Search for $tb$ resonances in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This Letter presents a search for $tb$ resonances in 1.04 fb$^{-1}$ of LHC proton-proton collision data collected by the ATLAS detector at a center-of-mass energy of 7 TeV. Events with a lepton, missing transverse momentum, and two jets are selected and the invariant mass of the corresponding final state is reconstructed. The search exploits the shape of the $tb$ invariant mass distribution compared to the expected Standard Model backgrounds. The model of a right-handed $W_R'$ with Standard Model-like couplings is chosen as the benchmark model for this search. No statistically significant excess of events is observed in data, and upper limits on the cross section times the branching ratio of $W_R'$ resonances at 95% CL lie in the range 6.1–1.0 pb for $W_R'$ masses ranging from 0.5 to 2.0 TeV. These limits are translated into a lower bound on the allowed right-handed $W_R'$ mass, giving $m_{W_R'} > 1.13$ TeV at 95% CL.
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This Letter presents a search for $tb$ ($\bar{t}\bar{b}$ or $t\bar{b}$) resonances using data collected in 2011 by the ATLAS detector [1] at the Large Hadron Collider (LHC), corresponding to an integrated luminosity of 1.04 ± 0.04 fb$^{-1}$ [2,3] from $pp$ collisions at a center-of-mass energy of 7 TeV. These resonances include new heavy gauge bosons such as the $W'$ boson. The $W'$ boson is a charged heavy gauge boson that is predicted in many extensions of the Standard Model (SM) such as universal extra dimensions [4] and little Higgs models [5]. If the $W'$ boson is assumed to have similar coupling strengths to those of the SM $W$ boson, searches in the $W' \to \ell\nu$ decay channel, where $\ell$ is a charged lepton, are the most sensitive. However, the $W' \to tb$ channel is competitive if $W' \to \ell\nu$ decay is suppressed. For example, for a right-handed $W'_R$ this can happen if the right-handed neutrino, $\nu_R$, is heavy enough to prevent $W'_R \to \ell\nu_R$ decay [6]. The model of a right-handed $W'_R$ with SM-like couplings is chosen as the benchmark model for the analysis presented in this Letter. The $W'_R \to \bar{t}b$ decay channel has been searched for at the Tevatron [7,8]. The best previous limit on a $W'_R$ with Standard Model-like couplings of the $W'$ to quarks was set by the D0 experiment and excludes a $W'_R$ mass below 890 GeV at 95% confidence level.

The innermost part of the ATLAS detector [9], a tracking system in a 2 T axial magnetic field, measures the momentum of the charged particles produced in the collisions. Outside of the solenoid are the calorimeter subsystems, which measure the electron, photon, and hadronic particle energies, and the muon spectrometer which is used to identify and measure the momentum of muons in a toroidal magnetic field. A three-level trigger system [10] reduces the event rate and selects the events for analysis.

The $tb$ resonances are searched for in the $t\bar{b} \to \ell\nu bb$ decay channel, where the lepton, $\ell$, is either an electron or a muon. $W'_R$ signal events are simulated to leading order (LO) with the PYTHIA v6.421 [11] Monte Carlo (MC) generator, using the MRST2007 LO* parton distribution functions (PDFs) [12]. Seven signal samples are simulated, with different $W'_R$ mass assumptions, ranging from 500 GeV to 2.0 TeV, as reported in Table I. The respective signal cross section times the branching ratio values are computed at next-to-leading-order (NLO) [13], using CTEQ6.6 PDFs [14].

<table>
<thead>
<tr>
<th>$m_{W'_R}$ [GeV]</th>
<th>$B(W'_R \to \bar{t}b)$</th>
<th>$\sigma \times B$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.298 ± 0.002</td>
<td>54.6 ± 2.1</td>
</tr>
<tr>
<td>750</td>
<td>0.319 ± 0.001</td>
<td>10.9 ± 0.6</td>
</tr>
<tr>
<td>1000</td>
<td>0.326 ± 0.001</td>
<td>2.92 ± 0.18</td>
</tr>
<tr>
<td>1250</td>
<td>0.328 ± 0.001</td>
<td>0.91 ± 0.07</td>
</tr>
<tr>
<td>1500</td>
<td>0.330 ± 0.001</td>
<td>0.31 ± 0.03</td>
</tr>
<tr>
<td>1750</td>
<td>0.331 ± 0.001</td>
<td>0.11 ± 0.01</td>
</tr>
<tr>
<td>2000</td>
<td>0.332 ± 0.001</td>
<td>0.044 ± 0.005</td>
</tr>
</tbody>
</table>

TABLE I: NLO branching ratios, $B(W'_R \to \bar{t}b)$, and $W'_R$ production cross section times the branching ratio value, $\sigma(pp \to W'_R) \times B(W'_R \to \bar{t}b)$, in $pp$ collisions at 7 TeV center-of-mass energy [13]. The uncertainties on the branching ratios are due to the top quark mass uncertainty. The uncertainties on the cross sections include statistical, $\alpha_s$, NLO renormalization and factorization scales, and PDF uncertainties.

Data-driven methods and MC simulated samples are used to estimate and model backgrounds. The $tt$ process is simulated with the MC@NLO v3.41 [15,16] MC generator, assuming a top quark mass of 172.5 GeV, and using the CTEQ6.6 PDFs. The parton shower is added using the HERWIG [17] and JIMMY [18] MC generators. The $tt$ cross section is obtained from the approximate NNLO prediction calculated with the HATHOR program [19] using the MSTW2008 NNLO PDF sets [20]. The single top quark processes are simulated using the ACERMC v3.7 [21] MC generator and hadronization is performed with the PYTHIA MC generator; the cross section is calculated to approximate NNLO [22,23] using the CTEQ6.6 PDFs. Diboson processes are simulated
using the HERWIG v6.5 MC generator and their cross sections are obtained at NLO using the MCFM \[28\] program with the MSTW2008 PDFs. The MC samples simulated with the AcerMC and HERWIG MC generators use the MRST2007 LO* PDFs. Vector boson production in association with jets (W+ light jets, Wbb, Wc\(\bar{c}\), Wc and Z+jets with up to five additional partons) is simulated using the ALPGEN v2.13 \[20\] MC generator, coupled with the CTEQ6L1 PDFs \[14\] and hadronization is performed with the HERWIG and JIMMY MC generators. In these samples, additional jets can be created from the parton shower. In order to avoid double counting between the inclusive W+\(n\) parton samples and the parton shower, overlaps are removed following the MLM matching prescription \[20\]. A cross section correction factor is applied to the LO W/Z+jet cross sections computed by comparing the LO and NLO predictions from the FEWZ \[27\] program. The Wc cross section correction factor is obtained using the MCFM \[28\] program with the CTEQ6.6 PDFs. All samples are passed through the full simulation of the ATLAS detector \[29\] and are then reconstructed using the same procedure as collision data. The simulated samples include the effect of multiple pp collisions per bunch crossing (pile-up) which on average is six events per bunch crossing. In order to ensure a good description of the energy scale and resolution, the trigger, the reconstruction and identification efficiency, corrections based on comparisons between data and MC events are applied to the simulated signal and background samples. The corresponding scale factors are obtained as a function of the object kinematics, resulting in final corrections of the order of a few percent.

Candidate events are identified using single high transverse momentum electron and muon triggers and stringent detector and data quality requirements. For each candidate, two jets, one isolated charged lepton, and missing transverse momentum, \(E_{\text{T}}^{\text{miss}}\), are required. The definition of the objects and details of a similar event selection including lepton isolation requirements are given in Ref. \[31\]. The reconstructed charged lepton is required to have a transverse momentum \(p_{\text{T}}>25\) GeV to ensure a constant trigger efficiency, \(|\eta|<2.5\) for a muon \[32\]-\[34\] and \(|\eta|<2.47\) for an electron \[35\] (the calorimeter transition region 1.37 < \(|\eta|\) < 1.52 is excluded), and to lie within \(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}<0.15\) of the corresponding triggered lepton. Jets are reconstructed from energy clusters in the calorimeters with the anti-\(k_t\) algorithm \[36\] with a radius parameter \(R=0.4\) and calibrated to the hadronic energy scale \[37\]. Exactly two jets with \(p_{\text{T}}>25\) GeV and \(|\eta|<2.5\) are required in the event, and at least one of them must be tagged as a b-jet. The b-tagging algorithm uses measurements of the impact parameters of tracks and the properties of reconstructed vertices; these are combined in a neural network to extract a tagging decision for each jet \[38\]. Based on a \(\bar{t}t\) MC sample, the working point is chosen at a b-tagging efficiency of 57\%, leading to a light-quark tagging probability of 0.2\% derived from the same sample. To account for the differences between observed and simulated jet \(p_{\text{T}}\) and \(\eta\) distributions, the b-tagging efficiency and the corresponding scaling factors to be applied to MC are derived from data \[39\]. Events before applying any b-tagging are referred to as pre-tagged events. Events where one or both jets are b-tagged are referred to as single- or double-tagged events respectively.

The \(E_{\text{T}}^{\text{miss}}\) is calculated using calorimeter energy clusters \[40\] calibrated according to the reconstructed physics object to which they are associated \[41\]; events are required to satisfy \(E_{\text{T}}^{\text{miss}} > 25\) GeV. The background contribution from multiple hadron jets (multijet background) is reduced by imposing a requirement on the sum of the W boson transverse mass \(m_{\text{T}}(W)\) \[42\] and \(E_{\text{T}}^{\text{miss}}\); \(m_{\text{T}}(W) + E_{\text{T}}^{\text{miss}} > 60\) GeV \[43\]. After applying all selection criteria, the acceptance times efficiency for \(Wt\) signal events with \(m_{Wt}=1.0\) TeV is 1.38\% for single-tagged events and 0.49\% for double-tagged events.

One of the most important backgrounds for the \(tb\) resonance search comes from W production in association with either heavy-flavor jets, or light-flavor jets misidentified as b-jets. Multijet production is another source of background, when either a hadronic jet is misidentified as a lepton, or when a real high-\(p_{\text{T}}\) lepton from semileptonic decay of a heavy hadron within a jet fulfills the selection requirements. Another important background comes from \(t\bar{t}\) pair production in the case that one W boson decays leptonically and the decay products of the other W boson are lost due to the detector acceptance. Other smaller backgrounds come from single top production, diboson production and Z+jet events.

Kinematic variable distributions for the W+jet background are taken from MC samples, while the overall normalization and flavor composition are derived from data; this is done after rejecting signal-like events with the \(tb\) invariant mass, \(m_{tb}\) which is described later, satisfying \(m_{tb}>500\) GeV. In each jet multiplicity bin, the number of W+jet events in the data is assumed to be the difference between the number of observed data events and the number of events estimated for SM non-W+jet processes including the multijet process estimated from a data-driven method. The overall W+jet normalization factor is the ratio of the number of W+jet events in the data to the number of W+jet events in simulation. The flavor composition of the W+jet background is estimated by comparing the MC prediction to data while its dependence on jet and b-tagging multiplicity is modeled using MC. The fractions of Wbb, Wc\(\bar{c}\), Wc and W+light jet components of the total W+jet MC are scaled such that the background sum equals the observed data in three separate samples: a single-tagged one-jet sample and the pre-tagged and single-tagged two-jet samples. The same scale factor is used for Wbb and Wc\(\bar{c}\).
The multijet background normalization and the shape of each distribution are obtained from data. The shape of each multijet background distribution is taken from a data sample which requires a jet instead of an isolated lepton. This jet is required to have a detector signature similar to an electron: it must have $p_T > 25$ GeV and between 80% and 95% of its energy deposited in the electromagnetic section of the calorimeter. The jet must also be associated with at least four tracks. The normalization is estimated using a binned likelihood fit to the $E_T^{miss}$ distribution in data in which the normalization of the W+jet and the multijet components is allowed to vary. The fit is performed separately in the pre-tagged, single- and double-tagged samples, after applying all selection criteria except the $E_T^{miss}$ cut. The uncertainty on the multijet rate is 50% for pre-tagged and single-tagged events, while it amounts to 100% for double-tagged events. The uncertainty is estimated using the $m_T(W)$ distribution instead of the $E_T^{miss}$ distribution in the binned likelihood fit, and by using multijet background models built from data samples with low and high numbers of $pp$ collisions per event.

