Status of New Physics in Lepton Flavour Universality Violating B Decays

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Particle Physics Phenomenology after the Higgs Discovery

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Flavour in the Standard Model (SM)

- Quark flavour violation described by CKM matrix

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

- 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. 3.8σ anomaly in semi-tauonic B decays, exhibiting lepton flavour universality violation
2. various *consistent* $2-3\sigma$ deviations in $b \to s\mu^+\mu^-$ transitions, leading to a $\sim 5\sigma$ tension in the global fit

Outline

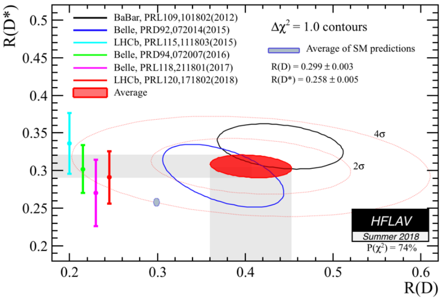
1. Status of the $b \to c\tau\nu$ anomaly
2. Semileptonic $b \to s$ transitions
3. A 5D warped Pati-Salam model

$b \to c\tau\nu$ – the anomalous trees

The $\mathcal{R}(D^{(*)})$ anomaly

Test of lepton flavour universality in semi-leptonic B decays

$$\mathcal{R}(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$



- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb (so far $\mathcal{R}(D^*)$ only)
- 3.8σ tension between HFLAV fit and SM value
- (qualitatively) supported by measurement of $\mathcal{R}(J/\psi)$ (LHCb)

Related $b \to c\tau\nu$ observables

- **ratio of baryonic decay rates**

$$\mathcal{R}(\Lambda_c) = \frac{\text{BR}(\Lambda_b \to \Lambda_c \tau\nu)}{\text{BR}(\Lambda_b \to \Lambda_c \ell\nu)} \qquad (\ell = e, \mu)$$

- **longitudinal D^* polarisation**

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

$$\text{Belle}: \; 0.60 \pm 0.08 \pm 0.035$$
$$\text{SM}: \; 0.46 \pm 0.04$$

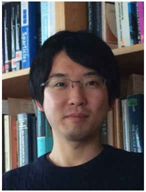
- **τ polarisation asymmetries**

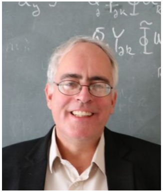
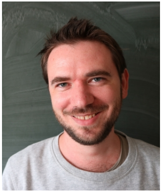
$$P_\tau(D^{(*)}) = \frac{\Gamma(B \to D^{(*)} \tau^{\lambda=+1/2}\nu) - \Gamma(B \to D^{(*)} \tau^{\lambda=-1/2}\nu)}{\Gamma(B \to D^{(*)} \tau\nu)}$$

- **BR($B_c \to \tau\nu$)** – particularly sensitive to scalar contributions

The Crew



MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić
arXiv:1811.09603

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

Constraints on BR($B_c \to \tau\nu$) advocated in the literature:

- measured total B_c lifetime ➢ **BR($B_c \to \tau\nu$) $< 30\%$**

  Alonso, Grinstein, Martin Camalich (2016)

  caveats of τ_{B_c} theory prediction — Beneke, Buchalla (1996)

  - 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

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- searches for $B_{u,c} \to \tau\nu$ at LEP1 ➢ **BR($B_c \to \tau\nu$) $< 10\%$**

  Akeroyd, Chen (2017)

  caveats of theory interpretation

  - relies crucially on ratio of $b \to B_c$ vs. $b \to B_u$ fragmentation functions
  - Tevatron and LHC determinations of f_c/f_u not applicable to LEP (hadron collisions vs. Z peak observables)

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Critical assessment:

- more refined studies needed
- our conservative bound: **BR$(B_c \to \tau\nu) < 60\%$**

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

Effective Hamiltonian

New Physics above B meson scale described model-independently by

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

with the vector, scalar and tensor operators

$$\begin{aligned} O_V^L &= (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \\ O_S^R &= (\bar{c}P_R b)\,(\bar{\tau}P_L \nu_\tau) \\ O_S^L &= (\bar{c}P_L b)\,(\bar{\tau}P_L \nu_\tau) \\ O_T &= (\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L \nu_\tau) \end{aligned}$$

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

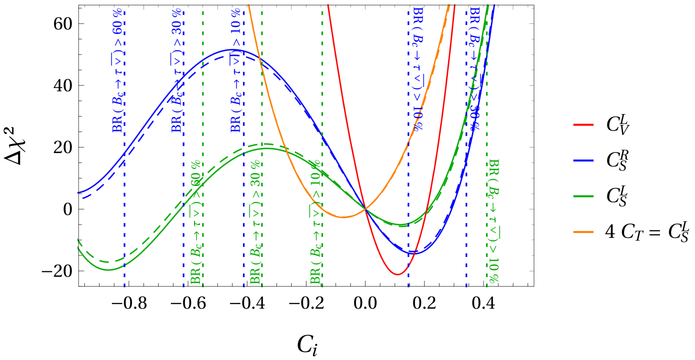
One-dimensional scenarios

single particle scenarios

C_V^L	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_S^R	charged Higgs (2HDM-II at large $\tan\beta$) SU$(2)_L$-doublet vector LQ
C_S^L	charged Higgs with generic flavor structure
$C_S^L = 4C_T$	scalar SU$(2)_L$-doublet (relation at NP scale, modified by RG effects)

One-dimensional fit results

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



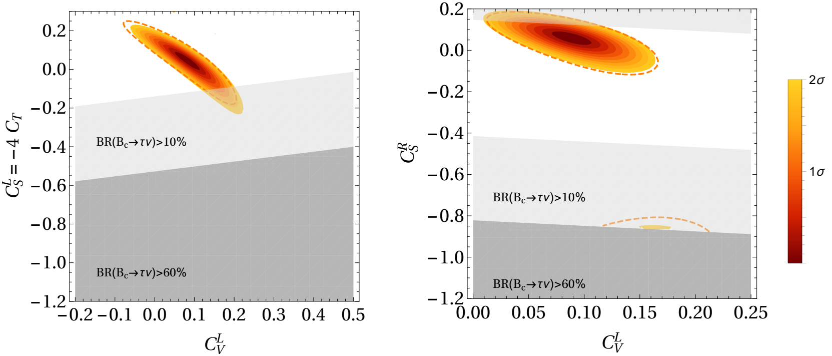
- best fit for $C_V^L \sim 0.11$
- small impact of $F_L(D^*)$ measurement (solid vs. dashed)
- large impact of BR$(B_c \to \tau\nu)$ on scalar scenarios

Two-dimensional scenarios

	single particle scenarios
$(C_V^L, C_S^L = -4C_T)$	$\mathrm{SU}(2)_L$-singlet scalar LQ
(C_V^L, C_S^R)	$\mathrm{SU}(2)_L$-singlet vector LQ
(C_S^R, C_S^L)	charged Higgs
$(\mathrm{Re}[C_S^L = 4C_T],$ $\mathrm{Im}[C_S^L = 4C_T])$	scalar $\mathrm{SU}(2)_L$-doublet LQ with CP-violating couplings

Two-dimensional fit results (I)

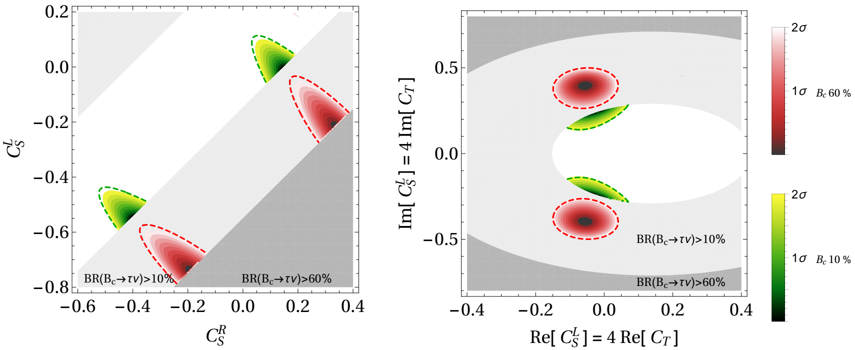
MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)



- good fit for both $(C_V^L,\, C_S^L = -4C_T)$ and $(C_V^L,\, C_S^R)$
- small impact of BR$(B_c \to \tau\nu)$ constraint

Two-dimensional fit results (II)

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



- very good fit for (C_S^R, C_S^L), but only allowed for $\text{BR}(B_c \to \tau\nu) < 60\%$
- good fit for $(C_S^L = 4C_T)$, unless $\text{BR}(B_c \to \tau\nu) < 10\%$ is imposed

The $\Lambda_b \to \Lambda_c \tau\nu$ 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**:

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

- enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\rm SM}(\Lambda_c) = 0.33 \pm 0.01$
- 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 $b \to c\tau\nu$?

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

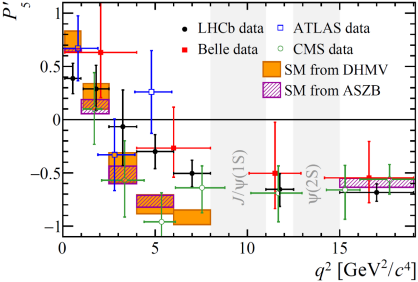
- updated 1D and 2D fits, including recent $F_L(D^*)$ measurement
  - 1D: best fit for $C_V^L \neq 0$
  - 2D: decent fit for all scenarios
  - large impact of BR$(B_c \to \tau\nu)$ limit on scalar scenarios

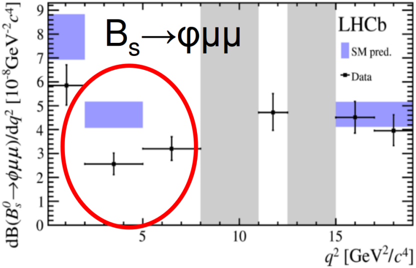
- $\Lambda_b \to \Lambda_c\tau\nu$ provides experimental cross-check of $\mathcal{R}(D^{(*)})$ anomaly

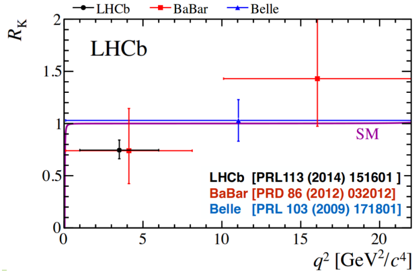
- **[not shown here due to lack of time]** polarisation observables well suited to distinguish among different EFT scenarios
  - requires better understanding of form factors

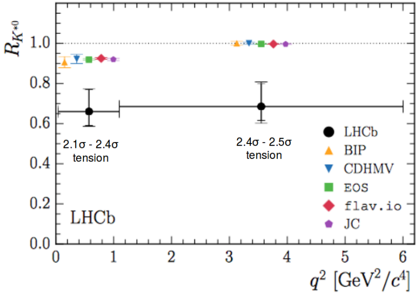
$b \to s\mu\mu$ – the anomalous penguins

The $b \to s\mu^+\mu^-$ transitions and LFU

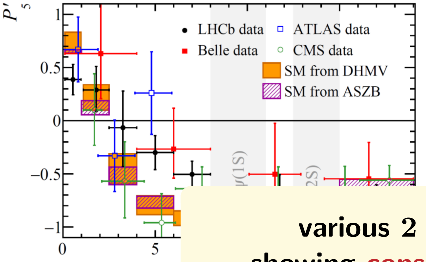


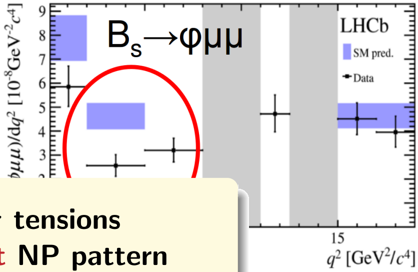




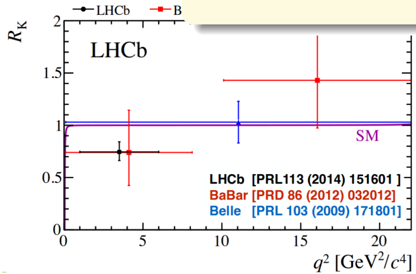


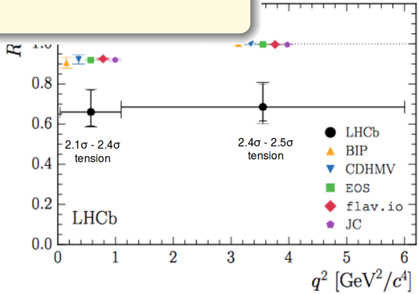
The $b \to s\mu^+\mu^-$ transitions and LFU





various $2-3\sigma$ tensions
showing consistent NP pattern





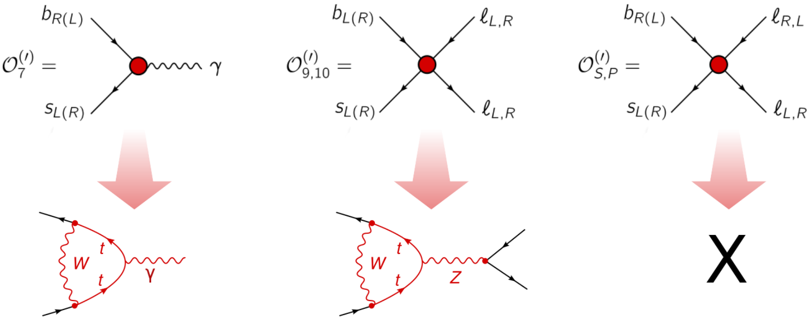
Theoretical description

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

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

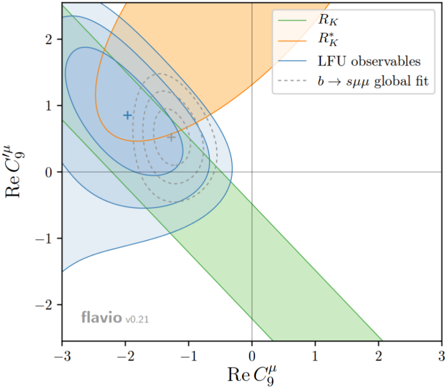
where the operators most sensitive to new physics are

SM:



Global analysis

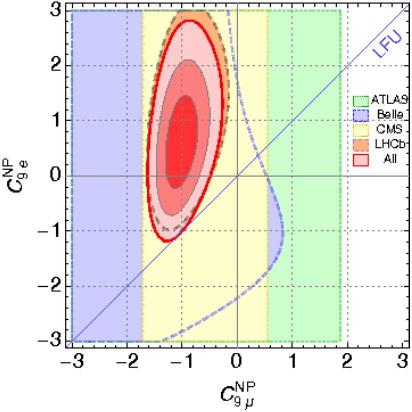
ALTMANNSHOFER, STANGL, STRAUB (2017)
see also CAPDEVILA ET AL. (2017)



➢ **consistent fit for $C_9^{\mathrm{NP}} \simeq -1$**, non-zero $C_9'^{\mathrm{NP}}$, C_{10}^{NP} possible
$\sim 5\sigma$ deviation from SM!

Yet not quite global experimentally

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

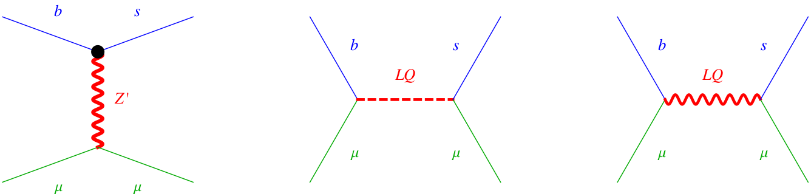


➢ **dominated by LHCb – we need independent cross-check!**

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

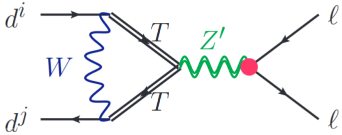
Loop induced NP?

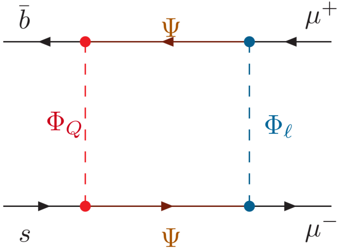
Large C_9^{NP} as model-killer Altmannshofer, Straub (2013)

- 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 — Bélanger, Delaunay, Westhoff (2015); Kamenik, Soreq, Zupan (2017)
- box contribution — 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 *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)
Bordone, Cornella, Fuentes-Martin, Isidori (2017); Marzocca (2018) ...

- $SU(2)_L$ singlet vector leptoquark appears most promising:
  - ➢ evades stringent constraints from B_s mixing and $b \to s\nu\bar{\nu}$
  - ➢ 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 $b \to s\nu\bar{\nu}$ transitions
- purely left-handed coupling structure favoured by
  - global $b \to s\mu^+\mu^-$ fits
  - total B_c lifetime
  - $B \to D\tau\nu$ differential rate

Towards UV-complete model
Vector LQ arising from Pati-Salam gauge group — Pati, Salam (1974)

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

has the right gauge quantum numbers!

Challenge: flavour non-universal couplings to fermions

The Crew

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

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

Pati-Salam in the Randall-Sundrum background

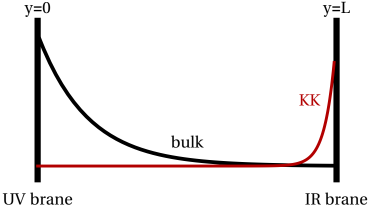
Idea: MB, Crivellin (2018)

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

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \qquad 0 \leq y \leq L$$

Randall, Sundrum (1999)

- 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



Gauge symmetry breaking pattern

Two step symmetry breaking pattern MB, Crivellin (2018)

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

$$SU(4) \times SU(2)_L \times SU(2)_R \to SU(3)_c \times SU(2)_L \times U(1)_Y$$

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

$$SU(2)_L \times U(1)_Y \to U(1)_{\text{em}}$$

- Higgs decoupled from KK modes at IR brane
- stringent EW precision constraints are evaded
- Yukawa couplings need to respect SM gauge symmetry only
- *but:* usual RS solution to gauge and flavour hierarchy problems lost

Fermion sector

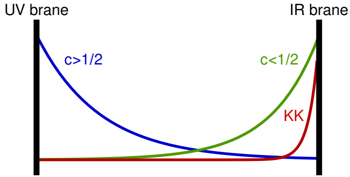
- fermions as 5D bulk fields in complete PS representations

$$\begin{pmatrix} u_L^1 & u_L^2 & u_L^3 & \nu_L \\ d_L^1 & d_L^2 & d_L^3 & \ell_L \end{pmatrix} \sim (4,2,1) \qquad \begin{pmatrix} u_R^1 & u_R^2 & u_R^3 & \nu_R \\ d_R^1 & d_R^2 & d_R^3 & \ell_R \end{pmatrix} \sim (4,1,2)$$

➢ massless zero modes correspond to SM fermions

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

➢ non-universal couplings to KK modes



***B* 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
- conposite 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

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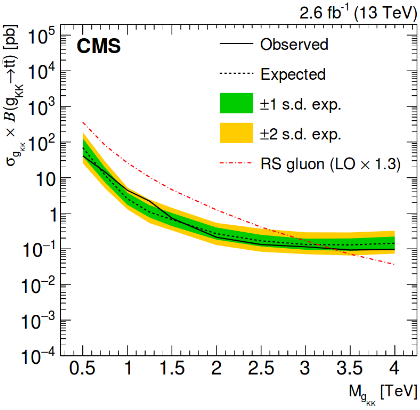
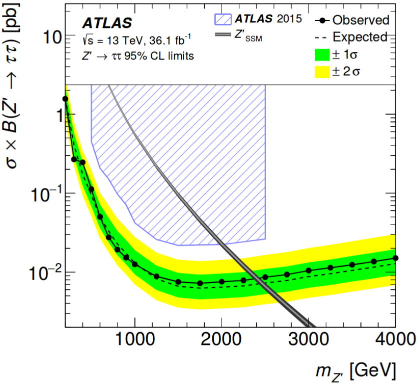
Simplified model: keep only SM fields + lowest-lying KK modes

- 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: $M_{\text{KK}} \geq 3\,\text{TeV}$

Flavour alignment

- generically, KK modes of gluons, $B-L$ gauge boson and W_L^3 mediate tree level FCNCs
  - ➢ reintroduces problematic contributions to meson mixings and $b \to s\nu\bar{\nu}$
- 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)

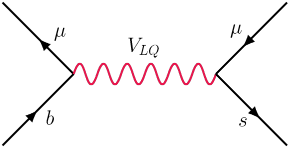
- resulting leptoquark coupling matrix

$$\Gamma^{LQ,L}_{d_i \ell_j} = \frac{i g_s^*}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_2^q s_2^\ell c_\ell & s_2^q s_2^\ell s_\ell \\ 0 & -s_3^q s_3^\ell s_\ell & s_3^q s_3^\ell 2 c_\ell \end{pmatrix}_{ij}$$

$u_i \nu_j$ coupling includes additional CKM rotation

Important tree level effects

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



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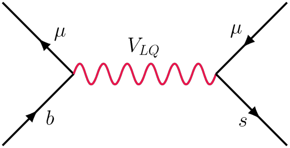
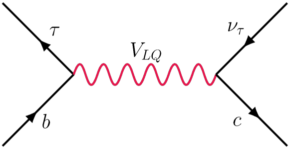
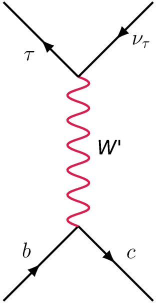


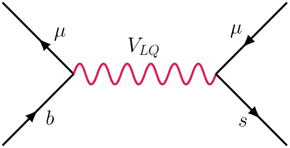
$b \to c\tau\nu$



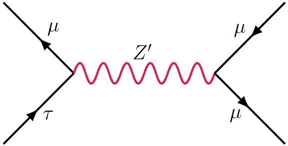


Important tree level effects

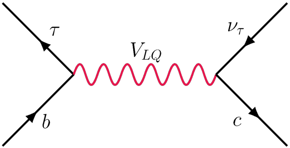
$b \to s\mu^+\mu^-$

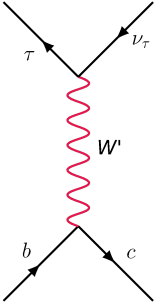


$\tau \to 3\mu$

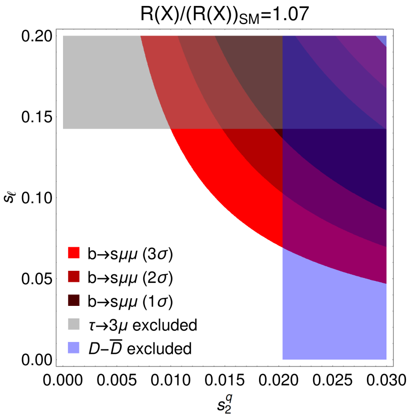


$b \to c\tau\nu$





Can we resolve the B decay anomalies?



MB, Crivellin (2018)

Benchmark point:

$M = 3$ TeV

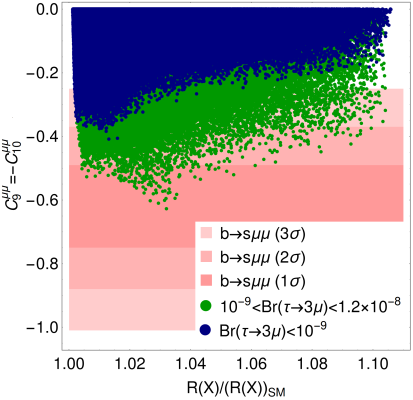
$s_2^\ell = 0.2$

$s_3^\ell = 1/\sqrt{2}$

$s_3^q = \sqrt{3}/2$

- ➢ $b \to s\mu^+\mu^-$ data can be explained at the $1\,\sigma$ level
- ➢ $\mathcal{R}(X)/\mathcal{R}(X)_{\rm SM} \approx 1.07$ (with $X = D, D^*, J/\Psi$)

Can we resolve the B decay anomalies?



MB, Crivellin (2018)

Parameter scan:

$M = 3$ TeV

$0.3 < s_3^q < \sqrt{3}/2$

$0 < s_2^q < 0.2$

$0.3 < s_3^\ell < \sqrt{3}/2$

$0 < s_2^\ell < 0.2$

$0 < s_\ell < 0.3$

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

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