Search for Monotop Signatures in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV

V. Khachatryan et al.* (CMS Collaboration)

(Received 5 October 2014; revised manuscript received 18 December 2014; published 10 March 2015)

Results are presented from a search for new decaying massive particles whose presence is inferred from an imbalance in transverse momentum ($E_T^{\text{miss}}$). Such particles can be produced in collider experiments, but escape detection so that their existence can only be inferred by a large imbalance in transverse momentum ($E_T^{\text{miss}}$). Both the ATLAS [4] and CMS [5] collaborations have performed searches for the invisible BSM particles in monotop [6,7] and monophoton [8,9] signatures that manifest themselves through the presence of a single jet or photon associated with large $E_T^{\text{miss}}$. These searches have not revealed any evidence for BSM monotop or monophoton final states, but this nonobservation can be accommodated in a theory where the new particles change the quark flavor and convert a light quark to a top quark. In this case, the BSM event signature would not correspond to monotop or monophoton final states, but to events containing single top quarks and large $E_T^{\text{miss}}$, referred to as “monotop” candidates. In this Letter, we present a search for such events in which an invisible BSM particle is produced in association with a top quark [10–20].

Depending on the spin statistics of the invisible particle, at tree level a monotop system can be produced through two main mechanisms: it can originate either (i) from the decay of a heavy baryonic resonance, with $E_T^{\text{miss}}$ arising from an invisible baryon-number violating fermionic state (for instance, $\bar{d}s \to \bar{u}_t \to \bar{c}_t$, where $\bar{d}$ and $\bar{s}$ denote anti-$d$ and anti-$s$ quarks, $\bar{u}_t$ are any of the up-type squarks of $R$-parity violating supersymmetry [21], and $t$ and $\bar{c}_t$ are the top quark and neutralino), or (ii) through flavor-changing (FC) interactions mediated by an invisible bosonic state (for instance, $u\bar{q} \to u \to t\bar{v}$, where $u$, $g$, $t$, and $\nu$ are an up quark, gluon, top quark, and invisible BSM particle, respectively) [10]. In both cases, the new invisible particles are assumed to have a branching fraction close to unity for decay to hidden sector particles. While this requires some degree of tuning, such scenarios are well motivated as discussed in Ref. [22]. Consequently, even in the presence of non-vanishing couplings to SM particles, which is necessary for the production of such invisible particles in collider experiments, an $E_T^{\text{miss}}$ signature is expected. The present study focuses on the second class of the above-mentioned processes where a bosonic invisible state is produced that yields a large $E_T^{\text{miss}}$ in association with a single top quark that decays to a bottom quark and a $W$ boson, with the latter decaying into a pair of quarks.

The search is performed on data from proton-proton collisions recorded at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.7 fb$^{-1}$, and recorded with the CMS detector [5] at the CERN LHC. The most important backgrounds for the event signature with three jets and large $E_T^{\text{miss}}$ are $Z + j$, $W + j$, and $t\bar{t}$ processes. The $Z + j$ and $W + j$ backgrounds are estimated from data, and the signal yield is determined simultaneously with multijet background, using a likelihood approach based on the observed multiplicity of $b$-tagged jets.

We interpret the results within a simplified field theory [10,11] where the invisible particle can be either a scalar ($\phi$) or a vector ($v$) boson, with its Lagrangian given by

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin}} + a_{\phi}^0\phi\bar{u}u + a_{v}^1v_\mu\bar{\nu}\gamma^\mu u + \text{H.c.},
$$

where $\mathcal{L}_{\text{SM}}$ denotes the SM Lagrangian, $\mathcal{L}_{\text{kin}}$ kinetic terms for the $\phi$ and $v$ fields, and the remaining terms model the interactions of the invisible states with up-type quarks. The coupling strengths are embedded in two $3 \times 3$ matrices in

* Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.