The $t\bar{t}$, single top, $Z$+jet and diboson events are normalized to the theoretical cross sections and the shape of each distribution is taken from the MC simulation.

Based on the theoretical predictions shown in Table I, the numbers of single- and double-tagged $W'$+jet signal events expected in 1.04 fb$^{-1}$ are listed in Table II as a function of $m_{W'}$. Table III lists the expected background yields.

<table>
<thead>
<tr>
<th>$m_{W'}$ [GeV]</th>
<th>Single-tagged</th>
<th>Double-tagged</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>973 ± 37</td>
<td>455 ± 17</td>
</tr>
<tr>
<td>750</td>
<td>174 ± 9</td>
<td>77 ± 4</td>
</tr>
<tr>
<td>1000</td>
<td>42 ± 3</td>
<td>15 ± 1</td>
</tr>
<tr>
<td>1250</td>
<td>11 ± 1</td>
<td>3.9 ± 0.3</td>
</tr>
<tr>
<td>1500</td>
<td>3.2 ± 0.3</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>1750</td>
<td>1.0 ± 0.1</td>
<td>0.26 ± 0.03</td>
</tr>
<tr>
<td>2000</td>
<td>0.36 ± 0.04</td>
<td>0.09 ± 0.01</td>
</tr>
</tbody>
</table>

Table II: Predicted signal event yields derived using the theoretical cross section times the branching ratio values for $W'_R \rightarrow tb$, for single- and double-tagged two-jet events in 1.04 fb$^{-1}$ of data. The uncertainties correspond to the NLO cross section uncertainties.

The $tb$ invariant mass is used as the observable to discriminate signal from background. The neutrino momentum in the decay $tb \rightarrow t\nu b\bar{b}$ is computed assuming the transverse component to be equal to $E_T^{miss}$, and extracting the longitudinal component ($p_z$) by constraining the $t$-$\nu$ invariant mass to $m_W = 80.42$ GeV. This gives a quadratic equation in $p_z$, and the solution with the smaller $|p_z|$ is used. If the solution is complex, only the real part is taken and the imaginary part is neglected.

Figure I shows the data and expected background distributions of $m_{tb}$ for single- and double-tagged two-jet events. The data event with the highest $m_{tb}$ value corresponds to a single-tagged event with $m_{tb} \approx 2.0$ TeV. The BUMPHUNTER tool is used to search for a local excess in the data due to the production of a $tb$ resonance. This tool is used to test the consistency of the data with the SM background only hypothesis, comparing the data to the SM prediction over the spectrum of the $tb$ invariant mass, scanning over sliding mass windows from 0.5 to 2.0 TeV. The width of the mass windows is chosen to be constant in $\log(m_{tb})$ as shown in Fig. I to deal with low background MC statistics in the higher mass bins. This comparison has been performed for single- and double-tagged events separately. The region with the highest data-background difference is 1024–1129 (764–842) GeV for single(double)-tagged events. The probability of observing the SM background fluctuating up or down the energy of observed data events in these regions is 0.66 for single-tagged events and 0.72 for double-tagged events.

Systematic uncertainties from various sources affecting the background and the signal acceptance (rate uncertainty), as well as shape changes in the invariant mass distribution (shape uncertainty) are considered.

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The jet energy scale and the uncertainty on the $b$-tagging scale factors are the dominant systematic uncertainties for the signal. The background normalization yields are the dominant systematic uncertainty for the background contribution. The jet energy scale uncertainty is evaluated by scaling $1\sigma$ up or down the energy of each jet. The $b$-tagging scale factors are $p_T$-dependent and have an uncertainty between 8% and 20%. The multijet background uncertainty has already been described. The uncertainty on the normalization of the W+jets background and its flavor composition include

<table>
<thead>
<tr>
<th>Samples</th>
<th>Single-tagged</th>
<th>Double-tagged</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+jets</td>
<td>5970 ± 1000</td>
<td>290 ± 180</td>
</tr>
<tr>
<td>Multijets</td>
<td>1120 ± 560</td>
<td>47 ± 47</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1560 ± 130</td>
<td>360 ± 30</td>
</tr>
<tr>
<td>Single top</td>
<td>1240 ± 90</td>
<td>120 ± 10</td>
</tr>
<tr>
<td>Diboson, $Z$+jets</td>
<td>320 ± 120</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>Total prediction</td>
<td>10200 ± 1200</td>
<td>830 ± 190</td>
</tr>
</tbody>
</table>

Table III: Predicted background event yields compared to the total observed event yields for single- and double-tagged two-jet events in 1.04 fb$^{-1}$ of data. All W+jet samples are scaled by the factors determined from data, with the uncertainties also derived from data. The multijet estimation is from the fitting method with a 50% (100%) uncertainty for single(double)-tagged events. All the other predictions are derived using the theoretical cross sections and uncertainties.
FIG. 1: The distribution of $m_{tb}$ for single-tagged (top) and double-tagged (bottom) two-jet events in data compared to Standard Model expectations. The expected double-tagged (bottom) two-jet events in data compared to normalized to the theoretical cross section times the residual differences between data and MC simulation are assigned, respectively. The $Z$ diboson and $W'$ events are shown, as are the data statistical uncertainties. The uncertainty due to the specific choice of PDFs in the simulated events is determined by re-weighting the MC events using the NNPDF20, MSTW2008 and CTEQ6.6 eigenvector PDF sets. Finally, an uncertainty to account for the limited MC sample sizes is also included.

No significant data excess is identified for any value of $m_{tb}$, and an upper limit on the $W' \rightarrow tb$ production cross section ($\sigma$) times the $B(W' \rightarrow tb)$ at 95% credibility-level (CL) is determined using a Bayesian approach assuming flat priors. The likelihood function used is the product of the Poisson probabilities over all mass bins per channel. The combination of single- and double-tagged events is done by extending the likelihood function; the joint likelihood is the product of Poisson probabilities for each individual bin in each channel. Systematic and statistical uncertainties are incorporated and treated as nuisance parameters with a Gaussian probability density function. Figure 2 shows the observed and the expected limits from single- and double-tagged events combined. Observed (expected) upper limits obtained on $\sigma(pp \rightarrow W'_R) \times B(W'_R \rightarrow tb)$ at 95% CL lie in the range 6.1 – 1.0 (4.5 – 1.4) pb for $W'_R$ masses ranging from 0.5 to 2.0 TeV. These $\sigma \times B$ limits are also applicable to a left-handed $W'$. The $\sigma \times B$ limits are converted into mass limits using the intersection between the theoretical $\sigma \times B$ curve as a function of $m_{W'_R}$ and the expected and observed $\sigma \times B$ limit curves. The corresponding observed (expected) 95% CL lower limit is: $m_{W'_R} > 1.13$ (1.13) TeV. These are currently the most stringent direct limits on production of $W'_R \rightarrow tb$.

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We thank Z. Sullivan for discussions on the $W'$ model and for providing NLO signal cross section calculations.

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FIG. 2: 95% CL limit on the cross section, $\sigma(pp \to W')$, times branching ratio for $W' \to tb$ as a function of the $W'$ boson mass. The theory curve is also shown.

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http://cdsweb.cern.ch/record/1376384

[9] In the ATLAS coordinate system the pseudorapidity, $\eta$, is defined as $\eta = -\ln[\tan(\theta/2)]$, where $\theta$ is measured with respect to the $z$-axis, defined to be parallel to the beam. The azimuthal angle, $\phi$, is measured with respect to the $x$-axis, which points towards the center of the LHC ring, and the $y$-axis points upwards.
https://cdsweb.cern.ch/record/1336750.
[42] The $W$ boson transverse mass is defined as $m_T(W) = \sqrt{2p_T\ell E_T^{miss}(1 - \cos \Delta \phi)}$, where $p_T\ell$ is the $p_T$ of the lepton and $\Delta \phi$ is the azimuthal angle separation between the lepton and $E_T^{miss}$.
Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Physics Department, National Technical University of Athens, Zografou, Greece

Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

Physics Department, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

Department for Physics and Technology, University of Bergen, Bergen, Norway

Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

Department of Physics, Humboldt University, Berlin, Germany

Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

Department of Physics, Brandeis University, Waltham MA, United States of America

Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

(a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania

Departamento de Fısica, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa ON, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong, China

Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France

Nevis Laboratory, Columbia University, Irvington NY, United States of America

Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

(a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavada di Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas TX, United States of America

Physics Department, University of Texas at Dallas, Richardson TX, United States of America

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany

Department of Physics, Duke University, Durham NC, United States of America

SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3 2700 Wiener Neustadt, Austria

INFN Laboratori Nazionali di Frascati, Frascati, Italy

Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
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

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

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

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

Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
\(^{158}\) (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

Department of Physics, University of Illinois, Urbana IL, United States of America
\(^{164}\) Department of Physics, University of British Columbia, Vancouver BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
\(^{170}\) Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan
\(^{173}\) Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison WI, United States of America
\(^{174}\) Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
\(^{176}\) Department of Physics, Yale University, New Haven CT, United States of America

Yerevan Physics Institute, Yerevan, Armenia
\(^{179}\) Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

\(^{a}\) Also at Laboratorio de Instrumentacao 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 TRIUMF, Vancouver BC, Canada
\(^{e}\) Also at Department of Physics, California State University, Fresno CA, United States of America

\(^{f}\) Also at Novosibirsk State University, Novosibirsk, Russia

\(^{g}\) Also at Fermilab, Batavia IL, United States of America

\(^{h}\) Also at Department of Physics, University of Coimbra, Coimbra, Portugal

\(^{i}\) Also at Università di Napoli Parthenope, Napoli, Italy

\(^{j}\) Also at Institute of Particle Physics (IPP), Canada

\(^{k}\) Also at Department of Physics, Middle East Technical University, Ankara, Turkey

\(^{l}\) Also at Louisiana Tech University, Ruston LA, United States of America

\(^{m}\) Also at Department of Physics and Astronomy, University College London, London, United Kingdom

\(^{n}\) Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada

\(^{o}\) Also at Department of Physics, University of Cape Town, Cape Town, South Africa

\(^{p}\) Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

\(^{q}\) Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
\* Also at Manhattan College, New York NY, United States of America
\* Also at School of Physics, Shandong University, Shandong, China
\* Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
\* Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
\* Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
\* 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
\* Also at Section de Physique, Université de Genève, Geneva, Switzerland
\* Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
\* Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
\* Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
\* Also at California Institute of Technology, Pasadena CA, United States of America
\* Also at Institute of Physics, Jagiellonian University, Krakow, Poland
\* Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France
\* Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
\* Also at Department of Physics, Oxford University, Oxford, United Kingdom
\* Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
\* Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

\* Deceased