Search for Physics Beyond the Standard Model in Events with High-Momentum Higgs Bosons and Missing Transverse Momentum in Proton-Proton Collisions at 13 TeV

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A search for physics beyond the standard model in events with one or more high-momentum Higgs bosons, H, decaying to pairs of b quarks in association with missing transverse momentum is presented. The data, corresponding to an integrated luminosity of 35.9 fb^{-1}, were collected with the CMS detector at the LHC in proton-proton collisions at the center-of-mass energy $\sqrt{s} = 13$ TeV. The analysis utilizes a new b quark tagging technique based on jet substructure to identify jets from $H \to b\bar{b}$. Events are categorized by the multiplicity of H-tagged jets, jet mass, and the missing transverse momentum. No significant deviation from standard model expectations is observed. In the context of supersymmetry (SUSY), limits on the cross sections of pair-produced gluinos are set, assuming that gluinos decay to quark pairs, H (or Z), and the lightest SUSY particle, LSP, through an intermediate next-to-lightest SUSY particle, NLSP. With large mass splitting between the NLSP and LSP, and 100% NLSP branching fraction to H, the lower limit on the gluino mass is found to be 2010 GeV.

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Primary motivations for building the CERN LHC [1] were to determine the source of electroweak symmetry breaking and to search for physics beyond the standard model (SM). In 2012, the first goal was achieved with the discovery of the Higgs boson H by the ATLAS and CMS Collaborations [2–4]. In this Letter, we exploit that discovery in a search for events containing high-momentum Higgs bosons in conjunction with hadronic jets and missing momentum transverse to the beam, $\vec{p}_T^{\,\mathrm{miss}}$. Large $p_T^{\mathrm{miss}} \equiv |\vec{p}_T^{\,\mathrm{miss}}|$ can arise from the production of energetic weakly interacting particles that escape detection. A new particle of this type would be a candidate for weakly interacting massive particle (WIMP) dark matter [5–7]. High-momentum Higgs bosons appear rarely in SM processes, and would provide a unique signature of new physics. Such a signature can arise in a variety of models for physics beyond the SM, including extended electroweak sectors [8,9], extended Higgs sectors [10], and supersymmetry (SUSY) [11,12].

The search presented here is based on 35.9 fb^{-1} of proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV collected in 2016 by the CMS experiment. High-momentum Higgs bosons are reconstructed in the leading $b\bar{b}$ decay channel in a regime in which the two jets from the hadronization of the b quarks overlap with each other. They are identified with a recently developed algorithm [13] that employs substructure techniques to large-radius jets. In previous studies CMS [14,15] and ATLAS [16] have searched for signatures with Higgs bosons, jets, and p_T^{miss}. This Letter presents the first search for pairs of Lorentz-boosted Higgs bosons produced in association with jets and p_T^{miss}.

Supersymmetry [17–24] is a widely studied extension of the SM that posits for each SM particle a new particle, called a superpartner, with a spin that differs from that of its SM counterpart by a half unit. Supersymmetry is attractive as a potential solution to the gauge hierarchy problem [25] that can help to explain the low mass of the Higgs boson without fine tuning of the theory [26–28]. The superpartners of quarks and gluons are squarks $\tilde{q}$ and gluinos $\tilde{g}$, respectively, while neutralinos $\tilde{\chi}^0$ and charginos $\tilde{\chi}^{\pm}$ are mixtures of the superpartners of the Higgs and electroweak gauge bosons. In a process such as the simplified model (SMS [29–31]) referred to as T5HH and illustrated in Fig. 1, gluinos are pair produced and decay into a quark, antiquark, and $\tilde{\chi}_2^0$, where $\tilde{\chi}_2^0$ is the second-lightest neutralino. The $\tilde{\chi}_2^0$ decays into a Higgs boson and the lightest neutralino, $\tilde{\chi}_1^0$, which we take to be the lightest SUSY particle (LSP) and represents the dark matter candidate. The results of this search are interpreted in the context of this model and the alternate T5HZ, in which the $\tilde{\chi}_2^0$ branching fractions to $H\tilde{\chi}_1^0$ and $Z\tilde{\chi}_1^0$ are both 50%, with primary focus on the T5HH model. We further assume a small $\tilde{g}$–$\tilde{\chi}_2^0$ mass splitting and a light $\tilde{\chi}_1^0$, leading to events with energetic Higgs bosons, large p_T^{miss}, and soft quark jets.

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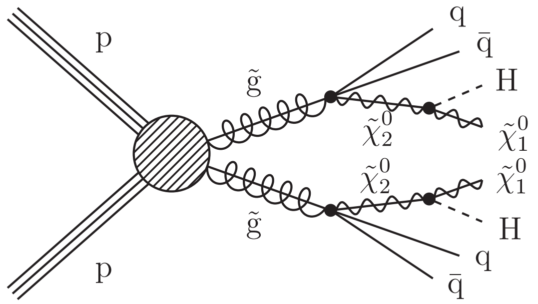

FIG. 1. Diagram for production of Higgs bosons via gluino pair production. We also consider channels in which a Z boson is substituted for H in one of the gluino decays.

A detailed description of the CMS detector, along with a definition of the coordinate system and pertinent kinematical variables, is given in Ref. [32]. Briefly, a cylindrical superconducting solenoid with an inner diameter of 6 m provides a 3.8 T axial magnetic field. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). The tracking detectors cover the pseudorapidity range $|\eta| < 2.5$. The ECAL and HCAL, each composed of a barrel and two endcap sections, cover $|\eta| < 3.0$. Forward calorimeters extend the coverage to $|\eta| < 5.0$. Muons are measured within $|\eta| < 2.4$ by gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, permitting accurate measurement of p_T^{miss}.

Individual particles are reconstructed with the CMS particle-flow (PF) algorithm [33], which identifies them as photons, charged hadrons, neutral hadrons, electrons, or muons. Jets are defined by forming clusters of PF particles using the anti-k_T jet algorithm [34,35] with a distance parameter of 0.8 (AK8) and 0.4 (AK4). The jet energies are corrected for the nonlinear response of the detector [36] and to account for the expected contributions of neutral particles from pp interactions other than the one of interest (pileup) [37]. The quantity $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is reconstructed as the negative of the vector transverse momentum sum over all PF particles, while H_T is the sum over AK4 jets of the magnitudes of their transverse momenta, p_T. The jets for this summation are required to be within the tracker volume and to have a minimum p_T of 30 GeV to suppress contributions from pileup.

The lepton content of events is used to characterize signal and control samples. We impose isolation requirements on electron and muon candidates to suppress those arising from jets erroneously identified as leptons, as well as genuine leptons from hadron decays. The isolation criterion is based on the variable I, defined as the activity within a cone of radius $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ around the lepton direction divided by the lepton p_T. Here activity is defined as the scalar p_T sum of charged hadron, neutral hadron, and photon PF particles, corrected for the contributions from pileup. The radius of the cone is 0.2 for lepton $p_T < 50$ GeV, 10 GeV$/p_T$ for $50 \leq p_T \leq 200$ GeV, and 0.05 for $p_T > 200$ GeV. The isolation requirement is $I < 0.1(0.2)$ for electrons (muons).

To recover electrons or muons that fail tight identification requirements, and τ leptons via their one-prong hadronic decays, we also make use of isolated charged tracks. For these candidates we require that the scalar p_T sum of all other charged-particle tracks within a cone of radius 0.3 around the candidate track direction, divided by the track p_T, be less than 0.2 if the track is identified as a PF electron or muon and less than 0.1 otherwise. Isolated tracks are required to satisfy $|\eta| < 2.4$.

Candidates for $H \to b\bar{b}$ jets are identified with a heavy-flavor tagging algorithm designed to identify a pair of b quarks clustered into a single AK8 jet [13]. The algorithm resolves the decay chains of the two b hadrons and associates secondary vertices along the decay directions, and then computes the likelihood that a jet contains two b hadrons. The jet pruning algorithm described in Ref. [38] is used to improve the jet mass resolution for $H \to b\bar{b}$ candidates.

The selection of events for analysis begins with the trigger described in Ref. [39]. For this analysis, signal event candidates were recorded by requiring p_T^{miss} and the magnitude H_T^{miss} of the vector p_T sum of jets, both computed at the trigger level, to exceed thresholds that varied between 100 and 120 GeV depending on the LHC instantaneous luminosity. The efficiency of this trigger, which exceeds 98% for events satisfying the selection criteria described below, is measured in data and is taken into account in the analysis. Additional triggers, requiring the presence of charged leptons, photons, or minimum values of H_T, are used to select samples, described below, employed in the evaluation of backgrounds.

