On mass limits for scalar color octet from the LHC data on the $t\bar{t}t\bar{t}$ and $tb\bar{b}$ production.

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Abstract. The full hadron cross section of the scalar octets $F_a F_a^*$-pairs production at the LHC13 is calculated. From the CMS data on $tb\bar{b}$ and $t\bar{t}t\bar{t}$ production cross sections we found the limits on masses of charged $m_{F_1} \gtrsim 549^{+27}_{-21}$ GeV and neutral $m_{F_2} \gtrsim 1336^{+87}_{-61}$ GeV scalar color octets.

1. Introduction
After the experimental discovery of the Higgs boson, the search for new scalar particles that extend the Standard Model is of particular interest. Such particles appear in almost all versions of the new physics. The most interesting of them seem to be the particles from the models predicting new effects due to enlarging the symmetry of the SM. Extended color symmetries are attractive variants of the physics beyond Standard Model. One of such a variant 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

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

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 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 result of the Higgs mechanism of splitting the masses of quarks and leptons the four color quark-lepton symmetry predicts in addition to the SM Higgs doublet $\Phi^{SM}$ the existence of the new scalar $SU_L(2)$-doublets

$$ \begin{pmatrix} F_1^a \\ F_2^a \end{pmatrix} = \begin{pmatrix} S_{1\alpha}^{(+)} \\ S_{2\alpha}^{(+)} \end{pmatrix} : \begin{pmatrix} S_{1\alpha}^{(-)} \\ S_{2\alpha}^{(-)} \end{pmatrix} : \begin{pmatrix} F_{1\alpha} \\ F_{2\alpha} \end{pmatrix} $$

with electric charges

$$ Q_{\Phi}^{sm} : \begin{pmatrix} 1 \\ 0 \end{pmatrix} : \begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix} : \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix} : \begin{pmatrix} 1 \\ 0 \end{pmatrix} $$
respectively.

The fields $\Phi$ belong to the $(1.2.1)+(15.2.1)$ representation of the group $[1]$, here the fields $\Phi'$, $\Phi''$ form an additional colorless scalar doublet, $S^{(\pm)}_{1\alpha}$, $S^{(\pm)}_{2\alpha}$, $\alpha = 1, 2, 3$ are the color triplets forming two scalar leptoquark doublets and the fields $F_{1\alpha}$, $F_{2\alpha}$, $a = 1, \ldots, 8$ 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 $m_f/\eta$ of the fermion masses $m_f$ to the SM VEV $\eta$ and are small for $u$, $d$- and $s$-quarks, are more significant for $c$- and $b$-quarks and are especially significant for $t$-quark ($m_t/\eta \sim 0.7$). In particular the scalar octets $F_1$, $F_2$ could manifest themselves as a contribution in $t\bar{t}b\bar{b}$ and $t\bar{t}t\bar{t}$ production at the LHC respectively. 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 \cite{4,16}.

Current limits on the masses of scalar octets in different models are

- MQLS model $m_{F_a} > 320$ GeV from Tevatron data \cite{17}.
- Flavorful Top-Coloron model $m_{G_H} > 440$ GeV \cite{18}.
- MQLS model $m_{F_a} > 300 \div 500$ GeV from the LHC on $t\bar{t}$ invariant mass spectra data \cite{19}.
- Simplified phenomenological model of sgluons $m_{O} > 1.06$ TeV from LHC13 CMS ($L = 35.9$ fb$^{-1}$) data \cite{20}.
- Unified leptoquark model $m_{G^+} > 1.0$ TeV (neutral scalar gluons in this model prefer decays to the $b$-quarks) \cite{21}.
- MSSM Minimal R-symmetric models $m_{O} > 1.0$ TeV \cite{22}.

We will discuss the processes $pp \to F_1F_1^* \to t\bar{t}b\bar{b}$ and $pp \to F_2F_2^* \to t\bar{t}t\bar{t}$ as way to find mass limits of the scalar gluons.

In the present paper we calculate the cross section of the scalar octets $F_a$, $F_a^*$-pair production at the LHC at $\sqrt{s} = 13$ TeV and find the mass limits on these particles from LHC data on the $t\bar{t}t\bar{t}$ and $t\bar{t}b\bar{b}$ production.

2. MQLS-model scalar color octets — scalar gluons

The details of interactions of the scalar doublets $(2)$ with quarks and leptons can be found in \cite{23,24}.

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

$$L_{F_1u,\bar{d}_j} = \bar{u}_i\left[(h^{L}_{F_1})_{ij}P_L + (h^{R}_{F_1})_{ij}P_R\right](t_k)_{\alpha\beta}d_j\beta F_{1k} + \text{h.c.}, \quad (3)$$

$$L_{F_2u,\bar{u}_j} = \bar{u}_i\left[(h^{L}_{F_2})_{ij}P_L\right](t_c)_{\alpha\beta}u_j\beta F_{2c} + \text{h.c.}, \quad (4)$$

$$L_{F_2d,\bar{d}_j} = \bar{d}_i\left[(h^{R}_{F_2})_{ij}P_R\right](t_c)_{\alpha\beta}d_j\beta F_{2c} + \text{h.c.}, \quad (5)$$

where $t_c, c = 1, \ldots, 8$ are the generators of the $SU(3)$ group, $P_{L,R} = (1 \pm \gamma_5)/2$ are the left and right projection operators and $(h^{L}_{F_2})_{ij}$, $(h^{R}_{F_2})_{ij}$ are the Yukawa coupling constants, $i, j = 1, 2, 3$ are the generation indices.

These interactions induce the scalar gluon decays

$$F_1 \to u_i\bar{d}_j, \quad F_2 \to u_i\bar{u}_j, \quad F_2 \to d_j\bar{d}_j. \quad (6)$$
Due to the smallness of the coupling constants with light quarks the dominant decays are

\[ F_1 \rightarrow t\bar{b}, \quad F_2 \rightarrow t\bar{t}, \]

(7)

\[ \text{Br}(F_1 \rightarrow t\bar{b}) \approx \text{Br}(F_2 \rightarrow t\bar{t}) \approx 1. \]

(8)

The calculation gives the following widths of the dominant modes \[23\]:

\[
\Gamma(F_1 \rightarrow t\bar{b}) = \frac{m_{F_1}}{32\pi} \left( \frac{m_t}{m_{F_1}} \right)^2 \left( 1 - \frac{m_t^2}{m_{F_1}^2} \right)^2 |(C_Q)_{33}| \sin^2 \beta, \]

(9)

\[
\Gamma(F_2 \rightarrow t\bar{t}) = \frac{m_{F_2}}{32\pi} \left( \frac{m_t}{m_{F_2}} \right)^2 \left( 1 - 2 \frac{m_t^2}{m_{F_2}^2} \right) \sqrt{1 - 4 \frac{m_t^2}{m_{F_2}^2} \frac{1}{\sin^2 \beta}}, \]

(10)

where \( \sin \beta \) and \((C_Q)_{33}\) are model parameters.

Production of the scalar color octet \( F_a F_a^* \)-pair in \( pp \)-collision is model independent due to gauge origin of interactions of any color scalar particles \( \Phi_i \) with gluons

\[
\mathcal{L}_{\Phi \Phi g} = \sum_{\text{scalars}} \left[ \left( D^a_{ij} \Phi^j \right)^\dagger \left( D^a_{ij} \Phi^j \right) - m_{\Phi}^2 \Phi^i \Phi^i \right],
\]

(11)

with covariant derivative

\[
D^a_{ij} \Phi_j = \partial_\mu \Phi^j - ig_s G^a_\mu T^a_{ij} \Phi_j,
\]

(12)

where \( T^a_{ij} \) are the generators of the gauge group representation \( SU_c(N) \) \((a=1,2,..d_A, d_A \) - dimension of the adjoint representation of \( SU_c(N) \)), realized by the multiplets \( \Phi_i, \) \( i, j = 1, 2, ..8 \) – color index for scalar gluons.

The interaction \[11\] leads to known LO parton cross sections for \( F_a F_a^* \)-pairs production \[4,10,25\]

\[
\hat{\sigma}^{\text{LO}}(gg \rightarrow F_a F_a^*) = \frac{3\pi\alpha_s^2}{16\pi} \left[ \beta(27 - 17\beta^2) + 3\ln \left( \frac{\beta + 1}{\beta - 1} \right) \left( \beta^4 + 2\beta^2 - 3 \right) \right],
\]

(13)

\[
\hat{\sigma}^{\text{LO}}(q\bar{q} \rightarrow F_a F_a^*) = \frac{4\pi\alpha_s^2}{9\pi} \beta^3,
\]

(14)

where \( \beta = \sqrt{1 - 4m_{F_a}^2/\hat{s}} \).

The total cross section \( \sigma_{\text{tot}}(pp \rightarrow F_a F_a^*) \) of the \( F_a F_a^* \)-pair production in \( pp \)-collisions can be obtained from partonic cross sections \[13,14\] by integrating the expression

\[
\frac{d\sigma_{\text{tot}}(pp \rightarrow t\bar{t})}{dx_1 dx_2} = \sum_k F^{pp}_{k}(x_1, x_2, \mu_f) K(m_F)\hat{\sigma}^{\text{LO}}(q\bar{q} \rightarrow F_a F_a^* \rightarrow t\bar{t}, \mu) + F^{pp}_{g}(x_1, x_2, \mu_f) K(m_F)\hat{\sigma}^{\text{LO}}(gg \rightarrow F_a F_a^*, \mu)
\]

(15)

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, \( K(m_F) \) is the \( K \)-factor, which we extract from \[12\] for the better suitability of the LO predictions of the cross section to the experimental data\[1\]. The partonic functions in \[15\] are given as

\[
F^{pp}_{k}(x_1, x_2, \mu_f) = f_{qk}(x_1, \mu_f) f_{qk}(x_2, \mu_f) + f_{c}(x_1, \mu_f) f_{c}(x_2, \mu_f),
\]

(16)

\[
F^{pp}_{g}(x_1, x_2, \mu_f) = f_{g}(x_1, \mu_f) f_{g}(x_2, \mu_f),
\]

(17)

\(^1\) Extracted \( K \)-factor has form \( K(m_F) = 1.452 + 0.000357(m_F/\text{GeV}) \).
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, $\mu_f$ is the factorization scale.

We have calculated the full hadron cross section at $\sqrt{s} = 13$ TeV with using the parton distribution functions CT18 [26] (NNLO, $\mu = \mu_f = m_t$, $m_t = 172$ GeV). Also we perform cross check our partons integrations with use of MMHT 2014 [27] PDF in the ManeParse (package for the Wolfram Mathematica for parsing various PDF functions) [28] — we get difference about 1 – 2%.

Below are the current experimental data on $t\bar{b}t\bar{b}$ and $t\bar{t}t\bar{t}$ production cross sections at the LHC ($\sqrt{s} = 13$ TeV):

- $\sigma (pp \to t\bar{b}t\bar{b}) = 5.5 \pm 0.3$ (stat) $^{+1.6}_{-1.3}$ (syst) pb, (CMS, $L = 35.9$ fb$^{-1}$, [29]),
- $\sigma (pp \to t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}$ (syst) fb, (CMS, $L = 137$ fb$^{-1}$, [30]),
- $\sigma (pp \to t\bar{t}t\bar{t}) = 24^{+7}_{-6}$ (syst) fb, (ATLAS, $L = 139$ fb$^{-1}$, [31]).

The scalar gluon $F_aF_a^*$ production cross section for LHC energy as functions of scalar particle masses is shown in figure 1. Here and below $F_1F_1^*$ or $F_2F_2^*$ pairs without summing.

Horizontal lines show experimental cross sections with their errors.

![Figure 1. $F_aF_a^*$ production cross section at the LHC, $\sqrt{s} = 13$ TeV.](image)

From comparison predicted cross section of $F_1F_1^*$ or $F_2F_2^*$ with experimental data on $t\bar{b}t\bar{b}$ and $t\bar{t}t\bar{t}$ production cross sections we found mass limits for color scalar octets $F_aF_a^*$.

Mass of the charged scalar gluon $F_1$

$$m_{F_1} \gtrsim 549^{+27}_{-21} \text{GeV}, \quad (18)$$

and mass of the neutral scalar gluon $F_1$

$$m_{F_2} \gtrsim 1336^{+87}_{-61} \text{GeV}. \quad (19)$$

In conclusion, we summarize the results of this paper.

The full hadron cross section of the scalar octets $F_aF_a^*$-pairs production at the LHC at $\sqrt{s} = 13$ TeV is calculated. From the CMS data on $t\bar{b}t\bar{b}$ and $t\bar{t}t\bar{t}$ production cross sections we found the limits on masses of charged $F_1$ and neutral $F_2$ scalar color octets.
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