Combined Constraints on First Generation Leptoquarks

Andreas Crivellin[a,b,c], Dario Müller[b,c], Luc Schnell[d,e,f]
[a]CERN Theory Division; [b]Universität Zürich; [c]Paul Scherrer Institut; [d]LPTHE Paris; [e]ETH Zürich; [f]École Polytechnique;

1 Introduction

Leptoquarks (LQs) are hypothetical beyond the Standard Model (BSM) particles that feature quark-lepton couplings.

They have attracted particular attention in recent years, since they can explain the **„flavor anomalies"**, deviations from SM predictions that hint at **Lepton Flavor Universality Violation (LFUV)**:

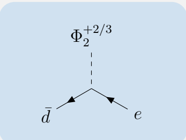
- $R(D^{(*)}) = \frac{\text{Br}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\text{Br}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$ with $\ell = e, \mu$ — $> 3\sigma$ [2]
- $b \to s\ell^+\ell^-$ transitions — $\sim 6\sigma$ [3]
  - $R_K \equiv \frac{\text{Br}(B^+ \to K^+\mu^+\mu^-)}{\text{Br}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\text{Br}(B^+ \to K^+e^+e^-)}{\text{Br}(B^+ \to J/\psi(\to e^+e^-)K^+)}$
  - R_{K^*}, B_s^ϕ, P_5'
- Muon anomalous magnetic moment (AMM): $a_\mu = \frac{g_\mu - 2}{2}$ — 4.2σ [4]

2 Setup

- We consider the complete set of **LQ interactions with first generation quarks and leptons**.

	L	e
$\bar{Q}$	$\kappa_1^L\gamma_\mu V_1^\mu + \kappa_3\gamma_\mu(\tau \cdot V_3^\mu)$	$\lambda_2^{LR}\Phi_2$
$\bar{d}$	$\tilde{\lambda}_2\tilde{\Phi}_2^T i\tau_2$	$\kappa_1^R\gamma_\mu V_1^\mu$
$\bar{u}$	$\lambda_2^{RL}\Phi_2^T i\tau_2$	$\tilde{\kappa}_1\gamma_\mu\tilde{V}_1^\mu$
$\bar{Q}^c$	$\lambda_3 i\tau_2(\tau \cdot \Phi_3)^\dagger + \lambda_1^L i\tau_2\Phi_1^\dagger$	$\kappa_2^{LR}\gamma_\mu V_2^{\mu\dagger}$
$\bar{d}^c$	$\kappa_2^{RL}\gamma_\mu V_2^{\mu\dagger}$	$\tilde{\lambda}_1\tilde{\Phi}_1^\dagger$
$\bar{u}^c$	$\tilde{\kappa}_2\gamma_\mu\tilde{V}_2^{\mu\dagger}$	$\lambda_1^R\Phi_1^\dagger$

Table 1: Interaction terms with the first-generation SM quarks (Q, u, d) and leptons (L, e).



Field	Φ_1	$\tilde{\Phi}_1$	Φ_2	$\tilde{\Phi}_2$	Φ_3	V_1	$\tilde{V}_1$	V_2	$\tilde{V}_2$	V_3
$SU(3)_c$	3	3	3	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	3	1	1	2	2	3
$U(1)_Y$	$-\frac{2}{3}$	$-\frac{8}{3}$	$\frac{7}{3}$	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{4}{3}$	$\frac{10}{3}$	$-\frac{5}{3}$	$\frac{1}{3}$	$\frac{4}{3}$

Table 2: The ten possible LQ representations (Φ with spin $S = 0$, V with $S = 1$) under the SM gauge group.

3 Observables

Low Energy Precision Observables

- **Cabibbo Angle Anomaly (CAA):** deficit in 1st row CKM unitarity, can be explained with 1st generation LQs.

$$\mathcal{H}_{\text{eff}}^{\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{jk}\hat{C}_{jk}^{e\nu}[\bar{u}_j\gamma^\mu P_L d_k][\bar{e}\gamma_\mu P_L\nu_e],$$

$C_{11}^{e\nu_e} \approx -0.001$

$$V_{us}^\beta = 0.2281(7) \qquad V_{ud}^\beta = V_{ud}^L(1 + C_{11}^{e\nu_e}) \qquad V_{us}^{K_{\mu3}} = 0.22345(67)$$

$$V_{us}^\beta|_{\text{NNC}} = 0.2280(14) \qquad \longleftrightarrow \qquad V_{us}^{K_{\mu2}} = 0.22534(42)$$

- **Tree-level neutral current:** constraints from parity violation experiments (QWEAK and APV), $K \to \pi e^+e^- / K \to \pi\mu^+\mu^-$ and $K \to \pi\nu\bar{\nu}$.
- $D^0 - \bar{D}^0$ **and** $K^0 - \bar{K}^0$ **mixing:** constraints on one-loop LQ contributions.

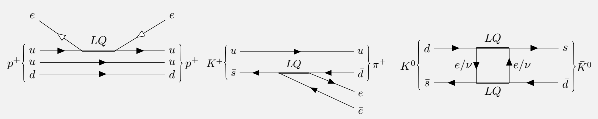


Figure 1: Feynman diagrams depicting the LQ contributions to the low energy processes $ep \to ep$ (QWEAK), $K \to \pi e^+e^-$ and $K^0 - \bar{K}^0$ mixing.

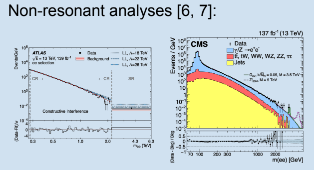
Direct LHC Searches

- **Pair production (PP):**
- **Single Resonant Production (SRP):**

Electron PDF of the proton

- **Drell-Yan-like Signatures (DY):**

Non-resonant analyses [6, 7]:



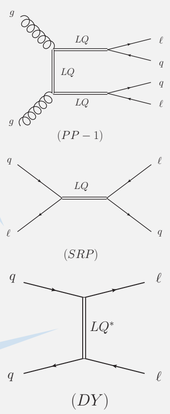


Figure 2: Feynman diagrams showing the high-energy search channels for first generation LQs at the LHC.

4 Phenomenological Analysis

Low Energy Precision Observables

- The **CAA** could be explained by contributions from Φ_3, V_3. However, DY searches as well as the meson mixing constraints exclude sizeable contributions $C_{11}^{e\nu}$ (black line in Figure 4).
- The **neutral current and meson mixing limits** (blue, cyan and orange lines in Figure 4) depend on the angle β relating left-handed down-type quark flavor and mass eigenstates.

Direct LHC Searches

- **PP** (gray region in Figure 4) sets coupling-independent limits on the LQ masses.
- The excess in electron pairs found in **CMS' non-resonant DY analysis** (yellow region in Figure 4) prefers the LQ representations $\tilde{\Phi}_1, \Phi_2, \Phi_3, \tilde{V}_1, V_2$ ($\kappa_2^{RL} \neq 0$) and V_3 interfering constructively with the SM.

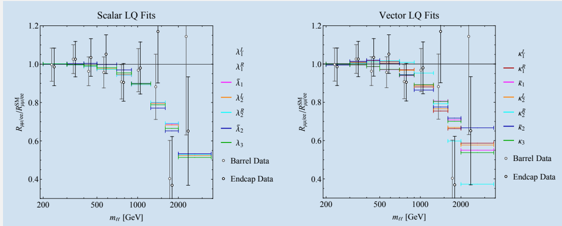


Figure 3: Ratio $R_{\mu\mu/ee}/R_{\mu\mu/ee}^{\text{SM}}$ for $R_{\mu\mu/ee} = \left(d\sigma(q\bar{q} \to \mu\bar{\mu})/dm_{\mu\mu}\right)/\left(d\sigma(q\bar{q} \to e\bar{e})/dm_{ee}\right)$ given as a function of the invariant di-lepton mass $m_{\ell\ell}$. The CMS measurements (black and gray points) prefer the LQ fits (colored lines) over the SM solution (black line at 1.0) [1].

- **ATLAS' non-resonant DY bounds** (green region in Figure 4) are more constraining than the resonant DY searches.

Exclusion Plots

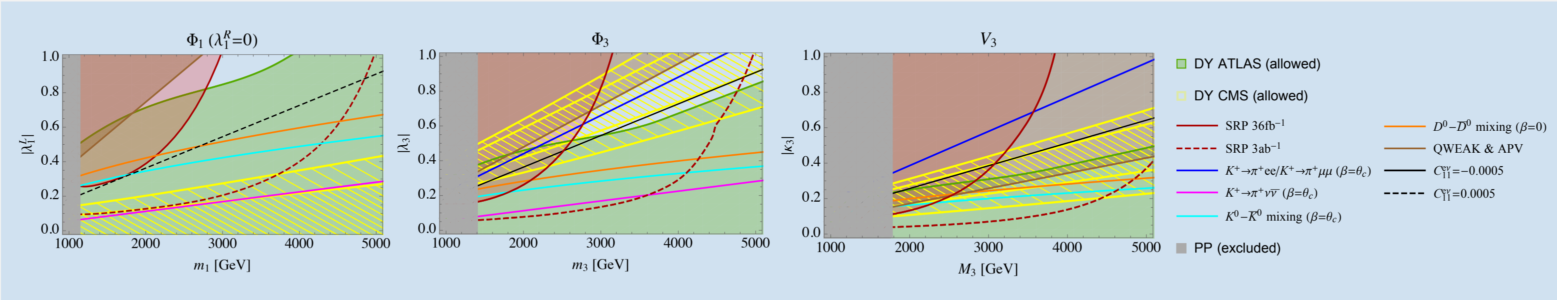


Figure 4: Limits on the parameter space for scalar and vector LQs. The region above the colored lines is excluded. The plots for the remaining LQ representations are given in Ref. [1].

5 Conclusions

- **We performed a combined analysis of constraints on first generation LQs, including both low energy precision observables and direct searches.**
- The **CAA** could be explained by first generation Φ_3, V_3, but the size of this effect is too constrained by DY and the meson mixing.
- The **non-resonant DY** analysis of ATLAS gives stringent constraints on first generation LQs. The representations $\tilde{\Phi}_1, \Phi_2, \tilde{V}_1, V_2$ ($\kappa_2^{RL} \neq 0$) and V_3 can account for the di-electron excess found in the CMS non-resonant DY analysis without violating other bounds.

References

1. Crivellin, Andreas, Dario Müller, and Luc Schnell. "Combined Constraints on First Generation Leptoquarks." ArXiv:2101.07811 (Addendum: ArXiv:2104.06417) (2021).
2. Abdesselam, A., et al. „Measurement of $R(D)$ and $R(D^*)$ with a semileptonic tagging method." ArXiv:1904.08794 (2019).
3. Virto, Javier. "Anomalies in $b \to s\ell\ell$ transitions and Global Fits." ArXiv:2103.01106 (2021).
4. Abi, B., et al. "Measurement of the positive muon anomalous magnetic moment to 0.46 ppm." Physical Review Letters 126.14 (2021): 141801. ArXiv:2104.03281 (2021).
5. Coutinho, Antonio M., Andreas Crivellin, and Claudio Andrea Manzari. "Global fit to modified neutrino couplings and the Cabibbo-Angle anomaly." Physical Review Letters 125.7 (2020): 071802. ArXiv:1912.08823 (2020).
6. Aad, Georges, et al. "Search for new non-resonant phenomena in high-mass dilepton final states with the ATLAS detector." Journal of High Energy Physics 2020.11 (2020): 1-41. ArXiv:2006.12946 (2020).
7. CMS Collaboration. "Search for resonant and nonresonant new phenomena in high-mass dilepton final states at √s = 13 TeV." ArXiv:2103.02708 (2021).