Candidates for signal events are characterized by jets of large angular radius containing a pair of b quarks from the decays of Lorentz-boosted Higgs bosons, accompanied by p_T^{miss} from escaping LSPs. They are required to have no isolated leptons, but we impose no requirements on the number of additional jets in the event. The specific requirements that define the search sample are $p_T^{\text{miss}} > 300$ GeV, $H_T > 600$ GeV, and at least two AK8 jets with $p_{\mathrm{T}} > 300$ GeV and mass m_J between 50 and 250 GeV. We exclude events with either a muon or an electron with $p_{\mathrm{T}} > 10$ GeV, or an isolated track with $m_T < 100$ GeV and $p_{\mathrm{T}} > 10(5)$ GeV for hadronic (leptonic) tracks. Here m_T is the transverse mass [40] evaluated from the $\vec{p}_T^{\text{miss}}$ and isolated-track p_T vectors. The isolated track requirement serves to improve the efficiency for suppressing background from leptonic W decays. To suppress events containing apparent p_T^{miss} caused by mismeasurement of the jet energies, we further impose thresholds on the azimuthal angles between the $\vec{p}_T^{\text{miss}}$ vector and those of the (up to) four leading-p_T AK4 jets, $\Delta\phi_{1,2,3,4} > 0.5$, 0.5, 0.3, 0.3. For enhanced sensitivity to diverse signal models, events are categorized into three ranges of p_T^{miss}: 300–500, 500–700, and > 700 GeV.

Considering the two leading-p_T AK8 jets, events are categorized as $0H$, $1H$, or $2H$ according to the number of these jets that have a double-b discriminator value greater than 0.3 (H-tagged jets). For true Higgs boson decays the efficiency of this requirement is 50%–80% per AK8 jet depending on the jet p_T, with the maximum around 500 GeV, dropping off to the lower value around 2 TeV. Jets are further categorized by m_J, with the Higgs signal region encompassing the range 85–135 GeV, for which the efficiency per jet is ~80%. The remaining mass regions, 50–85 and 135–250 GeV, serve as sidebands. The signal region A_1 (A_2) is defined as the class of $1H$ ($2H$) events in which both jets lie within the signal mass window. Distributions of m_J for the leading-p_T jet in $1H$ and $2H$ events are shown in Fig. 2, for the observed and simulated events in which the subleading AK8 jet lies within the signal mass window. Here the yields from simulation are scaled to the prediction based on control samples in data, described below, in this mass window. For the T5HH SUSY model the efficiency for selection of events in the signal regions is 9%–15% for $m(\tilde{g}) > 1200$ GeV, increasing with $m(\tilde{g})$.

The m_J resolution does not permit clean separation of the H and Z boson peaks. The chosen signal window optimizes the selection of H bosons in the absence of Z. As noted previously we treat both processes as potential signal, and the likelihood fit described below accounts for any signal population in the control regions.

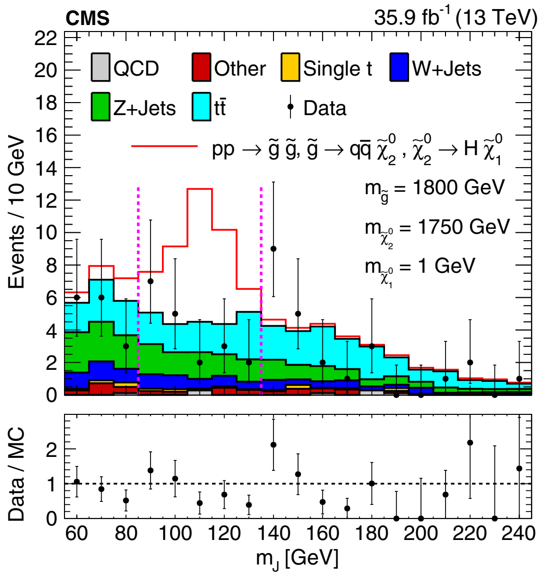

FIG. 2. Observed and expected distributions of the leading-p_T jet mass for selected $1H$ and $2H$ events with $p_T^{\mathrm{miss}} > 300$ GeV. The subleading jet is required to have m_J within the signal window denoted by vertical dashed magenta lines. The yields from simulation are scaled to the prediction based on control samples in data, in the signal mass window. A representative signal is shown stacked on top of the backgrounds. The bottom panel shows the ratio of the observed to SM-expected yields.

Simulated event samples for SM background processes are used to determine correction factors, typically near unity, that are used in conjunction with observed event yields in control regions to determine the SM background contribution in the signal regions. The production of $t\bar{t}$, W, Z, and quantum chromodynamics (QCD) multijet events is simulated with the Monte Carlo (MC) generator MadGraph 5_aMC@NLO 2.2.2 [41], with parton distribution functions (PDFs) taken from NNPDF 3.0 [42]. A detailed description of the simulated SM background samples is given in Ref. [43]. The detector simulation is performed with Geant4 [44]. Simulated event samples for SUSY signal models, used to determine the selection efficiency for signal events, are generated with MadGraph 5_aMC@NLO with up to two additional partons at leading order accuracy; they are normalized to cross sections computed to next-to-leading order (NLO) plus next-to-leading logarithmic (NLL) accuracy, based on Ref. [45].

