New physics implications from the B-meson anomalies

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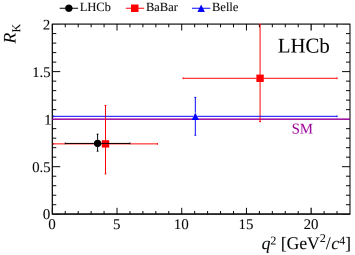
B-meson anomalies: R_K and R_{K*}

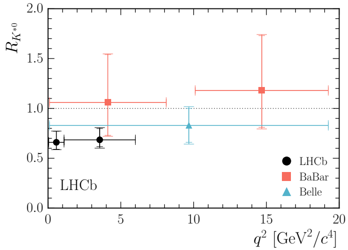


$$R_K \equiv \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to K e^+ e^-)}$$

$$= 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

$(1\ \text{GeV}^2 < q^2 < 6\ \text{GeV}^2)$.

2.6σ LHCb, PRL 113, 151601 (2014)

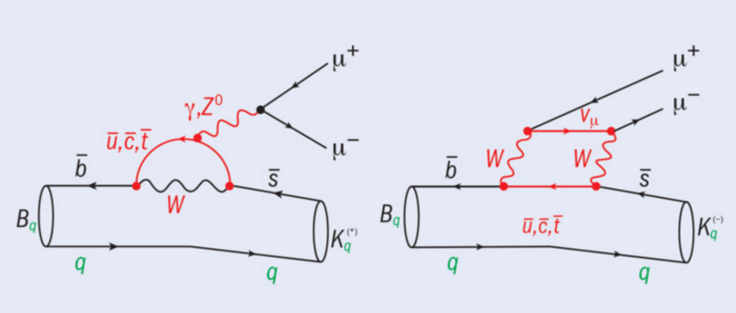


$$R_{K*} \equiv \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)}$$

$$= \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}) \\ (0.045\ \text{GeV}^2 < q^2 < 1.1\ \text{GeV}^2), \\ 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}) \\ (1.1\ \text{GeV}^2 < q^2 < 6.0\ \text{GeV}^2). \end{cases}$$

2.5σ LHCb, JHEP 08, 055 (2017)

B-meson anomalies: R_K and R_{K*}



- Assuming the lepton flavor universality (LFU),

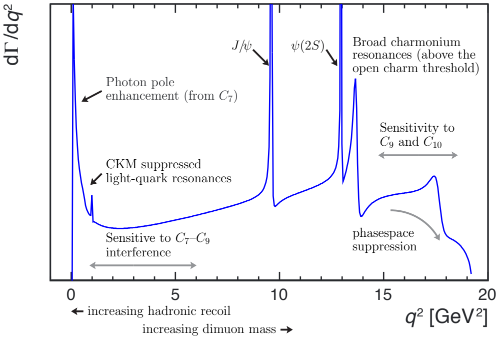
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 + \mathcal{O}(m_\mu^2/m_b^2)$$

- Theoretical predictions in the SM for $R_{K^{(*)}}$ are very accurate: hadronic uncertainties cancel.
  - Theoretical uncertainties are $\mathcal{O}(1\%)$ (M. Bordone et al, arXiv:1605.07633).

B-meson anomalies: effective operators

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i,\ell} \left(\mathcal{C}_i^\ell \mathcal{O}_i^\ell + \mathcal{C}_i^{\prime\ell} \mathcal{O}_i^{\prime\ell} \right) + \text{h.c.}$$

- vector coupling: $\mathcal{O}_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$, $\mathcal{O}_9^{\prime\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$,
- axialvector coupling: $\mathcal{O}_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)$, $\mathcal{O}_{10}^{\prime\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)$.



T. Blake et al, arXiv:1606.00916

B-meson anomalies: effective operators

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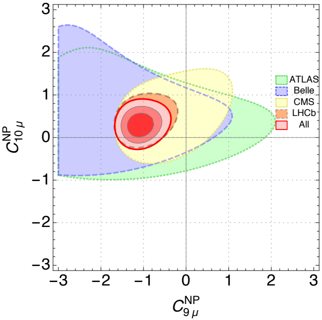
Global fit results (B. Capdevila, arXiv:1704.05340):

$$\mathcal{C}_9^\mu = -1.11 \quad \text{or}$$

$$(\mathcal{C}_9^\mu, \mathcal{C}_{10}^\mu) = (-1.01, 0.29).$$



B-meson anomalies: effective operators

$$\mathcal{H}_{\mathrm{eff}}^{\mathrm{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i,\ell} \left(\mathcal{C}_i^\ell \mathcal{O}_i^\ell + \mathcal{C}_i'^\ell \mathcal{O}_i'^\ell \right) + \mathrm{h.c.}$$

For an effective Hamiltonian,

$$\mathcal{H}_{\mathrm{eff}}^{\mathrm{NP}} = -\sum_i \frac{1}{\Lambda_i^2} \mathcal{O}_i^\ell$$

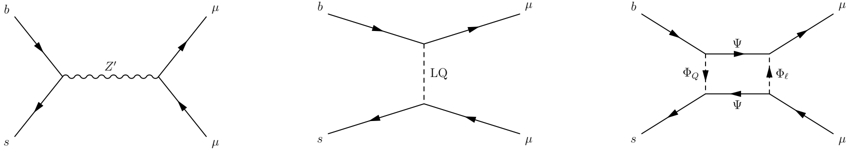
we find

$$\Lambda_i = \frac{4\pi}{e} \frac{1}{\sqrt{|V_{tb} V_{ts}^*|}} \frac{1}{\sqrt{|\mathcal{C}_i|}} \frac{v}{\sqrt{2}} \simeq \frac{35\ \mathrm{TeV}}{\sqrt{|\mathcal{C}_i|}}.$$

- For $|C_i| = \mathcal{O}(1)$,

$$\boxed{\Lambda_{\mathrm{NP}} \lesssim 35\ \mathrm{TeV}}$$

B-meson anomalies: new physics models



Z' Leptoquark Loop mediators

- Flavored Z' model:

$$-\mathscr{L}_{Z'} \supset \left(g_L^{sb} Z'_\rho \bar{s}\gamma^\rho P_L b + \text{h.c.}\right) + g_L^{\mu\mu} Z'_\rho \bar{\mu}\gamma^\rho P_L \mu$$

- Leptoquark model (For S_3 being $(\bar{3}, 3, 1/3)$ triplet scalar):

$$-\mathscr{L}_{\text{LQ}} \supset y_3 QLS_3 + y_q QQS_3^\dagger + \text{h.c.}$$

- Loop mediators (For a fermion Ψ and two scalars Φ_Q and Φ_ℓ):

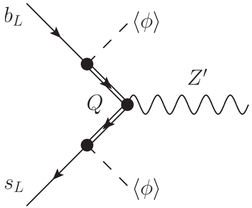
$$-\mathscr{L}_{\text{int}} \supset \Gamma_i^Q \bar{Q}_i P_R \Psi \Phi_Q + \Gamma_i^L \bar{L}_i P_R \Psi \Phi_\ell + \text{h.c.}$$

See G. D'Amico et al, arXiv:1704.05438 and references therein.

B-meson anomalies: flavored Z' models

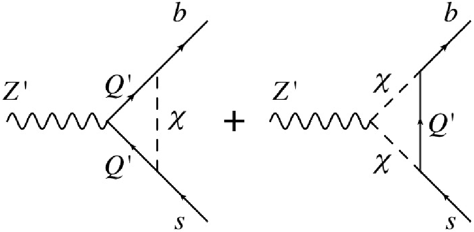
$L_\mu - L_\tau$

- The $U(1)'$ interactions must be flavor-dependent (*flavored* Z').
- The anomaly-free condition restricts the viable classes of $U(1)'$ models.
- The simplest model with ~~LFU~~ is $U(1)_{L_\mu - L_\tau}$.
  - Extra matters such as vector-like quarks are required.



W. Altmannshofer et al,

arXiv:1403.1269, 1508.07009



P. Ko et al, arXiv:1702.02699

B-meson anomalies: flavored Z' models

$B_3 - L_3$

- $U(1)'_{B-L}$ with three ν_R's.
  - gauge anomalies cancel within each generation.
  - generation of neutrino masses requires at least two ν_R's.
  - flavored $B-L$: $B_i - L_i$ $(i = 1, 2, 3)$, in particular $B_3 - L_3$ for B-anomalies

    (R. Alonso et al, arXiv:1705.03858)

BUT, the extra vector-like quarks and leptons are still required to have mixing between the third generation and the first two.

The flavored Z' model

Consider the linear combination of $L_\mu - L_\tau$ and $B_3 - L_3$:*

(L. Bian, S.-M. Choi, Y.-J. Kang, H. M. Lee, arXiv:1707.04811, L. Bian, H. M. Lee, CBP, arXiv:1711.08930)

$$Q_{Z'} = y(L_\mu - L_\tau) + x(B_3 - L_3)$$

(x and y are real parameters)†

- Two Higgs doublets H_1 and H_2 are necessary to have quark masses and mixings.
  - Only H_2 has the $U(1)'$ charge. The off-diagonal components of quark mass matrices are obtained from $\langle H_2 \rangle$.
- A complex singlet scalar S is necessary to have the Higgs bilinear term $H_1^\dagger H_2$.
- The neutrino masses are generated by extra singlet scalars, Φ_a ($a = 1, 2, 3$).

*cf. linear combinations of $L_\mu - L_\tau$ and $B_1 + B_2 - 2B_3$ (A. Crivellin et al, arXiv:1503.03477) or $B_3 - L_1$ (P. Ko et al, arXiv:1701.05788)

†y could be removed by rescaling the Z' coupling $g_{Z'}$.

The flavored Z' model

	q_{3L}	u_{3R}	d_{3R}	ℓ_{2L}	e_{2R}	ν_{2R}	ℓ_{3L}	e_{3R}	ν_{3R}
$Q_{Z'}$	$\frac{1}{3}x$	$\frac{1}{3}x$	$\frac{1}{3}x$	y	y	y	$-x-y$	$-x-y$	$-x-y$

	S	H_1	H_2	Φ_1	Φ_2	Φ_3
$Q_{Z'}$	$\frac{1}{3}x$	0	$-\frac{1}{3}x$	$-y$	$x+y$	x

$$-\mathscr{L}_Y^q = \bar{q}_i \left[\begin{pmatrix} y^u_{11} & y^u_{12} & 0 \\ y^u_{21} & y^u_{22} & 0 \\ 0 & 0 & y^u_{33} \end{pmatrix} \widetilde{H}_1 + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ h^u_{31} & h^u_{32} & 0 \end{pmatrix} \widetilde{H}_2 \right] u_j$$

$$+ \bar{q}_i \left[\begin{pmatrix} y^d_{11} & y^d_{12} & 0 \\ y^d_{21} & y^d_{22} & 0 \\ 0 & 0 & y^d_{33} \end{pmatrix} H_1 + \begin{pmatrix} 0 & 0 & h^d_{13} \\ 0 & 0 & h^d_{23} \\ 0 & 0 & 0 \end{pmatrix} H_2 \right] d_j \quad (\widetilde{H}_i = i\sigma_2 H_i^*).$$

- If $H_1 \longleftrightarrow H_2$ and $h^{u,d}_{ij} = 0$, the model corresponds to the **type-I 2HDM + singlet scalar**.

B-meson anomalies: the flavored Z' model

For $D_L = V_{\rm CKM}$,

$$\mathscr{L}_{Z'} \supset \frac{1}{2} m_{Z'}^2 Z'^2_\mu + g_{Z'} Z'_\mu \left[\frac{x}{3} \bar{d}_i \gamma^\mu V_{\rm CKM}^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} V_{\rm CKM} P_L d_j + y \bar{\mu} \gamma^\mu \mu \right]$$

$$= \frac{1}{2} m_{Z'}^2 Z'^2_\mu + g_{Z'} Z'_\mu \left(\frac{x}{3} V_{ts}^* V_{tb} \bar{s} \gamma^\mu P_L b + \text{h.c.} + y \bar{\mu} \gamma^\mu \mu \right) + \cdots$$

Integrating out Z' by the equation of motion,

$$-\mathscr{L}_{\rm eff} = \frac{xy g_{Z'}^2}{3 m_{Z'}^2} V_{ts}^* V_{tb} (\bar{s} \gamma^\mu P_L b)(\bar{\mu} \gamma_\mu \mu) + \text{h.c.}$$

Thus,

$$\boxed{\mathscr{C}_9^\mu = -\frac{8 x y \pi^2 \alpha_{Z'}}{3 \alpha} \left(\frac{v}{m_{Z'}} \right)^2}$$

The best-fit value $\mathscr{C}_9^\mu = -1.10$ (B. Capdevila, arXiv:1704.05340) gives us

$$\boxed{m_{Z'} = 1.2\ \text{TeV} \times \left(xy \frac{\alpha_{Z'}}{\alpha} \right)^{1/2}}$$

- The b-quark transition is only through CKM.

The flavored Z' model: Higgs sector

Two Higgs doublets H_1, H_2 + singlet scalar S:

$$
\begin{aligned}
V(H_1, H_2, S) = {} & \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \left(\mu S H_1^\dagger H_2 + \text{h.c.}\right) \\
& + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + 2\lambda_3 |H_1|^2 |H_2|^2 + 2\lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\
& + 2|S|^2 (\kappa_1 |H_1|^2 + \kappa_2 |H_2|^2) + m_S^2 |S|^2 + \lambda_S |S|^4
\end{aligned}
$$

with

$$
H_j = \begin{pmatrix} \phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix} \quad (j = 1, 2), \quad S = \frac{v_S + S_R + iS_I}{\sqrt{2}}.
$$

The flavored Z' model: quarks

Recall the quark mass matrices:

$$M_u = \begin{pmatrix} y^u_{11}\langle \tilde{H}_1\rangle & y^u_{12}\langle \tilde{H}_1\rangle & 0 \\ y^u_{21}\langle \tilde{H}_1\rangle & y^u_{22}\langle \tilde{H}_1\rangle & 0 \\ h^u_{31}\langle \tilde{H}_2\rangle & h^u_{32}\langle \tilde{H}_2\rangle & y^u_{33}\langle \tilde{H}_1\rangle \end{pmatrix},$$

$$M_d = \begin{pmatrix} y^d_{11}\langle H_1\rangle & y^d_{12}\langle H_1\rangle & h^d_{13}\langle H_2\rangle \\ y^d_{21}\langle H_1\rangle & y^d_{22}\langle H_1\rangle & h^d_{23}\langle H_2\rangle \\ 0 & 0 & y^d_{33}\langle H_1\rangle \end{pmatrix}$$

The mixing with the third generation is induced by H_2.

The flavored Z' model: quarks

For $V_{\rm CKM} = D_L$ and $D_R = \mathbb{1}$, the flavor-violating couplings are determined by $V_{\rm CKM}$, $\tan\beta$, and y^u_{33}.

$$h^d_{13} = \frac{\sqrt{2}m_b}{v\sin\beta} V_{ub}, \quad h^d_{23} = \frac{\sqrt{2}m_b}{v\sin\beta} V_{cb},$$

$$|y^u_{33}|^2 + \tan^2\beta(|h^u_{31}|^2 + |h^u_{32}|^2) = \frac{2m_t^2}{v^2\cos^2\beta},$$

$$y^u_{21}(h^u_{31})^* + y^u_{22}(h^u_{32})^* = 0, \quad y^u_{11}(h^u_{31})^* + y^u_{12}(h^u_{32})^* = 0.$$

The physical couplings are $\tilde{h}^d = D_L^\dagger h^d D_R$ and $\tilde{h}^u = U_L^\dagger h^u U_R$:

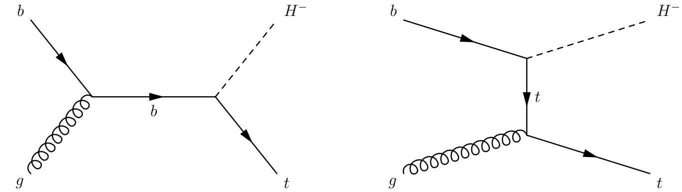
$$\tilde{h}^u_{33} = \frac{\sqrt{2}m_t}{v\sin\beta}\left(1 - \frac{v^2\cos^2\beta}{2m_t^2}|y^u_{33}|^2\right), \quad \tilde{h}^d_{13} = 1.80\times10^{-2}\left(\frac{m_b}{v\sin\beta}\right),$$

$$\tilde{h}^d_{23} = 5.77\times10^{-2}\left(\frac{m_b}{v\sin\beta}\right), \quad \tilde{h}^d_{33} = 2.41\times10^{-3}\left(\frac{m_b}{v\sin\beta}\right).$$

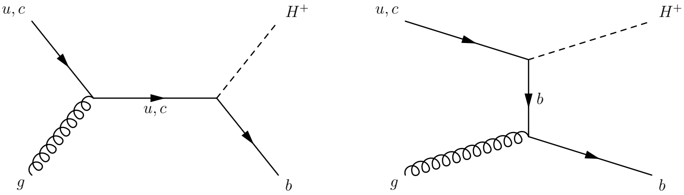
- small $\tan\beta \Rightarrow$ large flavor violation.

Higgs productions and decays at the LHC: charged

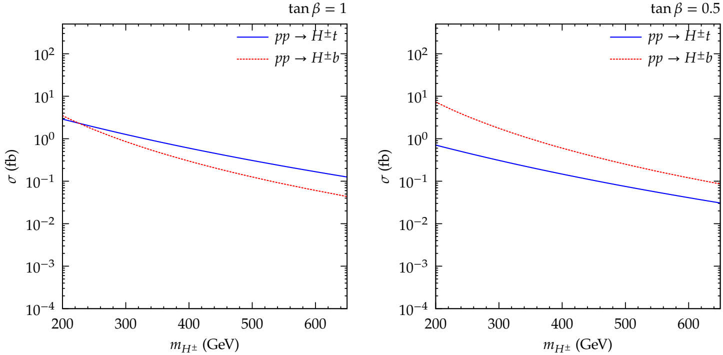
- The standard channels for charged Higgs production are top quark associated process, $bg \to tH^-$.



- The bottom quark associated production is possible: $u_i g \to bH^+$ ($u_i = u,\ c$)

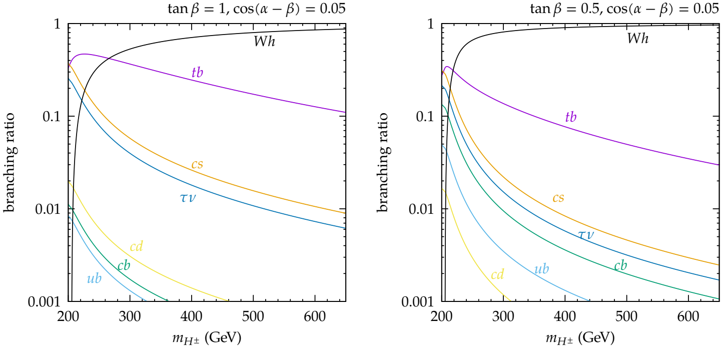


Higgs productions and decays at the LHC: charged



- The bottom-quark associated production can be dominant process for the charged Higgs if $\tan\beta$ is small.

Higgs productions and decays at the LHC: charged



- If kinematically allowed, $H^+ \to W^+ h$ is always the most dominant channel.
  - $pp \to H^\pm b \to W^\pm h + b \to 3b + \ell^\pm + \not{E}_T$ will be the smoking gun signal at the LHC and future hadron colliders.