Search for Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State using $pp$ Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector

The ATLAS Collaboration

Abstract

Searches are performed for resonant and non-resonant Higgs boson pair production in the $hh \rightarrow \gamma\gamma b\bar{b}$ final state using 20 fb$^{-1}$ of proton–proton collisions at a center-of-mass energy of 8 TeV recorded with the ATLAS detector at the CERN Large Hadron Collider. A 95% confidence level upper limit on the cross section times branching ratio of non-resonant production is set at 2.2 pb, while the expected limit is 1.0 pb. The corresponding limit observed for a narrow resonance ranges between 0.7 and 3.5 pb as a function of its mass.
Search for Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State using $pp$ Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector

Searches are performed for resonant and non-resonant Higgs boson pair production in the $hh \to \gamma\gamma b\bar{b}$ final state using 20 fb$^{-1}$ of proton–proton collisions at a center-of-mass energy of 8 TeV recorded with the ATLAS detector at the CERN Large Hadron Collider. A 95% confidence level upper limit on the cross section times branching ratio of non-resonant production is set at 2.2 pb, while the expected limit is 1.0 pb. The corresponding limit observed for a narrow resonance ranges between 0.7 and 3.5 pb as a function of its mass.

PACS numbers: 12.60.Fr,14.80.Da,14.80.Ec

Within two years of discovering a new boson with a mass near 125 GeV [1][2], the ATLAS and CMS collaborations have completed a slate of measurements demonstrating that its spin and couplings conform to the predictions of the Standard Model (SM) Higgs boson within current experimental and theoretical uncertainties [3][4]. Despite the lack of deviations from SM predictions, the Higgs boson, $h$, offers a rich potential for new physics searches. This Letter reports on searches for non-SM physics with events consistent with either resonant ($X \to hh$) or non-resonant pair production of Higgs bosons in the $hh \to \gamma\gamma b\bar{b}$ channel.

The predicted rate for Higgs boson pair production in the SM is several orders of magnitude smaller than the rate for the single $h$ process [3][8]; $hh$ production is thus not expected to be observable with current LHC data sets. However, a variety of extensions to the SM would enhance Higgs boson pair production. In many two Higgs doublet models (2HDMs) [9][11] the heavier of the neutral scalar Higgs bosons, $H$, may decay to a pair of its lighter scalar partners, $h$. Depending on the parameters of the 2HDM, $H \to hh$ production cross sections may reach more than a picobarn [11]. Altering the Higgs boson self-coupling, $\lambda_{hhh}$, could also increase the non-resonant production rate. Such deviations could be observed with future data sets [8]. Larger enhancements in the $pp \to hh$ rate could arise from a direct $t\bar{t}hh$ vertex, which is natural in composite models [12][13], or from the addition of light colored scalars to the SM [14]. Resonant production of two Higgs bosons could also appear from the production and decay of gravitons, radions or stoponium [15][17], as well as from a hidden sector mixing with the observed Higgs boson [18].

The $\gamma\gamma b\bar{b}$ channel is a powerful final state in which to search for Higgs boson pair production [19] thanks to the large $h \to b\bar{b}$ branching ratio, clean diphoton trigger, excellent diphoton invariant mass resolution, and low backgrounds. This channel is particularly important in the search for resonances with mass, $m_X$, in the range $260 < m_X < 500$ GeV considered in this Letter, where backgrounds and combinatorics make other channels such as $b\bar{b}b\bar{b}$ or $b\bar{b}τ^+τ^-$ challenging.

Processes that do not contain Higgs bosons are estimated from data; all other processes are simulated using Monte Carlo techniques. The standard ATLAS detector simulation [20] based on GEANT4 [21] is used. The simulation parameters are tuned to describe soft components of hadronic final states [22][23]. Simulated minimum bias collisions are overlaid on the hard scatter process, and events are reweighted so that the average number of interactions per bunch crossing ($\sim 20$) matches the observed distribution.

Background events with a single Higgs boson produced in association with a $W$ or $Z$ boson or $t\bar{t}$ are simulated with Pythia8 [24] using CTEQ6L1 parton distribution functions of the proton (PDFs) [25]. Higgs boson production via gluon or vector-boson fusion is simulated using CT10 PDFs [26] with Powheg-Box [27][28] interfaced to Pythia8 for showering and hadronization. Cross sections and associated uncertainties are taken from Ref. [29].

Two benchmark signal models are defined: SM Higgs boson pair production for the non-resonance search, and a gluon-initiated, spin-0 resonant state in the narrow-width approximation for the resonance search. Both models are generated using MadGraph5 [30][31] and CTEQ6L1 PDFs. A generator filter requires a pair of $b$-quarks and a pair of photons in each event. Pythia8 is used to decode the two Higgs bosons, and to shower and hadronize the events. The implementation of SM Higgs boson pair production includes the interference between diagrams with trilinear Higgs boson couplings and box diagrams. The next-to-leading-order inclusive production cross section of 9.2 fb is taken from Ref. [8]. Resonant samples are generated with a width of 10 MeV (corresponding to a narrow width approximation) at masses $m_X = 260, 300, 350,$ and $500$ GeV. Production cross sections for benchmark 2HDM models are calculated with SUsHi [32], and branching ratios with 2HDMC [33].

The analysis described in this Letter uses the full $\sqrt{s} = 8$ TeV data set of proton–proton collisions recorded by the ATLAS experiment in 2012, corresponding to an integrated luminosity of $20.3 \pm 0.6$ fb$^{-1}$ [24]. Data quality criteria are applied to reject events with diminished detector performance [35][36]. A description of the ATLAS detector can be found elsewhere [37].

The photon and event selection for the present search largely follow those of existing ATLAS $h \to γγ$ analyses [3][58]. Events are selected using a loose diphoton trigger that is nearly 100% efficient for events passing the offline photon selection. Photons are reconstructed starting from clusters of energy deposited in the electromagnetic calorimeter. Events are required to contain
two photon candidates whose calorimeter energy clusters match the expectations for photon-induced electromagnetic showers. The pseudorapidity, \( \eta \), of the two photons must fall within the geometric acceptance of the detector for photons, \( |\eta| < 2.57 \), excluding the region between the barrel and endcap calorimeters (1.37 < |\eta| < 1.56). The ratio of the transverse momentum of the leading (subleading) photon to the invariant mass of the pair, \( p_T/m_{\gamma\gamma} \), must exceed 0.35 (0.25). The invariant mass of the pair is calculated as in Ref. 3. Photons are required to be isolated: the energy in the calorimeter with a radius parameter of 0.4, starting from energy deposits grouped into topological clusters. Simulation is used to correct jets for instrumental effects and to account for the average energy in the detector in the event due to additional \( pp \) interactions and the underlying event. The calibration is refined using\textit{in situ} measurements. Jets are required to fall within the tracker acceptance of \( |\eta| < 2.5 \) and satisfy \( p_T > 35 \text{ GeV} \), with the leading jet in the event required to have \( p_T > 55 \text{ GeV} \). Events with jets arising from noisy regions in the calorimeters, beam backgrounds, or cosmic rays are rejected. Low-\( p_T \) jets from additional proton–proton interactions in the same bunch crossing are rejected with a requirement on the scalar sum of the \( p_T \) of tracks associated with the jet: for jets with \( |\eta| < 2.4 \) and \( p_T < 50 \text{ GeV} \), tracks associated with the hard scatter vertex must contribute over 50% of the sum.

Jets from the decay of long-lived heavy-flavor hadrons are selected using a multivariate tagging algorithm with an efficiency of 70% for jets from b-quark fragmentation in \( tt \) simulation. The four-momenta of muons closer than \( \Delta R = 0.4 \) to a b-tagged jet and with \( p_T > 4 \text{ GeV} \) are included in the jet four-momentum. Events containing both a pair of photons and a di-jet mass \( (m_{jj}) \) from the two leading jets satisfying \( 95 < m_{jj} < 135 \text{ GeV} \), consistent with the decay of a Higgs boson, are kept for further study. The mass resolution for pairs of b-tagged jets is approximately 13 GeV. The average reconstructed dijet mass is shifted downwards from the true value from effects such as unmeasured neutrinos from semi-leptonic b-decays.

