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

João Pedro Pino Gonçalves[1,2]

Work done in collaboration with:
Antonio P. Morais, Roman Pasechnik, António Onofre and Werner Porod

Based on arXiv:2206.01674 and arXiv:2306.15460;

`https://github.com/Mrazi09/LQ_collider_project`

`https://github.com/Mrazi09/Leptoquark-project`

[1]Physics Department and Centre for Research and Development in Mathematics and Applications (CIDMA), Department of Mathematics, University of Aveiro, Portugal.
[2]Department of Physics, Lund university, Sweden.

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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 . . .

- **LFV** : Various anomalous results in B meson decays ($B_s \to \phi\mu^+\mu^-$, $B \to K\mu^+\mu^-$, P_5');
- $\mathbf{a}_{\boldsymbol{\mu}}$: Tension with the SM [Phys.Rev.Lett. 126, 141801 (2021)]. Although lattice results indicate consistency [Nature 593 (2021) 7857, 51-55].
- $\mathbf{M}_W$: Tension primarily driven by the new CDF result [Science 376 (2022) 170–176].
- $\mathbf{U_{PMNS} + m_\nu}$ 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** $\mathrm{SU}(2)$ singlet: $S \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)^-$;
- **One** $\mathrm{SU}(2)$ doublet: $R \sim (\bar{\mathbf{3}}, \mathbf{2}, 1/6)^-$;
- Yukawas that generate proton decay $\rightarrow y_1 \bar{Q}^c Q S^\dagger + y_2 \bar{d} u S + \mathrm{h.c.}$

$$\mathbb{Z}_2 \text{ symmetry: } \mathbb{P}_B = (-1)^{3B+2S} \quad \Longrightarrow \quad S^-,\ R^-,\ q^+_{L,R},\ \ell^-_{L,R},\ H^-$$

Group charges and particles are emergent in a gauge-flavour unification model based on $\mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{F}$ [Eur. Phys. J. C 80, 1162 (2020)].

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

$$\boxed{\begin{aligned} V \supset\ & -\mu^2 |H|^2 + \mu_S^2 |S|^2 + \mu_R^2 |R|^2 + \lambda (H^\dagger H)^2 + g_{HR} (H^\dagger H)(R^\dagger R) + \\ & g'_{HR} (H^\dagger R)(R^\dagger H) + g_{HS} (H^\dagger H)(S^\dagger S) + \left(a_1 R S H^\dagger + \mathrm{h.c.} \right) . \end{aligned}}$$

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

$$M^2_{LQ^{1/3}} = \begin{bmatrix} \mu_S^2 + \frac{g_{HS} v^2}{2} & \frac{v a_1}{\sqrt{2}} \\ \frac{v a_1}{\sqrt{2}} & \mu_R^2 + \frac{(g_{HR} + g'_{HR}) v^2}{2} \end{bmatrix}$$

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

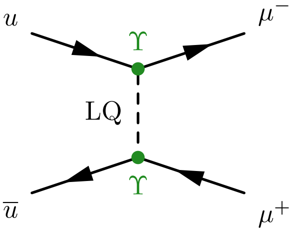
$$\mu_S^2 = \frac{1}{2}(m^2_{S_1^{1/3}} + m^2_{S_2^{1/3}} - g_{HS} v^2 + \sqrt{(m^2_{S_1^{1/3}} - m^2_{S_2^{1/3}})^2 - 2{a_1}^2 v^2}),$$
$$\mu_R^2 = \frac{1}{2}(m^2_{S_1^{1/3}} + m^2_{S_2^{1/3}} - (g_{HR} + g'_{HR}) v^2 - \sqrt{(m^2_{S_1^{1/3}} - m^2_{S_2^{1/3}})^2 - 2{a_1}^2 v^2}).$$

Mixing controlled by the relation $\sin(2\theta) = (\sqrt{2} v a_1)(m^2_{S_1^{1/3}} - m^2_{S_2^{1/3}})^{-1}$

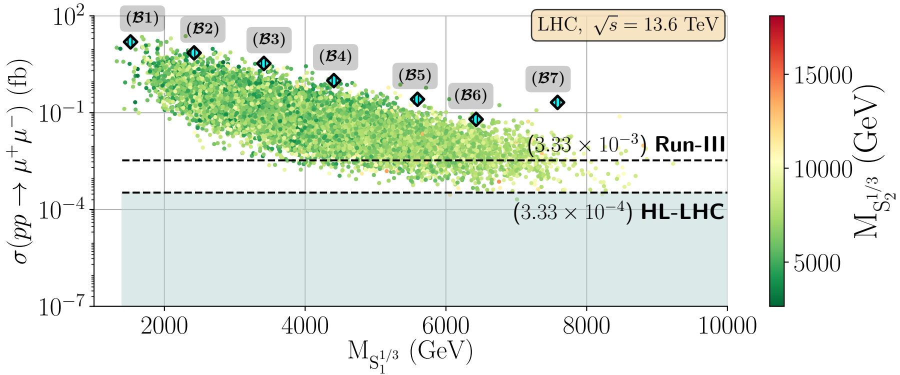
- A single $(2/3)e$ state appears and does not mix with $m^2_{S^{2/3}} = \mu_R^2 + \frac{g_{HR} v^2}{2}$.

	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

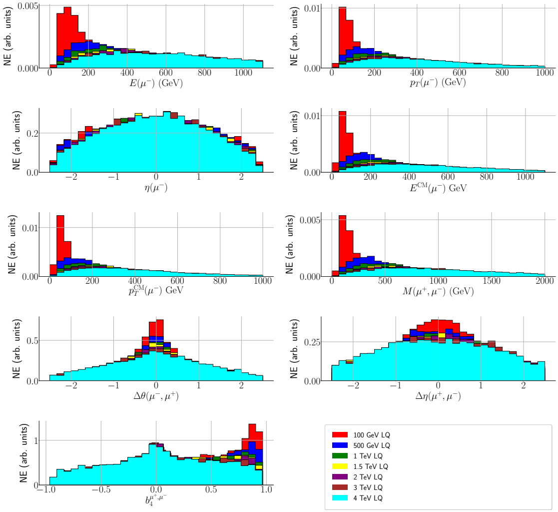
	d	s	b
e	$\|\lambda_{ed}\| \lesssim 0.22$ @ 1.5 TeV	$\|\lambda_{es}\| \lesssim 1.75$ @ 1.5 TeV	$\|\lambda_{eb}\| \lesssim 2.65$ @ 1.5 TeV
μ	$\|\lambda_{\mu d}\| \lesssim 0.5$ @ 1.5 TeV	$\|\lambda_{\mu s}\| \lesssim 1.5$ @ 1.5 TeV	$\|\lambda_{\mu b}\| \lesssim 2.1$ @ 1.5 TeV
τ	$\|\lambda_{\tau d}\| \lesssim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



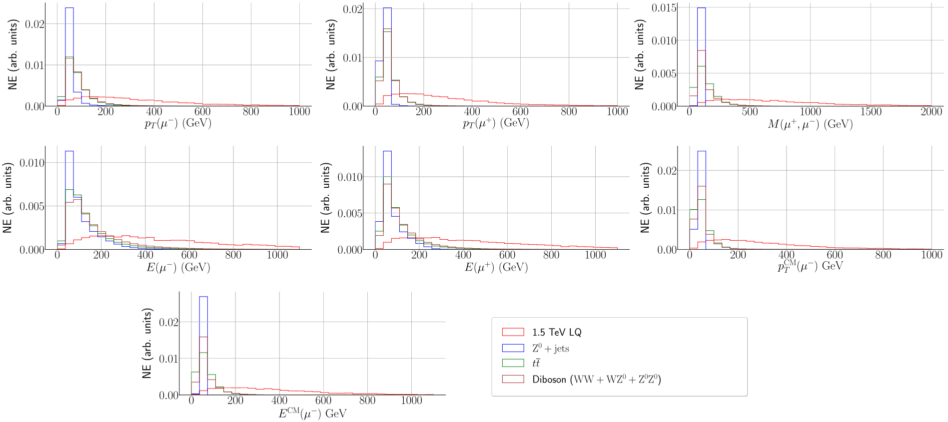
- Limits based on the combination of various channels (pair prod., single prod., recast) [JHEP 01 (2019) 132];
- Most searches tend towards diagonal channels. Current constraints are not strong for off-diagonal contributions. Particularly for 1st and 3rd generation couplings; **Substantial phase-space 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.

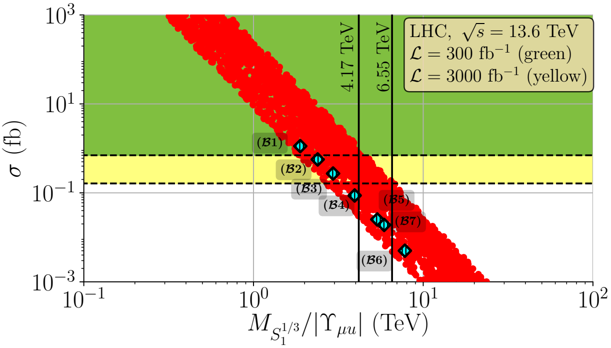


- Drell-Yan t-channel type process with two muons in the final state;
- LQ mass cannot be reconstructed. Although, kinematic distributions affected by it.
- Events generated at LO in `MadGraph`, with `Delphes` detector simulation. Backgrounds reweighted based on higher-order corrections;
- Selection 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;

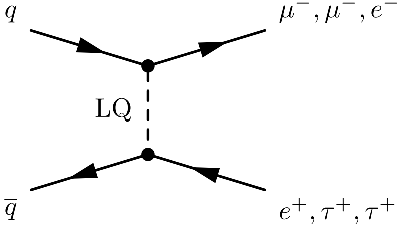
M_{LQ} (GeV)	$M(\mu^+,\mu^-)$ $\mathcal{L}=300$ fb^{-1}	$M(\mu^+,\mu^-)$ $\mathcal{L}=3000$ fb^{-1}	$E(\mu^+)$ $\mathcal{L}=300$ fb^{-1}	$E(\mu^+)$ $\mathcal{L}=3000$ fb^{-1}	Combined $(300,3000)$ fb^{-1}
1.5 TeV ($\mathcal{B}1$)	1.75σ	5.20σ	0.891σ	2.72σ	$(3.06\sigma,\ 9.72\sigma)$
2.5 TeV ($\mathcal{B}2$)	0.573σ	2.28σ	0.744σ	2.33σ	$(1.15\sigma,\ 4.97\sigma)$
3.5 TeV ($\mathcal{B}3$)	0.128σ	0.912σ	0.225σ	1.04σ	$(0.288\sigma,\ 1.97\sigma)$

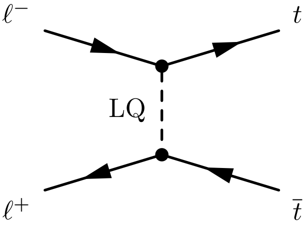


- The combination of the various distributions can extend the discovery threshold of our model's LQs;
- $M/\Upsilon < 4.17$ TeV @ 95% CL for run-III;
- $M/\Upsilon < 6.55$ TeV @ 95% CL for HL-LHC.

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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