Search for new phenomena in photon+jet events collected in proton–proton collisions at √s = 8 TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This Letter describes a model-independent search for the production of new resonances in photon + jet (γ + jet) events using 20 fb⁻¹ of proton–proton LHC data recorded with the ATLAS detector at a centre-of-mass energy of √s = 8 TeV. The γ+jet mass distribution is compared to a background model fit from data; no significant deviation from the background-only hypothesis is found. Limits are set at 95% credibility level on generic Gaussian-shaped signals and two benchmark phenomena beyond the Standard Model: non-thermal quantum black holes and excited quarks. Non-thermal quantum black holes are excluded below masses of 4.6 TeV and excited quarks are excluded below masses of 3.5 TeV.
Search for new phenomena in photon+jet events collected in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration

Abstract

This Letter describes a model-independent search for the production of new resonances in photon + jet ($\gamma + \text{jet}$) events using $20 \text{ fb}^{-1}$ of proton–proton LHC data recorded with the ATLAS detector at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The $\gamma + \text{jet}$ mass distribution is compared to a background model fit from data; no significant deviation from the background-only hypothesis is found. Limits are set at 95% credibility level on generic Gaussian-shaped signals and two benchmark phenomena beyond the Standard Model: non-thermal quantum black holes and excited quarks. Non-thermal quantum black holes are excluded below masses of 4.6 TeV and excited quarks are excluded below masses of 3.5 TeV.

1. Introduction

Several exotic production mechanisms have been proposed that produce massive photon + jet ($\gamma + \text{jet}$) final states. They include non-thermal quantum black holes (QBHs) [1–3], excited quarks [4–6], quirks [7–9], Regge excitations of string theory [10–12], and topological pions [13]. Of the past searches [14–18], the only LHC search for this signature was done using proton–proton ($pp$) collision data obtained at a centre-of-mass energy of $\sqrt{s} = 7$ TeV with the ATLAS detector. It found no evidence of new physics and placed upper limits on the visible signal cross-section in the range 1.5–100 fb and excluded excited-quark masses up to 2.46 TeV at the 95% credibility level (CL) [18]. The present Letter describes a model-independent search for $x$-channel $\gamma + \text{jet}$ production, improved over the earlier search. It presents the first limits on QBHs decaying to the $\gamma + \text{jet}$ final state and places new limits both on excited quarks and on generic Gaussian-shaped sources which describe other narrow resonant signals such as topological pions. Sensitivity to such signals has been improved compared to the previous search through a combination of an order-of-magnitude larger data sample (20.3 fb$^{-1}$), a higher centre-of-mass energy ($\sqrt{s} = 8$ TeV), reduced background uncertainties, and improved selection criteria at high invariant mass.

The $m_{\gamma\text{jet}}$ distribution is used to search for a peak over the SM background, estimated by fitting a smoothly falling function to the $m_{\gamma\text{jet}}$ distribution in the region $m_{\gamma\text{jet}} > 426$ GeV. In the absence of a signal, Bayes’ theorem is used to set limits on Gaussian-shaped signals and on two benchmark models: QBHs and excited quarks.

Models with extra dimensions, such as the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [23, 24], solve the mass hierarchy problem of the SM by lowering the fundamental scale of quantum gravity ($M_D$) to a few TeV. Consequently, the LHC could produce quantum black holes with masses at or above $M_D > 426$ GeV. In the absence of a signal, Bayes’ theorem is used to set limits on Gaussian-shaped signals and on two benchmark models: QBHs and excited quarks.

Regardless of the number of extra dimensions $n$, such a signal would appear as a local excess over the steeply falling $m_{\gamma\text{jet}}$ distribution near the threshold mass ($M_{\text{th}}$) and would fall exponentially at higher masses. Searches performed by
2. Signal and background simulation samples

To cross-check the data-driven background estimates, the SM prompt photon processes are simulated with PYTHIA 8.165 [31] and SHERPA 1.4.0 [32]. The PYTHIA and SHERPA prompt photon samples use CTEQ6L1 [33] and CT10 [34] leading-order and next-to-leading-order parton distribution functions (PDFs), respectively. The simulated samples of QBHs are obtained from the QED 1.05 generator [35] followed by parton showering using PYTHIA 8.165. The simulated $q^*$ signal samples are generated with the excited-quark model in PYTHIA 8.165. Both signal generators use the MSTW2008LO [36] leading-order PDF set with the AU2 underlying-event tune [37]. Additional inelastic $pp$ interactions, termed pileup, are included in the event simulation by overlying simulated minimum bias events with an average of 20 interactions per bunch crossing. All the above Monte Carlo (MC) simulated samples are produced using the ATLAS full GEANT4 [38] detector simulation [39]. Supplementary studies of the background shape are also performed with the next-to-leading-order JETPHOX 1.3.0 generator [19,21] at parton level using CT10 PDFs.

