Search for new phenomena in dijet angular distributions in proton-proton collisions at $s = 8$ TeV measured with the ATLAS detector


Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.114.221802

Link to publication

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: http://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.

UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)

Download date: 05 Jan 2019
A search for new phenomena in LHC proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV was performed with the ATLAS detector using an integrated luminosity of 17.3 fb$^{-1}$. The angular distributions are studied in events with at least two jets; the highest dijet mass observed is 5.5 TeV. All angular distributions are consistent with the predictions of the standard model. In a benchmark model of quark contact interactions, a compositeness scale below 8.1 TeV in a destructive interference scenario and 12.0 TeV in a constructive interference scenario is excluded at 95% C.L.; median expected limits are 8.9 TeV for the destructive interference scenario and 14.1 TeV for the constructive interference scenario.

The angular distribution of jets relative to the beam axis in events with high dijet invariant mass ($m_{jj}$) provides stringent tests of perturbative quantum chromodynamics (QCD) as well as theories of new phenomena. QCD calculations predict that dijet production, dominated by $t$-channel gluon exchange in the kinematic region of proton-proton (pp) collisions at the LHC, features steeply falling $m_{jj}$ distributions and angular distributions peaked at $|\cos(\theta^*)| = 1$, where $\theta^*$ is the polar scattering angle in the two-parton center-of-mass frame. New phenomena, such as strong gravity [1,2] or new interactions [3-6] typically predict angular distributions which are more isotropic.

Previous studies of dijet angular distributions, at the CERN SPS [7,8], the FNAL Tevatron [9,10], the CERN LHC at $\sqrt{s} = 7$ TeV [11-16], and by the CMS Collaboration at $\sqrt{s} = 8$ TeV [17], have reported results consistent with the standard model (SM). This Letter reports on studies of dijet angular distributions in pp collisions at $\sqrt{s} = 8$ TeV in data with an integrated luminosity of 17.3 fb$^{-1}$ collected with the ATLAS detector in 2012.

A detailed description of the ATLAS detector is published elsewhere [18]. The detector is instrumented over almost the entire solid angle around the pp collision point, with layers of tracking detectors, calorimeters, and muon detectors.

The jets are measured using a calorimeter system composed of different detector types covering different regions in $\eta$ [19] and depth. The electromagnetic calorimeter is composed of liquid-argon sampling calorimeters, using lead as an absorber, and is split into a barrel ($|\eta| < 1.475$) and two end caps ($1.375 < |\eta| < 3.2$). The hadronic calorimeter is divided into a barrel and two extended barrels ($|\eta| < 1.75$), and two endcaps ($1.5 < |\eta| < 3.2$). The barrel and extended barrels are sampling calorimeters with steel as absorber and scintillator tiles as the active medium, while the hadronic end caps are liquid-argon calorimeters with copper as the absorber. In the very forward regions ($3.1 < |\eta| < 4.9$) there are liquid argon calorimeters with copper and tungsten absorbers.

The data are selected using a trigger that requires a single high-$p_T$ [19] jet above one of eight thresholds, ranging from 25 to 220 GeV. Because of the high rate of jets at lower $p_T$, only a fraction of the events from the lower seven thresholds are stored.

Individual jets are reconstructed using the anti-$k_t$ jet clustering algorithm [20,21] with radius parameter $R = 0.6$. The inputs to this algorithm are clusters [22] of calorimeter cells with energy depositions significantly above the noise. Jet four-momenta are calculated by the vectorial addition of clusters of cells, treating each cluster as a four-momentum with zero mass. The jet four-momenta are then corrected to the jet energy scale [23] as a function of $\eta$ and $p_T$ for various effects, the largest of which are the hadronic shower response, detector material distribution, and pileup events [24]. This is done using a calibration scheme based on samples of simulated events and validated with test-beam [25] and collision data [22] studies.
The rapidity of a jet is defined as \( y = \frac{1}{2} \ln \left( \frac{E + p_T}{E - p_T} \right) \), where \( E \) is the jet energy and \( p_T \) is the momentum component along the beam axis. The scattering angle between two jets can be expressed using the variables \( \chi = e^{y_1 - y_2} = e^{2y^*} \), where \( y_1 \) and \( y_2 \) are the rapidities of the two jets, and \( y^* = \frac{1}{2} (y_1 - y_2) \). The rapidity boost of the dijet system with respect to the center of mass of the colliding protons is calculated as \( y_B = \frac{1}{2} (y_1 + y_2) \).

For each trigger, the event is required to have a jet with \( p_T \) sufficient to achieve a trigger efficiency greater than 99.5%. For the lowest (highest) threshold trigger, this corresponds to \( p_T > p_T^{\text{min}} = 47(333) \) GeV. Events are required to have at least two jets, each with \( p_T > 50 \) GeV; the dijet system, defined as the two jets with largest \( p_T \), is required to have \( |y^*| < 1.7, |y_B| < 1.1 \), and \( m_{jj} > 600 \) GeV (where the \( m_{jj} \) requirement avoids the kinematic bias in the angular distributions introduced by the minimum \( p_T \) requirement).

The detector covers the angular range \( |y^*| < 1.7 \), corresponding to \( \chi < 30 \). This interval is divided into 11 bins, with boundaries at \( \chi_n = e^{0.3 \times n} \) for \( n = 0 \) to 10, approximating the segmentation of the calorimeter in \( \Delta \eta \). The data are further binned coarsely in \( m_{jj} \) with the expectation that low-\( m_{jj} \) bins are dominated by QCD processes and that signals associated with new physics would be found in higher dijet invariant mass bins. The bin edges are chosen to optimize the expected sensitivity to the model of contact interactions. The highest dijet mass observed is 5.5 TeV.

The SM predictions are estimated using the PYTHIA8 [26] v8.160 event generator with the AU2 [27] underlying-event tune and the CT10 [28] parton distribution functions (PDF). The simulated events are propagated through a detector simulation [29] that uses the GEANT4 [30] simulation package. Pileup conditions vary as a function of the instantaneous luminosity and are taken into account by overlaying simulated minimum-bias events generated with PYTHIA8 onto the hard-scattering process such that the observed distribution of the average number of interactions per bunch crossing is reproduced. The same reconstruction and event selection are applied to the simulated events and the data.

The PYTHIA8 calculations are primarily to leading order (LO) in QCD with simulation of higher-order contributions included in the shower modeling. Events generated by PYTHIA8 are reweighted using a correction factor calculated based on the ratio of the next-to-leading-order (NLO) cross-section calculation from NLOJET++ [31–33] v4.1.2 to the LO+shower calculation from PYTHIA8:

\[
K(\chi, m_{jj}) = \frac{\sigma_{\text{NLO}}(\chi, m_{jj})^{\text{NLOJET++}}}{\sigma_{\text{LO+shower}}(\chi, m_{jj})^{\text{PYTHIA8}}}.
\]

The \( K \) factors decrease with \( \chi \) and thus modify the shape of the angular distributions; the impact ranges from a few percent at low \( m_{jj} \) to approximately 15% for the highest \( m_{jj} \) region. Additional processes accounting for electroweak (EW) effects not included in PYTHIA8 are shown in PYTHIA8 predictions. The SM predictions are estimated using the PYTHIA8 calculation from PYTHIA8 onto the hard-scattering process such that the overlaying simulated minimum-bias events generated with PYTHIA8 are reweighted using a correction factor calculated based on the ratio of the next-to-leading-order (NLO) in QCD with simulation of higher-order contributions.

Figure 1 shows the distributions of the data as a function of \( \chi \). The distribution in each \( m_{jj} \) region is normalized to unity, as the sensitivity to new phenomena is due to the angular distribution rather than normalization. The predicted SM distributions are shown in Fig. 1 and describe the data well. The EW corrections substantially improve the agreement of the SM prediction with data at high \( m_{jj} \), as can be appreciated from the comparison of the

![FIG. 1 (color online). Distributions of the dijet angular variable \( \chi \) for several regions of dijet invariant mass \( m_{jj} \). Shown are the data (dots), SM predictions (solid lines) with uncertainties, and predictions for a benchmark theory of new contact interactions with a left-chiral color-singlet coupling with constructive (dotted, \( \eta_{LL} = -1 \) and \( \Lambda = 12 \) TeV) or destructive (dashed, \( \eta_{LL} = +1 \) and \( \Lambda = 8 \) TeV) interference with the SM processes. Also shown is the impact of the electroweak (EW) corrections described in the text. The error bars on data represent the experimental and statistical uncertainties added in quadrature, with a tick representing experimental uncertainties only. The theoretical uncertainties are displayed as a shaded band around the SM prediction.](image-url)
predictions with and without these corrections shown in Fig. 1.

Models of quark compositeness are probed by searching for evidence of new interactions between quarks at a large characteristic energy scale, \( \Lambda \). At energies below this scale, the details of the new interaction and potential mediating particles can be integrated out to form a four-fermion contact interaction model [5,6] described by an effective field theory:

\[
L_{qq} = \frac{2\pi}{\Lambda^2} \left[ \eta_{LL} (\bar{q}_L \gamma_\mu q_L)(\bar{q}_L \gamma^\mu q_L) \\
+ \eta_{RR} (\bar{q}_R \gamma_\mu q_R)(\bar{q}_R \gamma^\mu q_R) \\
+ 2\eta_{RL} (\bar{q}_R \gamma_\mu q_R)(\bar{q}_L \gamma^\mu q_L) \right],
\]

where the quark fields have \( L \) and \( R \) chiral projections and the coefficients \( \eta_{LL}, \eta_{RR}, \) and \( \eta_{RL} \) turn on and off various interactions.

In this Letter, a contact interaction (CI) model with a left-chiral color-singlet coupling \(\eta_{LL} = \pm 1\) is used as a benchmark model, as many other models of new phenomena have similar predictions for the dijet scattering angle \( \chi \) at large \( m_{jj} \). Interference of the signal model with the SM process \( q\bar{q} \rightarrow q\bar{q} \) is also included.

Event samples were simulated with both QCD and contact interactions, taking interference into account and using the same event generator, underlying-event tune, and PDF as for the SM simulations. Events were generated for both constructive and destructive interference with \( \Lambda = 7 \) TeV and \( \Lambda = 10 \) TeV. The \( \Lambda = 7 \) TeV sample is then used for extrapolation to other values of \( \Lambda \), using the fact that the interference term is proportional to \( 1/\Lambda^2 \) and the pure CI cross section is proportional to \( 1/\Lambda^4 \). This procedure is validated with the \( \Lambda = 10 \) TeV sample. As with the QCD prediction, a \( K \)-factor correction is computed to correct the PYTHIA LO + shower prediction to a NLO calculation. Calculations at NLO are provided by CIJET [35] v1.0.

Uncertainties in the SM and signal predictions include theoretical uncertainties and experimental uncertainties on the measured angular distributions. Theoretical uncertainties in the SM and signal predictions are due to the choice of PDF, renormalization and factorization scales, choice of event generator, as well as statistical uncertainties due to limited simulation sample sizes. The impact of the uncertainty in the PDF is estimated using \( \text{NLOJET}++ \) with three different PDFs: CT10, MSTW2008 [36], and NNPDF23 [37]. These uncertainties are negligible (< 1%), as the choice of PDF largely impacts the total cross section rather than the angular distributions. The uncertainty due to the choice of renormalization and factorization scales were estimated by varying those independently up and down by a factor two in \( \text{NLOJET}++ \). The resulting uncertainty varies with \( m_{jj} \) and \( \chi \), rising to 4% at the smallest \( \chi \) values at high \( m_{jj} \). The uncertainty due to the choice of generator is estimated by comparing the predictions from the NLO generator \( \text{POWHEG} [38] \) v1.0 with those of PYTHIA8 with \( K \) factors applied. The largest uncertainty due to choice of generator is at the lowest \( m_{jj} \) values, where it approaches 20%, while for the highest \( m_{jj} \) values and smallest \( \chi \), it ranges from 10% to 14%. The uncertainty due to the choice of the showering model is estimated through comparison of \( \text{POWHEG} \) samples showered and hadronized with PYTHIA8 v8.175 to \( \text{HERWIG} [39] \) v6.520.2 samples using JIMMY [40,41] v4.31. The largest value of this uncertainty is less than 1% at the highest \( m_{jj} \) values and smallest values of \( \chi \). Finally the statistical uncertainties on the \( K \) factors due to limited simulation sample size are small and set to 1%.

