

Flavorful leptoquarks at the LHC and beyond: Spin 1

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Based on: [[arxiv:2103.12724](https://arxiv.org/abs/2103.12724) Hiller, Loose, I.N.]

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

The ratios R_{K,K^*} probe e - μ universality in rare FCNC-induced $B \rightarrow K^{(*)} \ell \ell$ transitions:

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

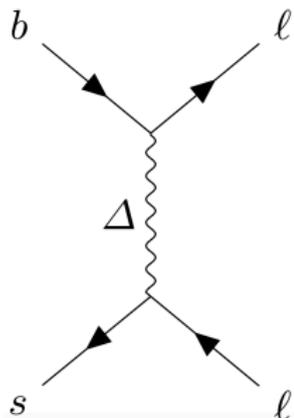
Latest values by the LHCb Collaboration [LHCb, 2103.11769], [LHCb, 1705.05802] in q^2 -bin [1.1, 6] GeV^2 :

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

(3.1σ and 2.6σ deviations from the SM prediction $R_K \simeq R_{K^*} \simeq 1$)

- Confirmation of these hints would be definite sign of beyond the standard model physics

The pattern $R_K < 1$, $R_{K^*} < 1$, $R_K \simeq R_{K^*}$ can be accommodated via exchange of leptoquarks S_3, V_1, V_3 at *tree level* (competing with the 1-loop standard model contribution)



- 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 LQs.

For a study of S_3 see [Hiller, Loose and I.N, 1801.09399]

- Couplings to leptons and quarks:

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

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

- R_{K,K^*} require contribution to $(\bar{s} \gamma_\mu P_L b)(\bar{\ell} \gamma_\mu P_L \ell)$ only $\implies \lambda_{\bar{D}E} = 0$
- We assume **dominant couplings to muons** - consistent with other global fits of $b \rightarrow s \mu \mu$ data involving **angular distributions** in $B \rightarrow K^* \mu \mu$.
- Additional 'anomalous' coupling κ to gluons:

$$\mathcal{L}_{\text{kin},V_1} \supset -ig_s \kappa V_1^{\dagger\mu} T^a V_1^\nu G_{\mu\nu}^a$$

affecting the collider production.

Coupling matrix:

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

■ R_{K,K^*} constrain 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 ~ 40 TeV.

For $\lambda_{b\mu}\lambda_{s\mu} \sim 10^{-2} - 10^{-3} \implies$ possible LHC reach.

Possible pattern from flavor symmetries:

$$\lambda_{dl} : \lambda_{sl} : \lambda_{bl} \sim \epsilon^3 \dots \epsilon^4 : \epsilon^2 : 1, \quad \epsilon \sim 0.2$$

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

■ Flavor benchmarks:

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 constraints from rare kaon decays, μ -e transitions
- The '*'-entries assumed to arise as higher order in ϵ – achievable in flavor models
[Hiller, Loose and Schönwald, 1609.08895]

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

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

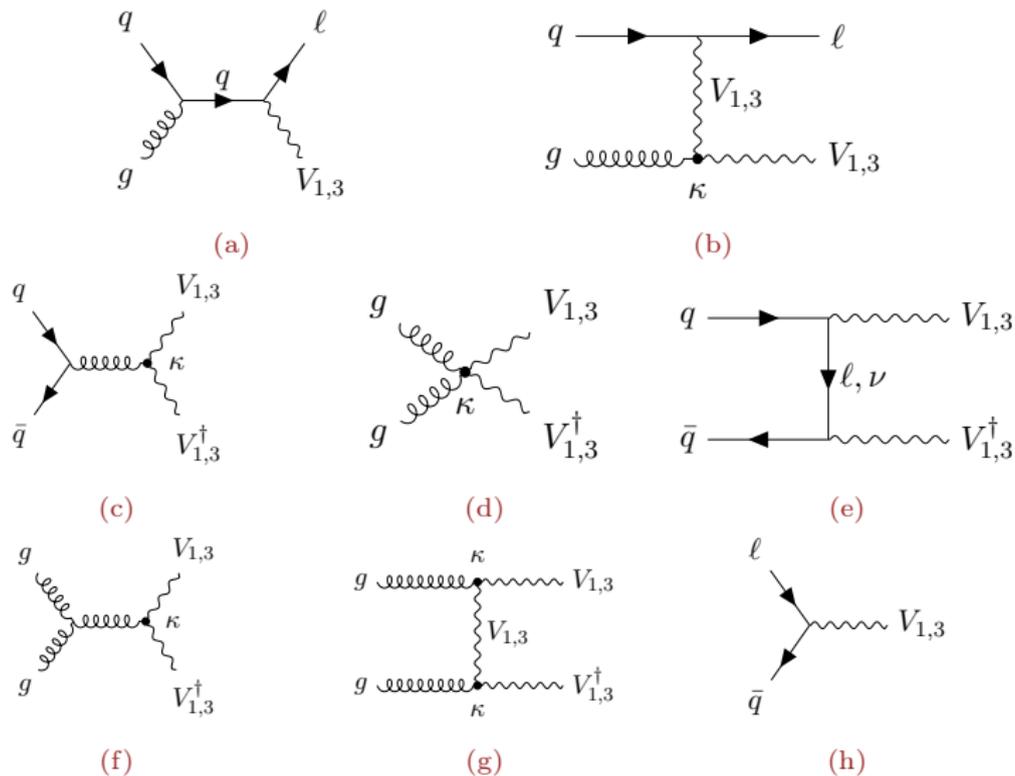
(Enhancement of single LQ production with pdf for s -quark, but weak foundation in flavor models)

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

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

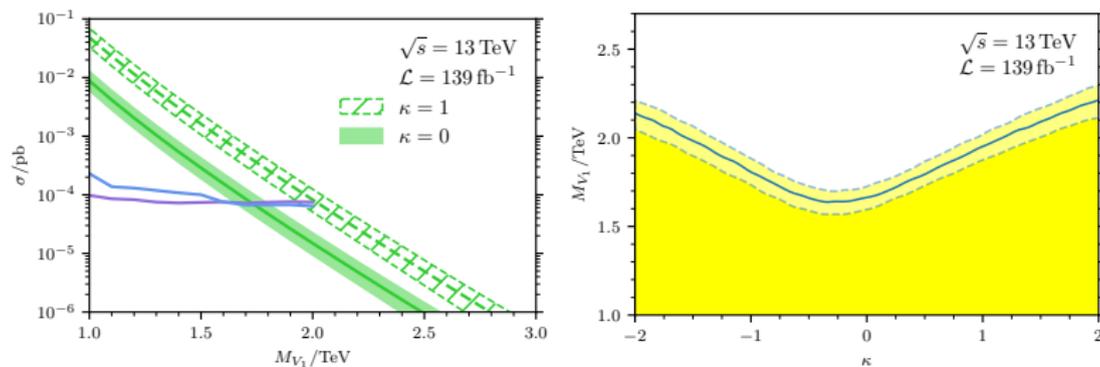
- We do not consider $V_{1,3}$ as solutions to the charged current anomalies in R_{D,D^*} that require $\lambda_{q\tau} \sim 10^2 \lambda_{q\mu}$, not supported by flavor models, and low-mass scale. For study of this possibility see talk by Arvind Bhaskar on this conference ([link](#))

Production at pp colliders



Single production (a,b), Pair production (c-g), Resonant production (h)

- 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: $M_{V_1} > 1.7(1) \text{ TeV}$ and $M_{V_1} > 2.0(1) \text{ TeV}$ for $\kappa = 0$ and $\kappa = 1$, respectively.
- Weakest bounds: $M_{V_1} > 1.4 \text{ TeV}$ (democratic) and $M_{V_3} > 1.6 \text{ TeV}$ (hierarchical) both for $\kappa = -0.3$.

See also the ATLAS-summary talk by Yoav Afik on this conference ([link](#))

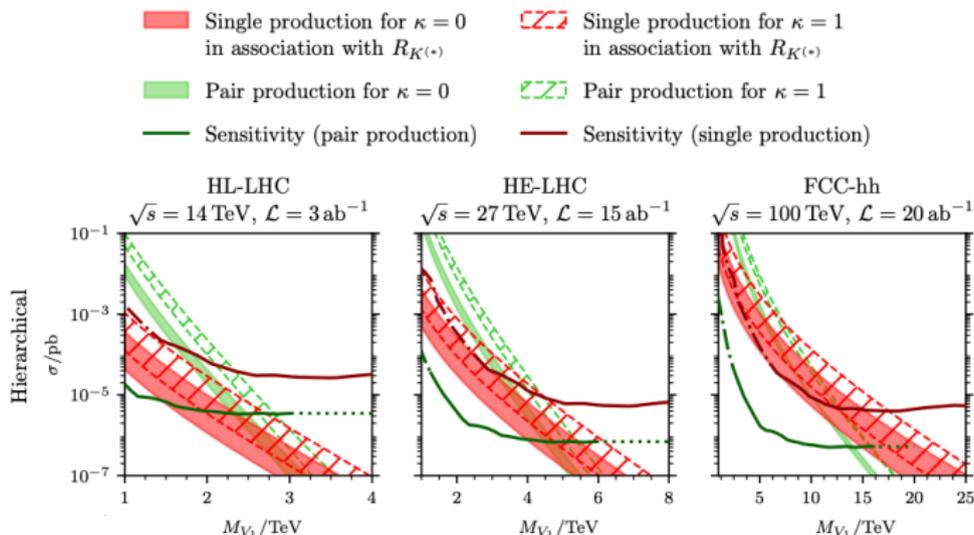
- Estimate the sensitivity of the future colliders by extrapolating current bounds from single- and pair production [see also \[Allanach, Gripaos, You, 1710.06363\]](#)

Starting points for the extrapolations of the sensitivity:

- **Single production**, CMS search, $pp \rightarrow (LQ \rightarrow \mu^j)\mu$, $\sqrt{s} = 8 \text{ TeV}$, $L_{\text{int}} = 19.6 \text{ fb}^{-1}$ [CMS, 1509.03750]
- **Pair production**, ATLAS search, $pp \rightarrow (LQ \rightarrow \mu Q)(LQ \rightarrow \mu Q)$ 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]

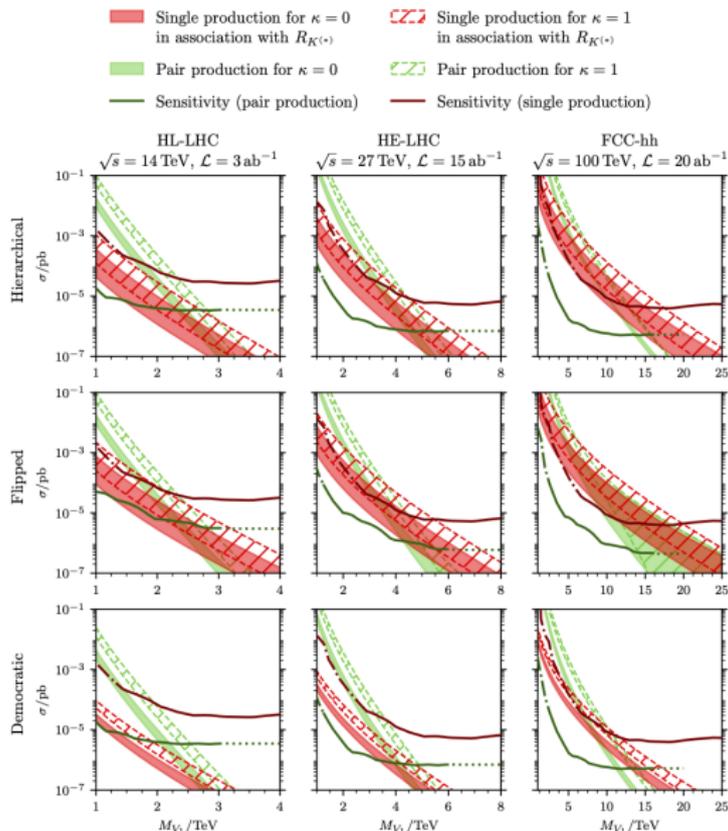
Collider	\sqrt{s}/TeV	$\mathcal{L}/\text{ab}^{-1}$
HL-LHC	14	3
HE-LHC	27	15
FCC-hh	100	20



Plots: **Single production** channel $pp \rightarrow \mu\mu j$, **pair production** channel $pp \rightarrow b\mu b\mu$ (hierarchical scenario)

- **Pair production** dominantly induced by QCD coupling - flavor determines the branching fractions into various final state channels
- The magnitude of **single production** $\sigma(qg \rightarrow V_1^{2/3}\ell) \propto |\lambda_{\bar{Q}\ell}|^2$ - probes the flavor

Scenarios for the future colliders:



For analogous results for V_3 , see [Hiller, Loose, I.N, 2103.12724]

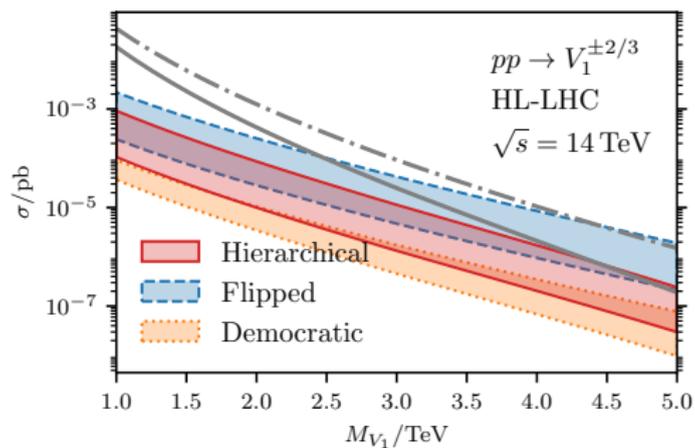
- b-tagging for **single production** could lead to improved limits

Future mass reach in TeV for V_1 (V_3):

Collider	\sqrt{s}/TeV	$\mathcal{L}/\text{ab}^{-1}$	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 ~ 45 TeV and ~ 20 TeV on the masses of the 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]

- 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
- Taking the data at face value points to possibility of vector leptoquarks at the collider reach
- Interesting to search for leptoquarks in single-, pair- and resonant production
- Rich phenomenology and dependence on the flavor structure
- Covering the full mass range supported presently by rare processes requires high energy machines.