On mass limits for scalar color octet from the LHC data on invariant mass spectra of $t\bar{t}$ production

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Outline

Extended color symmetries are attractive variants of the New Physics.

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

The Minimal four color Quark– Lepton Symmetry model (**MQLS-model**) is based on the gauge group [Smirnov'PLB346(1995)]

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

as minimal group containing the four color symmetry of quarks and leptons

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-1: Z'-boson, $V^{\pm}_{\alpha}$ vector leptoquarks

Spin-0:	$\Phi^{(1)}$,	$\Phi^{(2)}_a$,	$\Phi^{(3)}_a$,	$\Phi^{(4)}$
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

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

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

The interactions of the neutral scalar gluon F_2 with quarks:

$$L_{F_2 u_i u_j} = \bar{u}_{i\alpha}\Big[(h^L_{1F_2})_{ij} P_L\Big](t_k)_{\alpha\beta} u_{j\beta} F_{2k} + \text{h.c.},$$

$$L_{F_2 d_i d_j} = \bar{d}_{i\alpha}\Big[(h^R_{2F_2})_{ij} P_R\Big](t_k)_{\alpha\beta} d_{j\beta} F_{2k} + \text{h.c.}$$

Scalar gluons F_2 couplings to fermions:

$$(h^L_{1F_2})_{ij} = -\sqrt{3}\frac{1}{\eta \sin\beta}\Big[m_{u_i}\delta_{ij} - (K^R_1)_{ik} m_{\nu_k} (\overset{+}{K}{}^L_1)_{kj}\Big],$$

$$(h^R_{2F_2})_{ij} = -\sqrt{3}\frac{1}{\eta \sin\beta}\Big[m_{d_i}\delta_{ij} - (K^L_1)_{ik} m_{l_k} (\overset{+}{K}{}^R_1)_{kj}\Big].$$

$K_1^{L,R}$ are some mixing matrices specific for MQLS-model (similar V_{CKM}, V_{PMNS}), η is SM VEV, β is a angle of $\Phi^{(3)}_{15} - \Phi^{(2)}$-mixing in MQLS-model.

The largest constant with neglect of the neutrinos masses takes the form

$$(h^L_{1F_2})_{33} = -\sqrt{3}\frac{m_t}{\eta \sin\beta}$$

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

$$L_{F_2tt} = \bar{t}_\alpha (h^S_{F_2t\bar{t}} + h^P_{F_2t\bar{t}}\gamma_5)(t_c)_{\alpha\beta} t_\beta F_{2c} + \text{h.c.},$$

where scalar and pseudoscalar coupling constants take the form

$$h^S_{F_2t\bar{t}} = h^P_{F_2t\bar{t}} = -\frac{\sqrt{3}}{2}\frac{m_t}{\eta \sin\beta} \approx -0.61/\sin\beta$$

$h^{S,P}_{F_2t\bar{t}}$ increase with decreasing $\sin\beta$

the perturbation theory parameters	$(h^{S,P}_{F_2t\bar{t}})^2/4\pi$	$\approx$	0.03	0.06	0.18
for	$\sin\beta$	$=$	1	0.7	0.4

Below we restrict ourselves by the mixing angle region $\boxed{\mathbf{0.4 \le \sin\beta \le 1}}$

Width of the scalar gluon F_a is small

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

For the masses $m_{F_2} = 400 - 2000$ GeV the width F_2 is of about $(2-30)/\sin^2\beta$ GeV and $\Gamma_{F_2}/m_{F_2} = (0.5-1.5)\%/\sin^2\beta$ [Popov,Povarov *et al.*'MPLA20(2005)]

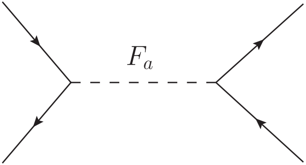
Possibility of the direct searches scalar gluons at the LHC

- $m_{F_a} > 320$ Gev from Tevatron data [Martynov,Smirnov'Quarks-2010 conf.]
- For Flavorful Top-Coloron model scalar octet $m_{G_H} > 440$ GeV
  [Chivukula,Simmons *et al.*'PRD88(2013)]
- Sgluons in SUSY models are EW singlets and have no direct interactions with quarks
  [Plehn,Tait'JPG36(2009)] ($m_G > 1.06$ TeV [Aad *et al.*(ATLAS)'J08(2015)])
- At $m_{F_1} \lesssim 1130\, GeV$ from analysis statistical significance the number of the signal $t\bar{t}b\bar{b}$ events will exceed the SM background by 3σ (LHC 14 TeV $L = 10\, fb^{-1}$)
  [Martynov,Smirnov'PAN73(2010)].
- 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 (14 TeV, $L = 10\, fb^{-1}$) [Martynov,Smirnov'MPLA23(2008)].

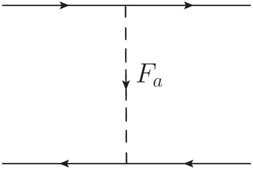
The most perspective way to search for scalar gluons is analysis of processes $pp \to F_1 F_1^* \to t\bar{t}b\bar{b}$ and $pp \to F_2 F_2^* \to t\bar{t}t\bar{t}$.
Another way is consideration of the resonance contribution of scalar gluons to $t\bar{t}$ production.

Scalar gluons tree processes

S-channel processes leads to enhancement cross section by the factor $\frac{1}{(\hat{s}-m_F^2)^2+m_F^2\Gamma_F^2}$, but interaction scalar gluons with initial light quarks is small.



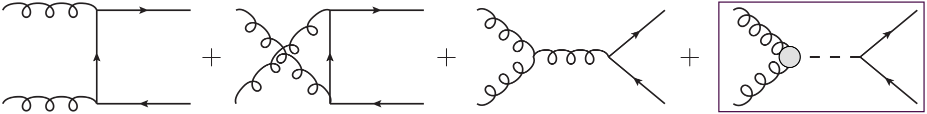
$\sigma \sim m_q^2/\hat{s}$



$\sigma \sim |(C_Q)_{i3}|^4$

These contributions are suppressed by factors $m_u^2/\hat{s}$, $m_d^2/\hat{s}$ or $|(V_{CKM})_{i3}|^4$ — $\Delta\sigma(p\bar{p} \to t\bar{t}) \sim 0.0001$ pb [Martynov,Smirnov'Quarks-2010 conf.].

Diagrams with account contribution of the $(gg\Phi)$-effective vertex

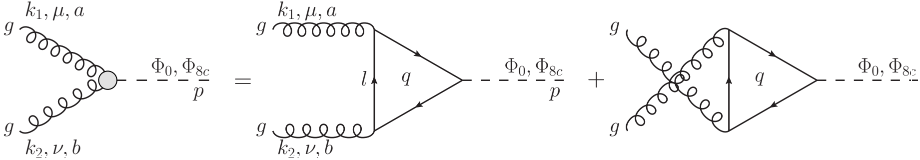


Flavour diagonal interactions of scalar octet and of the scalar color singlet with quarks in the model independent form [Frolov,Martynov *et al.*'MPLA31(2016)]

$$L_{\Phi q\bar{q}} = \bar{q}_\alpha (h^S_{\Phi q\bar{q}} + h^P_{\Phi q\bar{q}} \gamma_5) \Phi_{\alpha\beta} q_\beta + \text{h.c.},$$

$\Phi_{\alpha\beta} = \Phi_0\, \delta_{\alpha\beta}$ for the colorless scalar particle Φ_0
$\Phi_{\alpha\beta} = \Phi_{8c}\, (t_c)_{\alpha\beta}$ for the scalar octet Φ_8

The effective vertex $\Gamma^{(q)\mu\nu}_{ab\Phi}(p, k_1, k_2)$



$$\Gamma^{(q)\mu\nu}_{ab\Phi}(p, k_1, k_2) =$$

$$= c^{(1)}_{ab\Phi}\, g_s^2 \int \frac{d^n l}{i(2\pi)^n} \frac{\text{Tr}\big((h^S_{\Phi qq} + h^P_{\Phi qq}\gamma^5)(\hat{l} + \hat{k}_1 + m_q)\gamma^\mu (\hat{l} + m_q)\gamma^\nu (\hat{l} - \hat{k}_2 + m_q)\big)}{\big((l + k_1)^2 - m_q^2 + i\varepsilon\big)\big(l^2 - m_q^2 + i\varepsilon\big)\big((l - k_2)^2 - m_q^2 + i\varepsilon\big)} +$$

$$+ c^{(2)}_{ab\Phi}\, g_s^2 \int \frac{d^n l}{i(2\pi)^n} \frac{\text{Tr}\big((h^S_{\Phi qq} + h^P_{\Phi qq}\gamma^5)(\hat{l} + \hat{k}_2 + m_q)\gamma^\nu (\hat{l} + m_q)\gamma^\mu (\hat{l} - \hat{k}_1 + m_q)\big)}{\big((l + k_2)^2 - m_q^2 + i\varepsilon\big)\big(l^2 - m_q^2 + i\varepsilon\big)\big((l - k_1)^2 - m_q^2 + i\varepsilon\big)}$$

Effective vertex $\Gamma^{\mu\nu}_{ab\Phi}(p,k_1,k_2)$ in the case of real gluons ($k_1^2=0$, $k_2^2=0$, $p^2=\hat{s}=2(k_1k_2)$)

$$\Gamma^{\mu\nu}_{ab\Phi}(p,k_1,k_2)=\sum_q \Gamma^{(q)\mu\nu}_{ab\Phi}(p,k_1,k_2)=$$

$$=-C_{ab\Phi}\frac{\alpha_s\sqrt{\hat{s}}}{\pi}\left[\left(g^{\mu\nu}-\frac{2k_1^\nu k_2^\mu}{\hat{s}}\right)F^S_\Phi(\hat{s})-2i\varepsilon^{\mu\nu\rho\sigma}\frac{k_{1\rho}k_{2\sigma}}{\hat{s}}F^P_\Phi(\hat{s})+\frac{2k_1^\mu k_2^\nu}{\hat{s}}G^S_\Phi(\hat{s})\right]$$

$$F^{S,P}_\Phi(\hat{s})=\sum_q h^{S,P}_{\Phi q\bar{q}}\tilde{F}^{S,P}(\hat{s},m_q^2) \qquad G^S_\Phi(\hat{s})=\sum_q h^S_{\Phi q\bar{q}}\tilde{G}^S(\hat{s},m_q^2)$$

$C_{ab\Phi_0}=\delta_{ab}/2\equiv C_{ab}$ for the colorless scalar particle Φ_0

$C_{ab\Phi_{8c}}=d_{abc}/4\equiv C_{abc}$ for the scalar octet Φ_8

Form factors arising from quark q in the loop:

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

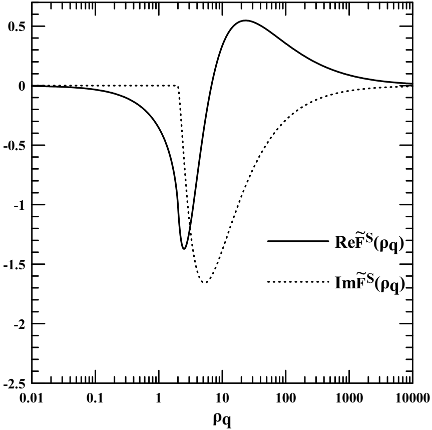
$$\rho_q=\frac{\sqrt{\hat{s}}}{m_q}$$

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

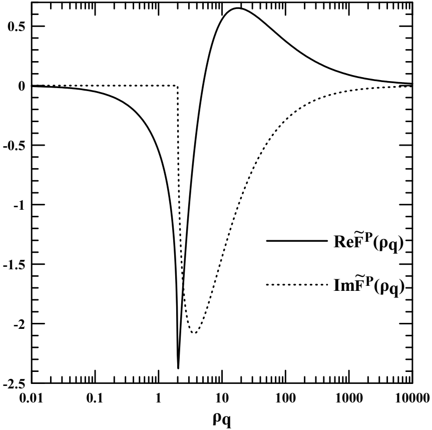
$$\tilde{G}^S(\hat{s},m_q^2)==\frac{m_q}{\sqrt{\hat{s}}}\left[(\hat{s}+4m_q^2)\,C_0(0,0,\hat{s},m_q^2,m_q^2,m_q^2)+4B_0(\hat{s},m_q^2,m_q^2)-\frac{4A_0(m_q^2)}{m_q^2}\right]\equiv\tilde{G}^S(\rho_q)$$

A_0, B_0, C_0 are the Passarino-Veltman integrals [Passarino,Veltman'NPB160(1979)]

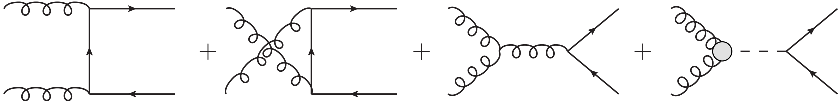
$\tilde{F}^S(\rho_q)$



$\tilde{F}^P(\rho_q)$



We have calculated the cross section of the process $gg \to Q\bar{Q}$ in QCD LO with account also of the effective vertex $\Gamma^{\mu\nu}_{ab\Phi}$
The diagrams of this process



The total cross section of the process $gg \to Q\bar{Q}$

$$\sigma_{LO}(gg{\to}Q\bar{Q},\mu) = \sigma^{\rm SM}_{LO}(gg{\to}Q\bar{Q},\mu) + \Delta\sigma^{\Phi}(gg{\to}Q\bar{Q},\mu)$$

$$\Delta\sigma^{\Phi}(gg{\to}Q\bar{Q},\mu) =$$

$$= \frac{\tilde{C}^{(1)}_{\Phi}}{64}\,\frac{\alpha_s^2(\mu)m_Q}{\pi\sqrt{\hat{s}}}\,\frac{\mathrm{Re}\left[\left(\hat{s}-m_\Phi^2 - i m_\Phi\Gamma_\Phi\right)\left(-h^{S^*}_{\Phi Q\bar{Q}}v^2 F^S_\Phi(\hat{s}) - h^{P^*}_{\Phi Q\bar{Q}}F^P_\Phi(\hat{s})\right)\right]}{(\hat{s}-m_\Phi^2)^2 + m_\Phi^2\Gamma_\Phi^2}\log\frac{1{+}v}{1{-}v} +$$

$$+ \frac{\tilde{C}^{(2)}_{\Phi}}{1024}\,\frac{\alpha_s^2(\mu)v\hat{s}}{\pi^3}\,\frac{\left|h^S_{\Phi Q\bar{Q}}\right|^2 v^2 + \left|h^P_{\Phi Q\bar{Q}}\right|^2}{(\hat{s}-m_\Phi^2)^2 + m_\Phi^2\Gamma_\Phi^2}\left(|F^S_\Phi(\hat{s})|^2 + |F^P_\Phi(\hat{s})|^2\right)$$

$$\boxed{v = \sqrt{1 - \frac{4m_Q^2}{\hat{s}}}}$$

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

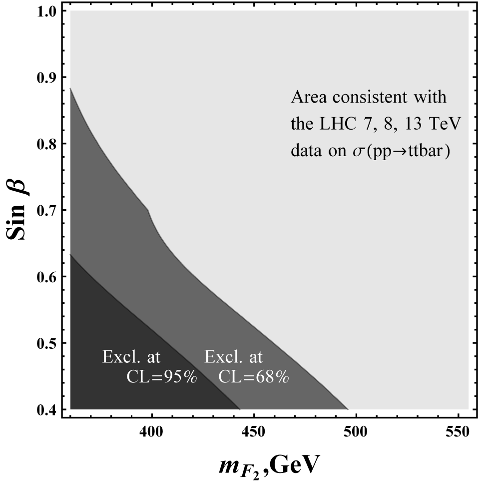
$$\tilde{C}^{(1)}_{\Phi_8} = C_{abc}C_{abc} = 5/6, \qquad \tilde{C}^{(2)}_{\Phi_8} = C_{abc}C_{abc}/2 = 5/12$$

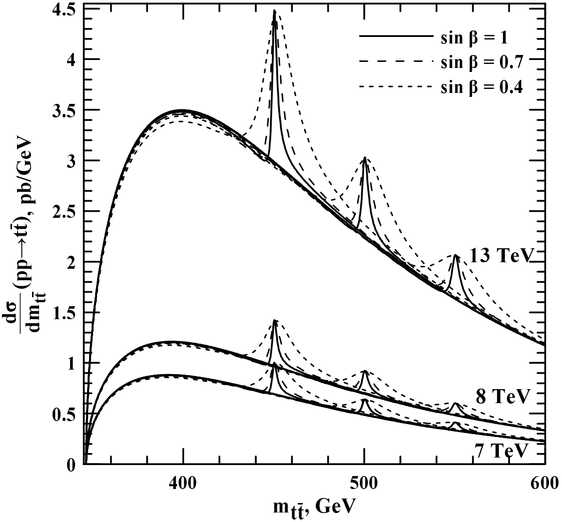
Contributions to cross section of $t\bar{t}$-pairs production at LHC

We calculate F_2 contributions to cross section of $t\bar{t}$-pairs production at LHC (7,8,13 TeV).

$\Delta\sigma^{F_2}(pp\to t\bar{t})$ varies from 0.3 to 54.9 pb (depending on $\sqrt{s}, m_{F_2}, \sin\beta$).

From LHC data on $t\bar{t}$ cross section we found exclusion area at the $(m_{F_2} - \sin\beta)$-plane





The invariant mass spectrum $d\sigma(pp \to t\bar{t})/dm_{t\bar{t}}$ 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 $\sin\beta = 1, 0.7, 0.4$.

The invariant mass spectrum of $t\bar{t}$-pairs production at LHC

Theoretical predictions

NNLL+aNNLO:[Ahrens,Ferroglia *et al.*'J1009(2010)]

NNLO: [Czakon,Heymes *et al.*'PRL116(2016), Czakon,Heymes *et al.*' (2017)],

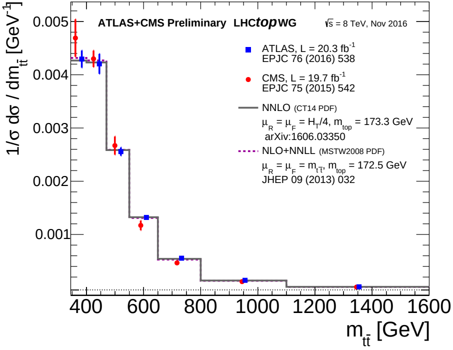
Experimental data

LHC CMS 8 TeV, $\mathrm{L} = 19.7\,\mathrm{fb}^{-1}$ [Khachatryan *et al.*(CMS)'EPJC75(2015)]

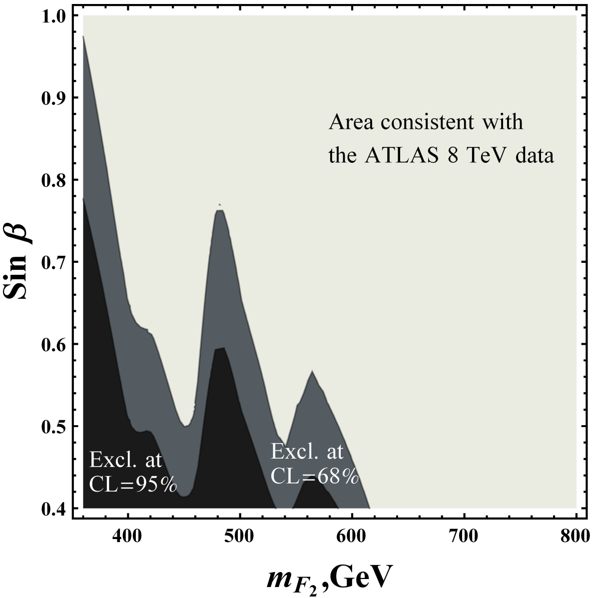
LHC ATLAS 8 TeV, $\mathrm{L} = 20.3\,\mathrm{fb}^{-1}$ [Aad *et al.*(ATLAS)'EPJC76(2016)]

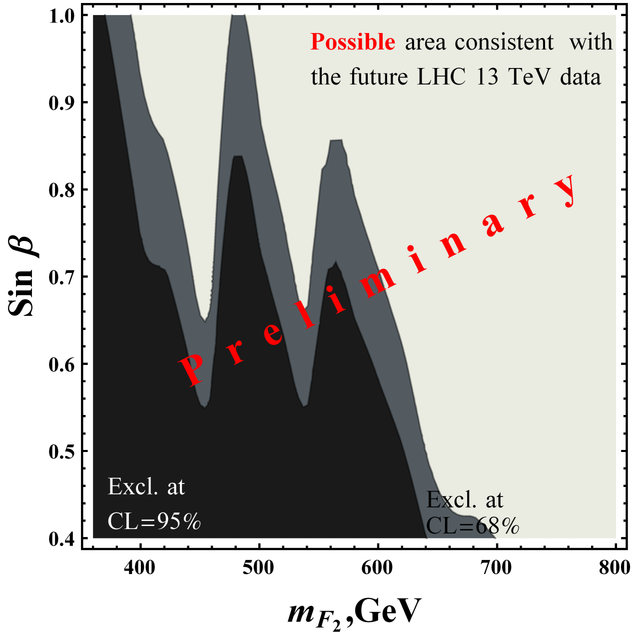
$$\chi^2_{r\mathrm{CMS}} = 3.6$$
$$\chi^2_{r\mathrm{ATLAS}} = 0.1$$

$$\chi^2_r = \frac{1}{NDF}\sum_i^N \frac{(\sigma_i^{exp} - \sigma_i^{th})^2}{(\Delta\sigma_i^{exp})^2}$$



Exclusion area from $t\bar{t}$ invariant mass spectrum (ATLAS 8 TeV, 20.3 fb^{-1})





Possible area consistent with
the future LHC 13 TeV data
Preliminary
Excl. at
CL=95%
Excl. at
CL=68%
Sin β
0.4
0.5
0.6
0.7
0.8
0.9
1.0
400
500
600
700
800
m_{F_2},GeV

Summary

- 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
- 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 ATLAS data on the differential cross sections of $t\bar{t}$ production at $\sqrt{s} = 8$ TeV it is shown that there is region of $(m_{F_2} - \sin\beta)$-plane of exclusion 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.

Backup slides

For numerical calculations we use the analytical expressions for scalar PV integrals A_0, B_0, C_0 from the Denner's paper [Denner'FP41(1993)] and we also perform the cross check with using LoopTools [Hahn,Perez-Victoria'CPC118(1999)].

We have calculated the cross section at $\sqrt{s} = 7, 8, 13$ TeV with using the parton distribution functions MMHT 2014 [Harland-Lang,Martin *et al.*'EC75(2015)] (NNLO, $\mu = \mu_f = m_t$, $m_t = 173.21$ GeV).

For calculations we use the values of K-factors $K(s) = 1.6687$, 1.6752, 1.6833 for energies $\sqrt{s} = 7, 8, 13$ TeV respectively, in this case the cross section $\sigma^{\rm SM}(pp{\to}t\bar{t})$ reproduces well the aNNNLO SM predictions for the cross section of $t\bar{t}$ production [Kidonakis'PRD90(2014)].

Also we perform cross check our partons integrations with use PDFs CT14, METAv10 in the ManeParse (package for the Wolfram Mathematica for parsing various PDF functions) [Clark,Godat *et al.*'CPC216(2017)] — we get difference about 1%.

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, ...

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

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

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)]

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

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.

For the comparison of the experimental and theoretical results we use the variable χ_r^2 („reduced" χ^2) defined as

$$\chi_r^2 = \frac{1}{n}\sum_i^N \frac{(\sigma_i^{exp} - \sigma_i^{th})^2}{(\Delta\sigma_i^{exp})^2},$$

where σ_i^{exp} denote the experimental value of $\overline{\frac{d\sigma(pp\to t\bar{t})}{dm_{tt}}}$ in the i-th bin,
σ_i^{th} is the corresponding theoretical value,
$\Delta\sigma_i^{exp}$ is the experimental error of this value,
$n = N - N_p$ is the number of degrees of freedom,
N is the number of the bins under consideration and
N_p is the number of the free parameters of the model.
$N_p = 0$ for the SM
$N_p = 2$ for the MQLS-model.

$$\sigma_i^{th} = \overline{\frac{d\sigma(pp\to t\bar{t})_i}{dm_{tt}}} = \frac{1}{\Delta m_{tt}^{(i)}} \int\limits_{m_{tt}^{i_-}}^{m_{tt}^{i_+}} \frac{d\sigma(pp\to t\bar{t})}{dm_{jj}}\, dm_{tt}$$

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