3. The ATLAS detector

A detailed description of the detector is available in Ref. [40], and the event selection is similar to that described in Ref. [18]. Photons are detected by a lead–liquid-argon sampling electromagnetic calorimeter (EMC). The EMC has a pre-sampler layer and three additional, differently segmented, layers; only the first two are used in photon identification. Upstream 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. For $|\eta| < 1.37$, 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 the electromagnetic and hadronic measurements. Events for this analysis were collected with a trigger requiring at least one photon candidate with transverse momentum ($p_T$) above 120 GeV [41]. The integrated luminosity of the data sample is $(20.3 \pm 0.6)$ fb$^{-1}$.

4. Event selection

Each event is required to contain a primary vertex with at least two tracks each with $p_T > 400$ MeV. If more than one vertex is found, the primary vertex is defined as the one with the highest scalar summed $p_T$ of associated tracks.

Jets are reconstructed from clusters of calorimeter cells [43], using the anti-$k_t$ clustering algorithm [44] with radius parameter $R = 0.6$. The effects on jet energies due to multiple $pp$ collisions in the same or in neighbouring bunch crossings are accounted for by a jet-area-based correction [45,46]. Jet energies are calibrated to the hadronic energy scale using corrections from MC simulation and the combination of several in situ techniques applied to data [47]. Events are discarded if the leading (highest-$p_T$) jet is affected by noise or hardware problems in the detector, or is identified as

---

1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.

2 The systematic uncertainty on the luminosity is derived, following the same methodology as that detailed in Ref. [22], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.
arising from non-collision backgrounds. Only jets with 
\[ |\eta_j| < 2.8 \] are considered further.

Photon candidates are reconstructed from clusters in the electromagnetic calorimeter and tracking information provided by the inner detector. Inner detector tracking information is used to reject electrons and to recover photons converted to e^+e^- pairs [48]. Photon candidates satisfy standard ATLAS selection criteria that are designed to reject backgrounds from hadrons [49]. The photon candidates must meet \( \eta \)-dependent requirements on hadronic leakage and shower shapes in the first two sampling layers of the electromagnetic calorimeter. Energy calibrations are applied to photon candidates to account for energy loss upstream of the electromagnetic calorimeter and for both lateral and longitudinal shower leakage. The simulation is corrected for differences between data and MC events for each photon shower shape variable. Events are discarded if the leading photon is reconstructed using calorimeter cells affected by noise bursts or transient hardware problems.

These photon identification criteria reduce instrumental backgrounds to a negligible level, but some background from fragmentation photons and hadronic jets remains. This background is further reduced by requirements on nearby calorimeter activity. Energy deposited in the calorimeter near the photon candidate, \( E_{\text{iso}} \), must be no larger than 0.011 \( p_T^2 + 3.65 \) GeV, a criterion that provides constant efficiency for all pileup conditions and over the entire \( p_T \) range explored. This transverse isolation energy is calculated by summing the energy as measured in electromagnetic and hadronic calorimeter cells inside a cone of radius \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4 \) centred on the photon cluster, but excluding the energy of the photon cluster itself, and is corrected on an event-by-event basis for the ambient energy density due to pileup and the underlying event, as well as energy leakage from the photon cluster into the cone. Additionally, the photon is required to have angular separation of \( \Delta R(y, \text{jet}) > 1.0 \) between the leading photon and all other jets with \( p_T > 30 \) GeV, with the exception of a required photon-matched jet. Such photon-matched jets arise from the fact that photon energy deposits in the calorimeter are also reconstructed as jets. To further suppress background from fragmentation photons, where the angular separation between the photon and the corresponding photon-matched jet can be large, the leading photon candidate is required to have exactly one reconstructed jet with \( \Delta R(y, \text{jet}) < 0.1 \).

This photon-matched jet is not considered in any other selection criteria, including those related to photon isolation.

Events containing at least one photon candidate and at least one jet candidate, each with \( p_T > 125 \) GeV, are selected for final analysis. The photon trigger is fully efficient for these events. In the events where more than one photon or jet is found, the highest-\( p_T \) candidates are selected to constitute the photon and jet pair to compute \( m_{\gamma j} \).

The sensitivity of the search is improved by requirements on photon and jet pseudorapidities. Dijet production rates increase with jet absolute pseudorapidity whereas rates for an s-channel signal would diminish. Photons are required to be in the barrel calorimeter, \( |\eta_\gamma| < 1.37 \), and the distance between the photon and jet, \( \Delta \eta = |\eta_\gamma - \eta_j| \), must be less than 1.6. The latter requirement was chosen by optimizing the expected significance of signals, using the \( \Delta \eta \) distribution found in QBH and excited-quark signal simulations, with respect to the SM background as predicted by the \( \psi^\prime \) prompt photon simulation.

The acceptance of the event selection is about 60%. It is calculated using parton-level quantities by imposing the kinematic selection criteria (photon/jet [\( |\eta| \), photon/jet \( p_T \), \( \Delta \eta \), \( \Delta R \)). All other selections, which in general correspond to event and object quality criteria, were used to calculate the efficiency based on the events included in the acceptance. The efficiency falls from 83% to 72% for masses from 1 TeV to 6 TeV for QBH signals and from 85% to 80% for excited-quark signals over the same mass range. There are 285356 events in the data sample after all event selections. The highest \( m_{\gamma j} \) value observed is 2.57 TeV.

5. Background estimation

The combined SM and instrumental background to the search is determined by fitting the \( m_{\gamma j} \) distribution to the four-parameter ansatz function [50].

\[
f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1-x)^{p_2}x^{-\left(p_3+p_4\log x\right)}.
\]

The functional form has been tested with \( \psi^\prime \) and \( \psi^\prime \prime \) prompt photon simulations and next-to-leading-order \( \psi^\prime \) photoproduction predictions with comparable sample size. Two additional control samples in the data are also defined to further validate the functional form. The first control sample is defined by reversing two of the photon identification criteria, \( \Delta E \) and \( E_{\text{ratio}} \), that compare the lateral shower shapes of single photons in the first layer of the calorimeter to those of jets with high electromagnetic energy fraction and low particle multiplicity, typical for meson decays. This sample has a similar \( m_{\gamma j} \) shape to the dominant background, SM \( \gamma + \) jet events. The second control sample is defined
6. Results

6.1. Search results

The search region is defined to be $m_{\gamma j} > 426$ GeV, which is the lower edge of the first bin for which binomial searches due to kinematic and trigger threshold effects are negligible. The $\gamma +$ jet search is sensitive to new resonances in the region between 426 GeV and 1 TeV, where the statistics of dijet searches are limited by the higher hadronic trigger thresholds. The BUMPHUNTER algorithm is used to search for statistical evidence of a resonance. The algorithm operates on the binned $m_{\gamma j}$ distribution, comparing the background estimate with the data in mass intervals of varying numbers of adjacent bins across the entire distribution. For each interval in the scan, it computes the significance of any excess found. The significance of the outcome is evaluated using the ensemble of possible outcomes in any part of the distribution under the background-only hypothesis, obtained by repeating the analysis on pseudodata drawn from the background function. The algorithm identifies the two-bin interval 785–916 GeV as the single most discrepant interval. Before including systematic uncertainties, the $p$-value is 61%, including the trials factor, or “look-elsewhere” effect. Thus, the excess is not significant and the data are consistent with a smoothly falling background.

6.2. Limit results

In the absence of any signal, three types of $\gamma +$ jet signals are explored: a generic Gaussian-shaped signal with an arbitrary production cross-section, resulting from resonances with varying intrinsic widths convolved with the detector resolution; the QBH model; and the excited-quark model. For each signal mass considered, the fit to the observed mass distribution is repeated with the sum of the four-parameter background function (Eq. (1)) and a signal template with a normalization determined during the fit. Bayesian limits at the 95% CL are computed as described in Ref. [28] using a prior probability density that is constant for positive values of the signal production cross-section and zero for unphysical, negative values.

Systematic uncertainties affecting the limits on production of new signals are evaluated. The signal yield is subject to systematic uncertainties on the integrated luminosity (2.8%), photon isolation efficiency (1.2%), trigger efficiency (0.5%), and photon identification efficiencies (1.5%). The last of these includes extrapolation to high $p_T$ (0.1%) and pileup effects (0.1%). Uncertainties on the jet and photon energy scale contribute 1.0 – 1.5% and 0.3%, respectively, through their effects on the shape and yield of the signal distribution. The sizes of the systematic uncertainties are similar for the $q^*$ and QBH signals. These systematic uncertainties are treated as marginalized nuisance parameters in the limit calculation. Systematic uncertainties on the value and shape...
of the signal acceptance due to the PDF uncertainties were examined and found to be negligible. To account for the statistical uncertainties on the background fit parameters, the background function is repeatedly fit to pseudodata for which the content of each bin is 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. The variations in the fit predictions for a given bin, 1% of the background at 1 TeV to about 20% of the background at 3 TeV, are taken as indicative of the systematic uncertainty. This bin-by-bin uncertainty is treated in the limit as fully correlated, using a single nuisance parameter that scales the entire background distribution. Several other fit functions from Ref. [50] were tested, and a negligible systematic uncertainty was found.

Fig. 2 shows the model-independent limits on the visible cross-section, defined as the product of the cross-section ($\sigma$) times branching fraction (BR) times acceptance (A) times efficiency ($\epsilon$), of a potential signal as a function of the mass of each signal template, and includes the systematic uncertainties discussed above. The signal line shape is modelled as a Gaussian distribution, with one of four relative widths: $\sigma_G/m_G = 5\%$, 7\%, 10\%, and 15\%, where $\sigma_G$ ($m_G$) is the width (mean mass) of the Gaussian. The differences between the limits for different widths are driven by the increased sensitivity to local fluctuations for the narrower signals. Beyond the highest-mass event recorded, 2.57 TeV, the limits begin to converge due to the absence of observed events. At 1 TeV and 4 TeV the limits are 8 fb and 0.1 fb, respectively, for $\sigma_G/m_G = 5\%$. At 3 TeV, the new limit improves the earlier ATLAS result in this channel by an order of magnitude.

The limit on the visible cross-section in the QBH model is shown in Fig. 3 as a function of $M_\gamma$. The observed (expected) lower limit on the QBH mass threshold is found to be 4.6 (4.6) TeV, at 95% CL. The uncertainty on the QBH theoretical cross-section arising from PDF uncertainties moves the uppermost excluded mass by 0.2\%.

The limit on the visible cross-section in the excited-quark model as a function of the $q^*$ mass, assumed to be the same for $u^*$ and $d^*$, is shown in Fig. 4. The rise in the expected and observed limits at high $m_{q^*}$ is due to the increased fraction of off-shell production of the $q^*$, which alters the signal distribution to lower masses with a wider peak. The observed (expected) lower limit on the excited-quark mass is found to be 3.5 (3.4) TeV, at 95% CL. With a much lower branching fraction than the dijet channel but also smaller backgrounds, this result improves on the present exclusion limits in the di-

![Figure 2: The 95% CL upper limits on $\sigma \times BR \times A \times \epsilon$ for a hypothetical signal with a Gaussian-shaped $m_G$ distribution as a function of the signal mass $m_G$ for four values of the relative width $\sigma_G/m_G$.](image)

7. Conclusions

In conclusion, the $\gamma +$ jet mass distribution measured in 20.3 fb$^{-1}$ of $pp$ collision data, collected at $\sqrt{s} = 8$ TeV by the ATLAS experiment at the LHC, is well described by the background model and no evidence for new phenomena is found. Limits at 95% CL using Bayesian statistics are presented for signal processes yielding a Gaussian line shape, non-thermal quantum black holes, and excited quarks. The limits on Gaussian-shaped resonances exclude 4 TeV resonances with visible cross-sections near 0.1 fb. Non-thermal quantum black hole and excited-quark models with a $\gamma +$ jet final state are excluded for masses up to 4.6 TeV and 3.5 TeV, respectively. The limits reported here on the production of new resonances in the $\gamma +$ 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.
Figure 3: The 95% CL upper limits on $\sigma \times BR \times A \times \varepsilon$ for QBHs decaying to a photon and a jet, as a function of the threshold mass $M_{th}$, assuming $M_D = M_{th}$ and $n = 6$. The limits take into account statistical and systematic uncertainties. Points along the solid black line indicate the mass of the signal where the limit is computed. The black short dashed line is the central value of the expected limit. Also shown are the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands indicating the underlying distribution of possible limit outcomes under the background-only hypothesis. The predicted visible cross-section for QBHs is shown as the long dashed line.

Acknowledgments

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC 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, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (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), CIN2P3 (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.

References

The ATLAS Collaboration


1 School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States of America
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 Physics Department, Ankara University, Ankara; Department of Physics, Gazi University, Ankara; Division of Physics, TOBB University of Economics and Technology, Ankara; Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université de Savoie, 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 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 Institute of Physics, University of Belgrade, Belgrade; Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) 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 Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (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,
CNRS/IN2P3, Paris, France

80 Fysiska institutionen, Lunds universitet, Lund, Sweden

81 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

82 Institut für Physik, Universität Mainz, Mainz, Germany

83 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

84 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

85 Department of Physics, University of Massachusetts, Amherst MA, United States of America

86 Department of Physics, McGill University, Montreal QC, Canada

87 School of Physics, University of Melbourne, Victoria, Australia

88 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

89 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

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

91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

92 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

93 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

94 Group of Particle Physics, University of Montreal, Montreal QC, Canada

95 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

97 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

98 D.V. Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia

99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

101 Nagasaki Institute of Applied Science, Nagasaki, Japan

102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

103 (a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy

104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

107 Department of Physics, Northern Illinois University, DeKalb IL, United States of America

108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

109 Department of Physics, New York University, New York NY, United States of America

110 Ohio State University, Columbus OH, United States of America

111 Faculty of Science, Okayama University, Okayama, Japan

112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

113 Department of Physics, Oklahoma State University, Stillwater OK, United States of America

114 Palacký University, RCPTM, Olomouc, Czech Republic

115 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America

116 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

117 Graduate School of Science, Osaka University, Osaka, Japan

118 Department of Physics, University of Oslo, Oslo, Norway

119 Department of Physics, Oxford University, Oxford, United Kingdom

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

121 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

122 Petersburg Nuclear Physics Institute, Gatchina, Russia

123 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America

125 (a) Laboratorio de Instrumentacão e Física Experimental de Partículas - LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
127 Czech Technical University in Prague, Praha, Czech Republic
128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
129 State Research Center Institute for High Energy Physics, Protvino, Russia
130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
131 Physics Department, University of Regina, Regina SK, Canada
132 Ritsumeikan University, Kusatsu, Shiga, Japan
133 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
134 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Énergie des Sciences Techniques Nucléaires, 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
137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Énergie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
139 Department of Physics, University of Washington, Seattle WA, United States of America
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
145 (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
146 (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
147 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto ON, Canada
160 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
165 (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
166 Department of Physics, University of Illinois, Urbana IL, United States of America
167 Department of Physics and Astronomy, University
of Uppsala, Uppsala, Sweden

168 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

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

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

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

172 Waseda University, Tokyo, Japan

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

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

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

176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

177 Department of Physics, Yale University, New Haven CT, United States of America

178 Yerevan Physics Institute, Yerevan, Armenia

179 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

a Also at Department of Physics, King’s College London, London, United Kingdom

b Also at Laboratorio de Instrumentacao e Fisica Experimental de Partículas - LIP, Lisboa, Portugal

c Also at Faculdade de Ciências and CFNUl, Universidade de Lisboa, Lisboa, Portugal

d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

e Also at TRIUMF, Vancouver BC, Canada

f Also at Department of Physics, California State University, Fresno CA, United States of America

g Also at Novosibirsk State University, Novosibirsk, Russia

h Also at Department of Physics, University of Coimbra, Coimbra, Portugal

i Also at Università di Napoli Parthenope, Napoli, Italy

j Also at Institute of Particle Physics (IPP), Canada

k Also at Department of Physics, Middle East Technical University, Ankara, Turkey

l Also at Louisiana Tech University, Ruston LA, United States of America

m Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

n Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

o Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece

p Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain

q Also at Department of Physics, University of Cape Town, Cape Town, South Africa

r Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

s Also at CERN, Geneva, Switzerland

t Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

u Also at Manhattan College, New York NY, United States of America

v Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

w Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China

x Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

y Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

z Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India

aa Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy

ab Also at 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

ac Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

ad Also at Section de Physique, Université de Genève, Geneva, Switzerland

ae Also at University of Cape Town, Cape Town, South Africa

af Also at Dipartimento di Fisica, Universidade de Minho, Braga, Portugal

ag Also at Department of Physics, Texas at Austin, Austin TX, United States of America

ah Also at Department of Physics and Astronomy, Wigner Research Centre for Physics, Budapest, Hungary

ai Also at DESY, Hamburg and Zeuthen, Germany

aj Also at International School for Advanced Studies (SISSA), Trieste, Italy

ak Also at Department of Physics, University of South Carolina, Columbia SC, United States of America

al Also at Faculty of Physics, M.V.Lomonosov
Moscow State University, Moscow, Russia

* Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America

mb Also at Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

ma Also at Department of Physics, Oxford University, Oxford, United Kingdom

an Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

ao Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

* Deceased