Search for New Physics in the Dijet Mass Distribution using 1 fb$^{-1}$ of $pp$ Collision Data at $\sqrt{s} = 7$ TeV collected by the ATLAS Detector

ATLAS Collaboration

Invariant mass distributions of jet pairs (dijets) produced in LHC proton-proton ($pp$) collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV have been studied using a data set corresponding to an integrated luminosity of 1.0 fb$^{-1}$ recorded in 2011 by ATLAS. Dijet masses up to $\sim 4$ TeV are observed in the data, and no evidence of resonance production over background is found. Limits are set at 95% CL for several new physics hypotheses: excited quarks are excluded for masses below 2.99 TeV, axigluons are excluded for masses below 3.32 TeV, and colour octet scalar resonances are excluded for masses below 1.92 TeV.

I. Introduction

The Standard Model (SM) description of high energy proton-proton ($pp$) collisions is based on the framework of quantum chromodynamics (QCD) in the perturbative regime, where the most energetic collisions result from the $2 \rightarrow 2$ scattering of a pair of partons (quarks or gluons). Partons emerging from the collision shower and hadronise, in the simplest case producing two jets of particles, a “dijet”, that may be reconstructed to determine the dijet invariant mass, $m_{jj}$, the mass of the two-parton system.

Previous studies of dijet mass distributions [1–6] have shown that these analyses are sensitive to the highest mass scales accessible with hadronic final states. In the present study, the dijet mass distribution is examined in a search for resonances due to new phenomena localised near a given mass, employing a data-driven background estimate that does not rely on detailed QCD calculations.

In addition to new physics benchmarks used in previous ATLAS dijet analyses, namely excited quarks ($q^{*}$) [7,8], and axigluons [9,11], the present study includes a third hypothetical object: the colour octet scalar (s8), one of many possible exotic colour resonances [12]. Any of these objects could produce a peak in the dijet spectrum in the vicinity of their mass.

The present study is based on $pp$ collisions at a centre-of-mass (CM) energy of 7 TeV produced at the CERN Large Hadron Collider (LHC), measured by the ATLAS detector. This data set corresponds to an integrated luminosity of 1.0 fb$^{-1}$ recorded between March and June 2011. The most stringent limits set previously by the ATLAS Collaboration were based on the full 2010 data sample, corresponding an integrated luminosity of 36 pb$^{-1}$ [6]. Excited quarks were excluded below 2.15 TeV, and axigluons below 2.10 TeV. The CMS Collaboration has recently completed a dijet resonances analysis in 1.0 fb$^{-1}$ of 2011 data, excluding excited quarks below 2.49 TeV and axigluons below 2.47 TeV, along with other limits [13].

A detailed description of the ATLAS detector is available in [14]. The detector is instrumented over almost the entire solid angle around the $pp$ collision point with layers of tracking detectors, calorimeters, and muon chambers. Jet measurements are made using a finely segmented calorimeter system designed to detect the high energy jets that are the focus of this study with high efficiency and excellent energy resolution. ATLAS has a three-level trigger system, with the first level trigger (L1) being based on custom-built hardware and the two higher level triggers (HLT) being realised in software.

ATLAS uses a right-handed coordinate system with the z-axis along the beam pipe. The x-axis points 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. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. Transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.

The dijet mass, $m_{jj}$, is derived from the vectorial sum of the four-momenta of the two highest $p_T$ jets in the event. Kinematic criteria based on momentum and angular variables are applied to increase the sensitivity to centrally produced high mass resonances.

The angular distribution for $2 \rightarrow 2$ parton scattering is predicted by QCD in the CM frame of the colliding partons, which moves along the beamline due to the differing momentum fractions (Bjorken $x$) of the colliding partons. If $E$ is the jet energy and $p_T$ is the $z$-component of the jet’s momentum, the rapidity of the jet is given by $y = \frac{1}{2} \ln \frac{E + p_T}{E - p_T}$. The rapidities of the two highest $p_T$ jets are denoted by $y_1$ and $y_2$, and the corresponding rapidity of these partons in their mutual CM frame is $y^* = \frac{1}{2}(y_1 - y_2)$.

II. Jet reconstruction and event selection

Individual jets are reconstructed using the anti-$k_t$ jet clustering algorithm [15,16] with the distance parameter $R = 0.6$. The inputs to this algorithm are clusters [17] of calorimeter cells with energy depositions significantly above the measured noise. Jet four-momenta are constructed as the vectorial sum of clusters of cells, treating each cluster as an ($E, \vec{p}$) four-vector with zero mass, assuming that the corresponding particle stems from the primary vertex.

The jet four-momenta are then corrected [18] as a function of $\eta$ and $p_T$ for various effects, the largest of which are the hadronic shower response and detector material distribution. This is done using a calibration
scheme based on Monte Carlo (MC) studies including full detector simulation, and validated with extensive test-beam [19] and collision data [20–22] studies. Measured dijet mass distributions are not corrected for detector resolution, which, in terms of mass smearing, is $\sigma_{m_{jj}}/m_{jj} \simeq 5\%$ at $m_{jj} \simeq 1 \text{ TeV}$, drops to 4.5\% at 2 TeV, and asymptotically approaches 4\% at $m_{jj}$ of 5 TeV and above.

The event selection starts with the first-level trigger, which selects events that have at least one large transverse energy deposition in the calorimeters, with the transverse energy threshold increasing over the period of the data-taking as the instantaneous luminosity of the LHC $pp$ collisions increased.

To achieve the highest possible effective integrated luminosity, the current data set has been recorded using a jet trigger that was usually not prescaled. The chosen trigger has a nominal jet $p_T$ threshold of 180 GeV. After applying all other analysis cuts, $m_{jj}$ is required to be greater than 717 GeV in order to attain a trigger efficiency of at least 99\% over the full range of the dijet mass distribution.

Events are required to have a primary collision vertex defined by at least five charged-particle tracks. Events with a poorly measured jet $p_T$ with $p_T$ greater than 30\% of the $p_T$ of the next-to-leading jet are vetoed, to avoid cases where such a jet would cause incorrect identification of the two leading jets. This rejects less than 0.002\% of the events.

Additional kinematic criteria are applied, requiring that the two leading jets each satisfy $|\eta_j| < 2.8$ and that the rapidity in the parton CM frame satisfies $|y^*| < 0.6$. These criteria favour central collisions and have been shown, based on studies of expected signals and QCD background, to optimise the analysis sensitivity.

A final selection is made to avoid the calorimeter region from -0.1 to 1.5 in $\eta$ and from -0.9 to -0.5 in $\phi$, which was in large part affected by readout problems for most of the data used in these studies. Events with jets in this region are discarded. This requirement reduces the data set by 3.7\%.

### III. Comparing data to a smooth background

The observed dijet mass distribution after all selection cuts is shown in Fig. 1. As in the previous ATLAS studies, the $m_{jj}$ spectrum is fit to the smooth functional form

$$f(x) = p_1(1 - x)^{p_2}x^{p_3} + p_4 \ln x,$$

where $x \equiv m_{jj}/\sqrt{s}$ and the $p_i$ are fit parameters. This ansatz has been shown empirically to accurately model the steeply falling QCD dijet mass spectrum [3, 6]. The $m_{jj}$ bins are of variable width, increasing from $\sim 50$ to $\sim 200$ GeV for dijet masses from 0.85 to 4.5 TeV, respectively, to optimise the performance of the resonance search algorithm discussed in the next section.

The bottom plot of Fig.1 shows the significance, in standard deviations, of the difference between the data and the prediction in each bin. These are purely statistical, and based on Poisson distributions. The contents of a given bin are used to determine the $p$-value - the probability of the background fluctuating higher than the observed excess, or lower than the observed deficit. The $p$-value is transformed to a significance, in terms of an equivalent number of standard deviations (the $\sigma$-value). Where there is an excess (deficit) in data in a given bin, the significance is plotted as positive (negative). In mass bins with small expected number of events, where the observed number of events is similar to the expectation, the Poisson probability of a fluctuation at least as high (low) as the observed excess (deficit) can be greater than 50\%, as a result of the asymmetry of the Poisson distribution. Such bins present no statistical interest and, for simplicity, bars are not drawn for them.

To determine the degree of consistency between data and the fitted background, the $p$-value of the fit is obtained by calculating the $\chi^2$ from the data, and comparing this result to the $\chi^2$ distribution obtained from pseudexperiments. The resulting $p$-value is 0.96, showing that there is good agreement between the data and the functional form.

### IV. Search for resonances

As a more sensitive test, the BUMP Hunter algorithm [24, 25] is used to establish the presence or absence of a resonance in the dijet mass spectrum. To optimise the sensitivity of this algorithm, the $m_{jj}$ binning strategy is to establish a minimum width for resonances to be considered physical. To this end, the relatively narrow $q^* m_{jj}$ template from full MC simulation [20], described below for subsequent studies, has been used to establish
the binning. If the width of the resonance is defined as \( \pm 1\sigma \), the greatest sensitivity at the minimum width is achieved by setting the bin width to \( 1\sigma \), half the resonance width. The final result of this procedure is that the variable bin sizes are typically 6.5% to 7.0% of \( m_{jj} \) in width, somewhat wider than detector resolution due to the finite natural width of \( q^* \), which varies between about 3% and 3.5% of the \( q^* \) mass.

In the current implementation, the BumpHunter algorithm searches for the signal window with the most significant excess of events above background. Starting with a two-bin window, the algorithm increases the signal window and shifts its location until all possible bin ranges, up to half the mass range spanned by the data, have been tested. The most significant departure from the smooth spectrum ("bump") is defined by the set of bins that have the smallest probability of arising from a background fluctuation assuming Poisson statistics.

The BumpHunter algorithm accounts for the so-called "look elsewhere effect" (or "trials factor effect") [27] by performing a series of pseudoexperiments to determine the probability that random fluctuations in the background-only hypothesis would create an excess as significant as the one observed anywhere in the spectrum. Variable width binning reduces the penalty due to this effect, while retaining sensitivity.

To prevent any new physics signal from biasing the background estimate, if the biggest local excess from the background fit has a p-value smaller than 0.01, this region is excluded and a new background fit is performed. No such exclusion is needed for this data set.

The most significant discrepancy identified by the BumpHunter algorithm in the observed dijet mass distribution reported in Fig. 1 is a 2-bin excess in the interval 1.16 to 1.35 TeV. The probability of observing such an excess or larger somewhere in the mass spectrum for a background-only hypothesis is 0.82. This test shows that there is no evidence for a resonance signal in the \( m_{jj} \) spectrum.

V. New physics models

Exclusion limits are set on three new physics scenarios expected to give rise to resonant dijet production.

For the first of these, excited quarks, \( q^* \), a \( qg \rightarrow q^* \) production model [9, 11] is used, with the assumption of spin 1/2 and quark-like SM coupling constants. The compositeness scale (\( \Lambda \)) is set to the \( q^* \) mass. Signal events are produced using the Pythia event generator [29], a leading-order parton-shower Monte Carlo generator, with the MRST2007LO* [29] parton distribution functions (PDF’s), with settings established by the ATLAS default MC10 [30] Monte Carlo tune. The renormalization and factorization scales are set to the mean \( p_T \) of the two leading partons for each event. Pythia is also used to decay the excited quarks to all possible SM final states, which are predominantly \( qg \), but also \( qW, qZ, \) and \( q\gamma \). The generated events are passed through to the detailed simulation of the ATLAS detector [20], which uses the GEANT4 package [31] for simulation of particle transport, interactions, and decays. The simulated events are then reconstructed in the same way as the data to produce predicted dijet mass distributions that can be compared with the observed distributions.