In the non-resonance search, the background and potential signal are fit to the unbinned \( m_{\gamma\gamma} \) distribution of all events passing the dijet and diphoton selections described above. This fit has three components: the signal with a pair of Higgs bosons, the SM single Higgs boson background that is resonant in \( m_{\gamma\gamma} \), and the continuum background. The combined acceptance and selection efficiency for the SM Higgs boson pair production signal is 80%.

7.4%. Simulation studies show that the continuum contribution in the signal region is split between events with two photons and events with a single photon in association with a jet faking the second photon. The b-tagged jets include real heavy-flavor jets and mis-tagged light-flavor jets. The contribution from dileptonic decays of \( tt \) events where two electrons fake the two photons is roughly 10% of the total background. The contribution from other processes is negligible.

The fit is performed simultaneously in two categories. The first category is the signal region, in which at least two jets are b-tagged. The second is a control region, containing events with fewer than two b-tags. The two classes of events are kinematically identical: in the signal region, the mass and \( p_T \) requirements defined above must be satisfied by the two leading tagged jets, whereas in the control region, they are met by the two leading jets. Following earlier ATLAS analyses, the shape of the \( m_{\gamma\gamma} \) resonance is described by the sum of a Crystal Ball function and a wide Gaussian component that models the tails of the distribution. An exponential function describes the continuum backgrounds that fall with \( m_{\gamma\gamma} \). The slope of the exponential is shared in the fit between the two categories so that the control region constrains the background shape in the signal region. Figure 1 shows the separate diphoton mass distributions for events with \( \geq 2 \text{ b-tags} \) and events with \( \leq 1 \text{ b-tag} \).

The search for resonant production of pairs of Higgs bosons starts with the same signal selection as above but imposes an additional requirement on \( m_{\gamma\gamma} \). Due to the small number of expected events after this additional requirement, the resonance analysis proceeds as a counting
experiment instead of a simultaneous fit. The $m_{\gamma\gamma}$ resolution, $\sigma_{m_{\gamma\gamma}}$, is set to the expected value of 1.6 GeV, and the diphoton mass is required to be within $\pm 2\sigma_{m_{\gamma\gamma}}$ of the Higgs boson mass, $m_h = 125.5$ GeV. The acceptance of this requirement on background events without Higgs bosons, $\epsilon_{m_{\gamma\gamma}}$, is measured by fitting an exponential function to the $m_{\gamma\gamma}$ sidebands for events with fewer than two $b$-tagged jets. For this fit, the $m_{\gamma\gamma}$ region of $m_h \pm 5$ GeV is excluded to eliminate any potential contamination from resonant Higgs boson production. For $N$ observed events with two $b$-tags in the sideband ($|m_{\gamma\gamma} - m_h| > 2\sigma_{m_{\gamma\gamma}}$), the number of expected non-Higgs boson background events ($N_{m_{\gamma\gamma}}$) within $2\sigma_{m_{\gamma\gamma}}$ around $m_h$ is given by:

$$N_{m_{\gamma\gamma}} = N \frac{\epsilon_{m_{\gamma\gamma}}}{1 - \epsilon_{m_{\gamma\gamma}}}$$  \hspace{1cm} (1)

where the denominator compensates for the fact that $\epsilon_{m_{\gamma\gamma}} = 0.13$ is derived relative to the full $m_{\gamma\gamma}$ spectrum while $N$ contains only those events in the sidebands.

Before reconstructing the four-object mass, $m_{\gamma\gamma \gamma \gamma}$, a scaling factor of $m_h/m_{\gamma\gamma \gamma \gamma}$ is applied to the four-momentum of the $b \bar{b}$ system, where $m_h$ is set to the value of 125 GeV used in simulation. This improves the $m_{\gamma\gamma \gamma \gamma}$ resolution by 30–60% depending on the mass hypothesis, without biasing or significantly altering the shape of the background. Requirements are then made on $m_{\gamma\gamma \gamma \gamma}$ to select the smallest window containing 95% of the signal events in the narrow-width simulation. These requirements vary linearly with the mass, $m_X$, of the resonance considered. The width of the signal window varies from 17 GeV at $m_X = 260$ GeV to 60 GeV at $m_X = 500$ GeV. The acceptance for the continuum background to pass this requirement, $\epsilon_{m_{\gamma\gamma \gamma \gamma}}$, also varies with $m_X$. It is measured using events in data with $|m_{\gamma\gamma} - m_h| < 2\sigma_{m_{\gamma\gamma}}$ and fewer than two $b$-tags. Studies in both data sidebands and simulation show that the shapes of $m_{\gamma\gamma \gamma \gamma}$ and $m_{\gamma\gamma \gamma \gamma}$ agree within statistical uncertainties. The distribution of $m_{\gamma\gamma \gamma \gamma}$ in data is fitted with a Landau function, which is integrated in the signal window to obtain $\epsilon_{m_{\gamma\gamma \gamma \gamma}}$ for each mass hypothesis. The bottom panel of Fig. 2 shows this fit. The value of $\epsilon_{m_{\gamma\gamma \gamma \gamma}}$ is small (< 8%) at low and high $m_X$, and peaks at 18% for $m_X = 300$ GeV. The combined acceptance and selection efficiency for a resonance signal to pass all requirements varies from 3.8% at $m_X = 260$ GeV to 8.2% at $m_X = 500$ GeV.

