Search for Pair Production of Second-Generation Scalar Leptoquarks in pp Collisions at $\sqrt{s} = 7$ TeV

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(Received 17 December 2010; published 17 May 2011)

A search for pair production of second-generation scalar leptoquarks in the final state with two muons and two jets is performed using proton-proton collision data at $\sqrt{s} = 7$ TeV collected by the CMS detector at the LHC. The data sample used corresponds to an integrated luminosity of 34 pb^{-1}. The number of observed events is in good agreement with the predictions from the standard model processes. An upper limit is set on the second-generation leptoquark cross section times β^2 as a function of the leptoquark mass, and leptoquarks with masses below 394 GeV are excluded at a 95% confidence level for $\beta = 1$, where β is the leptoquark branching fraction into a muon and a quark. These limits are the most stringent to date.

DOI: 10.1103/PhysRevLett.106.201803 PACS numbers: 14.80.Sv, 12.60.−i, 13.85.Rm

Several extensions of the standard model [1–5] predict the existence of leptoquarks (LQ), hypothetical particles that carry both lepton and baryon numbers and couple to both leptons and quarks. Leptoquarks are fractionally charged and can be either scalar or vector particles. In order to satisfy constraints from flavour-changing neutral currents and rare pion and kaon decays [6,7], leptoquarks are restricted to couple to a single lepton-quark generation.

In proton-proton collisions at the CERN Large Hadron Collider (LHC) the dominant mechanisms for pair production of scalar leptoquarks are gluon-gluon fusion and $q\bar{q}$-annihilation. The cross section depends on the strong coupling constant and the LQ mass and has been calculated at Next-to-Leading-Order (NLO) [8]; the dependence on the Yukawa coupling λ is negligible [8]. Leptoquarks decay to a quark and a charged lepton of the same generation with unknown branching fraction β and to a quark and a neutrino with branching fraction $(1 - \beta)$. In this analysis, we consider the decay of a second-generation leptoquark to a muon and a quark.

Several experiments have searched for leptoquarks, but so far no evidence has been observed. A review of LQ phenomenology and searches can be found in [9]. The most recent limits from the D0 experiment at the Fermilab Tevatron collider exclude second-generation scalar leptoquarks with masses below 316 GeV for $\beta = 1$, based on proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV [10].

This Letter describes a search for pair production of second-generation scalar leptoquarks with the CMS experiment using LHC proton-proton collisions at $\sqrt{s} = 7$ TeV. The data sample used corresponds to an integrated luminosity of 34.0 ± 3.7 pb^{-1}.

The CMS detector, described in detail elsewhere [11], uses a cylindrical coordinate system with the z axis along the counterclockwise beam direction The angles θ and ϕ are the polar and azimuthal angles, respectively. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is measured with respect to the $+z$-axis. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass-scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The inner tracking system consists of a silicon pixel and strip tracker, providing the required granularity and precision for the reconstruction of vertices of charged particles having pseudorapidities $|\eta| < 2.5$. The ECAL and HCAL are used to measure the energies of photons, electrons, and hadrons within a region of $|\eta| < 3.0$. The three muon systems surrounding the solenoid cover a region $|\eta| < 2.4$ and are composed of drift tubes in the barrel region ($|\eta| < 1.2$), of cathode strip chambers in the endcaps ($0.9 < |\eta| < 2.4$), and of resistive plate chambers in both the barrel region and the endcaps ($|\eta| < 1.6$). Events are recorded based on a first-level trigger decision coming from either the calorimeter or muon systems. The final trigger decision is based on the information from all subsystems, which is passed on to the high level trigger (HLT), consisting of a farm of computers running a version of the reconstruction software optimized for fast processing.

The signature of the decay of pair-produced second-generation leptoquarks studied here consists of two muons and two jets with high transverse momentum (p_T). Events are selected by a single muon trigger without isolation

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requirements and with lower p_T thresholds dependent upon the instantaneous luminosity. The combined HLT and first-level trigger efficiency is approximately 92%.