The experimental uncertainty is dominated by the \( \eta \) dependence of the jet energy scale calibration. This uncertainty varies from approximately 15% at small values of \( \chi \) for the highest \( m_{jj} \) values, to a few percent at lower \( m_{jj} \) values and higher \( \chi \) values. The uncertainty in the beam energy is found to introduce a negligible contribution. The total uncertainty at the lowest \( \chi \), highest \( m_{jj} \) amounts to 20%, decreasing to a few percent at high \( \chi \). The total theoretical and experimental uncertainties are shown in Fig. 1.

The \( p \) value for the SM hypothesis is (0.25) 0.30 for the (second) highest \( m_{jj} \) bin. In the absence of significant deviations from the SM prediction, upper bounds on CI contributions are calculated using a one-sided profile likelihood ratio and the CL_S technique [42,43], evaluated using the asymptotic approximation [44] on events with \( m_{jj} > 3.2 \) TeV; the validity of asymptotic approximation was confirmed using toy simulations. These bounds exclude a compositeness scale below 8.1 TeV in a destructive interference scenario and below 12.0 TeV in a constructive interference scenario. The median expected limits are 8.9 (14.1) TeV for the destructive (constructive) interference scenario.

In summary, dijet angular distributions have been measured by the ATLAS experiment in 17.3 fb\(^{-1}\) of 8 TeV \( pp \) collisions at the LHC. Over a wide angular range and dijet invariant mass spectrum, the data are well described by QCD predictions at NLO. A model of quark compositeness is used as a benchmark for theories of new phenomena that include new forces and mediating particles; such theories predict deviations at small values of \( \chi \). A compositeness scale below 8.1 (12.0) TeV in a destructive (constructive) interference scenario is excluded at 95% confidence level, similar to results from the CMS Collaboration [17] and representing a significant enhancement in sensitivity relative to the previous limit (at 7.6 TeV for destructive interference) from the ATLAS Collaboration [11].

We would like to thank S. Dittmaier and A. Huss for providing us with the electroweak correction factors. We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We
acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNF, DNSTC 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; RGC, Hong Kong SAR, China; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[19] The ATLAS Collaboration uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as \( \eta = -\ln \tan(\theta/2) \). The transverse energy and transverse momentum are defined by \( E_T = E \sin \theta \) and \( p_T = |\vec{p}| \sin \theta \), respectively.
PRL 114, 221802 (2015)  PHYSICAL REVIEW LETTERS week ending 5 JUNE 2015

