The Forward-Backward Asymmetry in $B \to D^{*} \ell \nu$:
One more hint for Scalar Leptoquarks?

AC, Andreas Crivellin, Diego Guadagnoli, Shireen Gangal
arXiv:2106.09610
Context & Motivations

Putative B-decay discrepancies involving $b \to s\ell\ell$ and $b \to c\ell\nu$

- Can be interpreted as the manifestation of New Physics in loops at the $\mathcal{O}(TeV)$ scale, at tree level $\mathcal{O}(10TeV)$

Muon magnetic dipole moment anomaly $a_\mu = (g - 2)_\mu / 2$

- Longstanding discrepancy wrt SM. Update by Fermilab 2021: $4.2\sigma$ pull
- Only receives contributions from loops, natural probe for NP at high energy
- The discrepancy is the same size as the EW contribution, could be NP at $\mathcal{O}(TeV)$ scale

Figure from Lindner et al. (1610.06587)
Context & Motivations

Putative B-decay discrepancies involving $b \to s\ell\ell$ and $b \to c\ell\nu$

- Can be interpreted as the manifestation of New Physics in loops at the $\mathcal{O}(TeV)$ scale, at tree level $\mathcal{O}(10TeV)$

Muon magnetic dipole moment anomaly $a_\mu = (g - 2)\mu/2$

- Longstanding discrepancy wrt SM. Update by Fermilab 2021: 4.2σ pull
- Only receives contributions from loops, natural probe for NP at high energy
- The discrepancy is the same size as the EW contribution, could be NP at $\mathcal{O}(TeV)$ scale

Playground for model builders
Popular solution: Leptoquarks

Figure from Lindner et al. (1610.06587)
New putative discrepancies in $B \rightarrow D^* \ell \nu$?

C. Bobeth, M. Bordone, N. Gubernari, M. Jung et D. van Dyk (2104.02094)

- Based on Belle 2018 untagged (1809.03290) which released the first dataset for angular distribution of $B \rightarrow D^* \ell \nu$ with separate $\mu$ and $e$ modes

- Includes binned decay rates and all angular coefficients in $B \rightarrow D^* \ell \nu$

- Among the angular observables Forward-Backward Asymmetry $\equiv A_{FB}$

- $\Delta A_{FB} = A_{FB}^\mu - A_{FB}^e$

\[
A_{FB}(q^2) = \frac{\int_0^1 d^2\Gamma/dq^2 d\cos \theta_{\ell} - \int_{-1}^0 d^2\Gamma/dq^2 d\cos \theta_{\ell}}{\int_0^1 d^2\Gamma/dq^2 d\cos \theta_{\ell} + \int_{-1}^0 d^2\Gamma/dq^2 d\cos \theta_{\ell}}
\]

\[
\langle A_{FB} \rangle = \int_{q_{min}^2}^{q_{max}^2} A_{FB}(q^2) dq^2
\]
Context & Motivations

New putative discrepancies in $B \rightarrow D^{*} \ell \nu$ ?

C. Bobeth, M. Bordone, N. Gubernari, M. Jung et D. van Dyk (2104.02094)

- $\sim 4\sigma$ pull in $\langle \Delta A_{FB} \rangle \rightarrow$ LFUV
- $\sim 2\sigma$ pull in $\langle A^\mu_{FB} \rangle \rightarrow$ NP coupled to muons ?
- Reduced uncertainty in theory predictions for « $\Delta$ » observables, good probe for LFUV
- Caveat:
  - Correlation between $\mu$ and $e$ modes were not provided explicitly $\rightarrow$ reconstructed by the authors
  - Inconsistencies in the statistical correlation matrix
  - The $\langle \Delta A_{FB} \rangle$ discrepancy holds even in the most unfavorable correlation $> 3\sigma$
Leptoquarks Models

Leptoquarks 101

• 10 possible representations of LQs
  5 scalars, 5 vectors. \( M_{LQ} \gtrsim 1 \text{TeV} \)

• Tree-level couplings to scalar LQs:

\[
\mathcal{L}_{\text{scalar}}^{LQ} = \left( \lambda_{f_i}^R u_f^c \ell_i + \lambda_{f_i}^L \bar{Q}_f^c i \tau_2 L_i \right) \Phi_1^\dagger + \lambda_{f_i}^1 d_f^c \ell_i \tilde{\Phi}_1^\dagger + \lambda_{f_i}^2 d_f \tilde{\phi}_2^\dagger L_i \\
+ (\lambda_{f_i}^{2R} u_f^c L_i + \lambda_{f_i}^{2L} \bar{Q}_f^c i \tau_2 \ell_i) \Phi_2^\dagger + \lambda_{f_i}^3 \bar{Q}_f^c i \tau_2 (\tau \cdot \Phi_3)^\dagger L_i + \text{h.c.}
\]

• LQs affect flavor physics at low energy, eg \( b \rightarrow c \tau \nu \)
Leptoquarks to EFTs

LQ in Weak Effective Theory (WET)

\[ \mathcal{H}_{\text{eff}}^{\ell_f \nu_i} = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_k C_k^{f_i} O_k^{f_i} + \text{h.c.} \]

\[ O^{f_i}_{VL(R)} = \bar{c} \gamma^\mu P_{L(R)} \ell_f \gamma_\mu P_L \nu_i , \]

\[ O^{f_i}_{SL(R)} = \bar{c} P_{L(R)} \ell_f P_L \nu_i , \]

\[ O^{f_i}_{TL} = \bar{c} \sigma^{\mu\nu} P_L \ell_f \sigma_{\mu\nu} P_L \nu_i . \]

For our model building purpose \( f, i = 2 \)

Each LQ model generates a unique set of WCs

Is one of these LQ models preferred by \( b \to c \ell \bar{\nu} \) data?

\[ \begin{array}{|c|c|c|c|c|c|c|}
\hline
b \to c \ell \bar{\nu} & C_{V_L}^{f_i} & C_{V_R}^{f_i} & C_{S_L}^{f_i} & C_{S_R}^{f_i} & C_{T_L}^{f_i} \\
\hline
\Phi_1 & -\lambda_3^{1L} \lambda_2^{1L} & 0 & \lambda_3^{1L} \lambda_2^{1R} & 0 & -\frac{1}{4} \lambda_3^{1L} \lambda_2^{1R} \\
\Phi_3 & \lambda_3^{3L} \lambda_2^{3L} & 0 & 0 & 0 & 0 \\
\Phi_2 & 0 & 0 & \lambda_2^{2RL} \lambda_3^{2LR} & 0 & \frac{1}{4} \lambda_2^{2RL} \lambda_3^{2LR} \\
\Phi_2' & 0 & 0 & 0 & 0 & 0 \\
\Phi_1' & 0 & 0 & 0 & 0 & 0 \\
\hline
V_1^{\mu} & -2\lambda_3^{1L} \lambda_2^{1L} & 0 & 0 & 4\lambda_3^{1L} \lambda_2^{1R} \lambda_3^{1L} & 0 \\
V_3^{\mu} & 2\lambda_3^{3L} \lambda_2^{3L} & 0 & 0 & 0 & 0 \\
V_2^{\mu} & 0 & 0 & 0 & 4\lambda_2^{2RL} \lambda_3^{2LR} & 0 \\
V_1^{\nu} & 0 & 0 & 0 & 0 & 0 \\
V_2^{\nu} & 0 & 0 & 0 & 0 & 0 \\
\hline
\end{array} \]

Table 4. Contribution of the various LQ representation to \( b \to c \ell \bar{\nu} \). Each entry should be multiplied by a factor \( \frac{\sqrt{2}}{8G_F V_{cb} M_t} \).
Global Fit using flavio

With a single leptoquark

Including $\Delta A_{FB}, \Delta F_L, \Delta S_3, \ R_{D(*)}^{\mu e} = \frac{BR(B \rightarrow D^{(*)}\mu\nu)}{BR(B \rightarrow D^{(*)}e\nu)}, \ldots$

<table>
<thead>
<tr>
<th>Leptoquark</th>
<th>Scenario</th>
<th>SM pull ($\sigma$)</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>SM</td>
<td>–</td>
<td>0.017</td>
</tr>
<tr>
<td>$\Phi_3, V_3^{\mu}$</td>
<td>$C_{VL}^{\mu}$</td>
<td>0.96</td>
<td>0.013</td>
</tr>
<tr>
<td>$\Phi_2$</td>
<td>$C_{SL}^{\mu} = 8.5 \ C_{T}^{\mu}$</td>
<td>1.60</td>
<td>0.017</td>
</tr>
<tr>
<td>$V_2^{\mu}$</td>
<td>$C_{SR}^{\mu}$</td>
<td>1.97</td>
<td>0.019</td>
</tr>
<tr>
<td>$V_1^{\mu}$</td>
<td>$C_{VL}^{\mu}, C_{SR}^{\mu}$</td>
<td>2.28</td>
<td>0.031</td>
</tr>
<tr>
<td>–</td>
<td>$C_{T}^{\mu}$</td>
<td>3.36</td>
<td>0.093</td>
</tr>
<tr>
<td>$\Phi_1$</td>
<td>$C_{VL}^{\mu}, C_{SL}^{\mu} = -8.5 \ C_{T}^{\mu}$</td>
<td>$\boxed{3.92}$</td>
<td>0.240</td>
</tr>
</tbody>
</table>
Global Fit using flavio

With a multiple leptoquarks

Including $\Delta A_{FB}, \Delta F_L, \Delta S_3$, 

$$R_{D(*)}^{\mu e} = \frac{BR(B \to D^{(*)}\mu\nu)}{BR(B \to D^{(*)}e\nu)}, \ldots$$

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SM pull ($\sigma$)</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>$-$</td>
<td>0.017</td>
</tr>
<tr>
<td>$C_{VL}^{\mu}, C_{SL}^{\mu}, C_{SR}^{\mu}, C_{T}^{\mu}$</td>
<td>3.39</td>
<td>0.196</td>
</tr>
<tr>
<td>$C_{VL}^{\mu}, C_{SL}^{\mu}, C_{T}^{\mu}$</td>
<td>3.72</td>
<td>0.237</td>
</tr>
<tr>
<td>$C_{VL}^{\mu}, C_{SL}^{\mu}, C_{SR}^{\mu}$</td>
<td>2.14</td>
<td>0.044</td>
</tr>
<tr>
<td>$C_{SL}^{\mu}, C_{SR}^{\mu}, C_{T}^{\mu}$</td>
<td>3.43</td>
<td>0.174</td>
</tr>
<tr>
<td>$C_{VL}^{\mu}, C_{SL}^{\mu} = -8.5 C_{T}^{\mu}$</td>
<td>3.92</td>
<td>0.240</td>
</tr>
<tr>
<td>$C_{VL}^{\mu}, C_{SL}^{\mu} = 8.5 C_{T}^{\mu}$</td>
<td>2.09</td>
<td>0.037</td>
</tr>
</tbody>
</table>
Global fit

In the $C^\mu_{VL}$ vs $C^\mu_T = -C^\mu_{SL}/8.5$ plane

- Pull with SM $\approx 4\sigma$

- $\Delta F_L, \Delta S_3$ do not allow large deviations in $C^\mu_T = -C^\mu_{SL}/8.5$

- Additional bound from $R^\nu\bar{\nu}_{K^{(*)}}$, which can be lowered by the addition of a triplet scalar leptoquark $\Phi_3$

- $\Phi_1$ and $\Phi_3$ together can explain $R_D^{(*)}, a_\mu$ and $b \to s\ell\ell$ (Crivellin et al. 1703.09226)
Conclusion

- In addition to existing hints at LFUV, and more specifically NP in muons, Bobeth et al. (2104.02094) finds a potential 4σ pull in $\Delta A_{FB} = A_{FB}^{\mu} - A_{FB}^{e}$ with respect to the SM.

- We find that the $SU(2)_L$-singlet LQ $\Phi_1$ is the only scenario that improves significantly the description of data.

- The bound from $R_{K^*}^{\ell\ell}$ and the $R_{D(*)}$ discrepancy call for $\Phi_3$.

- Need reanalysis of Belle 2018 data with full lepton specific correlation matrix.

- More updates are coming soon, eg $R_{D^*}$ at CMS.

Thank you!
Leptoquarks to EFTs

LQ in Weak Effective Theory (WET), eg $SU(2)_L$-singlet scalar $\Phi_1$

\[ \mathcal{H}_{\text{eff}}^{\ell V} = \frac{4G_F}{\sqrt{2}} V_{cb} \left( C_{\delta V L}^\ell O_{\delta V L}^\ell + C_{\delta S L}^\ell O_{\delta S L}^\ell + C_T^\ell O_T^\ell \right) \]

In the SM: $C_{\delta V L}^\mu = 1$, $C_{\delta S L}^\mu = 0$, $C_T^\mu = 0$ at the EW scale

Matching of singlet scalar $\Phi_1$ LQ to this effective Hamiltonian:

\[ C_{\delta V L}^\ell = \frac{\sqrt{2}}{8G_F} \frac{V_{cj} \lambda_{j \ell}^L \lambda_{3 \ell}^L}{M^2}, \quad C_{\delta S L}^\ell = -4C_T^\ell = -\frac{\sqrt{2}}{8G_F} \frac{\lambda_{2 \ell}^R \lambda_{3 \ell}^L}{M^2}. \]

RGE evolution from scale $M$ to $m_b$ provides

\[ \begin{pmatrix} C_{\delta S L}(m_b) \\ C_T^\ell(m_b) \end{pmatrix} \approx \begin{pmatrix} 1.8 & -0.3 \\ 0 & 0.8 \end{pmatrix} \begin{pmatrix} C_{\delta S L}(M) \\ C_T^\ell(M) \end{pmatrix} \]

At the $b$ mass scale this implies $C_{\delta S L}^\ell \approx -8.5C_T^\ell$. 
Log-Likelihood with flavio
A python package for flavour physics

Parameters: $G_F, m_q, V_{CKM}, \ldots$

Wilson Coeff: $WC_j = WC_j^{SM} + WC_j^{NP}$

Theory prediction $\vec{O}^{th}$
Covariance matrix $C_{th}$

Experimental data $\vec{O}^{exp}$ and $C_{exp}$

$\vec{O} = [\Delta A_{FB}, R_{D^*}^{\mu e}, \ldots]$

$-2 \ln \tilde{L}_{exp} = \tilde{x}^T (C_{exp} + C_{th})^{-1} \tilde{x},$

$\tilde{x} = \vec{O}^{exp} - \vec{O}^{th}$

Log-Likelihood
Partial Fit

Theoretical covariance

- Using \texttt{flavio} we compute the likelihood of NP contributions to WCs
- Large theoretical uncertainty for $C^\mu_T, C^\mu_{SL} \neq 0$
- $\Delta A_{FB}$ is independent of $C^\mu_{VL}$ at leading order in NP Wilson Coefficients.
**LQ analysis**

\[ \mathcal{L} = \left( \lambda^L_{fi} \overline{Q}^c_j i \tau_2 L_i + \lambda^R_{fi} \overline{u}^c_j e \ell_i \right) \Phi^{\dagger}_1 + \text{h.c.} \]

- In blue: allowed \( \lambda^L_{32} - \lambda^R_{22} \) in the best fit region from \( b \rightarrow c \ell \nu \), profiling over \( C_{VL} \)

- Strong bound from \( \tau \rightarrow \mu \nu \nu/\tau \rightarrow e \nu \nu \) via \( W \rightarrow \mu \nu \) coupling

\[ \mathcal{L} = \frac{g_2}{\sqrt{2}} \Lambda^W_{22} \left( \overline{\mu} \gamma^\alpha P_L \nu_{\mu} W^-_{\alpha} \right) + \text{h.c.} \]

\[ \Lambda^W_{22} = 1.0018 \pm 0.0014 \]

- Lower limit on LQ mass by CMS and ATLAS leptoquark searches via \( \mu j \) and \( t \tau \) final states respectively
Scalar LQs and \((g - 2)_\mu\)

Effective operator for muon g-2

\[
\mathcal{L} = y \frac{\nu}{M^2} \bar{\mu}_R \sigma^{\mu\nu} \mu_L F_{\mu\nu} + \text{h.c.}
\]

\[
\lambda_{fi}^R \bar{u}_i^c \ell_i \Phi_1^\dagger + \text{h.c.}\ .
\]

In this case the numerically relevant \(m_t\) enhanced contribution to \(a_\mu\) is given by

\[
\delta a_\mu = \frac{m_\mu}{4\pi^2} \text{Re} \left[ C_{R}^{22} \right] ,
\]

with

\[
C_L^{fi} = -\frac{N_c}{12M^2} m_t \lambda_{3f}^R \lambda_{3i}^L \left( 7 + 4 \log \left( \frac{m_t^2}{M^2} \right) \right) ,
\]

and \(C_R^{23}\) is obtained from \(C_L^{23}\) by \(L \leftrightarrow R\). We will assume that \(\lambda_{32}^R\) is small compared to \(\lambda_{32}^L\).