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Search for dark matter in events with a leptoquark and missing transverse momentum in proton-proton collisions at 13 TeV

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ABSTRACT

A search is presented for dark matter in proton-proton collisions at a center-of-mass energy of $\sqrt{s} =$ 13 TeV using events with at least one high transverse momentum (p_T) muon, at least one high-p_T jet, and large missing transverse momentum. The data were collected with the CMS detector at the CERN LHC in 2016 and 2017, and correspond to an integrated luminosity of 77.4 fb^{-1}. In the examined scenario, a pair of scalar leptoquarks is assumed to be produced. One leptoquark decays to a muon and a jet while the other decays to dark matter and low-p_T standard model particles. The signature for signal events would be significant missing transverse momentum from the dark matter in conjunction with a peak at the leptoquark mass in the invariant mass distribution of the highest p_T muon and jet. The data are observed to be consistent with the background predicted by the standard model. For the first benchmark scenario considered, dark matter masses up to 500 GeV are excluded for leptoquark masses $m_{LQ} \approx 1400$ GeV, and up to 300 GeV for $m_{LQ} \approx 1500$ GeV. For the second benchmark scenario, dark matter masses up to 600 GeV are excluded for $m_{LQ} \approx 1400$ GeV.

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1. Introduction

Dark matter (DM) has been a subject of intense interest for decades. Extensive astrophysical evidence for DM exists [1–3], such as from observations of the dynamics of galaxy clusters and measurements of anisotropies in the cosmic microwave background. Nonetheless, the nature of DM remains unknown and it has not been observed outside the astrophysical context. Its relic density is determined to be $\Omega_{DM} = (0.1186 \pm 0.0020)/h^2$ [4,5], where h is the Hubble constant.

Dark matter could potentially be created in high-energy proton-proton (pp) collisions, such as at the CERN LHC. Because of its presumed weakly interacting nature, a DM particle produced at the LHC would escape unobserved, manifesting itself as missing transverse momentum $\vec{p}_T^{miss}$ in the reconstructed events. The most generic signal for DM at the LHC thus consists of an excess, relative to the standard model (SM) expectation, of events with sizable $\vec{p}_T^{miss}$ recoiling against a visible SM object such as a jet, a photon, or an electroweak boson. Such searches have been conducted at the LHC by the ATLAS and CMS Collaborations [6–14] but with no evidence, to date, for DM [15]. The absence of a signal in these generic searches suggests that alternative strategies should be pursued.

In this Letter, we present a search for DM at the LHC using a new approach, based on the coannihilation paradigm introduced in Ref. [16]. The data, corresponding to an integrated luminosity of 77.4 fb^{-1} of pp collisions, were collected by the CMS Collaboration in 2016 (35.9 fb^{-1}) and 2017 (41.5 fb^{-1}) at a center-of-mass energy of $\sqrt{s} = 13$ TeV. The coannihilation process considered arises within a general class of simplified models in which a DM particle is either annihilated or produced in conjunction with a so-called coannihilation partner, denoted "X". At the LHC, DM could thus be produced through a reaction like $M \to DM + X$, where M is a mediator representing either an SM or a beyond-the-SM particle. To be consistent with the observed value of Ω_{DM}, the fractional mass difference $\Delta_{X,DM} \equiv (m_X - m_{DM})/m_{DM}$ between the X and DM particles should be less than $\approx$0.2 [16].

The considered coannihilation paradigm introduces many DM signatures that are not covered by current searches. Here, we consider the principal case-study scenario of Ref. [16], in which the mediator M is a scalar leptoquark (LQ) doublet and the particle X is a new Dirac fermion. An LQ is a hypothetical color-triplet, fractionally charged boson that carries both lepton and baryon quantum numbers. Leptoquarks appear in many extensions of the SM, such as grand unification theories [17–20] and models with

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composite quarks and leptons [21]. To be consistent with experimental constraints on flavor changing neutral currents, we assume the LQ to couple to a single SM flavor generation only [22], taken to be the second generation for this study. We choose the second generation because muons provide a clear experimental signature. We further assume pair production of LQs, as is predominantly expected in pp collisions. Following Ref. [16], the DM particle is assumed to be a Majorana fermion with the gauge group structure (1, 1, 0), where the numbers in parentheses indicate the color $SU(3)_C$, weak isospin $SU(2)_L$, and weak hypercharge $U(1)_Y$ multiplet dimensions, respectively. We use the convention $Q = T_3 + Y/2$ for the electric charge Q of the particle, with T_3 the third component of weak isospin and Y the weak hypercharge. The corresponding assignments for both the X and LQ particles are (3, 2, 7/3). For the LQ, $T_3 = \pm 1/2$ and $Q = 5/3, 2/3$ for the two members of the doublet, respectively. The interaction term of the Lagrangian for this model is:

$$\mathcal{L} = -(y_D \bar{X} M_s \, \mathrm{DM} + y_{Q\ell} \overline{Q_L} M_s \ell_R + y_{Lu} \overline{L_L} M_s^c u_R + \mathrm{h.c.}) \quad (1)$$

where the superscript c refers to charge conjugation. After the breaking of electroweak symmetry, the different doublet components of X, M_s, Q_L, and L_L take the form:

$$\mathcal{L} = -y_D \bar{X}^u M_s^u \, \mathrm{DM} - y_{Q\ell} \bar{u}_L M_s^u \ell_R - y_{Lu} \bar{e}_L (M_s^u)^c u_R \quad (2)$$

$$- y_D \bar{X}^d M_s^d \mathrm{DM} - y_{Q\ell} \bar{d}_L M_s^d \ell_R - y_{Lu} \bar{\nu}_L (M_s^d)^c u_R \quad (3)$$

The first line represents the interactions of the upper component of the LQ doublet M_s^u, which has electric charge -5/3. The first term in the first line describes the decay of the LQ to DM and X, with y_D the coupling strength. The second and third terms of the first line represent the interactions, with coupling strengths $y_{Q\ell}$ and y_{Lu}, for the different helicity couplings to the up-type quark and the lepton. The second line describes the interactions of the lower component of the leptoquark doublet M_s^d, which has electric charge -2/3. In the limit that $y_{Q\ell} \neq 0$ and $y_{Lu} = 0$, both the upper and lower components of the doublet have the same collider phenomenology. The SM decays of the upper component of the M_s^u doublet are to up-type quarks and leptons, while those of the lower component of the M_s^d doublet are to down-type quarks and leptons. In the limit that $y_{Q\ell} = 0$ and $y_{Lu} \neq 0$, the upper and lower components of the doublet have different collider phenomenology. The SM decays of the upper component of M_s^u are again to up-type quarks and leptons, but the only SM decays of the lower component are to neutrinos and up-type quarks, and not to the full leptoquark signature. Both the upper and lower components of the LQ doublet have been considered in this analysis. Following the example of Ref. [16], we assume $y_{Lu} = 0$. Thus it should be born in mind that the limits obtained in this analysis are valid under this explicit assumption. In the pair production of the LQ, one LQ decays to a muon and a c or an s quark, while the other decays through the coannihilation paradigm, to DM and X. The X particle subsequently decays through a crossed coannihilation process to a DM particle and an off-shell LQ, where the decay products of this latter particle, also a muon and a c or an s quark, have low transverse momentum (p_T) because of the smallness of $\Delta_{X,DM}$ and are potentially undetected. An example Feynman diagram is shown in Fig. 1.

The most restrictive lower limit on the mass of a pair-produced second-generation LQ, assuming an LQ branching fraction $\mathcal{B}(\mathrm{LQ} \to c\mu) = 100\%$, is currently 1530 GeV [23]. However, when the decay to DM and X is allowed, the $\mathrm{LQ} \to c\mu/s\mu$ branching fraction is reduced and the limit on m_{LQ} becomes weaker. The branching fraction then also depends on m_{DM}, $\Delta_{X,DM}$, and B, where B is defined

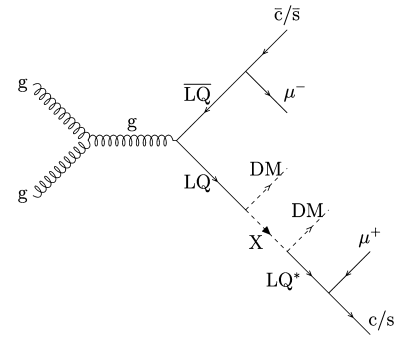

Fig. 1. An example Feynman diagram for the signal process considered in this study, where g is a gluon, LQ a leptoquark, DM a dark matter particle, an X a new Dirac fermion. The superscript "*" indicates an off-shell particle.

as $\mathcal{B}(\mathrm{LQ} \to c\mu/s\mu)$ in the limit of massless X and DM particles and is related to $y_{Q\ell}$ and y_D by the following formula:

$$B = \mathcal{B}(\mathrm{LQ} \to c\mu/s\mu)|_{m_{DM}=m_X=0} = \frac{y_{Q\ell}^2}{y_{Q\ell}^2 + 2y_D^2}. \quad (4)$$

Following Ref. [16], we set $y_D = 0.1$ and $\Delta_{X,DM} = 0.1$. We consider two values for B: 0.5 and 0.1. Recasting the results of Ref. [23] for the upper component of the LQ doublet, and taking $m_{DM} = 300$ GeV as a representative value, the lower limit on a second-generation LQ is reduced to 1340 GeV for $B = 0.5$ and to 960 GeV for $B = 0.1$.

In this analysis, the final state consists of a high-p_T muon and a high-p_T jet from the decay of the on-shell LQ, $\vec{p}_T^{miss}$ from the DM particles, and low-p_T SM objects from the decay of the off-shell LQ. Note that, in the analysis, we do not employ c quark tagging criteria but rather—to improve the signal event selection efficiency—utilize generic untagged jets as the c quark jet candidates. The existence of the signal process is inferred by a peak at the LQ mass m_{LQ}, in the invariant mass $m_{\mu j}$ distribution of the high-p_T muon and jet, in conjunction with significant $\vec{p}_T^{miss}$ from the DM. This peak at the LQ mass provides a striking experimental signature in the search for signal processes containing DM. In contrast, generic searches for DM, in which there are no new particles other than DM and intermediate mediator states, mostly rely on a mere enhancement in the tail of the $\vec{p}_T^{miss}$ distribution.

The principal SM backgrounds in this search arise from events with a W boson and jets (W+jets) or with a top quark-antiquark ($t\bar{t}$) pair: in both cases, the leptonic decay of a W boson can yield a high-p_T muon and neutrino, where the neutrino can lead to significant $\vec{p}_T^{miss}$. Events with single top quark or diboson (WW, WZ, and ZZ) production similarly can enter the background, although at a lower level. Other smaller sources of SM background arise from quantum chromodynamics (QCD) events, namely events with a multijet final state produced exclusively through the strong interaction, and from events with a Z boson and jets (Z+jets). A QCD event can enter the background if a muon and a neutrino are produced through the semileptonic decay of a quark, or if a jet is erroneously identified as a muon in conjunction with spurious $\vec{p}_T^{miss}$ arising from the mismeasurement of jet p_T. Events with Z+jets production can enter the background if one of the leptons in $Z \to \mu^+\mu^-$ decays is not reconstructed or lies outside the acceptance of the detector, leading to $\vec{p}_T^{miss}$, or if $\vec{p}_T^{miss}$ arises because of misreconstructed jet p_T.

2. The CMS detector and trigger

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of

3.8 T. Within the solenoid volume are a silicon pixel and strip inner tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, is given in Ref. [24].

Events of interest are selected using a two-tiered trigger system [25]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz. The second level, based on an array of microprocessors running a version of the full event reconstruction software optimized for fast processing, reduces the event rate to around 1 kHz before data storage. The set of triggers used for this analysis requires events to contain a muon with $p_T > 50$ GeV.

3. Event reconstruction and selection

Individual particles are reconstructed with the CMS particle-flow (PF) algorithm [26], which identifies them as charged hadrons, neutral hadrons, muons, electrons, or photons. Muon reconstruction is performed by matching a track segment reconstructed in the inner tracker with a track segment reconstructed in the muon detector and performing a global fit of the hits from the two track segments. The candidate muons are required to satisfy the tight selection criteria of Ref. [27], to pass within 2 mm of the primary event vertex in the direction along the beam axis and within 0.45 mm in the plane perpendicular to that axis, and to have $p_T > 60$ GeV and $|\eta| < 2.4$, where η is the pseudorapidity. Electrons are reconstructed by matching energy deposits in the electromagnetic calorimeter with track segments in the inner tracker [28] and are required to have $p_T > 15$ GeV and $|\eta| < 2.5$. Hadronically decaying τ leptons (τ_h) are reconstructed using the hadrons-plus-strips algorithm described in Ref. [29] and are required to have $p_T > 20$ GeV and $|\eta| < 2.3$. The electron and τ_h candidates are mainly used to veto Z+jets and diboson events, as described below, and are selected using loose [28,29] identification criteria.

The primary event vertex is defined to be the reconstructed interaction vertex with the largest value of summed physics-object p_T^2. The physics objects considered for this purpose are the jets found by clustering the charged-particle tracks assigned to the vertex, using the anti-k_T jet finding algorithm [30,31] with a distance parameter 0.4, and the associated missing transverse momentum, taken as the negative of the vector p_T sum of those jets. The transverse momentum imbalance $\vec{p}_T^{\,miss}$ in an event is calculated as the negative of the vector p_T sum of all PF candidates. Its magnitude is denoted p_T^{miss}. Events are required to have $p_T^{miss} > 100$ GeV.

To suppress the contributions of muons that arise from hadron decays, muon candidates are subjected to an isolation requirement. The scalar p_T sum of charged hadron, neutral hadron, and photon PF candidates within a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the muon direction, where ϕ is the azimuthal angle, is calculated. The expected contributions of neutral particles from additional pp interactions in the same or neighboring bunch crossings (pileup) are subtracted [32]. An isolation variable I is defined by dividing this sum by the muon p_T. The isolation requirement is $I < 0.15$. At least one isolated muon candidate is required to be present in the event.

The reconstruction of jets is performed by clustering PF candidates using the anti-k_T algorithm with a distance parameter of 0.4, excluding charged-particle tracks not associated with the primary vertex. The jet energies are corrected for the combined response function of the calorimeters [33] and to account for the expected contributions of neutral particles from pileup [32,34]. Jets are required to appear within $|\eta| < 2.4$. Bottom (b) quark jets are identified (b tagged) from this sample using the combined secondary vertex (CSVv2) algorithm at the tight working point [35], which yields a b quark jet identification efficiency of approximately 40%, and a misidentification probability of about 0.1% for gluon and light-flavored quark jets and of about 2% for charm quark jets. Jets tagged as b jets are required to have $p_T > 30$ GeV.

The leading (highest p_T) jet in an event is required to have $p_T > 100$ GeV and to be separated by $\Delta R > 0.5$ from the leading isolated muon candidate. The leading isolated muon and leading jet are then combined to form the LQ candidate. Studies with simulated signal events establish that, for the values of model parameters used in the present study, this matching identifies the correct combination over 98% of the time.

To suppress background from $t\bar{t}$ production, events are rejected if they contain a b-tagged jet, an electron candidate, or a τ_h candidate. The veto on events with a b-tagged jet reduces the background from events with a top quark by more than a factor of 2 while reducing the signal efficiency by only around 10%. The vetoes on electron and τ_h candidates also suppress the W+jets and Z+jets background. The W+jets background is further suppressed by requiring the transverse mass m_T [36] formed from the p_T vector of the leading muon and $\vec{p}_T^{\,miss}$ to exceed 100 GeV. The Z+jets background is further reduced by eliminating events with a loosely identified and isolated ($I < 0.25$) muon candidate if that muon candidate has $p_T > 10$ G a dimuon mass with the leading muon within 10 GeV of the Z boson mass

Background from QCD events mostly arises when the p_T of one of the highest p_T jets is underestimated or when a hadron in a jet undergoes a semileptonic decay, introducing $\vec{p}_T^{\,miss}$ that is aligned with that jet. To suppress this background, the angular difference $\Delta\phi$ between the leading jet and $\vec{p}_T^{\,miss}$, and between the leading muon and $\vec{p}_T^{\,miss}$, is required to exceed 0.5.

The above requirements are referred to as the "preselection" criteria, and form the basis for the definition of several control regions used to evaluate background, as described in Section 5. The final selection criteria, corresponding to the signal region, are the same as the preselection criteria except for a more stringent requirement on m_T, $m_T > 500$ GeV. This condition studies utilizing simulated signal and SM event samples. For $m_{LQ} > 800$ GeV, the signal efficiency for events satisfying the preselection criteria is around 73%, essentially independent of m_{LQ}. For the signal region criteria, the signal efficiency varies from 47 to 63% as m_{LQ} increases from 800 to 1500 GeV.

4. Event simulation

Monte Carlo (MC) simulation of signal and background processes is used to validate the analysis procedures, evaluate background, and determine the signal efficiency. Simulation of $t\bar{t}$ and single top quark events is performed at next-to-leading-order (NLO) accuracy with the POWHEG 2.0 [37–42] event generator. To describe W+jets and Z+jets production, the MADGRAPH5_aMC@NLO 2.2.2 [43,44] program at leading order (LO) is used. A K factor, calculated as described in Ref. [6], is applied as a function of boson p_T to account for next-to-NLO (NNLO) corrections. The statistical precision of our available MADGRAPH5_aMC@NLO W+jets sample is low for off-shell W boson masses above around 100 GeV. Therefore, to describe W+jets production for W boson masses above 100 GeV, we use the LO PYTHIA 8.212 [45] program with the CUETP8M1 tune [46], rather than MADGRAPH5_aMC@NLO, with a K factor to

account for NNLO corrections applied as a function of the W boson mass. This K factor is determined using the FEWZ 3.1 [47,48] program. Diboson production is simulated at NLO using either the POWHEG [49] or MADGRAPH5_AMC@NLO 2.2.2 generators.

Signal events are simulated at LO using MADGRAPH5_AMC@NLO 2.2.2. The signal samples are generated for LQ and DM masses in the ranges $800 \leqslant m_{\mathrm{LQ}} \leqslant 1500$ GeV in 100 GeV steps and $300 \leqslant m_{\mathrm{DM}} \leqslant 700$ GeV in 50 GeV steps, respectively, with cross sections normalized to NLO [50,51] accuracy.

For simulated samples at LO (NLO), the NNPDF3.0LO (NNPDF3.0NLO) [52] parton distribution functions (PDFs) are used. All samples are interfaced to PYTHIA 8.212 to describe parton showering and hadronization. Pileup interactions are modeled using simulated minimum bias event samples generated with PYTHIA, with the distribution of pp interactions per bunch crossing adjusted to reproduce the observed spectrum.

The response of the CMS detector is modeled, for both the signal and background samples, using the GEANT4 [53] suite of programs. Small differences between the data and simulation in the trigger, particle identification, and muon isolation efficiencies, and in the jet p_{T} resolution and $p_{\mathrm{T}}^{\mathrm{miss}}$, are accounted for through the application of scale factor corrections.

5. Background estimation

Background from $\mathrm{t\bar{t}}$ production is evaluated from simulation, with the events reweighted to reproduce the observed distribution of the top quark p_{T} [54,55]. The normalization is determined using a data-to-simulation scale factor derived from a $\mathrm{t\bar{t}}$-enhanced control sample. The control sample is defined using the preselection criteria of Section 3 except that events are required to contain at least one b-tagged jet. The purity of $\mathrm{t\bar{t}}$ events in the control sample is estimated to be 85%. The remaining 15% of the sample is composed primarily of events with W+jets and single top quark production. The scale factor is defined as the ratio of the number of events in the control sample from data, after subtraction of the non-$\mathrm{t\bar{t}}$ components, estimated from simulation, to the number in the corresponding simulated $\mathrm{t\bar{t}}$ control sample scaled to the same integrated luminosity. The scale factor is found to be $0.95 \pm 0.01\,(\mathrm{stat})$ for the 2016 data and $1.16 \pm 0.01\,(\mathrm{stat})$ for the 2017 data and is essentially independent of the m_{T} selection requirement. The difference in the scale factors between 2016 and 2017 arises from changes in the running conditions, the reconstruction procedures, and the tuning of the simulation programs. Fig. 2 (top) shows the distribution of $m_{\mu\mathrm{j}}$ in the combined 2016+2017 $\mathrm{t\bar{t}}$ control sample for data and simulation.

The systematic uncertainty in the scale factor is derived using an orthogonal $\mathrm{t\bar{t}}$-enhanced control sample, selected with the preselection criteria except that events must contain at least one electron candidate, in addition to the existing muon candidate, and the veto on the presence of a b-tagged jet is removed. The purity of $\mathrm{t\bar{t}}$ events in this control sample is around 90%, with the remainder of the events arising primarily from single top quark production. The scale factor obtained is $0.85 \pm 0.01\,(\mathrm{stat})$ for the 2016 data and $1.00 \pm 0.01\,(\mathrm{stat})$ for the 2017 data. On the basis of these results, a systematic uncertainty of 10% is assigned to both the 2016 and 2017 scale factors discussed in the previous paragraph.

The background from W+jets production is similarly estimated from simulation, with a correction to the normalization obtained from a W+jets-dominated control sample. The control sample is defined using the preselection criteria except with the additional requirement $50 < m_{\mathrm{T}} < 150$ GeV. The purity of W+jets events in this sample is about 80%. The main remaining contribution is from $\mathrm{t\bar{t}}$ production. A data-to-simulation normalization scale factor is

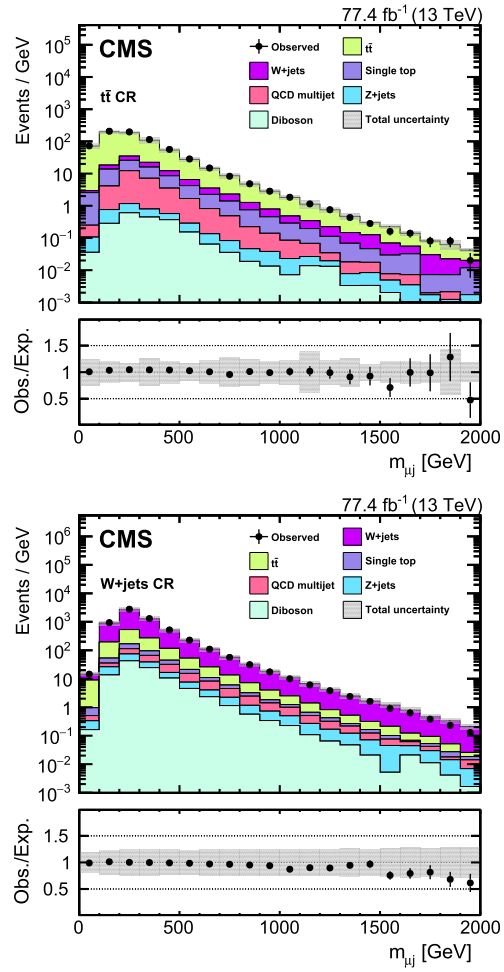

Fig. 2. The $m_{\mu\mathrm{j}}$ distributions in data and simulation for the (top) $\mathrm{t\bar{t}}$- and (bottom) W+jets-enriched control samples for the combined 2016 and 2017 data sets. The respective data-to-simulation normalization scale factors have been applied to the simulated distributions. The lower panels show the ratio of the observed to simulated results. The vertical error bars on the data points are statistical. The gray band shows the total uncertainty in the background prediction, including both statistical and systematic terms.

obtained by subtracting the non-W+jets contribution, estimated from simulation, from the control sample in data, and dividing the resulting number of events by the number of events in the simulated control region normalized to the same integrated luminosity. The $\mathrm{t\bar{t}}$ scale factor has been applied to the $\mathrm{t\bar{t}}$ background before subtracting it from the control sample in data. The scale factor is found to be $1.02 \pm 0.01\,(\mathrm{stat})$ and $1.11 \pm 0.01\,(\mathrm{stat})$ for the 2016 and 2017 data, respectively. The distribution of $m_{\mu\mathrm{j}}$ in the combined 2016+2017 W+jets control sample, for data and simulation, is shown in Fig. 2 (bottom).

To verify the stability of the scale factor in regions with larger m_{T}, corresponding to off-shell W boson production, the data-to-simulation scale factor has been remeasured in control regions with m_{T} in the ranges 150 to 200, 200 to 300 and 300 to 400 GeV. The measured scale factor is in agreement within 20% with the original scale factor. In a second test, we examine the level of agreement between the data and simulation for the normalization of the $m_{\mu\mathrm{j}}$ distribution in a $\mathrm{Z}(\rightarrow \mu^{+}\mu^{-})$+jets control sample with one of the two muons in each event removed to emulate a sample of W+jets events. This control sample is selected by requiring two oppositely charged isolated muons with $p_{\mathrm{T}} > 30$ GeV, with a dimuon invariant mass between 80 and 100 GeV, but with other-

wise similar selection criteria to those of the preselection. The Z boson candidate is boosted to its rest frame, the dimuon mass is scaled to the mass of the W boson, and the system is then boosted back to the original laboratory frame. One of the two muons is randomly removed to simulate a neutrino from W boson decay. The resulting missing momentum is added to the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ of the event and the value of m_{T} recalculated before applying the signal region selection criteria. The level of agreement in the resulting distribution of $m_{\mu\mathrm{j}}$ between data and simulation is also around 20%. On the basis of these two studies, a 20% uncertainty is assigned to the W+jets background prediction. In addition, relevant theoretical uncertainties are also taken into consideration in the shape and normalization of the W+jets background in the signal regions. This is discussed in Section 6.

The background from QCD processes is expected to be small. However, since the QCD background primarily arises as a consequence of jet mismeasurement, it is not well modeled by simulation. Thus, we evaluate the QCD background using a method based primarily on data. A control sample is defined using the signal region criteria of Section 3 except that muon candidates are required to fail the isolation condition. To estimate the QCD background in the signal region, the events in the control sample are weighted as a function of muon p_{T} by a muon misidentification probability, called the jet-to-muon misidentification rate, determined in a QCD-enriched event sample denoted the "low-$\Delta\phi$" sample. The low-$\Delta\phi$ sample is defined in the same manner as the signal region except the angle $\Delta\phi$ between $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and the leading jet is required to be $\Delta\phi < 0.5$ rather than $\Delta\phi > 0.5$ and we require $m_{\mathrm{T}} > 100$ GeV rather than $m_{\mathrm{T}} > 500$ GeV. The jet-to-muon misidentification rate is defined, from this sample, as the ratio of the number of events that satisfy the muon relative isolation criterion $I < 0.15$ to the number of events with no requirement on the isolation, after subtracting the non-QCD components, evaluated with simulation, from both the numerator and denominator. The purity of QCD events in the numerator is about 25%, while that in the denominator is approximately 70%. The jet-to-muon misidentification rate is parameterized in terms of the muon p_{T} using an analytical function and varies from 5% for muon $p_{\mathrm{T}} = 60$ GeV to 50% for $p_{\mathrm{T}} > 300$ GeV.

A 50% uncertainty is assigned to the QCD background prediction to account for the uncertainty in the jet-to-muon misidentification rate. This uncertainty primarily arises from the uncertainties in the normalization of the non-QCD processes subtracted from the numerator and denominator in calculating the misidentification rate. Other sources of uncertainty, such as the choice of the analytic function used to parameterize the jet-to-muon misidentification rate, or the uncertainties in the values of the fit parameters, are negligible in comparison.

The backgrounds from events with diboson, single top quark, and Z+jets production are estimated from simulation. An uncertainty of 15% is assigned to the diboson background prediction based on the level of agreement between data and simulation in a diboson-enhanced control sample selected by requiring events to contain three leptons (e or μ), two of which are consistent with arising from Z boson decay. Uncertainties of 15 and 10% are assigned to the single top quark and Z+jets backgrounds, respectively, based on the results of Refs. [56] and [57].

6. Systematic uncertainties

We evaluate systematic uncertainties that affect the normalization or shape of the $m_{\mu\mathrm{j}}$ spectrum, either in the signal or background predictions. Uncertainties specific to individual background components were presented in Section 5.

Table 1
Systematic uncertainties affecting the normalization of signal and background distributions. The PDF uncertainty affects the signal distribution only, while the other uncertainties affect both the signal and background distributions.

Item	Relative uncertainty (%)
Trigger efficiency	5.0
Muon identification efficiency	5.0
Electron identification (veto) efficiency	2.0
τ_{h} lepton identification (veto) efficiency	2.0
b jet identification (veto) efficiency	1.0
Pileup modeling	1.0
Integrated luminosity	2.5 (2016), 2.3 (2017)
PDF	3.0
Renormalization and factorization scales	1.0
$\mathrm{t\bar{t}}$ normalization	10
W+jets normalization	20

The uncertainty in the trigger efficiency is 5%. Those in the muon reconstruction and isolation efficiency [58], the electron reconstruction efficiency [58], and the τ_{h} reconstruction efficiency [59,60] are 5, 2, and 2%, respectively. The uncertainty related to the b-tagging misidentification is 1% [35]. The uncertainty in the pileup description in simulation is assessed by varying the total inelastic cross section by 4.6% [61], and is found to be 1%. Statistical uncertainties related to the limited number of events in the data control samples are accounted for as described in Ref. [62], while those related to the limited number of events in simulation are accounted for by allowing the content in each bin of the simulated distributions to vary within its statistical uncertainty. The uncertainty in the integrated luminosity is 2.5% [63] for the 2016 data and 2.3% [64] for the 2017 data. Uncertainties associated with the jet energy scale, the jet energy resolution, and $p_{\mathrm{T}}^{\mathrm{miss}}$ are also evaluated [65,66]. These uncertainties affect both the shape and normalization of the simulated signal and background distributions. Uncertainties related to the top quark p_{T} reweighting in simulated $\mathrm{t\bar{t}}$ events are evaluated by varying the reweighting parameters between zero and twice their nominal values [54,55]. Uncertainties related to the PDFs, evaluated for the signal acceptance, are determined following the PDF4LHC prescription [67] and are found to be 3%. Those related to the renormalization and factorization scales, evaluated for the signal yields and for the $\mathrm{t\bar{t}}$ and W+jets backgrounds, are estimated by varying each scale independently, and also coherently, by a factor of 2.0 and 0.5. The largest variations upward and downward in the results are used to define an uncertainty envelope. This uncertainty amounts to 1% for signal events, independent of the LQ mass. For the $\mathrm{t\bar{t}}$ and W+jets backgrounds, this uncertainty varies between 5 and 15% depending on m_{LQ} and thus accounts for a systematic uncertainty in the shape of the distribution. The uncertainty associated with the method chosen to determine the K factor for the W+jets background evaluation is estimated to be 5%.

Table 1 summarizes the systematic uncertainties affecting the normalization of distributions.

7. Results

The observed distribution of $m_{\mu\mathrm{j}}$ is presented in Fig. 3. The results are shown in comparison to the post-fit predictions for the SM background, where "post-fit" means that the constraints from the maximum likelihood fit are incorporated. For purposes of illustration, the predictions of two signal models with $m_{\mathrm{LQ}} = 1000$ GeV and $m_{\mathrm{DM}} = 400$ GeV are also shown: one with $B = 0.5$ and the other with $B = 0.1$. The difference is just an overall relative normalization of about 2 for the latter compared to the former. Numerical values are given in Table 2.

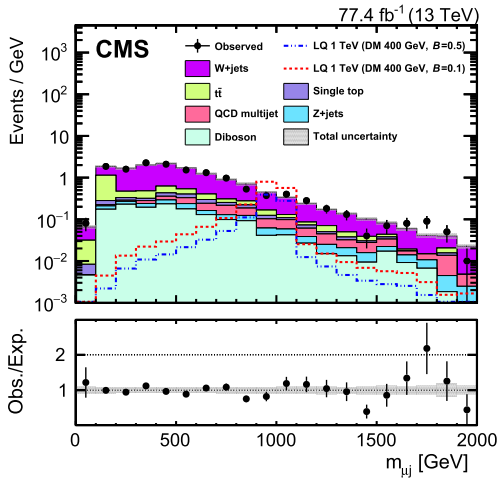

Fig. 3. The observed distribution of $m_{\mu j}$ in comparison to the post-fit SM background predictions for the combined 2016 and 2017 data "Post-fit" means that the constraints from the maximum likelihood fit are incorporated. The unstacked predictions for two signal models with $m_{LQ} = 1000$ GeV and $m_{DM} = 400$ GeV are also shown with $B = 0.5$ and the other with $B = 0.1$. The difference is just an overal relative normalization of about 2 for the latter compared to the former. The ratio of the observed results to the total SM prediction is shown in the lower panel. The vertical error bars on the data points are statistical. The gray shows the total uncertainty in the background prediction, including both statistical and systematic terms.

Table 2
Observed number of events, post-fit SM background predictions and post-fit uncertainties for the combined 2016 and 2017 data sets. "Electroweak" refers to the sum of expected events from the single top quark, Z boson, diboson background processes. The predictions for two signal models with $m_{LQ} = 1000$ GeV and $m_{DM} = 400$ GeV are also shown: one with $B = 0.5$ and the other with $B = 0.1$. The uncertainties represent the statistical and systematic terms added in quadrature.

Process	Events
W+jets	911 ± 55
$t\bar{t}$	185 ± 25
Electroweak	241 ± 26
QCD	63 ± 26
Total SM background	1401 ± 40
Signal; $B = 0.5$, $m_{LQ} = 1000$ GeV, $m_{DM} = 400$ GeV	96 ± 8
Signal; $B = 0.1$, $m_{LQ} = 1000$ GeV, $m_{DM} = 400$ GeV	195 ± 16
Observed	1390

The data are found to be consistent with the SM predictions within the uncertainties. There is a small excess of events above the SM prediction in the $m_{\mu j}$ region between 1600 and 1900 GeV, consistent with a statistical fluctuation. This excess corresponds to a statistical significance of around 1.5 standard deviations. Thus, we do not obtain evidence for DM or LQ production.

A binned maximum likelihood fit is applied to the $m_{\mu j}$ distribution in the signal region. The fitted parameters are the yields of the individual background components listed in Table 2, the signal yield, and various nuisance parameters. The nuisance parameters are introduced to treat systematic uncertainties. Log-normal probability distributions are used for nuisance parameters that affect the normalizations of the signal and background yields. Gaussian probability distributions are used for nuisance parameters that affect the shape of the $m_{\mu j}$ distribution. All normalization uncertainties are taken to be fully correlated across bins except those that are statistical in origin, which are assumed to be uncorrelated. The overall postfit uncertainty in the dominant W+jets background is substantially smaller than the prefit value shown in Table 1 because the normalization and shape of this background is highly constrained by the lower side of the mass distribution.

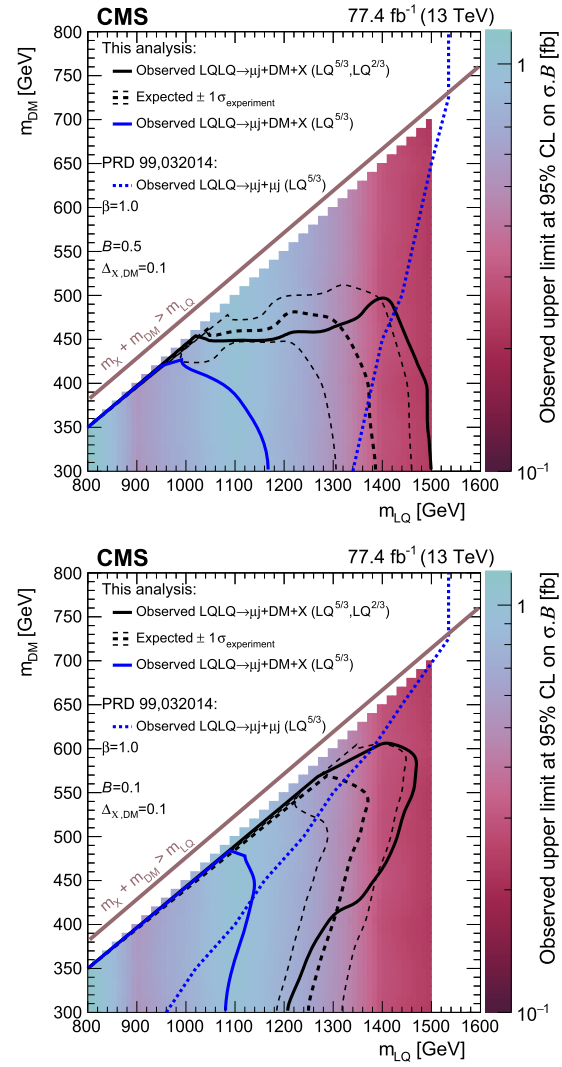

Fig. 4. Observed 95% CL upper limits on the product of cross section and branching fraction for the signal model of Fig. 1 assuming $B = \mathcal{B}(\mathrm{LQ} \to c\mu/s\mu)|_{m_{DM}=m_X=0}$ to be (top) 0.5 or (bottom) 0.1. The solid and dashed black curves show the observed and expected 95% CL exclusion curves, taking into account both upper and lower components of the LQ doublet. The solid blue curve shows the observed exclusion limit for the upper component of the LQ doublet, i.e. to a muon and a c quark. The dotted blue curve shows the corresponding observed limits from the recast of the results from a search for pair produced second-generation LQs [23].

Upper limits at 95% confidence level (CL) are determined on the product of the signal production cross section and branching fraction. These limits are calculated using a modified frequentist approach with the CL_s criterion [68,69] and an asymptotic approximation for the test statistic [70,71]. The limits are determined as a function of m_{LQ} and m_{DM}.

Fig. 4 (top) presents the results for $B = 0.5$. The region to the right and below the diagonal line is where LQ decay to DM and X is allowed. The solid and dashed black curves show the observed and expected exclusion limits, respectively, taking into account contributions from both upper and lower components of the LQ doublet. Combinations of m_{LQ} and m_{DM} to the left and below the solid curve are excluded. It can be seen that the signal scenario of Fig. 1 is excluded for values of m_{DM} up to 500 GeV for $m_{LQ} \approx 1400$ GeV and up to 300 GeV for $m_{LQ} \approx 1500$ GeV.

This is the first test of the co-annihilation process proposed in [16], thus it is not possible to make a direct comparison with other results. To give an indication of the extent to which our re-

sults explore untested regions of the m_{LQ}-m_{DM} parameter space we have therefore performed a recast of the results from a search for pair produced second-generation LQs, each decaying to a muon and a c quark [23]. The recast is performed in two steps. In the first step, the change in the branching fraction of the LQ to a lepton and a quark is calculated once the decay of the LQ to DM and X is allowed. The change depends on the parameters of the model including $\Delta_{X,DM}$, B, LQ and DM mass [16]. The altered branching fraction is then used to find the exclusion contour in the plane of m_{LQ} and m_{DM}. The resultant limit contour is shown as the dotted blue curve. This limit contour may be compared with the solid blue curve, which shows the observed exclusion limit that would be obtained from the present analysis if only the upper component of the LQ doublet, decaying to a muon and a c quark, contributed to the potential signal.

Fig. 4 (bottom) shows results obtained assuming the somewhat smaller value of 0.1 for B. In this case, the upper limit of excluded DM mass is extended significantly, reaching a maximum of ≈600 GeV for $m_{LQ} \approx 1400$ GeV.

8. Summary

A search has been performed for dark matter in events containing a muon, a jet, and significant missing transverse momentum. The study is conducted using proton-proton collision data at $\sqrt{s} = 13$ TeV recorded with the CMS detector, corresponding to an integrated luminosity of 77.4 fb^{-1}. It is assumed that dark matter is produced through the production of a leptoquark pair, with one leptoquark decaying to a muon and a jet, and the other to dark matter and low-p_T standard model particles. The analysis is performed by searching for a peak in the leptoquark candidate invariant mass $m_{\mu j}$ distribution formed from the highest p_T muon and jet in an event, with the requirement of significant missing transverse momentum, as is expected from the presence of dark matter. The observation of such a peak in this novel search would provide strong evidence for the existence of both dark matter particles and leptoquarks. The data are observed to agree with the standard model background predictions within the uncertainties. Upper limits on the product of the cross section and branching fraction are obtained at 95% confidence level as a function of the leptoquark and dark matter particle masses. For the first benchmark scenario considered, dark matter masses up to 500 GeV are excluded for leptoquark masses $m_{LQ} \approx 1400$ GeV, and up to 300 GeV for $m_{LQ} \approx 1500$ GeV. For the second benchmark scenario, dark matter masses up to 600 GeV are excluded for $m_{LQ} \approx 1400$ GeV.

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