Hunting for Leptoquarks

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Flavor anomalies hinting at leptoquarks (LQs)?

Hints for NP in $b \rightarrow c\tau\bar{\nu}$ transitions:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)}$$

World average:
- $R_D = 0.344 \pm 0.026$
- $R_{D^*} = 0.285 \pm 0.012$

SM prediction:
- $R_{D}^{SM} = 0.298 \pm 0.004$
- $R_{D^*}^{SM} = 0.254 \pm 0.005$

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Hints for NP in $b \to s\nu \bar{\nu}$ transitions:

$$\mathcal{B}(B^+ \to K^+\nu \bar{\nu})$$

- SM prediction:
  - $\mathcal{B}(B^+ \to K^+\nu \bar{\nu})^{SM} = (5.58 \pm 0.37) \times 10^{-6}$

- World average & SM prediction:
  - $\mathcal{B}(B^+ \to K^+\nu \bar{\nu}) = (2.3 \pm 0.5(stat)^{+0.5}_{-0.4}(syst)) \times 10^{-5}$

HFLAV Moriond 2024

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HFLAV SM Prediction

R(D) = 0.298 ± 0.004
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P(χ²) = 29%

68% CL contours

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- $\mathcal{B}(B^+ \to K^+ \nu \bar{\nu})^{SM} = (5.58 \pm 0.37) \times 10^{-6}$

→ NP in semileptonic transitions of 3rd generation fermions? → leptoquarks?
Leptoquark models with 3rd generation couplings

LQ explanations of $R_{D(*)}$:

- Vector LQ: $U_1 \sim (3, 1)_{2/3}$
- Scalar LQ: $S_1 \sim (\bar{3}, 1)_{1/3}$
- Scalar LQ: $R_2 \sim (3, 2)_{7/6}$

$$\mathcal{L}_{LQ} = y_{pr} \left( \bar{Q}_p \Gamma L_r \right) \phi_{LQ} \quad \text{for} \quad Q \in \{q, d, u\}, \ L \in \{\ell, e\}, \ \phi_{LQ} \in \{U_1, S_1, R_2, \ldots\}$$

- Different Lorentz structures $\Gamma$ depending on LQ state
- Only semi-leptonic interactions
  - No tree-level contribution to meson mixing
  - $S_1$ can have baryon-number violating interactions
  - $S_1$ only LQ of these 3 that can account for $B \rightarrow K \nu \bar{\nu}$
- LQ generally induce LFV (without imposing exact flavor symmetries)
Probing semileptonic transitions at different scales:

- Exploit complementarity of low- and high-energy measurements
Phenomenology of leptoquarks at LHC

Probing semileptonic transitions at different scales:

- Exploit complementarity of low- and high-energy measurements
- Various different channels for LQ searches:

  - Searches in different channels and different flavor combinations performed by ATLAS & CMS
Leptoquark channels at high-$p_T$

Leptoquark channel considered in analysis by CMS and ATLAS:

- Pair-production
- Single production
- Drell-Yan

Example: constraints on $U_1$ vector leptoquark from various channels (quark-lepton fusion not yet included)

**CMS Preliminary**

<table>
<thead>
<tr>
<th>Leptoquark mass [GeV]</th>
<th>Coupling strength $\lambda$</th>
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<tbody>
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<td>500</td>
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<td>3000</td>
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95% CL upper limits:
- Single
- Nonres.
- Observed
- Expected
- Expected by B anomalies
- Vector, $\beta=1$, $\kappa=1$

**ATLAS Preliminary**

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95% CL:
- Total (Obs.limit ± 1$\sigma$)
- Total (Exp.limit ± 1$\sigma$)
- Preferred by B anomalies

Interference with SM neglected

See e.g.:
- [hep-ph/9406235]
- [hep-ph/9709319]
- [2005.06475]
- [2012.02092]
- [2209.02599]
- [2308.06143]
Leptoquark channels at high-$p_T$

Leptoquark channel considered in analysis by CMS and ATLAS:
quark-lepton fusion / resonant production

Example: constraints on $U_1$ vector leptoquark from various channels (quark-lepton fusion not yet included)
**$S_1$ leptoquark explanation of $R_D^{(*)}$**

- $S_1 \sim (\bar{3}, 1)_{1/6}$ interaction Lagrangian:
  
  $$\mathcal{L}_{S_1} = y_{L}^{pr}(\bar{q}_p e^c \ell_r) S_1 + y_{R}^{pr}(\bar{u}_p e^c \ell_r) S_1 + h.\ c.\$$

- Minimal Yukawas required: $y_{L}^{b\tau}, y_{R}^{c\tau}$

- Weak LHC bounds for $y_{L}^{b\tau}$:
  
  - Only $(\bar{b}^c \nu) S_1$ and $(\bar{t}^c \tau) S_1$ transitions
  
  - $b - \tau$ coupling CKM suppressed

- Compatibility of measurements: $R_D^{(*)},$ Drell-Yan, $\Gamma(Z \rightarrow \tau\tau), \mathcal{B}(\tau \rightarrow \mu \nu \bar{\nu})$

- No tree-level contribution to $b \rightarrow s\nu\bar{\nu}$ in minimal setup → loop induced (can be enhanced by $y_{L}^{s\tau}$)

Becirevic, Fajfer, Kosnik, Pavicic [2404.16772]
$R_2$ leptoquark explanation of $R_D^{(*)}$

- $R_2 \sim (3, 2)_{7/6}$ interaction Lagrangian:
  
  $$\mathcal{L}_{R_2} = y^p_{R}(\bar{q}_p e_r)R_2 + y^p_{L}(\bar{u}_p R_2 e_\ell_r) + \text{h.c.}$$

  - Minimal Yukawas required: $y^b_\tau, y^c_\tau$
  - For $R_D^{exp} > R_D^{SM}$ we need $\text{Im}(y^b_\tau y^c_\tau) \neq 0$
    - No interference with SM
    - Larger couplings required (NP$^2$ effect)
    - Stronger LHC constraints
  - $R_D^{(*)}, \text{Drell-Yan, } \Gamma(Z \rightarrow \tau\tau)$ data shows 2 $\sigma$ tension in this model
  - No tree-level contribution to $b \rightarrow s\nu\bar{\nu}$

$M_{R_2} = 1.5 \text{ TeV}$

Becirevic, Fajfer, Kosnik, Pavicic [2404.16772]
**$U_1$ vector leptoquark and $b$-jet tagging**

$U_1$ leptoquark Lagrangian: \[ \mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}} \left[ \bar{q}_L \gamma_\mu \ell_L^3 + \beta_R \bar{d}_R \gamma_\mu e_R^3 + \sum_{k=1,2} \epsilon_{q_k} \bar{q}_L \gamma_\mu \ell_L^3 \right] U_{1\mu}^\mu + \text{h.c.} \]

- High-$p_T$ constraints
  - from: $b\bar{b} \rightarrow \tau^+ \tau^-$
  - on: effective scale $\Lambda_U = \sqrt{2M_U/g_U}$
  - Obtained with HighPT \[ \text{Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10756]} \]

- Resonant searches for $pp \rightarrow \tau \tau$
  - **ATLAS** (*no excess*) [2002.12223]
  - **CMS** (*$\sim 3\sigma$ excess*) [2208.02717]

**Constraints on right-handed coupling scenarios**

Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]
**$U_1$ vector leptoquark and $b$-jet tagging**

### $U_1$ leptoquark Lagrangian:

$$\mathcal{L}_{U_1} = \frac{g_{U_1}}{\sqrt{2}} \left[ \bar{q}_L \gamma_\mu \ell_L^3 + \beta_R \bar{d}_R \gamma_\mu \ell_R^3 + \sum_{k=1,2} \epsilon_{q_k} \bar{q}_L \gamma_\mu \ell_L^3 \right] U_1^\mu + \text{h.c.}$$

- **High-$p_T$ constraints**
  - from: $b\bar{b} \to \tau^+\tau^-$
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- **Resonant searches for $pp \to \tau\tau$**
  - **ATLAS** (*no excess*) [2002.12223]
  - **CMS** (*$\sim 3\sigma$ excess*) [2208.02717]

- **Initial state gluon splitting**: $g \to b\bar{b}$
  - Expect soft associated $b$ jet
  - Requiring associated $b$ jets reduces background and improves performance

- **Rescaled likelihood to account for $b$ tagging and including NLO corrections**
  [Haisch, Schnell, Schulte [2207.00356], [2209.12780]]
$U_1$ vector leptoquark at low energies

$U_1$ leptoquark Lagrangian: 
$$\mathcal{L}_{U_1} = \frac{g_{U_1}}{\sqrt{2}} \left[ q_L^3 \gamma_\mu \ell_L^3 + \beta_R \bar{d}_R^3 \gamma_\mu e_R^3 + \sum_{k=1,2} e_{q_k} \bar{q}_L^k \gamma_\mu \ell_L^3 \right] U_1^\mu + \text{h.c.}$$

- EFT Lagrangian for $b \to c\tau\nu$

$$\mathcal{L}_{b\to c} = - \frac{G_F}{\sqrt{2}} V_{cb} \left[ \left( 1 + \mathcal{C}_{LL}^c \right) (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) - 2 \mathcal{C}_{LR}^c (\bar{c}_L b_R)(\bar{\tau}_R \nu_L) \right]$$

where $\mathcal{C}_{LR}^c = \beta_R^* \mathcal{C}_{LL}^c$

- Left-handed couplings only: $\mathcal{C}_{LR}^c = 0$

- Equal magnitude: $\mathcal{C}_{LR}^c = - \mathcal{C}_{LL}^c$

- Observables relevant to low-energy fit:

  - $R_D$, $R_{D^*}$, $R_{A_c}$, $\mathcal{B}(B_d^- \to \tau\bar{\nu})$

- Combined fit shows $3\sigma$ discrepancy with SM

- Compatible with both $\beta_R = 0$ and $\beta_R = -1$

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See, e.g. also:
Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert [2103.16558]
Bhaskar, Das, Mandal, Mitra, Neeraj [2101.12069]
**$U_1$ vector leptoquark at high-$p_T$**

- Effective Lagrangian for $b \to c$ transitions:
  \[
  \mathcal{L}_{b\to c} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left[ (1 + \mathcal{C}^c_{LL})(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) - 2\mathcal{C}^c_{LR}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) \right]
  \]

- Match $\mathcal{C}^c_{LL(LR)}$ to the $U_1$ model
  - $\mathcal{C}^c_{LL} \sim g_U^2$
  - $\mathcal{C}^c_{LR} \sim \beta_R g_U^2$

**$U_1$ Lagrangian:**
\[
\mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}} \left[ d_3 L \ell_3 e + \beta_R \bar{d}_R \gamma_\mu e_R \right]
+ \sum_{k=1,2} \epsilon_k q_k q_{\ell_k} \gamma_\mu \ell_3 \ell_3 + h.c.
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Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]
**U_1 vector leptoquark at high-**p**T**

- Effective Lagrangian for \( b \rightarrow c \) transitions:
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  \mathcal{L}_{b\rightarrow c} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left[ (1 + C_{LL}^c)(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma_\nu \nu_L) - 2 C_{LR}^c(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) \right]
  \]

- Match \( C_{LL(LR)}^c \) to the \( U_1 \) model
  - \( C_{LL}^c \sim g_U^2 \)
  - \( C_{LR}^c \sim \beta_R g_U^2 \)

- Details of the fit:
  - \( C_{LL}^c \rightarrow 0 \) corresponds to \( |\beta_R| \rightarrow \infty \)
  - More model dependence
    - Depends on 2\(^{nd}\) gen. coupling \( \epsilon_q \)
    - Small \( \epsilon_q \) requires lower scale \( \Lambda_U \)

- Currently good compatibility of constraints
- CMS excess favors scenario with large \( \beta_R \)

\[ \mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}} \left[ q_3^3 \gamma_\mu \ell_3^3 + \beta_R d_R^3 \gamma_\mu e_R^3 \right] U_1^\mu + \text{h.c.} \]
Comparison of different searches

- Constraints on the $U_1$ leptoquark in the coupling $g_U$ vs. mass $M_U$ plane
  - Preferred regions from low-energy fit
    - [only left-handed couplings]
    - [equal size left- & right-handed couplings]
  - Excluded from high-$p_T$ Drell-Yan tails

\[
|\beta_R| = 0
\]

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|\beta_R| = 1
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$$|\beta_R| = 0$$

$$|\beta_R| = 1$$
Conclusions

- Leptoquark models well motivated in light of $R_{D^{(*)}}$ anomalies and $\mathcal{B}(B \to K\nu\bar{\nu})$

- To explain anomalies and, at the same time, be compatible with further low-energy data dominant couplings to 3\textsuperscript{rd} generation required
  - LQ models possibly linked to explanations of SM Yukawa structure?

- LQ models can be well tested at LHC:
  - Pair production, single production, Drell-Yan, quark-lepton fusion
  - Sensitivity improvements for 3\textsuperscript{rd} generation LQs by requiring associated $b$-tagged jets

- Different LQ models viable:
  - $U_1$ vector leptoquark: large parts of parameter space will be covered by HL-LHC
  - $S_1$ scalar leptoquark: improvements expected by HL-LHC
  - $R_2$ scalar leptoquark: already at 2\textsigma tension with current data

- Overall: important complementarity of low- and high-energy data
Backup
Drell-Yan in light of the $R_D^{(*)}$ anomalies: $U_1$ leptoquark

\[ \mathcal{L}_{U_1} = [x^L_1]_{ia} U^\mu_1 (\bar{q}_i \gamma_\mu \ell_a) + [x^R_1]_{ia} U^\mu_1 (\bar{d}_i \gamma_\mu e_a) + \text{h.c.} \quad \rightarrow \quad [C^{(1)}_{lq}]_{\alpha \beta ij} = [C^{(3)}_{lq}]_{\alpha \beta ij} = -\frac{1}{2} [x^L_1]_{i\beta} [x^L_1]^{*}_{j\alpha} \]

- Consider couplings to left-handed fields only $q^L_{3,2}$ and $\ell^L_3 \rightarrow [C^{(1,3)}_{lq}]_{3333(3323)}$
- Relevant processes: $b\bar{b} \rightarrow \tau^+ \tau^-$, $b\bar{s} \rightarrow \tau^+ \tau^-$, $b\bar{c} \rightarrow \tau^- \bar{\nu}$ ... (+ c.c.)

**SMEFT fit**

**HighPT SMEFT mode**

EW: $W \rightarrow \tau \nu$

Flavor: $R_D$ and $R_D^{*}$

$\Lambda = 2 \text{ TeV}$

$[C^{(1)}_{lq}]_{3333} = [C^{(3)}_{lq}]_{3333}$

$[C^{(1)}_{lq}]_{3323} = [C^{(3)}_{lq}]_{3323}$

**LQ mediator fit**

**HighPT mediator mode**

$U_1 \sim (3, 1, 2/3)$

$m_{U_1} = 2 \text{ TeV}$

Combined

$\bar{b} b \rightarrow \tau^+ \tau^-$, $\bar{b} s \rightarrow \tau^+ \tau^-$, $\bar{b} c \rightarrow \tau^- \bar{\nu}$ ...

(Felix Wilsch (RWTH Aachen))
Drell-Yan in light of the $R_{D(*)}$ anomalies: $S_1$ leptoquark

\[ \mathcal{L}_{S_1} = [y_L^1]_{\alpha \beta} S_1 (\bar{q}_i^c e \ell_{\alpha}) + [y_R^1]_{\alpha \beta} S_1 (\bar{u}_i^c e \ell_{\alpha}) + \text{h.c.} \]

- Consider couplings to 3rd (and 2nd) generation fermions only
- Relevant processes: $b \bar{c} \rightarrow \tau^+ \tau^- \ldots$ (+ c.c.)

**SMEFT fit**

**HighPT SMEFT mode**

**HighPT mediator mode**

Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714, 2207.10756]
Drell-Yan in light of the $R_D^{(*)}$ anomalies: $R_2$ leptoquark

$\mathcal{L}_{R_2} = - [y^L_2]_{i\alpha}(\bar{u}_i R_2 e^\alpha) + [y^R_2]_{i\alpha}(\bar{q}_i e^\alpha)R_2 + h.c. \quad \rightarrow \quad [C^{(1)}_{lequ}]_{\alpha\beta i j} = 4[C^{(3)}_{lequ}]_{\alpha\beta i j} = -\frac{1}{2} [y^R_2]_{i\beta}[y^L_2]^{*}_{j\alpha}$

SMEFT fit

LQ mediator fit

Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714, 2207.10756]
Lepton-Flavor Violation in the $U_1$ model

- $U_1 \sim (3, 1)_{2/3}$ leptoquark model:
- LFV requires 2 couplings turned on
  - LFV can be constrained by $pp \rightarrow \ell \bar{\ell}$ and $pp \rightarrow \ell \bar{\ell}'$
- Example: consider only 3rd generation quarks

⇒ LFV searches $pp \rightarrow \ell \bar{\ell}'$ can yield complementary information to flavor conserving searches