The Monte Carlo (MC) signal events are generated in the LQ mass range 250–500 GeV, using the PYTHIA [12] generator (version 6.422) and tune D6T [13,14]. The main background processes that can mimic the signature of the LQ signal are $Z/\gamma^* +$ jets, $t\bar{t}$, VV (WW, ZZ, WZ), $W +$ jets, and multijet events. The $t\bar{t}$, VV, and muon-enriched multijets events are generated with MADGRAPH [15,16]; $Z/\gamma^* +$ jets and $W +$ jets events are generated with ALPGEN [17]. In MADGRAPH and ALPGEN samples, parton showering and hadronization is performed with PYTHIA.

Muons are reconstructed as tracks in the muon system that are matched to the tracks reconstructed in the inner tracking system. Muons are required to have $p_T >$ 30 GeV, $|\eta| < 2.4$. The muon relative isolation parameter is defined as the scalar sum of the p_T of all tracks in the tracker and the transverse energies of hits in the ECAL and HCAL in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon track, excluding the contribution from the muon itself, divided by the muon p_T. Muons are required to have a relative isolation parameter less than 0.05. $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle differences between the muon track and other reconstructed tracks or hits in the calorimeter. To have a precise measurement of the transverse impact parameter of the muon relative to the beam-spot position, only muons with tracks containing more than 10 hits in the silicon tracker are considered. To reject muons from cosmic rays, the transverse impact parameter is required to be less than 2 mm. In addition, the two muon candidates are required to be separated from each other by at least $\Delta R = 0.3$ and at least one muon must be in the pseudorapidity region $|\eta| < 2.1$. The efficiency of selecting dimuon events is 61%–70% for the LQ mass range of 200–500 GeV.

Jets are reconstructed using the anti-k_T [18] algorithm with a distance parameter $R = 0.5$ and are required to have $p_T > 30$ GeV and $|\eta| < 3.0$. Jet-energy-scale corrections derived from MC simulated events are applied to establish a relative uniform response in η and an absolute uniform response in p_T. A residual jet energy correction is derived from data by looking at the balance in p_T in dijet events, and it is applied to jets in data.

Additional selection requirements are placed on two variables, which are effective at discriminating the LQ signal from the major sources of background. The first is the dimuon invariant mass, $M_{\mu\mu}$. The second variable, S_T, is defined as the sum of the magnitudes of the p_T of the two highest p_T muons and the two highest p_T jets. The two muons in the signal events come from the decays of two high-mass particles, and they tend to form a large invariant mass. Thus, events are selected if $M_{\mu\mu} >$ 115 GeV. This helps to reduce the contribution from $Z/\gamma^* +$ jets processes, which is one of the largest backgrounds. In addition, the LQ pair is expected to have a large S_T. The lower threshold on S_T is optimized for different LQ mass hypotheses by using a Bayesian approach [19,20] to minimize the expected upper limit on the LQ cross section in the absence of an observed signal. The S_T cut helps to further reduce background sources, most noticeably $t\bar{t}$. The optimal S_T threshold values for each mass hypothesis are given in Table I. While the LQ signal is expected to peak in the mass distribution of the μ-jet pairs, we find that the S_T variable gives sufficient power of discrimination in the range of LQ masses considered. The μ-jet mass distribution would nevertheless be important to establish the signal in case an excess is observed.

TABLE I. The data event yields in 34.0 pb^{-1} for different leptoquark mass hypotheses, together with the optimized S_T threshold values (in GeV) for each mass, background predictions, number of expected LQ signal events (S), and signal selection efficiency times acceptance (ϵ_S). M_{LQ} and S_T values are listed in GeV. The $Z/\gamma^* \to \mu\mu +$ jets and $t\bar{t}$ contributions are rescaled by the normalization factors determined from data. Other backgrounds correspond to VV, $W +$ jets, and multijet processes. Uncertainties are from MC statistics.

M_{LQ} (S_T Cut) [GeV]	Signal samples (MC) Selected Events	Acceptance × Efficiency	Standard model background samples (MC) Selected events in $t\bar{t}$ + jets	Z/γ^* + jets	Others	All	Events in data	Obs./Exp. 95% C.L. u.l. on σ [pb]
200 ($S_T > 310$)	160 ± 20	0.388 ± 0.003	4.6 ± 0.1	4.08 ± 0.07	0.1 ± 0.01	8.8 ± 0.2	5	0.438/0.695
225 ($S_T > 350$)	89 ± 9	0.421 ± 0.003	3.1 ± 0.1	2.99 ± 0.05	0.07 ± 0.01	6.2 ± 0.1	3	0.339/0.547
250 ($S_T > 400$)	51 ± 5	0.437 ± 0.003	1.88 ± 0.09	1.92 ± 0.04	0.051 ± 0.009	3.9 ± 0.1	3	0.366/0.436
280 ($S_T > 440$)	28 ± 3	0.467 ± 0.003	1.15 ± 0.07	1.53 ± 0.03	0.038 ± 0.008	2.72 ± 0.08	3	0.371/0.361
300 ($S_T > 440$)	21 ± 2	0.518 ± 0.004	1.15 ± 0.07	1.53 ± 0.03	0.038 ± 0.008	2.72 ± 0.08	3	0.335/0.326
320 ($S_T > 490$)	14 ± 1	0.509 ± 0.004	0.64 ± 0.05	1.12 ± 0.02	0.019 ± 0.005	1.78 ± 0.06	2	0.300/0.292
340 ($S_T > 530$)	9 ± 1	0.508 ± 0.003	0.4 ± 0.04	0.79 ± 0.01	0.01 ± 0.004	1.20 ± 0.04	1	0.245/0.264
400 ($S_T > 560$)	4.0 ± 0.4	0.578 ± 0.004	0.31 ± 0.04	0.67 ± 0.01	0.01 ± 0.004	0.99 ± 0.04	1	0.219/0.222
450 ($S_T > 620$)	1.9 ± 0.2	0.600 ± 0.004	0.19 ± 0.03	0.49 ± 0.01	0.006 ± 0.003	0.69 ± 0.03	0	0.153/0.199
500 ($S_T > 700$)	0.9 ± 0.1	0.602 ± 0.004	0.09 ± 0.02	0.277 ± 0.006	0.003 ± 0.002	0.37 ± 0.02	0	0.152/0.180

The contribution from $t\bar{t}$ is estimated with the MC sample, using normalization and uncertainties determined from data [21]. The contribution from W + jets is negligible once the full event selection is applied. The small contribution from VV is estimated from MC calculations. The multijet background is found to be negligible using a control data sample of same-sign dimuon events. The background from Z/γ^* + jets is determined by comparing Z/γ^* + jets events from data and MC samples in two different regions: at the Z boson peak, $80 < M_{\mu\mu} < 100$ GeV, and in the high-mass region, $M_{\mu\mu} > 115$ GeV. In the low-mass region, the ratio of data to MC events (R_L) is determined to be $R_L = 1.28 \pm 0.14$ after selecting two muons and two jets with $p_T > 30$ GeV, and a preliminary requirement of $S_T > 250$ GeV. This rescaling factor is applied to the number of Z/γ^* + jets MC events in the high-mass region after the full selection.

Reasonable agreement between data and MC predictions is observed at all selection levels. The dimuon invariant mass is shown in Fig. 1 (top) after the initial selection of muons and jets with $p_T > 30$ GeV and a preliminary requirement of $S_T > 250$ GeV. The $M_{\mu\mu}$ distribution in data is consistent with the expected SM background prediction. The S_T distribution is also shown in Fig. 1 (bottom) after the initial selection of muons and jets with $p_T > 30$ GeV and the additional requirement of $M_{\mu\mu} > 115$ GeV.

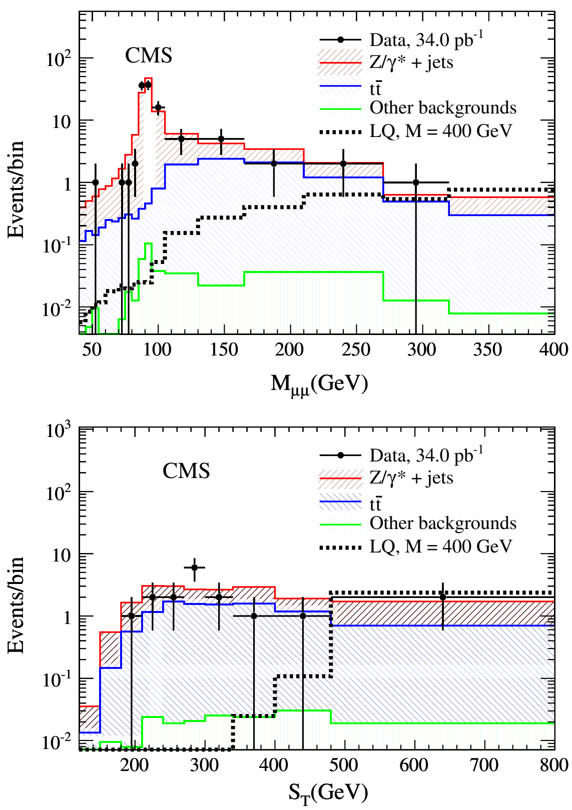

FIG. 1 (color online). The distribution of $M_{\mu\mu}$ (top) after requiring at least two muons and at least two jets with $p_T > 30$ GeV and $S_T > 250$ GeV, and the distribution of S_T (bottom) after requiring at least two muons and at least two jets with $p_T > 30$ GeV and $M_{\mu\mu} > 115$ GeV. The $Z/\gamma^* \rightarrow \mu\mu$ + jets and $t\bar{t}$ contributions are rescaled by the normalization factors determined from data. Other backgrounds correspond to VV, W + jets, and multijet processes. Uncertainties are statistical.

The event yields from data, expected LQ signal (for several mass hypotheses), signal selection efficiency times acceptance, and expected standard model backgrounds are summarized in Table I.

Several sources of systematic uncertainties are considered in this analysis. The uncertainty on the integrated luminosity is taken as 11% [22]. A 5% systematic uncertainty is assigned to the jet-energy scale (JES) [23] of each jet. A smaller, ~1% systematic uncertainty comes from the muon momentum scale. The 300 GeV LQ signal efficiency changes by 2% and 1% due to JES and muon momentum scale uncertainties, respectively. The effect of the muon momentum scale uncertainty on the total background is estimated to be <0.5%. The JES contributes 2% to the estimate of the Z/γ^* + jets background described above and 15% to the estimate of the VV background from MC. The statistical uncertainty on the value of R_L after a preselection requirement ($S_T > 250$ GeV), 11%, is used as an uncertainty on the estimated Z/γ^* + jets background. Additionally, an uncertainty of 16% is assigned on the shape of the Z/γ^* + jets background by comparing the number of Z/γ^* + jets events surviving final S_T cut selections in MADGRAPH samples with factorization orrenormalization scales and matching thresholds varied by a factor of 2. A 41% systematic uncertainty is taken from the CMS measurement of the $t\bar{t}$ production cross section [21] and assigned to the estimate of the $t\bar{t}$ background; it includes the effect of JES on the estimate of the $t\bar{t}$ background. The effect of jet energy and muon momentum resolution on expected signal and backgrounds is found to be negligible. A 5% systematic uncertainty per muon is assigned due to differences in reconstruction, identification, trigger, and isolation efficiencies between data and MC [24], resulting in a 10% uncertainty on the efficiency of selecting events with two muons both for the signal and background processes. A theoretical uncertainty on the LQ signal production cross sections due to the choice of renormalization or factorization scales has been calculated by varying the scales between half and twice the LQ mass, and is found to be 14–15% for LQ masses between 200 and 500 GeV. The effect on the signal acceptance of additional jets generated via initial and final state radiation is found to be less than 1%. The 90% C.L. PDF uncertainties on LQ cross section have been obtained using the CTEQ6.6 [25] PDF error set following a standard prescription and have been found to vary from 8 to 22% for leptoquarks in the mass range of 200–500 GeV [8]. The effect of PDF uncertainties is less than 0.5% on signal acceptance. The PDF uncertainties are not considered for background sources with uncertainties determined from data. The systematic uncertainties, their magnitude, and the relative impact on the number of signal and background events are summarized in Table II.

One candidate event survives the full selection criteria corresponding to a leptoquark mass hypothesis of 400 GeV, and no candidates survive for criteria corresponding to masses greater than 450 GeV. An upper limit on the LQ cross section is set using a Bayesian method [19,20] with a flat signal prior. A log-normal probability density function is used to integrate over the systematic uncertainties. Using Poisson statistics, a 95% confidence level (C.L.) upper limit is obtained on $\sigma \times \beta^2$. This is shown in Fig. 2 together with the NLO predictions for the scalar LQ pair production cross section. The 95% C.L. exclusion on β as a function of LQ mass is also shown in Fig. 2. The systematic uncertainties reported in Table II are included in the calculation as nuisance parameters. With the assumption that $\beta = 1$, second-generation scalar leptoquarks with masses less than 394 GeV are excluded at 95% C.L., 78 GeV higher than the limit set at the D0 Experiment at the Tevatron [10]. This is in agreement with the expected limit of 394 GeV. The corresponding observed limit on cross section is 0.223 pb. If the lower edge of the theoretical $\sigma \times \beta^2$ curve is used, the observed (expected) limit on LQ mass is 379 (377) GeV and the observed limit on cross section is 0.224 pb.

In summary, a search for pair production of second-generation scalar leptoquarks decaying to two muons and two jets has been performed using 7 TeV pp collision data corresponding to an integrated luminosity of 34.0 pb^{-1}. The number of observed candidate events agrees well with the number of expected standard model background events. A Bayesian approach that includes the treatment of systematic uncertainties as nuisance parameters is used to set limits on the LQ cross section times β^2 as a function of LQ mass. At 95% C.L., the pair production of second-generation scalar leptoquarks with masses below 394 GeV is excluded for $\beta = 1$, where β is the leptoquark branching fraction into a muon and a quark. This is the most stringent limit to date on the existence of second-generation scalar leptoquarks.

We extend our thanks to Michael Krämer for providing the tools for calculation of the leptoquark theoretical cross section and PDF uncertainty. We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU

TABLE II. Systematic uncertainties and their effects on number of signal and background events.

Systematic uncertainty	Magnitude	Effect on signal	Effect on background
JES	5%	2%	···
JES & Data Backgr. Est.	···	···	26%
Muon Momentum Scale	1%	1%	<0.5%
Muon Pair Reco/ID/Iso	10%	10%	<0.05%
Integrated Luminosity	11%	11%	···
Total		15%	26%

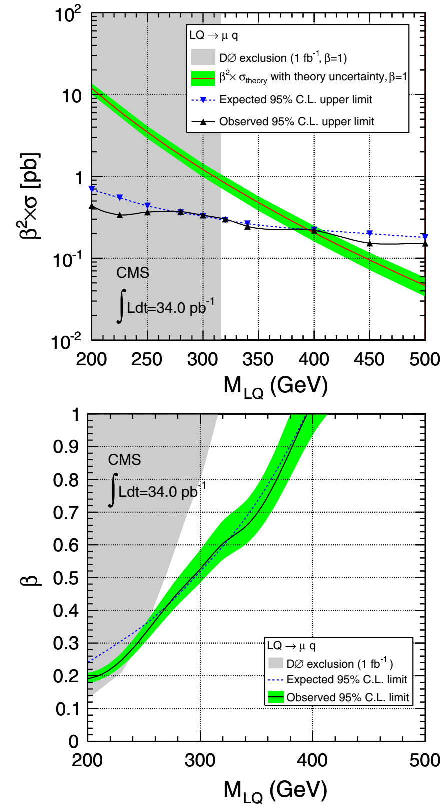

FIG. 2 (color online). (Top) The expected and observed 95% C.L. upper limit on the scalar leptoquark pair production cross section multiplied by β^2 as a function of the LQ mass, together with the NLO theoretical cross section curve. The shaded band on the theoretical values includes PDF uncertainties and the error on the leptoquark production cross section due to renormalization and factorization scale variation by a factor of 2. The shaded region is excluded by the current D0 limits [10]. (Bottom) The minimum β for 95% C.L. exclusion of the leptoquark hypothesis as a function of leptoquark mass. The observed limit and corresponding uncertainty band is obtained by considering the observed upper limit and theoretical branching ratio and its uncertainty in the top figure. Note: The shaded area excluded by the D0 experiment was determined with combined information from the decay channel with two muons and two jets and the decay channel with one muon, missing transverse energy, and two jets.

(Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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