Search for Low-Mass Dijet Resonances Using Trigger-Level Jets with the ATLAS Detector in \( pp \) Collisions at \( \sqrt{s} = 13 \) TeV

M. Aaboud et al.*
(ATLAS Collaboration)

(Received 11 April 2018; published 22 August 2018)

Searches for dijet resonances with sub-TeV masses using the ATLAS detector at the Large Hadron Collider can be statistically limited by the bandwidth available to inclusive single-jet triggers, whose data-collection rates at low transverse momentum are much lower than the rate from standard model multijet production. This Letter describes a new search for dijet resonances where this limitation is overcome by recording only the event information calculated by the jet trigger algorithms, thereby allowing much higher event rates with reduced storage needs. The search targets low-mass dijet resonances in the range 450–1800 GeV. The analyzed data set has an integrated luminosity of up to 29.3 fb\(^{-1}\) and was recorded at a center-of-mass energy of 13 TeV. No excesses are found; limits are set on Gaussian-shaped contributions to the dijet mass distribution from new particles and on a model of dark-matter particles with axial-vector couplings to quarks.

DOI: 10.1103/PhysRevLett.121.081801

Introduction.—If new particles beyond those of the standard model (SM) are directly produced in proton-proton (\( pp \)) collisions at the Large Hadron Collider (LHC), they must interact with the constituent partons of the proton, and can therefore also decay into the same partons, resulting in two-jet final states. Quantum chromodynamics (QCD) predicts that dijet events have an invariant mass distribution (\( m_{jj} \)) that falls smoothly, whereas a new state decaying to two partons would emerge as a localized excess in the distribution.

Traditional dijet searches at the LHC focus on the production of heavy particles with masses above 900 GeV [1–3]. LHC searches for lighter resonances with small production cross sections have been hampered by restrictions in the data-taking rate of the ATLAS and CMS detectors. Single-jet triggers with a jet \( p_T \) threshold below roughly 380 GeV are prescaled, a procedure whereby only a fraction of the events passing the trigger are recorded; hence, dijet events with an invariant mass below 1 TeV are largely discarded by the trigger system, as indicated in Fig. 1. Therefore, despite the large number of \( pp \) collisions produced by the LHC, traditional ATLAS and CMS searches are less sensitive to dijet resonances below 900 GeV than searches at the SPS and Tevatron colliders [4–9]. Alternative trigger strategies to search for low-mass resonances include selecting events with jets recoiling against either an energetic photon or an additional energetic jet [10–12], or selecting events with decays to heavy-flavor jets [13,14]. In these cases, additional features in the events reduce the data-taking rates, reducing the sensitivity to low-mass resonances.

This Letter describes an innovative data-taking approach to access the invariant mass region below 1 TeV; only a reduced set of information from the trigger system is recorded and subsequently analyzed. The Trigger-object Level Analysis (TLA) approach allows jet events to be recorded at a peak rate of up to twice the total rate of events using the standard approach, while using less than 1% of...
the total trigger bandwidth [15]. This strategy is used in dijet resonance searches in $\sqrt{s} = 8$ and 13 TeV LHC pp collision data by the CMS Collaboration [16,17], and it is used by the LHCb Collaboration (e.g. [18]). The analysis presented here uses 29.3 fb$^{-1}$ of $\sqrt{s} = 13$ TeV pp collision data recorded in 2016 by the ATLAS detector.

**ATLAS detector and data sample.**—The ATLAS detector [19] is a multipurpose detector with a forward-backward symmetric cylindrical geometry and nearly 4$\pi$ coverage in solid angle [20], consisting of tracking detectors, calorimeters, and a muon spectrometer. In the pseudorapidity region $|\eta| < 3.2$, high-granularity lead and liquid-argon (LAr) electromagnetic sampling calorimeters are used. A steel and scintillator hadronic tile calorimeter provides coverage in the range $|\eta| < 1.7$. Hadronic calorimetry in the endcap region, $1.5 < |\eta| < 3.2$, and electromagnetic and hadronic calorimetry in the forward region, $3.1 < |\eta| < 4.9$, are provided by LAr sampling calorimeters. A two-level trigger system is used to select events for offline storage [15]. A first-level (L1) trigger based on dedicated hardware identifies jets from $\sum_{i} p_{T} > 20$ GeV are stored. The stored information includes the four-momentum of each jet and a set of calorimeter variables characterizing the jet [24], such as information about the jet quality and structure. The average size of these events is less than 0.5% of the size of full offline events that contain all detector information. For this analysis, all events containing at least one L1 jet with $E_{T} > 100$ GeV are selected and recorded, corresponding to a total luminosity of 29.3 fb$^{-1}$. Events containing a L1 jet with $E_{T} > 75$ GeV are also selected, in a subset of these data corresponding to 3.6 fb$^{-1}$ that were collected at the start of the data-taking period. Events with at least one L1 jet with $E_{T} > 100$ GeV are therefore included in both data sets.

**Calibration procedure.**—After the events are recorded, the trigger-level jet energy and direction are corrected to those of simulated particle-level jets built from stable particles with a lifetime longer than 10 ps, excluding muons and neutrinos. Before any calibration, the jet $p_{T}$ response, defined as the $p_{T}$ ratio of a trigger-level jet to the same jet [25] reconstructed offline (offline jet), is between 0.95 and 1.05 in the $p_{T}$ range considered by this analysis. Since the energy scale for trigger-level and offline jet are very similar, the trigger-level jet calibration employs the same procedure and constants as derived for offline jets [26], with some modifications to account for the unavailability of tracking information for trigger-level jets.

In the calibration procedure, summarized in Fig. 2, an event-by-event jet-area-based calibration [27] is used to correct for contributions from additional proton-proton interactions (pileup) in the same and neighboring crossings of proton bunches. Then, the simulation-based calibration derived for offline jets is applied to trigger-level jets to correct both jet energy and direction. Next, calorimeter-based variables are used to reduce the dependence on the trigger-level jet flavor and to minimize the impact of energy leakage. Only variables related to the trigger-level jet energy fractions in the electromagnetic and hadronic calorimeters and the minimum number of calorimeter cells containing 90% of the trigger-level jet energy are used here since track-based variables, which are normally used in the offline calibration, are not available. With this correction, the trigger-level jet energy resolution is improved by 8% at jet $p_{T}$ values of 85 GeV and up to 40% for jet $p_{T}$ values of 1 TeV relative to the previous calibration step. Next, the calibration corrections that restore the relative calibration between central and forward jets in data and simulation are derived for offline jets and applied to trigger-level jets. After these calibration steps, any residual difference between trigger-level jets and offline jets is accounted for in a dedicated correction, based on the $p_{T}$ response and derived from data in bins of jet $\eta$ and $p_{T}$. The size of this correction is on average 1%, with values reaching up to 4% in the endcap regions of the calorimeter.

Finally, an in situ calibration is obtained from the data-to-simulation ratio of the $p_{T}$ balance between offline jets and well-calibrated objects against which the jets recoil. Three different types of well-calibrated objects are used to span the full $p_{T}$ range of the jets: $Z$ bosons decaying to electrons or muons, photons, and multijets. A polynomial in $\log(p_{T})$ is simultaneously fit to the three input measurements to combine them. The resulting curve is taken as

![Calibration stages for EM-scale trigger-level jets, each applied to the four-momentum of the jet. MC refers to the simulation.](image-url)

FIG. 2. Calibration stages for EM-scale trigger-level jets, each applied to the four-momentum of the jet. MC refers to the simulation.
the calibration correction to be applied to trigger-level jets. In deriving the final calibration curve, the fit is chosen over the simple spline-based combination procedure used for offline jets in Ref. [26]; this procedure is more robust against localized fluctuations in the jet $p_T$ distribution that result in deviations from the expected smoothly falling invariant mass spectrum. Any dependence of the final mass spectrum on the parametrization of the jet energy scale calibration is tested by comparing different parametrizations on the data as well as on simulations. The fitted *in situ* calibration curve is compared to the spline-based smoothing procedure in Fig. 3. After the full calibration procedure, the energy of trigger-level jets is equivalent to that of offline jets to better than 0.05% for invariant masses of 400 GeV and their difference is negligible for invariant masses of 1 TeV.

Energy scale and resolution uncertainties derived for offline jets [26] are applied to trigger-level jets in the signal simulation, with additional uncertainties equivalent to the size of the final trigger-to-offline correction (1\%-3\%). The uncertainty due to the modeling of pileup effects and due to the jet parton flavor are derived specifically for trigger-level jets, as described below. The efficiency and purity of jets passing the selection are measured with a tag-and-probe method using data events with the full detector information. The trigger-level jet reconstruction efficiency is 100% for jets with $p_T > 85$ GeV. The fraction of trigger-level jets that are not reconstructed and selected offline is below 0.1%.

This analysis searches for a dijet resonance with a mass between 450 and 1800 GeV. Two different selection criteria are used for different but overlapping ranges of the $m_{jj}$ spectrum. To search for resonances with $700 \text{ GeV} < m_{jj} < 1800 \text{ GeV}$, events are required to have $|y^*| < 0.6$, where $y^* = (y_1 - y_2)/2$ and $y_1$ and $y_2$ are the rapidities of the highest- and second-highest $p_T$ trigger-level jets. To search for lower-mass resonances, with $m_{jj} > 450$ GeV, events with $|y^*| < 0.3$ are selected from the smaller data sample requiring a L1 jet with $E_T > 75$ GeV. The more stringent choice of $|y^*| < 0.3$ selects higher-$p_T$ jets at a given invariant mass and thus provides a mass distribution that is unbiased by the leading-jet selection from $m_{jj} = 450$ GeV.

**Background estimation.**—The invariant mass spectrum expected from SM dijet production is predicted to be smooth and falling. Prior dijet searches at various collision energies [7,28–32] have found a variety of simple functional forms to describe this shape; however, given the statistical precision of the data and the wide invariant mass range covered by this search, none of the single, simple functional forms can provide a good description of the data.

The SM background distribution is determined using a sliding-window fit [3], where a fitted functional form is evaluated at the bin at the center of a window, which then slides in one-bin steps along the $m_{jj}$ distribution. The evaluated background estimates evaluated in each bin are then collated to form the final background estimate. The signal selection with $|y^*| < 0.6$ uses a window size of 19 bins in the $m_{jj}$ spectrum from 531 to 2080 GeV, which spans 34 bins in total. The signal selection with $|y^*| < 0.3$ uses a window size of 27 bins over a total of 40 bins, in the range $400 < m_{jj} < 2080$ GeV. The bin sizes have been chosen according to the simulated invariant mass resolution: $\sigma_{p_T}/p_T = 10.6/p_T \oplus 0.27/\sqrt{p_T} \oplus 0.039$. The sliding window, however, can not be extended beyond the lower edge of the $m_{jj}$ range used in each signal selection. Therefore, for the first 9 (13) bins in the $|y^*| < 0.6$ ($|y^*| < 0.3$) signal selection, which corresponds to one half of the window size, the window is fixed to the lower edge of the spectrum and instead of evaluating the fitted functional form at the window center, it is evaluated for each bin in turn. For invariant masses higher than the $m_{jj}$ range used for the search, the window is allowed to extend...
beyond the range, to 2970 (3490) GeV for the \(|y^*| < 0.6\)
(0.3) signal selection, and the fit is evaluated at the center of the
window.

In each sliding window, three functional forms are fit to the
data: a five-parameter function of the form

\[
f(x) = p_1(1 - x)^{p_2}x^{p_3} + p_4 \ln x + p_5 \ln^2 x,
\]

where \(p_i\) are free parameters and \(x \equiv m_{jj}/\sqrt{s}\); a four-
parameter function, which is the same as Eq. (1) but with \(p_5 = 0\); and a four-parameter function used by the UA2
Collaboration [28], defined as

\[
f(x) = \frac{p_1}{x^{p_2}} e^{-p_3 x - p_4 x^2}.
\]

The function used for each signal selection is the one that
yields the best \(\chi^2\) over the full fitted \(m_{jj}\) range. An
alternative function is chosen to evaluate a systematic
uncertainty. For the signal selection with \(|y^*| < 0.6\), Eq. (1) is used, yielding a \(\chi^2\) \(p\) value of 0.13, while the
alternative function is the four-parameter function with a \(\chi^2\)
value of 0.11. For the signal selection with \(|y^*| < 0.3\), the
four-parameter version of Eq. (1) yields the best \(\chi^2\) \(p\) value
of 0.42 and the alternative function is Eq. (2), with a \(\chi^2\)
value of 0.35.

The size of the sliding window is optimized to yield the
best \(\chi^2\) value for the full \(m_{jj}\) range while still being larger
than the width of the expected signals and therefore
insensitive to potential signal contributions. This latter
requirement is checked by including signal models in
pseudo-data samples and studying the dependence of the
signal sensitivity on different window sizes.

Systematic uncertainties in the estimate of the back-
ground used in setting limits include the uncertainty due to
the choice of functional form and uncertainties in the fit
parameter values. The effect of the choice of functional
form is evaluated by comparing the nominal function to the
alternative. The uncertainties in the fit parameter values are
evaluated using pseudoexperiments, where the pseudodata
are drawn from Poisson fluctuations around the nominal
background model.

Results and limits.—Figure 4 shows the invariant mass
distributions for dijet events in each signal region including
the results from the sliding-window background estimates.
The \(\chi^2\) \(p\) value of the overall background is 0.13 for the
\(|y^*| < 0.6\) signal selection and 0.42 for the \(|y^*| < 0.3\) signal
selection, indicating the data agrees well with the back-
ground estimate. The most discrepant interval identified by
the BumpHunter algorithm [33,34] is 889–1007 GeV for
events with \(|y^*| < 0.6\). Accounting for statistical uncer-
tainties only, the probability of observing a deviation at
least as significant as that observed in data, anywhere in this
distribution, is 0.44 and corresponds to significance of
0.16\(\sigma\). Thus, there is no evidence of any localized excess.

Limits are set on both a leptophobic Z' simplified
dark-matter model [36] and a generic Gaussian model.
The Z' simplified model assumes axial-vector couplings to
SM quarks and to a Dirac fermion dark-matter candidate.
No interference with the SM is simulated. Signal samples
were generated so that the decay rate of the Z' into
dark-matter particles is negligible and the dijet production
rate and resonance width depend only on the coupling of the Z'
quarks, \(g_q\), and the mass of the resonance, \(m_{Z'}\) [9]. The
model’s matrix elements were calculated in MADGRAPH 5
[37] and parton showering was performed in PYTHIA 8 [38]
with the A14 set of tuned parameters for underlying event
[39] and NNPDF2.3 parton distribution functions [40].

The width of a Z' resonance with \(g_q = 0.10\), including
parton shower and detector resolution effects, is approx-
imately 7%. Limits are set on the cross section, \(\sigma\), times
acceptance, \(A\), times branching ratio, \(B\), of the model, and
then displayed in the \((g_q, m_{Z'})\) plane [41]. The acceptance
for a mass of 550 GeV is 20% for a Z' simplified model with
\(g_q = 0.10\) for the \(|y^*| < 0.3\) signal selection, and 41% for
a signal of mass equal to 750 GeV for the \(|y^*| < 0.6\)
signal selection.

Limits are also set on a generic model where the signal is
modeled as a Gaussian contribution to the observed \(m_{jj}\)
distribution. For a given mean mass, \(m_G\), four different
Gaussian widths are considered: a width equal to the
simulated mass resolution (which ranges between 4% and
6%), and the fixed fractions 5%, 7%, and 10% of
\(m_G\). As the width increases, the expected signal contribu-
tion is distributed across more bins. Wider signals are
therefore less affected by statistical fluctuations from the
data in a single bin. The results can be used to set limits on
models of new phenomena besides that of the $Z'$ simplified
model and are applicable when the resonance is sufficiently
narrow and the parton distribution function and nonper-
turbative effects can be safely truncated or neglected, as
described in Ref. [31]. These criteria are often met if the
$m_{jj}$ distribution for a signal approaches a Gaussian dis-
tribution after applying the kinematic selection criteria of
the resonance analysis, so that 95% of the signal lies within
20% of the Gaussian mean mass. Models of new reso-
nances with an intrinsic width much smaller than 5% of its
mass should be compared to the results with a width
equal to the experimental resolution. For models with a
larger width, the limit that best matches their width should
be used. More-detailed instructions can be found in
Appendix A of Ref. [31].

A Bayesian method is applied to the data and simulation
of the signal models at a series of discrete masses to set
95% credibility-level upper limits on the cross section times
limits, the sliding window fit is performed for each value of
the mass parameter, adding the tested signal shape with a
floating normalization to the functional forms stated above.
The expected limits are calculated using pseudoequiva-
lent experiments generated from the fit parameters of those functional
forms. The uncertainties on the $Z'$ signal model include the
jet energy scale and the luminosity. The impact of the jet
energy resolution uncertainty is negligible. For the
Gaussian model, a constant jet energy scale uncertainty
of 3% is applied in accordance with the measured impact of
this uncertainty on the $Z'$ samples. The uncertainty in the
integrated luminosity is $\pm 2.2\%$, derived following a
methodology similar to that detailed in Ref. [42]. The
systematic uncertainties in the background estimate include the
choice of the fit function and the uncertainty in the fit
parameter values, as described above.

Figure 5 shows limits on the coupling to quarks, $g_{q}$, as a
function of the mass $m_{Z'}$ for the $Z'$ model. Figure 6 shows
limits on a possible Gaussian contribution with a width
equal to the detector resolution as a function of the mean
mass, $m_{G}$. In both the $Z'$ and Gaussian models, upper limits
for masses from 450 to 700 GeV are derived using the
distribution with $|y'| < 0.3$, which is sensitive to the lower
masses. Limits for masses above 700 GeV are derived from the
$m_{jj}$ distribution with $|y'| < 0.6$, except for Gaussian
signals with a width of 10% where only the $|y'| < 0.3$
distribution is used.

The limit results show an upward fluctuation at masses
of approximately 1 TeV in the $|y'| < 0.6$ signal region. This
is not seen in Fig. 4; when searching for excesses in the
data, a background-only hypothesis is used for the sliding
window fit. In the observed and expected limits, the fit
includes the signal shape in addition to the background
parameterization, and can adapt to local data fluctuations
that mimic a signal shape. The $|y'| < 0.6$ signal region,
which uses a smaller sliding-window size, is especially
sensitive to the difference in the two approaches. Therefore,
limits were not set on signals with a width of 10% for the $|y^J| < 0.6$ signal region as the signal is too wide for the sliding-window size.

Conclusions.—In conclusion, this analysis searches for resonances with masses between 450 GeV and 1800 GeV in dijet events using trigger-level jets in 29.3 fb$^{-1}$ of $\sqrt{s} = 13$ TeV proton-proton collision data recorded by the ATLAS detector at the LHC. The invariant mass distribution presents no significant local excesses compared to the estimated SM background. This analysis provides 95% credibility-level limits on $Z'$ signals and cross sections for new processes that would produce a Gaussian contribution to the dijet mass distribution. Over much of the mass range, the sensitivity to the coupling to quarks, $g_q$, is improved by a factor of 2 or more compared to pre-LHC and $\sqrt{s} = 8$ and 13 TeV ATLAS results, and is comparable to CMS searches at $\sqrt{s} = 8$ and 13 TeV using this technique. Gaussian contributions with effective cross sections times acceptance ranging from approximately 6.5 pb at 450 GeV, to 0.4 pb at 700 GeV, to 0.05 pb at 1800 GeV are excluded.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNISW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NCST, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, 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), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [43].

The trigger-level and offline jets are matched within a radius $R = 0.4$. The rapidity, $y$, is defined as $\frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)$, where $E$ denotes the energy of the jet and $p_z$ the momentum component of the jet along the beam direction. Angular distance is measured in units of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.


INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
Department of Physics, Stockholm University, Sweden
Oskar Klein Centre, Stockholm, Sweden
Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN e Laboratori Nazionali di Frascati, Frascati, Italy
Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
Dipartimento di Fisica, Università di Genova, Genova, Italy
INFN Sezione di Genova, Italy
II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
Department of Physics, Indiana University, Bloomington, Indiana, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
INFN Sezione di Lecce, Italy
Dipartimento di Matematica e Fisica,Università del Salento, Lecce, Italy
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
INFN Sezione di Napoli, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
INFN Sezione di Pavia, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
INFN Sezione di Roma, Italy
Dipartimento di Fisica, Sapienza Università di Roma, 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 Matematica e Fisica, Università Roma Tre, Roma, Italy
INFN-TIFPA, Italy
Università degli Studi di Trento, Trento, Italy
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, Dubna, Russia
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, University of Oxford, Oxford, United Kingdom
LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Portugal
Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
Departamento de Física, Universidade do Minho, Braga, Portugal
Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
Czech Technical University in Prague, Prague, Czech Republic
Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
State Research Center Institute for High Energy Physics, NRC KI, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
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
Department Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby British Columbia, Canada
SLAC National Accelerator Laboratory, Stanford, California, USA
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics and Astronomy, 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
Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
Department of Physics, Technion, Israel Institute 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, 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
Tomsk State University, Tomsk, Russia
Department of Physics, University of Toronto, Toronto, Ontario, Canada
TRIUMF, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of Illinois, Urbana, Illinois, USA
Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
Deceased.

Also at Department of Physics, King’s College London, London, United Kingdom.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at TRIUMF, Vancouver, British Columbia, Canada.

Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

Also at Department of Physics, California State University, Fresno, California, USA.

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.

Also at Department de Física de la Universitat Autonoma de Barcelona, Barcelona, Spain.

Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

Also at Universita di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.

Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at Borough of Manhattan Community College, City University of New York, New York, USA.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

Also at Louisiana Tech University, Ruston, Louisiana, USA.

Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.

Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

Also at Near East University, Nicosia, North Cyprus, Mersin, Turkey.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Manhattan College, New York, New York, USA.

Also at Hellenic Open University, Patras, Greece.

Also at The City College of New York, New York, New York, USA.

Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.

Also at Department of Physics, California State University, Sacramento, California, USA.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Giresun University, Faculty of Engineering, Giresun, Turkey.

Also at Department of Physics, Nanjing University, Nanjing, China.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at Department of Physics, University of Malaya, Kuala Lumpur, Malaysia.