The total background from sources without Higgs boson decays in the resonance analysis $N_B$ is given by:

$$N_B = N \frac{\epsilon_{m_{\gamma\gamma}}}{1 - \epsilon_{m_{\gamma\gamma}}} \epsilon_{m_{\gamma\gamma \gamma \gamma}}$$  \hspace{1cm} (2)

where $N_B$ and $\epsilon_{m_{\gamma\gamma \gamma \gamma}}$ are functions of $m_X$. Uncertainties on this extrapolation are described below.

Because they are not accounted for by the above $m_{\gamma\gamma}$ sideband techniques, contributions from single Higgs bosons produced in association with jets (particularly with $c\bar{c}$ or $b\bar{b}$ pairs) are estimated using simulation. In the resonance analysis, the yield from the non-resonant SM $hh$ processes is similarly included. SM cross sections and branching fractions are assumed in all cases.

Most systematic uncertainties are small when compared to statistical uncertainties, in particular for the resonance search. The evaluation of experimental uncertainties on photon identification (2.4%) and isolation efficiencies (2%) follow the methods used in the inclusive ATLAS $h \to \gamma\gamma$ analyses. The theoretical uncertainties on the single Higgs boson backgrounds are similarly adopted. Uncertainties from the modeling of Higgs bosons produced in association with extra heavy-flavor quarks are estimated from comparisons of data to simulation predictions for both $tt$ and $W$ boson production with extra heavy-flavor jets. The $tt$ ($W$ boson) study provides the uncertainty on extra heavy-flavor content in gluon- (quark-)initiated final states, leading to a 14% uncertainty on the combined single Higgs boson contribution in the signal region. PDF and scale uncertainties on SM $hh$ production are taken from Ref. [8].

Because of the cuts on the ratio $p_T/m_{\gamma\gamma}$, photon energy scale uncertainties are negligible. The uncertainty of 13% on the diphoton mass resolution in the non-resonance search is implemented in the resonance analysis as a 1.6% uncertainty on the number of events migrating into and out of the signal region. This represents the fraction of events where an upward variation of the photon resolution causes the diphoton mass to leave the $m_h \pm 2\sigma_{m_{\gamma\gamma}}$ window required for the signal region. The uncertainty on $m_h$ impacts the peak position in $m_{\gamma\gamma}$, in
the signal plus background fit of the non-resonance analysis, and in the resonance search it is transformed into a 1.7% uncertainty on the number of signal events in the mass window. The uncertainty for the acceptance of the $m_{\gamma\gamma}$ cuts on non-Higgs boson backgrounds is estimated by comparing fits of $m_{\gamma\gamma}$ to data in control regions with reversed photon identification or $b$-tagging requirements, and using different functional forms. The largest deviation observed from these fits (11%) is used for all searches.

Three components contribute to the uncertainty on $\epsilon_{m_{\gamma\gamma}X}$, and are combined in quadrature. (1) The limited number of events in the control region with fewer than two $b$-tags used for the Landau fit lead to a relative statistical uncertainty of 3–18% that varies as a function of $m_X$. (2) The $m_{\gamma\gamma jj}$ shape for untagged jets might not exactly mirror the one for tagged jets. The tagged and untagged samples are compared in simulation and the relative difference in $\epsilon_{m_{\gamma\gamma}X}$ is taken as the uncertainty. This value varies with $m_X$ and is always less than 30%. (3) Finally, an uncertainty of 16–30%, depending on $m_X$, is included to cover the choice of the analytic function. This was evaluated via comparisons of Landau shapes to alternate functions in simulation, including Landau shapes where the width varies with $m_{\gamma\gamma b}$, as well as Crystal Ball functions. Potential contamination from single Higgs boson processes in the control region is estimated to be less than 4% and is subtracted with negligible impact on the shape.

Uncertainties due to the $b$-tagging calibration are typically 2–4% for both the single Higgs boson and signal processes. Uncertainties due to the jet energy scale are 7% (22%) for single Higgs boson backgrounds in the non-resonance (resonant) analysis, and 1.4% (4.4%) for signal processes. Uncertainties due to the jet energy resolution are 4.8% (21%) for single Higgs boson backgrounds, and 6.3% (9.3%) for signal processes. The uncertainty on the integrated luminosity is 2.8%. It is derived, following the same methodology as that detailed in Ref. [34], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

The combined signal plus background fit for the non-resonance analysis is shown in Fig. 1. Within a $\pm 2\sigma_{m_{\gamma\gamma}}$ window around the Higgs boson mass, 1.5 events are expected, with 1.3 ± 0.5 from the continuum background and 0.17 ± 0.04 from single Higgs boson production, which is dominated by $t\bar{t}h$ events. About 0.04 events are expected from SM Higgs boson pair production. Five events are observed, corresponding to $2.4\sigma$ from the background-only hypothesis. The 95% confidence level (CL) upper limit on the Higgs boson pair production cross section is calculated using the frequentist $CL_S$ method [51]. Exclusions and significances are evaluated using pseudo-experiments. Assuming SM branching ratios for the light Higgs boson decays, the expected upper limit is $1.6^{+0.5}_{-0.2}$ pb; the observed limit is 2.2 pb.

For the resonance analysis, as before, SM branching fractions for the light Higgs boson are assumed. The expected exclusion improves from 1.7 to 0.7 pb as a function of $m_X$ from 260 to 500 GeV, as shown in Fig. 3. This behavior derives from increased event-level acceptance at larger masses. The observed exclusion ranges from 3.5 to 0.7 pb. The five events selected in the $m_{\gamma\gamma}$ signal region are shown in $m_{\gamma\gamma b}$ in Fig. 2. The local probability of compatibility to the background-only hypothesis, $p_0$, reaches a minimum of 0.002 at $m_X = 300$ GeV, corresponding to 3.0$\sigma$. After accounting for the look-elsewhere effect [52, 53], the global probability of such an excess occurring at any mass in the range studied is 0.019, corresponding to 2.1$\sigma$. The number of events lying within the $m_{\gamma\gamma b}$ window of each mass hypothesis is readily apparent in 'steps' in the exclusion plot.

The limits derived are juxtaposed in Fig. 3 with the expectation from a sample type I 2HDM [32, 33, 54] not excluded by current data with $\cos(\beta - \alpha) = -0.05$ and $\tan(\beta) = 1$. The heavy Higgs bosons are taken to be degenerate in mass, and the mass of the lightest CP-even Higgs boson is set to 125 GeV. All major production mechanisms of $H \to hh$ are considered. Cross sections and branching ratios were calculated as described in Ref. [55].

In conclusion, this Letter presents searches for resonant and non-resonant Higgs boson pair production using 20.3 fb$^{-1}$ of proton–proton collision data at $\sqrt{s} = 8$ TeV generated by the Large Hadron Collider and recorded by the ATLAS detector in 2012. A 95% confidence level upper limit is placed on the non-resonant production cross section at 2.2 pb, while the expected limit is $1.6^{+0.5}_{-0.2}$ pb. The difference derives from a small excess of events, corresponding to 2.4$\sigma$.

In the search for a narrow resonance decaying to a pair of Higgs bosons, the expected exclusion on the production cross section falls from 1.7 pb for a resonance at 260 GeV to 0.7 pb at 500 GeV. The observed exclusion ranges from 0.7–3.5 pb. It is weaker than expected for
resonances below 350 GeV.

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; BMWFW 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; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DRSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, 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; CNRST, 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; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

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, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[31] 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 pipe. The z-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η = − ln tan(θ/2).


(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China

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

Nevis Laboratory, Columbia University, Irvington NY, United States of America

Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas TX, United States of America

Physics Department, University of Texas at Dallas, Richardson TX, United States of America

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham NC, United States of America

SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

INFN Laboratori Nazionali di Frascati, Frascati, Italy

Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

Section de Physique, Université de Genève, Geneva, Switzerland

(a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy

(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

Department of Physics, Hampton University, Hampton VA, United States of America

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

Department of Physics, Indiana University, Bloomington IN, United States of America

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City IA, United States of America

Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America

Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

Department of Physics, Kyushu University, Fukuoka, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, United Kingdom

(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy

Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

Louisiana Tech University, Ruston LA, United States of America
<table>
<thead>
<tr>
<th>Institution</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France</td>
<td>France</td>
</tr>
<tr>
<td>Fysiska institutionen, Lunds universitet, Lund, Sweden</td>
<td>Sweden</td>
</tr>
<tr>
<td>Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain</td>
<td>Spain</td>
</tr>
<tr>
<td>Institut für Physik, Universität Mainz, Mainz, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France</td>
<td>France</td>
</tr>
<tr>
<td>Department of Physics, University of Massachusetts, Amherst MA, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Department of Physics, McGill University, Montreal QC, Canada</td>
<td>Canada</td>
</tr>
<tr>
<td>School of Physics, University of Melbourne, Victoria, Australia</td>
<td>Australia</td>
</tr>
<tr>
<td>Department of Physics, The University of Michigan, Ann Arbor MI, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus</td>
<td>Belarus</td>
</tr>
<tr>
<td>National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus</td>
<td>Belarus</td>
</tr>
<tr>
<td>Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Group of Particle Physics, University of Montreal, Montreal QC, Canada</td>
<td>Canada</td>
</tr>
<tr>
<td>P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>Nagasaki Institute of Applied Science, Nagasaki, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands</td>
<td>Netherlands</td>
</tr>
<tr>
<td>Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands</td>
<td>Netherlands</td>
</tr>
<tr>
<td>Department of Physics, Northern Illinois University, DeKalb IL, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>Department of Physics, New York University, New York NY, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Ohio State University, Columbus OH, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Faculty of Science, Okayama University, Okayama, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Department of Physics, Oklahoma State University, Stillwater OK, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Palacký University, RCPTM, Olomouc, Czech Republic</td>
<td>Czech Republic</td>
</tr>
<tr>
<td>Center for High Energy Physics, University of Oregon, Eugene OR, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France</td>
<td>France</td>
</tr>
<tr>
<td>Graduate School of Science, Osaka University, Osaka, Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>Department of Physics, University of Oslo, Oslo, Norway</td>
<td>Norway</td>
</tr>
<tr>
<td>Department of Physics, Oxford University, Oxford, United Kingdom</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Petersburg Nuclear Physics Institute, Gatchina, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>(a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Fisica, Universidade do Minho, Braga; (f) Departamento de Fisica Teorica y del Cosmos y CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal</td>
<td>Portugal</td>
</tr>
<tr>
<td>Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic</td>
<td>Czech Republic</td>
</tr>
<tr>
<td>Czech Technical University in Prague, Praha, Czech Republic</td>
<td>Czech Republic</td>
</tr>
<tr>
<td>Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic</td>
<td>Czech Republic</td>
</tr>
<tr>
<td>State Research Center Institute for High Energy Physics, Protvino, Russia</td>
<td>Russia</td>
</tr>
</tbody>
</table>
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

Physics Department, University of Regina, Regina SK, Canada

Ritsumeikan University, Kusatsu, Shiga, Japan

(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy

(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco

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

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

Department of Physics, University of Washington, Seattle WA, United States of America

Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Department of Physics, Shinshu University, Nagano, Japan

Fachbereich Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby BC, Canada

SLAC National Accelerator Laboratory, Stanford CA, United States of America

(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

(a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

(a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Department of Physics, University of Toronto, Toronto ON, Canada

(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

Department of Physics, University of Illinois, Urbana IL, United States of America

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

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

Department of Physics, University of British Columbia, Vancouver BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison WI, United States of America

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany