Status of New Physics in Lepton Flavour Universality Violating $B$ Decays

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Flavour in the Standard Model (SM)

- Quark flavour violation described by CKM matrix

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix}
= V_{\text{CKM}}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
= \begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d' \\
    s \\
    b
\end{pmatrix}
\]

- No flavour violating decays in the SM lepton sector
- Lepton flavour universality only violated by the (small) lepton masses

\[m_e \ll m_\mu \ll m_\tau\]

Overall, this simple picture works very well - but...
Recent anomalies in $B$ meson decays

1. $3.8\sigma$ anomaly in semi-tauonic $B$ decays, exhibiting lepton flavour universality violation

2. Various consistent $2 - 3\sigma$ deviations in $b \rightarrow s\mu^+\mu^-$ transitions, leading to a $\sim 5\sigma$ tension in the global fit
Outline

1. Status of the $b \to c\tau\nu$ anomaly
2. Semileptonic $b \to s$ transitions
3. A 5D warped Pati-Salam model
Status of the $b \to c\tau\nu$ anomaly

$b \to c\tau\nu$ – the anomalous trees
The $\mathcal{R}(D^{(*)})$ anomaly

Test of lepton flavour universality in semi-leptonic $B$ decays

\[ \mathcal{R}(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \quad (\ell = e, \mu) \]

- **Theoretically clean**, as hadronic uncertainties largely cancel in ratio
- **Measurements** by BaBar, Belle, and LHCb (so far $\mathcal{R}(D^*)$ only)
- **$3.8\sigma$ tension** between HFLAV fit and SM value
- (Qualitatively) supported by measurement of $\mathcal{R}(J/\psi)$ (LHCb)
Related $b \rightarrow c\tau\nu$ observables

- **ratio of baryonic decay rates**

  $$\mathcal{R}(\Lambda_c) = \frac{BR(\Lambda_b \rightarrow \Lambda_c\tau\nu)}{BR(\Lambda_b \rightarrow \Lambda_c\ell\nu)} \quad (\ell = e, \mu)$$

- **longitudinal $D^*$ polarisation**

  $$F_L(D^*) = \frac{\Gamma(B \rightarrow D^*_L\tau\nu)}{\Gamma(B \rightarrow D^*\tau\nu)}$$

  - Belle: $0.60 \pm 0.08 \pm 0.035$
  - SM: $0.46 \pm 0.04$

- **$\tau$ polarisation asymmetries**

  $$P_\tau(D^{(*)}) = \frac{\Gamma(B \rightarrow D^{(*)}\tau^{\lambda=+1/2}\nu) - \Gamma(B \rightarrow D^{(*)}\tau^{\lambda=-1/2}\nu)}{\Gamma(B \rightarrow D^{(*)}\tau\nu)}$$

- **$BR(B_c \rightarrow \tau\nu)$** – particularly sensitive to scalar contributions
Status of the $b \to c\tau\nu$ anomaly

The Crew

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić
arXiv:1811.09603
A closer look at $B_c \rightarrow \tau \nu$

Constraints on $\text{BR}(B_c \rightarrow \tau \nu)$ advocated in the literature:

- measured total $B_c$ lifetime $\Rightarrow \text{BR}(B_c \rightarrow \tau \nu) < 30\%$
  
  **Alonso, Grinstein, Martin Camalich (2016)**

  **caveats of $\tau_{B_c}$ theory prediction**

- large $m_c$ dependence (LO QCD calculation, $1.4 \text{ GeV} < m_c < 1.6 \text{ GeV}$)
- based on heavy quark expansion and non-rel. QCD, but $B_c$ decays dominantly through charm decay

A closer look at $B_c \rightarrow \tau \nu$

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  Alonso, Grinstein, Martin Camalich (2016)

- searches for $B_{u,c} \rightarrow \tau \nu$ at LEP1 $\Rightarrow \text{BR}(B_c \rightarrow \tau \nu) < 10\%$
  
  Akeroyd, Chen (2017)

Caveats of theory interpretation

- relies crucially on ratio of $b \rightarrow B_c$ vs. $b \rightarrow B_u$ fragmentation functions

- Tevatron and LHC determinations of $f_c/f_u$ not applicable to LEP (hadron collisions vs. $Z$ peak observables)
A closer look at $B_c \rightarrow \tau \nu$

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Critical assessment:

- more refined studies needed
- our conservative bound: $\text{BR}(B_c \rightarrow \tau \nu) < 60\%$

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)
Effective Hamiltonian

New Physics above $B$ meson scale described model-independently by

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = 2\sqrt{2}G_F V_{cb} \left[ (1 + C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T \right]$$

with the vector, scalar and tensor operators

$$O_V^L = (\bar{c}\gamma_\mu P_L b) (\bar{\tau}\gamma_\mu P_L \nu_\tau)$$
$$O_S^R = (\bar{c}P_R b) (\bar{\tau} P_L \nu_\tau)$$
$$O_S^L = (\bar{c}P_L b) (\bar{\tau} P_L \nu_\tau)$$
$$O_T = (\bar{c}\sigma_{\mu\nu} P_L b) (\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau)$$

