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


Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2012.01.035

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).
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\(^\star\)

**ATLAS Collaboration**

**A R T I C L E   I N F O**

Article history:
Received 31 August 2011
Received in revised form 8 November 2011
Accepted 11 January 2012
Available online 14 January 2012

**A B S T R A C T**

Invariant mass distributions of jet pairs (dijets) produced in LHC proton–proton 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% C.L. for several new physics hypotheses: excited quarks are excluded for masses below 299 TeV, axigluons are excluded for masses below 3.32 TeV, and colour octet scalar resonances are excluded for masses below 1.92 TeV.

© 2012 CERN. Published by Elsevier B.V. All rights reserved.

1. 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 \(p_z\) is the \(z\)-component of the jet’s momentum, the rapidity of the
jet is given by $y \equiv \frac{1}{2} \ln \left( \frac{1 + \mu}{1 - \mu} \right)$. 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 $y^* = \frac{1}{2}(y_1 - y_2)$.

2. 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 $(E, \mathbf{p})$ 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 testbeam [19] and collision data [20–22] studies. Measured dijet mass distributions are not corrected for detector resolution, which, in terms of mass smearing, is $\sigma_{\text{m}}/m_{jj} \sim 5\%$ at $m_{jj} \approx 1\text{ TeV}$, drops to $4.5\%$ at $2\text{ TeV}$, and asymptotically approaches $4\%$ at $m_{jj} / 5\text{ TeV}$ 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 selecting events that have at least one large $p_T$, and not prescaled. The chosen trigger has a nominal jet $p_T$ threshold of $180\text{ GeV}$. After applying all other analysis cuts, $m_{jj}$ is required to be greater than $717\text{ GeV}$ 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 $p_T$ of $180\text{ GeV}$ 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 $|\eta_{jj}| < 2.8$ 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 rejects less than $0.002\%$ of the events.

3. 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
\[
f(x) = p_1 (1 - x)^{p_2} x^{p_3} e^{p_4 \ln x},
\]
where $x = m_{jj}/\sqrt{s}$ 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 $\sim 200\text{ GeV}$ for dijet masses from $0.85$ to $4.5\text{ TeV}$, 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 $z$-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 pseudoexperiments. The resulting $p$-value is $0.96$, showing that there is good agreement between the data and the functional form.

4. Search for resonances

As a more sensitive test, the BUMPHunter 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 [26], 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 natu-
reral width of $q^*$, which varies between about 3% and 3.5% of the $q^*$ mass.

In the current implementation, the BUMP Hunter 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 BUMP Hunter 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 BUMP Hunter 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 spectrum. Variable width binning reduces the penalty due to this effect, while retaining sensitivity.

5. 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 [7,8] is used, with the assumption of spin 1/2 and quark-like SM-like coupling constants. The compositeness scale ($\Lambda$) is set to the $q^*$ mass. Signal events are produced using the Pythia event generator [28], a leading-order parton-shower MC generator, with the MRST2007LO* parton distribution functions (PDFs), 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 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 the initial 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-shell than $q^*$.

6. 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 parameterised 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%. These background parameterization uncertainties are 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 following bunches contribute to out-of-time pileup. Although the conditions modelled in MC are realistic, they may not perfectly match the data due to bunch train structure and instantaneous luminosity variations in the LHC. The MC events are therefore reweighted to remove these residual differences. Following this procedure the pileup description in MC is sufficiently good that no additional uncertainty on the JES is required for jets with $p_T > 100$ GeV.

The resulting limits are shown in Fig. 2. For excited quarks, the acceptance $A$ ranges from 37 to 51% for $m_{q^*}$ varying from 0.8 to 5.0 TeV, and is never lower than 47% above masses of 1.1 TeV. The main impact on the acceptance comes from the rapidity requirements. Using the theoretical prediction for $q^*$ production described above, the expected mass limit at 95% CL is 2.81 TeV, and the observed limit is 2.99 TeV.

The axigluon results are obtained from the $\sigma \times A$ limits determined from the $q^*$ analysis. The axigluon theoretical prediction is derived from the cross section provided by CalcHEP at each simulated mass, $m$, within the restricted mass range 0.7 to 1.3 mT, after applying the kinematic selections. Using the axigluon theoretical $\sigma \times A$ thus defined, the expected axigluon mass limit at 95% CL is 3.07 TeV, and the observed limit is 3.32 TeV. This method has been confirmed by full simulation of axigluon samples at three mass points, showing that the differences between parton level and full simulation are negligible compared to the effects of other uncertainties.

Fig. 2(b) shows the limits on the accepted cross section $\sigma \times A$ for colour octet scalar resonances. The expected mass limit at 95% CL is 1.77 TeV, and the observed limit is 1.92 TeV. Since the colour octet scalar cross section decreases much more rapidly with $m$ than those for excited quark and axigluon production, the resulting limits are considerably lower.

For all three models used in these studies, if systematic uncertainties had not been included the exclusion limits would be approximately 60 GeV higher.

7. 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 $m_{jj}$ 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. 3. 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 physics models beyond those considered in these studies, using the procedure described in Appendix A.
8. Conclusion

The dijet mass spectrum measured by the ATLAS experiment has been examined in a search for resonances from new phenomenology, 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 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 established for the first time in ATLAS. The results reported in this Letter are the strongest to date.

Acknowledgements

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, 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; DLRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMDF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States.

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-CNF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Appendix A. 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. 3 are provided in Table 2.

(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 \(p_\text{T}\) and |\(\eta\)| 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 2, which is derived from full ATLAS simulation. (4) Since a Gaussian signal shape has been assumed in determining the limit, 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 0.8M and 1.2M. 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 2 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 $q^*$ 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.

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References


Group of Particle Physics, University of Montreal, Montreal, QC, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science, Nagoya University, Nagoya, Japan
Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, Dekalb, IL, United States
Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
Department of Physics, New York University, New York, NY, United States
Ohio State University, Columbus, OH, United States
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
Department of Physics, Oklahoma State University, Stillwater, OK, United States
Palacký University, KFPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, OR, United States
LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
Petersburg Nuclear Physics Institute, Gatchina, Russia
Department of Physics, University of Pisa, (a) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
Laboratorio de Instrumentacion e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFFE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
Czech Technical University in Prague, Prague, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina, SK, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
Institut de Fisica de Informacion, Universidad Autonómica de Madrid, Madrid, Spain
Department of Physics, University of Alberta, Edmonton, AB, Canada
Dipartimento di Fisica, Università di Pisa, Pisa, Italy
Faculty des Sciences Ain Chock, Espace Universitaire de Physique des Hautes Energies - 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
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
Department of Physics, University of Washington, Seattle, WA, United States
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby, BC, Canada
SLAC National Accelerator Laboratory, Stanford, CA, United States
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
Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion – Israel Inst. of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto, ON, Canada
TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada
Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
Science and Technology Center, Tufts University, Medford, MA, United States
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Fisica, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana, IL, United States
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden