Search for resonances in the mass distribution of jet pairs with one or two jets identified as $b$-jets in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

Searches for high-mass resonances in the dijet invariant mass spectrum with one or two jets identified as $b$-jets are performed using an integrated luminosity of 3.2 fb$^{-1}$ of proton–proton collisions with a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. No evidence of anomalous phenomena is observed in the data, which are used to exclude, at 95% credibility level, excited $b^*$ quarks with masses from 1.1 TeV to 2.1 TeV and leptophobic $Z'$ bosons with masses from 1.1 TeV to 1.5 TeV. Contributions of a Gaussian signal shape with effective cross sections ranging from approximately 0.4 to 0.001 pb are also excluded in the mass range 1.5–5.0 TeV.
1 Introduction

Many extensions to the Standard Model (SM) predict the existence of new massive particles that couple to quarks or gluons. If produced in proton–proton ($pp$) collisions at the Large Hadron Collider (LHC), these new beyond-the-SM (BSM) particles could decay into quarks ($q$) or gluons ($g$), creating resonant excesses in the two-jet (dijet) invariant mass distributions [1–6]. If the new particle couples to the $b$-quark and decays into $b\bar{b}$, $bg$ or $bq$ pairs, a dedicated search for dijet resonances with one or both jets identified as originating from a $b$-quark (“$b$-jet”) could greatly increase the signal sensitivity.

Prior resonance searches in dijet events containing $b$-jets were performed by the CDF [7] and CMS [8, 9] experiments, probing the mass ranges 200–750 GeV and 1–4 TeV respectively. Excited heavy-flavour quarks have been investigated in alternative decay modes as well [10]. No BSM phenomena have been observed yet. The increase in centre-of-mass energy of the $pp$ collisions at the LHC from $\sqrt{s} = 7$ and 8 TeV to 13 TeV provides a new energy regime in which to search for such a heavy resonance. This is particularly true for heavy states coupling to $b$-quarks from the proton sea, when compared to states produced by valence quarks. The parton luminosity to create a 2 TeV object increases by an additional factor of 2–3 for $b\bar{b}$ and $bg$ over $qq$ and $qg$ pairs, when increasing the centre-of-mass energy from 8 TeV to 13 TeV. The total production rate for dijet BSM signals can become large enough to allow a good signal sensitivity even with a relatively small data sample. In this paper the search for a new narrow resonance decaying to $b$-quarks with the ATLAS detector, using 3.2 fb$^{-1}$ integrated luminosity of proton–proton collisions at $\sqrt{s} = 13$ TeV, is reported. The mass range 1.1–5.0 TeV is probed.

![Figure 1: Leading-order Feynman diagrams for the two processes considered: $gb \rightarrow b^* \rightarrow bg$ and $q\bar{q} \rightarrow Z' \rightarrow b\bar{b}$.](image)

The results are interpreted in the context of two benchmark processes shown in Figure 1: an excited heavy-flavour quark $b^*$ and a new gauge boson $Z'$. Excited quarks are a consequence of quark compositeness models that were proposed to explain the generational structure and mass hierarchy of quarks [11, 12]. The $Z'$ boson arises in many extensions to the SM with an additional $U(1)$ group. Two $Z'$ models are considered, one with SM-like fermion couplings in the Sequential Standard Model (SSM) and a leptophobic $Z'$ model [13, 14]. All benchmark model decays are expected to result in a narrow resonance superimposed on a smoothly falling dijet invariant mass distribution. This search divides the events into samples with one or two jets identified as $b$-jets to enhance the signal sensitivity to the benchmark models $b^* \rightarrow bg$ and $Z' \rightarrow b\bar{b}$. In addition, the results are interpreted in the context of possible Gaussian-shaped signal contributions to the dijet invariant mass spectra where one or both jets are identified as $b$-jets. The results, presented in terms of the the cross section times acceptance times branching ratio ($\sigma \times A \times BR$), are quoted for contributions with widths of up to 15% of the resonance mass.
2 The ATLAS detector

The ATLAS experiment [15] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of, in ascending order of radius from the beam-line, silicon pixel, silicon microstrip, and transition radiation tracking detectors. The pixel detectors are crucial for $b$-jet identification. For the second LHC data-taking period, a new inner pixel layer, the Insertable B-Layer (IBL) [16, 17], was added at a mean sensor radius of 3.2 cm from the beam-line. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadron (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the input rate from the nominal LHC collision rate to an acceptance rate of 100 kHz. This is followed by a software-based trigger that reduces the rate of events recorded to 1 kHz.

3 Data and simulated event samples

The data used in this analysis were collected by the ATLAS detector in $pp$ collisions at the LHC with a centre-of-mass energy of 13 TeV during 2015. Events were recorded using a jet-based trigger requiring at least one jet with a transverse momentum $p_T$ of at least 360 GeV. The full dataset corresponds to an integrated luminosity of 3.2 fb$^{-1}$ with an associated uncertainty of 5% after applying quality criteria to the data. The measurement of the integrated luminosity is derived, following a methodology similar to that detailed in Ref. [18], from a calibration of the luminosity scale using a pair of $x$–$y$ beam-separation scans.

Monte Carlo (MC) simulated event samples are used to model the expected signals and study the composition of SM background processes. The QCD dijet process is simulated with Pythia8 [19] using the A14 tuned parameter set [20] for the modelling of the parton shower, hadronization and underlying event. The leading-order (LO) parton distribution function (PDF) set NNPDF2.3 [21] is used for the generation of events. The renormalization and factorization scales are set to the average transverse momentum $p_T$ of the two leading jets. The EvrGen decay package [22] is used for bottom and charm hadron decays.

The three signal samples are generated with Pythia8 using the A14 set of tuned parameters and the NNPDF2.3 PDF set. For the $b^*$ model, the compositeness scale is set to the excited-quark mass and 85% of decays are to $b\gamma$. The remaining decay modes are to a SM gauge boson ($Z$ boson, $W$ boson or photon) and a $b$-quark. In the SSM $Z'$ model, the $Z'$ boson has the same couplings to SM fermions as the SM $Z$ boson and the bottom quark decay branching ratio $\text{BR}(Z' \to b\bar{b})$ is 13.8%. The leptophobic $Z'$ model differs by having vanishing couplings to leptons. The corresponding value of $\text{BR}(Z' \to b\bar{b})$ is

---

1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upwards. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. 

3
Jets are reconstructed from noise-suppressed topological clusters [26] of energy deposited in the calorimeters using the anti-$k_t$ algorithm [27] with a radius parameter of 0.4. Jet energies and directions are corrected by the jet calibrations derived from $\sqrt{s} = 13$ TeV simulation, and $pp$ collision data taken at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV, as described in Ref. [28]. Jets are required to have $p_T > 50$ GeV. Events where any of the three leading jets with $p_T > 50$ GeV is compatible with non-collision background or calorimeter noise are removed. Events are preselected in the same way as in the dijet analysis of Ref. [5], requiring that the $p_T$ of the leading jet is greater than 440 GeV to ensure full trigger efficiency. An additional requirement is placed on the jet pseudorapidity, $|\eta| < 2.4$, to ensure tracker coverage for $b$-jet identification. The analysis is performed in an unbiased dijet mass range of $m_{jj} > 1.1$ TeV. To reduce the background from QCD multijet processes and enhance $s$-channel processes, the rapidity difference $y^* = (y_1 - y_2)/2$ between the two leading jets is required to be $|y^*| < 0.6$. Here $y_1$ and $y_2$ are the rapidities of the leading and sub-leading jet respectively. To identify jets originating from $b$-hadrons ($b$-tagging) a multivariate algorithm that combines information about the impact parameters of inner detector tracks associated with the jet, the presence of displaced secondary vertices, and the reconstructed flight paths of $b$- and $c$-hadrons associated with the jet [29, 30] is employed. The $b$-tagging working point with 85% efficiency, as determined when integrating over all jets in a simulated sample of $t\bar{t}$ events, is chosen because it gives the highest signal sensitivity. As the average jet energies in this analysis are larger than in $t\bar{t}$ events and the $b$-tagging efficiency drops with jet $p_T$, the per-jet efficiencies are below 85% and are roughly 50% for jets with a $p_T$ of 1 TeV. The $b$-jet identification algorithm is applied to the two leading jets, and events are categorized as inclusive, single $b$-tagged “1b” or double $b$-tagged “2b”, in order to enhance the sensitivity of different signal compositions. The “1b” category is defined inclusively, including events from the “2b” category. The per-event $b$-tagging efficiencies as functions of the reconstructed invariant mass are shown in Figure 2. Efficiencies are for benchmark models with different $b^*$ and $Z'$ resonance masses, after the event selection is applied. The tagging efficiency for $Z'$ events in the inclusive “1b” category is higher than for $b^*$ events because this process has more $b$-quarks in the final state. At high mass, the gluon from the decay of the $b^*$ has a higher probability to produce a $b\bar{b}$-pair, which causes the event tagging efficiency to be comparable for the $Z'$ and $b^*$. The tagging efficiency in the “2b” category is about 2.5 times lower at low mass and a factor 10 lower at high mass compared to the inclusive “1b” category for the same $Z'$ events. The average light-flavour jet rejection factor for jets passing the kinematic selection is approximately 30 for jet transverse momenta up to ~ 1 TeV. Correction factors are applied to the simulated event samples to compensate for differences between data and simulation in $b$-tagging efficiencies and mis-identification rates. These corrections were derived from
comparisons of samples of $b$-quark-enriched events in data and simulation [31]. The average combined signal acceptance and efficiency is around 20% for the $b^*$ benchmark in the “1b” category and drops with increasing mass from 9% at 1.5 TeV to 2% at 5.0 TeV for the $Z'$ signals for the “2b” category.