**Note:** $(\bar{c}\gamma_\mu P_R b) (\bar{\tau}\gamma_\mu P_L \nu_\tau)$ not generated at dimension-six level in the $SU(2)_L \times U(1)_Y$-invariant theory
One-dimensional scenarios

**single particle scenarios**

\( C^L_V \)
- left-handed \( W' \) boson
- left-handed SU(2)\(_L\)-singlet vector leptoquark (LQ)
- scalar SU(2)\(_L\)-triplet and/or -singlet LQ (LH couplings only)

\( C^R_S \)
- charged Higgs (2HDM-II at large \( \tan \beta \))
- SU(2)\(_L\)-doublet vector LQ

\( C^L_S \)
- charged Higgs with generic flavor structure

\( C^L_S = 4C_T \)
- scalar SU(2)\(_L\)-doublet (relation at NP scale, modified by RG effects)
One-dimensional fit results

MB, Crivel lin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

- best fit for $C_V^L \sim 0.11$
- small impact of $F_L(D^*)$ measurement (solid vs. dashed)
- large impact of $\text{BR}(B_c \to \tau \nu)$ on scalar scenarios
Two-dimensional scenarios

\[(C_L^V, C_S^L = -4C_T)\]  
SU(2)_L-singlet scalar LQ

\[(C_L^V, C_S^R)\]  
SU(2)_L-singlet vector LQ

\[(C_S^R, C_S^L)\]  
charged Higgs

\[(\text{Re}[C_S^L = 4C_T], \text{Im}[C_S^L = 4C_T])\]  
scalar SU(2)_L-doublet LQ with CP-violating couplings
Two-dimensional fit results (I)

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

- good fit for both \((C^L_V, C^L_S = -4C_T)\) and \((C^L_V, C^R_S)\)
- small impact of \(\text{BR}(B_c \to \tau \nu)\) constraint
very good fit for \((C^R_S, C^L_S)\), but only allowed for \(\text{BR}(B_c \to \tau\nu) < 60\%\)

- good fit for \((C^L_S = 4C_T)\), unless \(\text{BR}(B_c \to \tau\nu) < 10\%\) is imposed
The $\Lambda_b \rightarrow \Lambda_c \tau \nu$ sum rule

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

From the phenomenological expressions for $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$, we derive an approximate sum rule:

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{SM}(\Lambda_c)} \simeq 0.262 \frac{\mathcal{R}(D)}{\mathcal{R}_{SM}(D)} + 0.738 \frac{\mathcal{R}(D^*)}{\mathcal{R}_{SM}(D^*)} + \mathcal{O}(10^{-2})$$

- enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{SM}(\Lambda_c) = 0.33 \pm 0.01$
- model-independent prediction from current $\mathcal{R}(D^{(*)})$ data:

$$\mathcal{R}(\Lambda_c) = 0.41 \pm 0.02 \mathcal{R}(D^{(*)}) \pm 0.01 \text{form factors}$$

- experimental cross-check of $\mathcal{R}(D^{(*)})$ anomaly
Summary: Where do we stand in $b \rightarrow c\tau\nu$?

MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

- updated 1D and 2D fits, including recent $F_L(D^*)$ measurement
  - 1D: best fit for $C_L^V \neq 0$
  - 2D: decent fit for all scenarios
  - large impact of $\text{BR}(B_c \rightarrow \tau\nu)$ limit on scalar scenarios

- $\Lambda_b \rightarrow \Lambda_c\tau\nu$ provides experimental cross-check of $\mathcal{R}(D^{(*)})$ anomaly

- [not shown here due to lack of time] polarisation observables well suited to distinguish among different EFT scenarios
- requires better understanding of form factors
\( b \rightarrow s\mu\mu \) – the anomalous penguins
The $b \to s \mu^+ \mu^-$ transitions and LFU

**Semileptonic $b \to s$ transitions**

The $b \to s \mu^+ \mu^-$ transitions and LFU showing consistent NP pattern.
The $b \to s \mu^+ \mu^-$ transitions and LFU

Various $2 - 3\sigma$ tensions showing consistent NP pattern
Theoretical description

$b \rightarrow s\ell^+\ell^-$ and $b \rightarrow s\gamma$ transitions described by effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O} + C'_i \mathcal{O}' \right) + \text{h.c.}$$

where the operators most sensitive to new physics are

$$\mathcal{O}_7^{(i)} = b_{R(L)} s_{L(R)} \gamma$$

$$\mathcal{O}_{9,10}^{(i)} = b_{L(R)} s_{L(R)} \ell_{L,R}$$

$$\mathcal{O}_{S,P}^{(i)} = b_{R(L)} s_{L(R)} \ell_{L,R}$$

SM: $W, Z$
Semileptonic $b \to s$ transitions

Global analysis

ALTSMANNSHOFER, STANGL, STRAUB (2017)
see also CAPDEVILA ET AL. (2017)

↗ consistent fit for $C^\text{NP}_9 \sim -1$, non-zero $C^\mu\nu^\text{NP}_9$, $C^{\text{NP}}_{10}$ possible
$\sim 5\sigma$ deviation from SM!
Yet not quite global experimentally

Capdevila et al. (2017)
see also Altmannshofer, Stangl, Straub (2017)

➢ dominated by LHCb – we need independent cross-check!
Who ordered that?

Altmannshofer, Straub (2013); Hiller, Schmaltz (2014)
Altmannshofer et al. (2014); Altmannshofer, Carena, Crivellin (2016)
D’Amico et al. (2017); Di Chiara et al. (2017)

The usual suspects: $Z'$ and leptoquarks

- tree level NP competing with SM one-loop diagrams
- constraints from $B_s - \bar{B}_s$ mixing can be accomodated
- potential relation to $(g - 2)_\mu$ anomaly
**Loop induced NP?**

**Large $C_9^{NP}$ as model-killer**

- new contributions to $Z$ penguin (e.g. in the MSSM) don’t yield required NP pattern – also no LFU violation

**Viable setups**

- $Z'$ penguin effect
  - **Altmanshofer, Straub (2013)**

- box contribution
  - **Belanger, Delaunay, Westhoff (2015)**
  - **Kamenik, Soreq, Zupan (2017)**
  - **Gripaios, Nardecchia, Renner (2015); Arnan et al. (2016)**
A combined resolution of the $B$ decay anomalies?

- several attempts to attribute the $B$ decay anomalies to a \textit{common} NP origin
  - Barbieri, Murphy, Senia (2016); Crivellin, Müller, Ota (2017)
  - Becirevic, Dorsner, Fajfer, Faroughy, Kosnik, Sumensari (2018)
  - Di Luzio, Greljo, Nardecchia (2017); Calibbi, Crivellin, Li (2017)

- $SU(2)_L$ singlet vector leptoquark appears most promising:
  - evades stringent constraints from $B_s$ mixing and $b \rightarrow s\nu\bar{\nu}$
  - $B_c$ life-time under control

Model building challenges

- identify UV origin of such vector LQ
- generate flavour non-universal LQ couplings
- avoid re-introduction of constraints due to additional particles present in UV-complete model
Let’s go model-building!
The Pati-Salam vector leptoquark

Prime BSM candidate for simultaneous explanation: 
$SU(2)_L$ singlet vector leptoquark with LH couplings to fermions

- no tree level contributions to $B_s - \bar{B}_s$ mixing and $b \rightarrow s\nu\bar{\nu}$ transitions
- purely left-handed coupling structure favoured by
  - global $b \rightarrow s\mu^+\mu^-$ fits
  - total $B_c$ lifetime
  - $B \rightarrow D\tau\nu$ differential rate

Towards UV-complete model
Vector LQ arising from Pati-Salam gauge group

$SU(4) \times SU(2)_L \times SU(2)_R$

has the right gauge quantum numbers!

Challenge: flavour non-universal couplings to fermions
A 5D warped Pati-Salam model

The Crew

MB, Crivellin – PRL 121 (2018) no.1, 011801
The Crew

Mont Blanc

Monika Blanke

MB, Crivellin – PRL 121 (2018) no.1, 011801
A 5D warped Pati-Salam model

Pati-Salam in the Randall-Sundrum background

**Idea:**

embed Pati-Salam model into the 5D Randall-Sundrum space-time

\[ ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2 \quad 0 \leq y \leq L \]

- extra space-time coordinate \( y \)
  confined to interval \( 0 \leq y \leq L \),
  and warped by \( e^{-2ky} \) factor

- 4D Kaluza-Klein (KK) decomposition
  - towers of massive KK modes localized near IR brane
  - massless zero modes depending on boundary conditions
    ➢ identified with SM particles

MB, Crivellin (2018)

Randall, Sundrum (1999)
Gauge symmetry breaking pattern

Two step symmetry breaking pattern

1. Pati-Salam gauge symmetry in the 5D bulk, broken by boundary conditions on the UV brane

\[ SU(4) \times SU(2)_L \times SU(2)_R \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \]

2. SM Higgs confined to the UV brane induces EW symmetry breaking

\[ SU(2)_L \times U(1)_Y \rightarrow U(1)_{em} \]

- Higgs decoupled from KK modes at IR brane
- Stringent EW precision constraints are evaded
- Yukawa couplings need to respect SM gauge symmetry only
- \textit{but}: usual RS solution to gauge and flavour hierarchy problems lost
Fermion sector

- fermions as 5D bulk fields in complete PS representations

\[
\begin{pmatrix}
  u_1^L & u_2^L & u_3^L & \nu_L \\
  d_1^L & d_2^L & d_3^L & \ell_L
\end{pmatrix} \sim (4, 2, 1) \quad \begin{pmatrix}
  u_1^R & u_2^R & u_3^R & \nu_R \\
  d_1^R & d_2^R & d_3^R & \ell_R
\end{pmatrix} \sim (4, 1, 2)
\]

- massless zero modes correspond to SM fermions

- zero mode localization along extra dimension \( y \) depends exponentially on 5D bulk mass parameter \( c = m_{5D}/k \)

- non-universal couplings to KK modes

\[ B \text{ anomalies require} \]

- hierarchical localization of LH fermions: \( c_{L1} > c_{L2} > c_{L3} \)

- RH fermions localized at UV brane
The 4D composite dual

AdS/CFT correspondence: dual 4D composite model

- elementary sector with SM gauge group
- elementary Higgs field
- composite sector with Pati-Salam global symmetry
- left-handed fermions partially composite – linear mixing of SM fermions with composite resonances: $0 \sim s_{1}^{q,\ell} \ll s_{2}^{q,\ell} \ll s_{3}^{q,\ell} \sim 1/\sqrt{2}$
- right-handed fermions (mostly) elementary
The 4D composite dual

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Simplified model: keep only SM fields + lowest-lying KK modes

- common mass scale \(M_{KK}\) for all new particles
- massive vector resonances for entire PS gauge group
- massive vectorlike fermions that mix with SM fermions
LHC constraints

strongest constraints from searches for $t\bar{t}$ and $\tau\bar{\tau}$ resonances

for our model: $M_{KK} \geq 3$ TeV
Flavour alignment

- generically, KK modes of gluons, $B - L$ gauge boson and $W^3_L$ mediate tree level FCNCs
  - reintroduces problematic contributions to meson mixings and $b \rightarrow s \nu \bar{\nu}$
- avoided by imposing flavour alignment between elementary-composite mixing (=5D bulk masses) and $Y_d$
  - no tree level FCNCs in the down sector
  - relevant tree level contribution to $D^0 - \bar{D}^0$ mixing (CKM)

- resulting leptoquark coupling matrix

\[
\Gamma^{LQ,L}_{d_i \ell_j} = \frac{ig^*_s}{\sqrt{2}} \begin{pmatrix}
0 & 0 & 0 \\
0 & s^q_2 s^\ell_2 c_\ell & s^q_2 s^\ell_2 s_\ell \\
0 & -s^q_3 s^\ell_3 s_\ell & s^q_3 s^\ell_3 2c_\ell
\end{pmatrix}_{ij}
\]

$u_i \nu_{\bar{j}}$ coupling includes additional CKM rotation
Important tree level effects

\[ b \rightarrow s \mu^+ \mu^- \]
**Important tree level effects**

\[ b \rightarrow s\mu^+\mu^- \]

\[ b \rightarrow c\tau\nu \]
Important tree level effects

$b \rightarrow s \mu^+ \mu^-$

$b \rightarrow c \tau \nu$

$\tau \rightarrow 3 \mu$

\[ V_{LQ} \]

\[ Z' \]

\[ W' \]
Can we resolve the $B$ decay anomalies?

Benchmark point:

- $M = 3$ TeV
- $s_2^\ell = 0.2$
- $s_3^\ell = 1/\sqrt{2}$
- $s_3^q = \sqrt{3}/2$

$\mathit{b \rightarrow s \mu^+ \mu^-}$ data can be explained at the $1\sigma$ level

- $\mathcal{R}(X)/\mathcal{R}(X)_{SM} \approx 1.07$ (with $X = D, D^*, J/\Psi$)
Can we resolve the $B$ decay anomalies?

Parameter scan:
$M = 3 \text{ TeV}$

- $0.3 < s_3^q < \frac{\sqrt{3}}{2}$
- $0 < s_2^q < 0.2$
- $0.3 < s_3^\ell < \frac{\sqrt{3}}{2}$
- $0 < s_2^\ell < 0.2$
- $0 < s_\ell < 0.3$

imposing $D - \bar{D}$ mixing constraint

- $b \rightarrow s \mu^+ \mu^-$ tension can be resolved
- $b \rightarrow c \tau \nu$ tension can be ameliorated
- observable rate for $\tau \rightarrow 3\mu$ predicted
Conclusions

- **B decay anomalies** still give one of the best hints for BSM physics

- Theoretically appealing common solution by $SU(2)_L$ singlet vector leptoquark

- Possible UV-completion in terms of Pati-Salam model in the Randall-Sundrum background