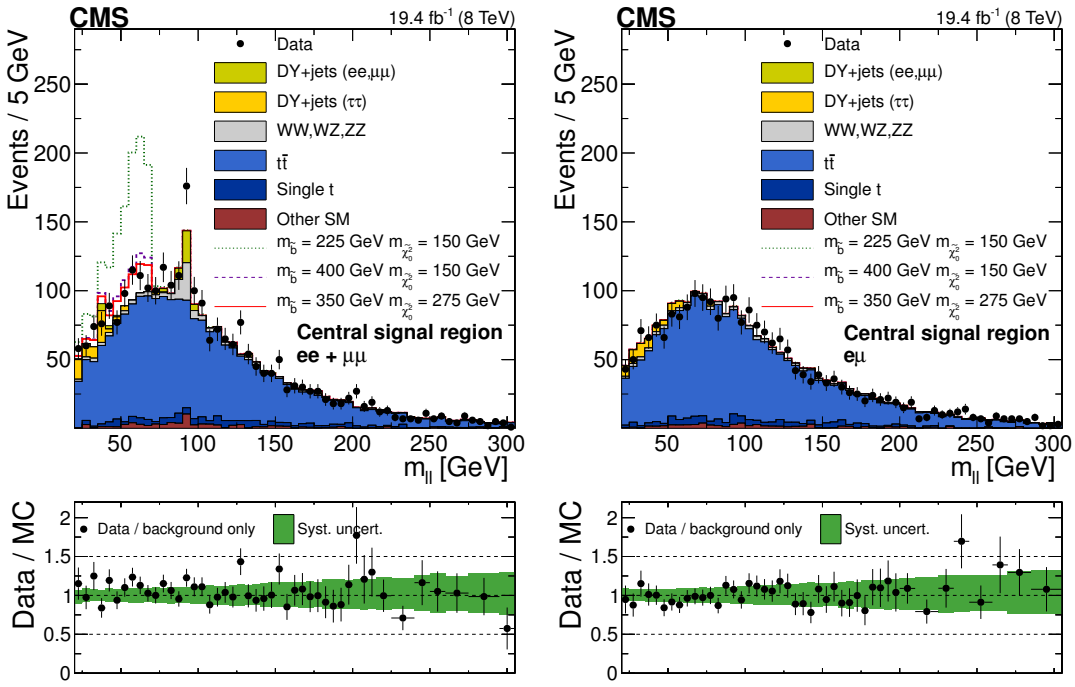

Figure 6. Data compared with SM simulation for the SF (left) and OF (right) event samples in the central region. Example signal scenarios based on the pair production of bottom squarks are shown (see text). In the ratio panel below each plot, the error bars on the points show the statistical uncertainties of the data and MC samples, while the shaded band indicates the MC systematic uncertainty.