The second model is axigluon production [3, 11] via an interaction given by the Lagrangian

\[
\mathcal{L}_{Aqq} = g_{QCD}A_\mu^A \frac{\alpha_s}{2} \rho^\mu \gamma_5 q, \tag{2}
\]

where \( g_{QCD}^2 = 4\pi\alpha_s \) is the QCD coupling constant and \( A_\mu^A \) is the axigluon field representing a massive state with axial coupling to quarks. Parity conservation prevents the axigluon from coupling to two gluons. Parton-level events are generated, at leading-order approximation, using the CalcHEP Monte Carlo package [32], for chosen masses, \( m_s \), of the axigluon. The MRST2007LO* PDF set was used. The axigluon dijet mass has longer tails at high and low masses than the \( q^* \) distribution, but these two shapes are interchangeable within the range 0.7\( m \) to 1.3\( m \) for all masses of interest. Since the axigluon tails outside this range are well below the SM background, the predicted signal may be analyzed by cutting events beyond this range and accounting for the reduced acceptance. The axigluon MC prediction for \( \sigma \times A \), the production cross section within the acceptance, is defined to include these cuts by applying them at the level of CalcHEP generation, along with the kinematic cuts in \( p_T \) and rapidity. In the limit setting analysis, these axigluon results are compared to the observed \( \sigma \times A \) limits from the \( q^* \) analysis. This method is discussed in more detail in Section VI.

The third resonant hypothesis, the colour octet scalar (s8) model, is a prototype for many possible exotic coloured resonances [12]. Colour octet resonances can couple to gluons, which have large parton luminosity at the LHC. One possible interaction is

\[
\mathcal{L}_{gg8} = g_{QCD}d_{ABC}^{A8} \frac{\kappa_s}{\Lambda_s} S^A_{8} F_{\mu\nu}^B F_{C,\mu\nu}, \tag{3}
\]

where \( S^A_{8} \) is the colour octet scalar field, \( \kappa_s \) is the scalar coupling (assumed to be unity), and \( d_{ABC}^{A8} \) is the SU(3) isoscalar factor. \( \Lambda_s \) is the new physics scale which is set to the resonance mass, \( M_{s8} \). This model leads to a very simple event topology, with two gluons in the initial and final states, yielding high \( p_T \) dijets. MadGraph 5 [33] is used to generate parton level events at leading-order approximation. Pythia with CTEQ6L1 PDF’s is used in this generation, with the ATLAS MC09 tune [34]. These samples are processed through the full ATLAS detector simulation.

The observed limits on \( s8 \) are less strict than the corresponding \( q^* \) limits, in part because the \( s8 \) signal is much wider than \( q^* \). Much of this width increase is due to final state radiation, which is larger for gluon-jets than for quark-jets. In addition, the initial state for \( s8 \) production contains gluons, which have small parton density at high mass. Thus, \( s8 \) are much more likely to be off-mass-shell than \( q^* \).
VI. Model dependent limit setting

In the absence of any observed significant discrepancy from the zero-signal hypothesis, the Bayesian method documented in [6] is used to set 95% credibility-level (CL) upper limits.

Bayesian credibility intervals are set by defining a posterior probability density from the Poisson likelihood function for the observed mass spectrum, obtained by a fit to the background functional form and a signal shape derived from MC simulations. A prior probability density constant in all positive values of signal cross section, and zero at negative values, is used. The posterior probability is then integrated to determine the 95% CL for a given range of models, usually parameterized by the mass of the resonance.

Limits are determined on $\sigma \times A$ for a hypothetical new particle decaying into dijets. The acceptance includes all reconstruction steps and analysis cuts described above, and assumes that the trigger is fully efficient. (The efficiency is greater than 99% for all analyses.)

The effects of systematic uncertainties due to the knowledge of the luminosity and of the jet energy scale (JES) are included. The luminosity uncertainty for the 2011 data is 3.7% [35]. The systematic uncertainty on the JES is taken from the 2010 data [18] analysis, and is adapted to the 2011 analysis taking into account in particular the new event pileup conditions (described below). The JES uncertainty shifts resonance peaks by less than 4%. The background parameterization uncertainty is taken from the fit results, as described in [6]. The effect of the jet energy resolution (JER) uncertainty is found to be negligible. All of these uncertainties are incorporated into the fit by varying all sources according to Gaussian probability distributions and convolving them with the Bayesian posterior probability distribution. Credibility intervals are then calculated numerically from the resulting convolutions. No uncertainties are associated with the theoretical model of new physics, as in each case the model is a benchmark that incorporates a specific choice of model parameters, of PDF set, and of MC tune. Previous ATLAS studies have already explored the impact of different MC tunes and PDF sets on the $q^*$ theoretical prediction [4].

In 2011, the instantaneous luminosity has risen to a level where corrections must be made for multiple $pp$ collisions occurring in the same bunch crossing (“pileup”), whose presence affects the measurement of calorimeter energy depositions associated with the hard-scattering event under study. All simulated samples used in this analysis include a Poisson distributed number of MC minimum bias events added to the hard interaction to account for “in-time” pileup caused by additional collisions in the same bunch crossing. Further account must be taken of “out-of-time” pileup originating from collisions in bunches preceding or following the one of interest, due to the long response time of the liquid argon calorimeters. With the 50 ns bunch spacing in the LHC for these data, up to 12 preceding bunches and 1-2 follow-

VII. Model independent limit setting

In addition to specific theoretical models, limits are set to a collection of hypothetical signals that are assumed to be Gaussian-distributed in $m_{q^*}$ with mean ($m_C$) ranging from 0.9 to 4.0 TeV and standard deviation ($\sigma_C$) from 5% to 15% of the mean.

Systematic uncertainties are treated using the same methods as applied in model dependent limit setting. The only difference for the Gaussian analysis arises from the decay of the dijet final state not being simulated. In place of this, it is assumed that the dijet signal distribution is Gaussian in shape, and the JES is adjusted by modelling it as an uncertainty of 4% in the central value of the Gaussian signal.

The resulting limits on $\sigma \times A$ for the Gaussian template model are shown in Fig. 2. Relative to previous studies [6] they are substantially improved in the region above 900 GeV. These results may be utilised to set limits on new
FIG. 2. The 95% CL upper limits on $\sigma \times A$ as a function of particle mass (black filled circles). The black dotted curve shows the 95% CL upper limit expected from Monte Carlo and the light and dark yellow shaded bands represent the 68% and 95% contours of the expected limit, respectively. Theoretical predictions for $\sigma \times A$ are shown in (a) for excited quarks (blue dashed) and axigluons (green dot-dashed), and in (b) for colour octet scalar resonances (blue dashed). For a given new physics model, the observed (expected) limit occurs at the crossing of its $\sigma \times A$ curve with the observed (expected) 95% CL upper limit curve.

VIII. Conclusion

The dijet mass spectrum measured by the ATLAS experiment has been examined in a search for resonances from new phenomena, using 1.0 fb$^{-1}$ of 7 TeV $pp$ collision data taken in 2011. The observed distribution, which extends up to masses of $\approx$ 4 TeV, is in good agreement with a smooth function representing the SM expectation. No evidence for the production of new resonances is found. 95% CL mass limits using Bayesian methodology have been set in the context of several models of new physics, as summarized in Table I. For excited quarks and axigluons, the current results exceed the limits obtained by ATLAS with the 2010 data by approximately one TeV. Exclusion limits on colour octet scalar resonances have been established for the first time in ATLAS. The limits reported in this paper are the most stringent to date.

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<td>Colour Octet Scalar</td>
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Appendix: Setting limits on new models

The following procedure is appropriate for resonances that are approximately Gaussian near the core, and with tails that are well below the background. For convenience, the results of Fig. 8 are provided in Table II.