The signal efficiencies from simulation are corrected for the modeling of initial-state radiation as measured in a data control sample [43], the double-b tagging efficiency [13], and the m_J resolution observed in data. Systematic uncertainties associated with these corrections are taken into account, as well as those arising from the determination of luminosity, trigger efficiency, PDFs, jet energy scale and resolution, isolated track veto efficiency, renormalization and factorization scales [46,47], and predicted yields from simulation due to limited sample sizes. The largest uncertainties are associated with the modeling of the double-b tagging efficiency (6%) and the mass resolution (1%–15%).

Dominant SM backgrounds arise from events containing jets misidentified as Higgs bosons in conjunction with W or Z bosons, which may originate from top quark decays, that decay to final states with neutrinos, yielding large p_T^{miss}. Multijet events in which jets are undermeasured can also give large p_T^{miss}; these backgrounds are highly suppressed by the Higgs boson identification requirements. All backgrounds are estimated from control regions in the data.

The SM backgrounds are estimated by simultaneously extrapolating yields from the $0H$ to the $1H$ and $2H$ H-tag multiplicity regions, and from the m_J sideband to the signal window. Events are assigned to the m_J sideband if one or both of the leading-p_T jets lie outside the signal window. Altogether we define four control regions: $1H$ and $2H$ events in the m_J sidebands, denoted B_1 and B_2, respectively; $0H$ events in the m_J signal window, denoted C; and $0H$ events in the m_J sidebands, denoted D. Each control region is split into three p_T^{miss} bins, corresponding to those defined for the signal regions. Based on the observed yields in these regions within the search sample, the total background is estimated as

$$\mathcal{A}_{1,2} = N(B_{1,2}) \frac{N(C)}{N(D)} \kappa_{1,2}, \qquad (1)$$

where the subscript indicates the number of double-b tagged jets, $\mathcal{A}_{1,2}$ is the predicted yield in the $A_{1,2}$ signal region, N is the population of the indicated control region, and $\kappa_{1,2}$ is a correction factor used to account for any correlations between the H-tag and m_J variables. While $B_{1,2}$, C, and D yields are taken directly from data, $\kappa_{1,2}$ is computed from simulation, corrected for observed discrepancies between data and simulation.

To obtain the corrections to $\kappa_{1,2}$ we compare data with simulation in auxiliary samples, defined to be orthogonal to the search sample, that are enriched in the SM backgrounds expected in the signal region: a single-lepton sample dominated by top quark and W boson production, a sample of single-photon plus jets events serving as proxy for invisibly decaying Z bosons [43], and a sample selected by inverting the $\Delta\phi$ requirement that contains predominantly QCD multijet events. The auxiliary samples satisfy the same requirement in H_T and contain the same control and signal regions, ($B_{1,2}$, C, D) and $A_{1,2}$, as the search sample. Scale factors given by ratios of the yields in data divided by those from simulation in these auxiliary samples, typically ranging in value from 0.5 to 2.0, are then applied to the yields of each of the simulated SM backgrounds, before they are combined to obtain the total background yields in the signal and control regions of the search sample. The yields from corrected simulation are found to be statistically compatible with the data in the control regions. From these corrected MC yields we compute $\kappa_{1,2}$ via Eq. (1), for each p_T^{miss} bin; the values are given in Table I below.

Systematic uncertainties in the background prediction enter through the factors $\kappa_{1,2}$. These include contributions from the uncertainties in the relative populations of the SM background processes, the yield statistics and simulation self-consistency in the auxiliary samples, the p_T^{miss} dependence of the scale factors where p_T^{miss} regions are combined to reduce statistical uncertainties, and the self-consistency of the method as applied to the simulated data.

The values of the κ factors with their uncertainties for each of the signal regions appear in Table I, along with the final background yield predictions, and the yields observed in the data. The observations are statistically compatible with those expected from the SM backgrounds, and thus we find no evidence for processes outside the SM.

TABLE I. Correction factors, predicted SM background yields, and observed yields, for the signal regions A_{N_H}. The uncertainties in the predictions include both statistical and systematic contributions.

N_H	p_T^{miss} (GeV)	κ	Predicted	Observed
1	300–500	0.98 ± 0.11	17.7 ± 3.8	15
1	500–700	0.86 ± 0.16	3.4 ± 1.5	2
1	> 700	0.86 ± 0.17	0.61 ± 0.45	1
2	300–500	0.73 ± 0.14	1.52 ± 0.57	1
2	500–700	0.43 ± 0.12	0.09 ± 0.08	0
2	> 700	0.62 ± 0.30	$0.09^{+0.11}_{-0.09}$	0

We compute upper limits on the gluino pair-production cross section using a maximum-likelihood fit in which the free parameters are the signal strength μ, the Poisson means of the total expected yields from SM backgrounds in each of the $B_{1,2}$, C, and D regions, and $\kappa_{1,2}$. The $\kappa_{1,2}$ parameters are constrained with a Gaussian prior to the expected values, with their statistical and systematic uncertainties. The signal model in the fit accounts for the populations of control as well as signal regions. Additional nuisance parameters account for systematic uncertainties in the yields predicted by the signal model.

We evaluate 95% confidence level (CL) upper limits based on the asymptotic form of a likelihood ratio test statistic [48], in conjunction with the CL_S criterion described in Refs. [49–51]. The test statistic is $q(\mu) = -2\ln(\mathcal{L}_\mu/\mathcal{L}_{\text{max}})$, where $\mathcal{L}_{\text{max}}$ is the maximum likelihood determined by allowing all parameters, including μ, to vary, and $\mathcal{L}_\mu$ is the maximum likelihood for fixed μ. Expected and observed 95% CL upper limits, and the predicted gluino pair-production cross sections, are shown in Fig. 3 for two choices of the $\tilde{\chi}_2^0$ decay branching fractions, taking $m(\tilde{\chi}_1^0) = 1$ GeV and $m(\tilde{g}) - m(\tilde{\chi}_2^0) = 50$ GeV. That is, we choose a model with a light LSP and a compressed spectrum for the heavy SUSY particles, thereby ensuring a Lorentz-boosted topology.

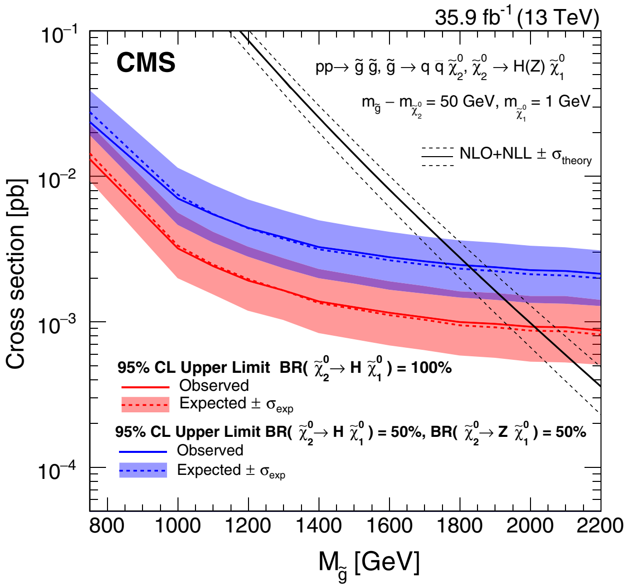

FIG. 3. Observed and expected cross section upper bounds at 95% CL for the T5HH and T5HZ models. The solid and dashed black lines show the SMS gluino-gluino production cross section with its uncertainty. The solid red (blue) line shows the observed limit for the T5HH (T5HZ) model; for each the like-colored dashed line and shaded band show the expected limit and the range associated with the experimental uncertainties.

In summary, this Letter has presented a search for production of energetic Higgs bosons in conjunction with large missing transverse momentum in proton-proton collisions. Higgs bosons with transverse momentum in the range 300 GeV to about 2 TeV are reconstructed as wide-cone jets with substructure indicative of the decay of the Higgs boson to a pair of b quarks. Background from standard model processes is estimated from data control regions. The observed event yields are found to be statistically compatible with these backgrounds.

The results are broadly applicable to models leading to signatures with energetic Higgs bosons and missing momentum. Here they are interpreted in the context of a simplified model of supersymmetry in which gluinos are pair produced and subsequently decay into several quarks, a Higgs or Z boson, and the lightest supersymmetric particle, a neutralino $\tilde{\chi}_1^0$. Gluinos with masses below 2010 (1825) GeV are excluded under the assumption of a large mass splitting between the next-to-lightest and lightest supersymmetric particle and that the branching fraction of $\tilde{\chi}_2^0 \rightarrow H\tilde{\chi}_1^0$ is 100% (50%). These are the first limits for pair production of gluinos measured in these decay channels.

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