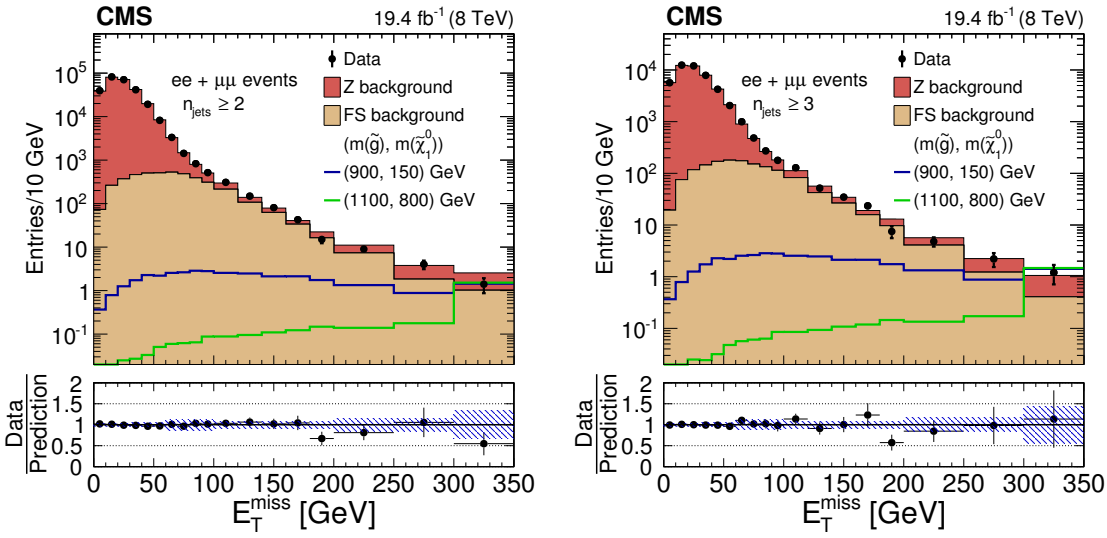

Figure 7. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions for the on-Z signal regions with (left) $\geq$2 jets and (right) $\geq$3 jets. The uncertainty band shown for the ratio includes both statistical and systematic uncertainties. Additionally, $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions are drawn for two choices of masses in the GMSB scenario. The rightmost bins contain the overflow.

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$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	100–200	200–300	>300
DY background	336 ± 89	28.6 ± 8.6	7.7 ± 3.6
FS background	868 ± 57	45.9 ± 7.3	5.1 ± 2.3
Total background	1204 ± 106	74.5 ± 11.3	12.8 ± 4.3
Data	1187	65	7
GMSB signal yields			
$m_{\tilde{\mathrm{g}}} = 900$, $m_{\tilde{\chi}_1^0} = 150$	22.1 ± 0.4	11.1 ± 0.3	7.2 ± 0.2
$m_{\tilde{\mathrm{g}}} = 1100$, $m_{\tilde{\chi}_1^0} = 800$	1.1 ± 0.04	1.6 ± 0.05	7.6 ± 0.1

Table 4. Event yields in the signal region for the dedicated on-Z counting experiment with $N_{\mathrm{jets}} \geq 2$. Both statistical and systematic uncertainties are included for the background estimates. Signal yields are also shown for two choices of masses (in GeV) in the GMSB scenario (statistical uncertainties only).

$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	100–200	200–300	>300
DY background	124 ± 33	12.7 ± 3.8	3.2 ± 1.8
FS background	354 ± 28	26.5 ± 5.4	2.0 ± 1.4
Total background	478 ± 43	39.2 ± 6.6	5.3 ± 2.3
Data	490	35	6
GMSB signal yields			
$m_{\tilde{\mathrm{g}}} = 900$, $m_{\tilde{\chi}_1^0} = 150$	22.0 ± 0.4	11.0 ± 0.3	7.1 ± 0.2
$m_{\tilde{\mathrm{g}}} = 1100$, $m_{\tilde{\chi}_1^0} = 800$	1.1 ± 0.04	1.5 ± 0.05	7.4 ± 0.1

Table 5. Event yields in the signal region for the dedicated on-Z counting experiment with $N_{\mathrm{jets}} \geq 3$. Both statistical and systematic uncertainties are included for the background estimates. Signal yields are also shown for two choices of masses (in GeV) in the GMSB (statistical uncertainties only).

8 Uncertainties in signal modeling

Systematic uncertainties associated with the estimation of the SM background are discussed in section 5. This section describes uncertainties in the signal modeling. The impact of the uncertainties on the considered signal models is shown in table 6.

The uncertainty related to the measurement of the integrated luminosity is 2.6% [36]. The uncertainty related to the parton distribution functions (PDF) is evaluated using the PDF4LHC recommendations [37–41] and amounts to 0–6% in the signal acceptance. Uncertainties in the modeling of the reconstruction, identification, and isolation efficiencies amount to 1% per lepton. The uncertainty of the corrections to account for lepton reconstruction differences between the fast and full simulations is 1% per lepton. The uncertainty in the trigger efficiencies is about 5%. Uncertainties in the muon momentum scale are negligible, whereas for electrons the uncertainty in the energy scale is 0.6% (1.5%) in the barrel (endcap) region, leading to a 0–5% uncertainty in the signal yield. The uncertainty

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Uncertainty source	Impact on signal yield [%]
Luminosity	2.6
PDFs on acceptance	0–6
Lepton identification/isolation	2
Fast simulation lepton identification/isolation	2
Dilepton trigger	5
Lepton energy scale	0–5
$E_{\mathrm{T}}^{\mathrm{miss}}$	0–8
Jet energy scale/resolution	0–8
ISR modeling	0–14
Additional interactions	1

Table 6. Summary of systematic uncertainties for the signal efficiency.

in the jet energy scale [42] varies between 0–8%. The uncertainty in the jet energy scale is propagated to evaluate the uncertainty associated with the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution, which is found to be 0–8%. The uncertainty associated with the modeling of initial-state radiation (ISR) [43] is 0–14%. The uncertainty in the correction to account for pileup in the simulation is evaluated by shifting the inelastic cross section by ±5%. The impact on the signal yield is found to be about 1%.

9 Interpretation

Based on the results of the counting experiments, exclusion limits are determined. The kinematic fit is not used for this purpose because it assumes a specific shape for the dilepton mass spectrum of signal events and so is more model dependent. The limits are calculated at 95% confidence level (CL) using the $\mathrm{CL_s}$ criterion with the LHC-style test statistic [34, 44, 45], taking into account the statistical and systematic uncertainties in the signal yields and the background predictions discussed in sections 8 and 5, respectively. The different systematic uncertainties are considered to be uncorrelated with each other, but fully correlated among the different signal regions. The systematic uncertainties are treated as nuisance parameters and are parametrized with log-normal distributions.

For the fixed- and slepton-edge scenarios all six signal regions (low-mass, on-Z, and high-mass, for the central and forward lepton regions) are combined. The resulting exclusion limits for these scenarios are shown in figure 8. The production of bottom squarks is considered, as the excess observed in data consists predominantly of events with at least one b jet. In the fixed-edge scenario, the mass difference between the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$ neutralinos is fixed to 70 GeV, resulting in an edge in the $m_{\ell\ell}$ spectrum at this value. This choice for the edge position is motivated by the observed excess in the low-mass region of the counting experiment. Bottom-squark masses between 200 and 350 GeV are probed,

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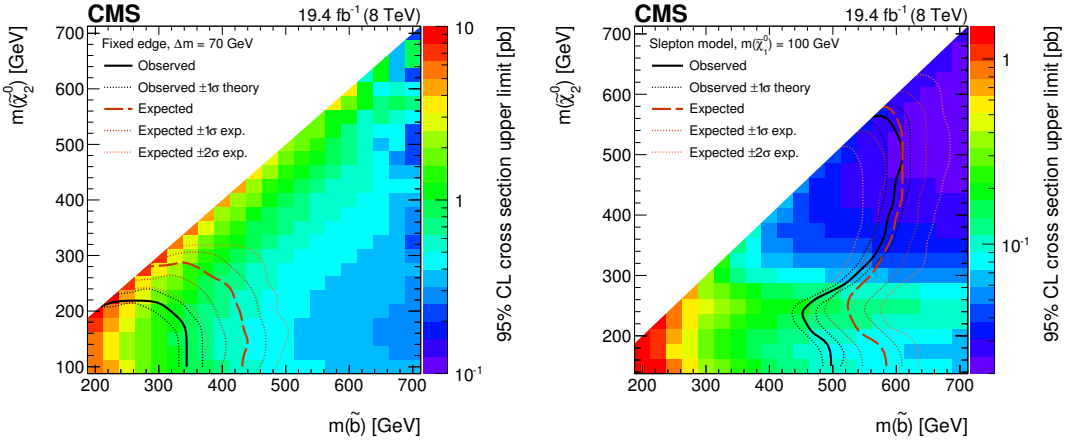

Figure 8. Exclusion limits at 95% CL for the fixed- (left) and slepton-edge (right) scenarios in the $m_{\tilde{b}}$-$m_{\tilde{\chi}^0_2}$ plane. The color indicates the excluded cross section for each considered point in parameter space. The intersections of the theoretical cross section with the expected and observed limits are indicated by the solid and hatched lines. The 1 standard deviation (σ) experimental and theoretical uncertainty contours are shown as dotted lines.

depending on the value of the $\tilde{\chi}^0_2$ mass. In the slepton-edge scenario, the $\tilde{\chi}^0_1$ mass is set to 100 GeV, leaving the position of the edge as a free parameter that approximately corresponds to the mass difference between the $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$. The branching fraction into dilepton final states is larger than in the fixed-edge scenario, and bottom-squark masses between 450 and 600 GeV are probed, again depending on the value of the $\tilde{\chi}^0_2$ mass. The loss of sensitivity seen in figure 8 (right) for $\tilde{\chi}^0_2$ masses around 250 GeV occurs because the peak of the triangular signal shape lies within, or close to, the gaps in acceptance between the low-mass and on-Z, or the on-Z and high-mass signal regions.

