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Search for Dark Matter in Events with Missing Transverse Momentum and a Higgs Boson Decaying to Two Photons in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

G. Aad *et al.**

(ATLAS Collaboration)

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Results of a search for new phenomena in events with large missing transverse momentum and a Higgs boson decaying to two photons are reported. Data from proton-proton collisions at a center-of-mass energy of 8 TeV and corresponding to an integrated luminosity of 20.3 fb^{-1} have been collected with the ATLAS detector at the LHC. The observed data are well described by the expected standard model backgrounds. Upper limits on the cross section of events with large missing transverse momentum and a Higgs boson candidate are also placed. Exclusion limits are presented for models of physics beyond the standard model featuring dark-matter candidates.

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Although the existence of dark matter (DM) is well established, nearly nothing is known of its underlying particle nature [1]. Many DM candidates have been proposed, and attempts made to connect them to physics beyond the standard model (SM) at the scale of electroweak symmetry breaking [2] that would naturally accommodate the observed relic density [3].

Collider searches for weakly interacting dark matter rely on the inferred observation of missing transverse momentum [4] $E_{\mathrm{T}}^{\mathrm{miss}}$ recoiling against a visible final-state object X, which may be a hadronic jet [5,6], photon (γ) [7,8], or W/Z boson [9–11]. The discovery of a Higgs boson [12,13] (H) creates a new opportunity to search for beyond-the-SM (BSM) physics giving rise to $H + E_{\mathrm{T}}^{\mathrm{miss}}$ signatures [14,15]. In contrast to the aforementioned probes, the visible H boson is unlikely to be radiated from an initial-state quark or gluon. This has the important consequence that the $H + E_{\mathrm{T}}^{\mathrm{miss}}$ signature directly probes the structure of the effective DM-SM coupling; see Fig. 1.

If the mass of the DM particle is less than half of the Higgs boson mass m_H, the Higgs boson may decay directly to DM. Such decays have been searched for using LHC data, and null results provide powerful constraints on the invisible branching ratio of the Higgs boson in several different production modes including WH or ZH [11,16,17], and qqH [18,19]. However, the mass of the DM particle may be larger than $m_H/2$, in which case these searches are not sensitive, and approaches such as analysis of $H + E_{\mathrm{T}}^{\mathrm{miss}}$ events are required.

Two approaches are commonly used to model generic processes yielding a final state with a particle X recoiling against a system of noninteracting particles. One option is to use nonrenormalizable operators in an effective field theory (EFT), which is agnostic about the details of the theory at energies beyond the experimental sensitivity. Alternatively, simplified models that explicitly include the particles at higher masses can be used. The EFT approach is more model independent but is not valid when the typical momentum transfer approaches the scale of the high-mass particles that have been integrated out. Simplified models do not suffer from these concerns but include more assumptions by design and are therefore less generic. The two approaches are thus complementary and both are considered here.

In this Letter, results are reported from a search for $H + E_{\mathrm{T}}^{\mathrm{miss}}$ events in data collected by the ATLAS detector from pp collisions with center-of-mass energy $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of 20.3 fb^{-1}, produced by the Large Hadron Collider. The $H \to \gamma\gamma$ decay mode is used exclusively, as the small branching ratio is mitigated by the distinct diphoton resonance signature and the low expected number of background events with significant $E_{\mathrm{T}}^{\mathrm{miss}}$ [14]. ATLAS measured previously the differential cross section of $H \to \gamma\gamma$ production with

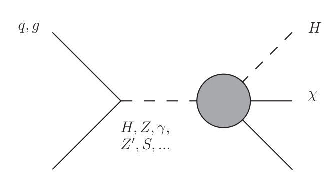

FIG. 1. Schematic diagram for production of DM particles χ in association with a Higgs boson in pp collisions, mediated by electroweak bosons (H, Z, γ) or new mediator particles such as a Z' or scalar singlet S. The gray circle denotes an effective interaction between DM, the Higgs boson, and other states.

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

respect to several kinematic quantities [20], including $E_{\mathrm{T}}^{\mathrm{miss}}$; the search reported here uses a subset of those data optimized for sensitivity to production of dark matter in association with a Higgs boson.

The ATLAS detector [21] is a multipurpose particle physics experiment with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle. Events were selected using a trigger that requires two photons, with leading (subleading) $E_{\mathrm{T}} > 35(25)$ GeV.

A photon is reconstructed as a cluster of energy with $|\eta| < 2.37$ deposited in the electromagnetic calorimeter, excluding the poorly instrumented region $\eta \in [1.37, 1.56]$. Clusters without matching tracks are classified as unconverted photon candidates. The photon energy is corrected by applying an energy calibration derived from $Z \to e^+e^-$ decays in data and cross-checked with $J/\psi \to e^+e^-$ and $Z \to \ell\ell\gamma$ decays in data [22]. Identification requirements are applied in order to reduce the contamination dominantly from π^0 or other neutral hadrons decaying to two photons. The photon identification is based on the profile of the energy deposit in the first and second layers of the electromagnetic calorimeter. Photons have to satisfy the "tight" identification criteria of Ref. [23]. They are also required to be isolated, i.e. the energy in the calorimeters in a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the cluster barycenter, excluding the energy associated with the photon cluster, is required to be less than 6 GeV. This in-cone energy is corrected for the leakage of the photon energy and for the effects of multiple pp interactions in the same or neighboring bunch crossings superimposed on the hard physics process (referred to as pileup interactions) [24]. Finally, for each photon the scalar sum of the transverse momenta p_{T} of tracks originating from the diphoton vertex with $p_{\mathrm{T}} > 1$ GeV and $\Delta R(\text{track, cluster}) < 0.2$ must be less than 2.6 GeV. The diphoton production vertex is selected from the reconstructed collision vertices using a neural-network algorithm as described in Ref. [23].

The momentum imbalance in the transverse plane is obtained from the negative vector sum of the reconstructed and calibrated electrons, muons, photons, and jets and is referred to as missing transverse momentum $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$. The symbol $E_{\mathrm{T}}^{\mathrm{miss}}$ is used for its magnitude. Calorimeter energy deposits are associated with a reconstructed and identified high-p_{T} object in a specific order: photons with $p_{\mathrm{T}} > 10$ GeV, electrons with $p_{\mathrm{T}} > 10$ GeV, and jets with $p_{\mathrm{T}} > 20$ GeV. Deposits not associated with any such objects are also taken into account in the $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ calculation [25] using an energy-flow algorithm that considers calorimeter energy deposits as well as inner-detector tracks [26]. The energy resolution is typically 11% near the threshold at 100 GeV for the considered signal scenarios.

Quality requirements are applied to photon candidates in order to reject those arising from instrumental problems. In addition, quality requirements are applied in order to remove jets arising from detector noise or out-of-time energy deposits in the calorimeter from cosmic rays or other noncollision processes [27].

Selected events are required to have a Higgs boson candidate consisting of two photons with diphoton invariant mass $m_{\gamma\gamma} \in [105, 160]$ GeV with transverse momenta satisfying leading (subleading) $p_{\mathrm{T}}^{\gamma} > 0.35(0.25)m_{\gamma\gamma}$. In addition, large missing transverse momentum is required, $E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV, as well as large transverse momentum of the $\gamma\gamma$ system, $p_{\mathrm{T}}^{\gamma\gamma} > 90$ GeV in order to suppress background events where $E_{\mathrm{T}}^{\mathrm{miss}}$ is caused by mismeasurement of the energies of identified physics objects. These selection requirements were derived by optimizing the expected upper limits on $H + E_{\mathrm{T}}^{\mathrm{miss}}$ production for the set of models described below.

Contributions to the $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ sample from SM processes include those that produce a Higgs boson in association with undetected particles (predominantly ZH with $Z \to \nu\bar{\nu}$ and WH with $W \to \ell\nu$) as well as nonresonant diphoton production ($\gamma\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$), $W\gamma$ and $Z\gamma$ production where an electron is misidentified as a photon, and photon + jet production in which the jet is misidentified as a photon.

Samples of simulated events are used in order to measure the efficiency of the selection for dark-matter models, as well as to estimate the contribution of SM $H + E_{\mathrm{T}}^{\mathrm{miss}}$ processes. Contributions from other background processes are estimated from $m_{\gamma\gamma}$ sidebands in the data.

Following the notation of Ref. [14], a set of EFT models are considered in which the effective operator Lagrangian term can be written as $|\chi|^2|H|^2$, $\bar{\chi}i\gamma_5\chi|H|^2$, $\chi^\dagger\partial^\mu\chi H^\dagger D_\mu H$, or $\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H$, where the DM field χ is a scalar in the first case and a fermion in the remaining cases and $B_{\mu\nu}$ is the $U(1)_Y$ field strength tensor. The interactions of SM and DM particles are described by two parameters: the DM particle mass m_χ and the suppression scale Λ of the heavy mediator that is integrated out of the EFT. In a theory that is valid to arbitrary energies (ultraviolet complete), the contact interaction would be replaced by an interaction via an explicit mediator V.

In addition, simplified models [14] with a massive vector (Z'), or a scalar (S) intermediate boson are tested. All $H + E_{\mathrm{T}}^{\mathrm{miss}}$ DM models are generated with Madgraph5 [28] version 1.4.8.4, with showering and hadronization modeled with Pythia8 [29] version 1.6.5 using the AU2 parameter settings [30]; the MSTW2008LO [31] parton distribution function (PDF) set is used. Values of m_χ from 1 to 1000 GeV are considered. Production of ZH and WH is modeled with Pythia8 using CTEQ6L1 PDFs [32]. Samples are normalized to cross sections for WH and ZH production calculated at next-to-leading order (NLO) [33], and next-to-next-to-leading order (NNLO) [34] in QCD, respectively, with NLO electroweak corrections [35] in both cases.

Differing pileup conditions as a function of the instantaneous luminosity are taken into account by overlaying simulated minimum-bias events generated with Pythia8 onto the hard-scattering process such that the observed distribution of the average number of interactions per bunch crossing is reproduced. The simulated samples are processed with a full ATLAS detector simulation [36] based on Geant4 [37] and a simulation of the trigger system.

To distinguish contributions from processes that include $H \to \gamma\gamma$ decays from those that contribute to the continuum background, a localized excess of events is searched for in the $m_{\gamma\gamma}$ spectrum near the Higgs boson mass, $m_H = 125.4$ GeV. Probability distribution functions that describe the $H \to \gamma\gamma$ resonance or the continuum background are defined in the range 105–160 GeV as described below. The contributions from each source are then estimated using an unbinned maximum-likelihood fit to the observed $m_{\gamma\gamma}$ spectrum.

The $m_{\gamma\gamma}$ spectra of the signal models of $H + \mathrm{DM}$ production and SM Higgs boson background processes are modeled with a double-sided Crystal Ball [38] function; the width and peak positions are fixed to values extracted from fits to simulated samples. An exponential function, $e^{am_{\gamma\gamma}}$ with free parameter a is used to describe the $m_{\gamma\gamma}$ distribution of the continuum background. The chosen continuum fit function is validated using simulated samples of the irreducible background processes and in three data samples adjacent to the signal region, but with relaxed requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$, on $p_{\mathrm{T}}^{\gamma\gamma}$, or on photon identification. Results of the fit to data in the signal region are shown in Fig. 2.

Systematic uncertainties from various sources affect the number of SM Higgs boson events in the resonant background, the predicted shape and location of its peak, as well as the efficiency of the selection for the signal models considered.

The uncertainty on the integrated luminosity, 2.8%, is derived following the same methodology as that detailed in

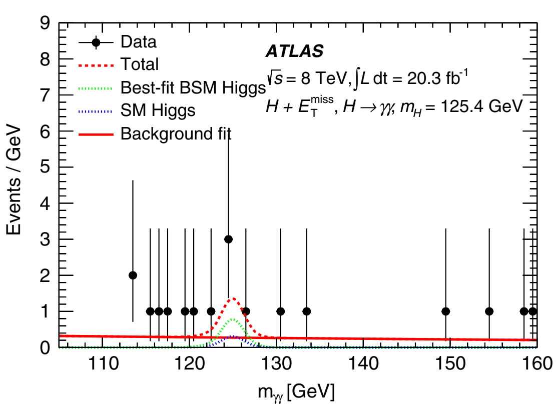

FIG. 2 (color online). The best-fit background estimates to the 18 observed events are 14.2 ± 4.0 (continuum backgrounds) 1.1 ± 0.1 (SM Higgs boson backgrounds) and 2.7 ± 2.2 (BSM Higgs boson), including both statistical and systematic uncertainties. An unbinned maximum-likelihood fit to the spectrum is used to estimate the number of events from the continuum background and from $H \to \gamma\gamma$ decays; the individual components are shown as well as their sum.

Ref. [39] using beam-separation scans. Uncertainties on the efficiency of the photon isolation requirement, photon identification requirement, and trigger selection are measured in an inclusive SM Higgs boson sample to be 2.8%, 2.1%, and 0.2%, respectively. Uncertainties in the photon energy scale and resolution lead to respective uncertainties of 11% and 0.3% in the position and width of the $H \to \gamma\gamma$ peak. Additional uncertainties on the jet energy scale and resolution as well as the calibration of unclustered hadronic recoil energy contribute to uncertainty in the $E_{\mathrm{T}}^{\mathrm{miss}}$, leading to 1.2% uncertainty on the efficiency of the selection for the signal models from the $E_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}^{\gamma\gamma}$ requirements. The impacts on the selection efficiency of the uncertainties on the levels of initial-state and final-state radiation are assessed by varying the Pythia8 parameters, as in Ref. [10]; these are found to be typically at the level of 1%. The total uncertainty on the selection efficiency for peaking SM Higgs backgrounds and signal models is 4.0%.

The theoretical uncertainties on the WH and ZH production cross sections come from varying the renormalization and factorization scales and from uncertainties on the parton distribution functions [31,40–42] following the PDF4LHC prescription. The Higgs boson decay branching fractions are taken from Refs. [43,44] and their uncertainties from Refs. [45,46]. The total theoretical uncertainty on the $H + E_{\mathrm{T}}^{\mathrm{miss}}$ contribution is 6%.

The number of events observed in the data corresponds to a 1.4σ deviation using the asymptotic formulas in Ref. [47]. As the events observed do not include a statistically significant BSM component, the results are interpreted in terms of exclusions on models that would produce an excess of $H + E_{\mathrm{T}}^{\mathrm{miss}}$ events. Upper bounds, detailed below, are calculated using a one-sided profile likelihood ratio and the CL_S technique [48,49], evaluated using the asymptotic approximation [47], which was ensured to be valid for the available number of events.

The most model-independent limits are those on the fiducial cross section of $H + E_{\mathrm{T}}^{\mathrm{miss}}$ events, including SM and BSM components, $\sigma \times A$, where σ is the cross section and A is the fiducial acceptance. The latter is defined using a selection identical to that defining the signal region but applied at particle level, where $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ is the vector sum of the momenta of the noninteracting particles, photon isolation requirements are not applied, and a simpler requirement on photon pseudorapidity $|\eta| < 2.37$ is made. The limit on $\sigma \times A$ is derived from a limit on the visible cross section $\sigma \times A \times \epsilon$, where ϵ is the reconstruction efficiency in the fiducial region. An estimate $\epsilon = 56\%$ is computed using the simulated signal samples described above with no quark or gluon produced from the main interaction vertex; the efficiencies vary across the set of models by less than 10%. The observed (expected) upper limit on the fiducial cross section is 0.70 (0.43) fb at 95% confidence level (C.L.). These limits are applicable to any model that predicts

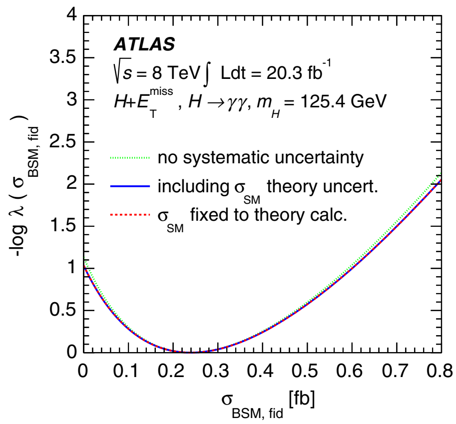

FIG. 3 (color online). Profile likelihood ratio (λ) as a function of $\sigma_{\mathrm{BSM,fid}}$, the fiducial cross section for production of a BSM $H+$ DM process in the $\gamma\gamma+E_{\mathrm{T}}^{\mathrm{miss}}$ channel taking into account the contribution of the SM component. The solid blue likelihood curve shows that the number of events observed in the data corresponds to a 1.4σ deviation using the asymptotic formulas in Ref. [47]. The dotted green likelihood curve only includes statistical uncertainties. The dashed red likelihood curve allows for modifications of the central value and uncertainty on the SM component as described in the text.

