G. Aad et al. (ATLAS Collaboration)
Search for tb resonances in proton-proton collisions at $\sqrt{s}=7$ TeV with the ATLAS detector

© 2012 CERN, for the ATLAS Collaboration. Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

Originally published at:
http://doi.org/10.1103/PhysRevLett.109.081801

http://creativecommons.org/licenses/by/3.0/

# PERMISSIONS

http://hdl.handle.net/2440/93264
Search for $tb$ Resonances in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

(Received 4 May 2012; published 21 August 2012)

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 $t\bar{b}$ 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 the data, and upper limits on the cross section times the branching ratio of $W_R$ resonances at 95% C.L. lie in the range of 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% C.L.

DOI: 10.1103/PhysRevLett.109.081801 PACS numbers: 14.70.Pw, 12.60.Cn, 13.85.Rm, 14.65.Ha

This Letter presents a search for $tb$ ($t\bar{b}$ 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 $1.04 \pm 0.04$ 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 $W' \rightarrow \ell \nu$ decay channel, where $\ell$ is a charged lepton, are the most sensitive. However, the $W' \rightarrow tb$ channel is competitive if $W' \rightarrow \ell \nu$ 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 $W_R \rightarrow \ell \nu_R$ decay [6]. The model of a right-handed $W_R$ with SM-like couplings is chosen as the benchmark model for this analysis presented in this Letter. The $W_R \rightarrow tb$ 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 $tb \rightarrow \ell v b b$ 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].

Data-driven methods and MC simulated samples are used to estimate and model backgrounds. The $t\bar{t}$ 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 $t\bar{t}$ cross section and the branching ratio values are used to estimate and model backgrounds. The $t\bar{t}$ 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 $t\bar{t}$ cross section and the branching ratio values are used to estimate and model backgrounds. The $t\bar{t}$ 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.
section is obtained from the approximate next-to-next-to-leading order (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 [22–24] 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 [25] 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, WbWb, WcWc, WeWc, and Z + jets with up to five additional partons) is simulated using the ALPGEN V2.13 [26] 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, overinclusive are removed following the MLM matching prescription [27]. 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 [28] program. The Wc cross section correction factor is obtained using the MCFM [29] program with the CTEQ6.6 PDFs. All samples are passed through the full simulation of the ATLAS detector [30] based on GEANT4 [31] and are then reconstructed using the same procedure as collision data. The simulated samples include the effect of multiple pp collisions per bunch crossing (pileup) 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 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 the missing transverse momentum ETmiss are required. The definition of the objects and details of a similar event selection, including lepton isolation requirements, are given in Ref. [32]. The reconstructed charged lepton is required to have a transverse momentum pT > 25 GeV to ensure a constant trigger efficiency, |η| < 2.5 for a muon [33–35] and |η| < 2.47 for an electron [36] (the calorimeter transition region 1.37 < |η| < 1.52 is excluded), and to lie within ΔR = √((Δη)² + (Δφ)²) < 0.15 of the corresponding triggered lepton. Jets are reconstructed from energy clusters in the calorimeters with the anti-kt algorithm [37] with a radius parameter R = 0.4 and calibrated to the hadronic energy scale [38]. Exactly two jets with pT > 25 GeV and |η| < 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 [39]. Based on a tt 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, pT and η, distributions, the b-tagging efficiency and the corresponding scaling factors are to be applied to MC simulations are derived from data [40]. Events before applying any b tagging are referred to as pretagged events. Events where one or both jets are b tagged are referred to as single- or double-tagged events, respectively.

The ETmiss is calculated using calorimeter energy clusters [41] calibrated according to the reconstructed physics object to which they are associated [42]; events are required to satisfy ETmiss > 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 mT(W) [43] and ETmiss: mT(W) + ETmiss < 60 GeV [32]. After applying all selection criteria, the acceptance times efficiency for Wb signal events with mWb = 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-pT lepton from semileptonic decay of a heavy hadron within a jet fulfills the selection requirements. Another important background comes from tt 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 mb, which is described later, satisfying mb > 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.
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 simulations. The fractions of $Wb\bar{b}$, $Wc\bar{c}$, $Wc$, and $W +$ light jet components of the total $W +$ jet MC simulations are scaled such that the background sum equals the observed data in three separate samples: a single-tagged one-jet sample and the pretagged and single-tagged two-jet samples. The same scale factor is used for $Wb\bar{b}$ 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 $E_T^{\text{miss}}$ 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 pretagged, single-, and double-tagged samples, after applying all selection criteria except the $E_T^{\text{miss}}$ cut. The uncertainty on the multijet rate is $50\%$ for pretagged and single-tagged events, while it amounts to $100\%$ for double-tagged events. The uncertainty is estimated by using the $m_T(W)$ distribution instead of the $E_T^{\text{miss}}$ 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 $W_R^\pm$ signal events expected in $1.04 \text{ fb}^{-1}$ are listed in Table II, as a function of $m_{W_R^\pm}$. Table III lists the expected background yields.

The $tb$ invariant mass is used as the observable to discriminate signal from background. The neutrino momentum in the decay $tb \rightarrow \ell vbb$ is computed assuming the transverse component to be equal to $E_T^{\text{miss}}$, and extracting the longitudinal component ($p_z$) by constraining the $\ell - v$ 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 1 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 BUMP Hunter tool [44] 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. 1 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 to or above the number of observed data events in these regions is $0.66$ for single-tagged events and $0.72$ for double-tagged events. These values, which are based on the statistical error only, indicate that there is no significant evidence for $tb$ resonances in the observed data.

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.

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.

---

**Table II.** Predicted signal event yields derived using the theoretical cross section times the branching ratio values for $W_R^\pm \rightarrow tb$, for single- and double-tagged two-jet events in 1.04 fb$^{-1}$ of data. The uncertainties correspond to the NLO cross section uncertainties [13].

<table>
<thead>
<tr>
<th>$m_{W_R}$ [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 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.

<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>
<tr>
<td>Data</td>
<td>10428</td>
<td>844</td>
</tr>
</tbody>
</table>
due to the small contribution of $Z +$ jet events. Systematic uncertainties due to the residual differences between data and MC simulation for the reconstruction and energy calibration of jets, electrons, and muons are estimated to have a small impact on the result. The uncertainty on the integrated luminosity is 3.7% [3]. The uncertainty on the background modeling in the $m_{t\bar{t}}$ distribution is evaluated using pretagged data and found to be negligible.

An uncertainty due to the MC event generator is estimated by comparing MC@NLO and POWHEG [45,46] for $t\bar{t}$ and ACERMC and MC@NLO for single top events. The uncertainty in parton shower modeling is estimated by comparing two POWHEG $t\bar{t}$ samples for which the hadronization is performed by PYTHIA or HERWIG. Uncertainties from modeling the amount of initial and final-state QCD radiation are also taken into account. The uncertainty due to the specific choice of PDFs in the simulated events is determined by reweighting the MC events using the NNPDF20, MSTW2008, and CTEQ6.6 [20] 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 $m_{t\bar{t}}$, and an upper limit on the $W_R^t \rightarrow t b$ production cross section ($\sigma$) times the $\mathcal{B}(W_R^t \rightarrow t b)$ at 95% credibility-level (C.L.) is determined using a Bayesian approach assuming flat priors [47]. The likelihood function used is the product of the Poisson probabilities over all mass bins [48] 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 over all mass bins [48] per 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 $\sigma(pp \rightarrow W'_R) \times \mathcal{B}(W'_R \rightarrow t b)$ at 95% C.L. lie in the range $10^{-1}$ to $10^{2}$ fb.

**FIG. 1** (color online). The distribution of $m_{t\bar{t}}$ for single-tagged (top) and double-tagged (bottom) two-jet events in data compared to standard model expectations. The expected $W_R^t$ signal, normalized to the theoretical cross section times the $\mathcal{B}(W_R^t \rightarrow t b)$ values from Table I, has been scaled by a factor of 10. The effect of the jet energy scale (JES) uncertainty on the predicted background is shown, as are the data statistical uncertainties. The bin width is constant in log($m_{t\bar{t}}$). The highest bin in each plot includes overflows.
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% C.L. lower limit is \(m_{W'_R} > 1.13(1.13)\) TeV. These are currently the most stringent direct limits on production of \(W'_R \rightarrow tb\).

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 thank Z. Sullivan for discussions on the \(W'\) model and for providing NLO signal cross section calculations. 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; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNF, DUNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, 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; MINSW, Poland; GRICES and FCT, Portugal; MERSY (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 of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

[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 toward the center of the LHC ring, and the \(y\) axis points upwards.

SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3
and Institut National Polytechnique de Grenoble, Grenoble, France
Department of Physics, Hampton University, Hampton Virginia, USA
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge Massachusetts, USA
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Indiana University, Bloomington Indiana, USA
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames Iowa, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce, Italy
Dipartimento di Fisica, Università del Salento, Lecce, Italy
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst Massachusetts, USA
Department of Physics, McGill University, Montreal Quebec, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor Michigan, United States of America, USA
Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, United States of America, USA
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge Massachusetts, USA
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
INFN Sezione di Napoli, Italy
Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque New Mexico, USA
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb Illinois, USA
Badger Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York New York, USA
The Ohio State University, Columbus Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene Oregon, USA
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
INFN Sezione di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh Pennsylvania, USA
Laboratorio de Instrumentación e Física Experimental de Partículas—LIP, Lisboa, Portugal
Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Prague, 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 Saskatchewan, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma I, Italy
Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Italy
Dipartimento di Fisica, Università Roma Tre, Roma, Italy
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
DMS/RFU (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 California, USA
Department of Physics, University of Washington, Seattle Washington, USA
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 British Columbia, Canada
SLAC National Accelerator Laboratory, Stanford California, USA
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Johannesburg, Johannesburg, South Africa
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University, Sweden
The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook New York, USA
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 Tokyo, Tokyo Ontario, Canada
TRIUMF, Vancouver BC, Canada
Department of Physics and Astronomy, York University, Toronto Ontario, Canada
Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, Canada
Department of Physics, University of British Columbia, Vancouver British Columbia, Canada
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison Wisconsin, USA
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia
Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

aDeceased.
bAlso at Laboratorio de Instrumentacao e Fisica Experimental de Particulas—LIP, Lisboa, Portugal.
cAlso at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
deAlso at TRIUMF, Vancouver BC, Canada.
fAlso at Department of Physics, California State University, Fresno CA, USA.
gAlso at Novosibirsk State University, Novosibirsk, Russia.
hAlso at Fermilab, Batavia IL, USA.
iAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.
jAlso at Università di Napoli Parthenope, Napoli, Italy.
kAlso at Institute of Particle Physics (IPP), Canada.
lAlso at Department of Physics, Middle East Technical University, Ankara, Turkey.
mAlso at LA Tech University, Ruston LA, USA.
Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
oAlso at Group of Particle Physics, University of Montreal, Montreal QC, Canada.
pAlso at Department of Physics, University of Cape Town, Cape Town, South Africa.
qAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
rAlso at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
sAlso at Manhattan College, New York NY, USA.
tAlso at School of Physics, Shandong University, Shandong, China.
uAlso at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
vAlso at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
wAlso at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
xAlso at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.