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# Leptoquark generator for hadron colliders

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**Abstract**

A new Monte Carlo Generator for 3rd Generation Vector Leptoquark production is now available for CDF. This program implements the appropriate Feynman Rules which follow from an effective Lagrangian[1] into a matrix element calculation using The Grace System[2]. This effective Lagrangian is parameterized in terms of $\kappa_G$ and $\lambda_G$ which allow for couplings to anomalous 'magnetic' $\mu_V$ and 'electric' quadrupole moments $q_V$

$$\mu_V = \frac{g_s}{2M_V}(2 - \kappa_G + \lambda_G)$$

$$q_V = -\frac{g_s}{M_V^2}(2 - \kappa_G - \lambda_G).$$

The Monte Carlo generator was implemented for proton-antiproton collider via the GR@PPA program[3].

## 1 Introduction

The Leptoquark (LQ) model [4, 5, 6] follows naturally from Grand Unified Theories (GUT) and other extensions to the Standard Model (SM). Leptoquarks are color triplet bosons carrying both lepton number and baryon number; they can be scalar or vector bosons. There are restrictions on the quantum numbers assigned to Leptoquark states that follow from the assumption that their direct interactions with ordinary fermion states have dimensionless couplings and are invariant under actions of the SM gauge group (see Table [1]). Since the relation between baryon and lepton quantum numbers cancels the triangle anomaly [7], rendering the theory renormalizable, one might expect Leptoquarks to play a natural and essential role in understanding any correspondence that exists between families of leptons and quarks. At the Tevatron, LQ's can be produced in pairs through strong interactions (couplings to gluons) and subsequently decay either into a charged lepton and a quark or a neutrino and a quark.

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Generally LQ's are classified by generation number because if an LQ couples to fermions of more than a single generation of SM fermions, then there can be four-fermion interactions which result in flavor-changing-neutral-currents and violation of lepton number. Such an occurrence, assuming non-chiral LQ's that can couple to right- and left-handed quarks can affect the cross section ratio[8]

$$\sigma(\pi \to e\nu)/\sigma(\pi \to \mu\nu)$$

as well as the anomalous magnetic moment of the muon[9, 10]. There exist indirect limits on these kind of LQs as well as Pati-Salam LQ's based on bounds for $K_L \to \mu e$ decays. Therefore it is assumed that LQs involve only chiral interactions within a single generation where the indirect limits are weak.

Models that contain Leptoquarks include not only grand unified theories [11], but also technicolor models [12], as well as superstring-inspired models [13].

The CDF and D0 have searched two scenarios of $\beta = 1$ and $\beta = 0$ for the scalar type Leptoquarks. The signatures are $l^+l^-q\bar{q}$ ($\beta = 1$), $\nu\bar{\nu}q\bar{q}$ ($\beta = 0$), and $l\nu q\bar{q}$ ($\beta = 0.5$) for the first and second generations of scalar Leptoquarks. The results are presented in [14]. The results on a search for the third generation Leptoquark is also presented in [15]. D0 has also searched[16] for charge–1/3 third generation scalar and vector leptoquarks.

In addition experimental searches have also be conducted to test the Technicolor model [17], where LQ's appear in a natural way.

We have developed a new Monte Carlo event generator based on GR@PPA [3]. The Feynman rules of the Leptoquark model is embedded into the GRACE [2] system and implemented as an event generator by the GR@PPA framework which is the extension of GRACE for hadron collisions.

# 2 Leptoquark production

We follow the notations of J. Blümlein, *et al.*[1]. The effective Lagrangian is given by

$$L = L_S^g \; + \; L_V^g \; ,$$

where

$$L_S^g \;=\; \sum_{scalars} [(D_{ij}^{\mu}\Phi^j)^{\dagger}(D_{\mu}^{ik}\Phi_k) - M_S^2\Phi^{i\dagger}\Phi_i] \quad \text{and}$$

$$L_V^g \;=\; \sum_{vectors} \left\{ -\frac{1}{2}G_{\mu\nu}^{i\dagger}G_i^{\mu\nu} + M_V^2\Phi_{\mu}^{i\dagger}\Phi_i^{\mu} - ig_s\left[(1-\kappa_G)\Phi_{\mu}^{i\dagger}t_{ij}^a\Phi_{\nu}^j\mathcal{G}_a^{\mu\nu} + \frac{\lambda_G}{M_V^2}G_{\sigma\mu}^{i\dagger}t_{ij}^aG_{\nu}^{j\mu}\mathcal{G}_a^{\nu\sigma}\right]\right\}.$$

In the above Lagrangians, $g_s$ is the strong coupling constant, $t^a$ are the generators of $SU(3)_c$ (in the appropriate representation), $M_S$ and $M_V$ are the scalar and vector

Table 1: Quantum numbers, decay channels, an couplings for scalar and vector leptquarks of the 3rd Generation. The subscript on the LQ is the dimensionality of the SU(2) group representation and coincides with the fifth column $\mathrm{SU(2)_W}$. The third column gives the fermion number F = 3B+L, where B is the baryon quantum number and L is the lepton quantum number. L and R refer to the chirality of the final states.

| LQ | Spin | 3B+L | $\mathrm{SU(3)_C}$ | $\mathrm{SU(2)_W}$ | $\mathrm{U(1)_Y}$ | $\mathrm{Q_{EM}}$ | Channel(s) [couplings(s)] |
|---|---|---|---|---|---|---|---|
| $\mathrm{S_1}$ | 0 | -2 | $3^*$ | 1 | $\frac{1}{3}$ | $-\frac{1}{3}$ | $\tau^-_{L,R}t\ [g_{1L,R}],\ \nu_L b\ [-g_{1L}]$ |
| $\tilde{\mathrm{S}}_1$ | 0 | -2 | $3^*$ | 1 | $\frac{4}{3}$ | $-\frac{4}{3}$ | $\tau^-_R b\ [\tilde{g}_{1R}]$ |
| $\mathrm{S_3}$ | 0 | -2 | $3^*$ | 3 | $\frac{1}{3}$ | $\frac{2}{3}$ | $\nu_L t\ [\sqrt{2}g_{3L}]$ |
| | | | | | | $-\frac{1}{3}$ | $\tau^-_L t\ [-g_{3L}],\ \nu_L b\ [-g_{3L}]$ |
| | | | | | | $-\frac{4}{3}$ | $\tau^-_L b\ [-\sqrt{2}g_{3L}]$ |
| $\mathrm{V_2}$ | 1 | -2 | $3^*$ | 2 | $\frac{5}{6}$ | $-\frac{1}{3}$ | $\tau^-_R t\ [g_{2R}],\ \nu_L b\ [g_{2L}]$ |
| | | | | | | $-\frac{4}{3}$ | $\tau^-_{L,R} b\ [g_{2L,R}]$ |
| $\tilde{\mathrm{V}}_2$ | 1 | -2 | $3^*$ | 2 | $-\frac{1}{6}$ | $\frac{2}{3}$ | $\nu_L t\ [\tilde{g}_{2L}]$ |
| | | | | | | $-\frac{1}{3}$ | $\tau^-_L t\ [\tilde{g}_{2L}]$ |
| $\mathrm{R_2}$ | 0 | 0 | 3 | 2 | $\frac{7}{6}$ | $-\frac{2}{3}$ | $\tau^-_R \overline{b}\ [-h_{2R}],\ \nu_L \overline{t}\ [h_{2L}]$ |
| | | | | | | $-\frac{5}{3}$ | $\tau^-_{L,R} \overline{t}\ [h_{2L,R}]$ |
| $\tilde{\mathrm{R}}_2$ | 0 | 0 | 3 | 2 | $\frac{1}{6}$ | $\frac{1}{3}$ | $\nu_L \overline{b}\ [\tilde{h}_{2L}]$ |
| | | | | | | $-\frac{2}{3}$ | $\tau^-_L \overline{b}\ [\tilde{h}_{2L}]$ |
| $\mathrm{U_1}$ | 1 | 0 | 3 | 1 | $\frac{2}{3}$ | $-\frac{2}{3}$ | $\tau^-_{L,R} \overline{b}\ [h_{1L,R}],\ \nu_L \overline{t}\ [h_{1L}]$ |
| $\tilde{\mathrm{U}}_1$ | 1 | 0 | 3 | 1 | $\frac{5}{3}$ | $-\frac{5}{3}$ | $\tau^-_R \overline{t}\ [\tilde{h}_{1R}]$ |
| $\mathrm{U_3}$ | 1 | 0 | 3 | 3 | $\frac{2}{3}$ | $\frac{1}{3}$ | $\nu_L \overline{b}\ [\sqrt{2}h_{3L}]$ |
| | | | | | | $-\frac{2}{3}$ | $\tau^-_L \overline{b}\ [-h_{3L}],\ \nu_L \overline{t}\ [h_{3L}]$ |
| | | | | | | $-\frac{5}{3}$ | $\tau^-_L \overline{t}\ [\sqrt{2}h_{3L}]$ |

Leptoquark masses and $\kappa_G$ and $\lambda_G$ are the anomolous couplings. $\kappa_G$ and $\lambda_G$ are assumed to be real and are related to the anomalous 'magnetic' moment, $\mu_V$, and 'electric' quadrupole moment, $q_V$, by the following relationship

$$\mu_V = \frac{g_s}{2M_V}(2 - \kappa_G + \lambda_G)$$

$$q_V = -\frac{g_s}{M_V^2}(2 - \kappa_G - \lambda_G).$$

The tensors for the field strength for the gluon and vector leptoquark fields are given by

$$\begin{aligned} \mathcal{G}^a_{\mu\nu} &= \partial_\mu \mathcal{A}^a_\nu - \partial \mathcal{A}^a_\mu + g_s f^{abc} \mathcal{A}_{a\mu} \mathcal{A}_{b\nu}, \\ G^i_{\mu\nu} &= D^{ik}_\mu \Phi_{\nu k} - D^{ik} \Phi_{\mu k}, \end{aligned}$$

with the usual covariant derivative on the gluon field

$$D^{ij}_\mu = \partial_\mu \delta^{ij} - i g_s t^{ij}_a \mathcal{A}^a_\mu.$$

This lagrangian is model independent modulo anomalous couplings for the 'magnetic' moment and the 'electric' quadrapole moment of the Leptoquarks in the color field. The case of $\kappa_G = \lambda_G = 0$ corresponds to the assumption that the Vector Leptoquark couples like a Yang-Mills gauge field and the case $\kappa_G = 1, \lambda_G = 0$ corresponds to the case of Minimal Coupling.

Since the above Lagrangian is really an effective Lagrangian, the Feynman rules which follow strictly speaking may not lead to a Renormalizable theory. In this case our strategy was to compute the cross sections only at tree level and not address the case of higher order contributions. The Feynman rules for the gluon, ghost, fermion, and scalar and vector leptoquark propagators are defined in the $R_\xi$ gauge as follows:

$$\begin{aligned} D^{ab,g}_{\mu\nu}(\mathbf{k}) &= \delta^{ab} d^{\mu\nu}(\mathbf{k}) \frac{1}{k^2} \\ \hat{\Delta}^{ab,\hat{g}}(\mathbf{k}) &= -\delta^{ab} \frac{1}{k^2} \\ G_{ij}(\mathbf{p}) &= \delta_{ij} \frac{1}{m_q - \not{p}} \\ D^S_{ab}(\mathbf{k}) &= -\delta_{ab} \frac{1}{k^2 - M_s^2} \\ D^{\mu\nu,V}_{ab}(\mathbf{k}) &= \delta_{ab} \Delta^{\mu\nu}(\mathbf{k}) \frac{1}{k^2 - M_V^2} \end{aligned}$$

with the following gauge-dependent spin sums

$$\begin{aligned} d_{\mu\nu}(\mathbf{k}) &= g_{\mu\nu} - (1 - \xi) \frac{k_\mu k_\nu}{k^2} \\ \Delta_{\mu\nu}(\mathbf{k}) &= g_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} \end{aligned}$$

The trilinear vertices are given by

$$\begin{aligned}
V^{ggg,a_1a_2a_3}_{\mu_1\mu_2\mu_3} &= -if^{abc}g_s\hat{V}_{\mu 1\mu 2\mu 3}(k_1,k_2,k_3)\\
V^{\hat{g}\hat{g}g,a_1,a_2,a_3}_{\mu} &= -ig_sf^{abc}k_{2\mu}\\
V^{qqg,jia}_{\mu} &= g_s\gamma_\mu t^a_{ij}\\
V^{\overline{S}Sg,aij}_{\mu_3}(k_1,k_2,k_3) &= g_s(t^a)^{ij}(k_2-k_1)_{\mu_3}\\
V^{\overline{V}Vg,aij}_{\mu_1\mu_2\mu_3}(k_1,k_2,k_3) &= g_s(t^a)^{ij}\left[\hat{V}_{\mu_1\mu_2\mu_3}+\kappa_G\hat{V}^{\kappa}_{\mu_1\mu_2\mu_3}+\frac{\lambda_G}{M_V^2}\hat{V}^{\lambda}_{\mu_1\mu_2\mu_3}\right]
\end{aligned}$$

with the following kinematic functions of momentum triples

$$\begin{aligned}
\hat{V}_{\mu_1\mu_2\mu_3}(k_1,k_2,k_3) &= (k_1-k_2)_{\mu_3}g_{mu_1\mu_2}+(k_2-k_3)_{\mu_1}g_{\mu_2\mu_3}+(k_3-k_1)_{\mu_2}g_{\mu_3\mu_1}\\
\hat{V}^{\kappa}_{\mu_1\mu_2\mu_3}(k_1,k_2,k_3) &= k_{3\mu_1}g_{\mu_2\mu_3}-k_{3\mu_2}g_{\mu_1\mu_2}\\
\hat{V}^{\lambda}_{\mu_1\mu_2\mu_3}(k_1,k_2,k_3) &= (k_1\cdot k_2)(k_{3\mu_1}g_{\mu_2\mu_3}-k_{3\mu_2}g_{\mu_1\mu_3})+(k_2\cdot k_3)(k_{1\mu_2}g_{\mu_1\mu_3}-k_{1\mu_3}g_{\mu_1\mu_2})\\
&+ (k_3\cdot k_1)(k_{2\mu_3}g_{\mu_1\mu_2}-k_{2\mu_1}g_{\mu_2\mu_3})+k_{1\mu_3}k_{2\mu_1}k_{3\mu_2}-k_{1\mu_2}k_{2\mu_3}k_{3\mu_1}
\end{aligned}$$

In addition to trilinear vertices involving couplings of vector particles, there also are the following quadralinear couplings

$$\begin{aligned}
W^{gggg,a_1a_2a_3a_4}_{\mu_1\mu_2\mu_3\mu_4}(k_1,k_2,k_3,k_4) &= -g_s^2\{f^{a_1a_2b}f^{a_3a_4b}(g_{\mu_1\mu_3}g_{\mu_2\mu_4}-g_{\mu_1\mu_4}g_{\mu_2\mu_3})\\
&+ f^{a_1a_3b}f^{a_2a_4b}(g_{\mu_1\mu_2}g_{\mu_3\mu_4}-g_{\mu_1\mu_4}g_{\mu_2\mu_3})\\
&+ f^{a_1a_4b}f^{a_3a_2b}(g_{\mu_1\mu_3}g_{\mu_2\mu_4}-g_{\mu_1\mu_2}g_{\mu_3\mu_4})\},\\
W^{\overline{S}Sgg,ija_1a_2}_{\mu_1\mu_2}(p_1,p_2,p_3,p_4) &= g_s^2(t^{a_1}t^{a_2}+t^{a_2}t^{a_2}t^{a_1})^{ij}g_{\mu_1\mu_2}\\
W^{\overline{V}Vgg,ija_1a_2}_{\mu_1\mu_2\mu_3\mu_4}(p_1,p_2,p_3,p_4) &= -g_s^2\Bigg((t^{a_1}t^{a_2})^{ij}\left[\hat{W}_{\mu_1\mu_2\mu_3\mu_4}+\kappa_G\hat{W}^{\kappa}_{\mu_1\mu_2\mu_3\mu_4}+\frac{\lambda_G}{M_V^2}\hat{W}^{\lambda}_{\mu_1\mu_2\mu_3\mu_4}\right]\\
&+ (t^{a_2}t^{a_1})^{ij}\left[\hat{W}_{\mu_1\mu_2\mu_4\mu_3}+\kappa_G\hat{W}^{\kappa}_{\mu_1\mu_2\mu_4\mu_3}+\frac{\lambda_G}{M_V^2}\hat{W}^{\lambda}_{\mu_1\mu_2\mu_4\mu_3}\right]\Bigg)
\end{aligned}$$

The corresponding kinematic functions are

$$\begin{aligned}
\hat{W}_{\mu_1\mu_2\mu_3\mu_4}(p_1,p_2,p_3,p_4) &= g_{\mu_1\mu_2}g_{\mu_3\mu_4}+g_{\mu_1\mu_3}g_{\mu_2\mu_4}-2g_{\mu_1\mu_4}g_{\mu_2\mu_3}\\
\hat{W}^{\kappa}_{\mu_1\mu_2\mu_3\mu_4}(p_1,p_2,p_3,p_4) &= g_{\mu_1\mu_4}g_{\mu_2\mu_3}-g_{\mu_1\mu_3}g_{\mu_2\mu_4}\\
\hat{W}^{\lambda}_{\mu_1\mu_2\mu_3\mu_4}(p_1,p_2,p_3,p_4) &= (p_1\cdot p_2)(g_{\mu_1\mu_4}g_{\mu_2\mu_3}-g_{\mu_1\mu 3}g_{\mu_2\mu_4})\\
&+ (p_1\cdot p_3)(g_{\mu_1\mu_4}g_{\mu_2\mu_3}-g_{\mu_1\mu 2}g_{\mu_3\mu_4})\\
&+ (p_2\cdot p_4)(g_{\mu_1\mu_4}g_{\mu_2\mu_3}-g_{\mu_1\mu 2}g_{\mu_3\mu_4})\\
&+ g_{\mu_1\mu_2}(p_{1\mu_3}p_{3\mu_4}+p_{2\mu_4}p_{4\mu_3}+p_{1\mu_4}p_{2\mu_3}-p_{1\mu_3}p_{2\mu_4})\\
&+ g_{\mu_1\mu_3}(p_{1\mu_2}p_{2\mu_4}+p_{1\mu_4}p_{3\mu_2}-p_{1\mu_2}p_{3\mu_4})\\
&- g_{\mu_1\mu_4}(p_{1\mu_2}p_{2\mu_3}+p_{1\mu_3}p_{3\mu_2}+p_{2\mu_3}p_{4\mu_2})\\
&- g_{\mu_2\mu_3}(p_{2\mu_1}p_{1\mu_4}+p_{2\mu_4}p_{4\mu_1}+p_{1\mu_4}p_{3\mu_1})\\
&+ g_{\mu_2\mu_4}(p_{2\mu_1}p_{1\mu_3}+p_{2\mu_3}p_{4\mu_1}-p_{2\mu_1}p_{4\mu_3})\\
&+ g_{\mu_3\mu_4}(p_{1\mu_2}p_{3\mu_1}+p_{2\mu_1}p_{4\mu_2})
\end{aligned}$$

For practical calculations, please note that the ghost field for a gluon is not required as long as we consider the physical polarization of gluons in the numerical calculation (GRACE uses physical gauges). Physical gauges simplify the matrix element calculation[18]

The production mechanism for Vector Leptoquark production at the Tevatron proceeds via gluon-gluon fusion shown in Figure 1 and quark-antiquark annihilation shown in Figure 2. At the Tevatron, the main contribution to the production cross section

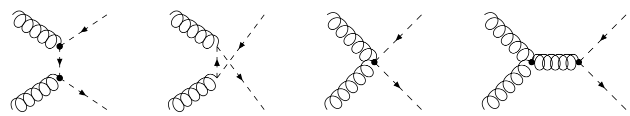

Figure 1: Leptoquark pair production via gluon-gluon fusion. The dashed lines are for the Vector Leptoquark pairs.

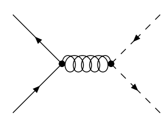

Figure 2: Leptoquark pair production via quark-antiquark annihilation

comes from the quark-antiquark annihilation diagram. At the LHC the primary production mechanism is gluon-gluon fusion. This difference is caused primarily because the abundance of anti-quarks at the Tevatron (a proton-antiproton collider) compared to the LHC (a proton-proton collider). For technical reason the quadralinear coupling involving direct coupling between the gluon-gluon pairs and the $V_{LQ}\overline{V}_{LQ}$ pairs, i.e., $W^{\overline{V}Vgg,ija_1a_2}_{\mu_1\mu_2\mu_3\mu_4}(p_1,p_2,p_3,p_4)$ had to be split into two different amplitudes within The Grace System to allow for the opposite directions of color flow. This required the introduction of an auxillary color triplet particle and splitting the quadralinear vertex into two trilinear vertices with the auxiliary color triplet exchanged between them. This auxiliary particle does not affect the kinematics because it propagates with a unit-valued propagator. This is a method used in many matrix element programs to deal with the Bose-Einstein symmetry for the vector quadralinear vector vertices and the fact that there are two terms in the quadralinear vertex with opposite color flows.

The cross sections from Grace for the hard subprocesses for quark-antiquark annihilation and also gluon-gluon fusion into pairs of Vector Leptoquarks can be compared directly with the theoretical results in Ref [1]. For $\kappa_g = \lambda_G = 0$, fixed values of $\alpha(s) = 0.13$ and center-of-mass energy of 1 TeV Figure 3 compares Equation (27) of

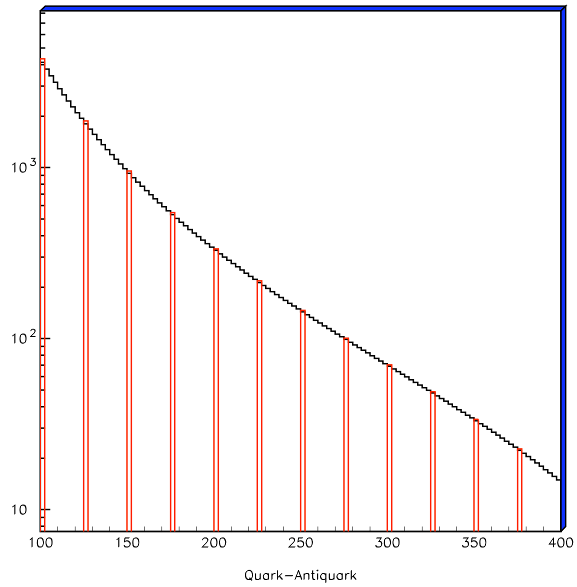


Figure 3: Quark-Antiquark Annihilation Cross Section in arbitrary units. Horizontal axis is Vector Leptoquark mass in [GeV/c$^2$]. Curve is Eq (27) in Ref[1]. Histogram is Grace calculation

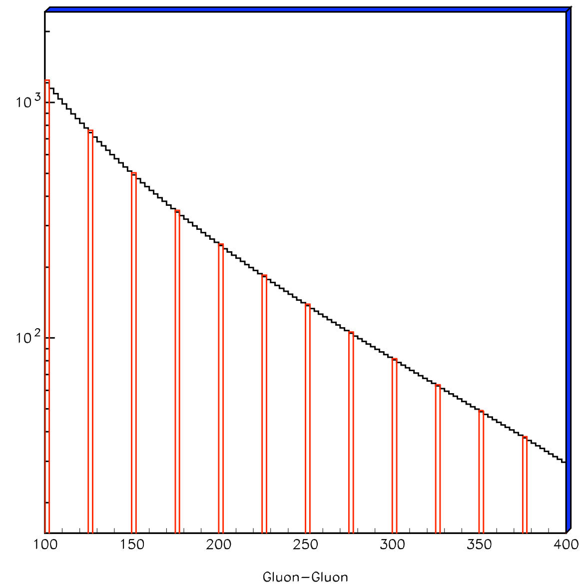


Figure 4: Gluon-Gluon Fusion Cross Section in arbitrary units. Curve is Eq (23) in Ref[1]. Horizontal axis is Vector Leptoquark mass in [GeV/c$^2$. Histogram is Grace Calculation.

Ref [1] and Figure 4 compares Equation (23) of Ref.[1] with the corresponding numerical calculation from Grace.

In addition to comparing the cross sections for the hard subprocesses between Ref[1] and Grace, we also compare the final proton-antiproton cross sections at the Tevatron, using the analysis assumptions of the Run-II CDF Vector Leptoquark search, obtained by imbedding the theoretical model from Ref[1] into a program which integrates over the same parton distribution function as is used in GR@PPA. Both calculations use 5-flavor CTEQ5L parton distribution functions with $\alpha_s(Q^2 = M^2_{VLQ})$. Figure 5 shows the comparison for both the quark-antiquark annihilation and gluon-gluon fusion contributions to $p\overline{p} \rightarrow V^-_{LQ}V^+_{LQ}$ as a function of Vector Leptoquark mass with $\kappa_G = \lambda_G = 0$ (Yang-Mills case).

Figure 6 shows the comparison for both the quark-antiquark annihilation and gluon-gluon fusion contributions to $p\overline{p} \rightarrow V^-_{LQ}V^+_{LQ}$ as a function of Vector Leptoquark mass with $\kappa_G = 1, \lambda_G = 0$ (Minimal Coupling case).

Both Figure 5 and Figure 6 show excellent agreement between the theoretical proton-antiproton cross section as obtained by a numerical integration of the differential cross sections in Ref[1] and the results from GR@PPA.

Also, we show the production cross sections for scalar and vector Leptoquarks, using the same assumptions for the cross section curves shown in Ref. [1] for parton distribution function and $Q^2$ scale, are shown in Figure 7 and 8, respectively. Both

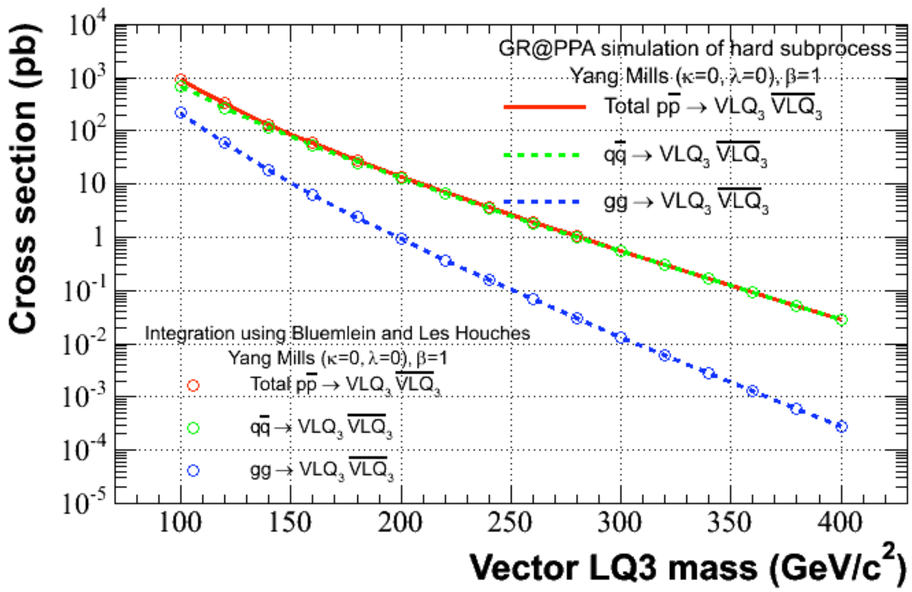


Figure 5: Tevatron Cross Sections for Yang-Mills case.

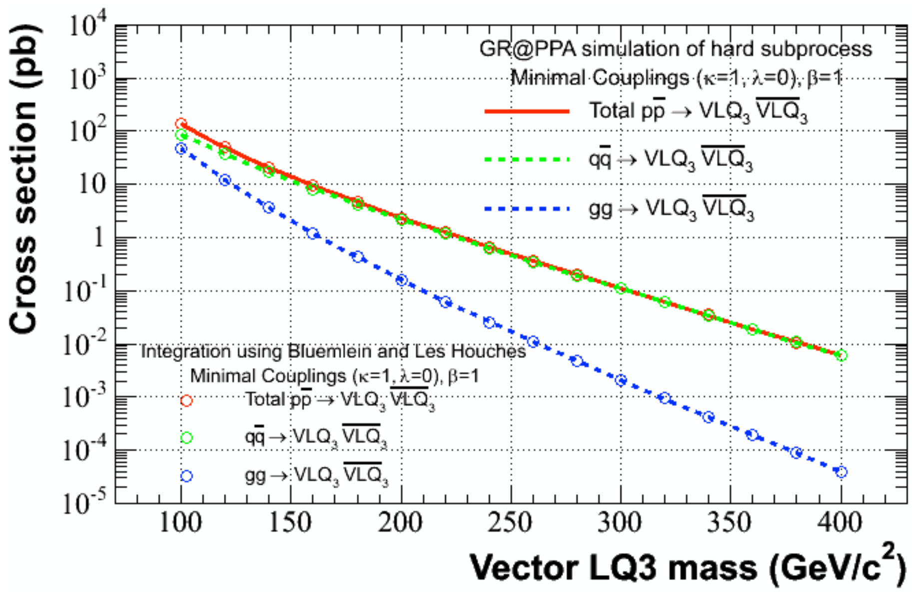


Figure 6: Tevatron Cross Sections for Minimal Coupling case.

results are calculated with CTEQ5L parton distribution function [19] and $Q^2 = \hat{s}$ at the Tevatron Run II condition ($p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV). For the vector Leptoquark production, we also show those with three different scenarios by taking various anomalous coupling parameters of $\kappa$ and $\lambda$. We can see the cross section of the vector Leptoquark pair production depends on those anomalous coupling parameters. In the case of the vector Leptoquark with mass 150 GeV this dependence is also shown in Figure 9. Again, these results are a good agreement with the results from [1].

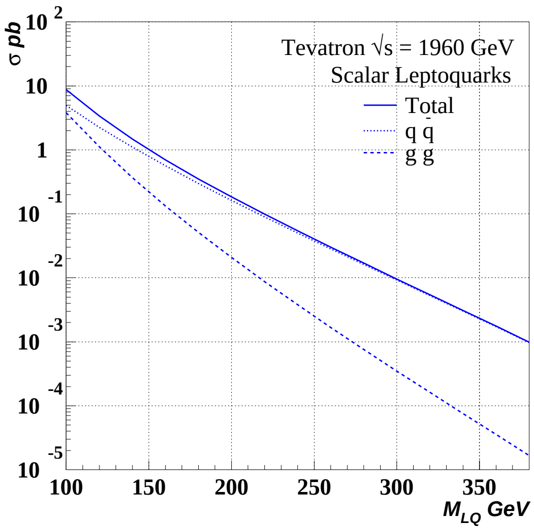


Figure 7: Production cross section for the scalar Leptoquark pair production at Tevatron Run II conditions of Fig 4a of Ref[1] .

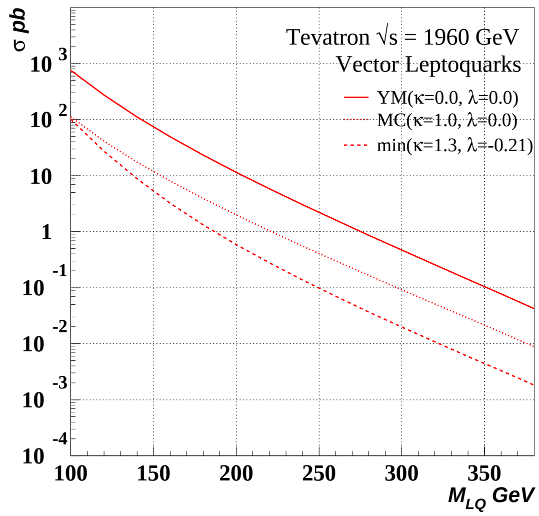


Figure 8: Production cross section for the vector Leptoquark pair production at Tevatron conditions of Fig 5a of Ref[1].

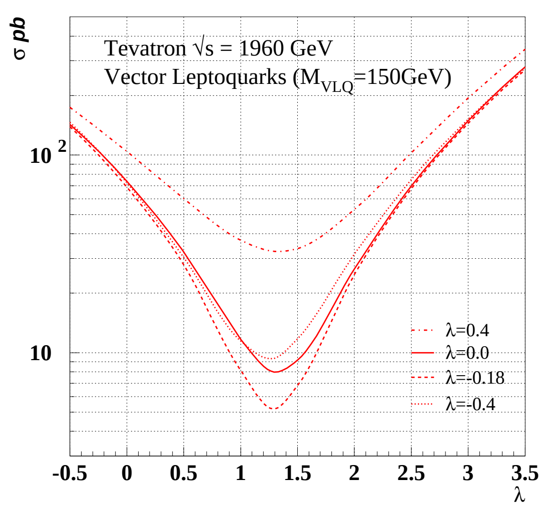


Figure 9: Dependence of the cross sections for the vector Leptoquark pair production on the anomalous couplings $\kappa$ and $\lambda$ at the Tevatron Run II for $M_V = 150$ GeV (compare with Fig 6a of Ref[1].

# 3 Leptoquark decays

Leptoquark decays into a lepton and a quark. Based on the quantum number of the Leptoquark, the decay mode is variety within the same generation in quarks and leptons. To keep a generality, we simply follow the SU(3)×SU(2)×U(1) symmetry group. We assume that all coupling constants with fermions are unified by one coupling parameter $\lambda$ and its value should be the order of $10^{-4\sim-8}$. The partial decay widths for the scalar and vector Leptoquarks are expressed as

$$\Gamma^{\rm Scalar}_{(R,L)} = \frac{3p\lambda^2}{4\pi}(1-\frac{(m_l+m_q)^2}{m^2_{LQ}}) \tag{1}$$

$$\Gamma^{\rm Scalar}_{R(L)} = \frac{3p\lambda^2}{8\pi}(1-\frac{m^2_l+m^2_q}{m^2_{LQ}}) \tag{2}$$

$$\Gamma^{\rm Vector}_{(R,L)} = \frac{p\lambda^2}{4\pi}(2-\frac{m^2_l+m^2_q}{m^2_{LQ}}-\frac{(m^2_l-m^2_q)^2}{m^4_{LQ}}+6\frac{m_l m_q}{m^2_{LQ}}) \tag{3}$$

$$\Gamma^{\rm Vector}_{R(L)} = \frac{p\lambda^2}{8\pi}(2-\frac{m^2_l+m^2_q}{m^2_{LQ}}-\frac{(m^2_l-m^2_q)^2}{m^4_{LQ}})\ , \tag{4}$$

where R(L) is a right(left)-handed coupling with fermions, and neutrinos only allow the left-handed type coupling. The decay modes and relative size of the coupling strength for Leptoquarks are listed in [23, 24]. The Leptoquark immediately decays to the lepton and quark without dilution of the QCD effects because of the small $\lambda$, so that the braching ration is uniquely decided regardless of the unknown coupling strength $\lambda$. There are several decay modes according to the quantum number of the Leptoquarks. If the third generation Leptoquark gets a larger mass than the top quark mass ($\approx$ 178 GeV), then the decay mode to the top quark is open.

# 4 GR@PPA generator for Leptoquark model

## 4.1 Subprocesses

Each matrix element is supplied by the GRACE system. The standard library functions for GRACE are found in the GRACE directory CHANEL (see Ref[2]). In order to handle the coupling of the Vector Leptoquarks to quarks and gluons several new amplitude functions had to be written. These are part of the leptoquark.mdl and leptoquark.fin files. At the moment, the incorporation of these amplitudes into the GR@PPA program is done by hand, but in the future the merging of GRACE amplitudes into GR@PPA event generation will be automated.

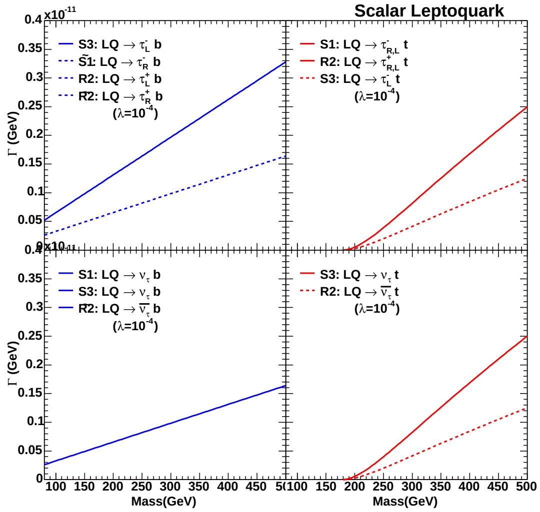


Figure 10: Partial width for the scalar Leptoquark.

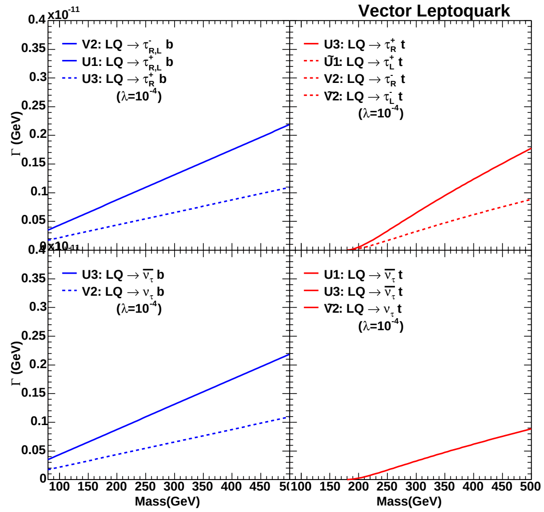


Figure 11: Partial width for the vector Leptoquark.

## 4.2 Distribution package

The GR@PPA generation program is arranged for the use on Unix systems. However, since the structure is rather simple, we expect that the program can be compiled and executed on other platforms without serious difficulties. The package is maintained by Soushi Tsuno (Soushi.Tsuno@cern.ch) and is composed of the following files and directories:

```
GR@PPA-2.74.lepto.tgz
matrix_slq2bdy_v0.40.tgz
matrix_vlq2bdy_v0.40.tgz
matrix_slq4bdy_v0.40.tgz
matrix_vlq4bdy_v0.40.tgz
```

For a copy of the above files please send an e-mail to the authors.

## 4.3 How to install

```
tar xzvf GR@PPA-2.74.lepto.tgz
cd GR@PPA-2.74.lepto/
tar xzvf matrix_slq2bdy_v0.40.tgz
tar xzvf matrix_vlq2bdy_v0.40.tgz
tar xzvf matrix_slq4bdy_v0.40.tgz
tar xzvf matrix_vlq4bdy_v0.40.tgz
At this point library pointers in Config.perl must be set
./Config.perl
```

```
make slq2bdy
make vlq2bdy
make slq4bdy
make vlq4bdy
make kinem
make integ
make install
make example
```

### 4.4 Test run output

The GR@PPA program first runs BASES which performs a Grid Optimization and the checks the Convergency. En example of the output of these respective sections is

```
              Convergency Behavior for the Grid Optimization Step
 ------------------------------------------------------------------------------
 <- Result of  each iteration ->  <-     Cumulative Result     -> < CPU  time >
  IT Eff R_Neg   Estimate  Acc %  Estimate(+- Error )order  Acc % ( H: M: Sec )
 ------------------------------------------------------------------------------
   1 100  0.00  8.975E+01  2.099  8.974740(+-0.188394)E 01  2.099   0: 0:16.66
   2 100  0.00  8.731E+01  0.818  8.761536(+-0.066812)E 01  0.763   0: 0:28.46
   3 100  0.00  8.767E+01  0.722  8.764457(+-0.045956)E 01  0.524   0: 0:39.14
   4 100  0.00  8.816E+01  0.723  8.782107(+-0.037279)E 01  0.424   0: 0:50.06
   5 100  0.00  8.755E+01  0.710  8.775027(+-0.031973)E 01  0.364   0: 1: 1.06
 ------------------------------------------------------------------------------


              Convergency Behavior for the Integration Step
 ------------------------------------------------------------------------------
 <- Result of  each iteration ->  <-     Cumulative Result     -> < CPU  time >
  IT Eff R_Neg   Estimate  Acc %  Estimate(+- Error )order  Acc % ( H: M: Sec )
 ------------------------------------------------------------------------------
   1 100  0.00  8.758E+01  0.694  8.757826(+-0.060752)E 01  0.694   0: 1:12.03
   2 100  0.00  8.756E+01  0.733  8.756887(+-0.044116)E 01  0.504   0: 1:22.89
   3 100  0.00  8.732E+01  0.717  8.748741(+-0.036064)E 01  0.412   0: 1:33.81
   4 100  0.00  8.713E+01  0.702  8.739505(+-0.031063)E 01  0.355   0: 1:44.52
   5 100  0.00  8.747E+01  0.680  8.741132(+-0.027538)E 01  0.315   0: 1:55.18
 ------------------------------------------------------------------------------
                         ****** END OF BASES *********
```

After this then final state fragmentation (Pythia) is initialzed and the output stream defined. The Grace System program called SPRING is run on the optimized grid from the BASES integration step to generate events according to the matrix element defined by the amplitude. A typical Les Houches formated event written to output has the form (for a 150 GeV Vector Leptoquark)

```
 ********************** PYINIT: initialization completed *********************
         Event listing of user process at input (simplified)

   I IST      ID Mothers   Colours     p_x       p_y       p_z        E         m
   1 -1        2   0   0  501     0    0.000     0.000   267.117   267.117     0.000
   2 -1       -2   0   0    0   502    0.000     0.000  -120.508   120.508     0.000
   3  2       42   1   2    0   502  -82.312     4.099    15.154   171.819   150.000
   4  2      -42   1   2  501     0   82.312    -4.099   131.455   215.807   150.000
   5  1       15   3   0    0     0  -26.422   -22.567    76.799    84.312     1.777
   6  1       -5   3   0    0   502  -55.890    26.665   -61.645    87.506     4.750
   7  1      -15   4   0    0     0  102.842    42.686    56.244   124.760     1.777
   8  1        5   4   0  501     0  -20.530   -46.784    75.211    91.047     4.750
```

At this point, the above event (the HEPEUP block in the Les Houches Accord) is written to an ascii file. Subsequent re-fragmentation and CDF Simulation is preformed within the Les Houches interface to mcProduction. The Tau polarization information is also written out per event and is available for setting the proper tau decay within mcProduction throught the Tauola talk-to block.

# 5 Results

This program was used by the CDF Leptoquark group to investigate the expected number of signal events in the recent search for 3rd Generation Vector Leptoquarks [25]. The final states for the 3rd Generation Vector Leptoquarks were set to $\tau b$, but other decays are possible, e.g. $\nu_\tau t$. The initial beams were set for the Tevatron, but it is also possible to use this implementation within GR@PPA for LHC.

# 6 Summary

This note describes a new Monte Carlo Generation based on The Grace/GR@PPA System for generating 3rd Generation Vector Leptoquark pairs in Proton-Antiproton collisions. The program is based on the helicity amplitude method for calculating the matrix element. As a result the final state polarizations are properly accounted for. For 3rd Generation Vector Leptoquarks this is very important because the final states involve the reaction $V_{LQ} \to \tau b$. It is known that $\tau$ polarizations affect the distribution of final states for the $\tau$ decays and therefore affect the experimental acceptances. By using the helicity amplitudes all these effects can be taken into account.

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