$H+E_{\mathrm{T}}^{\mathrm{miss}}$ events in the fiducial region and has similar reconstruction efficiency ϵ.

Limits on specific models of BSM $H+E_{\mathrm{T}}^{\mathrm{miss}}$ production depend on the prediction of the $H+E_{\mathrm{T}}^{\mathrm{miss}}$ component produced via ZH or WH; calculations of this theoretical quantity will improve with time and may depend on the details of a specific BSM theory. Following the proposal of Ref. [50], the profile likelihood ratio of the cross section for BSM $H+$ DM production in the $\gamma\gamma+E_{\mathrm{T}}^{\mathrm{miss}}$ channel is provided with the SM component fixed to the central value of the theoretical calculation, which allows later reinterpretation for any modified prediction and uncertainty, as shown in Fig. 3. This approach requires knowing how a change in the SM-like component modifies the best-fit BSM component; in this case where the SM-like and BSM components are indistinguishable, $\Delta N_{\mathrm{BSM}} = -\Delta N_{\text{SM-like}}$. The limits on the parameters of the specific BSM models considered in this Letter are calculated using the prediction and uncertainty for the SM component as described above.

Limits on DM production are derived from the cross-section limits at a given DM mass m_χ, and expressed as 95% C.L. limits on the suppression scale Λ or coupling parameter λ for the effective field theory operators; see Fig. 4 for limits for $\chi^\dagger\partial^\mu\chi H^\dagger D_\mu H$ and $\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H$ operators. For the lowest m_χ region not excluded by results from searches for invisible Higgs boson decays near $m_\chi = m_H/2$, values of Λ up to 6, 60, and 150 GeV are excluded for the $\bar{\chi}i\gamma_5\chi|H|^2$, $\chi^\dagger\partial^\mu\chi H^\dagger D_\mu H$, and $\bar{\chi}\gamma^\mu\chi B_{\mu\nu}H^\dagger D^\nu H$ operators, respectively; values of λ above 25.6 are excluded for the $|\chi|^2|H|^2$ operator. As discussed above, the effective field theory model becomes a poor approximation of an ultraviolet-complete model containing

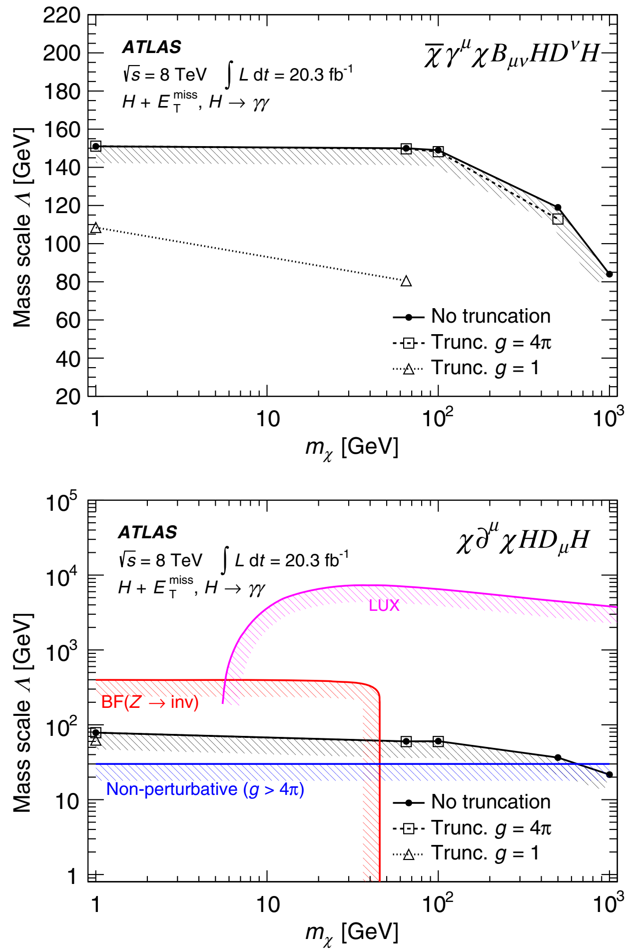

FIG. 4 (color online). Limits at 95% C.L. on the mass scale Λ as a function of the DM mass (m_χ) for two of the four EFT models considered. Solid black lines are due to $H+E_{\mathrm{T}}^{\mathrm{miss}}$ (this Letter); results where EFT truncation is applied are also shown, assuming coupling values $g=\sqrt{g_q g_\chi}=1, 4\pi$. The $g=4\pi$ case overlaps with the no-truncation result. The blue line indicates regions that fail the perturbativity requirement of $g<4\pi$, the red line indicates regions excluded by Z boson limits [53] on the invisible branching fraction (BF), and the pink line indicates regions excluded by the LUX Collaboration [54].

a heavy mediator V when the momentum transferred in the interaction, Q_{tr}, is comparable to the mass of the intermediate state $m_V = \Lambda\sqrt{g_q g_\chi}$ [51,52], where g_q and g_χ represent the coupling of V to SM and DM particles, respectively. To give an indication of the impact of the unknown ultraviolet details of the theory, limits are computed in which only simulated events with $Q_{\mathrm{tr}} = m_{\chi\chi} < m_V$ are retained; these limits are shown for values of $\sqrt{g_q g_\chi} = 1$ or 4π in Fig. 4. This procedure is referred to as truncation. In addition, limits are derived on coupling parameters for simplified models as shown in Fig. 5. For a vector-mediated model, limits are placed on the coupling g_q of the mediator to quarks, assuming maximal coupling g_χ to dark matter. For the scalar-mediated model, limits are placed on the parameter $\kappa\times\sin(\theta_{\mathrm{mix}})$, where $\sin(\theta_{\mathrm{mix}})$ is

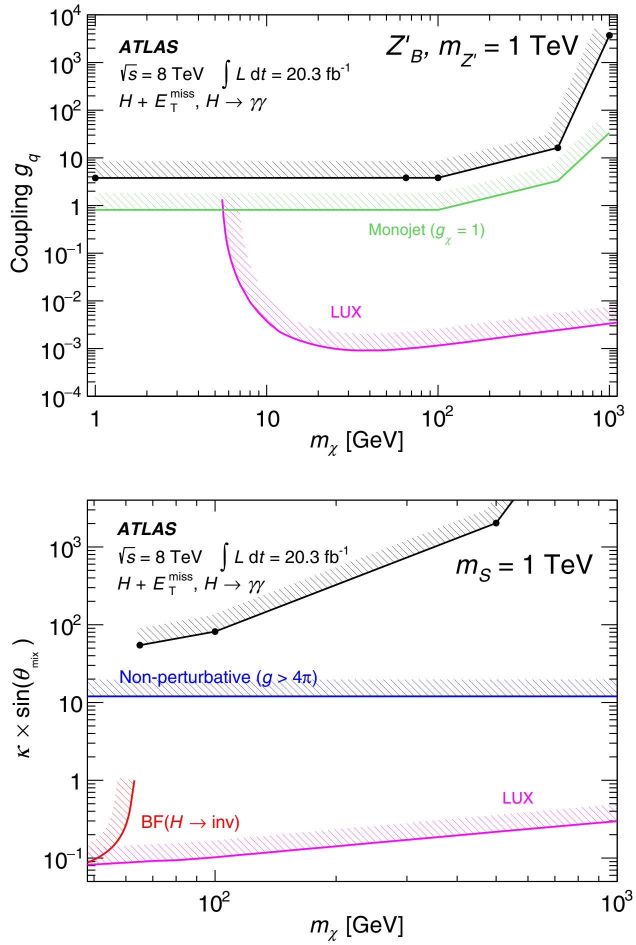

FIG. 5 (color online). Limits on coupling parameters for simplified models with a heavy mediator with mass of 1 TeV. All constraint contours exclude larger couplings or mixing angles. Regions excluded due to perturbativity arguments are indicated; red, green, and pink contours denote results from collider searches for invisible H decays [55], and monojet [6] searches, and the LUX Collaboration [54], respectively.

the mixing angle between the scalar S boson and the Higgs boson, and κ is a scaling constant; however, current calculations [14] of the $gg \to HS$ production mode may be overestimated due to approximations made in evaluating the top-quark loop.

In conclusion, a search for DM produced in association with a Higgs boson decaying to two photons has been conducted. Prior to these results, no bounds have been placed by collider experiments on the $H + \mathrm{DM}$ models discussed here. In addition, upper limits are placed on the cross section of events with large missing transverse momentum and a Higgs boson.