The results from the dedicated on-Z signal regions are used to place limits on the GMSB scenario. In this scenario, there are two free parameters: the masses of the gluino ($m_{\tilde{g}}$) and the $\tilde{\chi}^0_1$ ($m_{\tilde{\chi}^0_1}$). As signal events typically have large jet multiplicities, the exclusive bins requiring $N_{\text{jets}} \geq 3$ and $E_{\text{T}}^{\text{miss}}$ in the ranges $100 < E_{\text{T}}^{\text{miss}} < 200$ GeV, $200 < E_{\text{T}}^{\text{miss}} < 300$ GeV, and $E_{\text{T}}^{\text{miss}} > 300$ GeV are used. The results are shown in figure 9 in the plane of $m_{\tilde{\chi}^0_1}$ versus $m_{\tilde{g}}$. These results probe gluino masses up to about 900–1100 GeV depending on the $\tilde{\chi}^0_1$ mass. The limit is least stringent when $m_{\tilde{\chi}^0_1}$ is close to the Z boson mass.

10 Summary

We have presented a search for physics beyond the standard model in the opposite-sign dilepton final state using a data sample of pp collisions collected at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.4 fb^{-1} , recorded with the CMS detector in 2012. Searches are performed for signals that either produce a kinematic edge, or a peak at the Z boson mass, in the dilepton invariant mass distribution. For regions dominated by flavor-symmetric backgrounds, i.e., backgrounds that produce opposite-flavor events ($\text{e}^+\mu^-, \text{e}^-\mu^+$) as often as same-flavor events ($\text{e}^+\text{e}^-, \mu^+\mu^-$), we achieve a precision of about 5% (10%) for the estimated number of standard model background events in the

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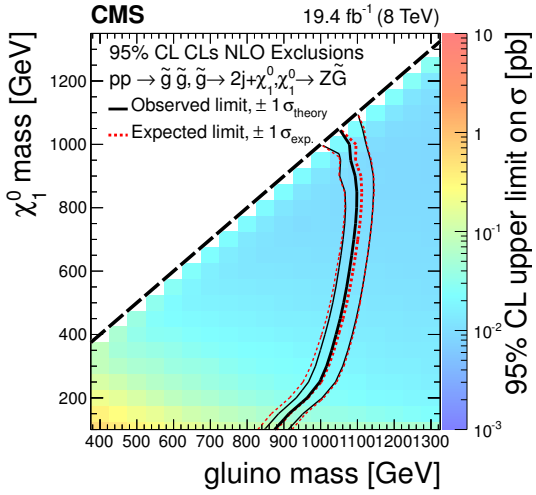

Figure 9. Exclusion limits at 95% CL for the GMSB scenario in the $m_{\tilde{g}}$-$m_{\tilde{\chi}_1^0}$ plane. The color indicates the excluded cross section for each considered point in parameter space. The intersections of the theoretical cross section with the expected and observed limits are indicated by the solid and hatched lines. The 1 standard deviation (σ) experimental and theoretical uncertainty contours are shown as dotted lines.

central (forward) lepton rapidity regions. We do not observe evidence for a statistically significant signal. The maximum deviation from the null hypothesis is at the level of 2.6 standard deviations and is observed in the dilepton mass window $20 < m_{\ell\ell} < 70\,\text{GeV}$.

We interpret the results of the search for a kinematic edge in the context of simplified models consisting of bottom-squark pair production, with each bottom-squark $\tilde{\text{b}}$ decaying to a bottom quark and the $\tilde{\chi}_2^0$ neutralino. Exclusion limits are set in the $m_{\tilde{\text{b}}}$-$m_{\tilde{\chi}_2^0}$ mass plane for two scenarios. In the fixed-edge scenario, the mass difference between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ particles is fixed to 70 GeV. Bottom-squark masses between 200 and 350 GeV are excluded at 95% confidence level in this scenario. In the slepton-edge scenario, the $\tilde{\chi}_2^0$ decays to an on- or off-shell Z boson and the $\tilde{\chi}_1^0$ lightest supersymmetric particle or to a slepton and a lepton, with a 50% probability for each possibility. Bottom-squark masses between 450 and 600 GeV are excluded at 95% confidence level in this second scenario. In both scenarios, the sensitivity depends on the mass of the $\tilde{\chi}_2^0$. Finally, a dedicated search for events containing an on-shell Z boson is interpreted in a model of gauge-mediated supersymmetry breaking, in which the Z bosons are produced in decay chains initiated through gluino pair production. Gluino masses between 900 and 1100 GeV are excluded at 95% confidence level, depending on the mass of the lightest neutralino $\tilde{\chi}_1^0$.

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