Inclusive Search for a Highly Boosted Higgs Boson Decaying to a Bottom Quark-Antiquark Pair

A. M. Sirunyan et al.*
(CMS Collaboration)

(Received 16 September 2017; published 14 February 2018)

An inclusive search for the standard model Higgs boson ($H$) produced with large transverse momentum ($p_T$) and decaying to a bottom quark-antiquark pair ($b\bar{b}$) is performed using a data set of $pp$ collisions at $\sqrt{s} = 13$ TeV collected with the CMS experiment at the LHC. The data sample corresponds to an integrated luminosity of 35.9 fb$^{-1}$. A highly Lorentz-boosted Higgs boson decaying to $b\bar{b}$ is reconstructed as a single, large radius jet, and it is identified using jet substructure and dedicated $b$ tagging techniques. The method is validated with $Z \rightarrow b\bar{b}$ decays. The $Z \rightarrow b\bar{b}$ process is observed for the first time in the single-jet topology with a local significance of 5.1 standard deviations (5.8 expected). For a Higgs boson mass of 125 GeV, an excess of events above the expected background is observed (expected) with a local significance of 1.5 (0.7) standard deviations. The measured cross section times branching fraction for production via gluon fusion of $H \rightarrow b\bar{b}$ with reconstructed $p_T > 450$ GeV and in the pseudorapidity range $-2.5 < \eta < 2.5$ is $74 \pm 48 \text{(stat)}^{+17}_{-10} \text{(syst)}$ fb, which is consistent within uncertainties with the standard model prediction.

DOI: 10.1103/PhysRevLett.120.071802

In the standard model (SM) [1–3], the Brout-Englert-Higgs mechanism [4–8] is responsible for electroweak symmetry breaking and the mass of elementary particles. Although a Higgs boson ($H$) was discovered [9–11], the LHC data sets of $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV were not sufficient to establish the coupling to bottom quarks [12], despite the 58.1% expected branching fraction of the Higgs boson to bottom quark-antiquark ($b\bar{b}$) pairs [13]. The most sensitive method to search for $H \rightarrow b\bar{b}$ decays at a hadron collider is to use events in which the Higgs boson is produced in association with a $W$ or $Z$ boson ($VH$) decaying to leptons, and recoiling with a large transverse momentum ($p_T$) [14], in order to suppress the overwhelming irreducible background from quantum chromodynamics (QCD) multijet production of $b$ quarks. Because of this background, an observation of $H(b\bar{b})$ decays in the gluon fusion production mode (GGF) as considered impossible. This Letter presents the first inclusive search for $H \rightarrow b\bar{b}$, where the Higgs boson is produced with high-$p_T$. Measurements of high-$p_T$ $H(b\bar{b})$ decays may resolve the loop induced and tree-level contributions to the GGF process [15] and provide an alternative approach to study the top quark Yukawa coupling in addition to the $iiH$ process.

The results reported in this Letter are based on a data set of $pp$ collisions at $\sqrt{s} = 13$ TeV, collected with the CMS detector at the LHC in 2016, and corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The main experimental difficulties for this search originate from the large cross section for background multijet events at low jet mass and the restrictive trigger requirements needed to reduce the data recording rate. Therefore, we require events to have a high-$p_T$ Higgs boson candidate and define six $p_T$ categories from 450 GeV to 1 TeV with variable width from 50 to 200 GeV. Combinatorial backgrounds are reduced by requiring the Higgs boson’s decay products to be clustered in a single jet [14]. The jet is required to have a two-prong substructure and $b$ tagging properties consistent with the $H(b\bar{b})$ signal. The nontrivial jet mass shape is difficult to model parametrically. For this reason, the dominant background from SM QCD multijet production is estimated in data by inverting the $b$ tagging requirement, which is, by design, decorrelated from jet mass and $p_T$. A simultaneous fit to the distributions of the jet mass in all categories is performed in the range 40 to 201 GeV to extract the inclusive $H(b\bar{b})$ and $Z(b\bar{b})$ production cross sections and to determine the normalizations and shapes of the jet mass distributions for the backgrounds.

A detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in Ref. [16]. The central feature of the CMS apparatus is a superconducting solenoid...
of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections, reside within the solenoid. Forward calorimeters extend the pseudorapidity ($\eta$) [16] coverage provided by the barrel and end cap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Simulated samples of signal and background events are produced using various Monte Carlo (MC) event generators, with the CMS detector response modeled using the GEANT4 [17] program. The MadGraph5_aMC@NLO 2.3.3 [18] generator is used for the diboson, $W + j$, $Z + j$, QCD multijet samples at leading order (LO) accuracy, with matching [19] between jets from the matrix element calculation and the parton shower description, while POWHEG 2.0 [20–22] at next-to-leading order (NLO) precision is used to model the $t\bar{t}$ and single-top processes. For parton showering and hadronization, the POWHEG and MadGraph5_aMC@NLO samples are interfaced with PYTHIA 8.212 [23]. The PYTHIA parameters for the underlying event description are set to the CUEUTPMI tune [24].

The production cross sections for the diboson samples are calculated to next-to-leading order (NLO) accuracy with the MCFM 7.0 program [25]. The cross section for top quark pair production is computed with TOP++ 2.0 [26] approximately twice the mass of the top quark [36]. A $p_T$ $\approx$ 450 GeV is assumed to be above a given threshold. In addition, a minimum threshold on the jet mass is imposed in order to further reduce the top quark background contamination. The leading (in $p_T$) jet in the event is assumed to be the Higgs boson candidate, the $H$ jet. The soft-drop algorithm [54,55] is used to remove soft and collinear-final-state hadrons.

The particles are clustered into jets using the anti-$k_T$ algorithm [51] with a distance parameter of 0.8 (AK8 jets). To isolate the Higgs boson signal, a high-$p_T$ signal jet is required. Combinations of several online selections are used, all requiring the total hadronic transverse energy in the event ($H_T$) or jet $p_T$ to be above a given threshold. In addition, a minimum threshold on the jet mass is imposed after removing remnants of soft radiation with the jet trimming technique [53] to reduce the $H_T$ or $p_T$ thresholds and improve the signal acceptance. The online selection is fully efficient at selecting events offline with at least one AK8 jet with $p_T > 450$ GeV and $|\eta| < 2.5$. Events containing identified and isolated electrons, muons, or $\tau$ leptons with $p_T > 10$, $10$, or 18 GeV and $|\eta| < 2.5$, 2.4, or 2.3, respectively, are vetoed to reduce backgrounds from SM EW processes. Since no genuine $p_T^{miss}$ is expected for signal processes, events with $p_T^{miss} > 140$ GeV are removed in order to further reduce the top quark background contamination.
The use of soft-drop grooming reduces the jet mass \(m_{SD}\) for background QCD events when large jet masses arise from soft gluon radiation. For signal events, the jet mass is primarily determined by the \(H(b\bar{b})\) decay kinematics and its distribution peaks at the mass of the Higgs boson. Dedicated \(m_{SD}\) corrections [56] are derived from simulation and data in a region enriched with merged \(W(q\bar{q})\) decays from \(t\bar{t}\) events. They remove a residual dependence on the jet \(p_T\) and match the jet mass scale and resolution to those observed in data.

The dimensionless mass scale variable for QCD jets, \(\rho = \log(m_{SD}^2/p_T^2)\) [54,57], whose distribution is roughly invariant in different ranges of jet \(p_T\), is used to characterize the correlation between the jet \(p_T\) tagging discriminator, jet mass, and jet \(p_T\). Only events in the range \(-6.0 < \rho < -2.1\) are considered, to avoid instabilities at the edges of the distribution due to finite cone limitations from the AK8 jet clustering \((\rho \gtrsim -2.1)\) and to avoid the nonperturbative regime of the soft-drop mass calculation \((\rho \lesssim -6.0)\). This requirement is fully efficient for the Higgs boson signal.

