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

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevLett.106.201803">http://dx.doi.org/10.1103/PhysRevLett.106.201803</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Wed Dec 12 19:59:14 EST 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/67252">http://hdl.handle.net/1721.1/67252</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td>ntenine:</td>
</tr>
</tbody>
</table>
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 leptoquark mass, and leptoquarks with masses below 394 GeV are excluded at a 95% confidence level for $\beta = 1$, where $\beta$ is the leptoquark branching fraction into a muon and a quark. These limits are the most stringent to date.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
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 $\eta$ 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 $\mu$-jet pairs, we find that the $S_T$ variable gives sufficient power of discrimination in the range of LQ masses considered. The $\mu$-jet mass distribution would nevertheless be important to establish the signal in case an excess is observed.

![Table 1](image-url)

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 ($\epsilon_S$). $M_{\mu\mu}$ and $S_T$ values are listed in 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 from MC statistics.
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 $Z/\gamma^{*} + jets$ is determined by comparing $Z/\gamma^{*} + jets$ 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 $Z/\gamma^{*} + jets$ 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.

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 $Z/\gamma^{*} + jets$ 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 $Z/\gamma^{*} + jets$ background. Additionally, an uncertainty of 16% is assigned on the shape of the $Z/\gamma^{*} + jets$ background by comparing the number of $Z/\gamma^{*} + jets$ 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.

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.
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 $\beta$ 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 $\beta^2$ 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 $\beta$ 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>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Magnitude</th>
<th>Effect on signal</th>
<th>Effect on background</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>5%</td>
<td>2%</td>
<td>···</td>
</tr>
<tr>
<td>JES &amp; Data Backgr. Est.</td>
<td>···</td>
<td>···</td>
<td>26%</td>
</tr>
<tr>
<td>Muon Momentum Scale</td>
<td>1%</td>
<td>1%</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Muon Pair Reco/ID/Iso</td>
<td>10%</td>
<td>10%</td>
<td>&lt;0.05%</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>11%</td>
<td>11%</td>
<td>···</td>
</tr>
<tr>
<td>Total</td>
<td>15%</td>
<td>26%</td>
<td></td>
</tr>
</tbody>
</table>

(CMS Collaboration)

PRL 106, 201803 (2011) PHYSICAL REVIEW LETTERS week ending 20 MAY 2011

1Yerevan Physics Institute, Yerevan, Armenia
2Institut für Hochenergiephysik der ÖAW, Wien, Austria
3National Centre for Particle and High Energy Physics, Minsk, Belarus
4Universiteit Antwerpen, Antwerpen, Belgium
5Vrije Universiteit Brussel, Brussel, Belgium
6Université Libre de Bruxelles, Bruxelles, Belgium
7Ghent University, Ghent, Belgium
8Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9Université de Mons, Mons, Belgium
10Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
11Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
12Instituto de Física Teórica, Universidade Estadual Paulista, Sao Paulo, Brazil
13Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
14University of Sofia, Sofia, Bulgaria
15Institute of High Energy Physics, Beijing, China
16State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
17Universidad de Bogotá, Bogotá, Colombia
18Technical University of Split, Split, Croatia
19University of Split, Split, Croatia
20Institute Rudjer Boskovic, Zagreb, Croatia
21University of Cyprus, Nicosia, Cyprus
22Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
23National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
24Department of Physics, University of Helsinki, Helsinki, Finland
25Helsinki Institute of Physics, Helsinki, Finland
26Lappeenranta University of Technology, Lappeenranta, Finland
27Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
28DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
29Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
30Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
31Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
32Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
33E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia
34Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

201803-11
Florida State University, Tallahassee, USA
Florida Institute of Technology, Melbourne, USA
University of Illinois at Chicago (UIC), Chicago, USA
The University of Iowa, Iowa City, USA
Johns Hopkins University, Baltimore, USA
The University of Kansas, Lawrence, USA
Kansas State University, Manhattan, USA
Lawrence Livermore National Laboratory, Livermore, USA
University of Maryland, College Park, USA
Massachusetts Institute of Technology, Cambridge, USA
University of Minnesota, Minneapolis, USA
University of Mississippi, University, USA
University of Nebraska-Lincoln, Lincoln, USA
State University of New York at Buffalo, Buffalo, USA
Northeastern University, Boston, USA
Northwestern University, Evanston, USA
University of Notre Dame, Notre Dame, USA
The Ohio State University, Columbus, USA
Princeton University, Princeton, USA
University of Puerto Rico, Mayaguez, USA
Purdue University, West Lafayette, USA
Purdue University Calumet, Hammond, USA
Rice University, Houston, USA
University of Rochester, Rochester, USA
The Rockefeller University, New York, USA
Rutgers, the State University of New Jersey, Piscataway, USA
University of Tennessee, Knoxville, USA
Texas A&M University, College Station, USA
Texas Tech University, Lubbock, USA
Vanderbilt University, Nashville, USA
University of Virginia, Charlottesville, USA
Wayne State University, Detroit, USA
University of Wisconsin, Madison, USA

aDeceased.
bAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
cAlso at Universidade Federal do ABC, Santo Andre, Brazil.
dAlso at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
eAlso at Suez Canal University, Suez, Egypt.
fAlso at Fayoum University, El-Fayoum, Egypt.
gAlso at Soltan Institute for Nuclear Studies, Warsaw, Poland.
hAlso at Massachusetts Institute of Technology, Cambridge, USA.
iAlso at Universite de Haute-Alsace, Mulhouse, France.
jAlso at Brandenburg University of Technology, Cottbus, Germany.
kAlso at Moscow State University, Moscow, Russia.
lAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
mAlso at Eötvös Loránd University, Budapest, Hungary.

Also at Tata Institute of Fundamental Research - HECR, Mumbai, India.
Also at University of Visva-Bharati, Santiniketan, India.
Also at Facoltà Ingegneria Università di Roma “La Sapienza”, Roma, Italy.
Also at Università della Basilicata, Potenza, Italy.
Also at California Institute of Technology, Pasadena, USA.
Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
Also at University of California, Los Angeles, Los Angeles, USA.
Also at University of Florida, Gainesville, USA.
Also at Université de Genève, Geneva, Switzerland.
Also at Scuola Normale e Sezione dell’ INFN, Pisa, Italy.
Also at INFN Sezione di Roma, Università di Roma “La Sapienza”, Roma, Italy.
\[ \text{Also at University of Athens, Athens, Greece.} \]
\[ \text{Also at The University of Kansas, Lawrence, USA.} \]
\[ \text{Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.} \]
\[ \text{Also at Paul Scherrer Institut, Villigen, Switzerland.} \]
\[ \text{Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.} \]
\[ \text{Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.} \]
\[ \text{Also at Paul Scherrer Institut, Villigen, Switzerland.} \]
\[ \text{Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.} \]
\[ \text{Also at Gaziosmanpasa University, Tokat, Turkey.} \]
\[ \text{Also at Adiyaman University, Adiyaman, Turkey.} \]
\[ \text{Also at Mersin University, Mersin, Turkey.} \]
\[ \text{Also at Izmir Institute of Technology, Izmir, Turkey.} \]
\[ \text{Also at Kafkas University, Kars, Turkey.} \]
\[ \text{Also at Suleyman Demirel University, Isparta, Turkey.} \]
\[ \text{Also at Ege University, Izmir, Turkey.} \]
\[ \text{Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.} \]
\[ \text{Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.} \]
\[ \text{Also at INFN Sezione di Perugia, Università di Perugia, Perugia, Italy.} \]
\[ \text{Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.} \]
\[ \text{Also at Institute for Nuclear Research, Moscow, Russia.} \]
\[ \text{Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.} \]