Exotic heavy quark contribution in hadron-hadron production of W^+W^- pairs

Y. A. Coutinho,* J. A. Martins Simões,† and P. P. Queiroz Filho‡
Instituto de Física, Universidade Federal do Rio de Janeiro, C.P. 68528, Ilha do Fundão, 21945-970 Rio de Janeiro, RJ, Brazil
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In this paper we study the contribution of new possible heavy quarks to the process hadron-hadron $\rightarrow W^+W^-X$. We consider new exotic quarks as proposed in three extended electroweak models: the vector singlet model (VSM), the vector doublet model (VDM), and the fermion–mirror-fermion model (FMFM). We discuss the high energy unitarity behavior for the elementary process and their implications. We present the predictions of the exotic quark contribution for the CERN Large Hadron Collider (LHC). We present some distributions that can separate the standard model contribution from the new exotic quark contribution. [S0556-2821(96)03217-1]

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I. INTRODUCTION

High energy ($\sqrt{\hat{s}} \gg M_W$) hadron-hadron collisions will allow experimental tests of many extensions of the standard model. The most clear signature would be the direct production and decay of some new object. However, there are kinematical limitations for the experimental search of new exotic particles. In most extensions we have new very massive particles with small mixing angles. One possible way out of this limitation is the high precision measurements of some known particle properties at an energy scale below the exotic thresholds. This is the well-known case of radiative corrections at the CERN e^+e^- collider LEP and SLAC Linear Collider (SLC) that improve bounds on new exotic matter couplings [1].

Following the approach of studying virtual exotic contributions to physical processes, we have presented another possible source for the search for new heavy particle properties [2,3]. We investigated the unitarity cancellation in the process $f+\overline{f}\rightarrow W^+W^-$. It is known [4] that in the standard model we have a delicate cancellation for the processes $e^+e^-\rightarrow W^+W^-$ and $q\overline{q}\rightarrow W^+W^-$. However, perturbation theory must be employed with some care in the analysis of unitarity cancellations. It is also well known that in the leading order standard model calculation for $e^+e^-\rightarrow W^+W^-$ there is a unitarity violation if we keep terms of the order m_e^2 In order to restore the correct unitarity behavior one has to consider the electron mass generation mechanism and include the Higgs boson exchange diagram. The main point in the present work is to investigate a similar situation in extended models. For the leptonic sector we have recently discussed the contributions of new possible heavy neutrinos in some extended models [2,3].

The process hadron-hadron$\rightarrow W^+W^-X$ was recently studied by Bagger *et al.* [5]. In addition to the analysis of a possible strongly interacting WW system, they also show the possibility of separating WW signals from the tt background.

In this paper we consider the contributions of new possible heavy quarks to the reaction hadron + hadron $\rightarrow W^+W^-X$. Heavy exotic quarks are present in many extensions of the standard model. We review some extended models with exotic quarks and their present bounds in Sec. II. In Sec. III we present the calculation for $q\overline{q}\rightarrow W^+W^-$. In Sec. IV we discuss the unitarity restrictions for the models considered here. In Sec. V we present the calculation of the exotic quark contribution to the hadron + hadron $\rightarrow W^+W^-X$ process. Finally in Sec. VI we present the main conclusions of our work.

II. EXTENDED MODELS FOR EXOTIC HEAVY QUARKS

In general, extended models predict a large number of new particles and new interactions. For our purposes we will consider only new exotic heavy quarks coupled to the usual standard gauge bosons: photons, gluons, W, and Z. New W' and Z' are predicted in many cases but we know that they must be very massive. This will imply small effective new interactions. We will also suppose that the leptonic sector is enlarged in order to cancel any anomaly contribution.

