Search for Higgs and Z Boson Decays to $\phi \gamma$ with the ATLAS Detector

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters

<table>
<thead>
<tr>
<th>Citation</th>
<th>ATLAS Collaboration. 2016. Search for Higgs and Z Boson Decays to $\phi \gamma$ with the ATLAS Detector. Physical Review Letters 117, no. 11. doi:10.1103/physrevlett.117.111802.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Published Version</td>
<td>doi:10.1103/PhysRevLett.117.111802</td>
</tr>
<tr>
<td>Citable link</td>
<td><a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:29366143">http://nrs.harvard.edu/urn-3:HUL.InstRepos:29366143</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Open Access Policy Articles, as set forth at <a href="http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP">http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#OAP</a></td>
</tr>
</tbody>
</table>


Search for Higgs and $Z$ Boson Decays to $\phi \gamma$ with the ATLAS Detector

The ATLAS Collaboration

Abstract

A search for the decays of the Higgs and $Z$ bosons to a $\phi$ meson and a photon is performed with a $pp$ collision data sample corresponding to an integrated luminosity of $2.7 \text{fb}^{-1}$ collected at $\sqrt{s} = 13 \text{TeV}$ with the ATLAS detector at the LHC. No significant excess of events is observed above the background, and 95% confidence level upper limits on the branching fractions of the Higgs and $Z$ boson decays to $\phi \gamma$ of $1.4 \times 10^{-3}$ and $8.3 \times 10^{-6}$, respectively, are obtained.

© 2016 CERN for the benefit of the ATLAS Collaboration.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.
Rare decays of the 125 GeV Higgs boson [1, 2] $H$ to a light meson and a photon $\gamma$ have been suggested to present one viable probe of the Yukawa coupling of the Higgs boson to light ($u, d, s$) quarks [3–5]. While the Standard Model (SM) predicts these couplings to be small, substantial modifications are predicted in several scenarios beyond the SM, which include the Minimal Flavor Violation framework [6], the Froggatt-Nielsen mechanism [7], the Higgs-dependent Yukawa couplings model [8], the Randall-Sundrum family of models [9], and the possibility of the Higgs boson being a composite pseudo-Goldstone boson [10]. The light-quark Yukawa couplings are almost entirely unconstrained by existing data and the large multijet background at the Large Hadron Collider (LHC) severely inhibits the study of such couplings with inclusive $H \to q\bar{q}$ decays. The decay of the Higgs boson to a $\phi$ meson and a photon would give access to the strange-quark Yukawa coupling and to potential deviations from the SM prediction. The expected SM branching fraction is $B(H \to \phi\gamma) = (2.3 \pm 0.1) \times 10^{-6}$ [4], and no direct experimental information about this decay mode currently exists. The analogous rare decays of the Higgs boson to a heavy quarkonium state and a photon offer sensitivity to the charm- and bottom-quark Yukawa couplings [11–13]. The Higgs boson decays to $J/\psi \gamma$ and $\Upsilon \gamma$ have already been searched for by the ATLAS collaboration [14]. The former decay mode has also been searched for by the CMS collaboration [15].

The corresponding decay of the $Z$ boson has also been considered from a theoretical perspective [16, 17], as it offers a precision test of the SM and the predictions of the factorization approach in quantum chromodynamics [17]. Owing to the large $Z$ boson production cross section at the LHC, rare $Z$ boson decays can be probed at branching fractions much smaller than for Higgs boson decays to the same final state. The most precise prediction for the SM branching fraction is $B(Z \to \phi\gamma) = (1.17\pm0.08)\times10^{-8}$ [16]. The decay $Z \to \phi\gamma$ has not yet been observed and is not well constrained by existing measurements of $Z$ boson decays.

This Letter describes a search for Higgs and $Z$ boson decays to the exclusive final state $\phi\gamma$. The decay $\phi \to K^+K^-$ is used to reconstruct the $\phi$ meson. The search is performed with a sample of $pp$ collision data corresponding to an integrated luminosity of 2.7 fb$^{-1}$ recorded at a center-of-mass energy $\sqrt{s} = 13$ TeV with the ATLAS detector, described in detail in Ref. [18].