\textsuperscript{51} Institute of Physics, Tbilisi State University, Tbilisi, Georgia
\textsuperscript{52} High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
\textsuperscript{53} SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
\textsuperscript{54} Laboratoire de Physique Nucléaire et de Hautes Énergies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
\textsuperscript{55} Department of Physics, Hampton University, Hampton, Virginia, USA
\textsuperscript{56} Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
\textsuperscript{57} Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
\textsuperscript{58} ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
\textsuperscript{59} Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
\textsuperscript{60} Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
\textsuperscript{61} Department of Physics, Indiana University, Bloomington, Indiana, USA
\textsuperscript{62} Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
\textsuperscript{63} University of Iowa, Iowa City, Iowa, USA
\textsuperscript{64} Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
\textsuperscript{65} Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
\textsuperscript{66} KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
\textsuperscript{67} Graduate School of Science, Kobe University, Kobe, Japan
\textsuperscript{68} Faculty of Science, Kyoto University, Kyoto, Japan
\textsuperscript{69} Kyoto University of Education, Kyoto, Japan
\textsuperscript{70} Department of Physics, Kyushu University, Fukuoka, Japan
\textsuperscript{71} Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
\textsuperscript{72} Physics Department, Lancaster University, Lancaster, United Kingdom
\textsuperscript{73} INFN Sezione di Lecce, Italy
\textsuperscript{74} Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
\textsuperscript{75} Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
\textsuperscript{76} Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
\textsuperscript{77} School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
\textsuperscript{78} Department of Physics, Royal Holloway University of London, Surry, United Kingdom
\textsuperscript{79} Department of Physics and Astronomy, University College London, London, United Kingdom
\textsuperscript{80} Louisiana Tech University, Ruston, Louisiana, USA
\textsuperscript{81} Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
\textsuperscript{82} Fysiska institutionen, Lunds universitet, Lund, Sweden
\textsuperscript{83} Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
\textsuperscript{84} Institut für Physik, Universität Mainz, Mainz, Germany
\textsuperscript{85} School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
\textsuperscript{86} Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
\textsuperscript{87} Department of Physics, McGill University, Montreal, Québec, Canada
\textsuperscript{88} School of Physics, University of Melbourne, Victoria, Australia
\textsuperscript{89} Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
\textsuperscript{90} Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
\textsuperscript{91} INFN Sezione di Milano, Italy
\textsuperscript{92} B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
\textsuperscript{93} National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
\textsuperscript{94} Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
\textsuperscript{95} Group of Particle Physics, University of Montreal, Montreal, Québec, Canada
\textsuperscript{96} P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
\textsuperscript{97} Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
\textsuperscript{98} National Research Nuclear University MEPhI, Moscow, Russia
\textsuperscript{99} D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
\textsuperscript{100} Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
\textsuperscript{101} Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
\textsuperscript{102} Nagasaki Institute of Applied Science, Nagasaki, Japan
\textsuperscript{103} Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
145a Department of Physics, University of Cape Town, Cape Town, South Africa
145b Department of Physics, University of Johannesburg, Johannesburg, South Africa
145 School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146a Department of Physics, Stockholm University, Sweden
146b The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA
149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
150 School of Physics, University of Sydney, Sydney, Australia
151 Institute of Physics, Academia Sinica, Taipei, Taiwan
152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
158 Department of Physics, University of Toronto, Toronto, Ontario, Canada
159a TRIUMF, Vancouver, British Columbia, Canada
159b Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
159 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
160 Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
161 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
162 Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
163 INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
164 ICTP, Trieste, Italy
165 Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
166 Department of Physics, University of Illinois, Urbana, Illinois, USA
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-CNMT), University of Valencia and CSIC, Valencia, Spain
169 Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
170 Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
171 Department of Physics, University of Warwick, Coventry, United Kingdom
172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
173 Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
175 Fachbereich 4 Physik, Bergische Universität Wuppertal, Wuppertal, Germany
176 Department of Physics, Yale University, New Haven, Connecticut, USA
177 Yerevan Physics Institute, Yerevan, Armenia
178 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

aDeceased.
1 Also at Department of Physics, King’s College London, London, United Kingdom.
2 Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
3 Also at Novosibirsk State University, Novosibirsk, Russia.
4 Also at TRIUMF, Vancouver BC, Canada.
5 Also at Department of Physics, California State University, Fresno CA, USA.
6 Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
7 Also at Department of Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.
8 Also at Tomsk State University, Tomsk, Russia.
9 Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
10 Also at Università di Napoli Parthenope, Napoli, Italy.
11 Also at Institute of Particle Physics (IPP), Canada.
12 Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
13 Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
14 Also at Louisiana Tech University, Ruston LA, USA.
15 Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
16 Also at Department of Physics, National Tsing Hua University, Taiwan.
17 Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
\[1\text{Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.}\]
\[2\text{Also at CERN, Geneva, Switzerland.}\]
\[3\text{Also at Georgian Technical University (GTU), Tbilisi, Georgia.}\]
\[4\text{Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.}\]
\[5\text{Also at Manhattan College, New York NY, USA.}\]
\[6\text{Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.}\]
\[7\text{Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.}\]
\[8\text{Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.}\]
\[9\text{Also at School of Physics, Shandong University, Shandong, China.}\]
\[10\text{Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.}\]
\[11\text{Also at Section de Physique, Université de Genève, Geneva, Switzerland.}\]
\[12\text{Also at International School for Advanced Studies (SISSA), Trieste, Italy.}\]
\[13\text{Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.}\]
\[14\text{Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.}\]
\[15\text{Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.}\]
\[16\text{Also at National Research Nuclear University MEPhI, Moscow, Russia.}\]
\[17\text{Also at Department of Physics, Stanford University, Stanford CA, USA.}\]
\[18\text{Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.}\]
\[19\text{Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.}\]
\[20\text{Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.}\]
\[21\text{Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.}\]