In order to fix our notation we now make some definitions. We consider two new heavy quarks "U" and "D" which are the generalization of the first standard model family (u,d). The other families are then easily obtained. The mass and interaction eigenstates are related through the mixings

$$\begin{pmatrix} u^0_{L,R} \\ U^0_{L,R} \end{pmatrix} = \begin{pmatrix} c^u_{L,R} & -s^u_{L,R} \\ s^u_{L,R} & c^u_{L,R} \end{pmatrix} \begin{pmatrix} u_{L,R} \\ U_{L,R} \end{pmatrix} \tag{1}$$

and

$$\begin{pmatrix} d^0_{L,R} \\ D^0_{L,R} \end{pmatrix} = \begin{pmatrix} c^d_{L,R} & -s^d_{L,R} \\ s^d_{L,R} & c^d_{L,R} \end{pmatrix} \begin{pmatrix} d_{L,R} \\ D_{L,R} \end{pmatrix}, \tag{2}$$

where $(s^i_a)^2 \equiv 1-(c^i_a)^2 \equiv \sin^2\theta^i_a$ with $i=u,d$ and $a=L,R$. $\theta^i_{L,R}$ is the mixing angle between the ith L-handed (R-handed) ordinary fermion and the exotic one.

The general interaction relevant for the process $q_i\overline{q}_i\rightarrow W^+W^-$ is

*Electronic address: yara@if.ufrj.br
†Electronic address: simoes@.if.ufrj.br
‡Electronic address: pedro@if.ufrj.br

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TABLE I. Quantum numbers of exotic quarks in the vector singlet model.

	U_R	D_R	U_L	D_L
Q	2/3	-1/3	2/3	-1/3
T	0	0	0	0
T_3	0	0	0	0
Y	4/3	-2/3	4/3	-2/3

$$\mathcal{L}_{\rm int}=\sum_{i=u,d}\{-q_i\overline{\Psi}_i\gamma^\mu\Psi_iA_\mu+\overline{\Psi}_i\gamma^\mu(g_V^i-g_A^i\gamma^5)\Psi_iZ_\mu\}$$
$$+G_{VA}\overline{u}\gamma^\mu(a+b\gamma^5)dW_\mu+G'_{VA}\overline{u}\gamma_\mu(a_1+b_1\gamma^5)DW_\mu$$
$$+G''_{VA}\overline{U}\gamma^\mu(a_2+b_2\gamma^5)dW_\mu, \tag{3}$$

with $G_{VA}=G'_{VA}=G''_{VA}=g/2\sqrt{2}$, q_i is the u,d charge, and the other couplings are given in Tables IV and V.

We consider the following models.

A. Vector singlet model (VSM)

The new quarks are taken as isosinglets of the type U_L, U_R, D_L, and D_R. In the low energy limit of superstring theories we can have the group E_6, with the basic representation of dimension 27. In addition to the 15 known fermions one has 12 more nonstandard fields. In particular we have a ‘‘down’’ isosinglet quark with $Q_D=-1/3$. In general we can have the quantum numbers shown in Table I.

B. Fermion–mirror-fermion model (FMFM)

Perhaps one of the deepest problems in elementary particle physics is the asymmetry in the left- and right-handed fermion coupling with the electroweak gauge bosons.

In order to restore the left-right symmetry one possibility is to consider new fermions with the opposite chirality shown by the standard fermions. This is condensated in Table II.

C. Vector doublet model (VDM)

In this case we have two isodoublets with left and right chiralities as shown in Table III.

With the assignment shown in Tables I–III and the general mixing given by Eqs. (1) and (2) we can easily compute the couplings in the interaction Lagrangian (3). The result is summarized in Tables IV and V.

Tables IV and V show a small deviation from the standard model couplings. The high precision data taken at LEP and SLC Large Detector (SLD) imply that all mixing angles must be small. Detailed analyses were done in Ref. [6].

TABLE II. Quantum numbers of exotic quarks in the fermion–mirror-fermion model.

	U_R	D_R	U_L	D_L
Q	2/3	-1/3	2/3	-1/3
T	1/2	1/2	0	0
T_3	1/2	-1/2	0	0
Y	1/3	1/3	4/3	-2/3

TABLE III. Quantum numbers of exotic quarks in the vector doublet model.

	U_R	D_R	U_L	D_L
Q	2/3	-1/3	2/3	-1/3
T	1/2	1/2	1/2	1/2
T_3	1/2	-1/2	1/2	-1/2
Y	1/3	1/3	1/3	1/3

If we suppose that only one mixing angle is dominant, then we must have $\sin^2\theta_{\rm mix}\simeq10^{-3}$. But if one allows more mixing angles of the same order, this bound can be smaller. For our purposes we take mixing angles of the order $\sin^2\theta_{\rm mix}\simeq10^{-2}$ so that our estimates can be easily scaled up or down.

We take $s_W^2\equiv\sin^2\theta_W\equiv1-c_W^2$ and $g_Z=g/4cos\,\theta_W$.

III. THE ELEMENTARY CROSS SECTION FOR $q_i+\overline{q_i}\rightarrow W^+W^-$

New exotic heavy quarks imply an additional diagram for the process $q_i+\overline{q_i}\rightarrow W^+W^-$. The basic reaction is shown in Fig. 1 where the indices i and j refer to quarks of type u,d and U,D, respectively.

We can now compute the elementary cross section. The result is

$$\frac{d\hat{\sigma}}{d\hat{t}}=\frac{2\pi\alpha^2}{\hat{s}^2}\sum_{lm}B_{lm}, \tag{4}$$

where the B_{lm} are given by

TABLE IV. Charged current couplings for ordinary and exotic quarks.

	VSM	VDM	FMFM
a	$c_L^uc_L^d$	$c_L^uc_L^d+s_L^us_L^d+s_R^us_R^d$	$c_L^uc_L^d+s_R^us_R^d$
b	$-c_L^uc_L^d$	$-c_L^uc_L^d-s_L^us_L^d+s_R^us_R^d$	$-c_L^uc_L^d+s_R^us_R^d$
a_1	$-c_L^us_L^d$	$-c_L^us_L^d+s_L^uc_L^d+s_R^uc_R^d$	$-c_L^us_L^d+s_R^uc_R^d$
b_1	$c_L^us_L^d$	$c_L^us_L^d-s_L^uc_L^d+s_R^uc_R^d$	$c_L^us_L^d+s_R^uc_R^d$
a_2	$s_L^uc_L^d$	$-s_L^uc_L^d+c_L^us_L^d+c_R^us_R^d$	$-s_L^uc_L^d+c_R^us_R^d$
b_2	$-s_L^uc_L^d$	$s_L^uc_L^d-c_L^us_L^d+c_R^us_R^d$	$s_L^uc_L^d+c_R^us_R^d$

TABLE V. Neutral current couplings for the models considered in this paper.

	VSM	VDM	FMFM
$g^u{}_V$	$g_Z(-8s_W^2/3+c_L^{u2})$	$g_Z(-8s_W^2/3+1+s_R^{u2})$	$g_Z(-8s_W^2/3+c_L^{u2}+s_R^{u2})$
$g^u{}_A$	$g_Z(c_L^{u2})$	$g_Z(c_R^{u2})$	$g_Z(c_L^{u2}-s_R^{u2})$
$g^d{}_V$	$g_Z(4s_W^2/3-c_L^{d2})$	$g_Z(4s_W^2/3-1+s_R^{d2})$	$g_Z(4s_W^2/3-c_L^{d2}+s_R^{d2})$
$g^d{}_A$	$g_Z(-c_L^{d2})$	$g_Z(-c_R^{d2})$	$g_Z(-c_L^{d2}+s_R^{d2})$

$$B_{\gamma\gamma}=q_i^2 A(\hat{s},\hat{t},\hat{u}),$$

$$B_{ZZ}=\left(\frac{e_Z}{e^2}\right)^2[g_V^2+g_A^2]\hat{s}^2\Delta_Z^2 A(\hat{s},\hat{t},\hat{u}),$$

$$B_{\gamma Z}=-2q_i\left(\frac{e_Z}{e^2}\right)g_V\hat{s}\Delta_Z A(\hat{s},\hat{t},\hat{u}),$$

$$B_{\gamma q_i}=-2q_i\mathrm{sgn}(q_i)\frac{G_{VA}^2}{e^2}[a^2+b^2]I(\hat{s},\hat{t},\hat{u}),$$

$$B_{\gamma Q_j}=-2q_i\mathrm{sgn}(q_i)\frac{G_{VA}'^2}{e^2}[a_j^2+b_j^2]I_1(\hat{s},\hat{t},\hat{u}),$$

$$B_{q_iq_i}=\frac{G_{VA}^4}{e^4}[a^4+b^4+6(ab)^2]E(\hat{s},\hat{t},\hat{u}),$$

$$B_{Q_jQ_j}=\frac{G_{VA}'^4}{e^4}[(a_j^4+b_j^4+6(a_jb_j)^2)E_2(\hat{s},\hat{t},\hat{u}) + M_{Q_j}^2(a_j^2-b_j^2)^2E_H(\hat{s},\hat{t},\hat{u})],$$

$$B_{q_iQ_j}=2\frac{G_{VA}^2}{e^2}\frac{G_{VA}'^2}{e^2}[(a^2+b^2)(a_j^2+b_j^2) + 4aa_jbb_j]E_1(\hat{s},\hat{t},\hat{u}),$$

$$B_{ZQ_j}=2\mathrm{sgn}(q_i)\frac{G_{VA}'^2}{e^2}\frac{e_Z}{e^2}[g_V(a_j^2+b_j^2) - 2a_jb_jg_A]\hat{s}\Delta_Z I_1(\hat{s},\hat{t},\hat{u}),$$

$$B_{Zq_i}=2\mathrm{sgn}(q_i)\frac{G_{VA}^2}{e^2}\frac{e_Z}{e^2}[g_V(a^2+b^2)-2abg_A] \times\hat{s}\Delta_Z I(\hat{s},\hat{t},\hat{u}), \tag{5}$$

where $e_Z=e\cot\theta_W$. The functions $A(\hat{s},\hat{t},\hat{u})$, $E(\hat{s},\hat{t},\hat{u})$, and $I(\hat{s},\hat{t},\hat{u})$ are given in [7]:

$$A(\hat{s},\hat{t},\hat{u})=\left(\frac{\hat{u}\hat{t}}{M_W^4}-1\right)\left(\frac{1}{4}-\frac{M_W^2}{\hat{s}}+3\frac{M_W^4}{\hat{s}^2}\right)+\frac{\hat{s}}{M_W^2}-4,$$

$$I(\hat{s},\hat{t},\hat{u})=\left(\frac{\hat{u}\hat{t}}{M_W^4}-1\right)\left(\frac{1}{4}-\frac{1}{2}\frac{M_W^2}{\hat{s}}-\frac{M_W^4}{\hat{s}\hat{t}}\right) +\frac{\hat{s}}{M_W^2}-2+2\frac{M_W^2}{\hat{t}},$$

$$E(\hat{s},\hat{t},\hat{u})=\left(\frac{\hat{u}\hat{t}}{M_W^4}-1\right)\left(\frac{1}{4}+\frac{M_W^4}{\hat{t}^2}\right)+\frac{\hat{s}}{M_W^2}. \tag{6}$$

The others are

$$E_1(\hat{s},\hat{t},\hat{u})=\frac{\hat{t}}{\hat{t}-M_{Q_j}^2}E(\hat{s},\hat{t},\hat{u}),$$

$$I_1(\hat{s},\hat{t},\hat{u})=\frac{\hat{t}}{\hat{t}-M_{Q_j}^2}I(\hat{s},\hat{t},\hat{u}),$$

$$E_2(\hat{s},\hat{t},\hat{u})=\left(\frac{\hat{t}}{\hat{t}-M_{Q_j}^2}\right)^2E(\hat{s},\hat{t},\hat{u}),$$

$$E_H(\hat{s},\hat{t},\hat{u})=\left(\frac{\hat{t}}{\hat{t}-M_{Q_j}^2}\right)^2\left[\frac{M_W^2}{\hat{t}^2}\left(\frac{\hat{u}\hat{t}}{M_W^4}-1\right) + \frac{\hat{s}}{M_W^4}\left(\frac{1}{4}+\frac{M_W^4}{\hat{t}^2}\right)\right], \tag{7}$$

with

$$\Delta_Z=\frac{1}{\hat{s}-M_Z^2} \tag{8}$$

and

$$R_Z=\frac{\hat{s}}{(\hat{s}-M_Z^2)^2+M_Z^2\Gamma_Z^2}. \tag{9}$$

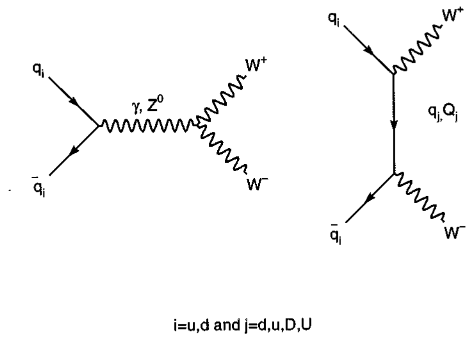

FIG. 1. Feynman diagrams for the process $qq \rightarrow W^+W^-$.

IV. UNITARITY BOUNDS

From the elementary cross section given in the previous section we can find the high energy ($\sqrt{\hat{s}} \rightarrow \infty$) behavior for $\hat{\sigma}$.

The linear term in $\hat{s}$ goes to zero if the following relations are satisfied:

$$-q_i + \mathcal{V} + \mathrm{sgn}(q_i)\frac{G_{VA}^2}{e^2}[(a^2+b^2)+(a_j^2+b_j^2)] = 0 \quad (10)$$

and

$$\mathcal{A} - 2\,\mathrm{sgn}(q_i)\frac{G_{VA}^2}{e^2}[ab + a_j b_j] = 0. \quad (11)$$

As expected, these relations are verified for the models that we have considered in Sec. II. However, the constant term in $\hat{s}$ is given by

$$C = \frac{1}{4M_W^2}\frac{G_{VA}^2}{e^2}[M_{Q_j}(a_j^2 - b_j^2) + M_{q_i}(a^2 - b^2)]^2 \quad (12)$$

and will be zero only for $(V \pm A)$ couplings between light quarks-heavy exotic quarks and the charged gauge boson W.

We analyze now the restrictions that this condition imply for exotic couplings.

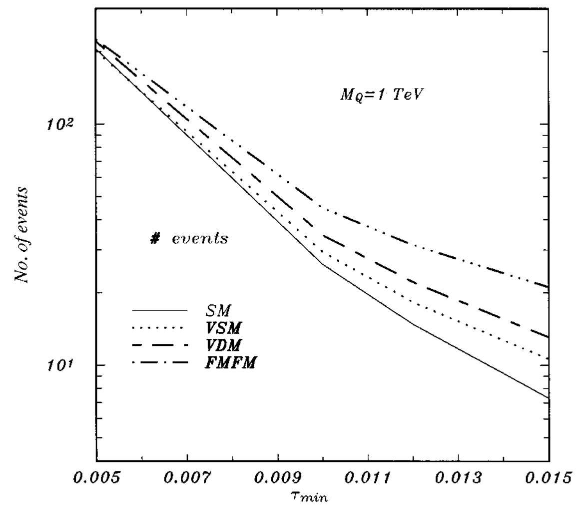

FIG. 3. Number of events against $\tau_{\min}$ for $\sqrt{s}=14$ TeV, $M_Q=1$ TeV, and $\sin^2\theta_{\mathrm{mix}}=10^{-2}$.

A. Vector singlet model

For the vector singlet model we see from Table IV that the unitarity condition is naturally satisfied. This means that the first order calculation can be employed without the need of additional terms.

B. Vector doublet model

For the vector doublet model we can have two possibilities. The first one is to impose some new symmetries that could justity the condition $\sin\theta_R^u = \sin\theta_L^u = 0$. The second one would be to enlarge the Higgs sector in order to recover the correct unitarity behavior at the order considered here. This opens a large number of possibilities that will be not considered here.

C. Fermion–mirror-fermion model

For the fermion–mirror-fermion model we have a situation similar to the previous case. Either we impose an additional constraint (in this case $\sin\theta_R^u = \sin\theta_R^u = 0$) or some new

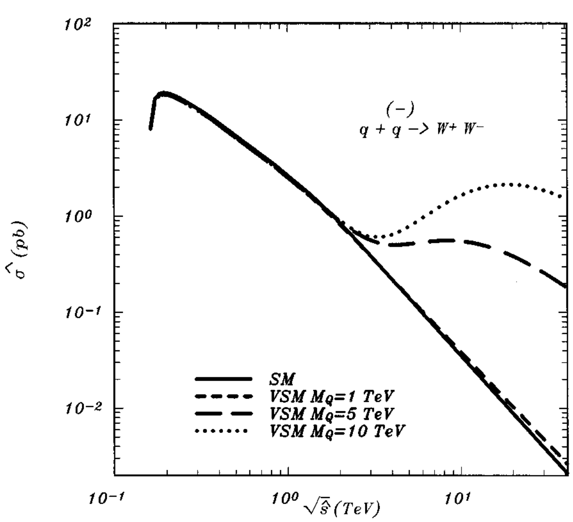

FIG. 2. Elementary cross section as a function of $\sqrt{\hat{s}}$.

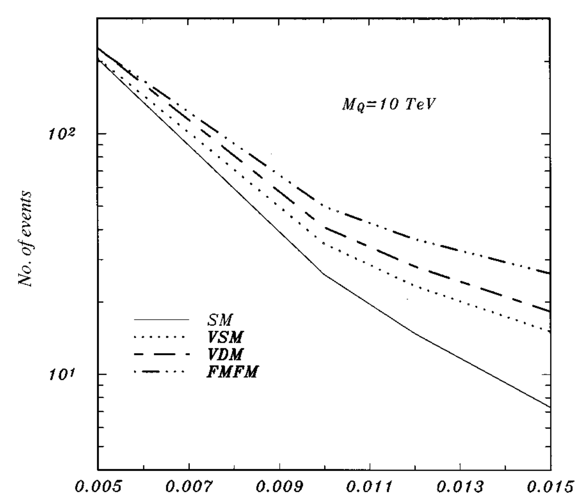

FIG. 4. The same as Fig. 3 but for $M_Q=10$ TeV.

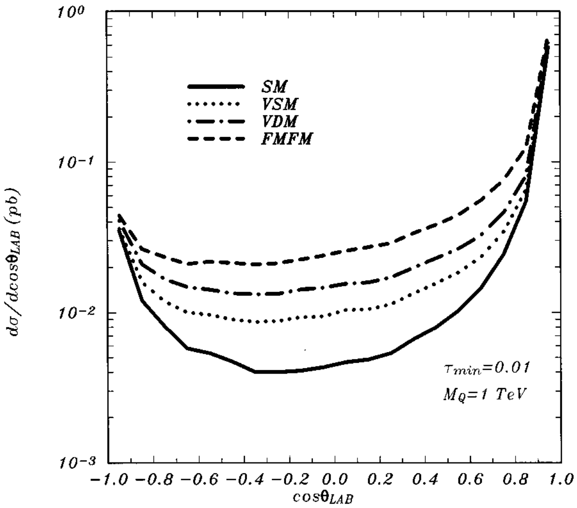

FIG. 5. Angular distribution in the pp frame using $\tau_{\mathrm{min}}=0.01$, $M_Q=1$ TeV, and $\sin^2\theta_{\mathrm{mix}}=10^{-2}$ for $\sqrt{s}=14$ TeV.

