

Exploring mixed lepton-quark interactions in non-resonant leptoquark production at the LHC

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Work done in collaboration with:

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Based on arXiv:2206.01674 and arXiv:2306.15460;

https://github.com/Mrazi09/LQ_collider_project

<https://github.com/Mrazi09/Leptoquark-project>

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Despite its successes, the SM either **fails** or is **insufficient** in tackling various observations, with **anomalous results** popping up in recent years ...

- R_{D/D^*}

$$R_{D^{(*)}} \equiv \frac{\text{Br}(\bar{B} \rightarrow D^{(*)} \tau \bar{\nu}_\tau)}{\text{Br}(\bar{B} \rightarrow D^{(*)} l \bar{\nu}_l)} \quad \text{with } l = \mu, e,$$

2.3σ tension with the SM [Eur. Phys. J. C 81, 226 (2021)];

- a_μ 4.2σ tension with the SM [Phys.Rev.Lett. 126, 141801 (2021)]. Although lattice results indicate consistency [Nature 593 (2021) 7857, 51-55].
- M_W 3.7σ tension with the SM [Phys.Rev.Lett. 129 (2022) 27, 271801]. Tension primarily driven by the new CDF result [Science 376 (2022) 170–176].
- $U_{PMNS} + m_\nu$ SM can not account for neutrino physics. Requires non-renormalisable 5D Weinberg operator [Phys. Lett. B 91 (1980) 51];

As shown in our previous work [2206.01674 [hep-ph]], a minimal LQ model is sufficient to address all of these open questions.

The model:

- **One** SU(2) singlet: $S \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)^{-}$;
- **One** SU(2) doublet: $R \sim (\bar{\mathbf{3}}, \mathbf{2}, 1/6)^{-}$;
- Yukawas that generate proton decay $\rightarrow y_1 \bar{Q}^c Q S^\dagger + y_2 \bar{d} u S + \text{h.c.}$

$$\mathbb{Z}_2 \text{ symmetry: } \mathbb{P}_B = (-1)^{3B+2S} \implies S^-, R^-, q_{L,R}^+, \ell_{L,R}^-, H^-$$

Group charges and particles are emergent in a gauge-flavour unification model based on $E_6 \times \text{SU}(3)_F$ [Eur. Phys. J. C 80, 1162 (2020)].

- Yukawa Lagrangian: $\mathcal{L}_Y = \Theta_{ij} \bar{Q}_j^c L_i S + \Omega_{ij} \bar{L}_i d_j R^\dagger + \Upsilon_{ij} \bar{u}_j^c e_i S + \text{h.c.}$
- Relevant scalar potential:

$$V \supset -\mu^2 |H|^2 + \mu_S^2 |S|^2 + \mu_R^2 |R|^2 + \lambda (H^\dagger H)^2 + g_{HR} (H^\dagger H) (R^\dagger R) + g'_{HR} (H^\dagger R) (R^\dagger H) + g_{HS} (H^\dagger H) (S^\dagger S) + (a_1 R S H^\dagger + \text{h.c.}) .$$

- After EWSB, two physical $(1/3)e$ appear in the spectrum

$$M_{LQ^{1/3}}^2 = \begin{bmatrix} \mu_S^2 + \frac{g_{HS}v^2}{2} & \frac{va_1}{\sqrt{2}} \\ \frac{va_1}{\sqrt{2}} & \mu_R^2 + \frac{(g_{HR} + g'_{HR})v^2}{2} \end{bmatrix}$$

Trade physical masses, $m_{S_1^{1/3}}$ and $m_{S_2^{1/3}}$, for the μ terms

$$\mu_S^2 = \frac{1}{2}(m_{S_1^{1/3}}^2 + m_{S_2^{1/3}}^2 - g_{HS}v^2 + \sqrt{(m_{S_1^{1/3}}^2 - m_{S_2^{1/3}}^2)^2 - 2a_1^2v^2}),$$

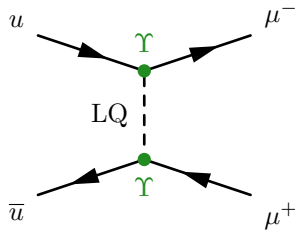
$$\mu_R^2 = \frac{1}{2}(m_{S_1^{1/3}}^2 + m_{S_2^{1/3}}^2 - (g_{HR} + g'_{HR})v^2 - \sqrt{(m_{S_1^{1/3}}^2 - m_{S_2^{1/3}}^2)^2 - 2a_1^2v^2}).$$

Mixing controlled by the relation $\sin(2\theta) = (\sqrt{2}va_1)(m_{S_1^{1/3}}^2 - m_{S_2^{1/3}}^2)^{-1}$

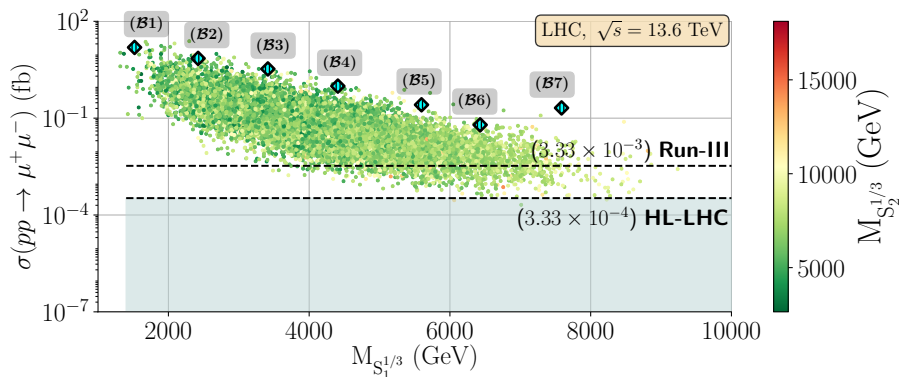
- A single $(2/3)e$ state appears and does not mix with $m_{S^{2/3}}^2 = \mu_R^2 + \frac{g_{HR}v^2}{2}$.

	u	c	t
e	$ \lambda_{eu} \lesssim 0.22$ @ 1.5 TeV	$ \lambda_{ec} \lesssim 2.0$ @ 1.5 TeV	$ \lambda_{et} \lesssim \sqrt{4\pi}$ @ 1.5 TeV
μ	$ \lambda_{\mu u} \lesssim 0.8$ @ 1.5 TeV (This work)	$ \lambda_{\mu c} \lesssim 1.7$ @ 1.5 TeV	$ \lambda_{\mu t} \lesssim \sqrt{4\pi}$ @ 1.5 TeV
τ	$ \lambda_{\tau u} \lesssim \sqrt{4\pi}$ @ 1.5 TeV	$ \lambda_{\tau c} \lesssim \sqrt{4\pi}$ @ 1.5 TeV	$ \lambda_{\tau t} \lesssim \sqrt{4\pi}$ @ 1.5 TeV

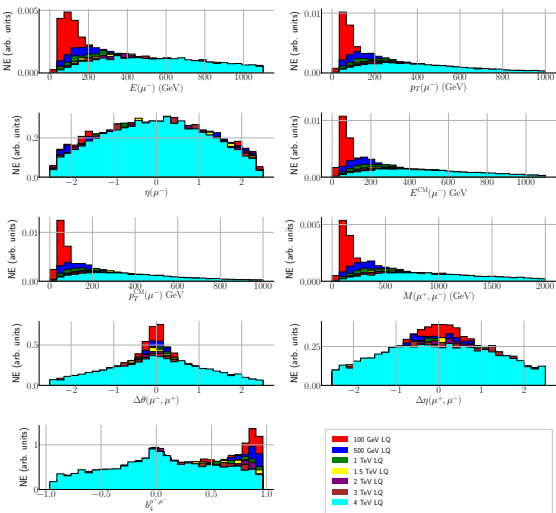
	d	s	b
e	$ \lambda_{ed} \lesssim 0.22$ @ 1.5 TeV	$ \lambda_{es} \lesssim 1.75$ @ 1.5 TeV	$ \lambda_{eb} \lesssim 2.65$ @ 1.5 TeV
μ	$ \lambda_{\mu d} \lesssim 0.5$ @ 1.5 TeV	$ \lambda_{\mu s} \lesssim 1.5$ @ 1.5 TeV	$ \lambda_{\mu b} \lesssim 2.1$ @ 1.5 TeV
τ	$ \lambda_{\tau d} \lesssim \sqrt{4\pi}$ @ 1.5 TeV	$ \lambda_{\tau s} \lesssim \sqrt{4\pi}$ @ 1.5 TeV	$ \lambda_{\tau b} \lesssim 3.0$ @ 1.5 TeV



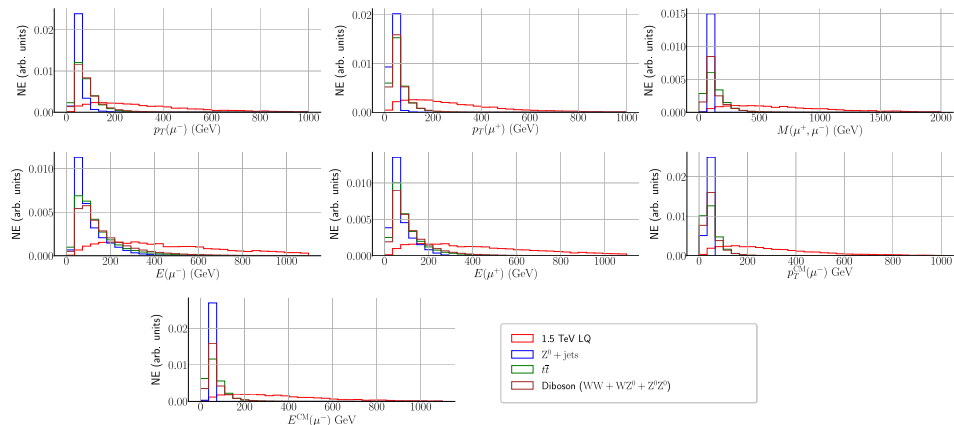
- Limits based on the combination of various channels (pair prod., single prod., recast) [JHEP 01 (2019) 132];
- Most searches tend towards diagonal channels. Current constraints are not strong for off-diagonal contributions. Particularly for 1st and 3rd generation couplings; **Substantial phase-space left unprobed.**
- We focus our analysis for the μc coupling and study its implications at future runs of the LHC.



- Vast region of the parameter space in reach of both run-III and HL-LHC;
- Cross-section driven primarily by $S_1^{1/3}$ due to small mixing
 $a_1 \sim \mathcal{O}(1 \text{ GeV}) \Rightarrow \sin(2\theta) \ll 1$;
- Various benchmarks are defined for different mass scales of the lightest $(1/3e)$ LQ.

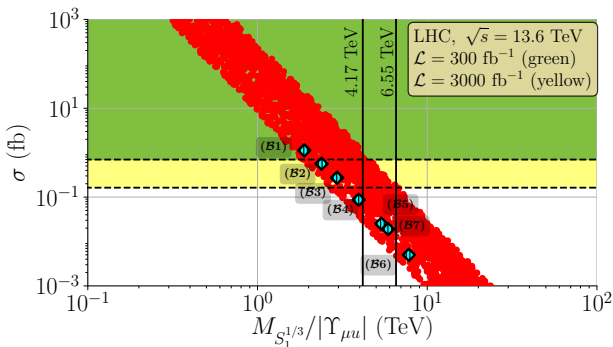


- Drell-Yan t -channel type process with two muons in the final state;
- LQ mass cannot be reconstructed. Although, kinematic distributions affected by it.
- Events generated at LO in MadGraph, with Delphes detector simulation. Backgrounds reweighted based on higher-order corrections;
- Selection criteria
 - $p_T(\mu^\pm) > 25$ GeV
 - $|\eta(\mu^\pm)| < 2.5$



- Dimension-full distributions offer the greater discriminating power. Angular distributions closely follow SM backgrounds;
- The signal tends to populate the high-energy regions, as opposed to the SM expectation;

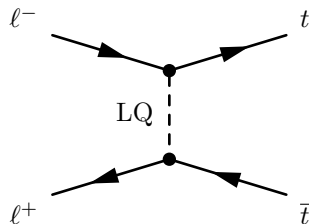
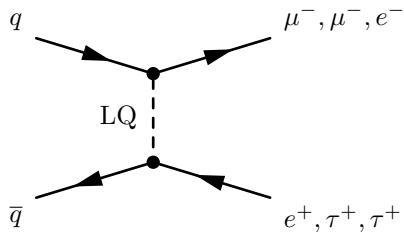
M_{LQ} (GeV)	$M(\mu^+, \mu^-)$ $\mathcal{L} = 300 \text{ fb}^{-1}$	$M(\mu^+, \mu^-)$ $\mathcal{L} = 3000 \text{ fb}^{-1}$	$E(\mu^+)$ $\mathcal{L} = 300 \text{ fb}^{-1}$	$E(\mu^+)$ $\mathcal{L} = 3000 \text{ fb}^{-1}$	Combined (300, 3000) fb^{-1}
1.5 TeV (B1)	1.75σ	5.20σ	0.891σ	2.72σ	$(3.06\sigma, 9.72\sigma)$
2.5 TeV (B2)	0.573σ	2.28σ	0.744σ	2.33σ	$(1.15\sigma, 4.97\sigma)$
3.5 TeV (B3)	0.128σ	0.912σ	0.225σ	1.04σ	$(0.288\sigma, 1.97\sigma)$



- The combination of the various distributions can extend the discovery threshold of our model's LQs;
- $M/\Upsilon < 4.17 \text{ TeV}$ @ 95% CL for run-III;
- $M/\Upsilon < 6.55 \text{ TeV}$ @ 95% CL for HL-LHC.

To conclude . . .

- Discussed a simple economical model and how it solves current open questions;
- Showed that there are regions of parameter space that can be probed at LHC (run-III and/or HL-LHC)



- Flavour off-diagonal channels also possible. LQ Yukawa couplings with top more easily measured in lepton colliders.

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Thank you for your attention

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