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Search for physics beyond the standard model in events with a Z boson, jets, and missing transverse energy in pp collisions at $\sqrt{s} = 7$ TeV ☆

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ABSTRACT

A search is presented for physics beyond the standard model (BSM) in events with a Z boson, jets, and missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). This signature is motivated by BSM physics scenarios, including supersymmetry. The study is performed using a sample of proton–proton collision data collected at $\sqrt{s} = 7$ TeV with the CMS experiment at the LHC, corresponding to an integrated luminosity of 4.98 fb^{-1}. The contributions from the dominant standard model backgrounds are estimated from data using two complementary strategies, the jet-Z balance technique and a method based on modeling $E_{\mathrm{T}}^{\mathrm{miss}}$ with data control samples. In the absence of evidence for BSM physics, we set limits on the non-standard-model contributions to event yields in the signal regions and interpret the results in the context of simplified model spectra. Additional information is provided to facilitate tests of other BSM physics models.

1. Introduction

This Letter describes a search for physics beyond the standard model (BSM) in proton–proton collisions at a center-of-mass energy of 7 TeV. Results are reported from a data sample collected with the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) at CERN corresponding to an integrated luminosity of 4.98 fb^{-1}. This search is part of a broad program of inclusive, signature-based searches for BSM physics at CMS, characterized by the number and type of objects in the final state. Since it is not known a priori how the BSM physics will be manifest, we perform searches in events containing jets and missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) [1–3], single isolated leptons [4], pairs of opposite-sign [5] and same-sign [6] isolated leptons, photons [7,8], etc. Here we search for evidence of BSM physics in final states containing a Z boson that decays to a pair of oppositely-charged isolated electrons or muons. Searches for BSM physics in events containing oppositely-charged leptons have also been performed by the ATLAS Collaboration [9–11].

This strategy offers two advantages with respect to other searches. First, the requirement of a leptonically-decaying Z boson significantly suppresses large standard model (SM) backgrounds including QCD multijet production, events containing Z bosons decaying to a pair of invisible neutrinos, and events containing leptonically-decaying W bosons, and hence provides a clean environment in which to search for BSM physics. Second, final states with Z bosons are predicted in many models of BSM physics, such as supersymmetry (SUSY) [12–16]. For example, the production of a Z boson in the decay $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0$ Z, where $\widetilde{\chi}_1^0$ ($\widetilde{\chi}_2^0$) is the lightest (second lightest) neutralino, is a direct consequence of the gauge structure of SUSY, and can become a favored channel in regions of the SUSY parameter space where the neutralinos have a large Higgsino or neutral Wino component [17–19]. Our search is also motivated by the existence of cosmological cold dark matter [20], which could consist of weakly-interacting massive particles [21] such as the lightest SUSY neutralino in R-parity conserving SUSY models [22]. If produced in pp collisions, these particles would escape detection and yield events with large $E_{\mathrm{T}}^{\mathrm{miss}}$. Finally, we search for BSM physics in events containing hadronic jets. This is motivated by the fact that new, heavy, strongly-interacting particles predicted by many BSM scenarios may be produced with a large cross section and hence be observable in early LHC data, and such particles tend to decay to hadronic jets. These considerations lead us to our target signature consisting of a leptonically-decaying Z boson produced in association with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$.

After selecting events with jets and a $\mathrm{Z} \to \ell^+\ell^-$ ($\ell = \mathrm{e}, \mu$) candidate, the dominant background consists of SM Z production accompanied by jets from initial-state radiation (Z + jets). The $E_{\mathrm{T}}^{\mathrm{miss}}$ in Z + jets events arises primarily when jet energies are mismeasured. The Z + jets cross section is several orders of magnitude larger than our signal, and the artificial $E_{\mathrm{T}}^{\mathrm{miss}}$ is not necessarily well reproduced in simulation. Therefore, the critical

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prerequisite to a discovery of BSM physics in the Z + jets + E_T^{miss} final state is to establish that a potential excess is not due to SM Z + jets production accompanied by artificial E_T^{miss} from jet mismeasurements. In this Letter, we pursue two complementary strategies, denoted the Jet-Z Balance (JZB) and E_T^{miss} template (MET) methods, which rely on different techniques to suppress the SM Z + jets contribution and estimate the remaining background. The two methods employ different search regions, as well as different requirements on the jet multiplicity and Z boson identification. After suppressing the Z + jets contribution, the most significant remaining SM background consists of events with a pair of top quarks that both decay leptonically (dilepton $t\bar{t}$). We exploit the fact that in dilepton $t\bar{t}$ events the two lepton flavors are uncorrelated, which allows us to use a control sample of eμ events, as well as events in the sideband of the dilepton mass distribution, to estimate this background.

The JZB method is sensitive to BSM models where the Z boson and dark matter candidate are the decay products of a heavier particle. In such models, the Z boson and E_T^{miss} directions are correlated, with the strength of this correlation dependent on the BSM mass spectrum. The Z + jets background contribution to the JZB signal region is estimated from a Z+jets sample, by exploiting the lack of correlation between the direction of the Z boson and E_T^{miss} in these events for large jet multiplicity. With this method, the significance of an excess is reduced in models where the E_T^{miss} and Z directions are not correlated.

The MET method relies on two data control samples, one consisting of events with photons accompanied by jets from initial-state radiation (γ + jets) and one consisting of QCD multijet events, to evaluate the Z+jets background in a high E_T^{miss} signal region. In contrast to the JZB method, the MET method does not presume a particular mechanism for the production of the Z boson and E_T^{miss}. The significance of an excess is reduced in models that also lead to an excess in both the jets + E_T^{miss} and γ + jets + E_T^{miss} final states.

The Letter is organized as follows: we first describe the detector (Section 2), and the data and simulated samples and event selection that are common to both strategies (Section 3). The two methods are then described and the results presented (Sections 4 and 5). Systematic uncertainties on the signal acceptance and efficiency are presented in Section 6. Next, the two sets of results are interpreted in the context of simplified model spectra (SMS) [23–25], which represent decay chains of new particles that may occur in a wide variety of BSM physics scenarios, including SUSY (Section 7). We provide additional information to allow our results to be applied to arbitrary BSM physics scenarios (Section 8). The results are summarized in Section 9.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The CMS coordinate system is defined with the origin at the center of the detector and the z axis along the direction of the counterclockwise beam. The transverse plane is perpendicular to the beam axis, with ϕ the azimuthal angle, θ the polar angle, and $\eta = -\ln[\tan(\theta/2)]$ the pseudorapidity. Muons are measured in the range $|\eta| < 2.4$. The inner tracker measures charged particles within the range $|\eta| < 2.5$. A more detailed description of the CMS detector can be found elsewhere [26].

3. Samples and event selection

Events are required to satisfy at least one of a set of ee, eμ or $\mu\mu$ double-lepton triggers, with lepton transverse momentum (p_T) thresholds of 17 GeV for one lepton and 8 GeV for the other. Events with two oppositely-charged leptons (e^+e^-, $e^\pm\mu^\mp$, or $\mu^+\mu^-$) are selected. Details of the lepton reconstruction and identification can be found in Ref. [27] for electrons and in Ref. [28] for muons. Both leptons must have $p_T > 20$ GeV, in the efficiency plateau of the triggers. Electrons (muons) are restricted to $|\eta| < 2.5$ (2.4). For the candidate sample, only e^+e^- and $\mu^+\mu^-$ events are used, and the dilepton system is required to have an invariant mass consistent with the mass of the Z boson (m_Z). The eμ events are used as a data control sample to estimate the $t\bar{t}$ background.

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 lepton isolation [29] is defined using the scalar sum of both the transverse momentum depositions in the calorimeters and the transverse momenta of tracks in a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around each lepton, excluding the lepton itself. Requiring the ratio of this sum to the lepton p_T to be smaller than 15% rejects the large background arising from QCD production of jets.

We select jets [30] with $p_T > 30$ GeV and $|\eta| < 3.0$, separated by $\Delta R > 0.4$ from leptons passing the analysis selection. We use the particle flow (PF) method [31] to reconstruct charged and neutral hadrons, muons, electrons, and photons. The PF objects are clustered to form jets using the anti-k_T clustering algorithm [32] with a distance parameter of 0.5, as implemented in the FASTJET package [33,34]. We apply p_T- and η-dependent corrections to account for residual effects of non-uniform detector response. The contribution to the jet energy from pile-up is estimated on an event-by-event basis using the jet area method described in Ref. [35], and is subtracted from the overall jet p_T. The missing transverse momentum E_T^{miss} is defined as the magnitude of the vector sum of the transverse momenta of all PF objects. The $\vec{E}_T^{miss}$ vector is the negative of that same vector sum.

The sample passing the above preselection requirements is dominated by SM Z + jets events, which must be suppressed in order to achieve sensitivity to BSM physics. As discussed in the introduction, we pursue two complementary approaches to evaluate the Z + jets background. Samples of Z + jets, $t\bar{t}$, WW, WZ, and ZZ Monte Carlo (MC) simulated events generated with MADGRAPH 5.1.1.0 [36] are used to guide the design of these methods, but the dominant backgrounds are estimated with techniques based on data control samples. Events produced by MADGRAPH are passed to PYTHIA 6.4.22 [37] for the generation of parton showers. Additional MC samples of Z + jets, γ + jets, and QCD multijet events generated with PYTHIA 6.4.22 are used to validate the E_T^{miss} template method of Section 5. We also present the expected event yields for two benchmark scenarios of the constrained minimal supersymmetric extension of the standard model (CMSSM) [38], denoted LM4 and LM8 [39], which are generated with the same version of PYTHIA. The CMSSM is described with five parameters: the universal scalar and gaugino masses m_0 and $m_{1/2}$, the universal soft SUSY-breaking parameter A_0, the ratio of vacuum expectation values of the two Higgs doublets $\tan\beta$, and the sign of the Higgs mixing parameter μ. The LM4 (LM8) parameter sets are $m_0 =$ 210 (500) GeV, $m_{1/2} = 285$ (300) GeV, $\tan\beta = 10$, sign(μ) = +, and $A_0 = 0$ (−300) GeV. The LM4 scenario is excluded in Ref. [3]; this Letter is the first to exclude LM8. In these two scenarios heavy neutralinos predominantly decay to a Z boson and a lighter