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Tomlinson,[84] M. Tomoto,[103] L. Tompkins,[143,jj] K. Toms,[105] E. Torrence,[116] H. Torres,[142] E. Torró Pastor,[167] J. Toth,[85,kk] F. Touchard,[85] D. R. Tovey,[139] T. Trefzger,[174] L. Tremblet,[30] A. Tricoli,[30] I. M. Trigger,[159a] S. Trincaz-Duvoid,[80] M. F. Tripiana,[12] W. Trischuk,[158] B. Trocmé,[55] C. Troncon,[91a] M. Trottier-McDonald,[15] M. Trovatelli,[134a,134b] P. True,[90] L. Truong,[164a,164c] M. Trzebinski,[39] A. Trzupek,[39] C. Tsarouchas,[30] J. C-L. Tseng,[120] P. V. Tsiareshka,[92] D. Tsionou,[154] G. Tsipolitis,[10] N. Tsirintanis,[9] S. Tsiskaridze,[12] V. Tsiskaridze,[48] E. G. Tskhadadze,[51a] I. I. Tsukerman,[97] V. Tsulaia,[15] S. Tsuno,[66] D. Tsybychev,[148] A. Tudorache,[26a] V. Tudorache,[26a] A. N. Tuna,[122] S. A. Tupputi,[20a,20b] S. Turchikhin,[99,hh] D. Turecek,[128] R. Turra,[91a,91b] A. J. Turvey,[40] P. M. Tuts,[35] A. Tykhonov,[49] M. Tylmad,[146a,146b] M. Tyndel,[131] I. Ueda,[155] R. Ueno,[29] M. Ughetto,[146a,146b] M. Ugland,[14] M. Uhlenbrock,[21] F. Ukegawa,[160] G. Unal,[30] A. Undrus,[25] G. Unel,[163] F. C. Ungaro,[48] Y. Unno,[66] C. Unverdorben,[100] J. Urban,[144b] P. Urquijo,[88] P. Urrejola,[83] G. Usai,[8] A. Usanova,[62] L. Vacavant,[85] V. Vacek,[128] B. Vachon,[87] C. Valderanis,[83] N. Valencic,[107] S. Valentinetti,[20a,20b] A. Valero,[167] L. Valery,[12] S. Valkar,[129] E. Valladolid Gallego,[167] S. Vallecorsa,[49] J. A. Valls Ferrer,[167] W. Van Den Wollenberg,[107] P. C. Van Der Deijl,[107] R. van der Geer,[107] H. van der Graaf,[107] R. Van Der Leeuw,[107] N. van Eldik,[152] P. van Gemmeren,[6] J. Van Nieuwkoop,[142] I. van Vulpen,[107] M. C. van Woerden,[30] M. Vanadia,[132a,132b] W. Vandelli,[30] R. Vanguri,[122] A. Vaniachine,[6] F. Vannucci,[80] G. Vardanyan,[177] R. Vari,[132a] E. W. Varnes,[7] T. Varol,[40] D. Varouchas,[80] A. Vartapetian,[8] K. E. Varvell,[150] F. Vazeille,[34] T. Vazquez Schroeder,[87] J. Veatch,[7] F. Veloso,[126a,126c] T. Velz,[21] S. Veneziano,[132a] A. Ventura,[73a,73b] D. Ventura,[86] M. Venturi,[169] N. Venturi,[158] A. Venturini,[23] V. Vercesi,[121a] M. Verducci,[132a,132b] W. Verkerke,[107] J. C. Vermeulen,[107] A. Vest,[44] M. C. Vetterli,[142,e] O. Viazlo,[81] I. Vichou,[165] T. Vickey,[139] O. E. Vickey Boeriu,[139] G. H. A. Viehhauser,[120] S. Viel,[15] R. Vigne,[30] M. Villa,[20a,20b] M. Villaplana Perez,[91a,91b] E. Vilucchi,[47] M. G. Vincter,[29] V. B. Vinogradov,[65] I. Vivarelli,[149] F. Vives Vaque,[3] S. Vlachos,[10] D. Vladoiu,[100] M. Vlasak,[128] M. Vogel,[32a] P. Vokac,[128] G. Volpi,[124a,124b] M. Volpi,[88] H. von der Schmitt,[101] H. von Radziewski,[48] E. von Toerne,[21] V. Vorobel,[129] K. Vorobev,[98] M. Vos,[167] R. Voss,[30] J. H. Vossebeld,[74] N. Vranjes,[13] M. Vranjes Milosavljevic,[13] V. Vrba,[127] M. Vreeswijk,[107] R. Vuillermet,[30] I. Vukotic,[31] Z. Vykydal,[128] P. Wagner,[21] W. Wagner,[175] H. Wahlberg,[71] S. Wahrmund,[44] J. Wakabayashi,[103] J. Walder,[72] R. Walker,[100] W. Walkowiak,[141] C. Wang,[33c] F. Wang,[173] H. Wang,[15] H. Wang,[40] J. Wang,[42] J. Wang,[33a] K. Wang,[87] R. Wang,[6] S. M. Wang,[151] T. Wang,[21] X. Wang,[176] C. Wanotayaroj,[116] A. Warburton,[87] C. P. Ward,[28] D. R. Wardrope,[78] M. Warsinsky,[48] A. Washbrook,[46] C. Wasicki,[42] P. M. Watkins,[18] A. T. Watson,[18] I. J. Watson,[150] M. F. Watson,[18] G. Watts,[138] S. Watts,[84] B. M. Waugh,[78] S. Webb,[84] M. S. Weber,[17] S. W. Weber,[174] J. S. Webster,[31] A. R. Weidberg,[120] B. Weinert,[61] J. Weingarten,[54] C. Weiser,[48] H. Weits,[107] P. S. Wells,[30] T. Wenaus,[25] T. Wengler,[30] S. Wenig,[30] N. Wermes,[21]