101801-1 © 2015 CERN, for the CMS Collaboration
respectively, as calculated using the FEWZ 3.1 program. Events are recorded using a trigger requiring \( E_{T}^{\text{miss}} > 150 \) GeV. For the background estimation we use an independent control sample of events with an isolated single-muon trigger with a transverse momentum threshold of \( p_{T} > 24 \) GeV.

The monotop model is implemented within the FeynRules package [23,24] and is interfaced [25,26] to the MadGraph 5 event generator [27]. Simulated events are produced for masses of invisible particles from 0 to 0.2 TeV in steps of 0.05 TeV, and from 0.2 to 1 TeV in steps of 0.1 TeV. The production cross sections are calculated at \( 0.2 \) TeV in steps of 0.05 TeV, and from 0.2 to 1 TeV in steps of 0.1 GeV. For the background estimation we use an independent control sample of events with an isolated single-muon trigger with a transverse momentum threshold of \( p_{T} > 24 \) GeV.

The Feynman diagrams for tree-level production are shown in Fig. 1.

Events are recorded using a trigger requiring \( E_{T}^{\text{miss}} > 150 \) GeV. For the background estimation we use an independent control sample of events with an isolated single-muon trigger with a transverse momentum threshold of \( p_{T} > 24 \) GeV.

The monotop model is implemented within the F"{u}rn}rules package [23,24] and is interfaced [25,26] to the MadGraph 5 event generator [27]. Simulated events are produced for masses of invisible particles from 0 to 0.2 TeV in steps of 0.05 TeV, and from 0.2 to 1 TeV in steps of 0.1 TeV. The production cross sections are calculated at \( 0.2 \) TeV in steps of 0.05 TeV, and from 0.2 to 1 TeV in steps of 0.1 GeV. For the background estimation we use an independent control sample of events with an isolated single-muon trigger with a transverse momentum threshold of \( p_{T} > 24 \) GeV.

The Feynman diagrams for tree-level production are shown in Fig. 1.

Events are recorded using a trigger requiring \( E_{T}^{\text{miss}} > 150 \) GeV. For the background estimation we use an independent control sample of events with an isolated single-muon trigger with a transverse momentum threshold of \( p_{T} > 24 \) GeV.

The monotop model is implemented within the F"{u}rn}rules package [23,24] and is interfaced [25,26] to the MadGraph 5 event generator [27]. Simulated events are produced for masses of invisible particles from 0 to 0.2 TeV in steps of 0.05 TeV, and from 0.2 to 1 TeV in steps of 0.1 TeV. The production cross sections are calculated at \( 0.2 \) TeV in steps of 0.05 TeV, and from 0.2 to 1 TeV in steps of 0.1 GeV. For the background estimation we use an independent control sample of events with an isolated single-muon trigger with a transverse momentum threshold of \( p_{T} > 24 \) GeV.

The Feynman diagrams for tree-level production are shown in Fig. 1.
limit on the production cross section. This threshold is also nearly optimal for attaining best significance in the signal.

The dominant backgrounds after implementing the selection criteria are $t\bar{t}$ and $V$ + jets events, with $V$ being either a Z or a W boson. For electroweak vector boson production up to three additional jets are considered, leading to a large systematic uncertainty in the predicted production rate. For this reason, we estimate the $V$ + jets background using data.

The control region for $W$ + jets and Z + jets backgrounds is defined with an alternative selection, requiring one or two isolated muons in addition to the three jets. A tighter selection is applied for muons, requiring them to satisfy $p_T \geq 40$ GeV and $|\eta| < 2.1$. In this case, the relative combined isolation variable in a cone of $\Delta R < 0.4$ must be below 0.12. As in the signal selection, the three jets are required to have $p_T > 60, 60, 40$ GeV respectively, and the invariant mass of the three jets has to be less than 250 GeV. Events with any additional jets with a $p_T$ above 35 GeV, as well as events with additional isolated electrons or muons are rejected.

