# Flavorfull Leptoquarks at LHC

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# Motivation

- Study of possible signatures of the scalar leptoquarks at hadron colliders.
- Motivation from recent experimental (LHCb) hints of BSM sources of lepton flavor universality violation (LFUV) in rare $b \to s\ell\ell$ transitions, $\ell = e, \mu$.
- Ratios for the LFUV:

[Hiller, Krüger, 0310219]

$$R_H = \frac{\mathcal{B}(B \to H\mu^+\mu^-)}{B(B \to He^+e^-)}\,, \qquad H = K, K^*, \tag{1}$$

$$R_H^{(\mathrm{SM})} = 1 \pm \mathcal{O}(\%), \tag{2}$$

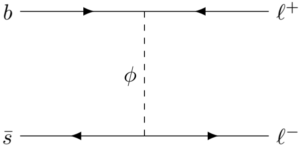
free of (lepton universal) hadronic uncertainties in SM.

- Compared to LHCb measurements:

[LHCb, 1406.6482 [hep-ex] and LHCb, 1705.05802v1 [hep-ex]]

$$R_{K\,[1,6]}^{\mathrm{LHCb}} = 0.745^{+0.090}_{-0.074} \pm 0.036, \quad R_{K^*\,[1.1,6]}^{\mathrm{LHCb}} = 0.69^{+0.11}_{-0.07} \pm 0.05. \tag{3}$$

- Possible to accommodate the discrepancies via mediation of a heavy *leptoquark* (LQ) boson, (LQs recently reviewed in [Doršner, Fajfer, Greljo, Kamenik, Košnik, 1603.04993])
- Contributions to $R_{K,K^*}$ at tree-level:



- One can identify scalar and spin-one LQs that can significantly modify $R_{K,K^*}$ at the tree level [Hiller, N., 1704.05444]
- Looking at scalars:

| | representation | $C_{AB}$ | Relation | $R_{K^{(*)}}$ |
|---|---|---|---|---|
| $\tilde{S}_2$ | $(3, 2, 1/6)$ | $C_{RL}$ | $C'_9 = -C'_{10}$ | $R_K < 1$, $R_{K^*} > 1$ |
| $S_3$ | $(\bar{3}, 3, 1/3)$ | $C_{LL}^{\text{NP}}$ | $C_9 = -C_{10}$ | $R_K \simeq R_{K^*} < 1$ |
| $S_2$ | $(3, 2, 7/6)$ | $C_{LR}$ | $C_9 = C_{10}$ | $R_K \simeq R_{K^*} \simeq 1$ |
| $\tilde{S}_1$ | $(\bar{3}, 1, 4/3)$ | $C_{RR}$ | $C'_9 = C'_{10}$ | $R_K \simeq R_{K^*} \simeq 1$ |

- Only a single scalar multiplet can accommodate both $R_{K,K^*}$ at tree-level
- At one loop: LQ $(3, 1, 1/3)$ [Bauer, Neubert, 1511.01900], not discussed here
- Note the vectors $V_1$, $V_3$ that could also induce $R_{K,K^*} < 1$
- *Large number of interesting papers* that study LQs for $R_{K,K^*}$, many of which attempt to also accommodate anomalies in $R_{D,D^*}$ (see talks by Crivellin, Sumensari, Isidori)
- Using $S_3$ to accommodate $R_{K,K^*}$ (as we do), one finds that thee effect in $R_{D,D^*}$ is too small to play role in the anomalies there [Hiller, Loose, Schönwald, 1609.08895; Angelescu, Bečirević, Faroughy, Sumensari, 1808.08179], hinting at more NP ingredients
- What do we "know" about the properties of $S_3$?
- $R_{K,K^*}$ fixes $\lambda \cdot \lambda / M^2$, while $B_s$-$\bar{B}_s$-mixing constraints $(\lambda \cdot \lambda)^2 / M^2$ giving upper limit on $S_3$ mass $\sim$ few $\times\, 10\,\text{TeV}$.

# $S_3$ on hadron colliders

- Limits from single production: $jee\,(1750\,\mathrm{GeV})$, $j\mu\mu\,(660\,\mathrm{GeV})$ [CMS, 1509.03744], assuming corresponding branching fractions equal to one.
- So far no searches for final states with $b\ell\ell$, $\ell = e, \mu$.
- Derived limits on $S_3$ from search [ATLAS, 1710.05544] of pair-production of R-parity violating squarks: $1.5\,(1.4)$ TeV for dominant decays to $be\,(b\mu)$ [Diaz, Schmaltz, Zhong, 1706.05033]

# $S_3$ on hadron colliders

## $S_3$ couplings to fermions

$$\mathcal{L}_{\rm Yuk} = \lambda\, \bar{Q}_L^{C\,\alpha} (i\sigma^2)^{\alpha\beta} (S_3)^{\beta\gamma} L_L^{\gamma} + Y_\kappa\, \bar{Q}_L^{C\,\alpha} (i\sigma^2)^{\alpha\beta} (S_3^\dagger)^{\beta\gamma} Q_L^{\gamma} + \text{h.c.} \tag{4}$$

- Assume the proton decay coupling matrix $Y_\kappa$ is forbidden, e.g. realization in GUT, see [Bečirević, Doršner, Fajfer, Faroughy, Košnik, Sumensari, 1806.05689] for a possible scenario

## Expanding in the components:

$$\mathcal{L}_{\rm QL} = -\sqrt{2}\lambda\, \bar{d}_L^C \ell_L\, S_3^{4/3} - \lambda\, \bar{d}_L^C\, \nu_L\, S_3^{1/3} + \sqrt{2}\lambda\, \bar{u}_L^C\, \nu_L\, S_3^{-2/3} - \lambda\, \bar{u}_L^C\, \ell_L\, S_3^{1/3} + \text{h.c.} \tag{5}$$

## The present $R_{K^{(*)}}$ data requires

$$\lambda_{b\mu}\lambda_{s\mu}^* - \lambda_{be}\lambda_{se}^* \simeq 1.1 \frac{M_{S_3}^2}{(35\,\text{TeV})^2}\,. \tag{6}$$

Assumptions:

- SM hierarchies from the quark Yukawas are intact for the case of LQ (couplings to 3-rd generation quarks dominate)

$$\lambda_{d\ell} \sim (\epsilon^3 \dots \epsilon^4)\, \lambda_{b\ell}\,, \quad \lambda_{s\ell} \sim \epsilon^2\, \lambda_{b\ell}, \quad \epsilon \sim 0.2\,,\ \ell = e, \mu, \tau\,. \tag{7}$$

- BSM effects in $R_{K,K^*}$ predominantly from $\mu$ and not $e$, as suggested by global fits.

## A simplified benchmark $\lambda_s$

$$\lambda_s \sim \lambda_0 \begin{pmatrix} 0 & 0 & 0 \\ * & \epsilon^2 & * \\ * & 1 & * \end{pmatrix} \tag{8}$$

Entries with "0" higher order in $\epsilon$ strongly constrained by flavor observables, entries with " $*$ " not required for $R_H$.

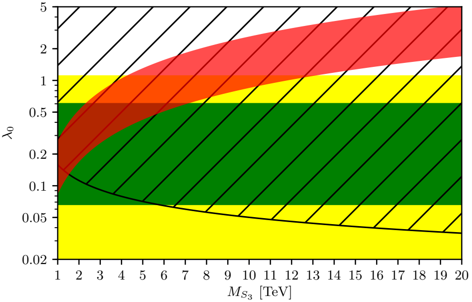
- Eq. (6) gives $\lambda_0 \simeq M_{S_3}/6.7\,\text{TeV}$; allowing $\mathcal{O}(1)$ factor, i.e $\kappa = (1/3, 3)$

$$M_{S_3}/11.6\,\text{TeV} \lesssim \lambda_0 \lesssim M_{S_3}/3.9\,\text{TeV}\,. \tag{9}$$

Using [Greljo, Marzocca, 1704.09015] we find the corresponding parameter space is well within the LHC-limits on $p\,p \to \mu\mu$.

## Dominant decay modes of $S_3$ isospin components

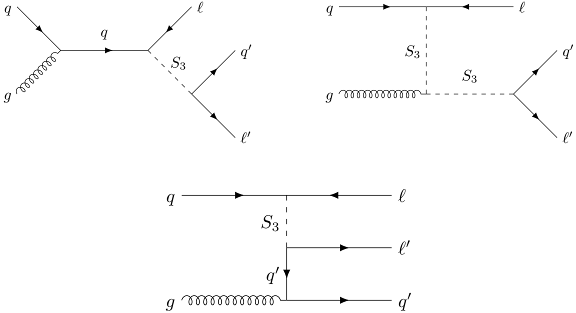
$$\begin{aligned} S_3^{-4/3} &\to b\,\mu^-, \\ S_3^{+2/3} &\to t\,\nu, \quad S_3^{-1/3} \to b\,\nu\;,\; t\,\mu^- \end{aligned} \tag{10}$$



Red - range for $R_K, R_{K*}$-data. Yellow - narrow width $\Gamma/M_{S_3} \lesssim 5\%$. Hatched area $\Gamma > \Lambda_{QCD}$. Green - flavor models expectations [Hiller, Loose Schönwald 1609.08895; de Medeiros Varzielas, Hiller 1503.01084 ]

# Single LQ production at LHC: diagrams

Leading order diagrams:



# Single LQ production: cross-sections

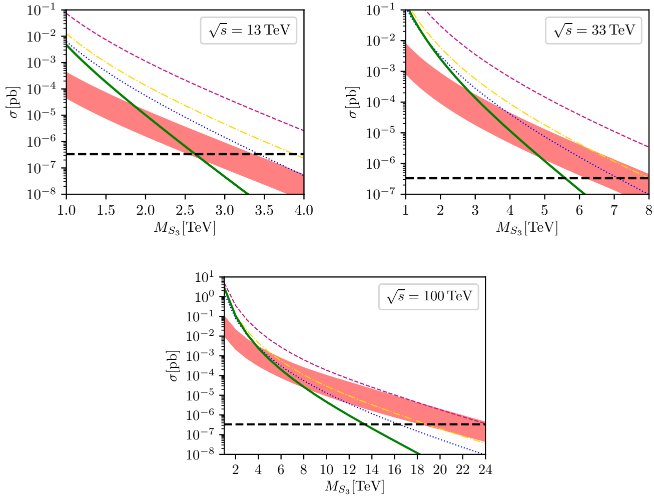
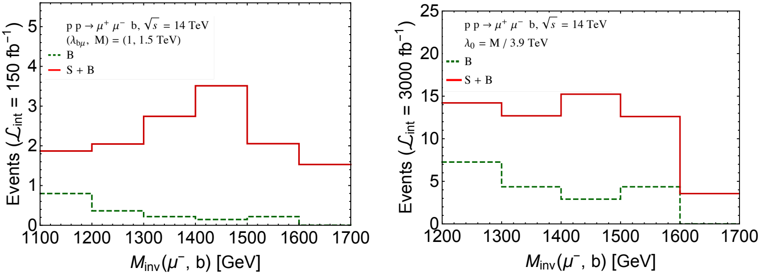


Figure: Single LQ production $\sigma(pp \to S_3^{-4/3}\mu^+ + S_3^{+4/3}\mu^-)$ at leading order. a) RED - flavor pattern (8) with $\lambda_0$ from $B$-anomalies (9). b) GREEN - Pair production $\sigma(pp \to S_3^{-4/3} S_3^{+4/3})$

# Single LQ production

- Pair-production - most likely a discovery channel in case of lower masses. Single production is important in order to check the connection with anomalies.
- The ability to tag a charge of $b$ required to distinguish different LQs.
- To estimate feasibility of the single LQ search, simulate the events for a fixed mass, here an example of $M = 1.5\,\text{TeV}$



Events for $pp \to b\mu^+\mu^-$ and $pp \to \bar{b}\mu^+\mu^-$ at $\sqrt{s} = 14\,\text{TeV}$.

a) $\lambda_{b\mu} = 1$ (disovery significance $\sim 4\sigma$), b) $\lambda_0 = M/3.9$ TeV with $B$-anomalies ($\sim 5\sigma$).

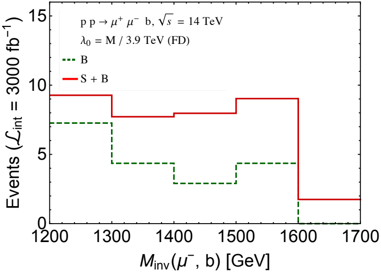
- Another benchmark: a more general parametrization

## "Flavor data" [de Medeiros Varzielas, Hiller 1503.01084 ]

$$\lambda_{\rm FD} = \lambda_0 \begin{pmatrix} \rho_d \kappa_e & \rho_d & \rho_d \kappa_\tau \\ \rho \kappa_e & \rho & \rho \kappa_\tau \\ \kappa_e & 1 & \kappa_\tau \end{pmatrix}, \qquad \kappa_\tau \sim 1\,. \tag{11}$$

with viable ranges

$$\rho_d \lesssim 0.02\,, \quad \kappa_e \lesssim 0.5\,, \quad 10^{-4} \lesssim \rho \lesssim 1\,, \quad \kappa_e/\rho \lesssim 0.5\,, \quad \rho_d/\rho \lesssim 1.6\,. \tag{12}$$



(c)

Events for $pp \to b\mu^+\mu^-$ and $pp \to \bar{b}\mu^+\mu^-$
"flavor data pattern" ($\sim 3\sigma$)

- Need for a high luminosity machine in order to probe for Yukawa couplings even for "just around the corner" LQ (assuming it is relevant for $R_{K,K^*}$ anomalies only).
- For the case of inverted hierarchy $\lambda_{s\mu}/\lambda_{b\mu} \sim 1/\epsilon^2$ situation more challenging due to larger backgrounds from $Z/\gamma^* + j$.
- To estimate the reach of future colliders for LQ production with final states $\mu\mu b$ - would be nice to have a corresponding LHC searches with current machine as a basis for extrapolation.
- Reach in pair production - estimated [Allanach, Gripaios, You, 1503.01084] by projecting the CMS search $(8\,\text{TeV}, 19.6\,\text{fb}^{-1})$ in pair-production with $\mu\mu jj$ in final state:

  HL-LHC: $2\,\text{TeV}$
  HE-LHC: $5\,\text{TeV}$ at $10\,\text{ab}^{-1}$
  FCC-hh: $10\,(12)$ TeV at $1\,(10)\,\text{ab}^{-1}$

- Estimate of future sensitivities for $\mu b \mu b$ final states?
- [ATLAS-CONF-2017-036] search for RPV squarks at $13\mathrm{TeV}, 36.1\,\mathrm{fb}^{-1}$ - provides only 95% C.L on a LQ mass at $1.4\,\mathrm{TeV}$. One can then make an estimate of future sensitivity using the predicted pair-production cross sections and extrapolation method from [Thamm, Torre, Wulzer, 1502.01701]

  HL-LHC: $\sim 2\,\mathrm{TeV}$ for $\sqrt{s} = 14\,\mathrm{TeV}$ and $3\,\mathrm{ab}^{-1}$
  HE-LHC: $\sim 5\,\mathrm{TeV}$ for $\sqrt{s} = 33\,\mathrm{TeV}$ and $10\,\mathrm{ab}^{-1}$
- More trustable estimate could be done with the information on the exclusion limit as a function of mass

# Conclusions

- B-physics data and flavor models identify $pp \to \phi\mu \to b\mu\mu$, $pp \to \phi\nu \to b\nu\nu$ and $pp \to \phi\nu \to t\mu\nu$ as the channels with leading cross sections in single production.
- We highlight $b\mu\mu$ as a prime channel
- $b\mu b\mu$ signature in pair-production
- Although preferred by the global fits, the possibility of (dominant) couplings to electrons are allowed by $R_{K,K^*}$
- The LHC (even with 3 $\mathrm{ab}^{-1}$) is not able to cover the full targeted parameter space
- If the anomalies are confirmed, this would present a strong motivation for future high-energy colliders.