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 $A_{t\bar{t}}^{FB}$ of $t\bar{t}$ production at the Tevatron from $Z'$-boson and scalar leptoquarks $S^a_1(\pm)$ 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 $m_F \gtrsim 320 \text{GeV}$ from the Tevatron data is obtained and it is shown that for $m_{F_1} \lesssim 990 \text{GeV}$ the scalar gluon $F_1$ can be evident at LHC at the significance not less that $3\sigma$ (for $\sqrt{s} = 14 \text{ TeV}$, $L = 10 \text{ fb}^{-1}$).

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

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

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

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

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

According to this group in addition to gluons $G_{\mu}^j$, $j = 1, 2, \ldots, 8$ and $W^\pm$, $Z$-bosons the gauge sector predicts the new gauge particles: vector leptoquarks $V_{\alpha\mu}^\pm$, $\alpha = 1, 2, 3$ with charges $Q_{V} = \pm 2/3$ 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 $\psi_{pA}$, $A = 1, 2, 3, 4$, $a = 1, 2$, $p = 1, 2, 3, \ldots$

$$\psi_{pA}^I : \left( \begin{array}{c} u_{\alpha}^I \\ e_{\nu}^I \\ c_{\alpha}^I \\ \nu_{\mu}^I \end{array} \right)$$

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where $Q^L,R_{pa}$, $\nu^L,R_{pa}$ are the basic left and right quark and lepton fields.

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

Fermion mixing in MQLS.

The basic left and right quark and lepton fields $Q^L,R_{pa}$, $\nu^L,R_{pa}$ can be written, in general, as superpositions

$$Q^L,R_{pa} = \sum_q (A^L,R_{qa})_{pq} Q^L,R_{qa}, \quad \nu^L,R_{pa} = \sum_q (A^L,R_{ta})_{pq} \nu^L,R_{ta},$$

(3)

of mass eigenstates $Q^L,R_{qa}$, $\nu^L,R_{q}$, Here $A^L,R_{qa}$ and $A^L,R_{ta}$ 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 $(A^L_{f_1})^+ A^L_{f_2} \equiv C_f$ is the analogous lepton mixing matrix $(C_f)^+ = U_{PMNS}$

$(A^L,R_{Q})^+ A^L,R_{e} = K^L,R_e$ 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

$$\mathcal{L}_\psi^{\text{gauge}} = \mathcal{L}_\psi^V + \mathcal{L}_\psi^W + \mathcal{L}_\psi^{QCD} + \mathcal{L}_\psi^{QED} + \mathcal{L}_\psi^{NC},$$

(4)

where

$$\mathcal{L}_\psi^V = \frac{g_s}{\sqrt{2}} \left\{ (Q_{pa} \left[ (K^L_{pq})_{\gamma^\mu} P_L + (K^R_{pq})_{\gamma^\mu} P_R \right] \ell_{qa}) V^\alpha_{\mu} + h.c. \right\},$$

(5)

$$\mathcal{L}_\psi^W = \frac{g_2}{\sqrt{2}} \left\{ \left[ \bar{Q}_{p1} (C_Q) \gamma^\mu P_L Q_{q2a} + \bar{\ell}_{p1} (C_f) \gamma^\mu P_L \ell_{q2} \right] W^+_\mu + h.c. \right\},$$

(6)

$$\mathcal{L}_\psi^{QCD} = g_s C_\mu^L \bar{Q} \gamma^\mu t_j Q,$$

(7)

$$\mathcal{L}_\psi^{QED} = -|e| A_\mu \left( \bar{\psi} \gamma^\mu Q^{em} \psi \right),$$

(8)

$$\mathcal{L}_\psi^{NC} = -Z_\mu J^Z_\mu - Z'_\mu J'^Z_\mu.$$  

(9)

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

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

(10)

$$J^Z_{\mu} = \bar{f} \gamma_\mu (v_1 Z_1 + a_1 Z_5) f,$$

(11)

$$J'^Z_{\mu} = \bar{f} \gamma_\mu (a_2 Z_2 + a_2 Z_5) f,$$

with couplings

$$v_{Z_1}^{Z_2} = \frac{1}{s_S \sqrt{1 - s_W^2 - s_S^2}} \left[ \lambda_2 \sqrt{\frac{2}{3}} (f_{15} f - \left( Q_{fa} - \frac{(\tau_3)_{aa}}{4} \right) s_S^2 \right],$$

(12)

$$a_{Z_1}^{Z_2} = \frac{s_S}{\sqrt{1 - s_W^2 - s_S^2}} \frac{(\tau_3)_{aa}}{4},$$

(13)
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 \([14]\)

$$\Gamma(Z' \to f_a\bar{f}_a) = N_f M_{Z'} \frac{\alpha}{3} ((v_{f_a}^Z)^2 + (a_{f_a}^{Z'})^2),$$

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

Writing the interaction of $Z'$ boson with scalar field $\Phi$ as

$$\mathcal{L}_{Z'\Phi} = i g_{Z'\Phi} Z'_\mu (\partial^\mu \Phi^* \Phi - \Phi^* \partial^\mu \Phi),$$

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

$$\Gamma(Z' \to \Phi \bar{\Phi}) = N_\Phi M_{Z'} \frac{g_{Z'\Phi}^2}{48\pi} \left(1 - \frac{4m_{\Phi}^2}{M_{Z'}^2}\right)^{3/2}$$

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

The scalar gluons $F_a$ and the scalar leptoquarks $S_a^{(\pm)}$ 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

$$g_{Z'F_aF_a} = -\frac{e}{2s_Wc_W}r, \quad g_{Z'S_a^{(\pm)}S_a^{(\pm)}} = -e\left(\frac{\sigma}{2s_Wc_W} \pm \frac{2t_W}{3}\right),$$

where $t_W = \tan\theta_W$ and $\sigma = s_Ws_s/\sqrt{1-s_W^2-s_s^2}$.

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

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

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{align*}
(4,1,1) : \Phi^{(1)} & = \begin{pmatrix} 
S^{(1)}_\alpha \\
\eta + \chi^{(1)} + \epsilon^{(1)}
\end{pmatrix}, \\
(1,2,1) : \Phi^{(2)}_a & = \frac{\eta_2}{\sqrt{2}} + \phi^{(2)}_a, \\
(15,2,1) : \Phi^{(3)}_a & = \begin{pmatrix} 
(F_a)_{\alpha\beta} & S^{(4)}_{a\alpha} \\
S^{(-)}_{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)}_{a\alpha} \\
\phi^{(4)}_{a\alpha} & 0
\end{pmatrix} + (\eta_1 + \chi^{(4)}) t_{15},
\end{align*}

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 $\Phi^{(3)}_{15,a} = \delta_{a2} \eta_3 + \phi^{(3)}_{15,a}$, $\eta_1$, $\eta_2$, $\eta_3$, $\eta_4$ are the vacuum expectation values.
Third multiplet (15.2.1) interacts with quarks.

\[(15.2.1) : \Phi^{(3)} : \begin{pmatrix} S_{1\alpha}^{(+)} \\ S_{2\alpha}^{(+)} \end{pmatrix}, \begin{pmatrix} S_{1\alpha}^{(-)} \\ S_{2\alpha}^{(-)} \end{pmatrix}, F_{1k}, F_{2k}, \Phi^{(3)}_{1,15}, \Phi^{(3)}_{1,15}, \tag{20}\]

where \( S_{2\alpha}^{(\pm)} \) and \( F_{ak} \) (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 \( \Phi^{'} \) doublet. These scalar doublets have the electric charges

\[Q_{em} : \begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix}, \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix}.\]

In general

\[
S_{2\alpha}^{(+)} = \sum_{m=0}^{3} c_{m}^{(+)} S_{m}, \quad S_{2}^{(-)} = \sum_{m=0}^{3} c_{m}^{(-)} S_{m},
\]

where \( S_{m} \) are three physical leptoquarks with electric charge 2/3 and \( S_{0} \) is the Goldstone mode, \( c_{m}^{(\pm)} \) are the elements of the unitary scalar leptoquark mixing matrix, \( |c_{0}^{(\pm)}|^{2} = 1 - g_{h}^{2} m_{H}^{2} / m_{V}^{2} \ll 1 \).

The experimental lower mass limits for the scalar leptoquarks from their direct search are \[m_{LQ} \gtrsim 250 \text{ GeV}.\] \( \tag{21} \)

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 \( m_{f} / \eta \) of the fermion masses \( m_{f} \) to the SM VEV \( \eta \). 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 \( F_{ak} \).

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 \( m_{t} \) \([11,12]\).

Figure 1: Cross sections of \( SS^{*}, FF^{*} \)-pair production at the Tevatron as functions of the masses of scalar particles.
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 \( m_F \lesssim 1300 \text{ GeV} \) is shown to be sufficient for the effective \( (N_{\text{events}} \gtrsim 100) \) production of these particles at the LHC \( (L = 10 \text{ fb}^{-1}) \) \[8\].

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

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

\[
\mathcal{L}^{\text{Yukawa}}_\psi = -\bar{\psi}_{R \alpha}L \left[(h^L_b)_{pq} \phi^{(2)k}_a \delta_{AB} + (h^R_b)_{pq} \phi^{(3)k}_a (t_i)_{AB} \right] \psi_{R \alpha b}^R + h.c.,
\]

where \( \phi^{(2)k}_a = \phi^{(2)1}_a \), \( \phi^{(2)2}_a = \varepsilon_{ac} \phi^{(2)c}_a \), \( \phi^{(3)k}_a = \phi^{(3)1}_a \), \( \phi^{(3)2}_a = \varepsilon_{ac} \phi^{(3)c}_a \), \( i = 1, 2, \ldots, 15 \), \( \varepsilon_{ac} \) is antisymmetrical symbol, \( h^L_b \) and \( h^R_b \) 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

\[
\mathcal{L}^{\text{int}}_\psi = \mathcal{L}^{(SM), ff} + \mathcal{L}^{\text{ff}'} + \mathcal{L}^{FQQ} + \mathcal{L}^{SQl}.
\]

\[
h \sim m_f/\eta, \\
m_u/\eta \sim m_d/\eta \sim 10^{-5}, m_s/\eta \sim 10^{-3}, \\
m_c/\eta \sim m_b/\eta \sim 10^{-2}, \\
m_l/\eta \sim 0.7. \tag{24}
\]

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

\[
L_{S_1^{(\pm)_{uij}}} = \bar{u}_{ia} \left[(h^L_+)^{ij} P_L + (h^R_+)^{ij} P_R \right] l_j S_{\alpha\alpha}^{(\pm)} + h.c.,
\]

\[
L_{S_{muij}} = \bar{u}_{a} \left[(h^L_{1m})^{ij} P_L + (h^R_{1m})^{ij} P_R \right] l_j S_{\alpha\alpha} + h.c.,
\]

\[
L_{S_{mdij}} = \bar{d}_{ia} \left[(h^L_{2m})^{ij} P_L + (h^R_{2m})^{ij} P_R \right] l_j S_{\alpha\alpha} + h.c.
\]

The interactions of the scalar gluons with quarks:

\[
L_{F_1uij} = \bar{u}_{ia} \left[(h^L_{F_1})^{ij} P_L + (h^R_{F_1})^{ij} P_R \right] (t_k)_{\alpha\beta} d_{j\beta} F_{1k} + h.c.,
\]

\[
L_{F_{2uij}} = \bar{u}_{ia} \left[(h^L_{F_2})^{ij} P_L \right] (t_k)_{\alpha\beta} u_{j\beta} F_{2k} + h.c.,
\]

\[
L_{F_{dij}} = \bar{d}_{ia} \left[(h^R_{F_2})^{ij} P_R \right] (t_k)_{\alpha\beta} d_{j\beta} F_{2k} + h.c.
\]

Scalar leptoquarks \( S_1^{(\pm)} \), \( S_m \) couplings to fermions:
\[ (h_+^L)_{ij} = \frac{\sqrt{3}}{2} \frac{1}{\eta \sin \beta} \left[ m_{u_i} (K_1^L C_l)_{ij} - (K_1^R)_{ik} m_{\nu_k} (C_l)_{kj} \right], \]
\[ (h_+^R)_{ij} = -\frac{\sqrt{3}}{2} \frac{1}{\eta \sin \beta} \left[ (C_Q)_{ik} m_{d_k} (K_2^R)_{kj} - m_{\nu_j} (C_Q K_2^R)_{ij} \right], \]
\[ (h_-^L)_{ij} = \sqrt{3} \frac{1}{\eta \sin \beta} \left[ (K_1^R)_{ik} m_{u_k} (C_Q)_{kj} - m_{\nu_j} (K_1^L C_Q)_{ij} \right], \]
\[ (h_-^R)_{ij} = -\sqrt{3} \frac{1}{\eta \sin \beta} \left[ (C_l K_2^L)_{ij} m_{d_j} - (C_l)_{ik} m_{t_k} (K_2^R)_{kj} \right], \]
\[ (h_{1m}^{L,R})_{ij} = -\sqrt{3} \frac{1}{\eta \sin \beta} \left[ m_{u_i} (K_1^{L,R})_{ij} - (K_1^{R,L})_{ij} m_{\nu_j} \right] c_{m}^{(+,-)}, \]
\[ (h_{2m}^{L,R})_{ij} = -\sqrt{3} \frac{1}{\eta \sin \beta} \left[ m_{d_i} (K_2^{L,R})_{ij} - (K_2^{R,L})_{ij} m_{\tau_j} \right] c_{m}^{(+)}, \]

where $\beta$ is $\Phi^{(2)} - \Phi^{(3)}$ mixing angle in MQLS model, $t_g \beta = \eta_3 / \eta_2$, $C_Q = V_{CKM}$, $C_l = U_{PMNS}$ and $K_a^{L,R} = (A_{aL}^{R}) + A_{aR}^{L}$ are the mixing matrices specific for the MQLS model.

Scalar gluons $F_a$ couplings to fermions:

\[ (h_+^{F_1})_{ij} = \sqrt{3} \frac{1}{\eta \sin \beta} \left[ m_{u_i} (C_Q)_{ij} - (K_1^R)_{ik} m_{\nu_k} (K_1^L C_l)_{kj} \right], \]
\[ (h_+^{F_2})_{ij} = -\sqrt{3} \frac{1}{\eta \sin \beta} \left[ (C_Q)_{ij} m_{d_i} - (C_l K_2^L)_{ik} m_{t_k} (K_2^R)_{kj} \right], \]
\[ (h_-^{F_2})_{ij} = -\sqrt{3} \frac{1}{\eta \sin \beta} \left[ m_{u_i} \delta_{ij} - (K_1^R)_{ik} m_{\nu_k} (K_1^L)_{kj} \right], \]
\[ (h_-^{F_2})_{ij} = 0, \]
\[ (h_0^{F_2})_{ij} = 0. \]

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

\[ S_1^{(+)} t \tau : (h_+^{F_1})_{33} = \sqrt{3}/2 \frac{m_t}{\eta \sin \beta} (K_1^L C_l)_{33}, \]
\[ S_1^{(-)} \bar{\nu}_\tau b : (h_-^{F_1})_{33} = \sqrt{3}/2 \frac{m_t}{\eta \sin \beta} (K_1^R)_{33} (C_Q)_{33}, \]
\[ S_m \bar{t} \nu_\tau : (h_-^{F_1})_{33} = -\sqrt{3}/2 \frac{m_t}{\eta \sin \beta} (K_1^{L,R})_{33} c_{m}^{(+,-)}, \]
\[ F_1 \bar{t} b : (h_-^{F_2})_{33} = \sqrt{3} \frac{m_t}{\eta \sin \beta} (C_Q)_{33}, \]
\[ F_2 \bar{t} t : (h_0^{F_2})_{33} = -\sqrt{3} \frac{m_t}{\eta \sin \beta}. \]

\[ m_t / \eta \sim 0.7! \]

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 \cite{14,15}:

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

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

$\sigma_{t\bar{t}}$ SM prediction \cite{11}:

$$\sigma_{t\bar{t}}^{SM} = 7.35_{-0.80}^{+0.38} \text{(scale)} +0.49_{-0.34}^{+0.24} \text{(PDFs) [CTEQ6.5]} \text{ pb} \div$$

$$7.93_{-0.56}^{+0.34} \text{(scale)} +0.24_{-0.20} \text{(PDFs) [MRST2006nnlo]} \text{ pb}.$$  
(32)

$A_{FB}^{t\bar{t}}$ SM prediction \cite{16}:

$$A_{FB}^{t\bar{t}} = 0.051(6),$$  
(33)  

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

The measured at CDF forward-backward asymmetry has significant ($\approx 2\sigma$) deviation from predictions \cite{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 $\alpha_s^2$.

![Figure 2: Partonic subprocesses $q\bar{q} \to t\bar{t}, \, gg \to t\bar{t}$](image)

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

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

$$\sigma(q\bar{q} \to t\bar{t}) = \frac{4\pi \alpha_s^2 \beta}{27\hat{s}} \left( 3 - \beta^2 \right),$$  
(36)

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

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

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 $\alpha_s^2$ for the forward-backward asymmetry.

MQLS model contributions in $t\bar{t}$ production

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**

$Z'$ tree s-channel process

![Z' tree s-channel process diagram](image)

Figure 3: Subprocess $q\bar{q} \rightarrow t\bar{t}$

Partonic subprocess $q\bar{q} \rightarrow t\bar{t}$ 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 $q\bar{q} \rightarrow t\bar{t}$ with account masses of final $t$-quarks in the form

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

(37)

where $\cos \theta \equiv c$.

Here,

$$
K_{ij} = A_{ij} (2 + \beta^2(c^2 - 1)) + B_{ij} \beta^2(c^2 + 1) + 2C_{ij} \beta c,
$$

$$
A_{ij} = (a^q_i a^q_j + v^q_i v^q_j) v^t_i v^t_j,
$$

$$
B_{ij} = (a^q_i a^t_j + v^q_i v^t_j) a^t_i a^t_j,
$$

$$
C_{ij} = (a^t_i v^t_j + v^t_i a^t_j)(a^t_i v^t_j + v^t_i a^t_j),
$$

(38)

$$
P_i(\hat{s}) = \frac{1}{\hat{s} - M_t^2 + i\Gamma_t}.
$$

$v^q_i$, $a^q_i$ – vector and axial-vector couplings of $q$-quark with $i$-th neutral boson.

For $M_{Z'} > 1.4$ TeV (current experimental limit [1, 6]), contributions of $Z'$ to cross section and FB asymmetry of the $t\bar{t}$ production is small due smallness of couplings

$$
\Delta \sigma(p\bar{p} \rightarrow t\bar{t}) \sim +0.05 \div 0.1 \text{ pb},
$$

(39)

$$
\Delta A_{FB}^{t\bar{t}} \sim +0.003.
$$

(40)

**Scalar gluons tree processes**

Contributions of diagrams at Fig. 4 are suppressed by factors $m_{Z'}^2/\hat{s}$ or $(|V_{CKM}| \beta)^4$

$$
\Delta \sigma(p\bar{p} \rightarrow t\bar{t}) \sim 0.0001 \text{ pb},
$$

(41)

$$
\Delta A_{FB}^{t\bar{t}} \sim 10^{-6}.
$$

(42)

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

\begin{equation}
-ig_s T^a \bar{u}_t \Gamma^\mu v_{\bar{t}},
\end{equation}

with

\begin{equation}
\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.
\end{equation}

where the loop-induced form factors $\alpha, \beta$ and $\xi$ 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 $q\bar{q} \rightarrow g \rightarrow t\bar{t}$ is [17]

\begin{equation}
\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\text{Re} \left[ (\hat{s} + 2m_t^2)\alpha + 3m_t\beta \right] \right\},
\end{equation}

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 $\alpha, \beta$ 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 $A_{FB}^{t\bar{t}}$ 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 ($\Delta\sigma \sim 0.1 \text{ pb}, \Delta A_{FB}^{t\bar{t}} \sim 0.003$).

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

- The lower mass limits for scalar gluons

$$m_F \gtrsim 320 \text{ GeV}$$

are obtained from the data on direct searches at Tevatron.

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

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