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

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Outline

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Extended color symmetries are attractive variants of the New Physics.

One of the variants of such new physics can be induced by the possible four color symmetry treating leptons as quarks of the fourth color [Pati,Salam'PRD10(1974)].

The **M**inimal four color **Q**uark–**L**epton **S**ymmetry model (**MQLS-model**) is based on the gauge group

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

as minimal group containing the four color symmetry of quarks and leptons [Smirnov'PLB346(1995), Smirnov'PAN58(1995)].

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

So each lepton have $SU_V(4)$ "color" $A = 4$

New particles:

Spin-$\frac{1}{2}$: None

Spin-1: Z'-boson, $V_\alpha^\pm$ vector leptoquarks

Spin-0:	$\Phi^{(1)}$,	$\Phi_a^{(2)}$,	$\Phi_a^{(3)}$,	$\Phi^{(4)}$
rep. –	$(4, 1, 1)$	$(1, 2, 1)$	$(15, 2, 1)$	$(15, 1, 0)$
VEV –	η_1	η_2	η_3	η_4

Symmetry breaking

$$SU_V(4) \times SU_L(2) \times U_R(1)$$
$$\downarrow \eta_4$$
$$SU_C(3) \times U_{15}(1) \times SU_L(2) \times U_R(1)$$
$$\downarrow \eta_1$$
$$SU_C(3) \times SU_L(2) \times U(1)$$
$$\downarrow \eta$$
$$G_{\rm SM} = SU_C(3) \times U_{em}(1)$$
$$\eta = \eta_{\rm SM} = \sqrt{\eta_2^2 + \eta_3^2}$$

Scalars interacting with fermions

As a result of the Higgs mechanism of splitting the masses of quarks and leptons the MQLS-model predicts in addition to the SM Higgs doublet $\Phi^{(SM)}$ the existence of the new scalar $SU_L(2)$-doublets

$$\begin{pmatrix} \Phi'_1 \\ \Phi'_2 \end{pmatrix}; \quad \begin{pmatrix} S^{(+)}_{1\alpha} \\ S^{(+)}_{2\alpha} \end{pmatrix}; \quad \begin{pmatrix} S^{(-)}_{1\alpha} \\ S^{(-)}_{2\alpha} \end{pmatrix}; \quad \boxed{\begin{pmatrix} F_{1a} \\ F_{2a} \end{pmatrix}}$$

with electric charges

$$Q^{em}_{\Phi}: \quad \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \quad \begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix}; \quad \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}; \quad \begin{pmatrix} 1 \\ 0 \end{pmatrix}.$$

$\Phi^{(3)}_{15} - \Phi^{(2)}$-mixing gives the SM Higgs doublet $\Phi^{(SM)}$ and an additional Φ' colorless scalar doublet.

$S^{(\pm)}_{1\alpha}$, $S^{(\pm)}_{2\alpha}$, $\alpha = 1, 2, 3$ form two scalar leptoquark doublets (doublet of scalar color triplets),

F_{1a}, F_{2a}, $a = 1, 2 \ldots 8$ form the scalar gluon doublet (doublet of scalar color octets).

Limits on the masses of the scalar gluons

- MQLS model $m_{F_a} > 320$ GeV from Tevatron data [Martynov,Smirnov'Quarks-2010 conf.]
- Flavorful Top-Coloron model $m_{G_H} > 440$ GeV [Chivukula,Simmons *et al.*'PRD88(2013)]
- MQLS model $m_{F_a} > 300 \div 500$ GeV from the LHC on $t\bar{t}$ invariant mass spectra data [Martynov, M. V.,Smirnov, A. D.'EWC158(2017)]
- Simplified phenomenological model of sgluons $m_O > 1.06$ TeV from LHC13 CMS ($L = 35.9\text{fb}^-1$) data [Darme,Fuks *et al.*'PLB784(2018)]
- Unified leptoquark model $m_{G+} > 1.0$ TeV (neutral scalar gluons in this model prefer decays to the b-quarks) [Faber,Liu *et al.*' (2018)]
- MSSM Minimal R-symmetric models $m_O > 1.0$ TeV [Carpenter,Murphy *et al.*' (2020)]

We will discuss the processes $pp \to F_1 F_1^* \to t\bar{t}b\bar{b}$ and $pp \to F_2 F_2^* \to t\bar{t}t\bar{t}$ as way to find mass limits of the scalar gluons.

Decays of scalar gluons F_a

The interactions of the scalar gluons with quarks have form

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

where $(h^{L,R}_{F1})_{ij}, (h^L_{1F1})_{ij}, (h^R_{2F1})_{ij}$ are the corresponding Yukawa coupling constants. and $t_k, k = 1, \dots 8$, are the generators of the $SU_c(3)$ group.

These interactions induce the scalar gluon decays

$$F_1 \to u_i\bar{d}_j, \;\; F_2 \to u_i\bar{u}_j, \;\; F_2 \to d_i\bar{d}_j.$$

Widths of F_a

The dominant decays are

$$F_1 \to t\bar{b}, \;\; F_2 \to t\bar{t},$$

$$\mathrm{Br}(F_1 \to t\tilde{b}) \approx \mathrm{Br}(F_2 \to t\tilde{t}) \approx \; 1$$

with widths of order of ten GeVs [Popov,Povarov *et al.*'MPLA20(2005)].

$$\begin{aligned} \Gamma(F_1 \to t\tilde{b}) &= m_{F_1}\frac{3}{32\pi}\left(\frac{m_t}{\eta_{\rm SM}}\right)^2\left(1-\frac{m_t^2}{m_{F_12}^2}\right)^2\frac{|(C_Q)_{33}|}{sin^2\beta}, \\ \Gamma(F_2 \to t\tilde{t}) &= m_{F_2}\frac{3}{32\pi}\left(\frac{m_t}{\eta_{\rm SM}}\right)^2\left(1-2\frac{m_t^2}{m_{F_2}^2}\right)\sqrt{1-4\frac{m_t^2}{m_{F_2}^2}}\frac{1}{sin^2\beta}. \end{aligned}$$

Interactions of color scalar particles Φ_i with gluons

$$\mathcal{L}_{\Phi\Phi g} = \sum_{scalars} \left[\left(D^{\mu}_{ij} \Phi^j \right)^{\dagger} \left(D^{ik}_{\mu} \Phi_k \right) - m^2_{\Phi} \Phi^{i\dagger} \Phi_i \right],$$

$$D^{ij}_{\mu} \Phi_j \ = \partial_{\mu} \Phi^i - i g_s G^a_{\mu} T^{ij}_a \Phi_j,$$

where T^{ij}_a are the generators of the 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 Φ_i, i, j – color index.

$i, j = 1, 2, 3$ for scalar leptoquarks and $i, j = 1, 2, ..8$ for scalar gluons.

Partonic cross sections for $F_a F_a^*$-pairs production

$$\hat{\sigma}_{gg\to F_a F_a^*} = \frac{3\pi\alpha_s^2}{16\hat{s}}\left[\beta(27-17\beta^2)+3\ln\left|\frac{\beta+1}{\beta-1}\right|(\beta^4+2\beta^2-3)\right],$$

$$\hat{\sigma}_{q\bar{q}\to F_a F_a^*} = \frac{4\pi\alpha_s^2}{9\hat{s}}\beta^3,$$

where $\beta = \sqrt{1-4m_F^2/\hat{s}}$.

[Blumlein,Boos *et al.*'ZPC76(1997), Manohar,Wise'PRD74(2006), Martynov,Smirnov'MPLA23(2008)]

We use appropiate $k(m_F)$–factors for consistency with NLO calculations of cross section [Goncalves-Netto,Lopez-Val *et al.*'PRD85(2012)].

We have calculated the full hadron cross section at $\sqrt{s} = 13$ TeV with using the parton distribution functions CT18 [Hou *et al.*' (2019)] (NNLO, $\mu = \mu_f = m_t$, $m_t = 172$ GeV).

Also we perform cross check our partons integrations with use PDFs MMHT 2014 [Harland-Lang,Martin *et al.*'EC75(2015)] in the ManeParse (package for the Wolfram Mathematica for parsing various the PDF functions) [Clark,Godat *et al.*'CPC216(2017)] — we get difference about $1-2\%$.

Experimental data on $tb\bar{t}\bar{b}$ and $t\bar{t}t\bar{t}$ production cross sections at LHC13

$$\sigma\left(pp \to tb\bar{t}\bar{b}\right) = \quad 5.5 \pm 0.3\,(\text{stat})^{+1.6}_{-1.3}\,(\text{syst})\,\text{pb}, \quad \text{CMS}\ (L = 35.9\,\text{fb}^{-1}).$$

[Sirunyan *et al.*(CMS)'PLB803(2020)]

$$\sigma\left(pp \to t\bar{t}t\bar{t}\right) = \quad 12.6^{+5.8}_{-5.2}\,(\text{syst})\,\text{fb}, \quad \text{CMS}\ (L = 137\,\text{fb}^{-1}).$$

[Sirunyan *et al.*(CMS)'EPJC80(2020)]

$$\sigma\left(pp \to t\bar{t}t\bar{t}\right) = \quad 24^{+7}_{-6}\,(\text{syst})\,\text{fb}, \quad \text{ATLAS}\ (L = 139\,\text{fb}^{-1}).$$

[Aad *et al.*(ATLAS)' (2020)]

Theoretical predictions

$$\sigma^{\text{SM}}\left(pp \to t\bar{t}t\bar{t}\right) = \quad 11.97^{+2.15}_{-2.51}\,\text{fb},$$

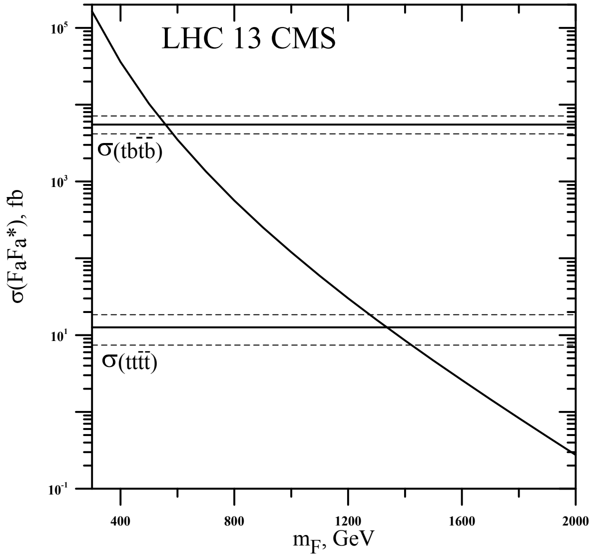
[Frederix,Pagani *et al.*'J02(2018)]

$$\sigma^{\text{SM}}\left(pp \to tb\bar{t}\bar{b}\right) = \quad 3.6 \pm 0.3\,\text{pb},$$

MADGRAPH5 aMC@NLO.

[Sirunyan *et al.*(CMS)'PLB803(2020)]

$F_a F_a^*$ production cross section at the LHC, $\sqrt{s} = 13$TeV



Mass limits for color scalar octets F_a (scalar gluons)

Mass of the charged scalar gluon F_1

$$m_{F_1} \gtrsim 549^{+27}_{-21}\,\text{GeV}.$$

Mass of the neutral scalar gluon F_2

$$m_{F_2} \gtrsim 1336^{+87}_{-61}\,\text{GeV}.$$

From CMS data on $tb\bar{t}\bar{b}$ and $t\bar{t}t\bar{t}$ production cross sections.

Summary

- 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 $tb\bar{t}\bar{b}$ and $t\bar{t}t\bar{t}$ production cross sections we found the limits on masses charged F_1 and neutral F_2 scalar color octets.

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Backup slides

Fermion sector of the model

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

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

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

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

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

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 four new mixing matrices which are specific for the models with the four color symmetry.

Scalar sector of the MQLS-model

The scalar sector contains in general four multiplets [Smirnov'PLB346(1995)], [Povarov,Smirnov'PAN64(2001)]

$$
\begin{aligned}
(4,1,1): \Phi^{(1)} &= \begin{pmatrix} S_\alpha^{(1)} \\ \frac{\eta_1 + \chi^{(1)} + i\omega^{(1)}}{\sqrt{2}} \end{pmatrix}, \\
(1,2,1): \Phi_a^{(2)} &= \delta_{a2}\frac{\eta_2}{\sqrt{2}} + \phi_a^{(2)}, \\
(15,2,1): \Phi_a^{(3)} &= \begin{pmatrix} (\mathbf{F_a})_{\alpha\beta} & \mathbf{S}^{(+)}_{\mathbf{a}\alpha} \\ \mathbf{S}^{(-)}_{\mathbf{a}\alpha} & 0 \end{pmatrix} + (\delta_{a2}\eta_3 + \phi^{(3)}_{15,a})t_{15}, \\
(15,1,0): \Phi^{(4)} &= \begin{pmatrix} F^{(4)}_{\alpha\beta} & \frac{1}{\sqrt{2}}S^{(4)}_\alpha \\ \overset{*}{S}{}^{(4)}_\alpha & 0 \end{pmatrix} + (\eta_4 + \chi^{(4)})t_{15},
\end{aligned}
$$

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 η_1, η_2, η_3, η_4 are the vacuum expectation values.