(1) For a MC sample generated with the mass of the hypothetical new particle set to \( M \), compute an initial acceptance including the branching ratio into dijets. Then apply the kinematic cuts on the parton \( \eta, p_T \), and \( |y^*| \) used in this analysis. (2) Approximate the reduction of acceptance due to the calorimeter (temporary) readout problem by eliminating events where a parton enters the region -0.1 to 1.5 in \( \eta \), and -0.9 to -0.5 in \( \phi \). (Indicatively, the acceptance of \( q^* \) is reduced by a factor 0.92.) (3) Smear the signal mass distribution to reflect the detector resolution. In the absence of a better detector simulation tool, use the mass resolution given in Section II, which is derived from full ATLAS simulation. (4) Since a Gaussian signal shape has been assumed in determining the limits, any long tails in the reconstructed \( m_{jj} \) should be removed in the sample under study. The recommendation (based on optimization using \( q^* \) templates) is to retain events with \( m_{jj} \) between 0.8\( M \) and 1.2\( M \). The mean mass, \( m \), of this truncated signal should be calculated. (5) The fraction of MC events surviving the first four steps determines the modified acceptance, \( A \). (6) From Table II select \( m_G \) so that \( m_G = m \). If the exact value of \( m \) is not among the listed values of \( m_G \), check the limit for the two values of \( m_G \) that are directly above and below \( m \), and use the larger of the two limits to be conservative. (7) To retain enough of the information in the full signal template, and at the same time reject tails that would invalidate the Gaussian approximation, the following truncation procedure is recommended. For this mass point, choose a value of \( \sigma_G/m_G \) such that the width \( 2\sigma_G \) is well contained in the (truncated) mass range. For the \( q^* \) case a good choice is empirically found to be \( \sigma_G = (1.2M - 0.8M)/5 \). This \( \sigma_G \) corresponds to a Gaussian distribution contained within the truncation interval of \([0.8M, 1.2M]\), since the interval \([0.8M, 1.2M]\) corresponds to \([m_G - 2.5\sigma_G, m_G + 2.5\sigma_G]\).

For the \( q^* \) case a good choice is \( \sigma_G = (1.2M - 0.8M)/5 \) so that 95% of the Gaussian spans \( 4 \times (0.4/5)M \). Use this value to pick the closest \( \sigma_G/m_G \) value, rounded up to be conservative. (8) Compare the tabulated 95% CL upper limit corresponding to the chosen \( m_G \) and \( \sigma_G/m_G \) values to the \( \sigma \times A \) obtained from the theoretical cross section of the model multiplied by the acceptance defined in step (5) above.

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### Table II. The 95% CL upper limit on \( \sigma \times A \) [pb] for the Gaussian “model-independent” scenario. The symbols \( m_G \) and \( \sigma_G \) are, respectively, the mean mass and standard deviation of the Gaussian.

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School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst MA, United States of America
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
Ann Arbor MI, United States of America
54x128)
89 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
92 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
93 Group of Particle Physics, University of Montreal, Montreal QC, Canada
94 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nagasaki Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science, Nagoya University, Nagoya, Japan
102 (a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
107 Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
108 Department of Physics, New York University, New York NY, United States of America
109 Ohio State University, Columbus OH, United States of America
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
112 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
113 Palacký University, RCPTM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
115 LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
117 Department of Physics, University of Oslo, Oslo, Norway
118 Department of Physics, Oxford University, Oxford, United Kingdom
119 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
120 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
124 (a) Laboratorio de Instrumentación e Física Experimental de Partículas - LIP, Lisboa, Portugal; (b) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
127 Czech Technical University in Prague, Praha, Czech Republic
128 State Research Center Institute for High Energy Physics, Protvino, Russia
129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130 Physics Department, University of Regina, Regina SK, Canada
131 Ritsumeikan University, Kusatsu, Shiga, Japan
132 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies - Université Hassan II, Casablanca; (b) Centre National de
l’Energie des Sciences Techniques Nucleaires, Rabat;
(c)Université Cadi Ayyad, Faculté des sciences Semlalia
Département de Physique, B.P. 2390 Marrakech 40000;
(d)Faculté des Sciences, Université Mohamed Premier
and LPTPM, Oujda; (e)Faculté des Sciences, Université
Mohammed V, Rabat, Morocco
136 DSM/IRFU (Institut de Recherches sur les Lois
Fondamentales de l’Univers), CEA Saclay
(Commissariat a l’Energie Atomique), Gif-sur-Yvette,
France
137 Santa Cruz Institute for Particle Physics, University
of California Santa Cruz, Santa Cruz CA, United States
of America
138 Department of Physics, University of Washington,
Seattle WA, United States of America
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 BC, Canada
143 SLAC National Accelerator Laboratory, Stanford
CA, United States of America
144 (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
145 (a)Department of Physics, University of
Johannesburg, Johannesburg; (b)School of Physics,
University of the Witwatersrand, Johannesburg, South
Africa
146 (a)Department of Physics, Stockholm University;
(b)The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology,
Stockholm, Sweden
148 Department of Physics and Astronomy, Stony Brook
University, Stony Brook NY, United States of America
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 Inst. 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 ON, Canada
159 (a)TRIUMF, Vancouver BC; (b)Department of
Physics and Astronomy, York University, Toronto ON,
Canada
160 Institute of Pure and Applied Sciences, University of
Tsukuba, Ibaraki, Japan
161 Science and Technology Center, Tufts University,
Medford MA, United States of America
162 Centro de Investigaciones, Universidad Antonio
Narino, Bogota, Colombia
163 Department of Physics and Astronomy, University
of California Irvine, Irvine CA, United States of America
164 (a)INFN Gruppo Collegato di Udine; (b)ICTP,
Trieste; (c)Dipartimento di Fisica, Università di Udine,
Udine, Italy
165 Department of Physics, University of Illinois,
Urbana IL, United States of America
166 Department of Physics and Astronomy, University
of Uppsala, Uppsala, Sweden
167 Instituto de Física Corpuscular (IFIC) and
Departamento de Física Atómica, Molecular y Nuclear
and Departamento de Ingeniería Electrónica y
Instituto de Microelectrónica de Barcelona (IMB-CNMM),
University of Valencia and CSIC, Valencia, Spain
168 Department of Physics, University of British
Columbia, Vancouver BC, Canada
169 Department of Physics and Astronomy, University
of Victoria, Victoria BC, Canada
170 Waseda University, Tokyo, Japan
171 Department of Particle Physics, The Weizmann
Institute of Science, Rehovot, Israel
172 Department of Physics, University of Wisconsin,
Madison WI, United States of America
173 Fakultät für Physik und Astronomie,
Julius-Maximilians-Universität, Würzburg, Germany
174 Fachbereich C Physik, Bergische Universität
Wuppertal, Wuppertal, Germany
175 Department of Physics, Yale University, New Haven
CT, United States of America
176 Yerevan Physics Institute, Yerevan, Armenia
177 Domaine scientifique de la Doua, Centre de Calcul
CNRS/IN2P3, Villeurbanne Cedex, France
a Also at Laboratorio de Instrumentacion e Fisica
Experimental de Particulas - LIP, Lisboa, Portugal
b Also at Faculdade de Ciencias and CFNUL,
Universidade de Lisboa, Lisboa, Portugal
c Also at Particle Physics Department, Rutherford
Appleton Laboratory, Didcot, United Kingdom
d Also at CPPM, Aix-Marseille Université and
CNRS/IN2P3, Marseille, France
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 Faculty of Physics and Applied Computer
Science, AGH-University of Science and Technology,
Krakow, Poland
h Also at Fermilab, Batavia IL, United States of America
i Also at Department of Physics, University of Coimbra, Coimbra, Portugal
j Also at Università di Napoli Parthenope, Napoli, Italy
k Also at Institute of Particle Physics (IPP), Canada
l Also at Department of Physics, Middle East Technical University, Ankara, Turkey
m Also at Louisiana Tech University, Ruston LA, United States of America
n Also at Group of Particle Physics, University of Montpellier, Montpellier QC, Canada
o Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
p Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
q Also at Manhattan College, New York NY, United States of America
r Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
s Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
 Also at High Energy Physics Group, Shandong University, Shandong, China
u Also at Section de Physique, Université de Genève, Geneva, Switzerland
v Also at Departamento de Física, Universidade de Minho, Braga, Portugal
w Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
x Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
y Also at California Institute of Technology, Pasadena CA, United States of America
z Also at Institute of Physics, Jagiellonian University, Krakow, Poland
aa Also at Department of Physics, Oxford University, Oxford, United Kingdom
ab Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
ac Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
ad 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
ae Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
af Also at Department of Physics, Nanjing University, Jiangsu, China
* Deceased