M. Werner,[48] P. Werner,[30] M. Wessels,[58a] J. Wetter,[161] K. Whalen,[29] A. M. Wharton,[72] A. White,[8] M. J. White,[1] R. White,[32b] S. White,[124a,124b] D. Whiteson,[163] F. J. Wickens,[131] W. Wiedenmann,[173] M. Wielers,[131] P. Wienemann,[21] C. Wiglesworth,[36] L. A. M. Wiik-Fuchs,[21] A. Wildauer,[101] H. G. Wilkens,[30] H. H. Williams,[122] S. Williams,[107] C. Willis,[90] S. Willocq,[86] A. Wilson,[89] J. A. Wilson,[18] I. Wingerter-Seez,[5] F. Winklmeier,[116] B. T. Winter,[21] M. Wittgen,[143] J. Wittkowski,[100] S. J. Wollstadt,[83] M. W. Wolter,[39] H. Wolters,[126a,126c] B. K. Wosiek,[39] J. Wotschack,[30] M. J. Woudstra,[84] K. W. Wozniak,[39] M. Wu,[55] M. Wu,[31] S. L. Wu,[173] X. Wu,[49] Y. Wu,[89] T. R. Wyatt,[84] B. M. Wynne,[46] S. Xella,[36] D. Xu,[33a] L. Xu,[33b,ll] B. Yabsley,[150] S. Yacoob,[145b,mm] R. Yakabe,[67] M. Yamada,[66] Y. Yamaguchi,[118] A. Yamamoto,[66] S. Yamamoto,[155] T. Yamanaka,[155] K. Yamauchi,[103] Y. Yamazaki,[67] Z. Yan,[22] H. Yang,[33e] H. Yang,[173] Y. Yang,[151] L. Yao,[33a] W-M. Yao,[15] Y. Yasu,[66] E. Yatsenko,[5] K. H. Yau Wong,[21] J. Ye,[40] S. Ye,[25] I. Yeletskikh,[65] A. L. Yen,[57] E. Yildirim,[42] K. Yorita,[171] R. Yoshida,[6] K. Yoshihara,[122] C. Young,[143] C. J. S. Young,[30] S. Youssef,[22] D. R. Yu,[15] J. Yu,[8] J. M. Yu,[89] J. Yu,[114] L. Yuan,[67] A. Yurkewicz,[108] I. Yusuff,[28,nn] B. Zabinski,[39] R. Zaidan,[63] A. M. Zaitsev,[130,cc] J. Zalieckas,[14] A. Zaman,[148] S. Zambito,[57] L. Zanello,[132a,132b] D. Zanzi,[88] C. Zeitnitz,[175] M. Zeman,[128] A. Zemla,[38a] K. Zengel,[23] O. Zenin,[130] T. Ženiš,[144a] D. Zerwas,[117] D. Zhang,[89] F. Zhang,[173] J. Zhang,[6] L. Zhang,[48] R. Zhang,[33b] X. Zhang,[33d] Z. Zhang,[117] X. Zhao,[40] Y. Zhao,[33d,117] Z. Zhao,[33b] A. Zhemchugov,[65] J. Zhong,[120] B. Zhou,[89] C. Zhou,[45] L. Zhou,[35] L. Zhou,[40] N. Zhou,[163] C. G. Zhu,[33d] H. Zhu,[33a] J. Zhu,[89] Y. Zhu,[33b] X. Zhuang,[33a] K. Zhukov,[96] A. Zibell,[174] D. Zieminska,[61] N. I. Zimine,[65] C. Zimmermann,[83] S. Zimmermann,[48] Z. Zinonos,[54] M. Zinser,[83] M. Ziolkowski,[141] L. Živković,[13] G. Zobernig,[173] A. Zoccoli,[20a,20b] M. zur Nedden,[16] G. Zurzolo,[104a,104b] and L. Zwalinski[30]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Physics Department, SUNY Albany, Albany, New York, USA*
[3]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[4a]*Department of Physics, Ankara University, Ankara, Turkey*
[4b]*Istanbul Aydin University, Istanbul, Turkey*
[4c]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[5]*LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA*
[9]*Physics Department, University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[12]*Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain*
[13]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[14]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[15]*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*
[16]*Department of Physics, Humboldt University, Berlin, Germany*
[17]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[18]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[19a]*Department of Physics, Bogazici University, Istanbul, Turkey*
[19b]*Department of Physics, Dogus University, Istanbul, Turkey*
[19c]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[20a]*INFN Sezione di Bologna, Italy*
[20b]*Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*
[21]*Physikalisches Institut, University of Bonn, Bonn, Germany*
[22]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[23]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[24a]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[24b]*Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[24c]*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*
[24d]*Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[25]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[26a]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[26b]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania*

[26c]University Politehnica Bucharest, Bucharest, Romania
[26d]West University in Timisoara, Timisoara, Romania
[27]Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[28]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[29]Department of Physics, Carleton University, Ottawa, Ontario, Canada
[30]CERN, Geneva, Switzerland
[31]Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
[32a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[32b]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[33a]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[33b]Department of Modern Physics, University of Science and Technology of China, Anhui, China
[33c]Department of Physics, Nanjing University, Jiangsu, China
[33d]School of Physics, Shandong University, Shandong, China
[33e]Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China
[33f]Physics Department, Tsinghua University, Beijing 100084, China
[34]Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
[35]Nevis Laboratory, Columbia University, Irvington, New York, USA
[36]Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[37a]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
[37b]Dipartimento di Fisica, Università della Calabria, Rende, Italy
[38a]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
[38b]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[39]Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[40]Physics Department, Southern Methodist University, Dallas, Texas, USA
[41]Physics Department, University of Texas at Dallas, Richardson, Texas, USA
[42]DESY, Hamburg and Zeuthen, Germany
[43]Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[44]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[45]Department of Physics, Duke University, Durham, North Carolina, USA
[46]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[47]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48]Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[49]Section de Physique, Université de Genève, Geneva, Switzerland
[50a]INFN Sezione di Genova, Italy
[50b]Dipartimento di Fisica, Università di Genova, Genova, Italy
[51a]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
[51b]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[52]II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54]II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55]Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
[56]Department of Physics, Hampton University, Hampton, Virginia, USA
[57]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[58a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[58b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[58c]ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60a]Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[60b]Department of Physics, The University of Hong Kong, Hong Kong, China
[60c]Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[61]Department of Physics, Indiana University, Bloomington, Indiana, USA
[62]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[63]University of Iowa, Iowa City, Iowa, USA
[64]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[65]Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[66]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[67]Graduate School of Science, Kobe University, Kobe, Japan

[68]Faculty of Science, Kyoto University, Kyoto, Japan
[69]Kyoto University of Education, Kyoto, Japan
[70]Department of Physics, Kyushu University, Fukuoka, Japan
[71]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[72]Physics Department, Lancaster University, Lancaster, United Kingdom
[73a]INFN Sezione di Lecce, Italy
[73b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[74]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[75]Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[76]School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[77]Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[78]Department of Physics and Astronomy, University College London, London, United Kingdom
[79]Louisiana Tech University, Ruston, Louisiana, USA
[80]Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[81]Fysiska institutionen, Lunds universitet, Lund, Sweden
[82]Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[83]Institut für Physik, Universität Mainz, Mainz, Germany
[84]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[85]CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[86]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
[87]Department of Physics, McGill University, Montreal, Québec, Canada
[88]School of Physics, University of Melbourne, Victoria, Australia
[89]Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
[90]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[91a]INFN Sezione di Milano, Italy
[91b]Dipartimento di Fisica, Università di Milano, Milano, Italy
[92]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[93]National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[94]Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[95]Group of Particle Physics, University of Montreal, Montreal, Québec, Canada
[96]P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[97]Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[98]National Research Nuclear University MEPhI, Moscow, Russia
[99]D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[100]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[101]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[102]Nagasaki Institute of Applied Science, Nagasaki, Japan
[103]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[104a]INFN Sezione di Napoli, Italy
[104b]Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[105]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[106]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[107]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[108]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[109]Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[110]Department of Physics, New York University, New York, New York, USA
[111]Ohio State University, Columbus, Ohio, USA
[112]Faculty of Science, Okayama University, Okayama, Japan
[113]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[114]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
[115]Palacký University, RCPTM, Olomouc, Czech Republic
[116]Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
[117]LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[118]Graduate School of Science, Osaka University, Osaka, Japan
[119]Department of Physics, University of Oslo, Oslo, Norway
[120]Department of Physics, Oxford University, Oxford, United Kingdom
[121a]INFN Sezione di Pavia, Italy
[121b]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[122]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA

[123]National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
[124a]INFN Sezione di Pisa, Italy
[124b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[125]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[126a]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
[126b]Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[126c]Department of Physics, University of Coimbra, Coimbra, Portugal
[126d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[126e]Departamento de Fisica, Universidade do Minho, Braga, Portugal
[126f]Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
[126g]Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[127]Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[128]Czech Technical University in Prague, Praha, Czech Republic
[129]Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[130]State Research Center Institute for High Energy Physics, Protvino, Russia
[131]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[132a]INFN Sezione di Roma, Italy
[132b]Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[133a]INFN Sezione di Roma Tor Vergata, Italy
[133b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134a]INFN Sezione di Roma Tre, Italy
[134b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[135a]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
[135b]Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco
[135c]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
[135d]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
[135e]Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
[136]DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
[137]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[138]Department of Physics, University of Washington, Seattle, Washington, USA
[139]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[140]Department of Physics, Shinshu University, Nagano, Japan
[141]Fachbereich Physik, Universität Siegen, Siegen, Germany
[142]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
[143]SLAC National Accelerator Laboratory, Stanford, California, USA
[144a]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
[144b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[145a]Department of Physics, University of Cape Town, Cape Town, South Africa
[145b]Department of Physics, University of Johannesburg, Johannesburg, South Africa
[145c]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[146a]Department of Physics, Stockholm University, Sweden
[146b]The Oskar Klein Centre, Stockholm, Sweden
[147]Physics Department, Royal Institute of Technology, Stockholm, Sweden
[148]Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
[149]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150]School of Physics, University of Sydney, Sydney, Australia
[151]Institute of Physics, Academia Sinica, Taipei, Taiwan
[152]Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[153]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[154]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[155]International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[156]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[157]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[158]Department of Physics, University of Toronto, Toronto, Ontario, Canada
[159a]TRIUMF, Vancouver, British Columbia, Canada
[159b]Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

[160]Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[161]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
[162]Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[163]Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
[164a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
[164b]ICTP, Trieste, Italy
[164c]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[165]Department of Physics, University of Illinois, Urbana, Illinois, USA
[166]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167]Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[168]Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
[169]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
[170]Department of Physics, University of Warwick, Coventry, United Kingdom
[171]Waseda University, Tokyo, Japan
[172]Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[173]Department of Physics, University of Wisconsin, Madison Wisconsin, USA
[174]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[175]Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[176]Department of Physics, Yale University, New Haven, Connecticut, USA
[177]Yerevan Physics Institute, Yerevan, Armenia
[178]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[d]Also at Novosibirsk State University, Novosibirsk, Russia.
[e]Also at TRIUMF, Vancouver BC, Canada.
[f]Also at Department of Physics, California State University, Fresno CA, USA.
[g]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[h]Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
[i]Also at Tomsk State University, Tomsk, Russia.
[j]Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[k]Also at Universita di Napoli Parthenope, Napoli, Italy.
[l]Also at Institute of Particle Physics (IPP), Canada.
[m]Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[n]Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[o]Also at Louisiana Tech University, Ruston LA, USA.
[p]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[q]Also at Department of Physics, National Tsing Hua University, Taiwan.
[r]Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
[s]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[t]Also at CERN, Geneva, Switzerland.
[u]Also at Georgian Technical University (GTU),Tbilisi, Georgia.
[v]Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
[w]Also at Manhattan College, New York NY, USA.
[x]Also at Hellenic Open University, Patras, Greece.
[y]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
[z]Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
[aa]Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[bb]Also at School of Physics, Shandong University, Shandong, China.
[cc]Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[dd]Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[ee]Also at International School for Advanced Studies (SISSA), Trieste, Italy.
[ff]Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
[gg]Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
[hh]Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
[ii]Also at National Research Nuclear University MEPhI, Moscow, Russia.

[jj] Also at Department of Physics, Stanford University, Stanford CA, USA.
[kk] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[ll] Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
[mm] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
[nn] Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.