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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)

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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.

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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 section, cross section times branching fraction times acceptance times efficiency, of the order of 1 pb and on excited-quark masses up to 460 GeV at the 95% confidence level [16].

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 $u^* \rightarrow ug$ and $u^* \rightarrow uy$ 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
accordian 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 $(2.11 \pm 0.08) \text{ fb}^{-1}$ [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,

$$f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1 - x)^{p_2}x^{-p_3-p_4\ln x}.$$  \hspace{1cm} (1)

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 $p$
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 ($<0.5\%$), 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 distribution.

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 parameterization 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 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 fb⁻¹ of pp collision data collected at √s = 7 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 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.

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The invariant mass $m_{\gamma j}$ is defined as $\sqrt{(E^2 + E_j^2) - (E^2 + E_j^2 - p^2)^2}$, where $E$ and $p$ denote the energy and momentum, respectively, of the photon and the jet.

References:

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[29] 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,34 V. V. Zmouchko,127,a 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
3aDepartment of Physics, Ankara University, Ankara, Turkey
3bDepartment of Physics, Dumlupinar University, Kutahya, Turkey
3cDepartment of Physics, Gazi University, Ankara, Turkey
3dDivision of Physics, TOBB University of Economics and Technology, 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
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
25aNational Institute of Physics and Nuclear Engineering, Bucharest, Romania
25bUniversity Politehnica Bucharest, Bucharest, Romania
25cWest 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
29CERN, Geneva, Switzerland
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 Maria, 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
137Department of Physics, University of Washington, Seattle, Washington, USA
138Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
139Department of Physics, Shinshu University, Nagano, Japan
140Fachbereich Physik, Universität Siegen, Siegen, Germany
141Department of Physics, Simon Fraser University, Burnaby BC, Canada
142SLAC National Accelerator Laboratory, Stanford, California, USA
143aFaculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
143bDepartment of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
144aDepartment of Physics, University of Johannesburg, Johannesburg, South Africa
144bSchool of Physics, University of the Witwatersrand, Johannesburg, South Africa
145aDepartment of Physics, Stockholm University, Sweden
145bThe Oskar Klein Centre, Stockholm, Sweden
146Physics Department, Royal Institute of Technology, Stockholm, Sweden
147Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
148Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
149School of Physics, University of Sydney, Sydney, Australia
150Institute of Physics, Academia Sinica, Taipei, Taiwan
151Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
152Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
153Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
154International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
155Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
156Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
157Department of Physics, University of Toronto, Toronto ON, Canada
158aTRIUMF, Vancouver BC, Canada
158bDepartment of Physics and Astronomy, York University, Toronto ON, Canada
159Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki 305-8571, Japan
160Science and Technology Center, Tufts University, Medford, Massachusetts, USA
161Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
162Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
163aINFN Gruppo Collegato di Udine, Italy
163bICTP, Trieste, Italy
163cDipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
164Department of Physics, University of Illinois, Urbana, Illinois, USA
165Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
166Instituto 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
167Department of Physics, University of British Columbia, Vancouver BC, Canada
168Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
169Waseda University, Tokyo, Japan
170Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
171Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
172Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
173Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
174Department of Physics, Yale University, New Haven, Connecticut, USA
175Yerevan Physics Institute, Yerevan, Armenia
176Domaine Scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

aDeceased.
bAlso at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal.
cAlso at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
dAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
eAlso at TRIUMF, Vancouver BC, Canada.
fAlso at Department of Physics, California State University, Fresno, CA, USA.
gAlso at Novosibirsk State University, Novosibirsk, Russia.
hAlso at Fermilab, Batavia, IL, USA.
iAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.
jAlso at Università di Napoli Parthenope, Napoli, Italy.
kAlso at Institute of Particle Physics (IPP), Canada.
1 Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
2 Also at LA Tech University, Ruston, LA, USA.
3 Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
4 Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.
5 Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
6 Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
7 Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
8 Also at Manhattan College, New York, NY, USA.
9 Also at School of Physics, Shandong University, Shandong, China.
10 Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
11 Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
12 Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
13 Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.
14 Also at Section de Physique, Université de Genève, Geneva, Switzerland.
15 Also at Departamento de Física, Universidade de Minho, Braga, Portugal.
16 Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
17 Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
18 Also at CA Institute of Technology, Pasadena CA, USA.
19 Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China.
20 Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
21 Also at Department of Physics, Oxford University, Oxford, United Kingdom.
22 Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
23 Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
24 Also at Laboratoire de Physique Nucléaire et de Hautes Énergies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.