The Z($\rightarrow \nu\nu$) + jets background is estimated from events with two muons and three jets. In such events, we replace the requirement for $E_T^{miss} > 350$ GeV with the requirement for the vector sum of the $p_T$ of the two muons and of $E_T^{miss}$ to be greater than 350 GeV. We also suppress the non-Z backgrounds by selecting events with $\mu^+\mu^-$ invariant mass between 60 and 120 GeV. The residual non-Z backgrounds are reduced to 1.5%; thus they make a negligible contribution to the overall uncertainty. The Z($\rightarrow \nu\nu$) + jets background is calculated using the following equation:

$$N(Z \rightarrow \nu\nu) = \frac{N^{obs}(\mu\mu)}{A \times e(\mu\mu)} \frac{B(Z \rightarrow \nu\nu)}{B(Z \rightarrow \mu\mu)}$$

where $N^{obs}(\mu\mu)$ is the number of observed events with two muons, $A \times e(\mu\mu)$ is the product of acceptance and efficiency to identify and select the two muons, as measured in simulation, and $B(Z \rightarrow \nu\nu)/B(Z \rightarrow \mu\mu) = 5.94$ [49] is the ratio of branching fractions for Z decays into two neutrinos and two muons. The accuracy of the background estimate is limited by the number of selected events with two muons. The estimated Z($\rightarrow \nu\nu$) + jets background is presented in Table I.

The $W$($\rightarrow \ell\nu$) + jets background is calculated from events with a single muon and three jets. Just as in the selected signal events, $E_T^{miss}$ has to be greater than 350 GeV. The transverse mass constructed with the muon-$p_T$ and $E_T^{miss}$ vectors has to be less than 180 GeV. From simulation we estimate the single-muon background that does not arise from W boson production (roughly a third of events), and subtract it from the observed number of events. The resulting number is divided by the acceptance and efficiency of the single-muon selection, providing thereby the number of $W$($\rightarrow \mu\nu$) + jets events. Assuming lepton universality, we use the same estimate for events with other lepton flavors. In the simulation, we calculate the probability that the $W$($\rightarrow \ell\nu$) + jets event can be present after applying the lepton veto that is used to select signal events. The resulting estimate of the $W$($\rightarrow \ell\nu$) + jets background is calculated as follows:

$$N(W \rightarrow \nu, \text{lost}\ell) = \frac{N^{obs}(\mu) - N^{MC}_{\text{non-W}}}{A \times e(\mu)} \sum_{\ell=e,\mu,\tau} P(\text{lost}\ell)$$

where $N^{obs}(\mu)$ is the observed number of single muon events, $N^{MC}_{\text{non-W}}$ is the background that does not arise from W bosons, and is estimated through simulation, $A \times e(\mu)$ is the product of acceptance and efficiency to identify and select the muon, as measured in simulation, and $P(\text{lost}\ell)$ are the probabilities that a W + jets event with an electron, a muon, or a tau lepton is not rejected by the signal selection, as defined through simulation. The background contributions from other kinematic regions [e.g., $W(\rightarrow e\nu)$ and $W(\rightarrow \tau\nu)$ with two jets] were found to be negligible. The accuracy of the $W$($\rightarrow \ell\nu$) + jets background estimate is limited by the number of selected muon events and by the uncertainty in the simulation of background from other than W boson sources. The rate of W + jets events with one b-tagged jet is estimated by scaling the rate without b-tagged jets by the probability to have a b-tagged jet in simulated W + jets events. The estimated background from W + jets is given in Table I.

The most important background after V+jets processes is from $t\bar{t}$ production, followed by single top quark and diboson production. These backgrounds are estimated through simulation. The leading systematic uncertainties arise in the simulated $t\bar{t}$ sample. They are related to the choice of the renormalization and factorization scales and the scale that determines the transition between modeling
additional partons at matrix element level and at the level of parton showers. Other systematic uncertainties originate from jet energy scale and resolution, $b$-tagging efficiency and mistagging rate, choice of PDF, and accuracy of the luminosity measurement. The yields from background $t\bar{t}$, single top quark, and diboson sources, together with the systematic uncertainties, are given in Table I.

Figure 2 shows the distribution of the invariant mass of the three jets before requiring their invariant mass to be less than 250 GeV, in events with one $b$-tagged jet. We do not present a simulation of the multijet background; thus, for the comparison between data and simulated backgrounds we suppress the potential contribution from this source with an additional cut on the opening azimuthal angle between the two leading jets: $|\phi^{\text{jet1}} - \phi^{\text{jet2}}| < 2.8$. The shaded areas represent the sum of the systematic uncertainties related to the renormalization and factorization scales for the $t\bar{t}$ and $V + \text{jets}$ backgrounds, smoothed in a second-order polynomial fit, and taken in quadrature. Agreement is observed between data and background predictions. The dashed line in Fig. 2 indicates the prediction from a model based on a 700 GeV invisible vector boson.

The signal cross section, as well as the number of multijet background events, are measured in data using a likelihood approach, where each systematic source is treated as a nuisance parameter. The method is based on the observed number of events without and with just a single $b$-tagged jet accepted in selecting the signal. These two event categories contain untagged and tagged signal and background events as shown in the following system of equations:

$$
N^{0\text{b}} = P_{\text{sig}}^{0\text{b}} N_{\text{sig}}^{0\text{b}} + P_{\text{MJ}}^{0\text{b}} N_{\text{MJ}}^{0\text{b}} + N_{\text{other}}^{0\text{b}},
$$

$$
N^{1\text{b}} = P_{\text{sig}}^{1\text{b}} N_{\text{sig}}^{1\text{b}} + P_{\text{MJ}}^{1\text{b}} N_{\text{MJ}}^{1\text{b}} + N_{\text{other}}^{1\text{b}},
$$

where $P_{\text{sig}}^{0\text{b}}$ and $P_{\text{sig}}^{1\text{b}}$ are the probabilities to tag 0 or 1 jet as a $b$ jet in the selected signal events, $P_{\text{MJ}}^{0\text{b}}$ and $P_{\text{MJ}}^{1\text{b}}$ are the corresponding probabilities for the selected multijet events in data, and $N_{\text{other}}^{0\text{b}}$ and $N_{\text{other}}^{1\text{b}}$ are the known contributions to 0 and 1 $b$-tagged event categories from other backgrounds. The $P_{\text{sig},\text{MJ}}^{0\text{b}}$ probabilities are estimated using simulation. The uncertainty in the $P_{\text{sig},\text{MJ}}^{0\text{b}}$ probabilities is taken as the difference between the estimate obtained from simulation and that obtained from data using a control region defined by relaxing the $E_{T}^{\text{miss}}$ requirement. The system above is solved to estimate the number of multijet ($N_{\text{MJ}}$) and signal ($N_{\text{sig}}$) events, by using a numerical minimization of the following likelihood:

$$
\mathcal{L}(\sigma_{\text{sig}}, \nu) = \text{Poisson}(N_{\text{obs}}^{0\text{b}} | N^{0\text{b}}) \times \text{Poisson}(N_{\text{obs}}^{1\text{b}} | N^{1\text{b}}),
$$

where $\sigma_{\text{sig}}$ is the signal cross section, $\nu$ is the vector of the nuisance parameters describing uncertainties in the expected number of events from the Eq. (4), and $N_{\text{obs}}^{0\text{b}}$ and $N_{\text{obs}}^{1\text{b}}$ are, respectively, the total number of observed events in event categories without and with one $b$ tag.

The number of expected SM background events is compared to the data after applying the final selections, and is presented in Table I. Systematic uncertainties in the simulated backgrounds ($t\bar{t}$, single top, and $VV'$) are presented as sums of the uncertainties from all of the respective sources, taken in quadrature. The multijet background is calculated using all the other backgrounds and data in Eq. (5). The uncertainty in the multijet background is determined by the uncertainties in the other backgrounds, and is therefore not included in the quadratic sum of background uncertainties.

No excess is observed above the background expectation, and limits are set at 95% confidence level (C.L.). The limits are calculated using the CL_s technique, which is based on statistical inference method jointly adopted by the ATLAS and CMS collaborations for the Higgs boson searches [50]. The resulting limits are calculated using the expected signal and background predictions along with their uncertainties, and the likelihood given in Eq. (5). Statistical uncertainties, arising from number of observed events with one or two muons in the control regions, are modeled with Poisson probabilities while all other uncertainties are modeled as log-normal distributions.

Figure 3 shows the 95% C.L. expected and observed limits on the product of the production cross section of the
monotop and the branching ratio of the $W$ decay to $q\bar{q}'$, as a function of mass of the invisible bosonic state, for scalar and vector fields.

In summary, a search has been performed by the CMS Collaboration for invisible particles produced in association with a single top quark that decays into three jets, one of which is $b$-tagged. The results are interpreted using a monotop model that predicts the existence of invisible scalar or vector particles. The signal and the backgrounds are extracted using a likelihood-based method. No excess of data over the standard model prediction is found and exclusion limits are set at 95% confidence level. The observed lower limits on mass for invisible scalar and vector particles are set at 330 and 650 GeV, respectively.

For a coupling constant $a_{PC} = 0.2$ these limits increase to 530 and 930 GeV, respectively. These results substantially extend a previous limit on monotop production of an invisible vector particle published by the CDF Collaboration [51] and complement the 8 TeV results of the ATLAS Collaboration [52] obtained with the leptonic top quark decay channel.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

FIG. 3 (color online). The 95% C.L. expected and observed CLs limits as functions of the mass of a scalar (top) and vector (bottom) invisible particle. The expected magnitude of a signal as a function of mass, calculated at leading order, is shown by the dashed curve. The confidence intervals for the expected limit are given at 68% and 95% coverage probability.
24 National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
25 Department of Physics, University of Helsinki, Helsinki, Finland
26 Helsinki Institute of Physics, Helsinki, Finland
27 Lappeenranta University of Technology, Lappeenranta, Finland
28 DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
29 Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
30 Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
31 Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
32 Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
33 E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia
34 RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
35 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
36 RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
37 Deutsches Elektronen-Synchrotron, Hamburg, Germany
38 University of Hamburg, Hamburg, Germany
39 Institut für Experimentelle Kernphysik, Karlsruhe, Germany
40 Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
41 University of Athens, Athens, Greece
42 University of Ioannina, Ioannina, Greece
43 Wigner Research Centre for Physics, Budapest, Hungary
44 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
45 University of Debrecen, Debrecen, Hungary
46 National Institute of Science Education and Research, Bhubaneswar, India
47 Panjab University, Chandigarh, India
48 University of Delhi, Delhi, India
49 Saha Institute of Nuclear Physics, Kolkata, India
50 Bhabha Atomic Research Centre, Mumbai, India
51 Tata Institute of Fundamental Research, Mumbai, India
52 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
53 University College Dublin, Dublin, Ireland
54 INFN Sezione di Bari, Bari, Italy
55 INFN Sezione di Bologna, Bologna, Italy
56 INFN Sezione di Catania, Catania, Italy
57 INFN Sezione di Firenze, Firenze, Italy
58 INFN Laboratori Nazionali di Frascati, Frascati, Italy
59 INFN Sezione di Genova, Genova, Italy
60 INFN Sezione di Milano-Bicocca, Milano, Italy
61 INFN Sezione di Napoli, Napoli, Italy
62 INFN Sezione di Padova, Padova, Italy
63 INFN Sezione di Perugia, Perugia, Italy
64 INFN Sezione di Pavia, Pavia, Italy
65 INFN Sezione di Pisa, Pisa, Italy
66 Scuola Normale Superiore di Pisa, Pisa, Italy