Search for production of resonant states in the photon-jet mass distribution using pp collisions at $\sqrt{s} = 7$ TeV collected by the ATLAS detector


Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.108.211802

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Search for Production of Resonant States in the Photon-Jet Mass Distribution Using \(pp\) Collisions at \(\sqrt{s} = 7\) TeV Collected by the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

(Received 15 December 2011; published 22 May 2012)

This Letter describes a model-independent search for the production of new resonant states in photon + jet events in 2.11 fb\(^{-1}\) of proton-proton collisions at \(\sqrt{s} = 7\) TeV. We compare the photon + jet mass distribution to a background model derived from data and find consistency with the background-only hypothesis. Given the lack of evidence for a signal, we set 95% credibility level limits on generic Gaussian-shaped signals and on a benchmark excited-quark \((q^*)\) model, excluding 2 TeV Gaussian resonances with cross section times branching fraction times acceptance times efficiency near 5 fb and excluding \(q^*\) masses below 2.46 TeV, respectively.

DOI: 10.1103/PhysRevLett.108.211802

PACS numbers: 13.85.Rm, 14.65.Jk, 14.70.Bh, 14.80.-j

In the standard model (SM), proton-proton \((pp)\) collisions do not produce photon + jet pairs through a resonance. Direct photon + jet production occurs at tree level via Compton scattering of a quark and a gluon or through quark-antiquark annihilation, the former accounting for the majority of direct photon + jet production at all center-of-mass energies. Events with a high transverse momentum photon and one or more jets can also arise from radiation off final-state quarks or from multijet processes where dijet or higher-order events produce secondary photons during fragmentation of the hard-scatter quarks and gluons [1–4]. The photon + jet invariant mass \((m_{\gamma j})\) [5] distribution resulting from this mixture of processes is smooth and rapidly falling, constituting a promising place to look for resonances.

Despite many possible exotic production mechanisms such as excited quarks [6,7], quirks [8–10], Regge excitations of string theory [11–14], and topological pions [15], the most recent searches for photon + jet resonances were published a decade ago [16–19]. The previous most sensitive search for new phenomena in the photon + jet final state places limits on effective signal cross sections, cross section times branching fractions for \(\gamma\) and \(\gamma\gamma\) with cross section times acceptance times efficiency near 5 fb and excluding \(q^*\) masses below 2.46 TeV, respectively.

This Letter describes a general search for resonant \(s\)-channel photon + jet production in 2.11 fb\(^{-1}\) of \(pp\) collisions at a center-of-mass energy \(\sqrt{s} = 7\) TeV with the ATLAS detector. It follows earlier measurements of isolated photon differential cross sections at the Large Hadron Collider (LHC) [20,21]. The entire \(m_{\gamma j}\) distribution is fit to a smooth function to obtain the background to this search. We look for evidence of a narrow resonance, not much wider than the detector mass resolution. This search extends the method used in the search for resonant dijet production [22] to handle the more diverse mixture of processes contributing to the \(m_{\gamma j}\) distribution. In the absence of a signal, we use Bayes’ theorem to set limits on Gaussian-shaped resonances and on a benchmark excited-quark \((q^*)\) model [6,7].

In the excited-quark model studied here, the LHC could produce single \(q^*\) states with vectorlike couplings to the \(W\) and \(Z\) gauge bosons via the absorption of a gluon by a quark. As in Ref. [7], we define the model by one parameter, the excited-quark mass \(m_{q^*}\), setting the compositeness scale equal to \(m_{q^*}\), and SU(3), SU(2), and U(1) coupling multipliers \(f_s = f = f' = 1\). At \(m_{q^*} = 2.5\) TeV, this gives branching fractions for \(u^* \rightarrow u\gamma\) and \(u^* \rightarrow u\gamma\) of 0.85 and 0.02, respectively. The corresponding branching fractions for \(d^*\) quarks are 0.85 and 0.005, respectively. We do not make any further assumptions about higher-order corrections or the excited-quark dynamics and neglect scale uncertainties and uncertainties on parton distribution functions in order to provide a convenient benchmark process for theoretical reinterpretation.

We simulate the SM direct photon processes and the \(q^*\) model with PYTHIA 6.4.25 [23] using the AMBT1 tune [24], MSTW2007 parton distribution functions [25], and a GEANT4-based detector simulation [26,27]. Supplementary studies of the background shape function are performed with next-to-leading-order JETPHOX 1.3.0 [1,2]. Additional inelastic \(pp\) interactions, termed pileup, are included in the event simulation, distributed so as to reproduce the number of collisions per bunch crossing in the data. The mean number of pileup interactions is approximately 6.

A detailed description of the detector is available in Ref. [28]. Photons are detected by a lead–liquid–argon sampling electromagnetic calorimeter (EMC) with an...
accordance geometry. In front of the EMC, the inner detector allows an accurate reconstruction of tracks from the primary $pp$ collision point and also from secondary vertices, permitting an efficient reconstruction of photon conversions in the inner detector up to a radius of 80 cm. For $|\eta| < 1.37$ [29], an iron–scintillator-tile calorimeter behind the EMC provides hadronic coverage. The endcap and forward regions, $1.5 < |\eta| < 4.9$, are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. For further details relevant to photon identification and measurement, see Ref. [20]. For details relevant to jet detection and measurement, see Ref. [30]. Events are collected with a trigger requiring at least one photon candidate with a transverse momentum ($p_T$) above 80 GeV. The integrated luminosity of the sample is $(2.11 \pm 0.08)$ fb$^{-1}$ [31,32].

Events containing at least one photon and at least one jet are selected for analysis. Each event must have a primary vertex with at least five charged-particle tracks with $p_T > 400$ MeV. Multiple vertices can appear when pileup interactions occur for the same bunch crossing. If more than one vertex is found, the primary vertex is taken as the vertex with the highest scalar sum $p_T^2$ of associated tracks. Photon candidates with $p_T > 85$ GeV and $|\eta| < 1.37$ and jet candidates with $p_T > 30$ GeV and $|\eta| < 2.8$ are used. These objects are identified using criteria that closely follow those applied in the isolated photon cross section measurement [20] and dijet resonance search [22]. Subleading photons or jets are allowed; when more than one photon or jet is found, the highest $p_T$ candidates are selected to constitute the photon + jet pair.

Jets are reconstructed from clusters of calorimeter cells using the anti-$k_T$ clustering algorithm [33] with radius parameter $R = 0.6$. Jet energies are corrected to the hadronic scale [30,34]. Jet candidates are rejected in regions of the calorimeter where the jet energy is not yet measured in an optimal way. Candidates consistent with spurious calorimeter noise or energy spikes are also rejected.

Photon candidates are reconstructed from clusters in the electromagnetic calorimeter and tracking information provided by the inner detector. They satisfy standard ATLAS selection criteria that are designed to reject instrumental backgrounds from hadrons [20]. The photon candidates must meet $p_T$- and $\eta$-dependent requirements on hadronic leakage, shower shapes in the electromagnetic strip layer, and shower shapes in the second sampling layer of the electromagnetic calorimeter. Inner detector tracking information is used to reject electrons and to recover photons converted to $e^+e^-$ pairs. Energy calibrations are applied to photon candidates to account for energy loss in front of the electromagnetic calorimeter and for both lateral and longitudinal leakage. Events are discarded if the leading photon appears in calorimeter cells affected by noise bursts or transient hardware problems.

These photon identification criteria reduce instrumental backgrounds to a negligible level, but much of the substantial background from secondary (jet fragmentation) photons remains. We reduce this background with requirements on nearby calorimeter activity. Associated “isolation” calorimeter energy near the photon candidate is calculated by summing the transverse momentum as measured in electromagnetic and hadronic calorimeter cells inside a cone of radius $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$ centered on the photon cluster, but excluding the energy of the photon cluster itself. The isolation energy is corrected on an event-by-event basis for the ambient energy density due to pileup and the underlying event. This isolation energy is required to be less than 7 GeV.

The photon deposits energy in the electromagnetic calorimeter in such a way that it is also reconstructed as a jet. Jets within $\Delta R < 0.2$ of the photon are therefore not considered in this analysis. We require an angular separation $\Delta R(\gamma, \text{jet}) > 0.6$ between the signal photon and all jets with $p_T > 30$ GeV to reduce the background from photons during fragmentation of final-state quarks (fragmentation photons) and to reduce the systematic effects from the leakage of nearby jet showers into the photon isolation energy measurement.

An additional reduction of the fragmentation photon background is achieved by requirements on the photon and jet pseudorapidities. Dijet production rates increase with jet pseudorapidity whereas rates for our assumed $s$-channel signal would diminish. We restrict the analysis to photons in the barrel calorimeter, $|\eta| < 1.37$, and require $|\eta_{\gamma} - \eta_j| < 1.4$ between the photon and jet. The former criterion was chosen to avoid kinematic bias of the $m_{\gamma j}$ distribution due to the inclusion of any $\eta$ range where reconstruction efficiency is lower, such as the barrel-endcap transition region $1.37 < |\eta| < 1.52$. The latter was chosen by optimizing the expected significance using the $|\eta_{\gamma} - \eta_j|$ distributions found in excited-quark signal simulation and background-dominated control data selected as in the nominal analysis but inverting the photon isolation requirement. This control sample is also used to check the background estimate.

After the above selections, Fig. 1 shows the distribution of the $m_{\gamma j}$ invariant mass in bins equal to the mass resolution. The $m_{\gamma j}$ resolution is about 4% at 600 GeV, improving to 3% at 2 TeV. We determine the combined SM and instrumental background to the search by fitting this distribution to the four-parameter ansatz,

$$f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1 - x)^{p_2}x^{-p_3}e^{-p_4 x},$$

The motivation for this function is discussed in Refs. [16,35–37]. The fit result is also shown in Fig. 1. The bottom panel of the figure shows the statistical significance of the difference between data and the fit in each bin [38]. With a negative log-likelihood test statistic, the $p$
FIG. 1 (color online). Invariant mass of the photon + jet pair for events passing the final selection. Overlaid: The fitted background function integrated over each bin (stepped solid line), the most discrepant region identified by BUMPHUNTER (two dashed vertical lines), and three examples of excited-quark signals, normalized to luminosity, as described in the text. The bottom panel shows the statistical significance of the difference between data and background in each bin.

The value is 23%, indicating that the data distribution is compatible with Eq. (1). The functional form also describes the leading-order PYTHIA direct photon prediction for comparable event statistics.

We search for statistical evidence of a resonance in this distribution using the BUMPHUNTER algorithm [39]. The algorithm operates on the binned $m_{\gamma j}$ distribution, comparing the background estimate with the data in mass intervals of varying contiguous bin multiplicities across the entire distribution. For each interval in the scan, it computes the significance of any excess found. The algorithm identifies the interval 784–1212 GeV, indicated by the vertical lines in Fig. 1, as the single most discrepant interval. The significance of the outcome is evaluated using the ensemble of possible outcomes for the significance of any region in the distribution in the background-only hypothesis, obtained by repeating the analysis on pseudodata drawn from the background function. Before including systematic uncertainties, the probability ($p$ value) of observing a background fluctuation at least as significant as the above, including the trials factor, or “look-elsewhere” effect, is 20%. Inclusion of systematic uncertainties renders the $p$ value similarly large.

Lacking evidence of any signal, we exclude two types of photon + jet signals: a generic signal with a Gaussian distribution and arbitrary production cross section, and the excited-quark model. We compute Bayesian limits at 95% credibility level (CL) using a prior probability density that is constant for positive values of the signal production cross section and zero for unphysical, negative values, as described in Ref. [40]. We consider systematic uncertainties on the expected signal yield due to imperfect knowledge of the detector: the integrated luminosity (3.7%), trigger efficiencies ($\leq 0.5\%$), and signal photon identification efficiencies (2.0%). The last of these consists of isolation (0.4%), pile-up interactions (0.5%), conversions (1.2%), simulation mismodeling (1.3%), and the extrapolation of the photon identification efficiency to high $p_T$ ($<0.3\%$). Uncertainties on the photon energy scale (0.5%–1.5%), jet energy scale (2%–4%), and jet energy resolution (5%–15%) contribute through their effects on the signal distribution. These systematic uncertainties are treated as marginalized Gaussian nuisance parameters in the limit calculation.

We also evaluate two systematic uncertainties on the background estimate. To account for the statistical uncertainties on the background fit parameters, we repeatedly fit the background function to pseudodata for each bin drawn from Poisson distributions. The mean of the Poisson distribution for a given bin corresponds to the number of entries actually observed in that bin in the data. We then take the variation in the fit predictions for a given bin, 0.5% of the background at low mass to almost 10% of the background at 2 TeV, as indicative of the systematic uncertainty. We treat this bin-by-bin uncertainty in the limit as fully correlated, using a single nuisance parameter that scales the entire background contribution.

While our function can describe the $m_{\gamma j}$ shape for direct photon production, as modeled in the PYTHIA direct photon + jet simulation, the function need not remain a good description of the full distribution after including nonisolated and fragmentation photon events. For example, the function describes the next-to-leading-order prediction implemented in JETPHOX, which includes the fragmentation photon contributions, for some viable choices of theory parameters but not for others.

The second background systematic uncertainty accounts for any unmodeled features of fragmentation photon events in our isolated photon sample. We fit the background function to the $m_{\gamma j}$ distribution in the control data selected with the inverted isolation requirement, then measure for each $m_{\gamma j}$ bin the magnitude of any deviation from the fit, and assign the ratio of the deviation to the fit expectation as a parametrization bias systematic uncertainty. To extrapolate this uncertainty to large $m_{\gamma j}$ where few control data exist, we fit the tail $m_{\gamma j} > 1$ TeV with a two-degree polynomial.

Figure 2 shows the model-independent limits on the effective cross section, cross section $\sigma$ times branching fraction $B$ times acceptance $A$ times efficiency $\epsilon$, of a potential signal as a function of the central mass of each signal template. We take the signal line shape to be a Gaussian distribution with one of three widths, $\sigma_G/m_G = 5\%$, 7\%, and 10\% of the central mass of the
Gaussian. The limit weakens as the width increases and the peak becomes less distinct. For example, for a 1 TeV signal the limit for a width of 10% is 1.6 times the limit for a width of 5%.

The limit on the effective cross section in the excited-quark model is shown in Fig. 3 as a function of the $q^*$ mass. Also shown are $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands indicating the underlying distribution of possible limit outcomes in the background-only hypothesis. The solid line indicates the prediction from the PYTHIA excited-quark implementation. We exclude such excited quarks with masses below 2.46 TeV at 95% CL, complementing the more stringent exclusion below 2.99 TeV on this specific $q^*$ model in the dijet final state [22].

In conclusion, the photon + jet mass distribution measured in $2.11 \text{ fb}^{-1}$ of $pp$ collision data collected at $\sqrt{s} = 7 \text{ TeV}$ by the ATLAS Collaboration has been examined for narrow resonances. The observed distribution extends up to masses of about 2 TeV. It is well described by a smooth function fitted to it and assumed to represent the SM expectation. No evidence for the production of resonances is found. We set limits at 95% CL on the Gaussian line shape and excited-quark signal using Bayesian statistics. The limits on Gaussian resonances, for example, exclude 2 TeV resonances with effective cross sections near $5 \text{ fb}$. We also exclude the excited-quark model in the photon + jet final state for masses up to 2.46 TeV. The limits reported here on the resonant production of new particles in the photon + jet final state are the most stringent limits set to date in this channel.

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, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; CONICET, Colombia; MEST CR, MPO CR and VSC CR, Czech Republic; DSRF, DNSRC and Lundenbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSA, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRSST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MÉRYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, 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.
The invariant mass $m_{\gamma j}$ is defined as $\sqrt{(E^2 + p^2) - (\vec{p}^2 + \vec{p}'^2)}$, where $E$ and $p$ denote the energy and momentum, respectively, of the photon and the jet.

The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln(\tan(\theta/2))$. The transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.

ATLAS uses a right-handed coordinate system with the $z$ axis along the beam pipe. The $x$ axis points to the center of the LHC ring, and the $y$ axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, with azimuthal angle $\phi$. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln(\tan(\theta/2))$. The transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.
M. Ziolkowski,140 R. Zitoun,4 L. Živković,3 V. V. Zmouchko,127,2 G. Zobernig,171 A. Zoccoli,19a,19b Y. Zolnierowski,4 A. Zsenei,29 M. zur Nedden,15 V. Zutshi,105 and L. Zwalinski29

(ATLAS Collaboration)

1University at Albany, Albany, New York, USA
2Department of Physics, University of Alberta, Edmonton AB, Canada
3Department of Physics, Ankara University, Ankara, Turkey
3aDepartment of Physics, Dumlupinar University, Kutahya, Turkey
3bDepartment of Physics, Gazi University, Ankara, Turkey
3dDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
3eTurkish Atomic Energy Authority, Ankara, Turkey
4LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
6Department of Physics, University of Arizona, Tucson, Arizona, USA
7Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
8Physics Department, University of Athens, Athens, Greece
9Physics Department, National Technical University of Athens, Zografou, Greece
10Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12Institute of Physics, University of Belgrade, Belgrade, Serbia
12aInstitute of Physics, University of Belgrade, Belgrade, Serbia
12bVinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
13Department for Physics and Technology, University of Bergen, Bergen, Norway
14Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
15Department of Physics, Humboldt University, Berlin, Germany
16Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18aDepartment of Physics, Bogazici University, Istanbul, Turkey
18bDivision of Physics, Dogus University, Istanbul, Turkey
18cDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
18dDepartment of Physics, Istanbul Technical University, Istanbul, Turkey
19aINFN Sezione di Bologna, Italy
19bDipartimento di Fisica, Università di Bologna, Bologna, Italy
20Physikalisches Institut, University of Bonn, Bonn, Germany
21Department of Physics, Boston University, Boston, Massachusetts, USA
22Department of Physics, Brandeis University, Waltham, Massachusetts, USA
23aUniversidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
23bFederal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
23cFederal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
23dInstituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
24Physics Department, Brookhaven National Laboratory, Upton, New York, USA
25National Institute of Physics and Nuclear Engineering, Bucharest, Romania
25aUniversity Politehnica Bucharest, Bucharest, Romania
25bWest University in Timisoara, Timisoara, Romania
26Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28Department of Physics, Carleton University, Ottawa ON, Canada
28aDepartment of Physics, Carleton University, Ottawa ON, Canada
29INAF, Italy
30Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
31aDepartamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
31bDepartamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32aInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
32bDepartment of Modern Physics, University of Science and Technology of China, Anhui, China
32cDepartment of Physics, Nanjing University, Jiangsu, China
32dSchool of Physics, Shandong University, Shandong, China
33Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
34Nevis Laboratory, Columbia University, Irvington, New York, USA
35Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

211802-14
INFN Gruppo Collegato di Cosenza, Italy

Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

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

Physics Department, Southern Methodist University, Dallas, Texas, USA

Physics Department, University of Texas at Dallas, Richardson, Texas, USA

DESY, Hamburg and Zeuthen, Germany

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

Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany

Department of Physics, Duke University, Durham, North Carolina, USA

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 i.Br., Germany

Section de Physique, Université de Genève, Geneva, Switzerland

INFN Sezione di Genova, Italy

Dipartimento di Fisica, Università di Genova, Genova, Italy

E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi, Georgia

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 Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France

Department of Physics, Hampton University, Hampton, Virginia, USA

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA

Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

Faculty of Science, Hiroshima University, Hiroshima, Japan

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

Department of Physics, Indiana University, Bloomington, Indiana, USA

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

University of Iowa, Iowa City, Iowa, USA

Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA

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

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

Physics Department, Lancaster University, Lancaster, United Kingdom

INFN Sezione di Lecce, Italy

Dipartimento di 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

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 and CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA

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, Michigan, USA

Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

INFN Sezione di Milano, Italy

Dipartimento di Fisica, Università di Milano, Milano, Italy
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
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, 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, Nagoya University, Nagoya, Japan
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

Department of Physics, University of New Mexico, Albuquerque, New Mexico, USA
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
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York, New York, USA
Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
INFN Sezione di Pavia, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentación e Física Experimental de Partículas - LIP, Lisboa, Portugal
Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina SK, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma I, Italy
Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Italy
Dipartimento di Fisica, Università Roma Tre, Roma, Italy
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat, Morocco
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des Sciences, Université Mohammed V- Agdal, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA