A search for an excited muon decaying to a muon and two jets in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

A new search signature for excited leptons is explored. Excited muons are sought in the channel $pp \rightarrow \mu \mu^* \rightarrow \mu \mu$ jet jet, assuming both the production and decay occur via a contact interaction. The analysis is based on 20.3 fb$^{-1}$ of $pp$ collision data at a centre-of-mass energy of $\sqrt{s} = 8$ TeV taken with the ATLAS detector at the Large Hadron Collider. No evidence of excited muons is found, and limits are set at the 95% confidence level on the cross section times branching ratio as a function of the excited-muon mass $m_{\mu^*}$. For $m_{\mu^*}$ between 1.3 TeV and 3.0 TeV, the upper limit on $\sigma B(\mu^* \rightarrow \mu q \bar{q})$ is between 0.6 and 1 fb. Limits on $\sigma B$ are converted to lower bounds on the compositeness scale $\Lambda$. In the limiting case $\Lambda = m_{\mu^*}$, excited muons with a mass below 2.8 TeV are excluded. With the same model assumptions, these limits at larger $\mu^*$ masses improve upon previous limits from traditional searches based on the gauge-mediated decay $\mu^* \rightarrow \mu \gamma$. 

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1 Introduction

The Standard Model (SM) of particle physics successfully describes a wide range of phenomena but does not explain the generational structure and mass hierarchy of quarks and leptons. Composite models of fermions [1–7] aim to reduce the number of matter constituents by postulating that SM fermions are bound states of more fundamental particles. A direct consequence of substructure would be the existence of excited fermion states.

This paper reports on a search for an excited muon $\mu^*$ using 20.3 fb$^{-1}$ of $pp$ collision data at a centre-of-mass energy of $\sqrt{s} = 8$ TeV recorded in 2012 with the ATLAS detector at the Large Hadron Collider (LHC). The search is based on a benchmark model [7] that describes excited-fermion interactions with an effective Lagrangian containing four-fermion contact interactions and gauge-mediated interactions. A contact interaction decay signature, $\mu^* \rightarrow \mu j j$ ($j$ represents a jet), not previously employed in excited lepton searches is used.

In this paper, as in Ref. [7], the model is assumed to be valid for $\mu^*$ masses up to the compositeness scale. The contact interaction terms are described by the Lagrangian

$$\mathcal{L}_{\text{contact}} = \frac{g^2_\ast}{2\Lambda^2} j^\mu_\mu, \quad \text{with} \quad j_\mu = \eta f_L \gamma_\mu f_L + \eta' \overline{f}_L \gamma_\mu f_L + \eta'' \overline{f}_L \gamma_\mu f_L + \text{h.c.},$$

where $\Lambda$ is the compositeness scale, $j_\mu$ is the fermion current for ground states ($f$) and excited states ($f^*$), $g_\ast$ and the $\eta$’s are constants, “h.c.” stands for Hermitian conjugate, and only left-handed fermion interactions are assumed. As is done in Ref. [7], $g^2_\ast$ is set to $4\pi$, and $\eta$, $\eta'$, and $\eta''$ are taken to be one.

The search described here focuses on the predominant single-$\mu^*$ production via the contact interaction ($q\bar{q} \rightarrow \mu^* \mu$) followed by the decay of the excited muon via the contact interaction to $\mu q\bar{q}$ ($q$ is any quark except a top quark), leading to a final state with two muons and two jets (figure 1). Previous searches at LEP [8–11], HERA [12, 13], the Tevatron [14–17], and the LHC [18–22] looked for the gauge-mediated...
decay $\mu^* \to \mu \gamma$. In the model of Ref. [7], this decay is dominant at low $\mu^*$ mass, but for $m_{\mu^*} \gtrsim 0.25 \Lambda$, the $\mu q \bar{q}$ decay mode is expected to have the largest branching ratio, rising to 65% for $m_{\mu^*} = \Lambda$. The search reported here complements the search in the $\mu \gamma$ channel and increases the sensitivity of the search for excited muons at higher masses. The ATLAS Collaboration recently published [23] another new search signature for excited muons decaying via a contact interaction to $\mu \ell \ell$, where $\ell$ is an electron or a muon.

2 ATLAS detector

The ATLAS experiment [24] uses a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadronic steel/scintillator-tile calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounding the calorimeters covers the pseudorapidity range $|\eta| < 2.7$ and is based on three large air-core toroid superconducting magnets with eight coils each. Their bending power is in the range from 2.0 to 7.5 T m. The muon spectrometer consists of three stations of precision tracking chambers and fast detectors for triggering. The majority of the precision tracking chambers are composed of drift tubes, while cathode-strip chambers provide coverage in the inner stations of the forward region for $2.0 < |\eta| < 2.7$. A three-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the accepted event rate to 400 Hz on average, depending on the data-taking conditions during 2012.

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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 along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in terms of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. 
3 Signal and background simulation

Simulation of the excited-muon signal is based on calculations from Ref. [7]. Signal samples are generated at leading order (LO) with CompHEP 4.5.1 [25] using MSTW2008lo [26] parton distribution functions (PDFs). CompHEP is interfaced with PYTHIA 8.170 [27, 28] with the AU2 parameters settings [29] for the simulation of parton showers and hadronization. Only the production of $\mu\mu^*$ followed by the decay $\mu^* \rightarrow \mu q\bar{q}$ is simulated. Signal samples are produced for $\Lambda = 5$ TeV and for the $\mu^*$ masses given in table 2. The distributions of kinematic variables should be independent of $\Lambda$, which was checked with generator-level studies. For a compositeness scale of $\Lambda = 5$ TeV, cross section times branching ratios are 10.4, 2.9, and 0.21 fb for $\mu^*$ masses of 500, 1500, and 2500 GeV, respectively. The intrinsic total width of the $\mu^*$ is expected to be less than 8% for $m_{\mu^*} < \Lambda$, which is smaller than the mass resolution of about 20% over the range of $\mu^*$ masses considered here.

The dominant background is from the process $Z/\gamma^* \rightarrow \mu\mu$ produced in association with jets ($Z/\gamma^* + \text{jets}$). The second most important background is $t\bar{t}$ production. Other processes, such as diboson ($WW$, $WZ$, and $ZZ$), single-top, $W+$ jets, and multi-jet production, give small contributions to the background.

The $Z/\gamma^* + \text{jets}$ samples are produced by the multi-leg LO generator SHERPA 1.4.1 [30] using CT10 [31] PDFs. The cross section for $Z/\gamma^* \rightarrow \mu\mu$ ($m_{\mu\mu} > 70$ GeV) plus any number of jets is 1.24 nb, calculated at next-to-leading order (NLO), corrected by a $K$-factor [32, 33] to next-to-next-to-leading order (NNLO) in QCD couplings and NLO in electroweak couplings. The $t\bar{t}$ events are generated at the parton level at NLO with POWHEG 1.0 [34] and the Perugia 2011c parameter settings [35], and the parton showering is done with PYTHIA 6.426 [36]. At least one of the $t$ or $\bar{t}$ must have a semileptonic decay ($e$, $\mu$, or $\tau$), giving a cross section for this process of 137 pb, calculated at NNLO + next-to-next-to-leading-log (NNLL) accuracy [37]. The diboson background samples are produced at LO by HERWIG 6.52 [38] with the AUET2 parameter settings [39] using CTEQ6L1 PDFs, and it is required that at least one light lepton ($e$ or $\mu$) with transverse momentum ($p_T$) above 10 GeV be produced. The $W+$ jets samples are produced by the multi-leg LO generator ALPGEN 2.14 [40] with Jimmy 4.31 [41] and HERWIG 6.52 using the AUET2 parameter settings with CTEQ6L1 PDFs, and the cross section is calculated at NNLO [32, 33]. The multi-jet samples are generated at LO by PYTHIA 8.160 using the AU2 parameter settings with CT10 PDFs. The single-top-$t$-channel samples are generated at LO corrected to NLO + NNLL by AcerMC 3.8 [42] using the AUET2B parameters settings [43] with the CTEQ6L1 PDFs, and the parton showering is done with PYTHIA 6.426. The single-top-$s$- and $Wt$-channel samples are generated at NLO with MC@NLO 4.01 [44–46] using the AUET2 parameters settings with CT10 PDFs. The background predictions from the $Z/\gamma^* + \text{jets}$ and $t\bar{t}$ samples are normalized using control regions discussed in Section 5. Cross sections for diboson processes are evaluated at NLO [47] with an uncertainty of 5%. The $W+$ jets and multi-jet backgrounds are determined from the Monte Carlo (MC) samples but are verified using data-driven methods. A summary of the Standard Model samples used in this analysis is given in table 1.

The generated samples are processed using a detailed detector simulation [48] based on GEANT 4 [49] to propagate the particles through the detector material and account for the detector response. Simulated minimum-bias events are overlaid on both the signal and background samples to reproduce the effect of additional $pp$ collisions. The simulated events are weighted to give a distribution of the number of interactions per bunch crossing that agrees with the data. The simulated background and signal events are processed with the same reconstruction programs as used for the data.
<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Parton showering/hadronization</th>
<th>PDF</th>
</tr>
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<td>SHERPA 1.4.1</td>
<td>SHERPA 1.4.1</td>
<td>CT10</td>
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<tr>
<td>$t\bar{t} (\geq 1\ell)$</td>
<td>POWHEG 1.0</td>
<td>PYTHIA 6.426</td>
<td>CT10</td>
</tr>
<tr>
<td>$WW, WZ, ZZ (\geq 1\ell)$</td>
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<td>HERWIG 6.52</td>
<td>CTEQ6L1</td>
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<td>Single top, $t$-channel</td>
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<td>PYTHIA 6.426</td>
<td>CTEQ6L1</td>
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<tr>
<td>Single top, $s$-channel</td>
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<td>JIMMY 4.31 + HERWIG 6.52</td>
<td>CT10</td>
</tr>
<tr>
<td>Single top, $Wt$-channel</td>
<td>MC@NLO 4.01</td>
<td>JIMMY 4.31 + HERWIG 6.52</td>
<td>CT10</td>
</tr>
<tr>
<td>$W (\rightarrow \mu\nu) + \text{jets}$</td>
<td>ALPGEN 2.14</td>
<td>JIMMY 4.31 + HERWIG 6.52</td>
<td>CTEQ6L1</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>PYTHIA 8.160</td>
<td>PYTHIA 8.160</td>
<td>CT10</td>
</tr>
<tr>
<td>Signal ($\mu\mu^* \rightarrow \mu\mu jj$)</td>
<td>CompHEP 4.5.1</td>
<td>PYTHIA 8.170</td>
<td>MSTW2008lo</td>
</tr>
</tbody>
</table>

Table 1: Summary of the background and signal MC sample generation used in this search. The columns give the process generated, the generator program, the parton shower program, and the PDF utilized.

4 Data set and event selection

The data were collected in 2012 during stable-beam periods of $\sqrt{s} = 8$ TeV $pp$ collisions. After selecting events where the relevant parts of the detector were functioning properly, the data correspond to an integrated luminosity of $20.3 \text{ fb}^{-1}$. The events are required to pass at least one of two single-muon triggers. The first has a nominal $p_T$ threshold of 36 GeV, and the second has a lower nominal threshold of 24 GeV but also has an isolation requirement that the sum of the $p_T$ of tracks with $p_T$ above 1 GeV and within a distance of $\Delta R = 0.2$ of the muon, excluding the muon from the sum, divided by the $p_T$ of the muon is less than 0.12.

A primary vertex with at least three tracks with $p_T > 0.4$ GeV within 200 mm of the centre of the detector along the beam direction is required. If there is more than one primary vertex in an event, the one with the highest sum of $p_T^2$ is selected, where the sum is over all tracks associated with the vertex.

Each muon candidate must be reconstructed independently in both the inner detector and the muon spectrometer. Its momentum is determined by a combination of the two measurements using their covariance matrices. Only muon candidates with $p_T^\mu$ above 30 GeV are considered. Muons must have a minimum number of hits in the inner detector and hits in each of the inner, middle, and outer layers of the muon spectrometer. These hit requirements, which restrict the muon acceptance to $|\eta| < 2.5$, guarantee a precise momentum measurement. To suppress background from cosmic rays, the muon tracks are required to have transverse and longitudinal impact parameters $|d_0| < 0.2$ mm and $|z_0| < 1$ mm with respect to the selected primary vertex. To reduce background from semileptonic decays of heavy-flavour hadrons, each muon is required to be isolated such that $\sum p_T/p_T^\mu < 0.05$, where the sum is over inner-detector tracks with $p_T > 1$ GeV within a distance $\Delta R = 0.3$ of the candidate muon, excluding the muon from the sum. The muon trigger and reconstruction efficiencies are evaluated using tag-and-probe techniques with $Z \rightarrow \mu\mu$ events [50, 51], and $p_T$- and $\eta$-dependent corrections are applied to simulated events. Events are required to have exactly two muons of opposite charge that meet these selection requirements.

Although electrons are not part of the signal for this search, they are used to define one of the control regions (see Section 5). Each electron candidate is formed from the energy in a cluster of cells in the electromagnetic calorimeter associated with a charged-particle track in the inner detector. Each electron must have $p_T$ above 30 GeV and have $|\eta| < 2.47$ but not be in the interval $1.37 < |\eta| < 1.52$ to avoid the
transition region between the barrel and endcap calorimeters. The ATLAS tight electron identification criteria (based on the methodology described in [52] and updated for 2012 running conditions) for the transverse shower shape, longitudinal leakage into the hadronic calorimeter, the association with an inner-detector track, and hits in the transition radiation detector are applied to the cluster. An electron track is required to have transverse and longitudinal impact parameters $|d_0| < 1$ mm and $|z_0| < 5$ mm with respect to the selected primary vertex. Finally, the electrons must pass the isolation requirement $\sum E_T < 0.007E_T^e + 5$ GeV, where the sum is of transverse energies deposited in cells within a cone of $\Delta R = 0.2$ around the electron, excluding those cells associated with the electron, and $E_T^e$ is the transverse energy of the electron.

Jets of hadrons are reconstructed using the anti-$k_t$ algorithm [53] with a radius parameter of $R = 0.4$ applied to clusters of calorimeter cells that are topologically connected. The jets are calibrated using energy- and $\eta$-dependent correction factors derived from simulation and with residual corrections from in-situ measurements [54]. Jets are required to have $|\eta| < 2.8$ and $p_T > 30$ GeV. Jets that overlap ($\Delta R < 0.4$) any electron or muon candidate satisfying the selection criteria described above are removed. The two jets with the highest $p_T$ are then selected.

The missing transverse momentum vector is the negative of the vector sum of the transverse momenta of muons, electrons, photons, jets, and clusters of calibrated calorimeter cells not associated with these objects. The missing transverse energy is the magnitude of the missing transverse momentum vector.

5 Background determination

Most of the SM background contributions are estimated from the MC samples. The expected yields from the $Z/\gamma^* +$ jets and $t\bar{t}$ production processes are normalized to the data using control regions. The $Z/\gamma^* +$ jets control region is defined by $70 < m_{\mu\mu} < 110$ GeV in addition to the selection criteria given in Section 4. The contribution from signal events in this control region is at most 0.7% for a compositeness scale of 5 TeV for any $\mu^*$ mass considered here. The $t\bar{t}$ control region is defined as events that meet the selection requirements given in Section 4, except there is exactly one muon and one electron of opposite sign, so it should contain no signal events. The normalization scale factors are determined from a simultaneous fit to data in the control and signal regions (see Section 8). From the fit, the scale factor is $1.010^{+0.087}_{-0.066}$ for the $Z/\gamma^* +$ jets sample and is $1.050 \pm 0.013$ for the $t\bar{t}$ sample. The MC predictions agree well with the data in the control regions, as can be seen, for example, in figure 2(a).

A jet can produce a prompt muon candidate either from the semileptonic decay of a heavy quark or from misidentification of a charged hadron in the jet as a muon. The expected background from jets, primarily from $W+$ jets and multi-jet processes, is determined from MC samples, giving zero expected events. This prediction is checked by the data-driven matrix method [55], which uses isolated and non-isolated muons and their data-determined efficiencies and misidentification rates to determine the number of prompt muons. The matrix method predicts $-0.07 \pm 0.55$ events from these backgrounds.

6 Signal regions

Signal regions (SR) are defined by three kinematic variables - the dimuon invariant mass $m_{\mu\mu}$, the invariant mass $m_{\mu\mu jj}$ of the two muons and two jets ($j$), and $S_T$, the scalar sum of transverse momenta of the four
Figure 2: The $\mu\mu jj$ mass distribution for (a) the $Z/\gamma^* + \text{jets}$ control region with the MC predictions and (b) for SR 2 ($m_{\mu\mu} > 550 \text{ GeV}, S_T > 900 \text{ GeV},$ and $m_{\mu\mu jj} > 1000 \text{ GeV}$) with three representative signal distributions for $\mu^*$ masses of 500, 2000, and 3000 GeV and for $\Lambda = 5 \text{ TeV}$. The background expectations are determined after the fit, and the grey band on the ratio plot in (a) gives the systematic uncertainty. For (b) there are no expected events from the single top, $W + \text{jets}$, and $Z \to \tau\tau$ processes. SR 2 is not the most sensitive signal region for the latter two $m_{\mu^*}$ masses. They are shown for comparison.

signal objects, that is, $S_T = p_T^{\mu_1} + p_T^{\mu_2} + p_T^{j_1} + p_T^{j_2}$. For all three of these variables, the signal tends to have higher values than the backgrounds, so all criteria are lower bounds in the selection. The values of these bounds are chosen to maximize the search sensitivity for each signal mass considered by scanning the three-dimensional parameter space for the values that minimize the expected 95% confidence level (CL) upper limit on the cross section times branching ratio. The selection criteria for the signal regions are shown in table 2. The $m_{\mu\mu jj}$ and $S_T$ criteria increase with increasing signal mass, but the $m_{\mu\mu}$ criterion decreases. The latter is because the increase in the other parameters sufficiently reduces the expected background so that the signal efficiency may be increased by decreasing the $m_{\mu\mu}$ criterion.

The dominant background in all signal regions is from the $Z/\gamma^* + \text{jets}$ process, which is 50% of the background in SR 1, rising to 90% or more in SR 5 through SR 10. The $t\bar{t}$ process contributes 40% of the background in SR 1, but this contribution falls quickly to 10% or less in SR 3 through SR 10. The contribution to the background from all other processes is between 10% and 20% in SR 1 through SR 5 and is less than 5% for SR 6 through SR 10.

7 Systematic uncertainties

Contributions to the systematic uncertainties in the background and signal yield predictions stem from both experimental and theoretical sources, as discussed below. 

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The $\mu jj$ invariant mass was considered as a discriminating variable instead of one of the three selection variables. Several methods for selecting the correct $\mu jj$ combination and the possibility of using both $\mu jj$ combinations were considered. No method that improved the sensitivity was found.
Table 2: The signal masses considered and the corresponding signal regions are listed. The $m_{\mu\mu}$, $S_T$, and $m_{\mu\mu jj}$ values giving the lower bound of each signal region are listed, along with the acceptance times efficiency, the expected number of signal events (\Lambda = 5 \text{ TeV}), expected number of background events, and the number of events observed in the data. The expected backgrounds are determined after the fit discussed in Section 8. The uncertainties in the expected numbers of signal and background events are the systematic uncertainties. The numbers of events observed are discussed in Section 8.

The luminosity is derived using the methodology in Ref. [56] and has an uncertainty of 2.8%. The luminosity uncertainty for the backgrounds is less than this because the largest backgrounds (Z/\gamma^* + jets and t\bar{t}) are normalized using control regions.

Uncertainties in the MC modelling of the detector, particularly for muons and jets in this analysis, must be taken into account and are derived from detailed studies of data. One-standard-deviation variation of a given parameter is determined, and then the parameter is varied up and down in the simulation by this amount to determine the effect on the signal and background yields.

The uncertainty in the jet energy scale is the largest contribution to the systematic uncertainty in the signal yield and a significant contribution to the uncertainty in the backgrounds. The uncertainty in the jet energy resolution also makes a contribution. These uncertainties are determined from $p_T$ balance in $\gamma$+ jet and Z+ jet events and in events with high-$p_T$ jets recoiling against multiple, low-$p_T$ jets [54, 57]. Contributions from additional energy deposited in the calorimeters from other pp interactions in the event are also included. The various effects are investigated separately and combined to give the values summarized in tables 3 and 4.

Muon performance is determined in $Z \rightarrow \mu\mu$ events. The most important parameters for this analysis are the muon efficiency and the muon spectrometer $p_T$ resolution. The inner-detector resolution and the muon $p_T$ scale are found to have negligible effect. The uncertainty in the trigger efficiency is less than 2% for the backgrounds and less than 1% for the signal yield.

The uncertainties in the signal and background yield predictions due to uncertainties in PDFs have two
contributions. The first is from one-standard-deviation variation of the parameters of the relevant PDFs (Section 3). The second is a comparison with the alternative NNPDF2.1 PDF set [58]. These variations produce changes in the predicted cross section and in kinematical distributions, which in turn affect the acceptance times efficiency. For the background, both effects are included in the systematic uncertainty. For the signal yield, the uncertainty in the acceptance times efficiency is included, but the uncertainty in the cross section is considered part of the uncertainty in the theoretical prediction and is not included in the statistical analysis.

The uncertainty in the background modelling in the signal regions is estimated by examining how well the MC prediction agrees with the data in two validation regions selected to be similar in kinematics to the signal regions but containing no signal. Both validation regions require the same selection as the signal regions except that $m_{\mu\mujj} < 500$ GeV and $m_{\mu\mu} > 200$ GeV with no selection on $S_T$. Requiring the missing transverse energy be greater (less) than 50 GeV (40 GeV) selects a validation region dominated by $t\bar{t}$ ($Z/\gamma^*$) events. For some of the kinematic variables, an extrapolation of the predicted yield from the validation regions to the signal regions is necessary to evaluate possible mismodelling effects. Of the several kinematic variables studied, only the modelling of the $S_T$ variable is found to have a significant effect. A linear fit to the ratio of the number of data events to the MC expectation is extrapolated to higher values of $S_T$, and the deviation from unity symmetrized about zero gives the uncertainty, referred to as “$Z/\gamma^*+\text{jets modelling}” and “t\bar{t} modelling” in table 4. For both validation regions, the linear fit is consistent within the uncertainties with a flat line at a ratio of one.

To produce sufficient numbers of events for high dimuon masses, the $Z/\gamma^*$ MC samples were produced in bins of dimuon mass above the $Z$ mass. For the $S_T$ and $m_{\mu\mujj}$ criteria in this analysis, this yields zero events in SR 7 through SR 10 for some ranges of the $m_{\mu\mu}$ distribution (for example, 110 to 400 GeV for SR 10). For these signal regions, an additional systematic uncertainty (referred to as “$Z/\gamma^*+\text{jets extrapolation}” in table 4) is estimated by loosening the $S_T$ criteria and extrapolating into the signal region. The uncertainty introduced by this procedure is small except in SR 10, where the effect on the statistical analysis is still small because the predicted number of background events is only 0.2.

Additional sources of uncertainty in the acceptance times efficiency are initial-state radiation, final-state radiation, renormalization and factorization scales, and the beam energy. The effects of initial- and final-state radiation are determined in generator-level studies by varying the relevant Pythia parameters and are less than 1%. The effect of the beam energy uncertainty (0.65%) [59] is determined by varying the momentum fraction of the initial partons in the PDFs by this amount, giving a change of less than 1%. The renormalization and factorization scales are independently varied in the simulation by factors of 2 and 1/2, changing the expected signal yield by about 2% at low mass and by less than 1% for masses above 750 GeV.

The uncertainties in the signal yield depend on the $\mu^*$ mass, and the largest contributions are summarized in table 3 for three representative masses. For the signal yield, uncertainties in jet energy scale, PDFs, and luminosity are the dominant sources. The uncertainties in the background depend on the signal region, and the largest contributions are shown in table 4 for three representative regions. The most significant contributions to the background uncertainty are from the modelling of the $Z/\gamma^*+\text{jets}$ and $t\bar{t}$ processes. The jet energy scale and the parton distribution functions also make significant contributions. Any source of systematic uncertainty contributing less than 2% to the background for all signal regions and less than 1% to the signal yield for all $\mu^*$ masses would have negligible effect in the statistical analysis in Section 8 and is not included.
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<thead>
<tr>
<th>$m_{\mu^+\mu^-}$ [GeV]</th>
<th>500</th>
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<th>2500</th>
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<tr>
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<td>2.8</td>
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<tr>
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<td><strong>Total</strong></td>
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<td>4.1</td>
<td>4.2</td>
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Table 3: Largest contributions to the relative systematic uncertainty in the signal yield. All uncertainties are given in percent and are determined after the fit discussed in Section 8.

<table>
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<td>Luminosity</td>
<td>0.4</td>
<td>0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>$Z/\gamma^* +$ jets extrapolation</td>
<td>–</td>
<td>–</td>
<td>480</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>35</td>
<td>49</td>
<td>490</td>
</tr>
</tbody>
</table>

Table 4: Largest contributions to the relative systematic uncertainty in the expected background for three representative signal regions. All uncertainties are given in percent and are determined after the fit discussed in Section 8.

8 Results

The numbers of events in the control and signal regions are fit [60] using a profile likelihood method [61, 62]. The likelihood function models the number of events as a Poisson distribution and the systematic effects are modelled using nuisance parameters with lognormal constraints. The parameters of interest in the fit are the signal yield in each signal region and the normalizations of the $Z/\gamma^*$ and $t\bar{t}$ backgrounds, with the latter two being primarily determined in the fit by the events in the control regions. Correlations of the systematic uncertainties are taken into account.

As an example of the result of the fit, the $m_{\mu\mu jj}$ distribution for signal region 2 is shown in figure 2(b) for the data, expected backgrounds, and three signal predictions for $\Lambda = 5$ TeV (the signal regions for the higher masses have fewer background events). The expected and observed numbers of events for each signal mass considered are shown in table 2 for $\Lambda = 5$ TeV. The data are consistent with the Standard Model expectations, and no significant excess is observed. Thus, limits on the cross section times branching ratio as a function of the $\mu^*$ mass are calculated.

A modified frequentist $CL_s$ method [63, 64] is used to derive the 95% CL upper limits on the signal yield. The expected limit is the median limit for a large number of background-only pseudo-experiments.
Table 5: Values of $\mu\mu$ mass, $\mu jj$ mass, $S_T$, $\mu jj$ mass for each $\mu jj$ combination, and $p_T$ of each muon and jet for the three events in SR 9 or 10.

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>all</td>
<td>1800</td>
<td>2410</td>
<td>1820</td>
<td>1200</td>
<td>1090</td>
<td>650</td>
<td>630</td>
<td>350</td>
<td>190</td>
</tr>
<tr>
<td>B</td>
<td>7–9</td>
<td>310</td>
<td>2250</td>
<td>2010</td>
<td>2200</td>
<td>630</td>
<td>840</td>
<td>46</td>
<td>990</td>
<td>130</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>113</td>
<td>2440</td>
<td>1760</td>
<td>2230</td>
<td>1850</td>
<td>150</td>
<td>35</td>
<td>890</td>
<td>690</td>
</tr>
</tbody>
</table>

The one- and two-standard-deviations bands cover 68% and 95%, respectively, of the pseudo-experiment limits. The observed limit is the 95% CL limit for the observed number of events. The $p$-value is a measure of how well the background-only hypothesis models the data. For a signal region, it is the fraction of background-only pseudo-experiments where the fitted signal value is greater than that for the observed data.

The smallest $p$-values are for SR 9 and 10 with values of 0.034 and 0.099, respectively, corresponding to 1.8 and 1.3 standard deviations on one side of a Gaussian distribution. Some kinematic properties of the events in these signal regions are given in table 5. There is one event (event A) that is in all signal regions.

An upper limit on the cross section times branching ratio $\sigma(pp \rightarrow \mu\mu^*) \times B(\mu^* \rightarrow \mu q\bar{q})$ (figure 3) is determined for each signal mass from the limit on the signal yield at the 95% CL. The theoretical uncertainties are not included in either the $\sigma B$ or $\Lambda$ limit determinations. For $m_{\mu^*}$ above 1.3 TeV, the limit is between 0.6 and 1 fb. The theoretical expectation for $\Lambda = m_{\mu^*}$ is also shown. The theoretical band represents uncertainties from PDFs and from renormalization and factorization scales.

The expected cross section and branching ratio depend on the $\mu^*$ mass and on $\Lambda$ [7]. For each signal mass, the limit on $\sigma B$ is translated into a lower bound on the compositeness scale (figure 4). The bound is the value of $\Lambda$ for which the theoretical prediction of $\sigma B(m_{\mu^*}, \Lambda)$ is equal to the upper limit on $\sigma B$. The region with $m_{\mu^*} > \Lambda$ is unphysical. For the limiting case where $\Lambda = m_{\mu^*}$, excited-muon masses below 2.8 TeV are excluded. Previous limits set by ATLAS [19, 23] are also shown. The analysis presented here improves upon the limits from $\mu^* \rightarrow \mu\gamma$ for masses above 1100 GeV and upon those from $\mu^* \rightarrow \mu\ell\ell$ for masses from 700 to 2100 GeV.
Figure 3: Limit at 95% CL on cross section times branching ratio $\sigma(pp \to \mu^*\mu)B(\mu^* \to \mu q\bar{q})$ as a function of the $\mu^*$ mass. The solid line is the limit and the dotted line is the expected limit. The theoretical $\sigma B$ for the limiting case $\Lambda = m_{\mu^*}$ along with its uncertainties is also shown (dot-dashed curve).

Figure 4: Limit at 95% CL on the compositeness scale $\Lambda$ as a function of the $\mu^*$ mass. The solid black line is the limit and the short dashed black line is the expected limit. Also indicated are previous results from ATLAS based on $\mu^* \to \mu\gamma$ (long dashed red line) and $\mu^* \to \mu\ell\ell$ (dot-dashed blue line), where $\ell$ is an electron or muon.
9 Conclusion

The results of a search for excited muons decaying to $\mu jj$ via a contact interaction are reported based on data from $\sqrt{s} = 8$ TeV $pp$ collisions collected with the ATLAS detector at the LHC corresponding to an integrated luminosity of 20.3 fb$^{-1}$. The observed data are consistent with SM expectations. An upper limit is set at 95% CL on the cross section times branching ratio $\sigma B(\mu^* \rightarrow \mu q\bar{q})$ as a function of the excited-muon mass. For $m_{\mu^*}$ between 1.3 and 3.0 TeV, the limit on $\sigma B$ is between 0.6 and 1 fb.

The $\sigma B$ upper limits are converted to lower bounds on the compositeness scale $\Lambda$. In the limiting case where $\Lambda = m_{\mu^*}$, excited-muon masses below 2.8 TeV are excluded. At higher $\mu^*$ masses, the signature explored in this paper, $\mu^* \rightarrow \mu jj$, has better sensitivity than the traditional signature $\mu^* \rightarrow \mu \gamma$. For $\mu^*$ masses above 0.8 TeV, the sensitivity is up to 15% better than a previous search using the signature $\mu^* \rightarrow \mu \ell \ell$. In models other than the benchmark model used here, the branching ratios to these modes could be different, affecting their relative importance for limits on the compositeness scale.

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References


The ATLAS Collaboration

G. Aad$^{85}$, B. Abbott$^{112}$, J. Abdallah$^{150}$, O. Abidin$^{11}$, B. Abeleos$^{116}$, R. Aben$^{106}$, M. Abolins$^{90}$, O.S. AbouZeid$^{37}$, H. Abramowicz$^{152}$, H. Abreu$^{151}$, R. Abreu$^{115}$, Y. Abulati$^{145a,145b}$, B.S. Acharya$^{163a,163b}$, L. Adamczyk$^{38a}$, D.L. Adams$^{25}$, J. Adelman$^{107}$, S. Adomeit$^{99}$, T. Adye$^{130}$, A.A. Affolder$^{74}$, T. Agatonovic-Jovin$^{13}$, J. Agricola$^{54}$, J.A. Aguilar-Saavedra$^{125a,125f}$, S.P. Ahlen$^{22}$, F. Ahmadov$^{65b}$, G. Aielli$^{132a,132b}$, H. Akerstedt$^{145a,145b}$, T.P.A. Åkesson$^{81}$, A.V. Akimov$^{95}$, G.L. Alberghi$^{103a,103b}$, M.J. Alconada Verzin$^{71}$, M. Aleksa$^{30}$, I.N. Aleksandrov$^{65}$, C. Alexa$^{36a}$, G. Alexander$^{152}$, T. Alexopoulos$^{10}$, M. Alhroob$^{112}$, G. Alimonti$^{91a}$, L. Aliò$^{85}$, J. Alison$^{31}$, S.P. Alkire$^{35}$, B.M.M. Allbrooke$^{144}$, B.W. Allen$^{115}$, P.P. Allport$^{18}$, A. Aloisio$^{103a,103b}$, A. Alonso$^{36}$, F. Alonso$^{71}$, C. Alpigiani$^{137}$, B. Alvarez Gonzalez$^{30}$, D. Álvarez Piqueras$^{166}$, M.G. Alviggi$^{103a,103b}$, B.T. Amadio$^{15}$, K. Amako$^{66}$, Y. Amaral Coutinho$^{24a}$, C. Amelung$^{23}$, D. Amidei$^{39}$, S.P. Amor Dos Santos$^{125a,125c}$, A. Amorim$^{125a,125b}$, S. Amoroso$^{30}$, N. Amram$^{52}$, G. Amundsen$^{23}$, C. Anastopoulos$^{138}$, L.S. Ancu$^{65}$, N. Andan$^{107}$, T. Andeen$^{21}$, C.F. Anders$^{58b}$, G. Anders$^{30}$, J.K. Anders$^{74}$, K.J. Anderson$^{31}$, A. Andreazza$^{12a,9b}$, V. Andrei$^{38a}$, S. Angelidakis$^{9}$, I. Angellozzi$^{106}$, P. Anger$^{14}$, A. Angerami$^{15}$, F. Anghinolfi$^{30}$, A.V. Anisenkov$^{108c}$, N. Anjos$^{12}$, A. Anno$^{123a,123b}$, M. Antonelli$^{47}$, A. Antonov$^{97}$, J. Antos$^{143b}$, F. Anulli$^{131a}$, M. Aoki$^{66}$, L. Aperio Bella$^{18}$, G. Arabidze$^{90}$, Y. Aran$^{66}$, J.P. Araque$^{125a}$, A.T.H. Arce$^{45}$, F.A. Arduh$^{71}$, J-F. Arquín$^{94}$, S. Argyropoulos$^{53}$, M. Ariki$^{92}$, A.J. Armbruster$^{30}$, O. Arnaez$^{30}$, H. Arnold$^{48}$, M. Arratia$^{26}$, O. Arslan$^{21}$, A. Artamonov$^{96}$, G. Artoni$^{119}$, S. Arti$^{83}$, S. Asai$^{151}$, N. Asabak$^{42}$, A. Ashkenazi$^{52}$, B. Åsman$^{145a,145b}$, L. Asquith$^{148}$, K. Assamagan$^{25}$, R. Astalos$^{28}$, M. Atkinson$^{132a,132b}$, M. Battaglia$^{135}$, N. Besson$^{8}$, M. Barbero$^{130}$, B.M. Barnett$^{15}$, G. Anders$^{166}$, P. Bartos$^{54}$, K. Belotskiy$^{99}$, D. Biedermann$^{49}$, M. Bianco$^{136}$, G. Belloni$^{96}$, K. Bennett$^{145a,145b}$, D. Bertsche$^{16}$, J.K. Beher$^{119}$, C. Belanger-Champagne$^{87}$, W.H. Bell$^{49}$, G. Bella$^{152}$, L. Bellagamba$^{20a}$, A. Bellerive$^{9}$, M. Bellomio$^{96}$, K. Belotskiy$^{97}$, O. Beltramello$^{30}$, O. Benay$^{152}$, D. Benchekroun$^{134a}$, M. Bender$^{99}$, K. Bendtz$^{145a,145b}$, N. Benekos$^{10}$, Y. Benhamou$^{152}$, E. Benhar Noccioli$^{175}$, J.A. Benitez Garcia$^{158b}$, D.P. Benjamin$^{45}$, J.R. Bentlinger$^{23}$, S. Bentvelsen$^{106}$, L. Beresford$^{119}$, M. Beretta$^{47}$, D. Berger$^{106}$, E. Berges$^{165}$, N. Berger$^{19}$, F. Berghaus$^{168}$, J. Beringer$^{15}$, C. Bernard$^{22}$, N.R. Bernard$^{86}$, C. Bernius$^{109}$, F.U. Bernlochner$^{21}$, T. Berry$^{77}$, P. Berta$^{128}$, C. Bertella$^{83}$, G. Bertoli$^{145a,145b}$, F. Bertolucci$^{123a,123b}$, C. Bertesch$^{12}$, D. Bertesch$^{112}$, G.J. Besjes$^{36}$, O. Bessidskaïa Bylund$^{145a,145b}$, M. Bessner$^{42}$, N. Besson$^{135}$, C. Betancourt$^{48}$, S. Bethke$^{100}$, A.J. Bevan$^{76}$, W. Bhimji$^{15}$, R.M. Bianchi$^{124}$, L. Bianchini$^{23}$, M. Bianco$^{30}$, O. Biebel$^{99}$, D. Biedermann$^{16}$, N.V. Biesius$^{125a,125b}$, M. Biglietti$^{133a}$, J. Billoo$^{49}$, H. Bilokon$^{47}$, M. Bindi$^{54}$, S. Binet$^{16}$, A. Bindi$^{131a,131b}$, S. Biondi$^{20a,20b}$, D.M. Bjergaard$^{45}$, C.W. Black$^{49}$, J.E. Black$^{142}$, K.M. Black$^{22}$, D. Blackburn$^{137}$, R.E. Blair$^{6}$, J.-B. Blanchard$^{135}$, J.E. Blance$^{77}$, T. Blazek$^{143a}$, I. Bloch$^{42}$, C. Blocker$^{21}$, W. Blum$^{83a}$, U. Blumenschein$^{54}$, S. Blumier$^{32a}$, G.J. Bobbink$^{106}$, V.S. Bobrovnikov$^{108c}$, S.S. Bocchetta$^{81}$, A. Bocci$^{45}$,

1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States of America
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Dogus University, Istanbul, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
34 Laboratoire de Physique Corpusculaire, Clermont Université et Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

27
Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas TX, United States of America
Physics Department, University of Texas at Dallas, Richardson TX, United States of America
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham NC, United States of America
SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
(a) INFN Sezione di Genova; (b) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
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 Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
Department of Physics, Hampton University, Hampton VA, United States of America
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, Indiana University, Bloomington IN, United States of America
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City IA, United States of America
Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
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
(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
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
78 Department of Physics and Astronomy, University College London, London, United Kingdom
79 Louisiana Tech University, Ruston LA, United States of America
80 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
81 Fysiska institutionen, Lunds universitet, Lund, Sweden
82 Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
83 Institut für Physik, Universität Mainz, Mainz, Germany
84 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
85 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
86 Department of Physics, University of Massachusetts, Amherst MA, United States of America
87 Department of Physics, McGill University, Montreal QC, Canada
88 School of Physics, University of Melbourne, Victoria, Australia
89 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
91 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
94 Group of Particle Physics, University of Montreal, Montreal QC, Canada
95 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
97 National Research Nuclear University MEPhI, Moscow, Russia
98 D. V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
101 Nagasaki Institute of Applied Science, Nagasaki, Japan
102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
103 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
107 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
109 Department of Physics, New York University, New York NY, United States of America
110 Ohio State University, Columbus OH, United States of America
111 Faculty of Science, Okayama University, Okayama, Japan
112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
113 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
114 Palacký University, RCPTM, Olomouc, Czech Republic
115 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 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
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
Department of Physics, University of Washington, Seattle WA, United States of America
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 BC, Canada
SLAC National Accelerator Laboratory, Stanford CA, United States of America
(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
(a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand,
Johannesburg, South Africa
\[145\ (a)\] Department of Physics, Stockholm University; \(b)\ The Oskar Klein Centre, Stockholm, Sweden
\[146\] Physics Department, Royal Institute of Technology, Stockholm, Sweden
\[147\] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
\[148\] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
\[149\] School of Physics, University of Sydney, Sydney, Australia
\[150\] Institute of Physics, Academia Sinica, Taipei, Taiwan
\[151\] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
\[152\] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
\[153\] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
\[154\] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
\[155\] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
\[156\] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
\[157\] Department of Physics, University of Toronto, Toronto ON, Canada
\[158\ (a)\] TRIUMF, Vancouver BC; \(b)\ Department of Physics and Astronomy, York University, Toronto ON, Canada
\[159\] Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
\[160\] Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
\[161\] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
\[162\] Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
\[163\ (a)\] INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; \(b)\ ICTP, Trieste; \(c)\ Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
\[164\] Department of Physics, University of Illinois, Urbana IL, United States of America
\[165\] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
\[166\] 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
\[167\] Department of Physics, University of British Columbia, Vancouver BC, Canada
\[168\] Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
\[169\] Department of Physics, University of Warwick, Coventry, United Kingdom
\[170\] Waseda University, Tokyo, Japan
\[171\] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
\[172\] Department of Physics, University of Wisconsin, Madison WI, United States of America
\[173\] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
\[174\] Fakultätf für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
\[175\] Department of Physics, Yale University, New Haven CT, United States of America
\[176\] Yerevan Physics Institute, Yerevan, Armenia
\[177\] Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
\[a\] Also at Department of Physics, King’s College London, London, United Kingdom
\[b\] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan