Search for strong gravity signatures in same-sign dimuon final states using the ATLAS detector at the LHC

ATLAS Collaboration

A search for microscopic black holes has been performed in a same-sign dimuon final state using 1.3 fb$^{-1}$ of proton–proton collision data collected with the ATLAS detector at a centre of mass energy of 7 TeV at the CERN Large Hadron Collider. The data are found to be consistent with the expectation from the Standard Model and the results are used to derive exclusion contours in the context of a low scale gravity model.

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1. Introduction

Models introducing extra dimensions can provide a solution to the hierarchy problem, the fact that the Planck scale $M_{Pl} \sim 10^{16}$ TeV is much larger than the electroweak scale. In some models of extra dimensions, the gravitational field can propagate into $(n + 4)$ dimensions, where $n$ is the number of extra dimensions, while the Standard Model particles are restricted to four-dimensional space–time. Therefore, the gravitational field as measured in four dimensions is reduced in strength from the fundamental gravitational field. As a result, the Planck scale in $(n + 4)$ dimensions $M_D$ would be much smaller than the Planck scale in four dimensions $M_{Pl}$, and possibly comparable to the electroweak scale. An example of such a model of extra dimensions is the ADD model, which is a model of large flat extra dimensions [1–3].

If extra dimensions exist and $M_D$ is in the TeV range, microscopic black holes with masses at the TeV scale could be produced at the Large Hadron Collider [4–8]. Black holes are expected to be produced when the classical impact parameter of two colliding partons is smaller than the higher-dimensional horizon radius corresponding to a black hole with mass equal to the invariant mass of the colliding parton system. This letter considers higher-dimensional Schwarzschild solutions, as well as Kerr solutions for black holes with initial angular momentum equal to the relative angular momentum between the two colliding partons; parton spin is ignored [9].

The production of black holes at the LHC would occur with a continuous mass distribution ranging from approximately the reduced Planck scale $M_D$ to the proton–proton centre of mass energy of 7 TeV. The classical approximations used for black hole production and the semi-classical approximations for decay are expected to be valid only for masses well above the higher-dimensional Planck scale. A lower threshold $M_{TH}$ is thus applied to the black hole mass to reduce the contributions from regions where the models are invalid. The production cross section is set to zero if the parton–parton centre of mass energy is below $M_{TH}$.

Once produced, a black hole starts to evaporate in a manner described by Hawking radiation [10] which determines the energy and multiplicity distributions of the emitted particles. The relative multiplicities of the emitted particles are determined by the number of degrees of freedom of each particle type and the decay modes of emitted unstable particles. Black hole events should therefore have a high multiplicity of high-$p_T$ particles which is the characteristic feature exploited in this analysis. Models with rotating and non-rotating black holes are considered in this letter. The multiplicity of high-$p_T$ particles is lower for rotating black holes [11]. No graviton initial-state radiation or emission from the black hole is considered. As a result of the emission of Hawking radiation, the mass of the produced black hole decreases. When the mass of the black hole approaches $M_D$, quantum gravity effects become important. In the final stage of the black hole decay, the classical evaporation is no longer a good
description. In such cases where the black hole mass is near the Planck scale, the burst model adopted by the BlackMax event generator [9,12] is used to model the final part of the decay.

A search for microscopic black holes in a multijet final state is presented in Ref. [13]. In this analysis, events are selected containing two muons of the same charge. This channel is expected to have low Standard Model backgrounds while retaining good signal acceptance. Isolated muons (i.e. muons with very little activity around them in the detector) can be produced directly from the black hole or from the decay of heavy particles such as W or Z bosons. Muons from the semi-leptonic decays of heavy-flavour hadrons produced from the black hole can have several other particles nearby and can therefore be non-isolated. In order to maintain optimal acceptance for a possible signal, only one of the muons is required to be isolated in this analysis, thereby typically increasing the acceptance in the signal region by 50%.

The decay of the black hole to multiple high-p_T objects is used to divide the observed events into background-rich and potentially signal-rich regions. This is done by using the number of high-p_T charged particle tracks as the criterion to assign events to each region. As will be quantified below, black hole events typically have a high number of tracks per event (N_tk), while Standard Model processes have sharply falling track multiplicity distributions. In the background-rich region, where only small signal contributions are expected, data and Monte Carlo simulations are used to estimate the number of events after selections. This background estimate is validated by comparing to data. The expected number of events from Standard Model processes in the signal-rich region is then compared with the measured number, and a constraint on the contribution from black hole decays is inferred.

The backgrounds from Standard Model processes are divided into two categories: processes where the two muons come from correlated decay chains and processes that produce same-sign dimuons in uncorrelated decay chains. Same-sign dimuon events in correlated decay chains are produced primarily in the decays of tt events and bb events. In tt events, the most likely case is that the leading isolated muon arises from the decay of a W-boson from one of the top-quarks, and the other muon of same charge comes from the semi-leptonic decay of a b-quark from the other top-quark. In bb events, the leading muon arises from the semi-leptonic decay of one b-quark, and the other muon from the sequential decay b → cX → μX'. Same-sign dimuons can also be produced due to B^0B^0 mixing. The backgrounds from tt and bb, and those from gauge boson pair production such as WZ are estimated from Monte Carlo samples.

Dimuon events in uncorrelated decay chains arise predominantly from the W + jets process, where the leading isolated muon comes from W-boson decay and the other muon from a π/K decay-in-flight, or the semi-leptonic decay of a b or c hadron in the remainder of the event. This background also has contributions from the Z + jets process, and from low-p_T dijet events. The background from uncorrelated decay chains is estimated from data. In the signal-rich region, the dominant backgrounds come from tt events and from muons produced in uncorrelated decays.

The rest of this letter is organised as follows. After a brief description of the ATLAS detector in Section 2, the data set and Monte Carlo samples are described in Section 3. The event selection and the procedures to determine the backgrounds and their uncertainties are explained in Sections 4 and 5 respectively. The results and their interpretation are discussed in Section 6.  

2. The ATLAS detector

The ATLAS detector [14] covers nearly the entire solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. The inner detector is immersed in a 2 T magnetic field along the z-axis and provides charged particle tracking in the range |η| < 2.5. The silicon pixel detector covers the vertex region and typically provides three measurements per track, followed by the silicon microstrip tracker (SCT) which provides measurements from eight strip layers. The silicon detectors are complemented by the transition radiation tracker (TRT) which provides more than 30 straw-tube measurements per track and improves the momentum resolution.

The calorimeter system covers the pseudorapidity range |η| < 4.9. Lead-liquid argon (LAr) electromagnetic sampling calorimeters cover the range |η| < 3.2, with an additional thin LAr presampling layer covering |η| < 1.8 to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by a scintillator-tile calorimeter over |η| < 1.7 and two copper/LAr endcap calorimeters over 1.75 < |η| < 3.2. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeters for electromagnetic and hadronic measurements respectively up to |η| < 4.9.

The muon spectrometer consists of separate trigger and high-precision tracking chambers which measure the deflection of muon tracks in a magnetic field with a bending integral of approximately 2 to 8 Tm. The magnetic field is generated by three superconducting air-core toroid magnet systems. The tracking chambers cover the region |η| < 2.7 with three layers of monitored drift tubes and cathode strip chambers in the innermost region of the endcap muon spectrometer. The muon trigger system covers the range |η| < 2.4 with resistive plate chambers in the barrel, and thin gap chambers in the endcap regions.

3. Data and Monte Carlo samples

The data used in this analysis were collected between March and July 2011 at the LHC operating at a centre of mass energy of 7 TeV. The total integrated luminosity after detector and data-quality requirements is 1.3 fb⁻¹, with an uncertainty of 3.7% [15,16]. The data were recorded with a single muon trigger with the threshold at 20 GeV on the muon’s transverse momentum. The muon trigger efficiency reaches the plateau regime for transverse momenta above 25 GeV. The plateau efficiency is 75% in the barrel and 88% in the endcap for muons reconstructed offline. In this analysis it is required that at least one of the selected muons with p_T above 20 GeV matches the trigger criteria. During the considered data-taking period, the LHC configuration was such that the mean number of primary proton–proton interactions per bunch crossing was close to 6. The effect of this “pile-up” is taken into account in the analysis.

Several Monte Carlo samples are used both for signal modelling and background estimation. These samples are processed with the ATLAS full detector simulation [17] which is based on the GEANT4 toolkit [18]. The simulated events are then reconstructed with the same software chain as the data. The effect of pile-up is modelled by overlaying simulated minimum bias events onto the original

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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 coinciding with the axis of the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe, referred to the x-axis. The pseudorapidity is defined in terms of the polar angle θ with respect to the z-axis as η = −ln(tan(θ/2)).
hard-scattering event. Monte Carlo events are then re-weighted so that the reconstructed vertex multiplicity distribution agrees with the data.

Background Monte Carlo samples are generated for \( t\bar{t} \), as well as for \( bb \) and \( cc \) processes. The latter are considered together in the following and referred to as \( b/c \) for simplicity. The \( t\bar{t} \) events are generated with MC@NLO [19,20] with an assumed top-quark mass of 172.5 GeV, and with the next-to-leading order CTEQ66 [21] parton distribution function (PDF) set. Fragmentation and hadronisation of the events is done with HERWIG [22] using JIMMY [23] for the underlying event model. The \( b/c \) Monte Carlo sample is generated and hadronised with PYTHIA [24] using the ATLAS AMBT1 tune [25]. It is produced with a filter at the generator level requiring two muons with \( p_T > 10 \) GeV each. The diboson samples (\( WZ \) and \( ZZ \)) are generated with HERWIG using the ATLAS AMBT1 tune. The samples are produced with the CTEQ66 PDF set with the mass of the black hole used as the QCD scale. For the signal samples, the uncertainty due to the top-quark mass is obtained by varying the black hole mass of 165 pb [33–35] is used to normalise the Monte Carlo prediction. This cross section is in agreement with the measurement of ATLAS [36]. The sources of systematic uncertainty on the \( t\bar{t} \) background described in Ref. [37] are considered and the uncertainty from each source is shown in Table 1. The sources considered are the choice of generator, the amount of initial and final state radiation (ISR/FSR), the top-quark mass, and the theoretical uncertainty on the predicted production cross section. The largest contribution to the uncertainty is 9.6% on the cross section which arises from variations in the renormalisation and factorisation scales (5.6%) and the PDF uncertainty (4%). The uncertainty due to the choice of generator is evaluated by comparing the predictions of MC@NLO with those of POWHEG [38] interfaced to PYTHIA. The POWHEG samples are generated using the MRST2007 PDF set. The uncertainty due to the top-quark mass is obtained by generating \( tt \) samples with top mass \( \pm 2.5 \) GeV from the nominal choice of 172.5 GeV. The ISR/FSR uncertainty is determined by using the ActMC generator interfaced to PYTHIA, and by varying the ISR and FSR \( A_{QCD} \), and the ISR and FSR cutoff. There is also an additional 2.6% uncertainty on the \( t\bar{t} \) estimate from trigger weight and muon reconstruction efficiency scale factors.

The background from \( b/c \) production is estimated in two steps. In the first step, the background is determined in the \( N_{\text{trk}} < 10 \)
This yields 6480 events. The flavour rich sample is selected by inverting the isolation and signal region. Applying this ratio to the heavy-flavour rich sample, where the uncertainty comes from the limited size of the Monte Carlo sample.

The control sample consists of \( W \)+jet and single-top Monte Carlo samples as pseudo-data to measure the rate and then make a prediction. Similar studies on fake muon probability, with different selection criteria, are reported in Ref. [39] and show consistent results.

The background estimation is tested in events with the same selections as the signal region except the track multiplicity which is required to be \( N_{\text{trk}} < 10 \). The prediction from the Standard Model is shown in Table 2, along with the number of observed events in data in the background region. The contribution from the signal in the background region has been checked to be less than 0.1% of backgrounds for various choices of the signal parameters. The event rates observed in the background region agree with the prediction within the uncertainties.

6. Results and interpretation

Figs. 1 and 2 show the \( p_T \) distributions of both muons and the track multiplicity in all same-sign dimuon events respectively before applying the \( N_{\text{trk}} \) requirement. The prediction for a sample...
ple signal model for non-rotating black holes with $M_D = 800$ GeV, $M_{TH} = 4$ TeV, and six extra dimensions is also shown. Good agreement is observed between the measured distributions and the background expectations. As shown in Fig. 2, the backgrounds peak at low values of the track multiplicity while a possible signal has a higher number of tracks. Table 3 shows the expected and observed numbers of same-sign dimuon events in the signal region. No excess over the Standard Model predictions is observed in the data.

The background in the signal region is dominated by the $t\bar{t}$ and by the uncorrelated decays from $W + $jet events. The relative contributions of the various backgrounds are different in the background-rich (Table 2) and signal-rich (Table 3) regions. In particular the $b/c$ contribution falls more rapidly with increasing $N_{trk}$ than the other backgrounds and is very small in the signal-rich region. By removing the isolation requirement on the leading muon, the distribution is dominated by $b/c$ background and the Monte Carlo simulation agrees with data giving confidence in the $b/c$ prediction.

Table 3

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b/c$</td>
<td>$0.77 \pm 0.77$ (syst)</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$29.2 \pm 4.1$ (syst) $\pm 1.1$ (lumi)</td>
</tr>
<tr>
<td>$W +$ fake</td>
<td>$25.6 \pm 0.3$ (stat) $\pm 0.2$ (syst)</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>$0.25 \pm 0.11$ (syst)</td>
</tr>
<tr>
<td>Predicted</td>
<td>$55.8 \pm 0.3$ (stat) $\pm 6.7$ (syst) $\pm 1.1$ (lumi)</td>
</tr>
<tr>
<td>Observed</td>
<td>60</td>
</tr>
<tr>
<td>Signal $M_{TH} = 4$ TeV</td>
<td>$72.1 \pm 4.5$ (syst)</td>
</tr>
</tbody>
</table>

$\sigma$ is the cross section, $BR$ the branching ratio to dimuons, and $A$ the acceptance of non-Standard Model contributions in this final state in the signal region. The CLs method [40] is used to derive these limits assuming Gaussian uncertainties on the predicted background and signal, and Poissonian fluctuations on the observed number of events. The observed 95% confidence level upper limit on $\sigma \times BR \times A$ is 0.018 pb. This result is compatible with the expected limit of 0.016 pb, which is determined from pseudo-experiments using simulation. The 1$\sigma$ and 2$\sigma$ ranges on the expected limit are from 0.012 to 0.022 pb and from 0.008 to 0.029 pb respectively. The $BR \times A$ for the signal model shown in Table 3 is 3%, and typically varies between 1% and 6% for the signal models considered here.

Limits on the reduced Planck mass ($M_{\nu}$) and the minimum mass of the black hole ($M_{TH}$) for several models are set using the BlackMax generator and the CTEQ66 PDF. The signal yield is affected by the PDF choice due to two distinct effects: the change in the production cross section and the change in signal acceptance. The signal cross section obtained from MRST2007 is typically 40% to 50% higher than that from CTEQ66 for $M_D = 1$ TeV, $M_{TH} = 4$ TeV. This difference is somewhat larger than the uncertainty on the cross section from the CTEQ66 PDF error sets. At the large values of $M_{TH}$ near the quoted limits, the invariant mass of the incoming partons is large and the PDFs are therefore used in a range of parton momentum fraction $x$ where they are not well constrained. The theoretical uncertainty on the production cross section is potentially very large. For these reasons, no theoretical uncertainty on the signal cross section is assigned, that is, the exclusion limits are set for the exact benchmark models as implemented in the BlackMax generator: using CTEQ66 rather than
MRST2007 gives a more conservative limit. The cross section for the signal point shown in Table 3 is 2.1 pb. The uncertainty on the signal acceptance from the choice of PDF is estimated to be 3% by using the 44 error sets of the CTEQ66 PDF and is a small contribution to the overall uncertainty.

The observed results are used to obtain exclusion contours in the plane of $M_D$ and $M_{TH}$. For a large number of points in the $(M_D, M_{TH})$ plane, the signal acceptance is measured using kinematic properties obtained from the event generator (truth). This truth level acceptance is compared to the acceptance from full detector simulation for a smaller set of points which are representative of the model parameters probed in this analysis. To account for the difference in acceptances, the truth level acceptance is scaled by a constant factor of $0.7 \pm 0.1$ which is determined by comparing truth to fully simulated points. Therefore the uncertainty on the signal prediction consists of the following components: the uncertainty due to rescaling of truth acceptance, the uncertainty on the luminosity of the data sample, the uncertainty on acceptance due to the PDF, the experimental uncertainty on acceptance due to muon trigger and identification efficiencies and a statistical uncertainty due to $\mu$ and $\tau$ decays to low multiplicity final states such as quantum black holes [41].

In view of the rapidly falling PDF's in this region, further significant improvements on these limits are not expected until the LHC energy is increased. For example, moving from $M_{TH} = 4.7$ TeV to $M_{TH} = 5$ TeV changes the signal cross section from 0.24 pb to 0.06 pb (for non-rotating black holes in models with $M_D = 500$ GeV and six extra dimensions). It is also worth noting that the exclusion contours are dependent on the model considered, and this analysis is not expected to be sensitive to black hole models with decays to low multiplicity final states such as quantum black holes [41].

In summary, a search for extra dimensions in the same-sign di-muon final state has been performed using 1.3 fb$^{-1}$ of data recorded with the ATLAS detector in 7 TeV proton–proton collisions at the LHC. No excess of events over the Standard Model prediction is observed and exclusion contours are obtained in the plane of the reduced Planck scale $M_D$ and the threshold $M_{TH}$ for black hole production. A model independent limit of 0.018 pb on any new physics contribution in the signal region with the described selection is set.

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References


1 University at Albany, Albany, NY, United States
2 Department of Physics, University of Alberta, Edmonton, AB, Canada
3 (a) Department of Physics, Ankara University, Ankara, (b) Division of Physics, TOBB University of Economics and Technology, Ankara, (c) Turkish Atomic Energy Authority, Ankara, Turkey
4 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
5 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
6 Department of Physics, University of Arizona, Tucson, AZ, United States
7 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
8 Physics Department, University of Athens, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Instituto de Física de Altas Energías and Departamento de Física de la Universidad Autónoma de Barcelona and ICREA, Barcelona, Spain
12 (a) Institute of Physics, University of Belgrade, Belgrade, (b) Vinca Institute of Nuclear Sciences, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18 (a) Department of Physics, Bogazici University, Istanbul, (b) Division of Physics, Dogus University, Istanbul, (c) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
19 (a) INFN Sezione di Bologna, (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20 Physikalisches Institut, University of Bonn, Bonn, Germany
21 Department of Physics, Boston University, Boston, MA, United States
22 Department of Physics, Brandeis University, Waltham, MA, United States
23 (a) Universidade Federal do Rio de Janeiro COPPE/EPF, Rio de Janeiro, (b) Federal University of Juiz de Fora, Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
25 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
26 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa, ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
31 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaíso, Chile
32 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui;
33 (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubière Cedex, France
35 Nevis Laboratory, Columbia University, Irvington, NY, United States
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavàda di Rende, Italy
38 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas, TX, United States
41 Physics Department, University of Texas at Dallas, Richardson, TX, United States
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
45 Physics Department, Duke University, Durham, NC, United States
46 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
48 INFN Laboratori Nazionali di Frascati, Frascati, Italy
49 Facultad de Matemáticas and Physics, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
50 Section de Physique, Université de Genève, Geneva, Switzerland
Czech Technical University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia

Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina, SK, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan

INFN Sezione di Roma I; (d) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma TRE; (b) Dipartimento di Fisica, Università Roma TRE, Roma, Italy

Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies – Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (a) Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (f) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (g) Faculté des Sciences, Université Mohammed V, Rabat, Morocco

SLAC National Accelerator Laboratory, Stanford, CA, United States
Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States

Department of Physics, Simon Fraser University, Burnaby, BC, Canada
National Accelerator Laboratory, Stanford, CA, United States

Department of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Košice, Slovak Republic

Department of Physics, University of Johannesburg, Johannesburg, South Africa
Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden
Physics Department and Astronomy, Stony Brook University, Stony Brook, NY, United States

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion – Israel Inst. of Technology, Haifa, Israel

Bryn Mawr and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto, ON, Canada

TRIUMF, Vancouver, BC; (b) Department of Physics and Astronomy, York University, Toronto, ON, Canada

Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
Science and Technology Center, Tufts University, Medford, MA, United States

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States

Department of Physics, University of Illinois, Urbana, IL, United States
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

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
Department of Physics, University of British Columbia, Vancouver, BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

Vaseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, WI, United States
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, CT, United States

Yerevan Physics Institute, Yerevan, Armenia

Domaine Scientifique de la Doua, Centre de Calcul CNRS-IN2P3, Villeurbanne Cedex, France

Also at Laboratorio de Instrumentacion e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
Also at Faculdade de Ciencias and CENFISE, Universidade de Lisboa, Lisboa, Portugal.

Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at TRIUMF, Vancouver, BC, Canada.

Also at Department of Physics, California State University, Fresno, CA, United States.
Also at Fermilab, Batavia, IL, United States.
Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at Università di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
Also at Louisiana Tech University, Ruston, LA, United States.

Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at Manhattan College, New York, NY, United States.
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 High Energy Physics Group, Shandong University, China.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Departamento de Física, Universidade de Minho, Braga, Portugal.