5 Dijet mass spectrum

The dijet mass spectrum is predominantly composed of jets arising from QCD interactions. Figure 3 shows the comparison between data and Pythia8 multijet MC simulation. The simulated distributions are normalized to the number of events observed in the data in each category separately. The bin widths are chosen to approximate the $m_{jj}$ resolution as derived from simulated QCD processes, which range from 3% at 1.0 TeV to 2% at 5.0 TeV. Good agreement between the shapes of the Pythia8 multijet predictions and the data is found. The inclusive distribution, not restricted in the inner tracking detector acceptance, was analysed in Ref. [5].

The dijet background estimation does not rely on the simulation as it is obtained directly from a fit to the $m_{jj}$ distribution. The following parameterization ansatz is adopted to fit the distribution in the $m_{jj}$ range from 1.1 TeV up to the last data point of the inclusive, “1b” and “2b” mass distributions separately,

$$f(z) = p_1(1 - z)^{p_2} z^{p_3},$$

where $p_i$ are free parameters and $z = m_{jj} / \sqrt{s}$. This ansatz was used in previous searches [5] and is found to provide a satisfactory fit to leading-order Pythia8 multijet MC simulation at $\sqrt{s} = 13$ TeV. Employing Wilks’ theorem [32], a log-likelihood statistic is used to confirm that no additional parameters are needed to model these distributions for a data set as large as the one used for this analysis.

The results of the fits are shown in Figure 4. The fits of this ansatz to the data without considering systematic uncertainties return $p$-values of 0.73, 0.90 and 0.66 for the inclusive, “1b” and “2b” categories.
Figure 3: The invariant mass distribution of the inclusive dijet (dots), “1b” (squares) and “2b” (triangles) categories in data. The inclusive distribution is similar to Ref. [5], but an additional requirement is placed on the jet pseudorapidity, $|\eta| < 2.4$. The MC distributions are normalized to the data in the three categories separately: a solid line for inclusive dijets, a dashed line for “1b” and a small dashed line for “2b” categories. The lower panels show the ratio between data and MC simulation for all three categories.
respectively. The $p$-value was calculated as a goodness-of-fit measure using a $\chi^2$ test statistic determined from pseudo-experiments.

The lower panels of Figure 4 show the significances of bin-by-bin differences between the data and the fit. These equivalent Gaussian significances are calculated from the Poisson probability, considering only statistical uncertainties.

