Search for Scalar Diphoton Resonances in the Mass Range $65–600$ GeV with the ATLAS Detector in $pp$ Collision Data at $\sqrt{s} = 8$ TeV

G. Aad et al.*

(ATLAS Collaboration)

(Received 25 July 2014; published 20 October 2014)

A search for scalar particles decaying via narrow resonances into two photons in the mass range $65–600$ GeV is performed using $20.3$ fb$^{-1}$ of $\sqrt{s} = 8$ TeV $pp$ collision data collected with the ATLAS detector at the Large Hadron Collider. The recently discovered Higgs boson is treated as a background. No significant evidence for an additional signal is observed. The results are presented as limits at the $95\%$ confidence level on the production cross section of a scalar boson times branching ratio into two photons, in a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The upper limits set extend over a considerably wider mass range than previous searches.

DOI: 10.1103/PhysRevLett.113.171801 PACS numbers: 14.80.Da, 13.85.Qk, 14.70.Bh, 14.80.Ec

In July 2012, the ATLAS and CMS collaborations reported the discovery of a new particle [1,2] whose measured couplings and properties are compatible with the standard model Higgs boson ($H$) [3–6]. However, several extensions to the standard model—in particular, models featuring an extended Higgs sector [7–13]—predict new scalar resonances below or above the $H$ mass which may be narrow when their branching ratio to two photons is non-negligible.

This Letter presents a search for a scalar particle $X$ of mass $m_X$ decaying via narrow resonances into two photons. It extends the method developed for the measurement of the $H$ couplings in the $H \rightarrow \gamma\gamma$ channel [3] to the range $65 < m_X < 600$ GeV. Analytical descriptions of the signal and background distributions are fitted to the measured diphoton invariant mass spectrum $m_{\gamma\gamma}$ to determine the signal and background yields. The result is presented as a limit on the production cross section times the branching ratio $BR(X \rightarrow \gamma\gamma)$, restricted to a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The resonance with mass $m_X$ is considered narrow when its intrinsic width is smaller than $0.09$ GeV $+ 0.01 m_X$. This upper limit is defined such that the bias in the number of fitted signal events is kept below $10\%$. This ensures that the diphoton invariant mass width is dominated by the experimental resolution in the ATLAS detector. Model-dependent interference effects between the resonance and the continuum diphoton background are not considered.

The ATLAS detector [14] at the LHC [15] covers the pseudorapidity [16] range $|\eta| < 4.9$ and the full azimuthal angle $\phi$. It consists of an inner tracking detector covering the pseudorapidity range $|\eta| < 2.5$, surrounded by electromagnetic and hadronic calorimeters and an external muon spectrometer.

The search is carried out using the $\sqrt{s} = 8$ TeV $pp$ collision data set collected in 2012, with stable beam conditions and all ATLAS subsystems operational, which corresponds to an integrated luminosity of $L = 20.3 \pm 0.6$ fb$^{-1}$ [17]. The data were recorded using a diphoton trigger that required two electromagnetic clusters with transverse energies $E_T$ above $20$ GeV, both fulfilling identification criteria based on shower shapes in the electromagnetic calorimeter. The efficiency of the diphoton trigger [18] is $(98.7 \pm 0.5)\%$ for signal events passing the analysis selection.

The event selection requires at least one reconstructed primary vertex with two or more tracks with transverse momenta $p_T > 0.4$ GeV, and at least two photon candidates with $E_T > 22$ GeV and $|\eta| < 2.37$, excluding the barrel and end cap transition region of the calorimeter, $1.37 < |\eta| < 1.56$.

Photon reconstruction is seeded by clusters of electromagnetic calorimeter cells. Clusters without matching tracks are classified as unconverted photons. Clusters with matched tracks are considered as electron candidates but are classified as converted photons if they are associated with two tracks consistent with a $\gamma \rightarrow e^+e^-$ conversion process, or a single track leaving no hit in the innermost layer of the inner tracking detector. The photon energy calibration procedure is the same as in Ref. [3].

Photon candidates are required to fulfill identification criteria based on shower shapes in the electromagnetic calorimeter, and on energy leakage into the hadronic calorimeter [19]. Identification efficiencies, averaged over $\eta$, range from $70\%$ to above $99\%$ for the $E_T$ range under consideration. To further reduce the background from jets, the calorimeter isolation transverse energy $E_T^{\text{iso}}$ is required.
to be smaller than 6 GeV, where $E_T^{\text{iso}}$ is defined as the sum of transverse energies of the positive-energy topological clusters [20] within a cone of size $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.4$ around the photon candidate. The core of the photon shower is excluded, and $E_T^{\text{iso}}$ is corrected for the leakage of the photon shower into the isolation cone. The contributions from the underlying event and pileup are subtracted using the technique proposed in Ref. [21] and implemented as described in Ref. [22]. In addition, the track isolation—defined as the scalar sum of the $p_T$ of the primary vertex tracks with $p_T > 1$ GeV in a $\Delta R = 0.2$ cone around the photon candidate, excluding the conversion tracks—is required to be smaller than 2.6 GeV.

The $m_{\gamma\gamma}$ invariant mass is evaluated using the leading photon ($\gamma_1$) and subleading photon ($\gamma_2$) energies measured in the calorimeter, the azimuthal angle $\Delta \phi$ and the pseudorapidity separation between the photons determined from their positions in the calorimeter, and the position of the reconstructed diphoton vertex [3].

After selection, the data sample consists of a continuum background with dominantly $\gamma\gamma$, $\gamma$-jet, and jet-jet events and Drell–Yan (DY) production of electron pairs where both electrons are misidentified as photons. Two peaking backgrounds arise from the $Z$ boson component of the DY and from $H \rightarrow \gamma\gamma$.

To increase the sensitivity, the search is split into two analyses: a categorized low-mass analysis covering the range $65 < m_X < 110$ GeV and an inclusive high-mass analysis covering $110 < m_X < 600$ GeV. To provide sidebands on both sides of the tested mass point $m_X$, the $m_{\gamma\gamma}$ ranges are wider than the $m_X$ ranges probed and overlap at the transition between the two analyses.

The low-mass analysis requires a precise modeling of the DY background, dominated by the $Z$ boson resonance, where both electrons are misidentified as photons, mostly classified as converted photons. The loss of signal sensitivity is mitigated by separating the events into three categories with different signal-to-background ratios, according to the conversion status of the photon pair: two unconverted (UU), one converted and one unconverted (CU), or two converted (CC) photons. Table I shows the fractions of signal and DY events expected in each category.

In each category, the $Z$ resonance shape is described by a double-sided Crystal Ball function [23]. Because of the limited size of the fully simulated $Z \rightarrow ee$ sample [25,26] where both electrons are misidentified as photons, the shape parameters are determined by a fit to a dielectron data sample, where both electrons are required to fulfill shower shape identification criteria and the same $E_T$ thresholds as the photons.

Since most of the electrons misidentified as photons underwent large bremsstrahlung, the invariant mass distribution of the $Z$ boson reconstructed as a photon pair is wider and shifted to lower masses by up to 2 GeV with respect to the $Z$ boson mass reconstructed as an electron pair. The $Z \rightarrow ee$ invariant mass distributions extracted from data in each category are transformed by applying $E_T$-dependent shifts and smearing factors to the electron $E_T$ and $\phi$, to match the kinematics of the electrons misidentified as photons. Two sets of transformations are derived for $\gamma_1$ and $\gamma_2$ depending on their conversion status, using a $Z \rightarrow ee$ sample generated with POWHEG [27,28], interfaced with PYTHIA8 [29] for showering and hadronization. Figure 1 illustrates the effect of the electrons’ transformations on the invariant mass shapes in the fully simulated $Z \rightarrow ee$ sample. Systematic uncertainties on the template shapes and the $Z$ peak position are evaluated by varying the parameters of the electrons’ transformations by $\pm 1\sigma$.

The DY normalization is computed from the $e \rightarrow \gamma$ fake rates, defined as the ratios of $e\gamma$ to $ee$ pairs measured in $Z \rightarrow ee$ data, separately for $\gamma_1$ and $\gamma_2$ and each conversion status. A correction factor obtained from fully simulated $Z \rightarrow ee$ events is applied to account for additional effects, mainly the differences in isolation efficiencies and vertex reconstruction efficiency between $\gamma\gamma$ and $ee$ events. The associated uncertainties (9% to 25%) are dominated by the

<table>
<thead>
<tr>
<th>$\gamma\gamma$ category</th>
<th>UU</th>
<th>CU</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{data}}$</td>
<td>272184</td>
<td>253804</td>
<td>63224</td>
</tr>
<tr>
<td>$N_{\text{DY}}$</td>
<td>1080 ± 260</td>
<td>3400 ± 600</td>
<td>2700 ± 250</td>
</tr>
<tr>
<td>$f_{\text{DY}}$</td>
<td>15.0%</td>
<td>47.3%</td>
<td>37.7%</td>
</tr>
<tr>
<td>$f_X$</td>
<td>48.7%</td>
<td>42.5%</td>
<td>8.8%</td>
</tr>
</tbody>
</table>

FIG. 1 (color online). Invariant mass distributions in the CC category for fully simulated $Z \rightarrow ee$ events reconstructed as $ee$ (dotted lines), reconstructed as $\gamma\gamma$ (squares), and reconstructed as $ee$ after transforming the electrons to match the kinematics of the electrons misidentified as converted photons (circles).
subtraction of the continuum background and the detector material description.

The determination of the analytical form of the continuum background and the corresponding uncertainties follow the method detailed in Ref. [1]. The sum of a Landau distribution and an exponential distribution is used over the full $m_{\gamma\gamma}$ range. The bias on the signal yield induced by the analytical shape function is required to be lower than 20% of the statistical uncertainty on the fitted signal yield for the background-only spectrum. This bias is measured from a large sample generated from a parametrized detector response and is accounted for by a mass-dependent uncertainty. Figure 2 shows background-only fits to the data in the low-mass analysis for the three conversion categories.

In the high-mass analysis, relative cuts $E_T^\gamma / m_{\gamma\gamma} > 0.4$ and $E_T^\gamma / m_{\gamma\gamma} > 0.3$ are added to the selection requirements to reduce the continuum backgrounds and thereby increase the signal sensitivity. In total, 108 654 events with $100 < m_{\gamma\gamma} < 800$ GeV are selected.

To determine the continuum background shape over this large mass range, an exponential of a second-order polynomial is fitted inside a sliding $m_{\gamma\gamma}$ window of width $80 \cdot (m_X - 110$ GeV$)/110 + 20$ GeV, centered on the mass point $m_X$. The analytical shape and the fit window width are chosen to fulfill the signal yield bias criterion, as defined for the low-mass analysis, to minimize the statistical uncertainty on the background.

The $H$ background shape is modeled by a double-sided Crystal Ball function and normalized for $m_H = 125.9$ GeV [30,31] using the most up-to-date standard model cross-section calculations and corrections [34] of the five main production modes: gluon fusion (ggF), vector-boson fusion (VBF), Higgsstrahlung ($WH$, $ZH$), and associated production with a top quark pair ($t\bar{t}H$). The ggF and VBF samples [3] are simulated with the POWHEG generator interfaced with PYTHIA8. The $WH$, $ZH$, and $t\bar{t}H$ samples [3] are simulated with PYTHIA8. Figure 3 shows background-only fits to the data in the high-mass analysis.

The expected invariant mass distribution of the narrow resonance signal X is also modeled with a double-sided Crystal Ball function in the mass range $65 \leq m_X \leq 600$ GeV, using fully simulated ggF($X$) samples generated as for $H$, where $H$ is replaced by a scalar boson with a constant width of 4 MeV. Polynomial parametrizations of the signal shape parameters as a function of $m_X$ are obtained from a simultaneous fit to all the generated mass points $m_X$, separately for the high-mass analysis and the three low-mass analysis categories. The signal shape parameters extracted from ggF($X$) are compared to the other production modes: VBF($X$), $WX$, $ZX$, and $t\bar{t}X$; the bias on the signal yield due to the choice of ggF($X$) shape is negligible. The systematic uncertainty on the signal shape due to the photon energy resolution uncertainty ranges from 10% to 40% as a function of $m_X$ [3]. The systematic uncertainty on the $X$ peak position due to the photon energy scale uncertainty is 0.6% [3].

The fiducial cross section $\sigma_{fid}BR(X \rightarrow \gamma\gamma)$ includes an efficiency correction factor $C_X$ through

$$\sigma_{fid}BR(X \rightarrow \gamma\gamma) = \frac{N_{data}}{C_X C_{MC \, \text{eff}}} \quad \text{with} \quad C_X = \frac{N_{MC \, \text{eff}}}{N_{MC \, \text{fid}}}. $$

FIG. 2 (color online). Background-only fits to the data (black dots) as functions of the diphoton invariant mass $m_{\gamma\gamma}$ for the three conversion categories in the low-mass range. The solid lines show the sum of the Drell–Yan and the continuum background components. The dashed lines show the continuum background component only.

FIG. 3 (color online). Background-only fits to the data (black dots) as functions of the diphoton invariant mass $m_{\gamma\gamma}$ for the inclusive high-mass analysis. The solid line shows the sum of the Higgs boson and the continuum background components. The dashed line shows the continuum background component only.
where \(N_{\text{data}}\) is the number of fitted signal events in data, \(N_{\text{MC}}^{\text{reco}}\) the number of simulated signal events passing the selection criteria and \(N_{\text{MC}}^{\text{fid}}\) the number of simulated signal events generated within the fiducial volume. The fiducial volume, defined from geometrical and kinematical constraints at the generated particle level, is optimized to reduce the model dependence of \(C_X\) using fully simulated samples of the five \(X\) production modes to cover a large variety of topologies. The photon selection at generation level is similar to the selection applied to the data: two photons with \(E_T > 22\) GeV and \(|\eta| < 2\) are required; for \(m_X\) greater than 110 GeV, the relative cuts \(E_T^1/m_{\gamma\gamma} > 0.4\) and \(E_T^2/m_{\gamma\gamma} > 0.3\) are imposed. The particle isolation, defined as the scalar sum of \(p_T\) of all the stable particles (except neutrinos) found within a \(\Delta R = 0.4\) cone around the photon direction, is required to be less than 12 GeV. The \(C_X\) factor is parametrized from the ggF(\(X\)) samples and ranges from 0.56 to 0.71 as a function of \(m_X\). Systematic uncertainties include the maximum difference between the

\(C_X\) of the five production modes, the effect of the underlying event (U.E.) and pileup.

The statistical analysis of the data uses unbinned maximum likelihood fits. The DY and \(H\) shapes and normalizations are allowed to float within the uncertainties. In the low-mass analysis, a simultaneous fit to the three conversion categories is performed. Only two excesses with 2.1 \(\sigma\) and 2.2 \(\sigma\) local significances above the background are observed over the full mass range \(65 - 600\) GeV, for \(m_X = 201\) GeV and \(m_X = 530\) GeV, respectively. This corresponds to a deviation of less than 0.5 \(\sigma\) from the background-only hypothesis. Consequently, a 95% limit on \(\sigma_{\text{fid}}\) is computed using the procedure of Ref. [1]. The systematic uncertainties listed in Table II are accounted for by nuisance parameters in the likelihood function. In the low-mass analysis, the dominant uncertainties are the DY normalization and the residual topology dependence of \(C_X\). In the high-mass analysis, the largest uncertainties arise from the energy resolution and the

![Figure 4](image-url)

**FIG. 4 (color online).** Observed and expected 95% C.L. limit on the fiducial cross section times branching ratio \(\text{BR}(X \rightarrow \gamma\gamma)\) as a function of \(m_X\) in the range \(65 < m_X < 600\) GeV. The discontinuity in the limit at \(m_X = 110\) GeV (vertical dashed line) is due to the transition between the low-mass and high-mass analyses. The green and yellow bands show the \(\pm 1\sigma\) and \(\pm 2\sigma\) uncertainties on the expected limit. The inset shows a zoom around the transition point.

TABLE II. Summary of the systematic uncertainties.

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Signal and Higgs boson yield</th>
<th>Z component of Drell–Yan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.8%</td>
<td>Normalization(^b) 9%–25%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.5%</td>
<td>Peak position(^b) 1.5%–3.5%</td>
</tr>
<tr>
<td>(\gamma) identification(^a)</td>
<td>1.6%–2.7%</td>
<td>Template shape(^b) 1.5%–3%</td>
</tr>
<tr>
<td>(\gamma) isolation(^a)</td>
<td>1%–6%</td>
<td>Higgs boson background</td>
</tr>
<tr>
<td>Energy resolution(^a, b)</td>
<td>10%–40%</td>
<td>Cross section(^c) 9.6%</td>
</tr>
<tr>
<td>(\text{Signal and Higgs boson peak position}) Energy scale</td>
<td>0.6%</td>
<td>Branching ratio 4.8%</td>
</tr>
<tr>
<td>Continuum (\gamma\gamma, \gamma j, jj, DY)</td>
<td></td>
<td>(C_X) factor</td>
</tr>
<tr>
<td>Signal bias(^a)</td>
<td>1–67 events</td>
<td>Topology(^a) 3%–15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pileup and U.E.(^a) 1.4%–3.2%</td>
</tr>
</tbody>
</table>

\(^a\)Mass dependent.

\(^b\)Category dependent.

\(^c\)Factorization scale plus parton density function uncertainties [34].
theoretical uncertainty on the production rate of the standard model Higgs boson around 126 GeV.

The observed and expected limits, shown in Fig. 4, are in good agreement, consistent with the absence of a signal. The limits on $\sigma_{bb} BR (X \rightarrow \gamma\gamma)$ for an additional scalar resonance range from 90 fb for $m_X = 65$ GeV to 1 fb for $m_X = 600$ GeV. These results extend over a considerably wider mass range than the previous searches by the ATLAS and CMS collaborations [1,35], are complementary to spin-2 particles searches [36,37], and are the first such limits independent of the event topology.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions, without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMAT CR, MPO CR, and VSC CR, Czech Republic; DNRF, DNSRC, and Lundbeck Foundation, Denmark; EPLANET, ERC, and NSRF, European Union; IN2P3-CNRS and CEA-DSM/IRFU, France; GNSF, Georgia; BMF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SENF, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society, and Leverhulme Trust, United Kingdom; DOE and NSF, U.S. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, and Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom) and BNL (U.S.), and in the Tier-2 facilities worldwide.

[16] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector, and the z axis along the beam line. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, \phi) are used in the transverse plane, with \phi being the azimuthal angle around the beam line. Observables labeled transverse are projected into the x-y plane. The pseudorapidity is defined in terms of the polar angle \theta as \eta = -\ln (\tan (\theta/2)).
[23] A double-sided Crystal Ball function is composed of a Gaussian distribution at the core, connected with two power-law distributions describing the lower and upper tails [24].
[31] Differences between this choice of reference mass and the new mass measurements [32,33] are covered by the energy scale uncertainties listed in Table II.
Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

5 Institute of Nuclear Physics, University of Belgrade, Belgrade, Serbia

6 High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, 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

13b Vinca Institute of Nuclear Sciences, 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

24 Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil

24b 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 Física, 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 Maria, Valparaiso, Chile

33 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

34 Department of Modern Physics, University of Science and Technology of China, Anhui, China

35 Department of Physics, Nanjing University, Jiangsu, China

36 School of Physics, Shandong University, Shandong, China

37 Physics Department, Shanghai Jiao Tong University, Shanghai, China

38 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

39 Nevis Laboratory, Columbia University, Irvington, New York, USA

40 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

40b INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy

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
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Chinese University of Hong Kong, China.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
Also at Louisiana Tech University, Ruston LA, USA.
Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
Also at CERN, Geneva, Switzerland
Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
Also at Manhattan College, New York NY, USA.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at International School for Advanced Studies (SISSA), Trieste, Italy.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Department of Physics, Nanjing University, Jiangsu, China.
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.