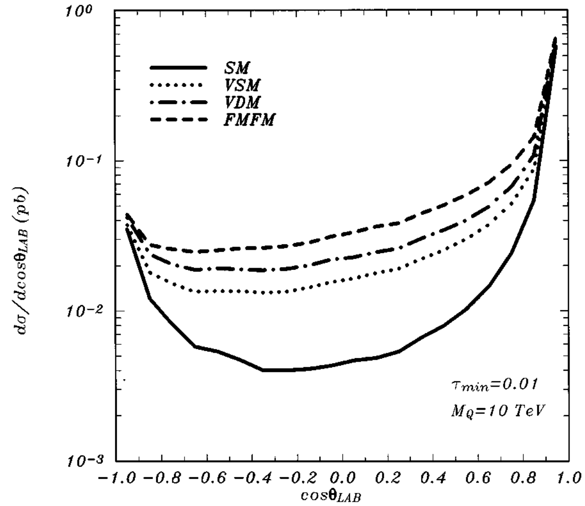

FIG. 6. The same as Fig. 5 but for $M_Q=10$ TeV.

contribution must be included. This last case was considered for some extended $\mathrm{SU}_L(2)\otimes\mathrm{SU}_R(2)\otimes\mathrm{U}_Y(1)$ models by Maalampi *et al.* in Ref. [8].

V. EXOTIC QUARK CONTRIBUTION FOR HADRON-HADRON→W^+W^-X

We can now compute the total cross section and distributions.

In Fig. 2 we show the elementary cross section for $q\overline{q}\rightarrow W^+W^-$. For the vector singlet model we have the correct high energy behavior. For the other models we must impose our unitarity condition given by Eq. (12). The elementary cross sections are then very close to the case of the VSM shown in Fig. 2. It is also shown the ''dip'' in the cross section due to the t-channel exchange of a new heavy quark. This behavior suggests that a cut should be done in the variable $\tau=\hat{s}/s$ in order to separate the standard model contribution from the new exotic quark contribution. The hadronic cross sections and distributions follow the standard approach as given in Eichten *et al.* [9]. This is shown in Fig. 3 where we compute the number of events for an annual luminosity of 100 fb^{-1} as a function of τ_{min}. The standard model supression is clearly shown. We employ the structure functions of Glück, Reya, and Vogt [10]. In Fig. 4 we compute the total number of events for an exotic heavy quark of mass equal to 10 TeV. From these two figures we conclude that the search for exotic quark contributions in the mass region of a few TeV is feasible.

The model dependence is shown in the center of mass angular distribution [11] of the final W's. This is shown in Figs. 5 and 6. The transverse (relative to the collision direction) W distribution is stronger for the FMFM.

VI. CONCLUSIONS

In this paper we propose that the process hadron+hadron $\rightarrow W^+W^-X$ can be viewed as a possible source for heavy exotic quark searches. Our main result is that for $V\pm A$ couplings between exotic and standard quarks we can use leading order diagrams for the high energy region. The unitarity condition is naturally satisfied for the vector singlet model. For the vector doublet model and for the fermion–mirror-fermion model we have two possibilities for preventing unitarity violations: Either a symmetry condition is imposed on some mixing angles or some new diagram, possibly originating from the symmetry-breaking mechanism, must be imposed. Since this last situation implies a large number of possibilities, it will be discussed elsewhere.

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