The statistical significance of any localized excess in the dijet mass distribution is quantified using the BUMPHunter algorithm [33]. The algorithm compares the binned $m_{jj}$ distribution of the data to the fitted background estimate, considering contiguous mass intervals in all possible locations, from a width of two bins to one-half of the distribution. For each interval in the scan, it computes the significance of any excess found. The algorithm identifies the intervals 1493–1614 GeV in the “1b” and 3596–3827 GeV in the “2b” sample, indicated by the two vertical lines in Figure 4, as the most discrepant intervals. The statistical significance of these outcomes is evaluated using the ensemble of Poisson outcomes across all intervals scanned, by applying the algorithm to many pseudo-data samples drawn randomly from the background fit. Without including systematic uncertainties, the probability that fluctuations of the background model would produce excesses at least as significant as those observed in the data, anywhere in the distribution, is greater than 60% in the “1b” and “2b” categories. Thus, there is no evidence of localized contributions to the mass distribution from BSM phenomena.
6 Systematic uncertainties

Uncertainties in the parameters of the fitted background function Eq. (1) are evaluated by fitting the ansatz to pseudo-data drawn via Poisson fluctuations around the fitted background model. The uncertainty in the prediction in each $m_{jj}$ bin is taken to be the root mean square of the function value for 10000 generated pseudo-experiments. To estimate an uncertainty due to the choice of background parameterization, one additional degree of freedom, $e^{\mu \log(z)}$, is appended as a multiplicative factor to the nominal ansatz (Eq. (1)), and the difference between the estimated parameters from the two fits is taken as an uncertainty.

The uncertainty in the jet energy scale is estimated using various methods in 8 TeV data, corrected to the new centre-of-mass energy by taking the difference between the 8 TeV and 13 TeV runs into account using MC simulation [28]. The jet energy scale uncertainty used in this analysis relies on a set of three nuisance parameters [34]. For untagged jets it is within the range 1–5% for jet transverse momenta greater than 200 GeV.

The relative additional uncertainty in the energy scale of $b$-tagged jets is estimated using the MC samples and verified with data following the method described in Ref. [35]. The ratio $r_{\text{trk}}$ of the sum of track transverse momenta inside the jet to the total jet transverse momentum measured in the calorimeter is used for this estimate. The double ratio of $r_{\text{trk}}$ from data and simulation is formed and compared for inclusive jets and $b$-jets. The estimated relative additional uncertainty for jets with 200 < $p_T$ < 800 GeV is found to be less than 2.6%, and this value is subsequently used in the higher $p_T$ regions. This relative uncertainty is applied in addition to the nominal jet energy scale uncertainty. The maximum uncertainty for $b$-tagged jets is estimated to be 6% and is conservatively applied to all $p_T$ regions.

The uncertainty in the jet energy resolution is estimated using the same method as the untagged jet energy scale uncertainty and relies on an additional Gaussian smearing of the reconstructed jet energies in MC simulation. For jets with $p_T$ > 50 GeV, the uncertainty is less than 2%.

The uncertainty introduced by the application of the $b$-tagging algorithm is the largest systematic uncertainty in the analysis. The uncertainty in the measured tagging efficiency of $b$-jets is estimated by studying $t\bar{t}$ events in 13 TeV data for jet $p_T$ up to 200 GeV [31]. The uncertainties in the measured rate of mistagging $c$-jets and light-flavour jets are estimated in 8 TeV data. The uncertainties are extrapolated to 13 TeV, taking into account the addition of the new IBL system as well as reconstruction and tagging improvements. An additional term is included to extrapolate the measured uncertainties to the high-$p_T$ region of interest. This term is calculated from simulated events by considering variations on the quantities affecting the $b$-tagging performance such as the impact parameter resolution, percentage of poorly measured tracks, description of the detector material, and track multiplicity per jet. The dominant effect on the uncertainty when extrapolating at high-$p_T$ is related to the different tagging efficiency when smearing the tracks impact parameters based on the resolution measured in data and simulation. The difference in the impact parameter resolution is due to effects from alignment, dead modules and additional material not properly modelled in the simulation. The impact of the $b$-tagging efficiency uncertainty increases with jet $p_T$ and reaches 50% above 2 TeV.
7 Results

Due to the absence of a signal, 95% credibility-level upper limits are set on the cross section for new processes that would produce a contribution to the dijet mass distribution with $b$-tagging. The signal shapes are taken as provided by $b^* \rightarrow bg$ and $Z' \rightarrow b\bar{b}$ production processes.

The limits on $b^*$ and $Z'$ cross sections are shown in Figures 5 and 6. The limits were obtained using a Bayesian method [36]. The Bayesian credible intervals were calculated using a posterior probability density from the likelihood function for the observed mass spectrum obtained by a fit to the background (Eq. (1)), while the signal shape was derived from MC simulations. The limit is interpolated between discrete values of the mass to create a continuous curve. The systematic uncertainties associated with the uncertainty in the integrated luminosity, jet energy scale, jet energy resolution, $b$-tagging and alternative fit functions are all included in the limit-setting.

Figure 5 shows that the $b^*$ model, with the decay to $g + b(\bar{b})$, is excluded for $b^*$ masses from 1.1 TeV up to 2.1 TeV at leading-order in QCD. Figure 6 shows that the leptophobic $Z' \rightarrow b\bar{b}$ model with SM-like couplings to quarks is excluded up to 1.5 TeV at leading-order in QCD. The present data are not sufficient to provide an exclusion limit for the SSM $Z'$ model.

As shown in Figure 7, narrow resonance contributions of various widths with visible cross sections $\sigma \times A \times BR$ ranging from approximately 0.4 to 0.001 pb are excluded in the mass range 1.5–5.0 TeV. These
Figure 6: Observed (filled circles) and expected (dotted line) 95% credibility-level upper limits on the cross section $\sigma$ times the acceptance $A$ times branching ratio BR, including kinematic acceptance and $b$-tagging efficiencies, for the $Z' \rightarrow b\bar{b}$ models. The dashed lines show the cross section calculated from theory. The plot shows the case with double $b$-tag.

Limits should be used when long low-mass off-shell tails from PDFs and non-perturbative effects on the narrow resonance signal shape can be safely truncated or neglected and, after applying the selection described in Section 4, the reconstructed mass distribution approximates a Gaussian distribution. For a detailed description of how to use these limits, see the instructions in Ref. [37]. To estimate the $b$-tagging efficiency, invariant-mass-dependent correction factors as given in Figure 2 can be used.

8 Summary

A search for new resonances decaying to jets with a single or double $b$-tag in $pp$ collisions with the ATLAS detector at the LHC is presented. The dataset corresponds to an integrated luminosity of 3.2 fb$^{-1}$ collected at $\sqrt{s} = 13$ TeV in 2015. The studies use the dijet invariant mass $m_{jj}$ in the range of 1.1–5.0 TeV with $b$-tagging applied to the leading and sub-leading jets and categorize the events according to their $b$-jet multiplicity.

The background from jets initiated by $b$-quarks is well described by the leading-order parton-shower models. The dijet background is also well described by the analytic fit function with three parameters which is used in the light-flavour dijet analysis [5].

No evidence of a significant excess of events is found compared to the expectations of the Standard Model. The largest observed local excess is less than 2$\sigma$ for both the single and double $b$-tag channels.
Figure 7: The 95% credibility-level upper limits on the cross section $\sigma$ times the acceptance $A$ times branching ratio $BR$, including kinematic acceptance and $b$-tagging efficiencies, for resonances exhibiting a generic Gaussian shape. The circles, squares and triangles correspond to the cases where the width of the Gaussian signal is 15%, 10% or 7% of the signal mass. The figure also shows as a red line the case where the width is given by the dijet mass resolution, which is as low as 2% at 5.0 TeV. The plots show the limits obtained, applying (a) at least one $b$-tag and (b) double $b$-tag.
The expected contribution from the $b^*$ model is excluded in the mass range 1.1–2.1 TeV at leading-order in QCD using the single $b$-jet channel. The results can not exclude contributions from the SSM $Z' \rightarrow b\bar{b}$ model in the mass range 1.1–5.0 TeV in the double $b$-jet channel. For the leptophobic $Z'$ model with SM-like couplings to quarks, the mass range 1.1–1.5 TeV is excluded at leading-order in QCD in this channel.

This analysis excludes generic high-mass particles decaying to two jets, where one or two jets originate from $b$-quarks, with visible cross sections ranging from 0.4 to 0.001 pb in the mass range 1.1–5.0 TeV. The exclusion limits are applicable for resonances exhibiting a Gaussian shape and width similar to the $b^*$ or $Z'$ models. The limits were calculated assuming that the width of the Gaussian signal is 15%, 10% or 7% of its mass.

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; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; RCN, Norway; MnI SW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; the Royal Society and Leverhulme Trust, United Kingdom.

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.
References


The ATLAS Collaboration

<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey</td>
<td>Turkey</td>
</tr>
<tr>
<td>LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France</td>
<td>France</td>
</tr>
<tr>
<td>High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Department of Physics, University of Arizona, Tucson AZ, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Physics Department, The University of Texas at Arlington, Arlington TX, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Physics Department, University of Athens, Athens, Greece</td>
<td>Greece</td>
</tr>
<tr>
<td>Physics Department, National Technical University of Athens, Zografou, Greece</td>
<td>Greece</td>
</tr>
<tr>
<td>Department of Physics, The University of Texas at Austin, Austin TX, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan</td>
<td>Azerbaijan</td>
</tr>
<tr>
<td>Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain, Spain</td>
<td>Spain</td>
</tr>
<tr>
<td>Institute of Physics, University of Belgrade, Belgrade, Serbia</td>
<td>Serbia</td>
</tr>
<tr>
<td>Department for Physics and Technology, University of Bergen, Bergen, Norway</td>
<td>Norway</td>
</tr>
<tr>
<td>Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Department of Physics, Humboldt University, Berlin, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland</td>
<td>Switzerland</td>
</tr>
<tr>
<td>School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Department of Physics, Bogazici University, Istanbul; Department of Physics Engineering, Gaziantep University, Gaziantep; Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey</td>
<td>Turkey</td>
</tr>
<tr>
<td>Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia</td>
<td>Colombia</td>
</tr>
<tr>
<td>INFN Sezione di Bologna; Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Physikalisches Institut, University of Bonn, Bonn, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>Department of Physics, Boston University, Boston MA, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Department of Physics, Brandeis University, Waltham MA, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; Electrical Circuits Department, Federal University of Juiz de Fora (UFJJ), Juiz de Fora; Federal University of Sao Joao del Rei (UFJS), Sao Joao del Rei; Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil</td>
<td>Brazil</td>
</tr>
<tr>
<td>Physics Department, Brookhaven National Laboratory, Upton NY, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Transilvania University of Brasov, Brasov, Romania; National Institute of Physics and Nuclear Engineering, Bucharest; National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; University Politehnica Bucharest, Bucharest; West University in Timisoara, Timisoara, Romania</td>
<td>Romania</td>
</tr>
<tr>
<td>Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina</td>
<td>Argentina</td>
</tr>
<tr>
<td>Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Department of Physics, Carleton University, Ottawa ON, Canada</td>
<td>Canada</td>
</tr>
<tr>
<td>CERN, Geneva, Switzerland</td>
<td>Switzerland</td>
</tr>
<tr>
<td>Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America</td>
<td>United States of America</td>
</tr>
<tr>
<td>Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile</td>
<td>Chile</td>
</tr>
<tr>
<td>Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; Department of Modern Physics, University of Science and Technology of China, Anhui; Department of Physics, Nanjing University, Jiangsu; School of Physics, Shandong University, Shandong; Department of</td>
<td>China</td>
</tr>
</tbody>
</table>
Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (also affiliated with PKU-CHEP); (J) Physics Department, Tsinghua University, Beijing 100084, China
36 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
37 Nevis Laboratory, Columbia University, Irvington NY, United States of America
38 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
39 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
40 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
41 Physics Department, Southern Methodist University, Dallas TX, United States of America
42 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
43 DESY, Hamburg and Zeuthen, Germany
44 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
45 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
46 Department of Physics, Duke University, Durham NC, United States of America
47 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
48 INFN Laboratori Nazionali di Frascati, Frascati, Italy
49 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
50 Section de Physique, Université de Genève, Geneva, Switzerland
51 INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
52 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi, Georgia
53 I Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68
70 Faculty of Science, Kyoto University, Kyoto, Japan
71 Kyoto University of Education, Kyoto, Japan
72 Department of Physics, Kyushu University, Fukuoka, Japan
73 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
74 Physics Department, Lancaster University, Lancaster, United Kingdom
75 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
76 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
77 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
78 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
79 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
80 Department of Physics and Astronomy, University College London, London, United Kingdom
81 Louisiana Tech University, Ruston LA, United States of America
82 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
83 Fysiska institutionen, Lunds universitet, Lund, Sweden
84 Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
85 Institut für Physik, Universität Mainz, Mainz, Germany
86 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
87 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
88 Department of Physics, University of Massachusetts, Amherst MA, United States of America
89 Department of Physics, McGill University, Montreal QC, Canada
90 School of Physics, University of Melbourne, Victoria, Australia
91 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
92 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
93 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
94 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
95 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
96 Group of Particle Physics, University of Montreal, Montreal QC, Canada
97 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
98 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
99 National Research Nuclear University MEPhI, Moscow, Russia
100 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
101 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
102 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
103 Nagasaki Institute of Applied Science, Nagasaki, Japan
104 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
105 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
106 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
107 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
108 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam,
Netherlands
109 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
110 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
111 Department of Physics, New York University, New York NY, United States of America
112 Ohio State University, Columbus OH, United States of America
113 Faculty of Science, Okayama University, Okayama, Japan
114 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
115 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
116 Palacký University, RCPTM, Olomouc, Czech Republic
117 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
118 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
119 Graduate School of Science, Osaka University, Osaka, Japan
120 Department of Physics, University of Oslo, Oslo, Norway
121 Department of Physics, Oxford University, Oxford, United Kingdom
122 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
123 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
124 National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
125 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
126 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
127 (a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Fisica, Universidade do Minho, Braga; (f) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
128 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
129 Czech Technical University in Prague, Praha, Czech Republic
130 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
131 State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
132 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
133 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
134 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
137 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
138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
139 Department of Physics, University of Washington, Seattle WA, United States of America
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
145 (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
146 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
147 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto ON, Canada
160 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
161 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
164 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
166 Department of Physics, University of Illinois, Urbana IL, United States of America
167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), 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 Department of Physics, University of Warwick, Coventry, United Kingdom
171 Waseda University, Tokyo, Japan
172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
\textsuperscript{a} Also at Department of Physics, King’s College London, London, United Kingdom
\textsuperscript{b} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
\textsuperscript{c} Also at Novosibirsk State University, Novosibirsk, Russia
\textsuperscript{d} Also at TRIUMF, Vancouver BC, Canada
\textsuperscript{e} Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America
\textsuperscript{f} Also at Department of Physics, California State University, Fresno CA, United States of America
\textsuperscript{g} Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
\textsuperscript{h} Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
\textsuperscript{i} Also at Departamento de Física e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal
\textsuperscript{j} Also at Tomsk State University, Tomsk, Russia
\textsuperscript{k} Also at Universita di Napoli Parthenope, Napoli, Italy
\textsuperscript{l} Also at Institute of Particle Physics (IPP), Canada
\textsuperscript{m} Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania
\textsuperscript{n} Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
\textsuperscript{o} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
\textsuperscript{p} Also at Louisiana Tech University, Ruston LA, United States of America
\textsuperscript{q} Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
\textsuperscript{r} Also at Graduate School of Science, Osaka University, Osaka, Japan
\textsuperscript{s} Also at Department of Physics, National Tsing Hua University, Taiwan
\textsuperscript{t} Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
\textsuperscript{u} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
\textsuperscript{v} Also at CERN, Geneva, Switzerland
\textsuperscript{w} Also at Georgian Technical University (GTU), Tbilisi, Georgia
\textsuperscript{x} Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
\textsuperscript{y} Also at Manhattan College, New York NY, United States of America
\textsuperscript{z} Also at Hellenic Open University, Patras, Greece
\textsuperscript{aa} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
\textsuperscript{ab} Also at School of Physics, Shandong University, Shandong, China
\textsuperscript{ac} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
\textsuperscript{ad} Also at Section de Physique, Université de Genève, Geneva, Switzerland
\textsuperscript{ae} Also at Eotvos Lorand University, Budapest, Hungary
\textsuperscript{af} Also at International School for Advanced Studies (SISSA), Trieste, Italy
\textsuperscript{ag} Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
\textsuperscript{ah} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
\textsuperscript{ai} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
\textsuperscript{aj} Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
ak Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
ad Also at National Research Nuclear University MEPhI, Moscow, Russia
am Also at Department of Physics, Stanford University, Stanford CA, United States of America
an Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
ao Also at Flensburg University of Applied Sciences, Flensburg, Germany
ap Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
aq Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
* Deceased