The \(N_0^2\) variable [58], which is based on a ratio of 2-point and 3-point generalized energy correlation functions (ECFs) [59], is exploited to determine how consistent a jet is with having a two-prong substructure. The calculation of \(N_0^2\) is based on the jet constituents after application of the soft-drop grooming algorithm to the jet. It provides excellent discrimination between two-prong signal jets and QCD background jets [58]. However, any selection on \(N_0^1\) or other similar variables [60] shapes the jet mass distributions differently depending on the \(p_T\) of the jet. Therefore a transformation of \(N_0^1\) to \(N_0^1,\text{DDT}\) is applied, where DDT stands for designed decorrelated tagger [57], to reduce its correlation with \(p_T\) and \(p_T\) in multijet events. We define \(N_0^{1,\text{DDT}} = N_0^1 - N_0^{1,\text{26%}}\), where \(N_0^{1,\text{26%}}\) is the 26th percentile of the \(N_0^1\) distribution in simulated QCD events as a function of \(\rho\) and \(p_T\). This ensures that the selection \(N_0^{1,\text{DDT}} < 0\) yields a constant QCD background efficiency of 26% across the entire \(\rho\) and \(p_T\) range considered in this search. The chosen percentile maximizes the sensitivity to the Higgs boson signal. In order to select events in which the \(H\) jet is most likely to contain two \(b\) quarks, we use the double-\(b\) tagger algorithm [61]. Several observables that characterize the distinct properties of \(b\) hadrons and their flight directions in relation to the jet substructure are used as input variables to this multivariate algorithm in order to distinguish between \(H\) jets and QCD jets. An \(H\) jet is considered double-\(b\) tagged if its double-\(b\) tag discriminator value is above a threshold corresponding to a 1% misidentification rate for QCD jets and a 33% efficiency for \(H(b\bar{b})\) jets.

Events with (without) a double-\(b\) tagged \(H\) jet define the passing (failing) region. In the passing region, the gluon fusion process dominates, although other Higgs boson production mechanisms contribute: VBF (12%), VH (8%), and \(ttH\) (5%). They are all taken into account when extracting the Higgs boson yield.

The contribution of \(t\bar{t}\) production to the total SM background is estimated to be less than 3%. It is obtained from simulation corrected with scale factors derived from a \(t\bar{t}\)-enriched control sample in which an isolated muon is required. This sample is included in a global fit used to extract the signal and the scale factors are treated as unconstrained parameters. They multiply the \(t\bar{t}\) contribution, correcting its overall normalization and the double-\(b\) mistag efficiency for jets originating from top quark decays.

The main background in the passing region, QCD multijet production, has a nontrivial jet mass shape that is difficult to model parametrically and dependent on jet \(p_T\), so we constrain it using the signal-depleted failing region. Since the double-\(b\) tagger discriminator and the jet mass are largely uncorrelated, the passing and failing regions have similar QCD jet mass distributions, and their ratio, the “pass-fail ratio” \(R_{pf}\), is expected to be nearly constant as a function of jet mass and \(p_T\). To account for the residual difference between the shapes of passing and failing events, \(R_{pf}(\rho, p_T) = \sum k,\ell a_k p_k^\rho p_T^\ell\). The coefficients \(a_k,\ell\) have no external constraints but are determined from a simultaneous fit to the data in passing and failing regions across the whole jet mass range. To determine the order of the polynomial necessary to fit the data, a Fisher F-test [62] is performed. Based on its results, a polynomial of second order in \(\rho\) and first order in \(p_T\) is selected.

