# Flavourful leptoquarks at the LHC and beyond: Spin 1

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# Overview

- Motivating the searches for spin-1 leptoquarks at $p$-$p$ colliders
- Overview of couplings of the spin-1 leptoquarks
- Mass limits
- Estimates of sensitivity reach of future colliders
- Summary

# Motivation

The ratios $R_K$ and $R_{K^*}$ probe $e$-$\mu$ universality in rare $b \to s\ell\ell$ processes $B \to K\ell\ell$ and $B \to K^*\ell\ell$:

$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{dB^{(\ell=\mu)}}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{dB^{(\ell=e)}}{dq^2} dq^2}\,, \qquad H = K, K^*.$$

Latest values by the LHCb Collaboration [LHCb, 2103.11769], [LHCb, 1705.05802] in $q^2$-bin $[1.1, 6]$ GeV$^2$:

$$R_K^{(2021)} = 0.846^{+0.044}_{-0.041}\,, \qquad R_{K^*}^{(2017)} = 0.69^{+0.12}_{-0.12}\,.$$

($3.1\sigma$ and $2.6\sigma$ deviations from the lepton-universality limit $R_K \simeq R_{K^*} \simeq 1$)

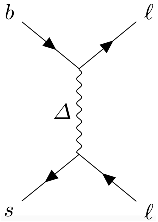
- Even more precise measurements required to clarify the anomalies. Eventual confirmation would be definite sign of BSM

- The pattern suggested by the experiment:

$$R_K < 1\,, \qquad R_{K^*} < 1\,, \qquad R_K \simeq R_{K^*}$$

- Intriguing solution provided by new contribution to the left-left operator $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma_\mu P_L \mu)$, that is: $\mathcal{C}_9^{(\mu)} = -\mathcal{C}_{10}^{(\mu)}$ - see talk by Peter Stangl on this conference (link)
- While sizeable couplings to electrons are not excluded, we assume dominant role played by muons - pointing to the same direction as the remaining $b \to s\mu\mu$ data involving e.g. angular distributions in $B \to K^*\mu\mu$.

Possible culprit: an exotic, colored, electroweak-charged boson called leptoquark. At the tree level $S_3, V_1, V_3$ competing with the 1-loop SM in $b \to s\mu\mu$.




- spin-0, $SU(2)_L$-triplet $S_3(\bar{3}, 3, 1/3)$
- spin-1, $SU(2)_L$-singlet $V_1(3, 1, 2/3)$
- spin-1, $SU(2)_L$-triplet $V_3(3, 3, 2/3)$

Focus of this talk: spin-1 $\Delta$.

- $V_1$ usually considered in the literature as a viable solution to charged-current anomalies in $b \to c\tau\nu$ observables $R_{D,D^*}$
- Adding the couplings to $\tau$ lepton, $\lambda_{q\tau} \sim 10^2 \lambda_{q\mu}$, lowers the LQ scale making it easier to discover - I consider more pessimistic possibility of small couplings to $\tau$, negligible for the present purposes.

- We assume that one of the LQ representations, either $V_1$ or $V_3$ provides the resolution to the anomalies
- Couplings to leptons and quarks:

$$\mathcal{L}_{\mathrm{f},V_1} = \lambda_{\bar{Q}L}\left(\bar{d}_L\gamma_\mu\ell_L + \bar{u}_L\gamma_\mu\nu_L\right)V_1^\mu + \lambda_{\bar{D}E}\bar{D}_R\gamma_\mu E_R\,V_1^\mu + \mathrm{h.c.}$$

We assume $\lambda_{\bar{D}E} \sim 0$. For $V_3$:

$$\mathcal{L}_{\mathrm{f},V_3} = \left(\lambda_{\bar{Q}L}\bar{Q}\gamma_\mu\vec{\sigma}L\right)\cdot\vec{V}_3^\mu + \mathrm{h.c.}$$

Expanding the triplet:

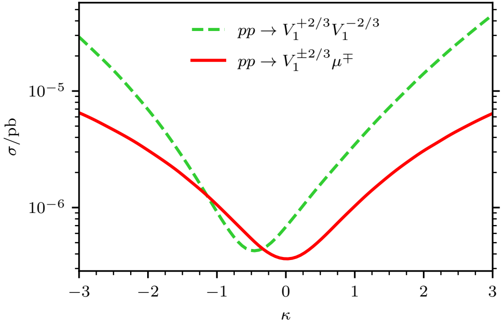
$$\vec{\sigma}\cdot\vec{V}_3 = \begin{pmatrix} V_3^{2/3} & \sqrt{2}V_3^{5/3} \\ \sqrt{2}V_3^{-1/3} & -V_3^{2/3} \end{pmatrix},$$

$$\mathcal{L}_{\mathrm{f},V_3} = -\lambda_{\bar{Q}L}\bar{d}_L\gamma_\mu\ell_L V_3^{2/3\,\mu} + \sqrt{2}\lambda_{\bar{Q}L}\bar{d}_L\gamma_\mu\nu_L V_3^{-1/3\,\mu} + \\ + \sqrt{2}\lambda_{\bar{Q}L}\bar{u}_L\gamma_\mu\ell_L V_3^{5/3\,\mu} + \lambda_{\bar{Q}L}\bar{u}_L\gamma_\mu\nu_L V_3^{2/3\,\mu} + \mathrm{h.c.}$$

- Additional (renormalizable) 'anomalous' coupling to gluons denoted by $\kappa$

$$\mathcal{L}_{\text{kin},V_1} \supset -i g_s \kappa V_1^{\dagger\mu} T^a V_1^{\nu} G^a_{\mu\nu}\,.$$

- Illustration of $\kappa$-dependence, with $\sqrt{s} = 14$ TeV, $M_{V_1} = 3$ TeV, $\lambda_{s\mu}/\lambda_{b\mu} = \epsilon^2$



Coupling matrix to the left-handed fermions

$$\lambda_{\bar{Q}L} = \begin{pmatrix} \lambda_{de} & \lambda_{d\mu} & \lambda_{d\tau} \\ \lambda_{se} & \lambda_{s\mu} & \lambda_{s\tau} \\ \lambda_{be} & \lambda_{s\mu} & \lambda_{b\tau} \end{pmatrix}$$

- $R_K$ and $R_{K^*}$ constrain the combination

$$\frac{\lambda_{b\mu}\lambda_{s\mu}^* - \lambda_{be}\lambda_{se}^*}{M_{V_{1,3}}^2} \simeq -\frac{1 \pm 0.24}{(40\,\text{TeV})^2}\,.$$

- For $\lambda_{b\mu}, \lambda_{s\mu} \sim 1$, the mass scale $\sim 40$ TeV
- Within collider reach for smaller values of $\lambda_{b\mu}\lambda_{s\mu} \sim 10^{-2} - 10^{-3}$.

- To quantitatively study the sensitivity to LQs at the LHC and beyond, the couplings to $b$ and $s$ quarks have to be given individually.

Possible pattern from translating the quark-mass hierarchies to LQ sector (achievable in flavor models):

$$\lambda_{d\ell} \;:\; \lambda_{s\ell} \;:\; \lambda_{b\ell} \quad \sim \quad \epsilon^3 \ldots \epsilon^4 \;:\; \epsilon^2 \;:\; 1, \qquad \epsilon \sim 0.2$$

translating hierarchies of SM masses and mixings to the LQ couplings.

Hierarchical: $$\lambda_{\bar{Q}L} \sim \lambda_0 \begin{pmatrix} 0 & 0 & 0 \\ * & \rho \cdot \epsilon^2 & * \\ * & 1 & * \end{pmatrix}$$

$$M_V/14\,\text{TeV} \lesssim \lambda_0 \lesssim M_V/5\,\text{TeV}$$

- The '0-entries' small due to the constraints from rare kaon decays, $\mu$-e transitions
- The '$*$'-entries assumed to arise as higher order in $\epsilon$ − achievable in flavor-model building [Hiller, Loose and Schönwald, 1609.08895]

Flipped: $$\lambda_{\bar{Q}L} \sim \lambda_0 \begin{pmatrix} 0 & 0 & 0 \\ * & \rho \cdot 1 & * \\ * & \epsilon^2 & * \end{pmatrix}$$

(Enhancement of single LQ production with pdf for $s$-quark, but any foundation in flavor model building unclear, needs to be imposed in the mass-basis)

Democratic: $$\lambda_{\bar{Q}L} \sim \lambda_0 \begin{pmatrix} 0 & 0 & 0 \\ * & \rho \cdot 1 & * \\ * & 1 & * \end{pmatrix}$$

$$M_V/70\,\text{TeV} \lesssim \lambda_0 \lesssim M_V/23\,\text{TeV}$$

$\mathcal{O}(1)$ parameter $\rho \in (1/3, 3)$

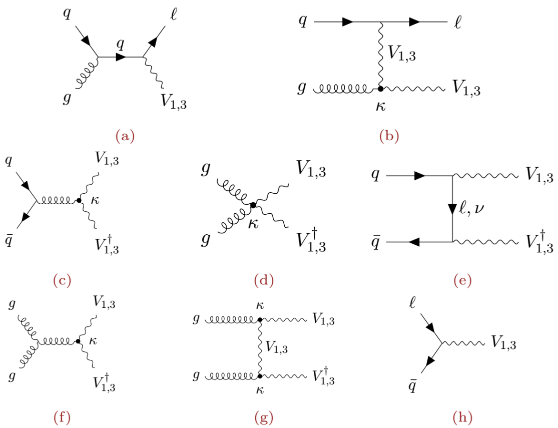
- Flavor structure determines the pattern of the branching fractions, e.g. in hierarchical scenario:

$$V_1^{+2/3} \to b\mu^+\,,\; t\bar{\nu}\,,$$

and

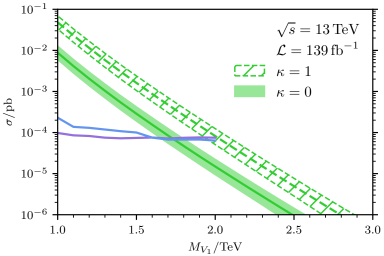
$$\begin{aligned} V_3^{-1/3} &\to b\bar{\nu}\,, \\ V_3^{+2/3} &\to b\mu^+\,,\; t\bar{\nu}\,, \\ V_3^{+5/3} &\to t\mu^+\,. \end{aligned}$$

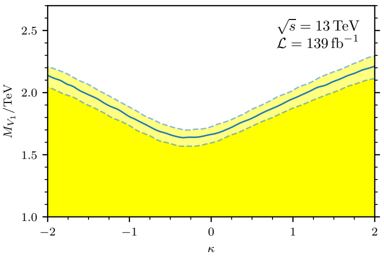
- We highlight the final states with muons.




- Pair production dominantly induced by QCD coupling - flavor determines the branching fractions into various final state channels
- Single production $\sigma(qg \to V_1^{2/3}\ell) \propto |\lambda_{\bar{Q}\ell}|^2$ - probes the flavor structure directly (also via the pdfs)

- Reinterpreting the search for pair produced scalar LQs ($13\,$TeV, $139$ fb$^{-1}$) [ATLAS, 2006.05872] in $(b\mu, b\mu), (c\mu, c\mu), (q\mu, q\mu)$-channels.
- E.g. in hierarchical scenario: $M_{V_1} > 1.7(1)$ TeV and $M_{V_1} > 2.0(1)$ TeV for $\kappa = 0$ and $\kappa = 1$, respectively:




- Weakest bounds: $M_{V_1} > 1.4$ TeV (democratic) and $M_{V_3} > 1.6$ TeV (hierarchical) both for $\kappa = -0.3$. For other bounds, see the paper.

# Future colliders

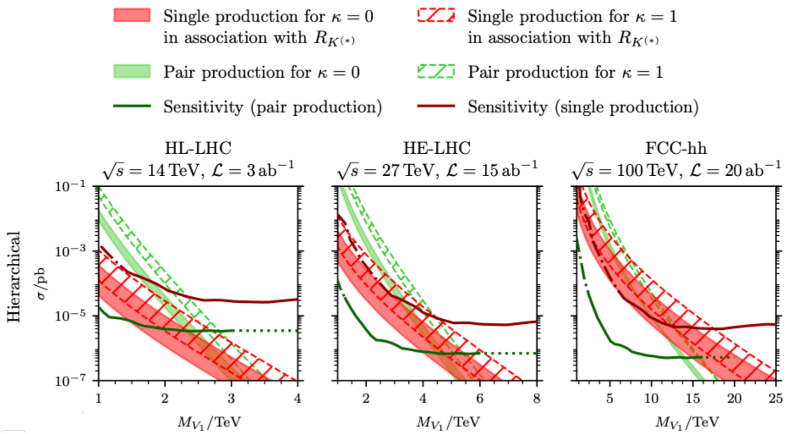
- Estimating the sensitivity of the future colliders by extrapolating current bounds from *single- and pair production*

Starting points for the extrapolations of the sensitivity:

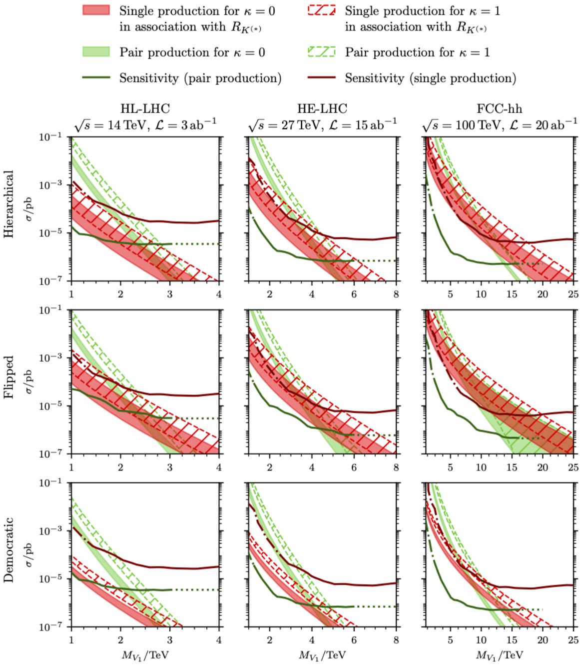
- Single production, CMS search, $pp \to (LQ \to \mu j)\mu$, $\sqrt{s} = 8\,\text{TeV}$, $L_{\text{int}} = 19.6\,\text{fb}^{-1}$ [CMS, 1509.03750]
- Pair production, ATLAS search, $pp \to (LQ \to \mu Q)(LQ \to \mu Q)$ where $Q = q, s, c, b$, $\sqrt{s} = 13\,\text{TeV}$, $L_{\text{int}} = 139\,\text{fb}^{-1}$ [ATLAS, 2006.05872]

Final points for the extrapolations of the sensitivity [Zimmermann, (2017)],[FCC Collaboration, HE-LHC design report, FCC-hh design report]

| Collider | $\sqrt{s}$/TeV | $\mathcal{L}$ /ab$^{-1}$ |
|---|---|---|
| HL-LHC | 14 | 3 |
| HE-LHC | 27 | 15 |
| FCC-hh | 100 | 20 |




Single production channel $pp \to \mu\mu b$, pair production channel $pp \to b\mu b\mu$ (hierarchical scenario)



Single production for κ = 0 in association with $R_{K^{(*)}}$
Single production for κ = 1 in association with $R_{K^{(*)}}$
Pair production for κ = 0
Pair production for κ = 1
Sensitivity (pair production)
Sensitivity (single production)
HL-LHC
$\sqrt{s} = 14$ TeV, $\mathcal{L} = 3\,\mathrm{ab}^{-1}$
HE-LHC
$\sqrt{s} = 27$ TeV, $\mathcal{L} = 15\,\mathrm{ab}^{-1}$
FCC-hh
$\sqrt{s} = 100$ TeV, $\mathcal{L} = 20\,\mathrm{ab}^{-1}$
Hierarchical
Flipped
Democratic
σ/pb
$M_{V_1}$/TeV

# Future mass reach

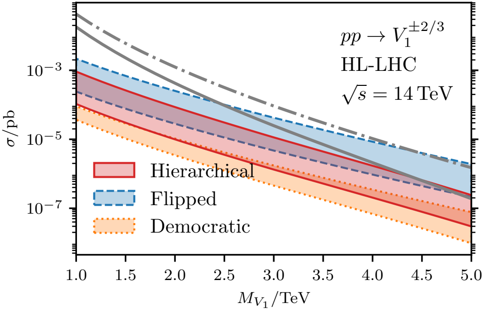
- b-tagging for single production $pp \to \mu(b\mu)$ could lead to improved limits in hierarchical scenario

Future mass reach in TeV for $V_1$ ($V_3$):

| Collider | $\sqrt{s}$/TeV | $\mathcal{L}$ /ab$^{-1}$ | Mass reach for $\kappa = 0$ | | | | Mass reach for $\kappa = 1$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | hierarchical | flipped | democratic | pair | hierarchical | flipped | democratic | pair |
| HL-LHC | 14 | 3 | — | — (2.3) | — | 2 (3) | — | 2.1 (2.8) | — | 3 (3) |
| HE-LHC | 27 | 15 | 2.7 (2.7) | 4.4 (5.6) | — | 5 (5) | 4.5 (4.5) | 5.5 (6.4) | — | 5 (6) |
| FCC-hh | 100 | 20 | 15.1 (15.1) | 17.7 (20.5) | — (10.7) | 13 (15) | 17.5 (17.5) | 19.9 (22.7) | 11.7 (14.0) | 15 (18) |

- $B_s$–$\bar{B}_s$ mass difference combined with $R_{K,K^*}$, impose upper bounds of $\sim 40$ TeV and $\sim 20$ TeV on the masses of $V_1$ and $V_3$ [Hiller, I.N, 1704.05444]
- Covering large part of the full mass range supported presently by $R_{K,K^*}$ requires high-energy colliders

Determinations of the lepton distribution functions [Buonocore, Nason, Tramontano, Zanderighi, 2005.06477 ] following the determinations of photon pdfs [Manohar, Nason, Salam, Zanderighi, 1607.04266], [Manohar, Nason, Salam, Zanderighi, 1708.01256] opened up the possibility to consider resonant LQ production




- Small lepton pdf, but less phase-space suppression, studied in more detail in [Haisch, Polesello, 2012.11474], [Greljo,Selimovic, 2012.11474]

# Summary

- Recent hints by the LHCb Collaboration of the deviations in $R_K$ and $R_{K^*}$ that point to new physics violation of lepton universality in rare semileptonic b-decays have yet to be confirmed.
- The data can be accommodated by introducing a vector leptoquark, possibly at the collider reach.
- Standard channels: single-, pair- and resonant production
- Rich phenomenology and dependence on the flavor structure
- Covering the full mass range hinted by the rare processes would require high energy collider setups.