

Resonance contribution of scalar color octet to $t\bar{t}$ production at the LHC in the minimal four color quark-lepton symmetry model

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Abstract

The scalar color octet contribution to the resonance $t\bar{t}$ -pair production at the LHC is calculated and analysed with account of the one loop effective two gluon vertex. It is shown that this contribution from the scalar color octet F_2 predicted by the minimal model with the four color quark-lepton symmetry is for $\sqrt{s} = 13$ TeV of about a few percents for $750 < m_{F_2} < 1800$ GeV and can exceed 10% for $400 < m_{F_2} < 750$ GeV. It is also pointed out that the search for the scalar octet F_2 as the resonance in the dijet mass spectra seems to be difficult because of the smallness of its one loop effective two gluon interaction.

Keywords: Beyond the SM; four color symmetry; scalar octet; scalar gluon; top quark physics.

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The search for new physics effects beyond the Standard Model (SM) is now one of the goals of the experiments at the LHC. There are many models predicting new physics effects. The most interesting of them look the models predicting new effects due to enlarging the symmetry of the SM because the search for such effects could help us to find the next symmetry in yet unknown hierarchy of the symmetries which possibly unify the known in the SM electroweak and strong interactions of quarks and leptons.

One of such variant of new physics beyond the SM can be induced by the possible four color symmetry between quarks and leptons of Pati-Salam type [1]. The four color quark-lepton symmetry can be unified with the electroweak $SU_L(2) \times U(1)$ symmetry of the SM in the minimal way by the group

$$G_{MQLS} = SU_V(4) \times SU_L(2) \times U_R(1), \quad (1)$$

where the first factor is the vector-like group of the four color quark-lepton symmetry the second one is the usual SM electroweak symmetry group for the left-handed fermions

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and the third one is the corresponding hypercharge factor for the right-handed fermions (the minimal quark-lepton symmetry model – MQLS-model [2, 3]). As a remarkable consequence the four color quark-lepton symmetry predicts for the electric charges of quarks and leptons the simple expression

$$Q_f^{em} = \sqrt{2/3} t_{15} + \tau_3^L/2 + Y^R/2$$

in terms of the generators t_{15} , $\tau_3^L/2$ of the group (1) with the hypercharge $Y^R = \pm 1$ for the "up" and "down" right-handed fermions, which naturally explains the fractionary charges of quarks in terms of the elementary charge.

As a result of the Higgs mechanism of splitting the masses of quarks and leptons the four color symmetry in its minimal realization on the gauge group (1) predicts in addition to the SM Higgs doublet $\Phi^{(SM)}$ the existence of the new scalar $SU_L(2)$ -doublets

$$\left(\begin{array}{c} \Phi'_1 \\ \Phi'_2 \end{array} \right); \left(\begin{array}{c} S_{1\alpha}^{(+)} \\ S_{2\alpha}^{(+)} \end{array} \right); \left(\begin{array}{c} S_{1\alpha}^{(-)} \\ S_{2\alpha}^{(-)} \end{array} \right); \left(\begin{array}{c} F_{1c} \\ F_{2c} \end{array} \right) \quad (2)$$

with electric charges

$$Q_\Phi^{em} : \quad \left(\begin{array}{c} 1 \\ 0 \end{array} \right); \left(\begin{array}{c} 5/3 \\ 2/3 \end{array} \right); \left(\begin{array}{c} 1/3 \\ -2/3 \end{array} \right); \left(\begin{array}{c} 1 \\ 0 \end{array} \right)$$

respectively. The fields (2) belong to the (1.2.1)+(15.2.1) representation of the group (1), here the fields Φ'_1 , Φ'_2 form an additional colorless scalar doublet, $S_{1\alpha}^{(\pm)}$, $S_{2\alpha}^{(\pm)}$, $\alpha = 1, 2, 3$ are the color triplets forming two scalar leptoquark doublets and the fields F_{1c} , F_{2c} , $c = 1, 2, \dots, 8$ form the scalar doublet of the color octets (the scalar gluon doublet).

Because of their Higgs origin the coupling constants of the doublets (2) with the fermions occur to be proportional to the ratios m_f/η of the fermion masses m_f to the SM VEV η and are small for u -, d -, s -quarks are more significant for c -, b -quarks and are especially significant for t -quark ($m_t/\eta \sim 0.7$). As a result the scalar doublets (2) can manifest themselves more probably in the processes with t -quarks. In particular the scalar octet F_2 could manifest itself as a resonance in $t\bar{t}$ -pair production at the LHC. It should be noted that the coupling constants of the doublets (2) with t -quark are known (up to the mixing parameters), which gives the possibility to estimate quantitatively the possible effects from these particles in dependence on their masses. The pair production of the scalar octets in pp -collisions at the LHC has been discussed in Refs [4–16].

In the present paper we calculate the contribution of the scalar octet to the cross section of the resonance $t\bar{t}$ -pair production in pp -collisions and analyse the possibility of manifestation of the scalar gluon F_2 of the MQLS-model as the corresponding resonance peak in $t\bar{t}$ -pair production at the LHC.

The details of interactions of the scalar doublets (2) with quarks and leptons can be found in [17, 18]. In particular the interaction of the scalar gluon F_2 with up- and down-quarks in the MQLS-model has the chiral form and can be written as

$$L_{F_2 u_i u_j} = \bar{u}_{i\alpha} \left[(h_{1F_2}^L)_{ij} P_L \right] (t_c)_{\alpha\beta} u_{j\beta} F_{2c} + \text{h.c.}, \quad (3)$$

$$L_{F_2 d_i d_j} = \bar{d}_{i\alpha} \left[(h_{2F_2}^R)_{ij} P_R \right] (t_c)_{\alpha\beta} d_{j\beta} F_{2c} + \text{h.c.}, \quad (4)$$

where t_c , $c = 1, 2, \dots, 8$ are the generators of the $SU_c(3)$ group, $P_{L,R} = (1 \pm \gamma_5)/2$ are the left and right projection operators and $(h_{1F_2}^L)_{ij}$, $(h_{2F_2}^R)_{ij}$ are the Yukawa coupling constants,

$i, j = 1, 2, 3$ are the generation indices. As a result of the Higgs mechanism of generating the quark and lepton masses the Yukawa coupling constants $(h_{1F_2}^L)_{ij}, (h_{2F_2}^R)_{ij}$ are defined by the expressions

$$(h_{1F_2}^L)_{ij} = -\sqrt{3} \frac{1}{\eta \sin \beta} \left[m_{u_i}(\delta)_{ij} - (K_1^R)_{ik} m_{\nu_k} (K_1^L)_{kj}^+ \right], \quad (5)$$

$$(h_{2F_2}^R)_{ij} = -\sqrt{3} \frac{1}{\eta \sin \beta} \left[m_{d_i}(\delta)_{ij} - (K_2^L)_{ik} m_{l_k} (K_2^R)_{kj}^+ \right], \quad (6)$$

where m_{u_i}, m_{d_i} and m_{ν_k}, m_{l_k} are the masses of up- and down-quarks and of neutrinos and charged leptons, $K_1^{L,R}, K_2^{L,R}$ are the mixing matrices in leptoquark currents which are specific for the model with the four color quark-lepton symmetry and β is a mixing angle of two colorless scalar doublets of MQLS model. Among the coupling constants (5), (6) the largest is the constant $(h_{1F_2}^L)_{33}$ which with neglect of the neutrinos masses takes the form

$$(h_{1F_2}^L)_{33} = -\sqrt{3} \frac{m_t}{\eta \sin \beta}. \quad (7)$$

The interaction of the scalar gluon F_2 with t -quark can be written as

$$L_{F_2 tt} = \bar{t}_\alpha (h_{F_2 t\bar{t}}^S + h_{F_2 t\bar{t}}^P \gamma_5) (t_c)_{\alpha\beta} t_\beta F_{2c} + \text{h.c.}, \quad (8)$$

where the correspondent scalar and pseudoscalar coupling constants with account of (7) take the form

$$h_{F_2 t\bar{t}}^S = h_{F_2 t\bar{t}}^P = -\frac{\sqrt{3}}{2} \frac{m_t}{\eta \sin \beta} \approx -0.61 / \sin \beta. \quad (9)$$

The coupling constants (9) increase with decreasing $\sin \beta$ so that for $\sin \beta = 1, 0.7, 0.4$ the perturbation theory parameters take the values $(h_{F_2 t\bar{t}}^{S,P})^2 / 4\pi \approx 0.03, 0.06, 0.18$ respectively. Below we restrict ourselves by the mixing angle region $0.4 \leq \sin \beta \leq 1$.

The interactions (3), (4) lead to the decays $F_2 \rightarrow u_i \bar{u}_i, F_2 \rightarrow d_i \bar{d}_i$ and in the case of $m_{F_2} > 2m_t$ the decay $F_2 \rightarrow t\bar{t}$ is dominant with the width [17, 18]

$$\Gamma(F_2 \rightarrow t\bar{t}) = m_{F_2} \frac{3}{32\pi} \left(\frac{m_t}{\eta} \right)^2 \left(1 - 2 \frac{m_t^2}{m_{F_2}^2} \right) \sqrt{1 - 4 \frac{m_t^2}{m_{F_2}^2}} \frac{1}{\sin^2 \beta}. \quad (10)$$

For the masses $m_{F_2} = 400 - 2000$ GeV the width (10) is of about $(2 - 30) / \sin^2 \beta$ GeV and $\Gamma_{F_2} / m_{F_2} = (0.5 - 1.5)\% / \sin^2 \beta$.

As seen from the expressions (5), (6) the coupling constants of the interaction of the scalar gluon F_2 with u - and d - quarks are of order of $m_u / \eta \sim m_d / \eta \sim 10^{-5}$ and the interactions of these quarks as the initial partons with the scalar gluon F_2 are negligibly small. On the other hand the Lagrangian (8), (9) can induce through the loop contribution of t -quark the more significant effective interaction of two initial gluons with the scalar gluon F_2 , which should be taken into account. The analogous effective two gluon interaction is induced also with the colorless scalar Φ_2' .

The calculation of the effective two gluon vertex of interaction with the scalar octet is like to that with the colorless scalar and we perform below these calculations simultaneously. For this purpose we write the flavour diagonal interactions of scalar octet and of the scalar color singlet with quarks in the model independent form as

$$L_{\Phi q\bar{q}} = \bar{q}_\alpha (h_{\Phi q\bar{q}}^S + h_{\Phi q\bar{q}}^P \gamma_5) \Phi_{\alpha\beta} q_\beta + \text{h.c.}, \quad (11)$$

where $\Phi_{\alpha\beta} = \Phi_0\delta_{\alpha\beta}$ for the colorless scalar particle Φ_0 and $\Phi_{\alpha\beta} = \Phi_{8c}(t_c)_{\alpha\beta}$ for the scalar octet Φ_8 , t_c are the generators of the $SU_c(3)$ group ($c = 1, 2, \dots, 8$), $h_{\Phi q\bar{q}}^S$ and $h_{\Phi q\bar{q}}^P$ are the corresponding scalar and pseudoscalar coupling constants. For the MQLS-model the scalars Φ_8 and Φ_0 correspond to F_2 and Φ'_2 respectively.

The effective vertex $\Gamma_{ab\Phi}^{(q)\mu\nu}(p, k_1, k_2)$ of interaction of two gluons with scalar field $\Phi = \Phi_0, \Phi_{8c}$ induced by the Lagrangian (11) with account of one loop contribution of quark q is described by the diagrams in the Fig. 1

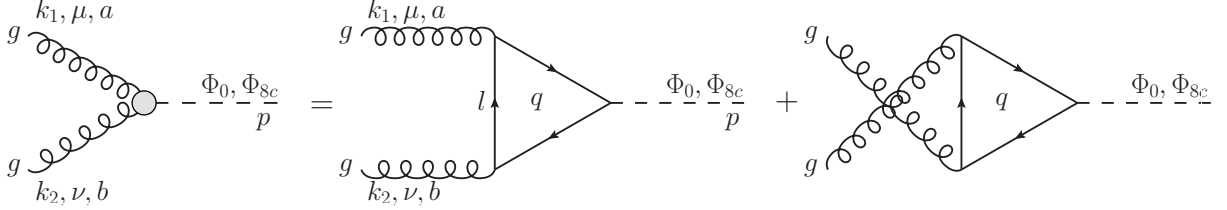


Figure 1: The effective vertex $\Gamma_{ab\Phi}^{(q)\mu\nu}(p, k_1, k_2)$ induced by one loop contribution of quark q for $\Phi = \Phi_0, \Phi_{8c}$.

and can be written as

$$\begin{aligned} \Gamma_{ab\Phi}^{(q)\mu\nu}(p, k_1, k_2) &= \\ &= c_{ab\Phi}^{(1)} g_s^2 \int \frac{d^n l}{i(2\pi)^n} \frac{\text{Tr}((h_{\Phi qq}^S + h_{\Phi qq}^P \gamma^5)(\hat{l} + \hat{k}_1 + m_q)\gamma^\mu(\hat{l} + m_q)\gamma^\nu(\hat{l} - \hat{k}_2 + m_q))}{((l + k_1)^2 - m_q^2 + i\varepsilon)(l^2 - m_q^2 + i\varepsilon)((l - k_2)^2 - m_q^2 + i\varepsilon)} + \\ &+ c_{ab\Phi}^{(2)} g_s^2 \int \frac{d^n l}{i(2\pi)^n} \frac{\text{Tr}((h_{\Phi qq}^S + h_{\Phi qq}^P \gamma^5)(\hat{l} + \hat{k}_2 + m_q)\gamma^\nu(\hat{l} + m_q)\gamma^\mu(\hat{l} - \hat{k}_1 + m_q))}{((l + k_2)^2 - m_q^2 + i\varepsilon)(l^2 - m_q^2 + i\varepsilon)((l - k_1)^2 - m_q^2 + i\varepsilon)}, \end{aligned} \quad (12)$$

where $c_{ab\Phi}^{(1)}, c_{ab\Phi}^{(2)}$ are the color factors, $c_{ab\Phi_0}^{(1)} = c_{ab\Phi_0}^{(2)} = \delta^{ab}/2$ for the colorless particle Φ_0 and $c_{ab\Phi_{8c}}^{(1)} = \text{Tr}(t_a t_b t_c) = \frac{1}{4}(d_{abc} + if_{abc})$, $c_{ab\Phi_{8c}}^{(2)} = \text{Tr}(t_b t_a t_c) = \frac{1}{4}(d_{abc} - if_{abc})$ for the color octet Φ_8 , $a, b, c = 1, 2, \dots, 8$ are the color indices, d_{abc} and f_{abc} are the d - and f - constants of the $SU_c(3)$ group.

To regulate ultraviolet divergences in one loop calculation of $\Gamma_{ab\Phi}^{(q)\mu\nu}(p, k_1, k_2)$ we use the dimensional regularization with $n = 4 - 2\varepsilon$ and use for γ_5 the Larin's prescription [19] based on the t'Hooft-Veltman scheme [20].

With account of the contributions of all the quarks the resulted effective vertex $\Gamma_{ab\Phi}^{\mu\nu}(p, k_1, k_2)$ in the case of real gluons ($k_1^2 = 0, k_2^2 = 0, \hat{s} = p^2 = 2(k_1 k_2)$) can be parametrized as

$$\begin{aligned} \Gamma_{ab\Phi}^{\mu\nu}(p, k_1, k_2) &= \sum_q \Gamma_{ab\Phi}^{(q)\mu\nu}(p, k_1, k_2) = \\ &= -C_{ab\Phi} \frac{\alpha_s \sqrt{\hat{s}}}{\pi} \left[\left(g^{\mu\nu} - \frac{2k_1^\nu k_2^\mu}{\hat{s}} \right) F_\Phi^S(\hat{s}) - 2i\varepsilon^{\mu\nu\rho\sigma} \frac{k_{1\rho} k_{2\sigma}}{\hat{s}} F_\Phi^P(\hat{s}) + \frac{2k_1^\mu k_2^\nu}{\hat{s}} G_\Phi^S(\hat{s}) \right] \end{aligned} \quad (13)$$

by the form factors

$$F_\Phi^{S,P}(\hat{s}) = \sum_q h_{\Phi q\bar{q}}^{S,P} \tilde{F}^{S,P}(\hat{s}, m_q^2), \quad G_\Phi^S(\hat{s}) = \sum_q h_{\Phi q\bar{q}}^S \tilde{G}^S(\hat{s}, m_q^2), \quad (14)$$

where $C_{ab\Phi}$ is the color factor with

$$C_{ab\Phi_0} = \delta_{ab}/2 \equiv C_{ab}, \quad C_{ab\Phi_{8c}} = d_{abc}/4 \equiv C_{abc} \quad (15)$$

for the color singlet Φ_0 and for the color octet Φ_8 .

For the form factors $\tilde{F}^{S,P}(\hat{s}, m_q^2)$, $\tilde{G}^S(\hat{s}, m_q^2)$ we have found the expressions

$$\tilde{F}^S(\hat{s}, m_q^2) = \frac{m_q}{\sqrt{\hat{s}}} [(\hat{s} - 4m_q^2) C_0(0, 0, \hat{s}, m_q^2, m_q^2, m_q^2) - 2] \equiv \tilde{F}^S(\rho_q), \quad (16)$$

$$\tilde{F}^P(\hat{s}, m_q^2) = m_q \sqrt{\hat{s}} C_0(0, 0, \hat{s}, m_q^2, m_q^2, m_q^2) \equiv \tilde{F}^P(\rho_q), \quad (17)$$

$$\begin{aligned} \tilde{G}^S(\hat{s}, m_q^2) &= \\ &= \frac{m_q}{\sqrt{\hat{s}}} \left[(\hat{s} + 4m_q^2) C_0(0, 0, \hat{s}, m_q^2, m_q^2, m_q^2) + 4B_0(\hat{s}, m_q^2, m_q^2) - \frac{4A_0(m_q^2)}{m_q^2} \right] \equiv \tilde{G}^S(\rho_q), \end{aligned} \quad (18)$$

where A_0 , B_0 , C_0 are the Passarino–Veltman (PV) scalar integrals [21,22], with account of the explicit form of these integrals the form factors (16)–(18) depend only on the variable $\rho_q = \sqrt{\hat{s}}/m_q$. The form factors (16)–(18) account the one loop contribution of quark q in the model independent way, the specific features of the model are presented by the coupling constants $h_{\Phi q\bar{q}}^{S,P}$ in the form factors (14).

Due to the gauge invariance the longitudinal component of the vertex (13) parametrized by the form factor $G_\Phi^S(\hat{s})$ do not enter to the observed variables. The real and imaginary parts of the form factors $\tilde{F}^S(\rho_q)$, $\tilde{F}^P(\rho_q)$ as a functions of ρ_q are shown in the Fig. 2.

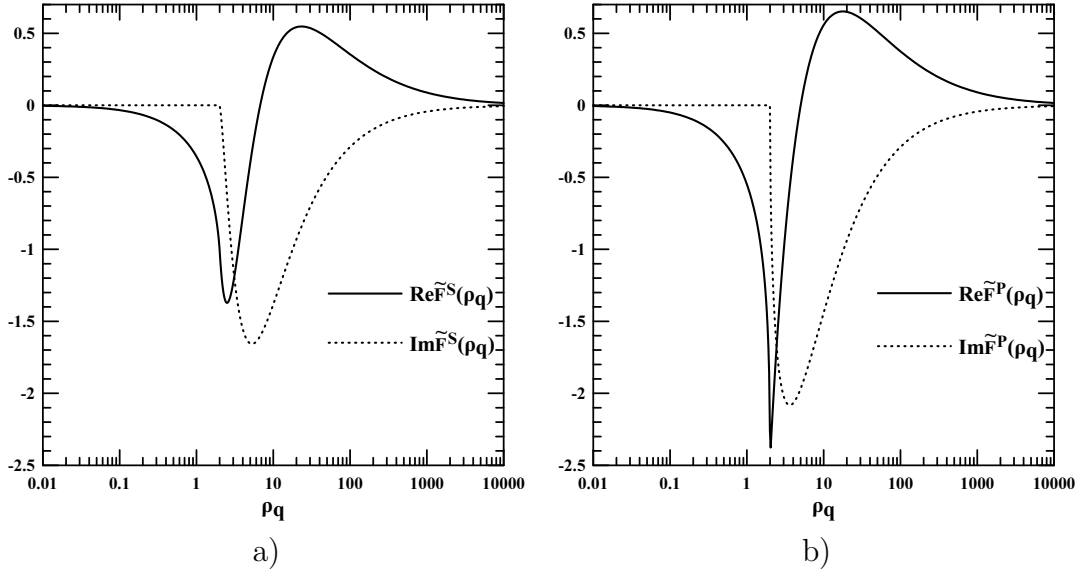


Figure 2: The real and imaginary parts of form factors a) $\tilde{F}^S(\rho_q)$ and b) $\tilde{F}^P(\rho_q)$ as the function of $\rho_q = \sqrt{\hat{s}}/m_q$.

We have calculated the cross section of the process $gg \rightarrow Q\bar{Q}$ of $Q\bar{Q}$ pair production in gluon fusion in QCD LO with account also of the effective vertex (13). The diagrams of this process are shown in the Fig. 3.

The total cross section of the process $gg \rightarrow Q\bar{Q}$ can be written as the sum

$$\sigma_0(gg \rightarrow Q\bar{Q}, \mu) = \sigma_0^{\text{SM}}(gg \rightarrow Q\bar{Q}, \mu) + \Delta\sigma^\Phi(gg \rightarrow Q\bar{Q}, \mu) \quad (19)$$

of the well known QCD LO cross section

$$\sigma_0^{\text{SM}}(gg \rightarrow Q\bar{Q}, \mu) = \frac{\alpha_s^2(\mu) \pi}{48\hat{s}} \left[(v^4 - 18v^2 + 33) \log \frac{1+v}{1-v} + v(31v^2 - 59) \right], \quad (20)$$

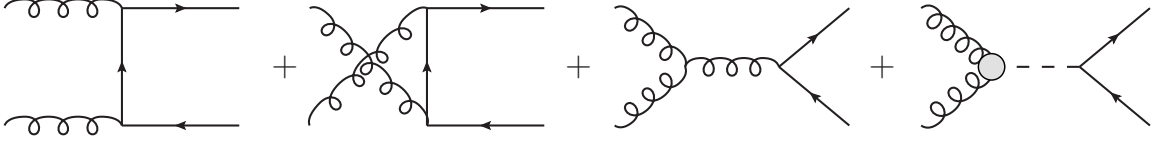


Figure 3: Diagrams of the process $gg \rightarrow Q\bar{Q}$ in the SM LO and with account of the effective vertex $\Gamma_{ab\Phi}^{\mu\nu}(p, k_1, k_2)$.

where $v = \sqrt{1 - 4m_Q^2/\hat{s}}$ is the velocity of quark Q in the center of mass frame, \hat{s} is the squared energy in the center of momentum frame of the gluons, μ is a typical mass scale of the process, and the contribution $\Delta\sigma^\Phi(gg \rightarrow Q\bar{Q}, \mu)$ to this process from the scalar Φ .

For the contribution $\Delta\sigma^\Phi(gg \rightarrow Q\bar{Q}, \mu)$ we have found the expression

$$\begin{aligned} \Delta\sigma^\Phi(gg \rightarrow Q\bar{Q}, \mu) &= \\ &= \frac{\tilde{C}_\Phi^{(1)}}{64} \frac{\alpha_s^2(\mu)m_Q}{\pi\sqrt{\hat{s}}} \frac{\text{Re} \left[(\hat{s} - m_\Phi^2 - im_\Phi\Gamma_\Phi) \left(-(h_{\Phi Q\bar{Q}}^S)^* v^2 F_\Phi^S(\hat{s}) - (h_{\Phi Q\bar{Q}}^P)^* F_\Phi^P(\hat{s}) \right) \right]}{(\hat{s} - m_\Phi^2)^2 + m_\Phi^2 \Gamma_\Phi^2} \log \frac{1+v}{1-v} + \\ &+ 2 \frac{\tilde{C}_\Phi^{(2)}}{2048} \frac{\alpha_s^2(\mu)v\hat{s}}{\pi^3} \frac{|h_{\Phi Q\bar{Q}}^S|^2 v^2 + |h_{\Phi Q\bar{Q}}^P|^2}{(\hat{s} - m_\Phi^2)^2 + m_\Phi^2 \Gamma_\Phi^2} (|F_\Phi^S(\hat{s})|^2 + |F_\Phi^P(\hat{s})|^2), \end{aligned} \quad (21)$$

where the form factors $F_\Phi^{S,P}(\hat{s})$ are given by the expressions (14),(16),(17) and $\tilde{C}_\Phi^{(1)}, \tilde{C}_\Phi^{(2)}$ are the color factors with

$$\tilde{C}_{\Phi_0}^{(1)} = C_{ab}C_{ab} = 2, \quad \tilde{C}_{\Phi_0}^{(2)} = C_{ab}C_{ab} n_c = 6, \quad (22)$$

$$\tilde{C}_{\Phi_8}^{(1)} = C_{abc}C_{abc} = 5/6, \quad \tilde{C}_{\Phi_8}^{(2)} = C_{abc}C_{abc}/2 = 5/12 \quad (23)$$

for the color singlet Φ_0 and for the color octet Φ_8 respectively, n_c is the number of colors of the $SU_c(n_c)$ group, the numerical values in (22), (23) correspond to the $SU_c(3)$ group.

The total cross section $\sigma_{tot}(pp \rightarrow t\bar{t})$ of the $t\bar{t}$ production in pp -collisions with account of the contribution of scalar octet F_2 can be written as the sum

$$\sigma_{tot}(pp \rightarrow t\bar{t}) = \sigma^{\text{SM}}(pp \rightarrow t\bar{t}) + \Delta\sigma^{F_2}(pp \rightarrow t\bar{t}) \quad (24)$$

of the SM cross section $\sigma^{\text{SM}}(pp \rightarrow t\bar{t})$ and the contribution $\Delta\sigma^{F_2}(pp \rightarrow t\bar{t})$ induced by scalar gluon F_2 via effective vertex (13)–(17).

We obtain the total cross section from partonic cross sections (20), (21) by integrating the expression

$$\begin{aligned} \frac{d\sigma_{tot}(pp \rightarrow t\bar{t})}{dx_1 dx_2} &= \sum_k F_k^{pp}(x_1, x_2, \mu_f) K(s) \sigma_0^{\text{SM}}(\bar{q}_k q_k \rightarrow t\bar{t}, \mu) + \\ &+ F_g^{pp}(x_1, x_2, \mu_f) K(s) \sigma_0^{\text{SM}}(gg \rightarrow t\bar{t}, \mu) + F_g^{pp}(x_1, x_2, \mu_f) \Delta\sigma^{F_2}(gg \rightarrow t\bar{t}, \mu) \end{aligned} \quad (25)$$

over the variables $0 \leq x_1, x_2 \leq 1$, where x_1, x_2 are partonic parts of the momenta of protons, $\hat{s} = x_1 x_2 s$, $s = (P_1 + P_2)^2$, P_1, P_2 are the momenta of the colliding protons, $\sigma_0^{\text{SM}}(\bar{q}_k q_k \rightarrow t\bar{t}, \mu)$ is the well known SM LO cross section, $K(s)$ is the K -factor, which we use for the better agreement of the SM LO predictions of the cross section of $t\bar{t}$ -pair production with the corresponding aNNLO SM predictions [23]. The partonic functions in (25) are given as

$$F_k^{pp}(x_1, x_2, \mu_f) = f_{q_k}^p(x_1, \mu_f) f_{\bar{q}_k}^p(x_2, \mu_f) + f_{\bar{q}_k}^p(x_1, \mu_f) f_{q_k}^p(x_2, \mu_f), \quad (26)$$

$$F_g^{pp}(x_1, x_2, \mu_f) = f_g^p(x_1, \mu_f) f_g^p(x_2, \mu_f), \quad (27)$$

where $f_{q_k}^p(x, \mu_f)$, $f_{\bar{q}_k}^p(x, \mu_f)$, $f_g^p(x, \mu_f)$ are the parton distribution functions of quark q_k of flavor k , antiquark \bar{q}_k and gluons in the proton, μ_f is the factorization scale.

For numerical calculations we use the analytical expressions for scalar PV integrals A_0, B_0, C_0 from the Denner's paper [22] and we also perform the cross check with using LoopTools/FF [24, 25].

We have calculated the cross section (24) at $\sqrt{s} = 7, 8, 13$ TeV with using the parton distribution functions MSTW2008 [26] (NNLO, $\mu = \mu_f = m_t$, $m_t = 173.21$ GeV). For calculations we use the values of K -factors $K(s) = 1.7110, 1.7095, 1.7024$ for energies $\sqrt{s} = 7, 8, 13$ TeV respectively, in this case the cross section $\sigma^{\text{SM}}(pp \rightarrow t\bar{t})$ reproduces well the aNNLO SM predictions for the cross section of $t\bar{t}$ production [23].

We have calculated the contributions $\Delta\sigma^{F_2}(pp \rightarrow t\bar{t})$ to the total cross section of the $t\bar{t}$ production from the scalar gluon F_2 defined by the last term in the expression (25) for $\sqrt{s} = 7, 8, 13$ TeV, $m_{F_2} = 400 \div 1000$ GeV and $\sin \beta = 1, 0.7, 0.4$. These contributions for

$$\sin \beta = 0.4, \quad m_{F_2} \lesssim 460 \text{ GeV} \quad (28)$$

exceed the experimental uncertainties of the measurements of the total $t\bar{t}$ cross sections performed by ATLAS($20.3fb^{-1}$) [27] and CMS($19.7fb^{-1}$) [28] at $\sqrt{s} = 7, 8$ TeV and by ATLAS($3.2fb^{-1}$) [29] and CMS($2.3fb^{-1}$) [30] at $\sqrt{s} = 13$ TeV (hence the values (28) are excluded by these data) whereas the other parameters regions are consistent with these data within the experimental uncertainties. As seen the exclusion limit (28) resulting from the data on the total $t\bar{t}$ cross sections is low.

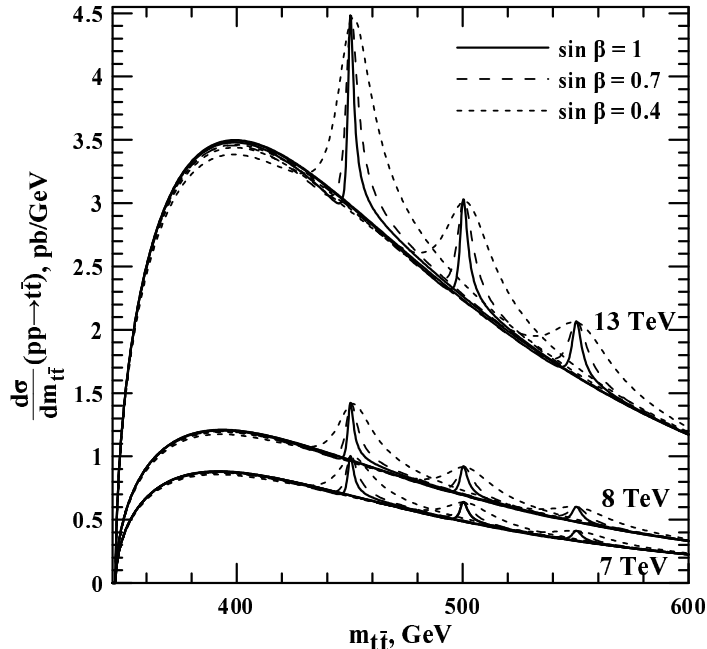


Figure 4: The invariant mass spectrum $d\sigma(pp \rightarrow t\bar{t})/dm_{t\bar{t}}$ of the $t\bar{t}$ -pair production in pp collisions at the LHC at energies $\sqrt{s} = 7, 8, 13$ TeV with account of the contributions of scalar gluon F_2 with masses $m_{F_2} = 450, 500, 550$ GeV for $\sin \beta = 1, 0.7, 0.4$.

Using the known relations between the variables x_1, x_2 and the invariant mass $m_{t\bar{t}}$ of $t\bar{t}$ pair and the rapidity y of the final t -quark

$$m_{t\bar{t}}^2 = x_1 x_2 s, \quad y = \ln \frac{x_1}{x_2}, \quad x_{1,2} = \frac{m_{t\bar{t}}}{\sqrt{s}} e^{\pm y/2} \quad (29)$$

and integrating the expression (25) over the rapidity y with account of the scalar gluon contribution $\Delta\sigma^{F_2}(gg\rightarrow t\bar{t}, \mu_f)$ we obtain the invariant mass spectrum $d\sigma(pp\rightarrow t\bar{t})/dm_{t\bar{t}}$ in the form

$$\frac{d\sigma_{tot}(pp\rightarrow t\bar{t})}{dm_{t\bar{t}}} = \frac{m_{t\bar{t}}}{s} \int_{-\ln(s/m_{t\bar{t}}^2)}^{+\ln(s/m_{t\bar{t}}^2)} \frac{d\sigma_{tot}(pp\rightarrow t\bar{t})}{dx_1 dx_2} dy. \quad (30)$$

In the same way but with neglect of the scalar gluon contribution $\Delta\sigma^{F_2}(gg\rightarrow t\bar{t}, \mu_f)$ we obtain the background invariant mass spectrum $d\sigma_b(pp\rightarrow t\bar{t})/dm_{t\bar{t}}$ which is in agreement with the theoretical predictions [31] and with the experimental results [32–34].

The invariant mass spectra $d\sigma(pp\rightarrow t\bar{t})/dm_{t\bar{t}}$ at the LHC energies $\sqrt{s} = 7, 8, 13$ TeV for the scalar gluons masses $m_{F_2} = 450, 500, 550$ GeV and for $\sin\beta = 1, 0.7, 0.4$ are shown in the Fig. 4. As seen in the Fig. 4 the distribution (30) at $m_{t\bar{t}} \sim m_{F_2}$ has the typical peaks induced by the scalar gluon F_2 with widths depending on $\sin\beta$.

To distinguish the signal and background events we use the significance estimator [35, 36]

$$\mathcal{S} = 2(\sqrt{n_s + n_b} - \sqrt{n_b}), \quad (31)$$

where n_s (n_b) – are number of signal (background) events in the $t\bar{t}$ invariant mass region $m \pm \Delta m/2$ near the scalar gluon mass m_{F_2} . These numbers can be calculated as

$$n_s = n_{tot} - n_b, \quad (32)$$

$$n_{tot, b} = L \sigma_{tot, b}(m, \Delta m), \quad (33)$$

$$\sigma_{tot, b}(m, \Delta m) = \int_{m-\frac{1}{2}\Delta m}^{m+\frac{1}{2}\Delta m} \frac{d\sigma_{tot, b}(pp\rightarrow t\bar{t})}{dm_{t\bar{t}}} dm_{t\bar{t}}, \quad (34)$$

where L is integrated luminosity.

Table 1: The signal significance \mathcal{S} and the ratio n_s/n_b in the bin ranges $m \pm \Delta m/2$ of CMS data on $t\bar{t}$ production at $\sqrt{s} = 8$ TeV [34] for $\sin\beta = 1(0.4)$

$m_{t\bar{t}}$ bin range [GeV] { $m \pm \Delta m/2$ }	δ_{Syst} [%]	δ_{Total} [%]	m_{F_2} [GeV]	$\sin\beta$	\mathcal{S}	n_s/n_b [%]
345 – 400 {372.5 ± 22.5}	7.1	7.5	373	1(0.4)	59(327)	5.8(33.2)
			400	1(0.4)	11(18)	1.0(1.7)
400 – 470 {435 ± 35}	2.9	3.6	435	1(0.4)	32(174)	2.7(14.8)
			470	1(0.4)	3.5(21)	0.2(1.7)
470 – 550 {510 ± 40}	6.1	6.4	510	1(0.4)	22(113)	2.1(11.3)
			550	1(0.4)	0.6(26)	0.05(2.5)
550 – 650 {600 ± 50}	7.3	7.7	600	1(0.4)	13(68)	1.7(8.5)
			650	1(0.4)	1.8(20)	0.2(2.5)
650 – 800 {725 ± 75}	4.2	4.9	725	1(0.4)	6.7(35)	1.0(5.5)
			800	1(0.4)	1.3(11)	0.2(1.7)

The signal significance \mathcal{S} and the ratio n_s/n_b in the bin ranges $m \pm \Delta m/2$ of CMS data on $t\bar{t}$ production at $\sqrt{s} = 8$ TeV [34] are shown for corresponding masses m_{F_2} and for $\sin\beta = 1(0.4)$ in the Table 1, δ_{Syst} and δ_{Total} are the experimental systematic and total relative uncertainties of the values of the cross sections in the bin ranges. As seen from the Table 1 for

$$\sin\beta = 0.4, \quad m_{F_2} < 725 \text{ GeV} \quad (35)$$

the ratios n_s/n_b exceed the experimental relative uncertainties δ_{Total} and hence the values (35) are excluded by the data of ref. [34]. At the same time for $\sin\beta = 1$ and for all the masses m_{F_2} the ratios n_s/n_b do not exceed the experimental relative uncertainties and the scalar gluon F_2 in this case can not be visible in the data of ref. [34]. The exclusion limit (35) resulting from the current CMS data on the differential $t\bar{t}$ cross section at $\sqrt{s} = 8$ TeV is slightly higher than the limit (28) nevertheless it is also rather low.

In the case of $\sqrt{s} = 13$ TeV we have calculated the ratios n_s/n_b in dependence on m_{F_2} and $\sin\beta$ assuming $\Delta m = 100$ GeV (as close to the experimental facilities) and to maximize the significance estimator \mathcal{S} we use also the optimized bin width $\Delta m = 1.28 \Gamma_{F_2}$ which corresponds to the 3σ width in the case of a Gaussian distribution.

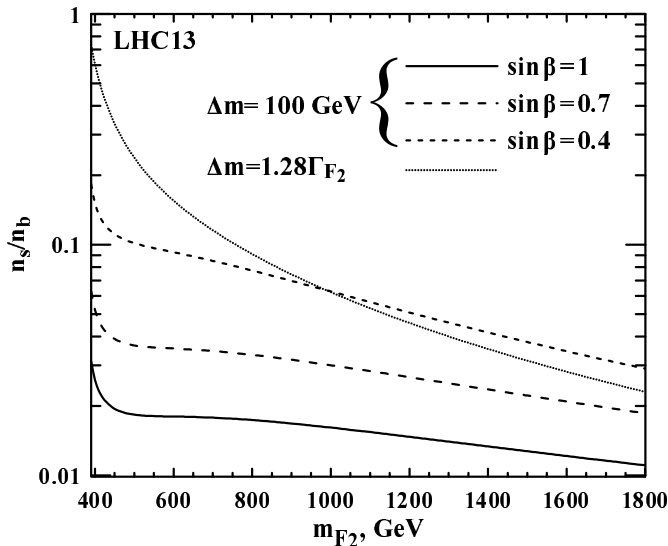


Figure 5: The ratios n_s/n_b for the $t\bar{t}$ production at the LHC with account of the scalar gluon F_2 contribution for $\sqrt{s} = 13$ TeV and bin sizes $\Delta m = 100$ GeV and $\Delta m = 1.28 \Gamma_{F_2}$ as the functions of m_{F_2} .

For $\sqrt{s} = 13$ TeV the ratios n_s/n_b as the functions of m_{F_2} for $\sin\beta = 1, 0.7, 0.4$ are shown in the Fig. 5 (in the case of $\Delta m = 1.28 \Gamma_{F_2}$ the ratio n_s/n_b practically does not depend on $\sin\beta$). As seen from the Fig. 5 for $0.4 \lesssim \sin\beta \leq 1$ the ratios n_s/n_b in the region $500 < m_{F_2} < 1800$ GeV for $\Delta m = 100$ GeV and in the region $750 < m_{F_2} < 1800$ GeV for $\Delta m = 1.28 \Gamma_{F_2}$ are of about a few percents (do not exceed 10%). By this reason the search for such scalar octet F_2 as the resonance peak in $t\bar{t}$ -pair production at the LHC in these regions can need the experimental relative accuracy in measuring the corresponding cross section of about one percent. In the region $400 < m_{F_2} < 750$ GeV for $\Delta m = 1.28 \Gamma_{F_2}$ the ratio n_s/n_b exceeds 10% and in this case the experimental relative accuracy of about a few percent can be sufficient to search for the F_2 resonance peak in $t\bar{t}$ -pair production with using the optimized bin width. It should be noted that the current total (systematic) experimental accuracy in measuring the differential $t\bar{t}$ cross section at $\sqrt{s} = 8$ TeV in the range $400 < m_{t\bar{t}} < 1600$ GeV is of about $\delta_{\text{Total}}(\delta_{\text{Syst}}) = (3.6(2.9) - 12.7(9.8))\%$ [34]. If one assumes that the experimental accuracy in measuring the differential $t\bar{t}$ cross section at the initial stage of the experiments at $\sqrt{s} = 13$ TeV will be of the same order as that for $\sqrt{s} = 8$ TeV the search for the F_2 resonance peak in $t\bar{t}$ -pair production in the region $750 < m_{F_2} < 1800$ GeV at this stage will be rather difficult but will be possible in the region $400 < m_{F_2} < 750$ GeV with using the optimized bin width. At the present time at $\sqrt{s} = 13$ TeV there are measured the total $t\bar{t}$ cross sections by

ATLAS($3.2fb^{-1}$) [29] and CMS($2.3fb^{-1}$) [30] Collaborations with the accuracies of 4.4% and 3.9% respectively which are of the same order as the accuracies of 4.3% and 3.7% of the corresponding measurements of the total $t\bar{t}$ cross sections by ATLAS($20.3fb^{-1}$) [27] and CMS($19.7fb^{-1}$) [28] at $\sqrt{s} = 8$ TeV.

The recent CMS data [37] on search for narrow resonances in the dijet mass spectra at $\sqrt{s} = 13$ TeV and $L = 2.4fb^{-1}$ exclude in particular the color-octet scalar S_8 with the effective interaction [38,39]

$$\mathcal{L}_{S_8} = g_s d_{abc} \frac{k_S}{\Lambda_S} S_8^a G_{\mu\nu}^b G^{c\mu\nu} \quad (36)$$

for the masses $m_{S_8} < 3.1$ TeV with assuming $\Lambda_S = m_{S_8}$ and $k_S = 1$. In the effective Lagrangian (36) Λ_S is a typical mass scale and k_S is an arbitrary dimensionless parameter. The interaction (36) in notation (13) corresponds to the form factor $F_{S_8}^S(\hat{s}) = 16\pi^{3/2} \frac{k_S \sqrt{\hat{s}}}{\sqrt{\alpha_s} \Lambda_S}$ which is real and for $\Lambda_S = 3100$ GeV and $k_S = 1$ in the region $\sqrt{\hat{s}} = 400 \div 4000$ GeV takes the large values $F_{S_8}^S(\hat{s}) \approx 35 \div 347$. At the same time the real part of the form factor $F_{F_2}^S(\hat{s})$ defined for the scalar octet F_2 by the equations (13)–(16) for $\sqrt{\hat{s}} = 400 \div 4000$ GeV has the values of order unity, $Re(F_{F_2}^S(\hat{s})) = -(-0.79 \div 0.31)/\sin\beta$. It means that the effective parameter k_S in (36) for the scalar octet F_2 with $m_{F_2} = 3100$ GeV in the region $\sqrt{\hat{s}} = 400 \div 4000$ GeV has the values $k_S^{F_2} = -(-0.023 \div 0.0009)/\sin\beta$ which are essentially less in magnitude than the unity. In the region $\sqrt{\hat{s}} = 2500 \div 3500$ GeV including the mass $m_{F_2} = 3.1$ TeV the parameter $k_S^{F_2}$ has the very small in magnitude values $k_S^{F_2} = -(0.0011 \div 0.0012)/\sin\beta$ and as a result the quoted lower exclusion mass limit $m_{S_8} < 3.1$ TeV becomes for the scalar octet F_2 essentially more lower. Moreover keeping also in mind that the dominant decay of the scalar octet F_2 is the decay $F_2 \rightarrow t\bar{t}$ and hence $Br(F_2 \rightarrow jj) \ll 1$ it will be difficult to see the scalar octet F_2 as the resonance in the dijet mass spectra.

As seen, the search for the scalar octet F_2 as the resonance peak in $t\bar{t}$ production will be a some experimental problem needing the relatively high accuracy in measuring the differential $t\bar{t}$ cross section and is difficult in the case of the search for the corresponding resonance peak in the dijet mass spectra. In this situation the other way to find the possible manifestation of the scalar octet F_2 in pp -collisions at the LHC can be the process of the $F_2\bar{F}_2$ -pair production followed by the decays of the $F_2\bar{F}_2$ pairs to $t\bar{t}t\bar{t}$ quarks, $pp \rightarrow F_2\bar{F}_2 \rightarrow t\bar{t}t\bar{t}$. The cross section of the pair production of the scalar octets in pp -collisions occurs to be rather large and can be accessible for the experimental investigations at the LHC [4–15]. One should keep in mind however that in many models [4–8,12,14] the interactions of the scalar octets with quarks have ambiguities in the coupling constants, which gives no possibility to estimate quantitatively the scalar octet contributions to the cross section of $t\bar{t}t\bar{t}$ production. Unlike this the scalar octet F_2 has the known coupling constants (9) of interaction with t quark which are sufficiently large. As a result the scalar octet F_2 can give the contribution to the cross section of $t\bar{t}t\bar{t}$ production which can be measurable at the LHC [9,11]. Keeping also in mind that the SM cross section of $t\bar{t}t\bar{t}$ production (which forms the background) is less then that of the $t\bar{t}$ production it would be interesting to search for the scalar octet F_2 also as the peak in the $t\bar{t}$ invariant mass spectra among the $t\bar{t}t\bar{t}$ events.

In conclusion, we summarize the results of this paper.

The effective vertex of interaction of the scalar color octet with two gluons is calculated with account of the one loop quark contribution. With account of this interaction the contribution of the scalar color octet to the partonic cross section of resonance $Q\bar{Q}$ -pair production in the gluon fusion is calculated.

The total and differential cross sections of the $t\bar{t}$ production in pp -collisions at the LHC are calculated with account of the resonance contribution of scalar color octet F_2 predicted by the minimal model with the four color quark-lepton symmetry and analysed in dependence on two parameters of the model, the F_2 mass m_{F_2} and mixing angle β .

From the comparison with the CMS data on the differential cross sections of $t\bar{t}$ production at $\sqrt{s} = 8$ TeV [34] it is shown that the scalar color octet F_2 with $\sin\beta = 0.4$, $m_{F_2} < 725$ GeV is excluded by these data but for $\sin\beta = 1$ and for all the masses m_{F_2} the scalar color octet F_2 gives the contribution to this process of about a few percents and can not be visible in these data.

For $\sqrt{s} = 13$ TeV it is shown that the contribution of the scalar color octet F_2 with $750 < m_{F_2} < 1800$ GeV to resonance $t\bar{t}$ -pair production at the LHC is of about a few percents (do not exceed 10%) and the search for such scalar color octet in this process in this mass region can need the experimental accuracy of about one percent in measuring the corresponding cross section, at the same time in the region $400 < m_{F_2} < 750$ GeV this contribution can exceed 10% and in this case the experimental relative accuracy of about a few percent can be sufficient to search for the F_2 resonance peak in $t\bar{t}$ -pair production with using the optimized bin width.

Taking the mass limits resulting from the recent CMS data [37] on the search for narrow resonances in the dijet mass spectra for the color-octet scalar S_8 into account it is pointed out that because of the smallness of the effective two gluon coupling constant and of the dijet branching ratios $Br(F_2 \rightarrow jj) \ll 1$ the search for the scalar color octet F_2 as the resonance in the dijet mass spectra seems to be difficult.

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