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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

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Abstract

A new search signature for excited leptons is explored. Excited muons are sought in the channel $pp \to \mu\mu^* \to \mu\mu$ 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_{μ^*}. For m_{μ^*} between 1.3 and 3.0 TeV, the upper limit on $\sigma B(\mu^* \to \mu q\bar{q})$ is between 0.6 and 1 fb. Limits on σB are converted to lower bounds on the compositeness scale Λ. 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 μ^* masses improve upon previous limits from traditional searches based on the gauge-mediated decay $\mu^* \to \mu\gamma$.

Contents

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 μ^* 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

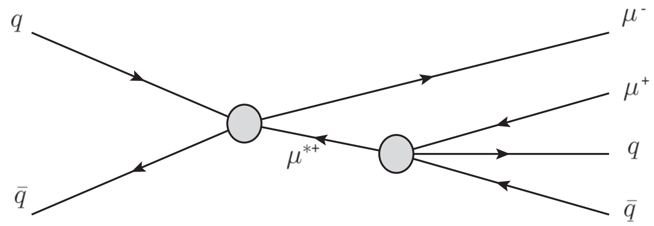


Figure 1. Feynman diagram for the process $q\bar{q} \to \mu^*\mu \to \mu\mu q\bar{q}$, where both the production and decay are via contact interactions.

containing four-fermion contact interactions and gauge-mediated interactions. A contact interaction decay signature not previously employed in excited leptons searches, $\mu^* \to \mu\, j\, j$ (j represents a jet), is used.

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

$$\mathcal{L}_{\text{contact}} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu, \quad \text{with } j_\mu = \eta \bar{f}_{\text{L}} \gamma_\mu f_{\text{L}} + \eta' \bar{f}_{\text{L}}^* \gamma_\mu f_{\text{L}}^* + \eta'' \bar{f}_{\text{L}}^* \gamma_\mu f_{\text{L}} + \text{h.c.},$$

where Λ is the compositeness scale; j_μ is the fermion current for ground states (f) and excited states (f^*); g^* and the η's are constants; 'h.c.' stands for Hermitian conjugate; and only left-handed fermion interactions are assumed. As is done in [7], g_*^2 is set to 4π, and η, η', and η'' are taken to be one for all fermions. To calculate branching ratios, the compositeness scale Λ is assumed to be the same for gauge-mediated interactions, and the parameters f and f' in [7] are taken to be one.

The search described here focuses on the predominant single-μ^* production via the contact interaction ($q\bar{q} \to \mu^*\mu$) followed by the decay of the excited muon via the contact interaction to $\mu q\bar{q}$, leading to a final state with two muons and two jets (figure 1). Top quarks from excited muons with masses accessible in the 8 TeV LHC data would not have sufficient energy to form narrow jets and are excluded from the analysis in this paper. Previous searches at LEP [8–11], the Tevatron [12–15], and the LHC [16–20] looked for the gauge-mediated decay $\mu^* \to \mu\gamma$. The analysis reported in [20] also includes the gauge-mediated decay $\mu^* \to \mu Z$ followed by $Z \to \ell\ell$ or $q\bar{q}$. In the model of [7], this decay is dominant at low μ^* 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 [21] another new search signature for excited muons decaying via a contact interaction to $\mu\ell\ell$, where ℓ is an electron or a muon.

2. ATLAS detector

The ATLAS experiment [22] uses a multi-purpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle[271]. 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 pseudorapidty 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 Tm. 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.

[271] 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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in terms of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

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 utilised.

Process	Generator	Parton showering/ hadronisation	PDF
Z/γ^* ($\rightarrow\mu\mu$) + jets	SHERPA 1.4.1	SHERPA 1.4.1	CT10
$t\bar{t}$ ($\geqslant 1\ell$)	POWHEG 1.0	PYTHIA 6.426	CT10
WW, WZ, ZZ ($\geqslant 1\ell$)	HERWIG 6.52	HERWIG 6.52	CTEQ6L1
Single top, t-channel	AcerMC 3.8	PYTHIA 6.426	CTEQ6L1
Single top, s-channel	MC@NLO 4.01	JIMMY 4.31 + HERWIG 6.52	CT10
Single top, Wt-channel	MC@NLO 4.01	JIMMY 4.31 + HERWIG 6.52	CT10
W ($\rightarrow\mu\nu$) + jets	ALPGEN 2.14	JIMMY 4.31 + HERWIG 6.52	CTEQ6L1
Multi-jet	PYTHIA 8.160	PYTHIA 8.160	CT10
Signal ($\mu\mu^* \rightarrow \mu\mu jj$)	CompHEP 4.5.1	PYTHIA 8.170	MSTW2008lo

3. Signal and background simulation

Simulation of the excited-muon signal is based on calculations from [7]. Signal samples are generated at leading order (LO) with CompHEP 4.5.1 [23] using MSTW2008lo [24] parton distribution functions (PDFs). CompHEP is interfaced with PYTHIA 8.170 [25, 26] with the AU2 parameters settings [27] for the simulation of parton showers and hadronisation. 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 μ^* masses given in table 2. The distributions of kinematic variables should be independent of Λ, 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 μ^* masses of 500, 1500, and 2500 GeV, respectively. The intrinsic total width of the μ^* 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 μ^* masses considered here.

The dominant background is from the process $Z/\gamma^* \rightarrow \mu\mu$ produced in association with jets (Z/γ^*+ 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/γ^*+ jets samples are produced by the multi-leg LO generator SHERPA 1.4.1 [28] using CT10 [29] 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 [30, 31] 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 [32] and the Perugia 2011c parameter settings [33], and the parton showering is done with PYTHIA 6.426 [34]. At least one of the t or $\bar{t}$ must have a semileptonic decay (e, μ, or τ), giving a cross section for this process of 137 pb, calculated at NNLO + next-to-next-to-leading-log (NNLL) accuracy [35]. The diboson background samples are produced at LO by HERWIG 6.52 [36] with the AUET2 parameter settings [37] using CTEQ6L1 PDFs, and it is required that at least one light lepton (e or μ) 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 [38] with JIMMY 4.31 [39] and HERWIG 6.52 using the AUET2 parameter settings with CTEQ6L1 PDFs, and the cross section is calculated at NNLO [30, 31]. 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 [40] using the AUET2B parameters settings [41] 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 [42–44] using the AUET2 parameters settings with CT10 PDFs. The background predictions from the Z/γ^*+ jets and $t\bar{t}$ samples are normalised using control regions discussed in section 5. Cross sections for diboson processes are evaluated at NLO [45] 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 SM samples used in this analysis is given in table 1.

The generated samples are processed using a detailed detector simulation [46] based on GEANT 4 [47] 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.

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 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 $p_{\mathrm{T}} > 0.4$ 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}^{μ} 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 $\sum p_{\mathrm{T}}/p_{\mathrm{T}}^{\mu} < 0.05$, where the sum is over inner-detector tracks with $p_{\mathrm{T}} > 1$ 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 $Z \to \mu\mu$ events [48, 49], and p_{T}- and η-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 [50] 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 $\sum E_{\mathrm{T}} < 0.007 E_{\mathrm{T}}^{e} + 5$ 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.

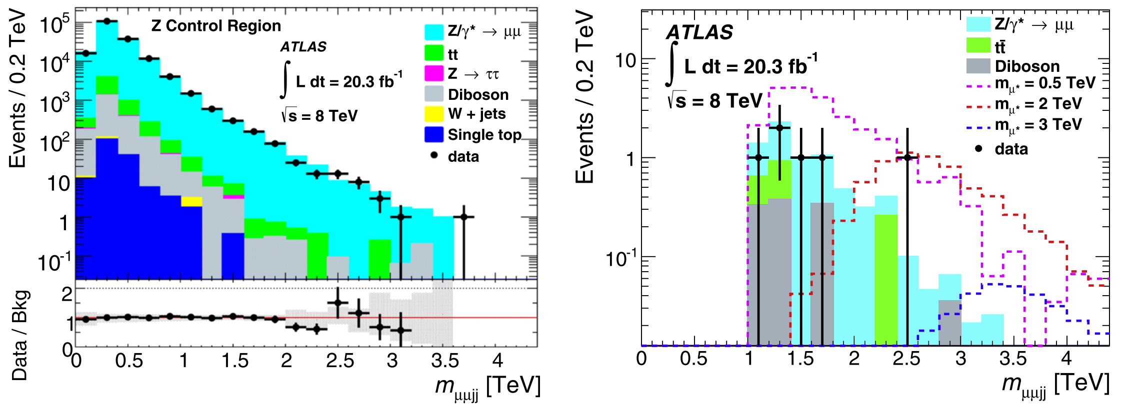
Jets of hadrons are reconstructed using the anti-k_t algorithm [51] with a radius parameter of $R = 0.4$ applied to clusters of calorimeter cells that are topologically connected. The jets are calibrated using energy- and η-dependent correction factors derived from simulation and with residual corrections from *in situ* measurements [52]. Jets are required to have $|\eta| < 2.8$ and $p_{\mathrm{T}} > 30$ 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 [53], 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/γ^*+ jets and $t\bar{t}$ production processes are normalised to the data using control regions. The Z/γ^*+ jets control region is defined by $70 < m_{\mu\mu} < 110$ GeV in addition to the selection criteria given in section 4. 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 normalisation scale factors are determined from simultaneous fits to data in the control and signal regions (SRs) (see section 8). The scale factors are primarily determined from the control regions, giving the same values in all cases. From the fits, the scale factor is $1.010^{+0.087}_{-0.066}$ for the Z/γ^*+ jets sample and is 1.050 ± 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



(a) Z/γ^{*}+ jets Control Region (b) SR 2

Figure 2. The $\mu\mu jj$ mass distribution for (a) the Z/γ^{*}+ jets control region with the MC predictions and (b) for SR 2 ($m_{\mu\mu} > 550$ GeV, $S_{\mathrm{T}} > 900$ GeV, and $m_{\mu\mu jj} > 1000$ GeV) with three representative signal distributions for μ^{*} masses of 500, 2000, and 3000 GeV and for $\Lambda = 5$ 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+ jets, and $Z \rightarrow \tau\tau$ processes. SR 2 is not the most sensitive signal region for the latter two $m_{\mu^{*}}$ masses. They are shown for comparison.

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 [54], 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 ± 0.55 events from these backgrounds.

6. Signal regions

SRs 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 signal objects, that is[272], $S_{\mathrm{T}} = p_{\mathrm{T}}^{\mu 1} + p_{\mathrm{T}}^{\mu 2} + p_{\mathrm{T}}^{j1} + p_{\mathrm{T}}^{j2}$.

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 maximise 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 SRs 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 SRs is from the Z/γ^{*}+ 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.

The luminosity is derived using the methodology in [55] and has an uncertainty of 2.8%. The luminosity uncertainty for the backgrounds is less than this because the largest backgrounds (Z/γ^{*}+ jets and $t\bar{t}$) are normalised 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.

[272] The μjj invariant mass was considered as a discriminating variable instead of one of the three selection variables. Several methods for selecting the correct μjj combination and the possibility of using both μjj 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 ($\Lambda = 5$ TeV), expected number of background events before and after the fit discussed in section 8, and the number of events observed in the data. The uncertainties in the expected numbers of signal and backgound events are the systematic uncertainties. The numbers of events observed are discussed in section 8.

m_{μ^*} (GeV)	Signal region	$m_{\mu\mu}$ (GeV)	S_T (GeV)	$m_{\mu\mu jj}$ (GeV)	Acc× Eff	Exp signal	Exp BG (prefit)	Exp BG (postfit)	Obs events
100	1	500	450	0	0.041	3.0 ± 0.3	73 ± 17	71.7 ± 8.6	71
300	2	550	900	1000	0.088	12.5 ± 0.9	10.1 ± 3.5	7.8 ± 2.2	6
500	2	550	900	1000	0.15	29.4 ± 1.6	10.1 ± 3.5	7.8 ± 2.2	6
750	3	450	900	1300	0.23	43.7 ± 2.2	6.6 ± 2.5	5.8 ± 1.9	5
1000	4	450	1050	1300	0.31	44.1 ± 1.8	4.6 ± 1.8	4.6 ± 1.9	5
1250	5	450	1200	1500	0.38	29.8 ± 1.3	2.1 ± 0.9	2.1 ± 1.0	3
1500	6	400	1200	1700	0.38	19.8 ± 0.8	1.5 ± 0.7	1.3 ± 0.6	1
1750	7	300	1350	1900	0.41	11.8 ± 0.5	0.9 ± 0.7	0.9 ± 0.5	2
2000	8	300	1350	2000	0.40	6.6 ± 0.2	0.7 ± 0.4	0.7 ± 0.4	2
2250	9	300	1500	2100	0.37	3.4 ± 0.1	0.4 ± 0.3	0.4 ± 0.3	2
2500	10	110	1650	2300	0.39	1.65 ± 0.07	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2
2750	10	110	1650	2300	0.45	0.72 ± 0.02	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2
2900	10	110	1650	2300	0.45	0.52 ± 0.02	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2
3000	10	110	1650	2300	0.46	0.38 ± 0.02	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2
3100	10	110	1650	2300	0.45	0.30 ± 0.02	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2

Table 3. Largest contributions to the relative systematic uncertainty in the signal yield. The uncertainties for the hadronisation and factorisation scales and for the PDFs are only for the signal acceptance times efficiency. All uncertainties are given in percent and are determined after the fit discussed in section 8.

m_{μ^*} (GeV)	500	1500	2500
Luminosity	2.8	2.8	2.8
Jet energy scale	2.7	1.5	1.1
Hadronisation and factorisation scales	2.0	0.5	0.1
PDFs	3.0	2.5	2.7
Muon efficiency	0.7	0.8	0.9
Jet energy resolution	0.9	0.2	0.5
Muon spectrometer resolution	0.3	<0.1	0.2
Total	5.1	4.1	4.2

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 [52, 56]. The uncertainty in contributions from additional energy deposited in the calorimeters from other pp interactions in the event is also included. The various effects are investigated separately and combined to give the values summarised 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 [57]. 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 SRs 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 SRs but

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.

Signal region	2	6	10
$Z/\gamma^* +$ jets modelling	25	47	65
Jet energy scale	19	9.0	6.2
$t\bar{t}$ modelling	12	<0.1	<0.1
Muon spectrometer resolution	6.2	0.6	63
PDFs	4.2	8.8	17
Jet energy resolution	3.2	1.7	0.6
Muon efficiency	0.7	0.8	0.9
Luminosity	0.4	0.1	<0.1
$Z/\gamma^* +$ jets extrapolation	—	—	500
Total	35	49	500

containing no signal. Both validation regions require the same selection as the SRs except that $m_{\mu\mu jj} < 500$ 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/γ^*) events. For some of the kinematic variables, an extrapolation of the predicted yield from the validation regions to the SRs 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/γ^*+ jets modelling' and '$t\bar{t}$ modelling' in table 4. For both validation regions, the linear fit is consistent within the statistical uncertainties with a flat line at a ratio of one.

To produce sufficient numbers of events for high dimuon masses, the Z/γ^* MC samples were produced in bins of dimuon mass above the Z mass. For the S_{T} and $m_{\mu\mu jj}$ 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 SRs, an additional systematic uncertainty (referred to as 'Z/γ^*+ jets extrapolation' in table 4) is estimated by loosening the S_{T} criteria and extrapolating into the SR. 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, renormalisation and factorisation 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%) [58] 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 renormalisation and factorisation scales are independently varied in the simulation by factors of 2 and 1/2, changing the expected signal acceptance times efficiency 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 μ^* mass, and the largest contributions are summarised 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 SR, 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/γ^*+ 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 SRs and less than 1% to the signal yield for all μ^* masses would have negligible effect in the statistical analysis in section 8 and is not included.

8. Results

For each μ^* mass considered, the numbers of events in the corresponding SR and in the two control regions are simultaneously fit [59] using a profile likelihood method [60, 61]. 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 the corresponding SR and the normalisations of the Z/γ^* and $t\bar{t}$ backgrounds, with the latter two being primarily determined in the fit by the events in the control regions. The possible contribution of signal to the control regions is included in the fit and found to be negligible. Correlations of the systematic uncertainties are taken into account.

Table 5. Values of $\mu\mu$ mass, $\mu\mu jj$ mass, S_T, μjj mass for each μjj combination, and p_T of each muon and jet for the three events in SR 9 or 10.

Event	SR	$m_{\mu\mu}$ (GeV)	$m_{\mu\mu jj}$ (GeV)	S_T (GeV)	$m_{\mu_1 jj}$ (GeV)	$m_{\mu_2 jj}$ (GeV)	$p_T^{\mu_1}$ (GeV)	$p_T^{\mu_2}$ (GeV)	$p_T^{j_1}$ (GeV)	$p_T^{j_2}$ (GeV)
A	all	1800	2410	1820	1200	1090	650	630	350	190
B	7–9	310	2250	2010	2200	630	840	46	990	130
C	10	113	2440	1760	2230	1850	150	35	890	690

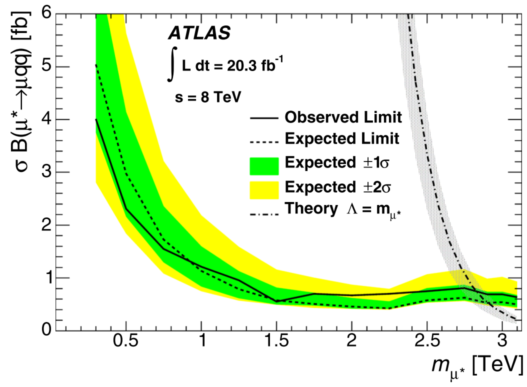


Figure 3. Limit at 95% CL on cross section times branching ratio $\sigma(pp \to \mu\mu^*)B(\mu^* \to \mu q\bar{q})$ as a function of the μ^* mass. The theory curve only includes contact-interaction decays and does not include the top quark. The solid line is the limit and the dotted line is the expected limit. The theoretical σB for the limiting case $\Lambda = m_{\mu^*}$ along with its uncertainties is also shown (dot-dashed curve).

As an example of the result of the fit, the $m_{\mu\mu jj}$ distribution for SR 2 is shown in figure 2(b) for the data, expected backgrounds, and three signal predictions for $\Lambda = 5$ TeV (the SRs 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. Due to correlations among the nuisance parameters, the uncertainties on the expected backgrounds are reduced after the fits. The data are consistent with the SM expectations, and no significant excess is observed. Thus, limits on the cross section times branching ratio as a function of the μ^* mass are calculated.

A modified frequentist CL_s method [62, 63] 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. 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 SR, 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 SRs are given in table 5. There is one event (event A) that is in all SRs.

An upper limit on the cross section times branching ratio $\sigma(pp \to \mu\mu^*) \times B(\mu^* \to \mu q\bar{q})$ (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 σB or Λ limit determinations. For m_{μ^*} 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 renormalisation and factorisation scales.

The expected cross section and branching ratio depend on the μ^* mass and on Λ [7]. For each signal mass, the limit on σB is translated into a lower bound on the compositeness scale (figure 4). The bound is the value of Λ for which the theoretical prediction of $\sigma B(m_{\mu^*}, \Lambda)$ is equal to the upper limit on σB. 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 [17, 21] are also shown. The analysis presented here improves upon the limits from $\mu^* \to \mu\gamma$ for masses above 1100 GeV and upon those from $\mu^* \to \mu\ell\ell$ for masses from 700 to 2100 GeV.

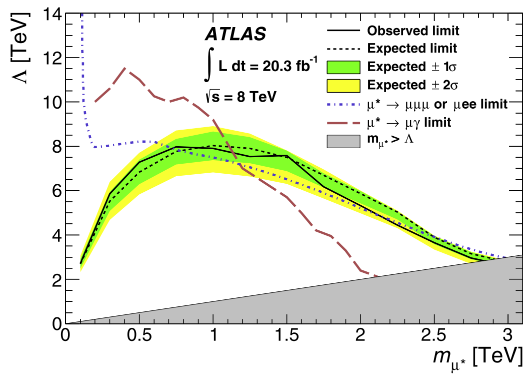


Figure 4. Limit at 95% CL on the compositeness scale Λ as a function of the μ^* mass. The solid black line is the limit and the short dashed black line is the expected limit. Also indicated are previous results from ATLAS based on $\mu^* \to \mu\gamma$ (long dashed red line) and $\mu^* \to \mu\ell\ell$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

9. Conclusion

The results of a search for excited muons decaying to μjj 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 $\sigma B(\mu^* \to \mu q\bar{q})$ as a function of the excited-muon mass. For m_{μ^*} between 1.3 and 3.0 TeV, the limit on σB is between 0.6 and 1 fb.

The σB upper limits are converted to lower bounds on the compositeness scale Λ. In the limiting case where $\Lambda = m_{\mu^*}$, excited-muon masses below 2.8 TeV are excluded. At higher μ^* masses, the signature explored in this paper, $\mu^* \to \mu\, j\, j$, has better sensitivity than the traditional signature $\mu^* \to \mu\, \gamma$. For μ^* masses above 0.8 TeV, the sensitivity is up to 15% better than a previous search using the signature $\mu^* \to \mu\ell\ell$. 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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