The systematic uncertainties associated with the jet mass scale, the jet mass resolution, and the \(N_0^{1,\text{DDT}}\) selection efficiency are correlated among the \(W\), \(Z\), and \(H(b\bar{b})\) processes. These uncertainties are estimated using an independent sample of merged \(W\) jets. Additional details are available in the Supplemental Material [63], which includes Ref. [64]. The efficiency of the double-\(b\) tagger is measured in data and simulation in a sample enriched in \(bb\) from gluon splitting [61]. Scale factors relating data and simulation are then computed and applied to the simulation. These scale factors determine the initial distributions of the jet mass for the \(W(q\bar{q})\), \(Z(q\bar{q})\), and \(H(b\bar{b})\) processes, and they are further constrained in the fit to data due to the presence of the \(W\) and \(Z\) resonances in the jet mass distribution. The uncertainty associated with the modeling of the GGF Higgs \(p_T\) spectrum is propagated to the overall normalization of the GGF Higgs signal. In addition, the shape of the GGF Higgs \(p_T\) distribution is allowed to vary depending on the Higgs boson \(p_T\) by up to 30% at 1000 GeV, without changing the overall normalization. To account for some potentially \(p_T\)-dependent deviations due to missing higher-order corrections, uncertainties are applied to the \(W(q\bar{q})\) and \(Z(q\bar{q})\) yields that are \(p_T\)-dependent and correlated per \(p_T\) bin. An additional
TABLE I. Summary of the systematic uncertainties affecting the signal, $W$ and $Z + \text{jets}$ processes. Instances where the uncertainty does not apply are indicated by “…”.

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>$W/Z$</th>
<th>$H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Pileup</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>$N^{\text{jet}}_2$ selection</td>
<td>4.3%</td>
<td>4.3%</td>
</tr>
<tr>
<td>efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double-$b$ tag</td>
<td>4% ($Z$)</td>
<td>4%</td>
</tr>
<tr>
<td>Jet energy scale/ resolution</td>
<td>10/15%</td>
<td>10/15%</td>
</tr>
<tr>
<td>Jet mass scale ($p_T$)</td>
<td>0.4%/100 GeV ($p_T$)</td>
<td>0.4%/100 GeV ($p_T$)</td>
</tr>
<tr>
<td>Simulation sample size</td>
<td>2–25%</td>
<td>4–20% (GGF)</td>
</tr>
<tr>
<td>$H(p_T)$ correction</td>
<td>…</td>
<td>30% (GGF)</td>
</tr>
<tr>
<td>NLO QCD corrections</td>
<td>10%</td>
<td>…</td>
</tr>
<tr>
<td>NLO EW corrections</td>
<td>15–35%</td>
<td>…</td>
</tr>
<tr>
<td>NLO EW W/Z decorrelation</td>
<td>5–15%</td>
<td>…</td>
</tr>
</tbody>
</table>

A binned maximum likelihood fit to the observed $m_{SD}$ distributions in the range 40 to 201 GeV with 7 GeV bin width is performed using the sum of the $H(b\bar{b})$, $W$, $Z$, $t\bar{t}$, and QCD multijet contributions. The fit is done simultaneously in the passing and failing regions of the six $p_T$ categories within $450 < p_T < 1000$ GeV, and in the $t\bar{t}$-enriched control region. The production cross sections relative to the SM cross sections (signal strengths) for the Higgs and the $Z$ bosons, $\mu_H$ and $\mu_Z$, respectively, are extracted from the fit. Figure 1 shows the $m_{SD}$ distributions in data for the passing and failing regions with measured SM background and $H(b\bar{b})$ contributions. Contributions from $W$ and $Z$ boson production are clearly visible in the data.

The measured Z boson signal strength is $\mu_Z = 0.78 \pm 0.14^{+0.10}_{-0.13}$(stat)\(+0.19/-0.13$(syst), which corresponds to an observed significance of 5.1 standard deviations ($\sigma$) with 5.8$\sigma$ expected. This constitutes the first observation of the Z boson signal in the single-jet topology [67] and validates the substructure and $b$ tagging techniques for the Higgs boson search in the same topology. The measured cross section for the $Z + \text{jets}$ process for jet $p_T > 450$ GeV and $|\eta| < 2.5$ is $0.85 \pm 0.16$(stat)\(+0.20/-0.14$(syst) pb, which is
consistent within uncertainties with the SM production cross section of $1.09 \pm 0.11$ pb \cite{30}. Likewise, the measured Higgs boson signal strength is $\mu_H = 2.3 \pm 1.5(\text{stat})^{+1.3}_{-0.6}(\text{syst})$ and includes the corrections to the Higgs boson $p_T$ spectrum described earlier. The corresponding observed (expected) upper limit on the Higgs boson signal strength at a 95% confidence level is 5.8 (3.3), while the observed (expected) significance is 1.5$\sigma$ (0.7$\sigma$). The observed $\mu_H$ implies a measured GGF cross section times $H(b\bar{b})$ branching fraction for jet $p_T > 450$ GeV and $|\eta| < 2.5$ of 74 $\pm$ 17 (stat) $^{+17}_{-10}$ (syst) fb, assuming the SM values for the ratios of the different $H(b\bar{b})$ production modes. This measurement is consistent within uncertainties with the SM GGF cross section times $H(b\bar{b})$ branching fraction of 31.7 $\pm$ 9.5 fb.

Table II summarizes the measured signal strengths and significances for the Higgs and $Z$ boson processes. In particular, they are also reported for the case in which no corrections to the Higgs boson $p_T$ spectrum are applied. Figure 2 shows the profile likelihood test statistic scan in data as function of the Higgs and $Z$ boson signal strengths ($\mu_H$, $\mu_Z$).

<table>
<thead>
<tr>
<th>$H$</th>
<th>$\mu_H$ no $p_T$ corrections</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed signal strength</td>
<td>$2.3^{+1.8}_{-1.6}$</td>
<td>$3.2^{+2.2}_{-2.0}$</td>
</tr>
<tr>
<td>Expected UL signal strength</td>
<td>$&lt;3.3$</td>
<td>$&lt;4.1$</td>
</tr>
<tr>
<td>Observed UL signal strength</td>
<td>$&lt;5.8$</td>
<td>$&lt;7.2$</td>
</tr>
<tr>
<td>Expected significance</td>
<td>$0.7\sigma$</td>
<td>$0.5\sigma$</td>
</tr>
<tr>
<td>Observed significance</td>
<td>$1.5\sigma$</td>
<td>$1.6\sigma$</td>
</tr>
</tbody>
</table>

In summary, an inclusive search for the standard model Higgs boson with $p_T > 450$ GeV decaying to bottom quark-antiquark pairs and reconstructed as a single, large-radius jet is presented. The $Z +$ jets process is observed for the first time in the single-jet topology with a significance of 5.1$\sigma$. The Higgs production is measured with an observed (expected) significance of 1.5$\sigma$ (0.7$\sigma$) when including Higgs boson $p_T$ spectrum corrections accounting for higher-order and finite top quark mass effects. The measured cross section times branching fraction for the gluon fusion $H(b\bar{b})$ production for reconstructed $p_T$ and $|\eta| < 2.5$ is $74 \pm 48(\text{stat})^{+17}_{-10}(\text{syst})$ fb, which is consistent with the SM prediction within uncertainties.

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); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MESHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (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).

Université Libre de Bruxelles, Bruxelles, Belgium
Ghent University, Ghent, Belgium
Université Catholique de Louvain, Louvain-la-Neuve, Belgium
Université de Mons, Mons, Belgium
Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
Universidade Estadual Paulista, São Paulo, Brazil
Universidade Federal do ABC, São Paulo, Brazil
Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences
University of Sofia, Sofia, Bulgaria
Beihang University, Beijing, China
Institute of High Energy Physics, Beijing, China
State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Universidad de Los Andes, Bogota, Colombia
University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
University of Split, Faculty of Science, Split, Croatia
Institute Rudjer Boskovic, Zagreb, Croatia
University of Cyprus, Nicosia, Cyprus
Charles University, Prague, Czech Republic
Universidad San Francisco de Quito, Quito, Ecuador
Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
Department of Physics, University of Helsinki, Helsinki, Finland
Helsinki Institute of Physics, Helsinki, Finland
Lappeenranta University of Technology, Lappeenranta, Finland
IRFU, CEA, Université Paris-Saclay, GIF-sur-Yvette, France
Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
Georgian Technical University, Tbilisi, Georgia
Thilisi State University, Thilisi, Georgia
RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
Deutsches Elektronen-Synchrotron, Hamburg, Germany
University of Hamburg, Hamburg, Germany
Institut für Experimentelle Kernphysik, Karlsruhe, Germany
Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
National and Kapodistrian University of Athens, Athens, Greece
National Technical University of Athens, Athens, Greece
University of Ioánnina, Ioánnina, Greece
MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
Wigner Research Centre for Physics, Budapest, Hungary
Institute of Nuclear Research ATOMKI, Debrecen, Hungary
Institute of Physics, University of Debrecen, Debrecen, Hungary
Indian Institute of Science (IISc), Bangalore, India
National Institute of Science Education and Research, Bhubaneswar, India
Panjab University, Chandigarh, India
University of Delhi, Delhi, India
Saha Institute of Nuclear Physics, HBNI, Kolkata, India
Indian Institute of Technology Madras, Madras, India
Bhabha Atomic Research Centre, Mumbai, India
Tata Institute of Fundamental Research-A, Mumbai, India
Tata Institute of Fundamental Research-B, Mumbai, India
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University College Dublin, Dublin, Ireland
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Wayne State University, Detroit, USA
University of Wisconsin—Madison, Madison, WI, USA

Also at Vienna University of Technology, Vienna, Austria.
Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
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Also at Universidade Federal de Pelotas, Pelotas, Brazil.
Also at Université Libre de Bruxelles, Bruxelles, Belgium.
Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
Also at Joint Institute for Nuclear Research, Dubna, Russia.
Also at Suez University, Suez, Egypt.
Also at British University in Egypt, Cairo, Egypt.
Also at Fayoum University, El-Fayoum, Egypt.
Also at Helwan University, Cairo, Egypt.
Also at Université de Haute Alsace, Mulhouse, France.
Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
Also at University of Hamburg, Hamburg, Germany.
Also at Brandenburg University of Technology, Cottbus, Germany.
Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
Also at IIT Bhubaneswar, Bhubaneswar, India.
Also at Institute of Physics, Bhubaneswar, India.
Also at University of Visva-Bharati, Santiniketan, India.
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Also at Purdue University, West Lafayette, USA.
Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
Also at Institute for Nuclear Research, Moscow, Russia.
Also at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia.
Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at University of Florida, Gainesville, USA.
Also at P. N. Lebedev Physical Institute, Moscow, Russia.
Also at California Institute of Technology, Pasadena, USA.
Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.

Also at National and Kapodistrian University of Athens, Athens, Greece.

Also at Riga Technical University, Riga, Latvia.

Also at Universität Zürich, Zurich, Switzerland.

Also at Stefan Meyer Institute for Subatomic Physics.

Also at Adiyaman University, Adiyaman, Turkey.

Also at Istanbul Aydin University, Istanbul, Turkey.

Also at Mersin University, Mersin, Turkey.

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Also at Piri Reis University, Istanbul, Turkey.

Also at Izmir Institute of Technology, Izmir, Turkey.

Also at Necmettin Erbakan University, Konya, Turkey.

Also at Marmara University, Istanbul, Turkey.

Also at Kafkas University, Kars, Turkey.

Also at Istanbul Bilgi University, Istanbul, Turkey.

Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.

Also at Utah Valley University, Orem, USA.

Also at Beykent University.

Also at Bingol University, Bingol, Turkey.

Also at Erzincan University, Erzincan, Turkey.

Also at Sinop University, Sinop, Turkey.

Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

Also at Texas A&M University at Qatar, Doha, Qatar.

Also at Kyungpook National University, Daegu, Korea.