Unveiling E_6SSM Leptoquarks at the LHC

Murad Ali

In collaboration with S. Khalil, S. Moretti, S. Munir, R. Nevzorov, A. Nikitenko, H. Waltari

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3rd Generation Scalar LQs and fully hadronic $t\bar{t}\tau\tau$ final state at the LHC Run 2

- Consider a scalar S_1-type, denoted by D henceforth, charged as $(3, 1, -1/3)$ under the G_{SM} with interaction:

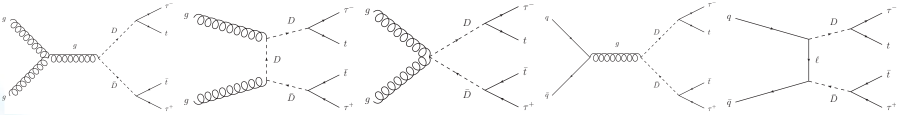
$$\mathcal{L} = \lambda \bar{Q}_L D \bar{\ell}_L + \lambda' \bar{t}_R D \bar{\tau}_R \,, \tag{1}$$

- LO partonic cross sections are give by:

$$\sigma(gg \to D\overline{D}) = \frac{\alpha_s^2 \pi}{96\hat{s}} \left[\beta(41 - 31\beta^2) + (18\beta^2 - \beta^4 - 17) \log \frac{1+\beta}{1-\beta} \right] ,$$

$$\sigma(q\bar{q} \to D\overline{D}) = \frac{2\alpha_s^2 \pi}{27\hat{s}} \beta^3 .$$

3rd Generation Scalar LQs and fully hadronic $t\bar{t}\tau\tau$ final state at the LHC Run 2



m_D (GeV)	σ_{LO} (fb)	σ_{NLO} (fb)
1000	3.22	5.73
1100	1.57	2.86
1200	0.79	1.50
1300	0.42	0.79
1400	0.22	0.44
1500	0.12	0.25
1600	0.070	0.146

Table: Computed with MADGRAPH5 v3.2.0 and PROSPINO v2.1

Decay Mode	Mass Limit [GeV]	Experiment
$t\bar{t}\tau\tau$	900	CMS
	1400	ATLAS
$tb\tau\nu$	950	CMS
	1250	ATLAS
	1220	ATLAS

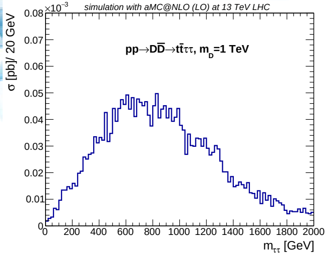
*CMS: arXiv:*1803.02864, 2012.04178
*ATLAS:arXiv:*2101.11582,2108.07665

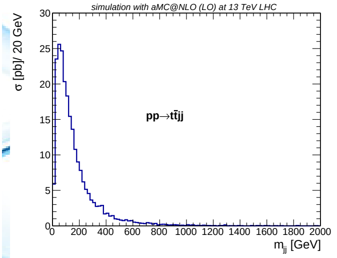
3rd Generation Scalar LQs and fully hadronic $t\bar{t}\tau\tau$ final state at the LHC Run 2: Event Selection Strategy

- We propose to complement the ATLAS and CMS probes of the $t\bar{t}\tau\bar{\tau}$ intermediate state with the fully hadronic topology.
- Background: $t\bar{t}jj$, $t\bar{t}b\bar{b}$, $t\bar{t}Z(\longrightarrow \tau\tau)$, $t\bar{t}W(\longrightarrow jj)$, $Z(\longrightarrow \tau\tau) + 6j$, and $W(\longrightarrow jj) + 6j$.
- Select events with two τ_h and at least six jets.
- Forced τ to decay hadronically, i.e, $\tau^{\pm} \longrightarrow \pi^{\pm}\pi^{0}\nu_{\tau}$.
- Kinematics selection for jets: $\Delta R(jj) > 0.4$, $p_T^j > 20\text{GeV}$, and $|\eta^j| < 2.4$.

3rd Generation Scalar LQs and fully hadronic $t\bar{t}\tau\tau$ final state at the LHC Run 2: Event Selection Strategy

- Tagging efficiencies and Fake rates:
  - $\varepsilon^{\tau}_{1(2)} = 0.7(0.5)$ with $p^{\tau}_T > 100$ GeV (< 100 GeV), and $\varepsilon_{\tau-fake} = 3 \times 10^{-3}$.
  - $\varepsilon_b = 0.8$, and $\varepsilon_{b-fake} = 10^{-2}$.
  - 15% di-τ mass resolution for the Z and Higgs bosons, i.e., 14 GeV and 19 GeV, respectively.





- Exploit the difference between the $m_{\tau\tau}$ and m_{jj}.

3rd Generation Scalar LQs and fully hadronic $t\bar{t}\tau\tau$ final state at the LHC Run 2: Event Selection Strategy

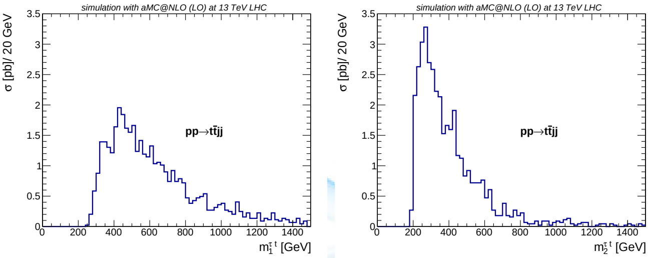
- Events must contain eight jets with $m_{jj} > 200$ GeV.
- For the efficiency of the di-jet mass selection:
  - For Signal: use the generator-level τ_h.
  - For $t\bar{t}jj$: parton jets with $p_T > 40$ GeV and $|\eta| < 2.4$, and 100% events with correct j-to-t association[1].

Process	σ [fb]	bb–tagging	$\tau\tau$–tagging	$m_{\tau\tau} > 200$ GeV	$\sigma^{\rm sel}$[fb]
Signal	0.5 (5.73)	p_b^2	$(p_1^\tau)^2$	0.97	0.15 (1.74)
$t\bar{t}jj$	275×10^3	p_b^2	$(p_{\tau-\rm fake})^2$	0.45	0.71
$t\bar{t}Z$	$950 \times {\rm BR}(Z \to \tau\tau)$	p_b^2	$(p_2^\tau)^2$	$< 5.7 \times 10^{-7}$	$< 2.6 \times 10^{-6}$
$t\bar{t}W$	$770 \times {\rm BR}(W \to qq')$	p_b^2	$(p_{\tau-\rm fake})^2$		$< 3.1 \times 10^{-3}$
$t\bar{t}H$	32	p_b^2	$(p_2^\tau)^2$	6.3×10^{-5}	3.2×10^{-4}
$Z + 6j$	50	${\rm C}_6^2 p_{b-\rm fake}^2(1 - p_{b-\rm fake})^4$	$(p_2^\tau)^2$	$< 5.7 \times 10^{-7}$	$< 1.0 \times 10^{-8}$
$W + 6j$	$600 \times {\rm R}_{\mu\nu}^{qq'}$	${\rm C}_8^2 p_{b-\rm fake}^2(1 - p_{b-\rm fake})^6$	$(p_{\tau-\rm fake})^2$		$< 1.0 \times 10^{-4}$

1. arXive : 1909.05306

3rd Generation Scalar LQs and fully hadronic $t\bar{t}\tau\tau$ final state at the LHC Run 2: Event Selection Strategy

- Further suppression of the $t\bar{t}jj \longrightarrow$ Full reconstruction of the D mass.



- For the selection $m_2^{t\tau} > m_D - 2\sigma_D^{exp} = 800$ GeV, ($\sigma_D^{exp} = 100$ GeV for $m_D = 1$ TeV)[1]:
  - For the background ($t\bar{t}jj$) $\longrightarrow$ 0.06
  - For the signal $\longrightarrow$ 0.95

1. arXive : 1812.10534

3rd Generation Scalar LQs and fully hadronic $t\bar{t}\tau\tau$ final state at the LHC Run 2: Results and Expected Significance

- Signal and Background Cross Sections:
  - Signal $\longrightarrow$ 0.14 (1.65) fb
  - Background $\longrightarrow$ 0.04 fb
- Expected Events:
  - Signal $\longrightarrow$ 20 (231)
  - Background $\longrightarrow$ 6
- Signal Significance:
  - 5.2 ($>$ 5) computed with $(2(\sqrt{S+B} - \sqrt{B}))$[1]

1.physics/9811025

Interpretation in the E_6SSM

- Provide an elegant solution to the μ problem: Forbids $\mu \hat{H}_d \hat{H}_u$, Allows $\lambda \hat{S} \hat{H}_d \hat{H}_u$, and therefore $\mu \equiv \mu_{eff} = \lambda < S >$.
- Allows the light Higgs mass to be as heavy as 125 GeV.
- Allows unification of the gauge coupling to within 2 S.D.
- Predict a new Z' boson, exotic colored objects, exotic objects and sterile right-handed neutrino.

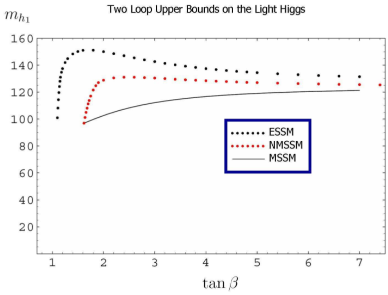


Figure: taken from hep-ph/0510419

Interpretation in the E_6SSM

- The E_6SSM is an E_6 inspired model with an extra gauged $U(1)$ symmetry. The symmetry breaking pattern is:

$$E_6 \xrightarrow{M_{\rm GUT}} SO(10)\times U(1)_\psi \xrightarrow{M_{\rm GUT}} SU(5)\times U(1)_\psi \times U(1)_\chi \xrightarrow{M_{\rm GUT}} G_{SM}\times U(1)_N$$

Where $U(1)_N$ is defined as: $U(1)_N = \frac{1}{4}U(1)_\chi + \frac{\sqrt{15}}{4}U(1)_\psi$

- Low energ gauge invariant superpotential:

$$\begin{aligned}
W &= W_0 + W_1 + W_2 \\
W_0 &= \lambda_{ijk} S_i H_{d_j} H_{u_k} + k_{ijk} S_i \bar{D}_j D_k + h^N_{ijk} N^c_i H_{u_j} L_k \\
&\quad + h^U_{ijk} U^c_{R_i} H_{u_j} Q_{L_k} + h^D_{ijk} D^c_{R_i} H_{d_j} Q_{L_k} + h^E_{ijk} E^c_{R_i} H_{d_j} L_{L_k} \\
W_1 &= g^Q_{ijk} D_i Q_{L_j} Q_{L_k} + g^q_{ijk} \bar{D}_i D^c_{R_j} U^c_{R_k} \\
W_2 &= g^N_{ijk} N^c_i D_j D^c_{R_k} + g^E_{ijk} E^c_{R_i} D_j U^c_{R_k} + g^Q_{ijk} Q_{L_i} L_{L_j} \bar{D}_k
\end{aligned}$$

Interpretation in the E_6SSM

- Low energy matter content of the E6SSM:

$$3[(Q_i, u_i^c, d_i^c, e_i^c, L_i, N_i^c)] + 3(S_i) + 3(H_u) + 3(H_d) + 3(D_i, \bar{D}_i)$$

Particles	Z_2^M	Z_2^L	Z_2^B	Z_2^H
$S_\alpha, H_{d\alpha}, H_{u\alpha}$	$+$	$+$	$+$	$-$
S_3, H_{d3}, H_{u3}	$+$	$+$	$+$	$+$
$Q_{L_i}, D^c_{R_i}, U^c_{R_i}$	$-$	$+$	$+$	$-$
$L_{L_i}, E^c_{R_i}, N^c_i$	$-$	$-$	$-$	$-$
$\bar{D}_i, D_i$	$+$	$+$	$-$	$-$

- Imposing Z_2^B

$$W = W_0 + W_2 \quad (E_6\text{SSM-LQ})$$

Interpretation in the E_6SSM

- The mass matrix for exotic squarks:

$$M^2(i) = \begin{pmatrix} M_{11}^2(i) + \Delta_{11}(i) & \mu_{D_i} X_{D_i} + \Delta_{12}(i) \\ \mu_{D_i} X_{D_i} + \Delta_{12}(i) & M_{22}^2(i) + \Delta_{22}(i) \end{pmatrix},$$

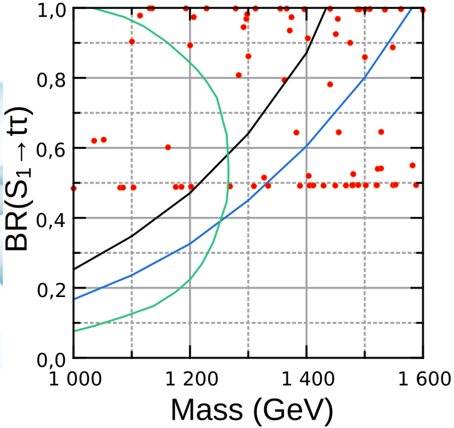
$$\text{with} \quad M_{11}^2(i) = m_{D_i}^2 + \mu_{D_i}^2 + \Delta_D\,, \quad M_{22}^2(i) = m_{\overline{D}_i}^2 + \mu_{D_i}^2 + \Delta_{\overline{D}}\,,$$

$$X_{D_i} = A_{\kappa_i} - \frac{\lambda}{\sqrt{2}\varphi} v_1 v_2\,, \quad \text{and} \quad \Delta_\phi = \frac{g_1'^2}{2}\left(\tilde{Q}_{\overline{D}} v_1^2 + \tilde{Q}_D v_2^2 + \tilde{Q}_\Phi \varphi^2\right)\tilde{Q}_\phi\,,$$

- The mass of the D (S_1-type LQ):

$$m_{S_1}^2 = \frac{1}{2}\Bigg[M_{11}^2(1) + \Delta_{11}(1) + M_{22}^2(1) + \Delta_{22}(1) - \sqrt{\left(M_{11}^2(1) + \Delta_{11}(1) - M_{22}^2(1) - \Delta_{22}(1)\right)^2 + 4\left(\mu_{D_1} X_{D_1} + \Delta_{12}(1)\right)^2}\Bigg].$$

- SARAH v4.14.4, SPheno v4.0.5: Model interpretation and performing phenomenological studies



- Black line (ATLAS), Green line (CMS), Blue line (E_6SSM)

Summary and Conclusions

- LQs, being coloured, can be produced efficiently at the LHC, and are thus among the potential signatures of BSM physics.
- We have studied the possibility of searching third-generation LQs decaying to $t\tau$ in the fully hadronic channel.
- This analysis complements existing semi-leptonic searches, offering larger statistics and the ability to reconstruct LQ mass.
- In the fully hadronic channel, we expect significant QCD backgrounds, but with proper event selection, the $t\bar{t}jj$ background becomes manageable, and other backgrounds are negligible.

Summary and Conclusions

- We discussed a variant of the E_6SSM where the fundamental representation includes scalar and fermion LQs. This model shows a high sensitivity in Run 2 data, with an expected LQ mass exclusion limit of up to 1580 GeV (assuming $\text{BR}(S_1 \to t\tau) = 1$), surpassing the ATLAS semi-leptonic channel result by about 150 GeV.

- Our current research explores the LHC investigation of a pair scalar diquarks and the new physics impact on muon g-2 within the scalar and fermionic sectors of the E6SSM.


Thank you