Cross Section and Forward-Backward Asymmetry of $t\bar{t}$ Production in the Model with Four Color Symmetry

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Abstract

The contributions to the cross section $\sigma_{t\bar{t}}$ and to the forward-backward asymmetry $A_{\rm FB}^{t\bar{t}}$ of $t\bar{t}$ production at the Tevatron from Z'-boson and scalar leptoquarks $S_a^{(\pm)}$ and scalar gluons F_a predicted by the minimal model with four color quark-lepton symmetry are calculated. These contributions are shown to be small in tree approximation and can be significant with account of the 1-loop $gt\bar{t}$ effective vertex induced by the scalar doublets. The lower mass limit for scalar gluons $m_F \gtrsim 320\,GeV$ from the Tevatron data is obtained and it is shown that for $m_{F_1} \lesssim 990\,GeV$ the scalar gluon F_1 can be evident at LHC at the significance not less that 3σ (for $\sqrt{s} = 14$ TeV, $L = 10\,fb^{-1}$).

1 Introduction. Minimal Quark-Lepton Symmetry model.

The search for a new physics beyond the Standard Model (SM) is now one of the aims of the high energy physics. One of the new physics can be induced by the possible four color symmetry treating leptons as quarks of the fourth color [1]. This symmetry can be unified with the SM by the gauge group

$$G_{new} = G_c \times SU_L(2) \times U_R(1) \tag{1}$$

where G_c is the group of the four color symmetry. The color group G_c can be the vectorlike group $G_c = SU_V(4)$ or the general chiral group $G_c = SU_L(4) \times SU_R(4)$ or one of the special groups of the left or right four color symmetry $G_c = SU_L(4) \times SU_R(3)$, $G_c = SU_L(3) \times SU_R(4)$.

The Minimal four color Quark-Lepton Symmetry model (MQLS-model) is based on the gauge group

$$G_{new} = SU_V(4) \times SU_L(2) \times U_R(1) \tag{2}$$

as on the minimal group containing the four color symmetry of quarks and leptons [2, 3].

According to this group in addition to gluons G_μ^j, $j = 1, 2, \ldots, 8$ and $W^\pm$-, Z-bosons the gauge sector predicts the new gauge particles: vector leptoquarks $V^\pm_{\alpha\mu}$, $\alpha = 1, 2, 3$ with charges $Q_V^{em} = \pm 2/3$ and an extra Z'-boson originating from the four color quark-lepton symmetry.

Fermion sector of the model

In MQLS-model quarks and leptons form the $SU_V(4)$-quartets ψ_{paA}, $A = 1, 2, 3, 4$, $a = 1, 2$, $p = 1, 2, 3, \ldots$

$$\psi'_{p1A} \;:\quad \begin{pmatrix} u'_\alpha \\ \nu'_e \end{pmatrix}, \begin{pmatrix} c'_\alpha \\ \nu'_\mu \end{pmatrix}, \begin{pmatrix} t'_\alpha \\ \nu'_\tau \end{pmatrix}, \ldots$$

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$$\psi'_{p2A} \;:\quad \begin{pmatrix} d'_\alpha \\ e^{-\prime} \end{pmatrix}, \begin{pmatrix} s'_\alpha \\ \mu^{-\prime} \end{pmatrix}, \begin{pmatrix} b'_\alpha \\ \tau^{-\prime} \end{pmatrix}, \ldots$$

where ${Q'}^{L,R}_{pa\alpha}$, ${\ell'}^{L,R}_{pa}$ are the basic left and right quark and lepton fields.

Each lepton have $SU_V(4)$ "color" $A = 4$.

Fermion mixing in MQLS.

The basic left and right quark and lepton fields ${Q'}^{L,R}_{pa\alpha}$, ${\ell'}^{L,R}_{pa}$ can be written, in general, as superpositions

$$ {Q'}^{L,R}_{pa\alpha} = \sum_q \left(A^{L,R}_{Q_a}\right)_{pq} Q^{L,R}_{qa\alpha}, \qquad {l'}^{L,R}_{pa} = \sum_q \left(A^{L,R}_{l_a}\right)_{pq} l^{L,R}_{qa}, \tag{3}$$

of mass eigenstates $Q^{L,R}_{qa\alpha}$, $\ell^{L,R}_{qa}$. Here $A^{L,R}_{Q_a}$ and $A^{L,R}_{\ell_a}$ are unitary matrices diagonalizing the mass matrices of quarks and leptons respectively.

$(A^L_{Q_1})^+ A^L_{Q_2} \equiv C_Q = V_{CKM}$ is Cabibbo-Kobayashi-Maskawa matrix $(A^L_{\ell_1})^+ \, A^L_{\ell_2} \equiv C_\ell$ is the analogous lepton mixing matrix $((C_l)^+ = U_{PMNS})$

$(A^{L,R}_{Q_a})^+ A^{L,R}_{\ell_a} \equiv K^{L,R}_a$ are the new mixing matrices which are specific for the models with the four color symmetry.

The interaction of the gauge fields with the fermions has the form

$$ \mathcal{L}^{gauge}_\psi = \mathcal{L}^V_\psi + \mathcal{L}^W_\psi + \mathcal{L}^{QCD}_\psi + \mathcal{L}^{QED}_\psi + \mathcal{L}^{NC}_\psi, \tag{4}$$

where

$$\begin{aligned}
\mathcal{L}^V_\psi &= \frac{g_4}{\sqrt{2}} \{ (\bar{Q}_{pa\alpha} [(K^L_a)_{pq} \gamma^\mu P_L + (K^R_a)_{pq} \gamma^\mu P_R] \ell_{qa}) V^\alpha_\mu + h.c. \}, &(5)\\
\mathcal{L}^W_\psi &= \frac{g_2}{\sqrt{2}} \{ [\bar{Q}_{p1\alpha} (C_Q)_{pq} \gamma^\mu P_L Q_{q2\alpha} + \bar{\ell}_{p1} (C_\ell)_{pq} \gamma^\mu P_L \ell_{q2}] W^+_\mu + h.c. \}, &(6)\\
\mathcal{L}^{QCD}_\psi &= g_{st} G^j_\mu (\bar{Q} \gamma^\mu t_j Q), &(7)\\
\mathcal{L}^{QED}_\psi &= -|e| A_\mu (\bar{\psi} \gamma^\mu Q^{em} \psi), &(8)\\
\mathcal{L}^{NC}_\psi &= -Z_\mu J^Z_\mu - Z'_\mu J^{Z'}_\mu. &(9)
\end{aligned}$$

Features of Z'-boson originating from the four color symmetry.

In general case the mass eigenstates Z and Z' are superposition of two basic fields Z_1 and Z_2. In MQLS model the $Z - Z'$ mixing angle is small ($\theta_m < 0.006$) and we neglect below the $Z - Z'$ mixing believing $Z \approx Z_1$ and $Z' \approx Z_2$. The interaction of the neutral gauge fields with the fermions has the form

$$ \mathcal{L}^{\text{gauge}}_{\text{NC}} = -e Z_{1\mu} J^{Z_1}_\mu - \frac{e}{c_W} Z_{2\mu} J^{Z_2}_\mu, \tag{10}$$

$$\begin{aligned}
J^{Z_1}_\mu &= \bar{f} \gamma_\mu (v^{Z_1}_f + a^{Z_1}_f \gamma_5) f, &(11)\\
J^{Z_2}_\mu &= \bar{f} \gamma_\mu (v^{Z_2}_f + a^{Z_2}_f \gamma_5) f,
\end{aligned}$$

with couplings

$$\begin{aligned}
v^{Z_2}_{f_a} &= \frac{1}{s_S \sqrt{1 - s^2_W - s^2_S}} \left[c^2_W \sqrt{\frac{2}{3}} (t_{15})_f - \left(Q_{f_a} - \frac{(\tau_3)_{aa}}{4} \right) s^2_S \right], &(12)\\
a^{Z_2}_{f_a} &= \frac{s_S}{\sqrt{1 - s^2_W - s^2_S}} \frac{(\tau_3)_{aa}}{4}. &(13)
\end{aligned}$$

The fermionic decays of Z' boson are defined by the coupling constants (13) and the corresponding partial widths of Z' boson decays to $f_a\bar{f}_a$ pairs for $m_{f_a} \ll M_{Z'}$ have the form [4]

$$\Gamma(Z' \to f_a\bar{f}_a) = N_f M_{Z'} \frac{\alpha}{3}\big((v^{Z'}_{f_a})^2 + (a^{Z'}_{f_a})^2\big), \tag{14}$$

where the color factor $N_f = 1(3)$ for leptons(quarks) $f = l(q)$.

Writing the interaction of Z' boson with scalar field Φ as

$$\mathcal{L}_{Z'\Phi\Phi} = ig_{Z'\Phi\Phi} Z'_\mu \left(\partial^\mu \Phi^* \Phi - \Phi^* \partial^\mu \Phi\right), \tag{15}$$

where $g_{Z'\Phi\Phi}$ is the corresponding coupling constant for the width of Z' boson decay into $\Phi\tilde{\Phi}$ pair we have the expression

$$\Gamma(Z' \to \Phi\tilde{\Phi}) = N_\Phi M_{Z'} \frac{g^2_{Z'\Phi\Phi}}{48\pi}\left(1 - \frac{4m^2_\Phi}{M^2_{Z'}}\right)^{3/2} \tag{16}$$

where N_Φ is the color factor ($N_{F_a} = 8$ for scalar gluons, $N_{S^{(\pm)}_a} = 3$ for scalar leptoquarks, $N_{\Phi'_a} = 1$ for the additional colorless scalar doublet) and m_Φ is a mass of the scalar particle.

The scalar gluons F_a and the scalar leptoquarks $S^{(\pm)}_a$ gives the main contribution into Z' boson width of type (16). The coupling constants of these particles with Z' boson are predicted by the MQLS model as

$$g_{Z'F_aF_a} = -\frac{e}{2}\frac{\sigma}{s_W c_W}, \quad g_{Z'S^{(\pm)}_a S^{(\pm)}_a} = -e\left(\frac{\sigma}{2s_W c_W} \pm \frac{2t_W}{3\sigma}\right), \tag{17}$$

where $t_W = \tan\theta_W$ and $\sigma = s_W s_S/\sqrt{1 - s^2_W - s^2_S}$.

The parameter s_S is defined by the mass scale $M_c \sim M_V$ of the four-color symmetry breaking and by the intermediate mass scale $M' \sim M_{Z'}$. For example for $M' \sim 10\,TeV$ and for $M_c = 10^4\,TeV,\ 10^6\,TeV,\ 10^8\,TeV$ we have $s^2_s = 0.070,\ 0.112,\ 0.154$ respectively [2]. For numerical estimations we use below the value $s^2_s = 0.114$ which corresponds to $M_{Z'} \sim 1 - 5\,TeV$ and $M_c \sim 10^3\,TeV$. With these values of s^2_s and of the masses of scalar particles the relative total width of Z'–boson $\Gamma_{Z'}/M_{Z'}$ occurs to be equal to

$$\Gamma_{Z'}/M_{Z'} = 4.3\,\%\ (1.1\,\%,\ 3.2\,\%),\ \ 5.2\,\%\ (2.0\,\%,\ 3.2\,\%),\ \ 5.3\,\%\ (2.1\,\%,\ 3.2\,\%) \tag{18}$$

for $M_{Z'}$ of about respectively 1 TeV, 3 TeV, 5 TeV and above, the corresponding values of the relative widths of the Z' decays respectively into scalar particles and into fermions are shown in parenthesis.

The scalar sector contains in general four multiplets [2,3,5]

$$\begin{aligned}
(4,1,1) : \Phi^{(1)} &= \begin{pmatrix} S^{(1)}_\alpha \\ \frac{\eta_1 + \chi^{(1)} + i\omega^{(1)}}{\sqrt{2}} \end{pmatrix}, \\
(1,2,1) : \Phi^{(2)}_a &= \delta_{a2}\frac{\eta_2}{\sqrt{2}} + \phi^{(2)}_a, \\
(\mathbf{15},\mathbf{2},\mathbf{1}) : \Phi^{(3)}_a &= \begin{pmatrix} (\mathbf{F_a})_{\alpha\beta} & \mathbf{S}^{(+)}_{\mathbf{a}\alpha} \\ \mathbf{S}^{(-)}_{\mathbf{a}\alpha} & 0 \end{pmatrix} + \Phi^{(3)}_{15,a} t_{15}, \\
(15,1,0) : \Phi^{(4)} &= \begin{pmatrix} F^{(4)}_{\alpha\beta} & \frac{1}{\sqrt{2}} S^{(4)}_\alpha \\ \overset{*}{S}{}^{(4)}_\alpha & 0 \end{pmatrix} + (\eta_4 + \chi^{(4)}) t_{15},
\end{aligned} \tag{19}$$

transforming according to the (4,1,1)-,(1,2,1)-,(15,2,1)-,(15,1,0)- representations of the $SU_V(4) \times SU_L(2) \times U_R(1)$-group respectively. Here $\Phi^{(3)}_{15,a} = \delta_{a2}\eta_3 + \phi^{(3)}_{15,a}$, η_1, η_2, η_3, η_4 are the vacuum expectation values.

Third multiplet (15.2.1) interacts with quarks.

$$(15.2.1) : \Phi^{(3)} : \qquad \begin{pmatrix} S^{(+)}_{1\alpha} \\ S^{(+)}_{2\alpha} \end{pmatrix}; \begin{pmatrix} S^{(-)}_{1\alpha} \\ S^{(-)}_{2\alpha} \end{pmatrix}; \begin{pmatrix} F_{1k} \\ F_{2k} \end{pmatrix}; \begin{pmatrix} \Phi^{(3)}_{1,15} \\ \Phi^{(3)}_{1,15} \end{pmatrix}, \tag{20}$$

where $\mathbf{S}^{(\pm)}_{\mathbf{a}\alpha}$ and $\mathbf{F_{ak}}$ (k=1,2...8) are the scalar leptoquark and scalar gluons doublets. $\Phi^{(3)}_{15} - \Phi^{(2)}$-mixing gives the SM Higgs doublet $\Phi^{(SM)}$ and an additional Φ' doublet. These scalar doublets have the electric charges

$$Q_{em} : \qquad \begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix}; \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix}.$$

In general

$$S^{(+)}_{2\alpha} = \sum_{m=0}^{3} c^{(+)}_m S_m, \qquad \overset{*}{S}{}^{(-)}_2 = \sum_{m=0}^{3} c^{(-)}_m S_m,$$

where S_m are three physical leptoquarks with electric charge 2/3 and S_0 is the Goldstone mode, $c^{(\pm)}_m$ are the elements of the unitary scalar leptoquark mixing matrix, $|c^{(\pm)}_0|^2 = \frac{1}{3} g_4^2 \eta_3^2 / m_V^2 \ll 1$.

The experimental lower mass limits for the scalar leptoquarks from their direct search are [6]

$$m_{LQ} \gtrsim 250 \text{ GeV}. \tag{21}$$

The indirect data set the limits on the relations of scalar leptoquark coupling constants to their masses.

In MQLS-model the leptoquark Yukawa coupling constants are (due their Higgs origin) proportional to the ratios m_f/η of the fermion masses m_f to the SM VEV η. As a result these coupling constants are known (up to mixing parameters) and are small for light quarks. So, the indirect mass limits for MQLS scalar leptoquarks are weaker then those from direct searchers.

Mass limits for scalar gluons F_{ak}.

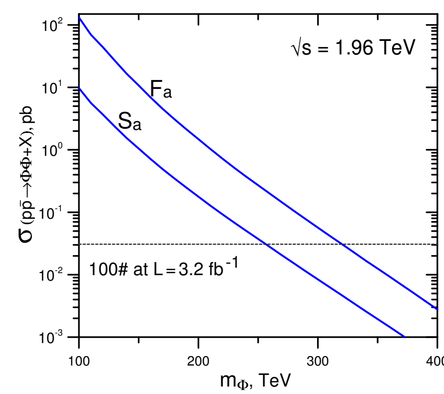

Figure 1: Cross sections of SS^*-,FF^*-pair production at the Tevatron as functions of the masses of scalar particles.

The partonic cross sections of scalar gluon pair production are known [7–9], which gives now possibility to calculate cross section of scalar gluon pair production at the Tevatron in dependence on scalar gluon mass. In these calculations we use PDF's set AL'03 [10] (NLO, variable-favor-number) with the K-factor chosen as $K = 1.45$ for consistency with theoretically predicted dependence of $\sigma^{NLO}(t\bar{t})$ on m_t [11, 12].

Our estimate for mass limits for scalar gluons F_a from direct searches at Tevatron is

$$m_{F_a} \gtrsim 320 \text{ GeV}. \tag{22}$$

Possibility of the direct searches scalar gluon at the LHC

The production cross section of scalar gluons F at the LHC with masses $m_F \lesssim 1300\,GeV$ is shown to be sufficient for the effective ($N_{events} \gtrsim 100$) production of these particles at the LHC ($L = 10\,fb^{-1}$) [8].

At $m_{F_1} \lesssim 990\,GeV$ from analysis statistical significance the number of the signal $t\bar{t}b\bar{b}$ events will exceed the SM background by 3σ (LHC $L = 10\,fb^{-1}$) [9].

The interaction of the fermions with the scalars.

The Yukawa interaction of the fermions with the scalar $SU_L(2)$- doublets $\phi^{(2)}$ and $\phi_i^{(3)}$ has, in general, the form

$$\mathcal{L}_{\psi}^{Yukawa} = -\bar{\psi}'^{L}_{paA}\big[\big(h_b\big)_{pq}\phi_a^{(2)b}\delta_{AB} + \big(h'_b\big)_{pq}\phi_{ia}^{(3)b}\big(t_i\big)_{AB}\big]\psi'^{R}_{qbB} + h.c., \tag{23}$$

where $\phi_a^{(2)2} = \phi_a^{(2)}$, $\phi_a^{(2)1} = \varepsilon_{ac}(\phi_c^{(2)})^*$, $\phi_{ia}^{(3)2} = \phi_{ia}^{(3)}$, $\phi_{ia}^{(3)1} = \varepsilon_{ac}(\phi_{ic}^{(3)})^*$, $i = 1,\ 2,\ \ldots,\ 15$, ε_{ac} is antisymmetrical symbol, h_b and h'_b are four arbitrary matrices.

After symmetry breaking this Lagrangian gives the arbitrary masses to the quarks and leptons and gives the interactions of fermions with the scalar fields

$$\mathcal{L}_{\Psi}^{int} = \mathcal{L}_{\chi^{(SM)}ff} + \mathcal{L}_{\Phi' ff} + \mathcal{L}_{FQQ} + \mathcal{L}_{SQl}. \tag{24}$$

$$h \sim m_f/\eta,$$
$$m_u/\eta \sim m_d/\eta \sim 10^{-5}, m_s/\eta \sim 10^{-3}, \quad m_c/\eta \sim m_b/\eta \sim 10^{-2},$$
$$m_t/\eta \sim 0.7. \ \ !!!$$

The interactions of the scalar leptoquarks $S_{a\alpha}^{(\pm)}$ with quarks and leptons:

$$\begin{aligned}
L_{S_1^{(+)}u_i l_j} &= \bar{u}_{i\alpha}\Big[(h_+^L)_{ij}P_L + (h_+^R)_{ij}P_R\Big] l_j S_{1\alpha}^{(+)} + \text{h.c.},\\
L_{S_1^{(-)}\nu_i d_j} &= \bar{\nu}_i\Big[(h_-^L)_{ij}P_L + (h_-^R)_{ij}P_R\Big] d_{j\alpha} S_{1\alpha}^{(-)} + \text{h.c.},\\
L_{S_m u_i \nu_j} &= \bar{u}_{i\alpha}\Big[(h_{1m}^L)_{ij}P_L + (h_{1m}^R)_{ij}P_R\Big] \nu_j S_{m\alpha} + \text{h.c.}\\
L_{S_m d_i l_j} &= \bar{d}_{i\alpha}\Big[(h_{2m}^L)_{ij}P_L + (h_{2m}^R)_{ij}P_R\Big] l_j S_{m\alpha} + \text{h.c.}
\end{aligned} \tag{25}$$

The interactions of the scalar gluons with quarks:

$$\begin{aligned}
L_{F_1 u_i d_j} &= \bar{u}_{i\alpha}\Big[(h_{F_1}^L)_{ij}P_L + (h_{F_1}^R)_{ij}P_R\Big](t_k)_{\alpha\beta} d_{j\beta} F_{1k} + \text{h.c.},\\
L_{F_2 u_i u_j} &= \bar{u}_{i\alpha}\Big[(h_{1F_2}^L)_{ij}P_L\Big](t_k)_{\alpha\beta} u_{j\beta} F_{2k} + \text{h.c.},\\
L_{F_2 d_i d_j} &= \bar{d}_{i\alpha}\Big[(h_{2F_2}^R)_{ij}P_R\Big](t_k)_{\alpha\beta} d_{j\beta} F_{2k} + \text{h.c.}
\end{aligned} \tag{26}$$

Scalar leptoquarks $S_1^{(\pm)}$, S_m couplings to fermions:

$$
\begin{aligned}
(h_+^L)_{ij} &= \sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[m_{u_i}(K_1^L C_l)_{ij} - (K_1^R)_{ik} m_{\nu_i}(C_l)_{kj}\Big], \\
(h_+^R)_{ij} &= -\sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[(C_Q)_{ik} m_{d_k}(K_2^R)_{kj} - m_{l_j}(C_Q K_2^L)_{ij}\Big], \\
(h_-^L)_{ij} &= \sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[(\overset{+}{K}{}_1^R)_{ik} m_{u_k}(C_Q)_{kj} - m_{\nu_j}(\overset{+}{K}{}_1^L C_Q)_{ij}\Big], \\
(h_-^R)_{ij} &= -\sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[(C_l \overset{+}{K}{}_2^L)_{ij} m_{d_j} - (C_l)_{ik} m_{l_k}(\overset{+}{K}{}_2^R)_{kj}\Big], \\
(h_{1m}^{L,R})_{ij} &= -\sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[m_{u_i}(K_1^{L,R})_{ij} - (K_1^{R,L})_{ij} m_{\nu_j}\Big] c_m^{(\pm)}, \\
(h_{2m}^{L,R})_{ij} &= -\sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[m_{d_i}(K_2^{L,R})_{ij} - (K_2^{R,L})_{ij} m_{l_j}\Big] c_m^{(\mp)},
\end{aligned}
\tag{27}
$$

where β is $\Phi_a^{(2)} - \Phi_{15}^{(3)}$ mixing angle in MQLS model, $tg\beta = \eta_3/\eta_2$, $C_Q = V_{CKM}$, $C_l = U_{PMNS}$ and $K_a^{L,R} = (A_{Q_a}^{L,R})^+ A_{l_a}^{L,R}$ are the mixing matrices specific for the MQLS model.

Scalar gluons F_a couplings to fermions:

$$
\begin{aligned}
(h_{F_1}^L)_{ij} &= \sqrt{3}\frac{1}{\eta\sin\beta}\Big[m_{u_i}(C_Q)_{ij} - (K_1^R)_{ik} m_{\nu_k}(\overset{+}{K}{}_1^L C_l)_{kj}\Big], \\
(h_{F_1}^R)_{ij} &= -\sqrt{3}\frac{1}{\eta\sin\beta}\Big[(C_Q)_{ij} m_{d_i} - (C_l K_2^L)_{ik} m_{l_k}(\overset{+}{K}{}_2^R)_{kj}\Big], \\
(h_{1F_2}^L)_{ij} &= -\sqrt{3}\frac{1}{\eta\sin\beta}\Big[m_{u_i}\delta_{ij} - (K_1^R)_{ik} m_{\nu_k}(\overset{+}{K}{}_1^L)_{kj}\Big], \\
(h_{2F_2}^R)_{ij} &= -\sqrt{3}\frac{1}{\eta\sin\beta}\Big[m_{d_i}\delta_{ij} - (K_1^L)_{ik} m_{l_k}(\overset{+}{K}{}_1^R)_{kj}\Big], \\
(h_{1F_2}^R)_{ij} &= 0, \\
(h_{2F_2}^L)_{ij} &= 0.
\end{aligned}
\tag{28}
$$

The largest couplings $h \sim m_t/\eta$:

$$
\begin{aligned}
S_1^{(+)}\bar{t}\tau: \quad (h_+^L)_{33} &= \sqrt{3/2}\frac{m_t}{\eta\sin\beta}(K_1^L C_l)_{33}, \\
S_1^{(-)}\bar{\nu_\tau} b: \quad (h_-^L)_{33} &= \sqrt{3/2}\frac{m_t}{\eta\sin\beta}(\overset{+}{K}{}_1^R)_{33}(C_Q)_{33}, \\
S_m\bar{t}\nu_\tau: \quad (h_{1m}^{L,R})_{33} &= -\sqrt{3/2}\frac{m_t}{\eta\sin\beta}(K_1^{L,R})_{33} c_m^{(\pm)}, \\
F_1\bar{t}b: \quad (h_{F_1}^L)_{33} &= \sqrt{3}\frac{m_t}{\eta\sin\beta}(C_Q)_{33}, \\
F_2\bar{t}t: \quad (h_{1F_2}^L)_{33} &= -\sqrt{3}\frac{m_t}{\eta\sin\beta}.
\end{aligned}
\tag{29}
$$

$m_t/\eta \sim 0.7!$

2 $t\bar{t}$ Production at the Tevatron

With account these large couplings of scalars with t-quarks, scalar leptoquarks and scalar gluons may give significant contribution in $t\bar{t}$-quark production at Tevatron.

The latest CDF data on cross section and forward-backward asymmetry of the $t\bar{t}$ production at the Tevatron CDF [14, 15]

$$\sigma_{t\bar{t}} = 7.5 \pm 0.31(stat) \pm 0.34(syst) \pm 0.15(lumi)\text{pb}, \tag{30}$$

$$A^{t\bar{t}}_{\text{FB}} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (sys)}. \tag{31}$$

<u>$\sigma_{t\bar{t}}$ SM prediction</u> [11]:

$$\sigma^{SM}_{t\bar{t}} = 7.35 \ {}^{+0.38}_{-0.80} \text{ (scale) } {}^{+0.49}_{-0.34} \text{ (PDFs)[CTEQ6.5] pb} \div \tag{32}$$
$$7.93 \ {}^{+0.34}_{-0.56} \text{ (scale) } {}^{+0.24}_{-0.20} \text{ (PDFs)[MRST2006nnlo] pb.}$$

<u>$A^{t\bar{t}}_{\text{FB}}$ SM prediction</u> [16]:

$$A^{t\bar{t}}_{\text{FB}} = 0.051(6), \tag{33}$$

$$A^{t\bar{t}}_{\text{FB}} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)}. \tag{34}$$

The measured at CDF forward-backward asymmetry has significant ($\approx 2\sigma$) deviation from predictions [16]. This may be indication of new physics.

The LO parton subprocesses of $p\bar{p} \to t\bar{t}$ in SM are described by diagrams at Fig. 2 of order α_s^2.

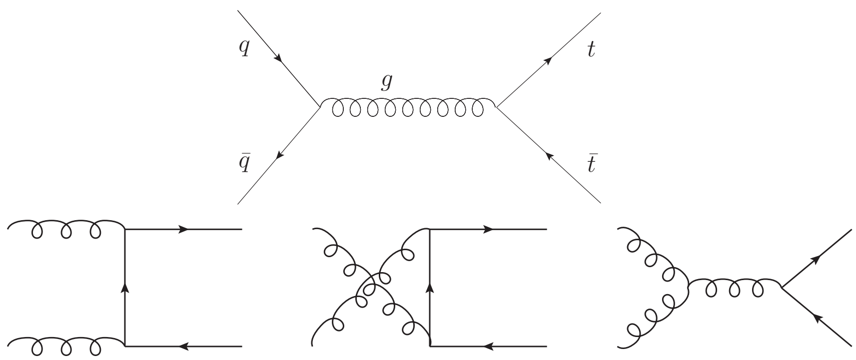

Figure 2: Partonic subprocesses $q\bar{q} \to t\bar{t}$, $gg \to t\bar{t}$

The well-known $p\bar{p} \to t\bar{t}$ LO cross sections have form

$$\frac{d\sigma(q\bar{q} \to t\bar{t})}{d\cos\hat{\theta}} = \frac{\alpha_s^2 \pi\beta}{9\hat{s}} \left(1 + \beta^2 c^2 + 4m_t^2/\hat{s}\right), \tag{35}$$

$$\sigma(q\bar{q} \to t\bar{t}) = \frac{4\pi\alpha_s^2\beta}{27\hat{s}} \left(3 - \beta^2\right),$$

$$\frac{d\sigma(gg \to t\bar{t})}{d\cos\hat{\theta}} = \alpha_s^2 \frac{\pi\beta}{6\hat{s}} \left(\frac{1}{1-\beta^2c^2} - \frac{9}{16}\right)\left(1 + \beta^2c^2 + 2(1-\beta^2) - \frac{2(1-\beta^2)^2}{1-\beta^2c^2}\right), \tag{36}$$

$$\sigma(gg \to t\bar{t}) = \frac{\pi\alpha_s^2}{48\hat{s}} \left[\left(\beta^4 - 18\beta^2 + 33\right) \log\left(\frac{1+\beta}{1-\beta}\right) + \beta\left(31\beta^2 - 59\right)\right],$$

where $c = \cos\hat{\theta}$, $\hat{\theta}$ is the scattering angle of t-quark in the parton center of mass frame, $\hat{s}$ is the invariant mass of $t\bar{t}$ system, $\beta = \sqrt{1 - 4m_t^2/\hat{s}}$.

No sources of order α_s^2 for the forward-backward asymmetry.

<u>MQLS model contributions in $t\bar{t}$ production</u>

In MQLS there are three kind of contributions in $t\bar{t}$-production.

1. Z' tree s-channel process,
2. Scalar gluons tree processes,
3. 1-loop $gt\bar{t}$ effective vertex.

Z' tree s-channel process

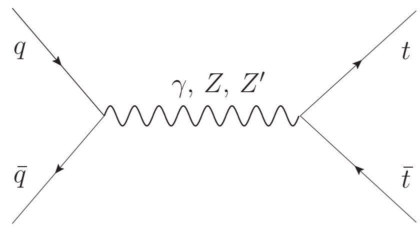

Figure 3: Subprocess $q\bar{q} \overset{\gamma,Z,Z'}{\longrightarrow} t\bar{t}$

Partonic subprocess $q\bar{q} \overset{\gamma,Z,Z'}{\longrightarrow} t\bar{t}$ is pictured at Fig. 3. Because initial quarks have singlet color state these diagrams do not interfere with octet state QCD tree processes.

We obtain differential cross section of $q\bar{q} \overset{\gamma,Z,Z'}{\longrightarrow} t\bar{t}$ with account masses of final t-quarks in the form

$$\frac{d\sigma(q\bar{q} \overset{\gamma,Z,Z'}{\longrightarrow} t\bar{t})}{d\cos\hat{\theta}} = \frac{\pi\alpha_{em}^2 \hat{s}\beta}{2} \sum_{i,j=\gamma,Z,Z'} K_{ij} \mathrm{Re}(P_i(\hat{s})P_j^*(\hat{s})), \tag{37}$$

$\cos\hat{\theta} \equiv c$.

Here,

$$\begin{aligned} K_{ij} &= A_{ij}\left(2+\beta^2(c^2-1)\right) + B_{ij}\beta^2(c^2+1) + 2C_{ij}\beta c, \\ A_{ij} &= (a_i^q a_j^q + v_i^q v_j^q) v_i^t v_j^t, \\ B_{ij} &= (a_i^q a_j^q + v_i^q v_j^q) a_i^t a_j^t, \\ C_{ij} &= (a_i^q v_j^q + v_i^q a_j^q)(a_i^t v_j^t + v_i^t a_j^t), \\ P_i(\hat{s}) &= \frac{1}{\hat{s} - M_i^2 + iM_i\Gamma_i}, \end{aligned} \tag{38}$$

v_i^q, a_i^q – vector and axial-vector couplings of q-quark with i-th neutral boson.

For $M_{Z'} > 1.4$ TeV (current experimental limit [4, 6]), contributions of Z' to cross section and FB asymmetry of the $t\bar{t}$ production is small due smallness of couplings

$$\Delta\sigma(p\bar{p} \to t\bar{t}) \sim +0.05 \div 0.1\,\mathrm{pb}, \tag{39}$$
$$\Delta A_{FB}^{t\bar{t}} \sim +0.003. \tag{40}$$

Scalar gluons tree processes

Contributions of diagrams at Fig. 4 are suppressed by factors $m_q^2/\hat{s}$ or $|(V_{CKM})_{i3}|^4$

$$\Delta\sigma(p\bar{p} \to t\bar{t}) \sim 0.0001\,\mathrm{pb}, \tag{41}$$
$$\Delta A_{FB}^{t\bar{t}} \sim 10^{-6}. \tag{42}$$

1-loop $gt\bar{t}$ effective vertex

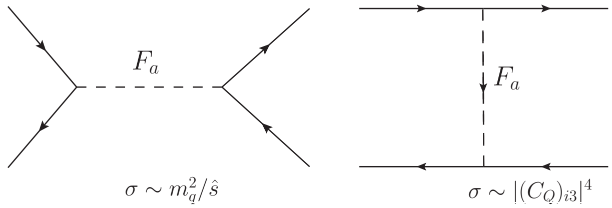

Figure 4: s- and t-channel diagrams of $q\bar{q} \to F_a \to t\bar{t}$.

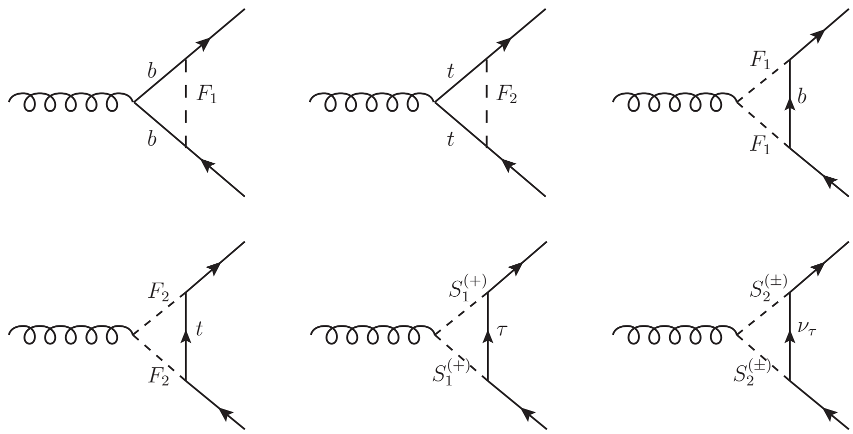

Figure 5: 1-loop main contributions into effective $gt\bar{t}$-vertex in MQLS-model.

The significant contributions to $t\bar{t}$ production may arise from loop corrections to the $gt\bar{t}$-vertex.

Following the parametrization in Ref. [17, 18], the effective matrix element of $gt\bar{t}$, including the one-loop corrections, can be written as

$$-ig_s T^a \bar{u}_t \Gamma^\mu v_{\bar{t}}, \tag{43}$$

with

$$\Gamma^\mu = (1+\alpha)\gamma^\mu + i\beta\sigma^{\mu\nu}q_\nu + \xi\left(\gamma^\mu - \frac{2m_t}{\hat{s}}q^\mu\right)\gamma_5. \tag{44}$$

where the loop-induced form factors α, β and ξ are usually refereed as the chromo-charge, chromo-magnetic-dipole and chromo-anapole, respectively. Here, g_s is the strong coupling strength, T^a are the color generators, $q = p_t + p_{\bar{t}}$, and $\hat{s} = q^2$. After summing over the final state and averaging over the initial state colors and spins, the partonic total cross section of $q\bar{q} \to g \to t\bar{t}$ is [17]

$$\hat{\sigma} = \frac{8\pi\alpha_s^2}{27\hat{s}^2}\sqrt{1-\frac{4m_t^2}{\hat{s}}}\left\{\hat{s} + 2m_t^2 + 2\mathrm{Re}\left[(\hat{s}+2m_t^2)\alpha + 3m_t\hat{s}\,\beta\right]\right\}, \tag{45}$$

where $\alpha_s \equiv g_s^2/(4\pi)$, and Re denotes taking its real part. In MQLS-model main 1-loop contributions into effective $gt\bar{t}$-vertex are described by diagrams at Fig.5. The parameters α, β can be calculated using the diagrams shown in Fig. 5 and the coupling constants (27-28).

3 Summary

- The contributions to the cross section $\sigma_{t\bar{t}}$ and to the forward-backward asymmetry $A_{\rm FB}^{t\bar{t}}$ of $t\bar{t}$ production at the Tevatron from new Z',$S_a^{(\pm)}$, F_a particles predicted by the MQLS-model are calculated.

- These contributions in tree approximation are shown to be small ($\Delta\sigma \sim 0.1$ pb, $\Delta A^{t\bar{t}}_{\mathrm{FB}} \sim 0.003$).

- The scalar doublets $S_a^{(\pm)}$, F_a may give the significant contributions to the 1-loop $gt\bar{t}$ effective vertex.

- The lower mass limits for scalar gluons

$$m_F \gtrsim 320\, GeV$$

are obtained from the data on direct searches at Tevatron.

- At $m_{F_1} \lesssim 990\, GeV$ the scalar gluon F_1 can be evident at LHC at the significance not less that 3σ (for $L = 10\, fb^{-1}$).

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References

[1] J. C. Pati, A. Salam, Lepton number as the fourth 'color', Phys. Rev. D **10**(1), 275–289 (1974).

[2] A. D. Smirnov, Minimal four-color model with quark-lepton symmetry and constraints on the Z'-boson mass, Phys. At. Nucl. **58**(12), 2137–2143 (1995).

[3] A. D. Smirnov, The Minimal Quark-Lepton Symmetry Model and the Limit on Z'-mass, Physics Letters B **346**, 297 (1995). arXiv:hep-ph/9503239.

[4] A. D. Smirnov, Y. S. Zaitsev, On a possible manifestation of the four color symmetry Z' boson in $\mu^+\mu^-$ events at the LHC, Mod. Phys. Lett. **A24**, 1199–1207 (2009). arXiv:0902.2931.

[5] A. V. Povarov, A. D. Smirnov, Phys. At. Nucl. **64**, P. 74 (2001).

[6] C. Amsler, et al. (PDG), Review of Particle Physics, Phys. Lett. B **667**, 1 (2008).

[7] A. V. Manohar, M. B. Wise, Flavor Changing Neutral Currents, an Extended Scalar Sector, and the Higgs Production Rate at the LHC, Phys. Rev. **D74**, 035009 (2006). arXiv:hep-ph/0606172.

[8] M. V. Martynov, A. D. Smirnov, Colored scalar particles production in *pp*-collisions and possible mass limits for scalar gluons from future LHC data, Mod. Phys. Lett. **A23**, 2907–2913 (2008). arXiv:0807.4486.

[9] M. V. Martynov, A. D. Smirnov, Production of Colored Scalar Particles in *pp* Collisions and Masses of Scalar Gluons from Future LHC Data, Phys. At. Nucl. **73**(7), pp. 1207–1213 (2010).

[10] S. Alekhin, Parton distributions from deep-inelastic-scattering data, Phys.Rev.D **67**, 014002 (2003).

[11] M. Cacciari, S. Frixione, M. L. Mangano, P. Nason, G. Ridolfi, Updated predictions for the total production cross sections of top and of heavier quark pairs at the Tevatron and at the LHC, JHEP **09**, 127 (2008). arXiv:0804.2800.

[12] N. Kidonakis, R. Vogt, The Theoretical top quark cross section at the Tevatron and the LHC, Phys. Rev. **D78**, 074005 (2008). arXiv:0805.3844.

[13] M. V. Martynov, A. D. Smirnov, Chiral color symmetry and possible G'-boson effects at the Tevatron and LHC, Mod. Phys. Lett. **A24**, 1897–1905 (2009). arXiv:0906.4525.

[14] CDF Collaboration, Combination of CDF top quark pair production cross section measurements with up to 4.6 fb^{-1}, Public Note 9913 (2009).

[15] CDF Collaboration, Measurement of the Forward-Backward Asymmetry in Top Pair Production in 3.2/fb of ppbar collisions at sqrt(s)=1.96 TeV, CDF/ANAL/TOP/PUBLIC/9724 (2009).

[16] O. Antunano, J. H. Kuhn, G. Rodrigo, Top Quarks, Axigluons and Charge Asymmetries at Hadron Colliders, Phys. Rev. **D77**, 014003 (2008), arXiv.org:0709.1652.

[17] A. Stange, S. Willenbrock, Yukawa correction to top quark production at the Tevatron, Phys. Rev. **D48**, 2054–2061 (1993). arXiv:hep-ph/9302291.

[18] Q.-H. Cao, C.-R. Chen, F. Larios, C. P. Yuan, Anomalous gtt couplings in the Littlest Higgs Model with T-parity, Phys. Rev. **D79**, 015004 (2009). arXiv:0801.2998.