Search for a new Z' gauge boson via the $pp \to W^{\pm(*)} \to Z'\mu^{\pm}\nu \to \mu^{\pm}\mu^{\mp}\mu^{\pm}\nu$ process in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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A search for a new Z' gauge boson predicted by $L_\mu - L_\tau$ models, based on charged-current Drell–Yan production, $pp \to W^{\pm(*)} \to Z'\mu^{\pm}\nu \to \mu^{\pm}\mu^{\mp}\mu^{\pm}\nu$, is presented. The data sample used corresponds to an integrated luminosity of 140 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. The search examines a final state of 3μ plus large missing transverse momentum. Upper limits are set on the Z' production cross section times branching ratio in the mass range of 5–81 GeV. After combining with the previous Z' search using the neutral-current Drell–Yan production with a 4μ final state, the most stringent exclusion limits to date are achieved in the parameter space of the Z' coupling strength and mass.

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I. INTRODUCTION

Various extensions of the Standard Model (SM) feature an extra $U(1)$ gauge symmetry and predict a new massive gauge boson, generally referred to as Z' [1,2]. Typical benchmark models include the sequential Standard Model [3], grand unified theories based on the E_6 gauge group [4], and left (L)-right (R) symmetric extensions of the SM based on the $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ gauge group [5–7], where $B-L$ denotes the difference between baryon and lepton numbers. For Z' boson that significantly couples to light quarks, the constraint on its mass from LHC is up to 5 TeV [8,9]. Alternatively, $U(1)$ gauge symmetries based on the difference between lepton family numbers are less constrained and are anomaly free [10]. The model based on gauging the difference between μ-lepton number and τ-lepton number, $L_\mu - L_\tau$, is particularly interesting since it is the least constrained experimentally, because the $L_\mu - L_\tau$ Z' boson only couples to the second and third generations of leptons. In recent years, this model has attracted interest in both theoretical and experimental communities [11–13] because it could address some of the reported anomalies, such as the measured muon anomalous magnetic moment [14,15] and lepton flavor anomalies [16–20]. In addition, these models also provide a viable solution to dark matter and neutrino mass [2,21,22].

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The interaction between the Z' boson and the second- and third-generation leptons can be described with the following Lagrangian:

$$L_{Z'} = -\frac{1}{4}F_{\alpha\beta}F^{\alpha\beta} + \frac{1}{2}m_{Z'}^2 Z'^{\alpha}Z'_{\alpha} - g_{Z'}Z'_{\alpha}(\overline{\ell}_2\gamma^{\alpha}\ell_2 + \mu_L\gamma^{\alpha}\mu_R - \overline{\ell}_3\gamma^{\alpha}\ell_3 - \tau_L\gamma^{\alpha}\tau_R),$$

where $F_{\alpha\beta} = \partial_\alpha Z'_\beta - \partial_\beta Z'_\alpha$ is the Z' field strength tensor; $\ell_i = (\nu_i, e_i)^T$ ($i = 2$, 3, denoting the second and the third generation left-handed lepton doublets); and $g_{Z'}$ (from hereon referred to as g) is the coupling constant of the interaction between the Z' boson and the SM leptons. The Z'-boson mass, $m_{Z'}$, and g are the free parameters of the model. In proton–proton (pp) collisions at the Large Hadron Collider (LHC), the Z' boson could be produced by final state radiation from μ, ν_μ, τ and ν_τ leptons originating from other physics processes.

This paper presents the first search for a $L_\mu - L_\tau$ Z' boson produced from leptons arising from charged-current Drell–Yan (DY) process, $pp \to W^{\pm(*)} \to Z'\mu^{\pm}\nu \to \mu^{\pm}\mu^{\mp}\mu^{\pm}\nu$ (see Fig. 1), giving a final state of 3μ plus large missing transverse momentum. This novel search complements previous analyses by the ATLAS and CMS Collaborations using the neutral-current DY process with a 4μ final state, $pp \to Z^{(*)} \to Z'\mu^+\mu^- \to \mu^+\mu^-$, and has a much higher cross section by a factor of 3–6. The CMS Collaboration searched for the Z' boson in the mass range of 5–70 GeV using 77.3 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV [23]. The ATLAS Collaboration searched for the Z' boson with a mass up to 81 GeV using 139 fb^{-1} of data at $\sqrt{s} = 13$ TeV [24].

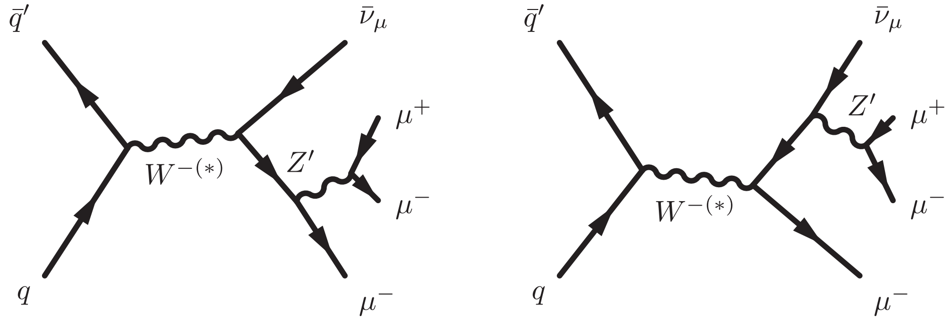


FIG. 1. Representative Feynman diagrams of a Z' boson via radiation off a lepton in charged-current Drell–Yan production giving a $\mu^-\mu^+\mu^-\bar{\nu}_\mu$ final state.

II. DATASET AND MONTE CARLO SIMULATION

The ATLAS experiment at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle [25–27].[1] The pp collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment during 2015–2018 are used. The corresponding integrated luminosity is 140 fb^{-1} after applying data quality requirements [28]. A combination of single-lepton and multilepton triggers [29,30] is used, with transverse momentum (p_T) thresholds varying from 20 to 26 GeV for single-muon triggers, 10 to 14 GeV for dimuon triggers, and 6 GeV for trimuon triggers. The overall trigger efficiency is greater than 96% for events passing the offline event selection. An extensive software suite [31] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

Monte Carlo (MC) signal samples are simulated using MADGRAPH5_AMC@NLO2.9.5 [32], with matrix elements (ME) calculated at leading order (LO) in perturbative quantum chromodynamics (QCD) and with the NNPDF3.0NLO [33] parton distribution function (PDF) set. The events were interfaced to PYTHIA 8.245 [34] to model the parton shower, hadronization, and underlying event, with parameter values set according to the A14 parton-shower tune [35] and using the NNPDF2.3LO [36] set of PDFs. The appropriate next-to-next-to-leading-order to LO K factor of 1.3 is used to correct the MC LO signal cross sections [37,38]. Benchmark signal samples are generated in the mass range of 5–81 GeV following the previous 4μ search [24] and to ensure a negligible Z' width compared with the detector resolution. The contribution from $pp \to Z'\tau\bar{\nu}_\tau$ to this search is found to be negligible and thus is not included in the MC signal samples.

The dominant SM background processes, $q\overline{q'} \to W(Z/\gamma^*) \to \ell^\pm\nu\ell^\pm\ell^\mp$ ($l = e, \mu, \tau$; $\nu = \nu_e, \nu_\mu, \nu_\tau$; referred to as $q\overline{q'} \to \ell^\pm\nu\ell^\pm\ell^\mp$) and $q\bar{q} \to (Z/\gamma^*)(Z/\gamma^*) \to \ell^+\ell^-\ell^+\ell^-$ (referred to as $q\bar{q} \to \ell^+\ell^-\ell^+\ell^-$), are simulated with the SHERPA 2.2.2 event generator [39]. Matrix elements are calculated at next-to-leading-order (NLO) accuracy in QCD for up to one additional parton and at LO accuracy for two and three additional parton emissions. The ME calculations are matched and merged with the SHERPA parton shower based on Catani–Seymour dipole factorization [40,41], using the MEPS@NLO prescription [42–45]. SHERPA 2.2.2 is also used for the $gg \to \ell^+\ell^-\ell^+\ell^-$ process, with LO precision for zero- and one-jet final states, where a constant K factor of 1.7 [46] is applied to account for NLO effects on the cross section. The events with nonprompt leptons arising from $Z +$ jets and $t\bar{t}$ processes are modeled using SHERPA 2.2.1 and POWHEG BOX v2 generators [47–50], respectively. Samples for other subdominant processes, such as the resonant $H \to ZZ^* \to 4\ell$ process, triboson processes (VVV, $V = W, Z$) and W/Z bosons produced along with a $t\bar{t}$ pair ($t\bar{t}V$), are also simulated as described in Ref. [24], and their contribution is found to be negligible and thus ignored.

Except for the signal, all samples are produced with a detailed simulation of the ATLAS detector [51] based on GEANT4 [52] to produce predictions that can be compared with the data. The signal samples are processed through a faster simulation where the full GEANT4 simulation of the calorimeter response is replaced by a parametrization of the shower shapes [51]. Furthermore, simulated inelastic minimum-bias events are overlaid to model additional pp collisions in the same and neighboring bunch crossings (pileup) [53]. Simulated events are reweighted to match the pileup conditions in the data. All simulated events were processed using the same reconstruction algorithms as used for data.

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe.The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan\theta/2$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

III. EVENT RECONSTRUCTION AND SELECTION

Interaction vertices from the pp collisions are reconstructed from at least two tracks with $p_{\mathrm{T}} > 500$ MeV that are consistent with originating from the beam collision region in the x-y plane. If more than one primary vertex candidate is found in the event, the candidate for which the associated tracks form the largest sum of squared p_{T} is selected as the hard-scatter primary vertex.

Muon candidates are reconstructed by combining the information from both the muon spectrometer and the inner detector (ID). Muons are required to satisfy the "Medium" identification criterion [54] and have $p_{\mathrm{T}} > 3$ GeV and $|\eta| < 2.5$. Electrons and jets are used to select control samples for the background estimate. Electrons are reconstructed from energy clusters in the electromagnetic calorimeter matched to ID tracks. Candidate electrons must satisfy the "Tight" likelihood identification criterion [55] and have $p_{\mathrm{T}} > 4.5$ GeV and $|\eta| < 2.47$, excluding the transition region between the barrel and endcaps in the calorimeter ($1.37 < |\eta| < 1.52$). All muons and electrons must be isolated from other particles based on a particle-flow algorithm and satisfy the "PflowLoose" and "PflowTight" isolation criteria [54,55], respectively. Furthermore, muons (electrons) are required to have matched tracks satisfying $|d_0|/\sigma_{d_0} < 3(5)$ and $|z_0 \sin(\theta)| < 0.5$ mm, where d_0 is the transverse impact parameter relative to the beam line, σ_{d_0} is its uncertainty, and z_0 is the longitudinal impact parameter relative to the primary vertex.

Jet candidates are reconstructed from particle flow objects [56] using the anti-k_t algorithm with a radius parameter of $R = 0.4$ [57,58]. They are calibrated using simulation with corrections obtained from *in situ* techniques in data [59]. A jet vertex tagger algorithm [60] is applied to suppress pileup jets. All jets must have $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 4.5$. Jets containing b-hadrons, referred to as b-jets, are identified using a deep-learning neural network, `DL1r` [61]. The chosen working point has an efficiency of 85% for selecting b-jets with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$ and a rejection factor of about 3 and 40 for charm jets and light-flavor jets, respectively [61].

The missing transverse momentum, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ (with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$), is defined as the negative vector sum of the p_{T} of all selected and calibrated objects in the event, including a term to account for the momentum from soft particles in the event that are not associated with any of the selected objects [62].

Events are required to contain exactly three muon candidates satisfying the selection criteria previously described. Events with a fourth muon candidate satisfying a looser selection criterion as defined in the 4μ channel [24] are rejected to ensure the two search regions are disjoint. Candidate events are required to have a total charge from the muons equal to ± 1. The three p_{T}-ordered muons are required to satisfy p_{T} thresholds of 20, 10, and 7 GeV, respectively. The muons firing triggers are also required to satisfy the corresponding trigger p_{T} thresholds. Events are required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 15$ GeV. To suppress the background contribution from top-quark production, events containing b-jets are rejected. Two opposite-sign muon pairs ($\mu^+\mu^-$) are selected from the three muons in each event. Each $\mu^+\mu^-$ pair must have an invariant mass greater than 4 GeV to suppress the background contribution from low-mass resonances. The $\mu^+\mu^-$ pair with the largest mass is referred to as the leading pair Z_1, and the other pair is referred to as the subleading pair Z_2. Events are required to satisfy $m_{Z_1} < 85$ GeV to suppress the background from Z-boson production. These selection requirements define the signal region (SR).

IV. BACKGROUND ESTIMATION

Background sources are classified into two categories: the irreducible background with events containing prompt muons, and the reducible background with events containing at least one nonprompt muon from hadron decays or misidentification of jets.

The irreducible background, which mainly originates from diboson production of $\overline{qq'} \to \ell^\pm \nu \ell^\pm \ell^\mp$ and $q\bar{q} \to \ell^+\ell^-\ell^+\ell^-$, is estimated by using simulation. The contribution from $t\bar{t}V$, VVV and Higgs boson production processes is found to be negligible. The background event yield of the dominant contribution from $\overline{qq'} \to \ell^\pm \nu \ell^\pm \ell^\mp$ production is normalized to the data with the help of a control region (CR) enriched in $\ell^\pm \nu \ell^\pm \ell^\mp$ events, referred to as $\mathrm{CR}_{3\ell}$. The $\mathrm{CR}_{3\ell}$ sample is defined by selecting events with three leptons, where the lowest- p_{T} lepton must be a muon, satisfying the p_{T} requirements of 25, 20, and 20 GeV, respectively, and with $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV. The same selection of lepton pairs used for the SR is implemented in the $\mathrm{CR}_{3\ell}$, and the leading lepton pair forming the Z-boson candidate must have an invariant mass in the range of 85–100 GeV.

The reducible background, with contributions from $Z + \text{jets}$, $Z + \gamma$, and $t\bar{t}$ production processes, is estimated by using a fake-factor method as described in Refs. [63,64]. The fake factor is defined as the ratio of numbers of nonprompt muons $N_{\mathrm{fake}}^{\mathrm{tight}}/N_{\mathrm{fake}}^{\mathrm{loose}}$, where "tight" or "loose" indicates whether those muons satisfy the impact parameter and isolation requirements, or fail to meet at least one of the requirements. The fake factor is measured in $Z + \text{jets}$ events, considering an additional muon candidate that does not originate from the Z-boson decay. The measurement is performed in bins of p_{T} of the additional muon and $E_{\mathrm{T}}^{\mathrm{miss}}$. The nonprompt muon background is then estimated by applying the fake factor as a weight to events satisfying the same selection as the SR, but with at least one loose-not-tight muon required. The modeling of the estimated reducible background is studied in a validation region (VR), which is disjoint to both the SR and the $CR_{3\ell}$. The VR is defined using the same selections used for the SR but with two opposite-sign electrons with $p_T > 20$ GeV and a muon that satisfies the "tight" identification criteria. The nonprompt muon background in this VR is also estimated with the fake-factor method. The sum of the estimated nonprompt background yield and the MC prediction is consistent with data within the statistical uncertainties.

V. EVENT CLASSIFICATION WITH A PARAMETRIZED DEEP NEURAL NETWORK

The signal and background have different distributions for the various kinematic variables. A *parametrized deep neural network* (pDNN) [65] is used to combine several discriminating variables into a single final discriminant. The pDNN architecture allows the training of a single classifier for multiple signal mass hypotheses in the search range by adding a mass parameter together with other inputs. The mass parameter is equal to the value of the nominal generated Z' mass for the signal component, while a random value is drawn from the same distribution for the background mass parameter. In the evaluation process, when applying the training results to real data, the mass parameter takes the value of the investigated signal mass. The algorithm was implemented in the PyTorch [66] framework. Two classifiers are trained for low (high) Z' mass searches using mass parameters less than (greater than or equal to) 40 GeV. A set of kinematic distributions was used for pDNN training input features: the p_T of each muon, the invariant mass of the Z_1, Z_2 and three-muon system, $\Delta\phi$ of each muon pair that forms the Z_1 and Z_2, E_T^{miss}, H_T, which is the scalar sum of E_T^{miss} and the p_T of all muons, $V_T = \sqrt{H_{T,x}^2 + H_{T,y}^2}$, and $M_T = \sqrt{H_T^2 - V_T^2}$, where $H_{T,x}(H_{T,y})$ is the scalar sum of E_T^{miss} and the p_T of all muons along the direction of the $x(y)$ axis.

VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties due to imperfect modeling of the detector in the simulation or the underlying physics of each process are also considered for the prediction of signal and background processes.

Experimental uncertainties originate mainly from E_T^{miss} resolution and scale, measurements of muon momentum resolutions and scales, muon reconstruction and identification efficiencies, jet energy scale and resolution, and b-tagging efficiency. Uncertainties due to the trigger selection efficiency and pileup correction are also considered. In addition, the uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [28], obtained using the LUCID-2 detector [67] for the primary luminosity measurements. Overall, the total experimental uncertainty in the predicted yields is 5% (7%) for the signal (background with prompt muons).

The theoretical uncertainties in the signal, and the major prompt background due to the diboson processes, include the uncertainties in PDFs, QCD scales, and α_s. The PDF uncertainty is estimated following the PDF4LHC [68] procedure. The α_s uncertainty is estimated by varying the nominal $\alpha_s = 0.118$ by its uncertainty of ± 0.001. The QCD scale uncertainty is estimated by varying the renormalization and factorization scales, following the procedure described in Ref. [69]. The parton showering uncertainty is estimated by comparing events with different parton shower parameters in the Sherpa MC samples. The total theoretical uncertainties in the reconstructed event yields for the signal and the $q\overline{q'} \to \ell^\pm\nu\ell^\pm\ell^\mp$ background processes are estimated to be 15% and 13%, respectively, dominated by the QCD scale uncertainty. The interference effect between the signal and SM DY background is about 2%, and this effect is accounted as an uncertainty affecting the signal.

Systematic uncertainties assigned to the reducible background, about 11% in total, mainly account for the measurement of the fake factors, the differences between the composition of the events with fake leptons between $Z+$jets events and the events in the SR, and data statistical uncertainties in the dedicated region where fake factors are applied. The overall impact of systematic uncertainties in the search sensitivity is a degradation on the expected cross section limits up to 14% in the mass range considered.

VII. RESULTS

A simultaneous profile binned maximum-likelihood fit [70–72] to the distribution of pDNN score in the SR and the event yield of the $CR_{3\ell}$ is performed to constrain uncertainties and obtain information about a possible signal. The normalizations of both the signal and the $q\overline{q'} \to \ell^\pm\nu\ell^\pm\ell^\mp$ background are allowed to vary freely in the fit. The systematic uncertainties are modeled as nuisance

TABLE I. Summary of observed and expected background yields in the SR after the likelihood fit under the background-only hypothesis. The "Nonprompt" represents the contribution from nonprompt muons. The uncertainty in the total background yield can be smaller than the quadrature sum of the contributions because of correlations resulting from the fit. The expected signal yield obtained using the theoretical cross section for a benchmark point ($m_{Z'} = 19$ GeV, $g_{Z'} = 0.0085$) is also shown with its prefit uncertainty.

Data	Total background	$q\overline{q'} \to \ell^\pm\nu\ell^\pm\ell^\mp$	$q\bar{q}/gg \to \ell^+\ell^-\ell^+\ell^-$	Nonprompt	Signal
3089	3080 ± 54	1125 ± 75	396 ± 51	1559 ± 86	36.5 ± 0.5

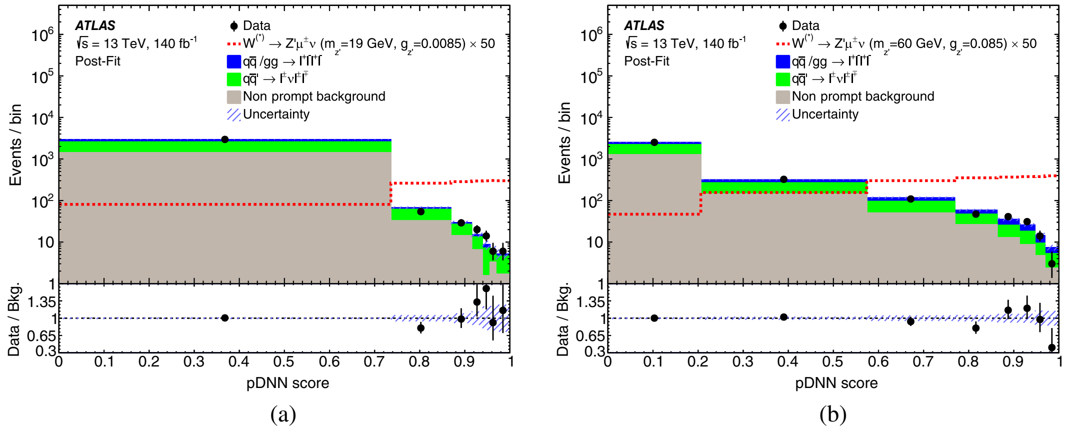


FIG. 2. The distributions of the pDNN score corresponding to (a) $m_{Z'} = 19$ GeV and (b) $m_{Z'} = 60$ GeV in the SR for the data and postfit background contributions. Signals are overlaid, with the predicted yield scaled up by a factor of 50. The error bands include experimental and theoretical systematic uncertainties. The ratio of the data to the background ("Bkg") prediction is shown in the lower panel.

parameters subject to Gaussian constraints in the likelihood fit. The expected signal yields and pDNN scores are interpolated across the MC generated signal samples and are used in the fitting process. The fit is independently performed for each signal mass point since the pDNN score depends on the value of $m_{Z'}$ under test. The binning of the pDNN distribution varies with each signal mass point to limit the size of the MC statistical uncertainties to at most 20% per bin and also to maximize the expected signal sensitivity.

Table I shows the expected background and observed event yields in the SR after the background-only fit. The normalization factor of the $q\overline{q'} \to \ell^\pm\nu\ell^\pm\ell^\mp$ background is determined to be 0.92 ± 0.08 and 0.91 ± 0.09 when the pDNN score is obtained with $m_{Z'} = 19$ GeV and $m_{Z'} = 60$ GeV, respectively. The corresponding distributions of the pDNN score are presented in Fig. 2. Examples of kinematic distributions after the background-only fit are presented in Appendix.

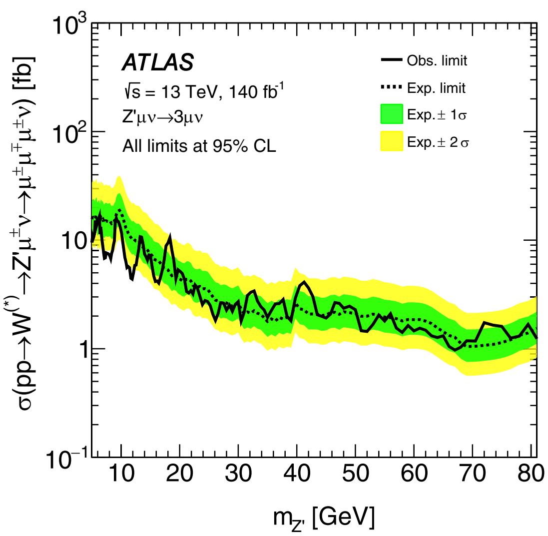
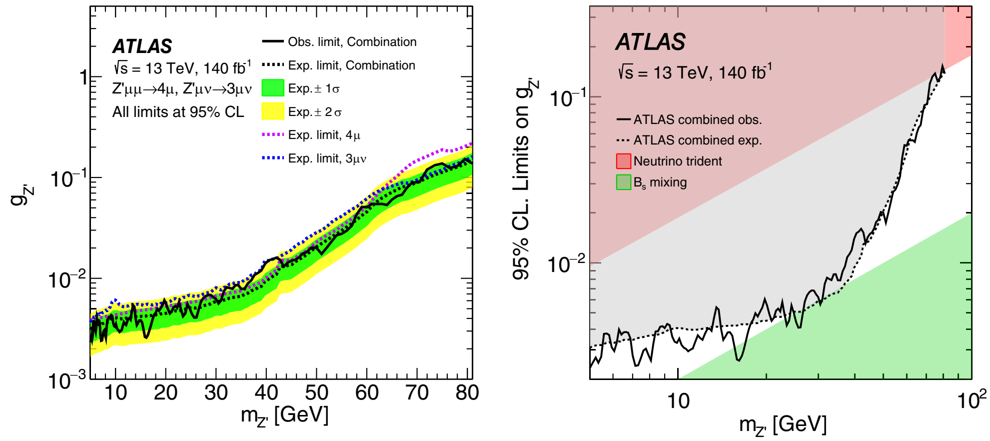


FIG. 3. Observed (solid line) and expected (dashed line) upper limits at 95% CL on the production cross section times branching fraction of the process $pp \to W^{\pm(*)} \to Z'\mu^\pm\nu \to \mu^\pm\mu^\mp\mu^\pm\nu$ as a function of $m_{Z'}$. The surrounding shaded bands correspond to ±1 and ±2 standard deviations around the expected limit.

No significant deviation from the SM background hypothesis is observed, and the largest excess of events is found for $m_{Z'}$ around 18.3 GeV, with a local significance of 2.4σ and global significance of 0.8σ. Exclusion limits are set using the $\mathrm{CL_s}$ method [73]. Upper limits at 95% confidence level (CL) on the cross section times branching fraction of the process $pp \to W^{\pm(*)} \to Z'\mu^\pm\nu \to \mu^\pm\mu^\mp\mu^\pm\nu$ are shown in Fig. 3 as a function of $m_{Z'}$.

A statistical combination with the ATLAS search for Z' in the 4μ channel [24] is performed to improve the overall sensitivity. The coupling parameter g is used as a common parameter of interest for the 3μ and 4μ channels. The contribution of the signal process $pp \to Z^{(*)} \to Z'\mu^+\mu^- \to \mu^+\mu^-\mu^+\mu^-$ in the SR of the 3μ channel is also considered. Common experimental uncertainties and theoretical modeling uncertainties are fully correlated. The uncertainties relevant to backgrounds are uncorrelated due to a different background estimate in the 4μ channel. Upper limits at 95% CL on the coupling parameter g as a function of $m_{Z'}$ are shown in Fig. 4(a). The combined exclusion limits are significantly improved relative to the 4μ channel. The improvement is up to 40% in the high-mass region, where the 3μ channel dominates the sensitivity. In Fig. 4(b), the results are also compared with the exclusion regions inferred from a measurement of neutrino tridents by the CCFR Collaboration [74] and the B_s mixing measurements by a global analysis performed in Ref. [21]. The large region in the parameter space up to 81 GeV allowed by the neutrino trident and B_s measurements is now largely excluded.



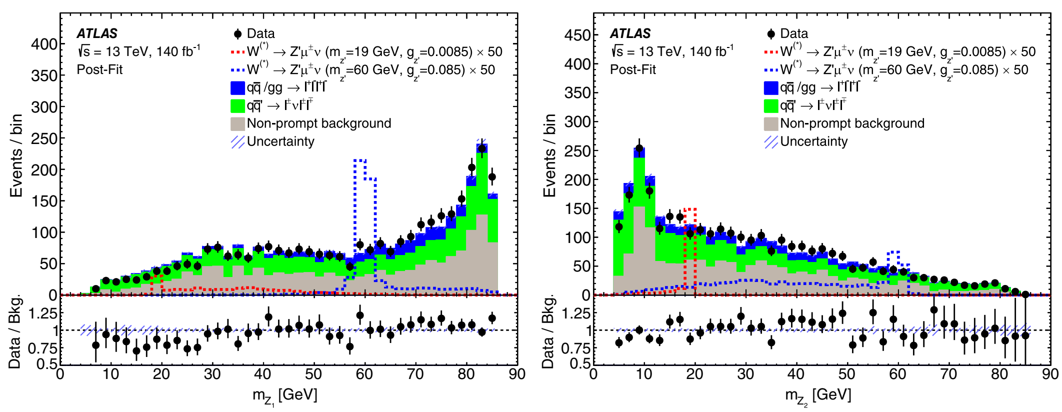
(a) (b)

FIG. 4. Results from the statistical combination of the 3μ and 4μ channels: (a) observed and expected 95% CL upper limits on g as a function of $m_{Z'}$, (b) exclusion contour of g compared with the limits inferred from the neutrino-trident (red) and the B_s mixing (green) experimental results [21].

In conclusion, the search for a $L_\mu - L_\tau$ gauge boson Z' using charged-current Drell–Yan production is reported for the first time at the LHC, with a final state of 3μ plus large missing transverse momentum, using 140 fb^{-1} of $\sqrt{s} = 13$ TeV proton–proton collision data collected with the ATLAS detector. This search benefits from the considerably higher Z' production cross section compared with previous searches using the neutral-current Drell–Yan production, and has better sensitivity for $m_{Z'} > 60$ GeV. No significant excess of events over the expected SM background is observed. Upper limits are set on the Z' production cross section times the decay branching fraction of the $pp \to W^{\pm(*)} \to Z'\mu^\pm\nu \to \mu^\pm\mu^\mp\mu^\pm\nu$ process in a Z' mass range of 5–81 GeV. The search is further statistically combined with the Z' search using neutral-current Drell–Yan production with a 4μ final state [24]. The most stringent exclusion limits to date are set in the allowed parameter space of the Z' coupling strength and $m_{Z'}$.

APPENDIX

The Z' mass resonance can be reconstructed either from m_{Z_1} or m_{Z_2} as shown in Fig. 5, depending on the value of $m_{Z'}$.



(a) (b)

FIG. 5. Comparison of data and postfit SM prediction for (a) the invariant mass of the leading $\mu^+\mu^-$ pair, m_{Z_1}, (b) the invariant mass of the subleading $\mu^+\mu^-$ pair, m_{Z_2}, in the SR. Two representative signals with masses of 19 GeV and 60 GeV are also overlaid, with the predicted yield scaled up by a factor of 50. The error bands include experimental and theoretical systematic uncertainties. The ratio of the data to the background ("Bkg") prediction is shown in the lower panel.

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