Higgs boson production is modeled using the POWHEG-BOX v2 Monte Carlo (MC) event generator [19–23] for the gluon fusion ($ggH$) and vector-boson fusion (VBF) processes calculated up to next-to-leading order in $\alpha_S$ with CT10 parton distribution functions [24]. Additional contributions from the associated production of a Higgs boson and a $W$ or $Z$ boson (denoted $WH$ and $ZH$, respectively) are modeled by the PYTHIA 8.186 MC event generator [25, 26] with NNPDF 2.3 parton distribution functions [27]. The production rates and dynamics for a SM Higgs boson with $m_H = 125$ GeV, obtained from Ref. [28], are assumed throughout this analysis. The $ggH$ signal model is appropriately scaled to account for the production of a Higgs boson in association with a $t\bar{t}$ or $b\bar{b}$ pair. The POWHEG-BOX v2 MC event generator, with the CTEQ6L1 parton distribution functions [29], is used to model $Z$ boson production. The total cross section is obtained from the measurement in Ref. [30], with an uncertainty of 5.5%.

The Higgs and $Z$ boson decays are simulated as a cascade of two-body decays. Effects of the helicity of the $\phi$ mesons on the $K^\pm$ kinematics are found to modify the acceptance by at most $\pm1\%$ and this is corrected for in the Higgs boson case and treated as a systematic uncertainty in the $Z$ boson case, due to the unknown $Z$ boson polarization.

PYTHIA 8.186 [25, 26] with the AZNLO set of hadronization and underlying-event parameters [31] is used to simulate showering and hadronization. The simulated events are passed through the detailed GEANT4 simulation of the ATLAS detector [32, 33] and processed with the same software used to reconstruct data.
The data sample used in this analysis was collected with a dedicated trigger, commissioned in September 2015, requiring an isolated photon with a transverse momentum $p_T > 400$ MeV originating from the primary vertex, which is defined as the vertex with the largest $\sum p_T^2$ in the event. The charged kaons are reconstructed from inner-detector tracks that satisfy quality requirements, including a requirement on the number of hits in the silicon detectors [35]. The $K^\pm$ candidates are required to have pseudorapidity $|\eta| < 2.5$ and $p_T > 15$ GeV. The $\phi \rightarrow K^+K^-$ decays are reconstructed from pairs of oppositely charged inner detector tracks. The higher-$p_T$ track in a pair, denoted the leading track, is required to have $p_T > 20$ GeV. The experimental resolution in $m_{K^+K^-}$ is around 4 MeV, comparable to the natural width of the $\phi$ meson, $\Gamma_\phi = 4.266 \pm 0.031$ MeV [34]. Track pairs with a mass $m_{K^+K^-}$ within $\pm 20$ MeV of the $\phi$ meson mass [34] are selected as $\phi \rightarrow K^+K^-$ candidates. Selected $\phi \rightarrow K^+K^-$ candidates are required to satisfy an isolation requirement: the sum of the $p_T$ of the reconstructed inner detector tracks from the main vertex within $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.2$ of the leading track (excluding both tracks constituting the $\phi \rightarrow K^+K^-$ candidate) is required to be less than 10% of the $p_T$ of the $\phi$ candidate, $p_T^{\phi,K^+K^-}$.

Photons are reconstructed from clusters of energy in the electromagnetic calorimeter. Clusters without matching tracks are classified as unconverted photon candidates while clusters matched to tracks consist of multiple $e^+e^-$ pairs are classified as converted photon candidates [36]. Reconstructed photon candidates are required to have transverse momentum $p_T^\gamma > 35$ GeV, pseudorapidity $|\eta^\gamma| < 2.37$, excluding the barrel/endcap calorimeter transition region $1.37 < |\eta^\gamma| < 1.52$, and to satisfy the “tight” photon identification criteria [37]. An isolation requirement is imposed to further suppress the contamination from jets. The sum of the transverse momenta of all tracks within $\Delta R = 0.2$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than 5% of $p_T^\gamma$. The effects of multiple $pp$ interactions per bunch crossing (pile-up) in this calculation are reduced by removing tracks that do not originate from the primary vertex. Additionally, the sum of the transverse momenta of all energy deposits in the calorimeters within $\Delta R = 0.4$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than $(2.45 \text{ GeV} + 0.022 \times p_T^\gamma)$. The calorimeter isolation measurements are also corrected for the effects of pile-up.

Combinations of a $\phi \rightarrow K^+K^-$ candidate and a photon, satisfying $\Delta \phi(K^+K^-, \gamma) > 0.5$, are retained for further analysis. When multiple combinations are possible, the combination of the highest-$p_T$ photon and the $\phi \rightarrow K^+K^-$ candidate with a mass closest to the $\phi$ meson mass is retained. The transverse momentum of $\phi \rightarrow K^+K^-$ candidates is required to be greater than a threshold that varies as a function of the invariant mass of the three-body system, $m_{K^+K^-\gamma}$. Thresholds of 40 GeV and 45 GeV are imposed for the regions $m_{K^+K^-\gamma} < 91$ GeV and $m_{K^+K^-\gamma} \geq 125$ GeV, respectively. The threshold is varied from 40 GeV to 45 GeV as a linear function of $m_{K^+K^-\gamma}$ in the region $91 \leq m_{K^+K^-\gamma} < 125$ GeV. This approach ensures optimal sensitivity for both the Higgs and Z boson searches. The total signal efficiency (kinematic acceptance, 

\footnote{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 x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates are used in the transverse plane, with $\Delta \phi$ being the difference in azimuthal angles around the z-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.}
and trigger and reconstruction efficiencies) is 18% and 8% for the Higgs and Z boson decays, respectively. The difference in efficiencies primarily arises due to the softer $p_T$ and $p_{T,K+K-}$ distributions in the case of $Z \rightarrow \phi \gamma$ production. The $m_{K+K-\gamma}$ resolution is around 1.8% for both the Higgs and Z boson decays. The $m_{K+K-}$ distribution for selected $\phi \gamma$ candidates, with no $m_{K+K-}$ requirement applied, is shown in Figure 1 and exhibits a clear peak at the $\phi$ meson mass.

The $m_{K+K-}$ distribution of selected $\phi \gamma$ combinations with the complete event selection applied (see text), apart from the requirement on $m_{K+K-}$. The data are fitted with the convolution of a Breit-Wigner distribution, using the $\phi$ width [34], and a Gaussian distribution to represent the experimental resolution, while the background is modeled with an analytical function, commonly used to describe a kinematic threshold [38]. The main source of background to the search comes from events involving inclusive multijet or photon + jet processes where a $\phi \rightarrow K+K-$ candidate is reconstructed from tracks associated with a jet. The normalization of this inclusive background is extracted directly from a fit to data. The selection criteria discussed earlier shape the $m_{K+K-\gamma}$ distribution for background such that it exhibits a threshold structure near 100 GeV, and falls then smoothly towards higher mass values. Given the nontrivial shape of this background, these processes are modeled with a nonparametric data-driven approach using templates to describe the kinematic distributions. A similar procedure was used in the search for Higgs and Z boson decays to $J/\psi \gamma$ and $\Upsilon(nS) \gamma$ described in Ref. [14]. The approach exploits a sample of around 4000 $K^+K^-\gamma$ candidate events passing all of the kinematic selection requirements described previously, except that the photon and $\phi \rightarrow K^+K^-$ candidates are not required to satisfy the nominal isolation requirements. The events satisfying this selection are collected in a generation region (GR). The contamination of this sample from signal events is expected to be negligible and is verified not to affect the shape of the background model. Probability density functions (pdfs) that model the $p_{T,K}^\phi$, $p_{T,K}^\gamma$, $\Delta\eta(K^+K^-,\gamma)$, and $\Delta\phi(K^+K^-,\gamma)$ distributions of this sample are constructed using a Gaussian kernel density estimation [39]. Correlations between these variables and $p_{T,K}^\gamma$ in the event were studied and accounted for in the background model by deriving separate pdfs in 13 exclusive regions of $p_{T,K}^\gamma$. In the case of the $\phi \rightarrow K^+K^-$ and photon isolation variables, correlations are accounted for by using two-dimensional histograms derived in the same 13 exclusive regions of $p_{T,K}^\gamma$. Values of $m_{K+K-}$ are sampled from the corresponding distribution in the GR. The pdfs of these kinematic and isolation variables are sampled to generate an ensemble.

Figure 1: The $m_{K+K-}$ distribution of selected $\phi \gamma$ combinations with the complete event selection applied (see text), apart from the requirement on $m_{K+K-}$. The data are fitted with the convolution of a Breit-Wigner distribution, using the $\phi$ width [34], and a Gaussian distribution to represent the experimental resolution, while the background is modeled with an analytical function, commonly used to describe a kinematic threshold [38].
of pseudocandidates, each with a complete $K^+K^-\gamma$ four-vector and an associated pair of $\phi \rightarrow K^+K^-$ and photon isolation values. The nominal selection requirements are imposed on the ensemble and the surviving pseudocandidates are used to construct templates for the $m_{K^+K^-\gamma}$ distribution.

To validate this background model with data, the $m_{K^+K^-\gamma}$ distributions in several validation regions, defined by kinematic and isolation requirements looser than the nominal signal requirements, are used to compare the prediction of the background model with the data. The $m_{K^+K^-\gamma}$ distribution in one of these validation regions, defined by the GR selection with the addition of the nominal photon isolation requirement, is shown in Figure 2. The background model is found to describe the data well, and within the observed statistical uncertainties. A consistency test of the background modelling procedure has been performed with a sample of simulated photon + jet events in place of the data; similarly good agreement is observed. The robustness of the background model is further validated by splitting the data into high- and low-$p_T^{K^+K^-\gamma}$ subsets, that exhibit different threshold structures, and confirming that the background model describes the shapes of both $m_{K^+K^-\gamma}$ distributions. Further exclusive background contributions from $Z \rightarrow \ell\ell\gamma$ decays have been studied but are found to represent a negligible contribution for the selection requirements and dataset used in this analysis.

![Figure 2: The distribution of $m_{K^+K^-\gamma}$ in data compared to the prediction of the background model for a validation control sample defined by the GR selection with the addition of the nominal photon isolation requirement. The background model is normalized to the observed number of events within the region shown. The uncertainty band corresponds to the uncertainty envelope derived from variations in the background modeling procedure.](image)

Trigger and identification efficiencies for photons are determined from samples enriched with $Z \rightarrow e^+e^-$ events in data [36, 40]. The systematic uncertainty on the expected signal yield associated with the trigger efficiency is estimated to be 2%. The photon identification efficiency uncertainties, for both the converted and unconverted photons, are estimated to be 2.4% and 2.6% for the Higgs and Z boson signals, respectively. An uncertainty of 6% is assigned to the track reconstruction efficiency and includes effects associated with the material budget of the inner detector and the behavior of the track reconstruction algorithm if a nearby track is present. The integrated luminosity of the data sample has an uncertainty of
5% derived using the method described in Ref. [41]. The photon energy scale uncertainty, determined from $Z \rightarrow e^+e^-$ events and validated using $Z \rightarrow \ell\ell\gamma$ events [42], is propagated through the simulated signal samples as a function of $\eta^\gamma$ and $p_T^\gamma$. The uncertainty associated with the description of the photon energy scale in the simulation is found to be less than 0.3% of the three-body invariant mass while the uncertainty associated with the photon energy resolution is found to be negligible relative to the overall three-body invariant mass resolution. Similarly, the systematic uncertainty associated with the track momentum measurement is found to be negligible.

The uncertainty on the shape of the inclusive multijet and photon + jet background is estimated through the study of variations in the background modeling procedure. The shape of the background model is allowed to vary around the nominal shape within an envelope associated with shifts in the $p_T^{K^+K^-}$ distribution, tilts of the $\Delta\phi(K^+K^-,\gamma)$ distribution, and by neglecting the weakest correlation accounted for in the nominal background model.

Results are compared to background and signal predictions using an unbinned maximum-likelihood fit to the $m_{K^+K^-\gamma}$ distribution. The fit uses the selected events with $m_{K^+K^-\gamma} < 300$ GeV. The systematic uncertainties described above result in a 3% deterioration of the sensitivity to the $H \rightarrow \phi\gamma$ decay. For the $Z$ boson decay the reduction is larger, 13%, mainly due to the systematic uncertainty in the background shape. The expected and observed numbers of background events within the $m_{K^+K^-\gamma}$ ranges relevant to the Higgs and $Z$ boson signals are shown in Table 1.

<table>
<thead>
<tr>
<th>Mass Range [GeV]</th>
<th>Observed (Expected) Background</th>
<th>Expected Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Z$</td>
<td>$H$</td>
</tr>
<tr>
<td>All</td>
<td>81–101</td>
<td>120–130</td>
</tr>
<tr>
<td></td>
<td>$10^6$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>1065</td>
<td>288 (266 ± 9)</td>
<td>89 (87 ± 3)</td>
</tr>
<tr>
<td></td>
<td>6.7 ± 0.7</td>
<td>13.5 ± 1.5</td>
</tr>
</tbody>
</table>

Table 1: The number of observed events and the expected background yield for the two $m_{K^+K^-\gamma}$ ranges of interest. The Higgs and $Z$ boson contributions expected for branching fraction values of $10^{-3}$ and $10^{-6}$, respectively, and estimated using Monte Carlo simulations are also shown.

On the basis of the observed data, upper limits are set on the branching fractions for the Higgs and $Z$ boson decays to $\phi\gamma$ using the CL$_s$ modified frequentist formalism [43] with the profile-likelihood ratio test statistic [44]. The result of the background-only fit is shown in Figure 3; a small excess of two standard deviations is observed in the $Z$ boson mass region, estimated using the asymptotic approximation for the distribution of the test statistic. The expected SM production cross section is assumed for the Higgs boson while the ATLAS measurement of the inclusive $Z$ boson cross section is used for the $Z$ boson signal [30]. The results are summarized in Table 2. The observed 95% confidence level (CL) upper limits on the branching fractions for $H \rightarrow \phi\gamma$ and $Z \rightarrow \phi\gamma$ decays are around 600 and 700 times the expected SM branching fractions, respectively.

<table>
<thead>
<tr>
<th>Branching Fraction Limit (95% CL)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(H \rightarrow \phi\gamma)$ [ $10^{-3}$ ]</td>
<td>1.5$^{+0.7}_{-0.4}$</td>
<td>1.4</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \rightarrow \phi\gamma)$ [ $10^{-6}$ ]</td>
<td>4.4$^{+2.0}_{-1.2}$</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Table 2: Expected and observed branching fraction limits at 95% CL for 2.7 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 13$ TeV. The ±1σ intervals of the expected limits are also given.

In conclusion, a search for the decay of Higgs or $Z$ bosons to $\phi\gamma$ has been performed with a $pp$ collision data sample at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 2.7 fb$^{-1}$ collected with the
Figure 3: The $m_{K^+K^-\gamma}$ distributions of the selected $\phi\gamma$ candidates, along with the results of the maximum-likelihood fit with background-only model. The $1\sigma$ uncertainty band corresponds to the total uncertainty of the background model. The Higgs and $Z$ boson contributions, expected for branching fraction values of $10^{-3}$ and $10^{-6}$, respectively, are also shown.

ATLAS detector at the LHC. No significant excess of events is observed above the background. Upper limits at the 95% CL are set on the branching fractions for the decay of the 125 GeV SM Higgs boson and the $Z$ boson to $\phi\gamma$. The obtained limits are $\mathcal{B}(H \to \phi\gamma) < 1.4 \times 10^{-3}$ and $\mathcal{B}(Z \to \phi\gamma) < 8.3 \times 10^{-6}$.

Acknowledgements

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 and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCUK, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia;
The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, 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), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [45].

References


[29] J. Pumplin et al.,
New generation of parton distributions with uncertainties from global QCD analysis,


[31] ATLAS Collaboration, Measurement of the Z/γ* boson transverse momentum distribution in pp collisions at \( \sqrt{s} = 7 \text{ TeV} \) with the ATLAS detector, JHEP 09 (2014) 145,


[37] ATLAS Collaboration, Measurement of the inclusive isolated prompt photon cross section in pp collisions at \( \sqrt{s} = 7 \text{ TeV} \) with the ATLAS detector, Phys. Rev. D 83 (2011) 052005,
arXiv:1012.4389 [hep-ex].


[39] K. S. Cranmer, Kernel estimation in high-energy physics,

[40] ATLAS Collaboration, Performance of the ATLAS Electron and Photon Trigger in p-p Collisions at \( \sqrt{s} = 7 \text{ TeV} \) in 2011,


[42] ATLAS Collaboration, Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data,


[44] G. Cowan et al., Asymptotic formulae for likelihood-based tests of new physics,

Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) 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, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Department of Physics, The University of Texas at Austin, Austin TX, United States of America
12 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
13 Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain, Spain
14 Institute of Physics, University of Belgrade, Belgrade, Serbia
15 Department for Physics and Technology, University of Bergen, Bergen, Norway
16 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
17 Department of Physics, Humboldt University, Berlin, Germany
18 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; (d) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, Turkey
21 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
22 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
23 Physikalisches Institut, University of Bonn, Bonn, Germany
24 Department of Physics, Boston University, Boston MA, United States of America
25 Department of Physics, Brandeis University, Waltham MA, United States of America
26 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
27 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
28 (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
29 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
30 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
31 Department of Physics, Carleton University, Ottawa ON, Canada
32 CERN, Geneva, Switzerland
33 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
34 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
35 (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) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (also affiliated with PKU-CHEP); (f) Physics Department, Tsinghua University, Beijing 100084, China

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

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

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

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

40 (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

41 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

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

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

44 DESY, Hamburg and Zeuthen, Germany

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

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

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

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

49 INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

51 Section de Physique, Université de Genève, Geneva, Switzerland

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

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

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

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

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

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

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

59 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

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

61 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

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

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

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

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

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

67 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

68 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
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université et CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst MA, United States of America
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam,
Netherlands
108 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
110 Department of Physics, New York University, New York NY, United States of America
111 Ohio State University, Columbus OH, United States of America
112 Faculty of Science, Okayama University, Okayama, Japan
113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
114 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
115 Palacký University, RCPTM, Olomouc, Czech Republic
116 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
117 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 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
121 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
122 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
123 National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
124 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
126 (a) Laboratório de Instrumentação e Física Experimental de Partículas - 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 Física, Universidade do Minho, Braga; (f) Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) 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), NRC KI, Russia
131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
132 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
133 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
135 (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, 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 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
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Cape Town, Cape Town; Department of Physics, University of Johannesburg, Johannesburg; School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University; 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
TRIUMF, Vancouver BC; Department of Physics and Astronomy, York University, Toronto ON, Canada
Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ICTP, Trieste; Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of Illinois, Urbana IL, United States of America
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
\[ak\] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
\[ad\] Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
\[am\] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
\[an\] Also at National Research Nuclear University MEPhI, Moscow, Russia
\[ao\] Also at Department of Physics, Stanford University, Stanford CA, United States of America
\[ap\] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
\[aq\] Also at Flensburg University of Applied Sciences, Flensburg, Germany
\[ar\] Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
\[as\] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
* Deceased