Leptoquark Pair Production Cross Sections at Hadron Colliders

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Abstract
A compilation is given of the pair production cross sections for scalar and vector leptoquarks in the kinematic range of the hadron colliders Tevatron and LHC.
1 Introduction

In many extensions of the Standard Model leptoquark states do emerge. The couplings of the leptoquarks to the gauge sector are predicted due to the gauge symmetries, up to eventual anomalous couplings in the case of vector leptoquarks, whereas the fermionic couplings $\lambda$ are free parameters of the models. Model-independent searches do therefore refer to the pair-production processes [2], which are widely dominated by the gauge-couplings of leptoquarks. Future searches may be carried out both at the forthcoming hadron and linear $e^+e^-$ colliders. The production cross sections are largest at hadron colliders in general. Specific channels, on the other hand, may be identified unambiguously only in $e^+e^-$ annihilation [3, 4].

In this note a compilation of the hadronic pair-production cross sections for leptoquarks at hadron colliders is provided for the kinematic range of Tevatron and LHC. The scattering cross sections were calculated by the code LQPAIR 1.00 [5] both for scalar and vector leptoquarks. In the latter case typical choices for the anomalous couplings $\kappa_G$ and $\lambda_G$ to the gluon are considered. For scalar leptoquarks also the $O(\alpha_s)$-corrections [6] are presented. The numerical values given below correspond to the integrated cross section values without cuts and may be used in the experimental analyses to obtain fast estimates in the forthcoming searches. This is particularly useful for the case of vector leptoquarks for which time consuming minimizations have to be carried out in searching the complete parameter space.

2 Scattering Cross Sections

Leptoquarks may be searched for at hadron colliders both studying single and pair production processes. In the case of the single production processes [7] the reaction cross sections are $\propto \lambda^2$ and amount to $\sigma_{\text{sing}} \sim 0.4 \text{ fb}...1.3 \text{ fb}$ at Tevatron energies for fermionic couplings of the order $(\lambda/e)\sqrt{Br} \approx 0.075$, only, [1a], and are too small to be detected currently. These values of $\lambda$ would correspond to an interpretation of the HERA-events as due to single leptoquark-production, setting an upper bound.

On the other hand, given the small fermionic couplings, the pair production processes [2] depend on the leptoquark–gluon couplings only. In the case of scalar leptoquarks the production cross section is completely predicted, whereas it depends on anomalous couplings, such as $\kappa_G$ and $\lambda_G$, in the case of vector leptoquarks. As was shown in ref. [2], however, there exists a global minimum $\min_{\kappa_G,\lambda_G} \left[ \sigma(\Phi V \Phi V) \right] > 0$ allowing for a model-independent analysis.

The production cross sections for scalar leptoquarks in the partonic subsystem read [2]

$$
\sigma^{q\bar{q}}_{\Phi S \bar{\Phi} S} = \frac{2\pi\alpha_s^2}{27s} \beta^3,
$$

$$
\sigma^{gg}_{\Phi S \bar{\Phi} S} = \frac{\pi\alpha_s^2}{96s} \left[ \beta(41 - 31\beta^2) - (17 - 18\beta^2 + \beta^4) \ln \frac{1 + \beta}{1 - \beta} \right],
$$

with $\beta = \sqrt{1 - 4M_{\Phi}^2/s}$. The $O(\alpha_s)$ correction to the production cross section was calculated in ref. [8] and amounts to a $K$-factor of 1.12 only for the choice $\mu = M_{\Phi}$ of the factorization scale, for $M_{\Phi} \simeq 200 \text{ GeV}$. The cross sections in the case of vector leptoquark pair production are more complicated, cf. [2], due to the presence of the anomalous couplings $\kappa_G$ and $\lambda_G$ and have the general structure

$$
\sigma^V_{\Phi V \Phi V} = \frac{4\pi\alpha_s^2}{9M_V} \sum_{i=0}^{5} \chi_i^V(\kappa_G, \lambda_G)G_i(\hat{s}, \beta)
$$

with $\chi_i^V$ the amplitudes for scalar leptoquarks. For vector leptoquarks the calculation is more involved due to the presence of anomalous couplings. The numerical evaluation of the cross sections can be done using the code LQPAIR 1.00.
\[ \sigma_{\Phi \Phi}^{gg} = \frac{\pi \alpha_s^2}{96 M_V} \sum_{i=0}^{14} \chi_i^q(\kappa_G, \lambda_G) \tilde{F}_i(s, \beta). \] 

(4)

The functions \( \chi^q,g \), \( \tilde{G}_i \) and \( \tilde{F}_i \) are given in ref. [2]. For \( \kappa_G = \lambda_G = 0 \) (Yang–Mills type couplings) one obtains [2]

\[ \sigma_{\Phi \Phi}^{gg} = \frac{\pi \alpha_s^2}{54 M_V} \left[ \frac{s}{M_V^2} + 23 - 3\beta^2 \right]. \]

(5)

Choosing the factorization and renormalization scales by \( \mu = M_\Phi \) the pair production cross sections for scalar and vector leptoquarks (minimizing for \( \kappa_G \) and \( \lambda_G \)) at Born level and using the parametrization [8] for the parton densities are [1a]:

\[ \sigma_S(M_\Phi = 200 \text{ GeV}) = 0.16 \text{ pb} \quad \sigma_V(M_\Phi = 200 \text{ GeV}) = 0.29 \text{ pb}. \]

(6)

3 Numerical values of the Integral Cross Sections

The mass-range for first-generation scalar leptoquarks already excluded by the Tevatron experiments is

\[ M < \begin{array}{ll} 213 \text{ GeV} & \text{CDF} \quad Br(eq) = 1 \\ 176 \ (225) \text{ GeV} & \text{D0} \quad Br(eq) = 0.5 \ (1) \\ 242 \text{ GeV} & \text{combined} \quad Br(eq) = 1 \end{array} \]

(7)

at 95% CL [4]. The mass bounds for vector leptoquarks are correspondingly higher because of the larger production cross section. These limits have still to be determined by the Tevatron experiments. The region for future searches is thus \( M \gtrsim 200 \text{ GeV} \), because the branching ratios \( Br(eq) \) can be as small as 0.5.

In Figures 1, 2 and 5 the scalar leptoquark pair–production cross sections are shown for cms energies of \( \sqrt{S} = 1.8 \) and 2 TeV (Tevatron) and 14 TeV (LHC) as a function of the leptoquark mass choosing the factorization and renormalization scales \( \mu = M_\Phi \). The band due to a variation of this scale in the range \( \mu \in [M_\Phi/2, 2M_\Phi] \) is also given. The cross sections both for scalar and vector leptoquarks behave almost as

\[ \log(\sigma) \sim A - BM_\Phi \]

(8)

in the region of large masses.

Figures 3 and 5 present the mass-dependence of the \( O(\alpha_s) \) \( K \)-factor at Tevatron and LHC, respectively, with values between 1.05 and 1.15 for \( 200 < M_\Phi < 350 \) GeV for Tevatron and 1.35 to 1.55 for \( 200 < M_\Phi < 1500 \) GeV for LHC.

In Figures 6–11 the integrated cross sections for vector leptoquark pair–production are shown correspondingly. Three typical cases are considered for the anomalous couplings:

- Yang-Mills type coupling (YM) : \( \kappa_G = \lambda_G = 0 \)
minimal coupling (MC) : $\kappa_G = 1, \lambda_G = 0$

the global minimum of the cross section w.r.t. $\kappa_G$ and $\lambda_G$ for fixed $M_\Phi$.

The minimal cross sections are neither obtained for the Yang-Mills-type or the minimal couplings, showing that a search in the two-parameter space $(\kappa_G, \lambda_G)$ is required to obtain a global bound.

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Figure 1: Integrated cross sections for scalar leptoquark pair production at the Tevatron, $\sqrt{S} = 1.8$ TeV, $\mu = M_{LQ}$, full line. Dotted lines: range of scale variation $\mu \in [M_{LQ}/2, 2M_{LQ}]$. 

$\sigma_{\text{tot}} / \text{pb}$

$\sqrt{S} = 1800$ GeV

Tevatron

CTEQ4, MSBAR

$L = 100 \text{ pb}^{-1}$
Figure 2: Integrated cross sections for scalar leptoquark pair production at Tevatron at \( \sqrt{S} = 2.0 \) TeV. Full line: \( \mu = M_{LQ} \), dotted lines: range of scale variation \( \mu \in [M_{LQ}/2, 2M_{LQ}] \).
Figure 3: Ratio of the scalar pair production cross section in next-to-leading and leading order QCD at Tevatron, $\mu = M_{LQ}$. Full line: $\sqrt{S} = 1.8$ TeV, dashed line: $\sqrt{S} = 2.0$ TeV.
Figure 4: Integrated cross sections for scalar leptoquark pair production at LHC at $\sqrt{S} = 14$ TeV. Full line: $\mu = M_{LQ}$, dotted lines: range of scale variation $\mu \in [M_{LQ}/2, 2M_{LQ}]$. 
Figure 5: Cross section ratio $\sigma_{\text{tot}}^{\text{NLO}} / \sigma_{\text{tot}}^{\text{LO}}$ for scalar leptoquark pair production at LHC, $\sqrt{S} = 14$ TeV.
Figure 6: Integrated cross sections for vector leptoquark pair production at Tevatron for the Yang–Mills type coupling (YM) and minimal coupling (MC) at $\sqrt{S} = 1.8$ TeV. Full line: $\mu = M_{LQ}$, dotted lines: range of scale variation $\mu \in [M_{LQ}/2, 2M_{LQ}]$. 

Vector Leptoquarks

$\sqrt{S} = 1800$ GeV
Tevatron
CTEQ4, MSBAR

$\sigma_{tot}/\text{pb}$

$M_{LQ}/\text{GeV}$
Figure 7: Integrated cross sections for vector leptoquark pair production at Tevatron for the Yang–Mills type coupling (YM) and minimal coupling (MC) at $\sqrt{S} = 2.0$ TeV. Full line: $\mu = M_{LQ}$, dotted lines: range of scale variation $\mu \in [M_{LQ}/2, 2M_{LQ}]$. 

$\sigma_{tot}/pb$

$\sqrt{S}=2000$ GeV

Tevatron

CTEQ4, MSBAR

Vector Leptoquarks

$M_{LQ}/GeV$

$L = 100$ pb$^{-1}$
Figure 8: Integrated cross sections for vector leptoquark pair production at LHC for the Yang–Mills type coupling (YM) and minimal coupling (MC) at $\sqrt{S} = 14$ TeV. Full line: $\mu = M_{LQ}$, dotted lines: range of scale variation $\mu \in [M_{LQ}/2, 2M_{LQ}]$. 
Figure 9: Integrated cross sections for vector leptoquark pair production at Tevatron minimizing the cross section for $\kappa_G$ and $\lambda_G$ at $\sqrt{S} = 1.8$ TeV. Full line: $\mu = M_{LQ}$, dotted lines: range of scale variation $\mu \in [M_{LQ}/2, 2M_{LQ}]$. 
Figure 10: Integrated cross sections for vector leptoquark pair production at Tevatron minimizing the cross section for $\kappa_G$ and $\lambda_G$ at $\sqrt{S} = 2.0$ TeV. Full line : $\mu = M_{LQ}$, dotted lines : range of scale variation $\mu \in [M_{LQ}/2, 2M_{LQ}]$. 

$\sqrt{S}=2000$ GeV

Tevatron

CTEQ4, MSBAR

$\sigma_{\text{tot}} / \text{pb}$

$M_{LQ} / \text{GeV}$

$L = 100 \text{ pb}^{-1}$
Figure 11: Integrated cross sections for vector leptoquark pair production at LHC minimizing the cross section for $\kappa_G$ and $\lambda_G$ at $\sqrt{S} = 14$ TeV. Full line: $\mu = M_{LQ}$, dotted lines: range of scale variation $\mu \in [M_{LQ}/2, 2M_{LQ}]$. 