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


DOI
10.1103/PhysRevLett.114.221802

Publication date
2015

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):
Search for New Phenomena in Dijet Angular Distributions in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV Measured with the ATLAS Detector

G. Aad et al.\textsuperscript{*} (ATLAS Collaboration) (Received 3 April 2015; published 4 June 2015)

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.

DOI: 10.1103/PhysRevLett.114.221802 PACS numbers: 13.85.Rm, 12.60.Rc

The search for an internal structure of fermions and new forces that might govern that structure is a major goal of modern particle physics. The most powerful probes are scattering experiments with large momentum transfer. Collisions of protons at the Large Hadron Collider (LHC) resulting in two energetic jets of particles (dijets) provide the largest momentum transfer currently available, and therefore the deepest probe.

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 constructed 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.

---

Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
The rapidity of a jet is defined as \( y = \frac{1}{2} \ln [(E + p_z)/(E - p_z)] \), where \( E \) is the jet energy and \( p_z \) is the momentum component along the beam axis [19]. The scattering angle between two jets can be expressed using the variable \( \chi = e^{y_1 - y_2} = e^{y_1 y_2} \), 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 \( p_T > p_T^{\text{min}} = 47(333) \text{ GeV} \). Events are required to have at least two jets, each with \( p_T > 50 \text{ GeV} \); the dijet system, defined as the two jets with largest \( p_T \), is required to have \( |y^*| < 1.7 \), \( |y_B| < 1.1 \), and \( m_{jj} > 600 \text{ GeV} \) (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 \( y < 30 \). 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:

\[
K(\chi, m_{jj}) = \frac{\sigma_{NLO}(\chi, m_{jj})^{\text{NLOJET++}}}{\sigma_{LO+shower}(\chi, m_{jj})^{\text{Pythia8}}}. 
\]

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 (virtual weak boson exchange and Sudakov-type logarithms) are included as EW corrections [34]. The effect is most pronounced at high \( m_{jj} \) and low \( \chi \), and the correction factors range from unity at low \( m_{jj} \) to 0.98–1.12 in the highest \( m_{jj} \) region. The EW corrections and the NLO \( K \) factors are applied as a function of \( \chi \) and \( m_{jj} \) to the Pythia8 prediction.

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 also 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

![Graph showing distributions](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 \( q\bar{q} \to q\bar{q} \) 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 C\textsc{ijet} [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 NLO\textsc{jet++} 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 NLO\textsc{jet++}. 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 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 POWHEG samples showered and hadronized with PYTHIA8 v8.175 to 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 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\textsc{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; 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; DFN, DGS and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, 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 STFC, 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 η = −ln(1/tan(θ/2)). The transverse energy and transverse momentum are defined by ET = E sin θ and pT = |p| sin θ, respectively.
Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
Institute of Physics, University of Belgrade, Belgrade, Serbia
Department for Physics and Technology, University of Bergen, Bergen, Norway
Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
Department of Physics, Humboldt University, Berlin, Germany
Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
Department of Physics, Bogaziçi University, Istanbul, Turkey
Department of Physics, Dogus University, Istanbul, Turkey
Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
INFN Sezione di Bologna, Italy
Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
Physikalisches Institut, University of Bonn, Bonn, Germany
Department of Physics, Boston University, Boston, Massachusetts, USA
Department of Physics, Brandeis University, Waltham, Massachusetts, USA
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton, New York, USA
National Institute of Physics and Nuclear Engineering, Bucharest, Romania
National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
University Politehnica Bucharest, Bucharest, Romania
West University in Timisoara, Timisoara, Romania
Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa, Ontario, Canada
CERN, Geneva, Switzerland
Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Modern Physics, University of Science and Technology of China, Anhui, China
Department of Physics, Nanjing University, Jiangsu, China
School of Physics, Shandong University, Shandong, China
Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China
Physics Department, Tsinghua University, Beijing 100084, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
Dipartimento di Fisica, Università della Calabria, Rende, Italy
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova, Italy
Dipartimento di Fisica, Università di Genova, Genova, Italy
104a INFN Sezione di Napoli, Italy  
104b Dipartimento di Fisica, Università di Napoli, Napoli, Italy  

105 Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA  

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

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

108 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA  

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

110 Department of Physics, New York University, New York, New York, USA  

111 Ohio State University, Columbus, Ohio, USA  

112 Faculty of Science, Okayama University, Okayama, Japan  

113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA  

114 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA  

115 Palacký University, RCPTM, Olomouc, Czech Republic  

116 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA  

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

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

119 Department of Physics, University of Oslo, Oslo, Norway  

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

121 INFN Sezione di Pavia, Italy  

122 Dipartimento di Fisica, Università di Pavia, Pavia, Italy  

123 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA  

124 INFN Sezione di Roma, Italy  

125 Dipartimento di Fisica E. Fermi, Università di Roma, Roma, Italy  

126 Laboratorio de Instrumentacion and Fisica Experimental de Particulas - LIP, Lisboa, Portugal  

126b Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal  

126c Department of Physics, University of Coimbra, Coimbra, Portugal  

126d Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal  

126e Departamento de Física, Universidade do Minho, Braga, Portugal  

126c Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain  

126g Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal  

127 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic  

128 Czech Technical University in Prague, Praha, Czech Republic  

129 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic  

130 State Research Center Institute for High Energy Physics, Protvino, Russia  

131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom  

132 INFN Sezione di Roma, Italy  

132b Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy  

132c INFN Sezione di Roma Tor Vergata, Italy  

133 Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy  

134 INFN Sezione di Roma Tre, Italy  

135a Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco  

135b Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco  

135c Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco  

135d Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco  

135e Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco  

136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France  

137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA  

138 Department of Physics, University of Washington, Seattle, Washington, USA  

139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom  

140 Department of Physics, Shinshu University, Nagano, Japan  

141 Fachbereich Physik, Universität Siegen, Siegen, Germany  

142 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada  

143 SLAC National Accelerator Laboratory, Stanford, California, USA  

144 Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic  

145 Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
1 Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
2 Also at CERN, Geneva, Switzerland.
3 Also at Georgian Technical University (GTU), Tbilisi, Georgia.
4 Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
5 Also at Manhattan College, New York NY, USA.
6 Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
7 Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
8 Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
9 Also at School of Physics, Shandong University, Shandong, China.
10 Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
11 Also at Section de Physique, Université de Genève, Geneva, Switzerland.
12 Also at International School for Advanced Studies (SISSA), Trieste, Italy.
13 Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
14 Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
15 Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
16 Also at National Research Nuclear University MEPhI, Moscow, Russia.
17 Also at Department of Physics, Stanford University, Stanford CA, USA.
18 Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
19 Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
20 Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
21 Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.