B-meson anomalies and Higgs physics in flavored $U(1)'$ model

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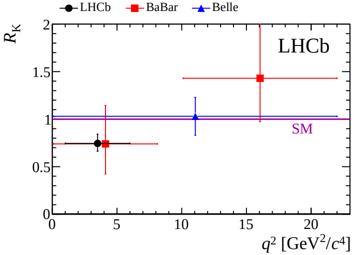
Ref: L. Bian, H. M. Lee, CBP, EPJC78, 306 (2018)

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

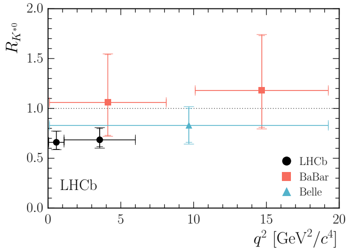


$$R_K \equiv \frac{\mathscr{B}(B \to K\mu^+\mu^-)}{\mathscr{B}(B \to Ke^+e^-)}$$

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

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

2.6σ LHCb, PRL 113, 151601 (2014)

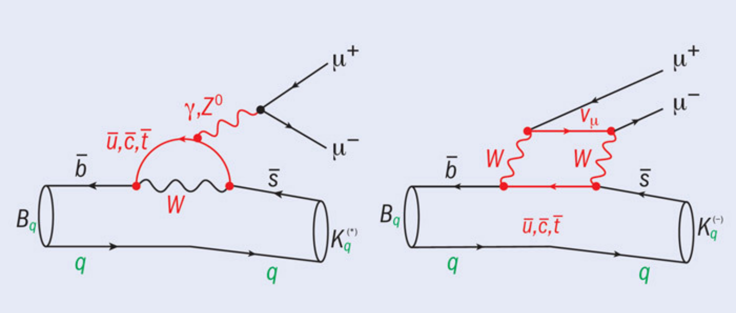


$$R_{K*} \equiv \frac{\mathscr{B}(B \to K^*\mu^+\mu^-)}{\mathscr{B}(B \to K^*e^+e^-)}$$

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

2.5σ LHCb, JHEP 08, 055 (2017)

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



- Assuming the lepton flavor universality (LFU),

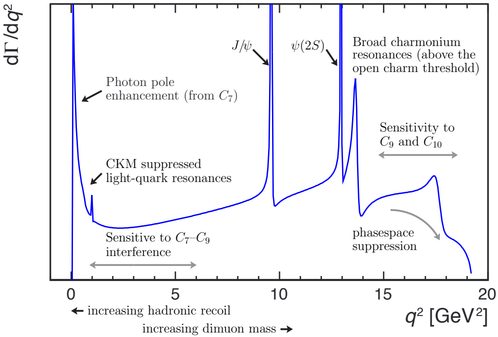
$$R_{K^{(*)}} = \frac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)} = 1 + \mathscr{O}(m_\mu^2/m_b^2)$$

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

B-meson anomalies: effective operators

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

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



T. Blake et al, arXiv:1606.00916

B-meson anomalies: effective operators

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

- vector coupling: $\mathcal{O}_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$, $\quad \mathcal{O}_9^{\prime\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$,
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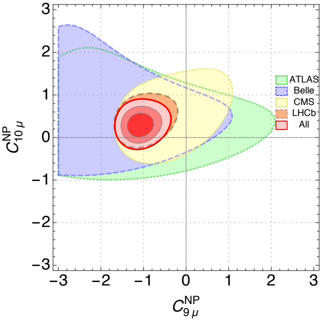
Global fit results (B. Capdevila, arXiv:1704.05340):

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

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



B-meson anomalies: effective operators

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

For an effective Hamiltonian,

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

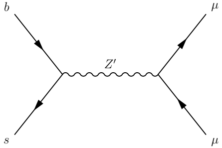
we find

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

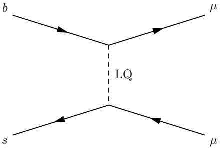
- For $|C_i| = \mathcal{O}(1)$,

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

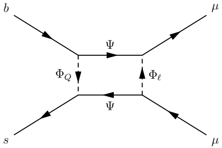
B-meson anomalies: new physics models



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):

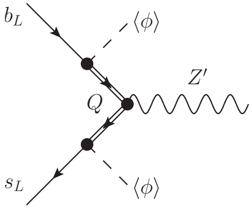
$$-\mathscr{L}_{\text{int}} \supset \Gamma_i^Q \bar{Q}_i P_R \Psi \Phi_Q + \Gamma_i^L \bar{L}_i P_R \Psi \Phi_\ell + \text{h.c.}$$

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

B-meson anomalies: flavored Z' models

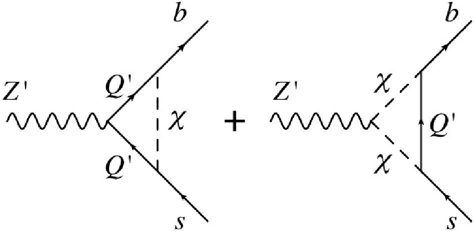
$L_\mu - L_\tau$

- 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)

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

(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

$$
\begin{aligned}
-\mathscr{L}_Y^q = \bar{q}_i &\left[\begin{pmatrix} y_{11}^u & y_{12}^u & 0 \\ y_{21}^u & y_{22}^u & 0 \\ 0 & 0 & y_{33}^u \end{pmatrix}\widetilde{H}_1 + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ h_{31}^u & h_{32}^u & 0 \end{pmatrix}\widetilde{H}_2\right] u_j \\
+ \bar{q}_i &\left[\begin{pmatrix} y_{11}^d & y_{12}^d & 0 \\ y_{21}^d & y_{22}^d & 0 \\ 0 & 0 & y_{33}^d \end{pmatrix} H_1 + \begin{pmatrix} 0 & 0 & h_{13}^d \\ 0 & 0 & h_{23}^d \\ 0 & 0 & 0 \end{pmatrix} H_2\right] d_j \quad (\widetilde{H}_i = i\sigma_2 H_i^*).
\end{aligned}
$$

- If $H_1 \longleftrightarrow H_2$ and $h_{ij}^{u,d} = 0$, the model corresponds to the type-I 2HDM.

The flavored Z' model

$$(M_u)_{ij} = \frac{v\cos_\beta}{\sqrt{2}} \begin{pmatrix} y^u_{11} & y^u_{12} & 0 \\ y^u_{21} & y^u_{22} & 0 \\ 0 & 0 & y^u_{33} \end{pmatrix} + \frac{v\sin_\beta}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ h^u_{31} & h^u_{32} & 0 \end{pmatrix}$$

$$(M_d)_{ij} = \frac{v\cos_\beta}{\sqrt{2}} \begin{pmatrix} y^d_{11} & y^d_{12} & 0 \\ y^d_{21} & y^d_{22} & 0 \\ 0 & 0 & y^d_{33} \end{pmatrix} + \frac{v\sin_\beta}{\sqrt{2}} \begin{pmatrix} 0 & 0 & h^d_{13} \\ 0 & 0 & h^d_{23} \\ 0 & 0 & 0 \end{pmatrix} \quad (\tan\beta = v_2/v_1).$$

Diagonalization of quark matrices:

$$U_L^\dagger M_u U_R = M_u^D = \mathrm{diag}(m_u, m_c, m_t),$$
$$D_L^\dagger M_d D_R = M_u^D = \mathrm{diag}(m_d, m_s, m_b).$$

and $V_{\mathrm{CKM}} = U_L^\dagger D_L$.

- h^u_{31} and h^u_{32} correspond to the right-handed rotations.
  - $U_L \simeq \mathbb{1}$, so $\boxed{V_{\mathrm{CKM}} \simeq D_L}$.

B-meson anomalies: the flavored Z' model

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

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

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

Integrating out Z' by the equation of motion,

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

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

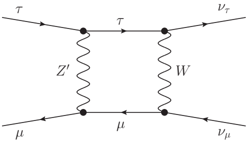
$$\boxed{m_{Z'} = 1.2\ \text{TeV} \times \left(xy \frac{\alpha_{Z'}}{\alpha} \right)^{1/2}}$$

- The b-quark transition is only through CKM.

The flavored Z' model: constraints

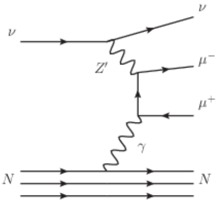
Important bounds include:

- $B_s^0 - \bar{B}_s^0$ mixing and $B \to X_s \gamma$,
- $\tau \to \mu \nu_\tau \bar{\nu}_\mu$,



$$\frac{\Delta \mathscr{B}(\tau \to \mu \nu_\tau \bar{\nu}_\mu)}{\mathscr{B}(\tau \to \mu \nu_\tau \bar{\nu}_\mu)_{\rm SM}} = \frac{3y(x+y)g_{Z'}^2}{4\pi^2} \frac{\ln(m_W^2/m_{Z'}^2)}{1 - m_{Z'}^2/m_W^2}$$

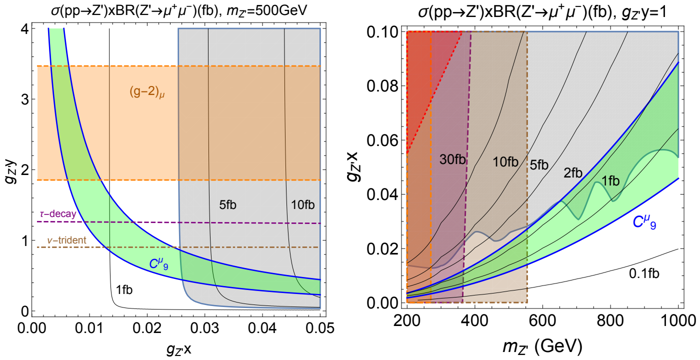
- Neutrino trident production at CHARM-II, CCFR, and NuTeV,



$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1 + (1 + 4s_W^2 + 2y^2 g_{Z'}^2 v^2/m_{Z'}^2)^2}{1 + (1 + 4s_W^2)^2}$$

- $pp \to Z' \to \mu^+ \mu^-$ at ATLAS and CMS.

The flavored Z' model: constraints



from L. Bian et al, arXiv:1707.04811

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: Higgs sector

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

- v_S determines the Z' mass,
- $G^0 = \cos\beta\,\eta_1 + \sin\beta\,\eta_2$ is eaten by the Z boson.
- The mass of the CP-odd scalar $A^0 = \sin\beta\,\eta_1 - \cos\beta\,\eta_2$ is

$$m_A^2 = \frac{\mu \sin\beta \cos\beta}{\sqrt{2} v_S} \left(v^2 + \frac{v_S^2}{\sin^2\beta \cos^2\beta} \right).$$

- And, the charged Higgs boson $H^+ = \sin\beta\,\phi_1^+ - \cos\beta\,\phi_2^+$ is

$$m_{H^+}^2 = m_A^2 - \left(\frac{\mu \sin\beta \cos\beta}{\sqrt{2} v_S} + \lambda_4 \right) v^2.$$

The flavored Z' model: Higgs sector

For CP-even scalars:

$$M_S = \begin{pmatrix} 2\lambda_1 v_1^2 + \frac{\mu v_2 v_s}{\sqrt{2} v_1} & 2v_1 v_2(\lambda_3+\lambda_4) - \frac{\mu v_s}{\sqrt{2}} & 2\kappa_1 v_1 v_s - \frac{\mu v_2}{\sqrt{2}} \\ 2v_1 v_2(\lambda_3+\lambda_4) - \frac{\mu v_s}{\sqrt{2}} & 2\lambda_2 v_2^2 + \frac{\mu v_1 v_s}{\sqrt{2} v_2} & 2\kappa_2 v_2 v_s - \frac{\mu v_1}{\sqrt{2}} \\ 2\kappa_1 v_1 v_s - \frac{\mu v_2}{\sqrt{2}} & 2\kappa_2 v_2 v_s - \frac{\mu v_1}{\sqrt{2}} & 2\lambda_S v_s^2 + \frac{\mu v_1 v_2}{\sqrt{2} v_s} \end{pmatrix}$$

Suppose that mixing with singlet scalar is negligible. Then,

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \\ S_R \end{pmatrix}.$$

And, for $h = h_1$ and $H = h_2$,

$$\lambda_1 \approx \frac{2(m_h^2 \cos^2\alpha + m_H^2 \sin^2\alpha) - \sqrt{2}\mu v_s \tan\beta}{4v^2\cos^2\beta},$$

$$\lambda_2 \approx \frac{2(m_h^2 \sin^2\alpha + m_H^2 \cos^2\alpha) - \sqrt{2}\mu v_s \cot\beta}{4v^2\sin^2\beta},$$

$$\lambda_3 + \lambda_4 \approx \frac{(m_h^2 - m_H^2)\sin 2\alpha + \sqrt{2}\mu v_s}{4v^2 \sin 2\beta}.$$

If $m_h = 125$ GeV, the input parameters for the CP-even Higgses are $m_H, \mu v_s, \tan\beta, \sin\alpha$.

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 $V_{\text{CKM}} = D_L$ and $D_R = \mathbb{1}$, the flavor-violating couplings are determined by V_{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.

The flavored Z' model: leptons

The mass matrix for charged leptons are diagonal:

$$M_\ell = \begin{pmatrix} y^\ell_{11}\langle H_1\rangle & 0 & 0 \\ 0 & y^\ell_{22}\langle H_1\rangle & 0 \\ 0 & 0 & y^\ell_{33}\langle H_1\rangle \end{pmatrix}.$$

On the other hand, the neutrinos are

$$-\mathcal{L}^\nu_Y = \bar{\ell} M_D \nu_R + \overline{(\nu_R)^c} M_R \nu_R + \text{h.c.},$$

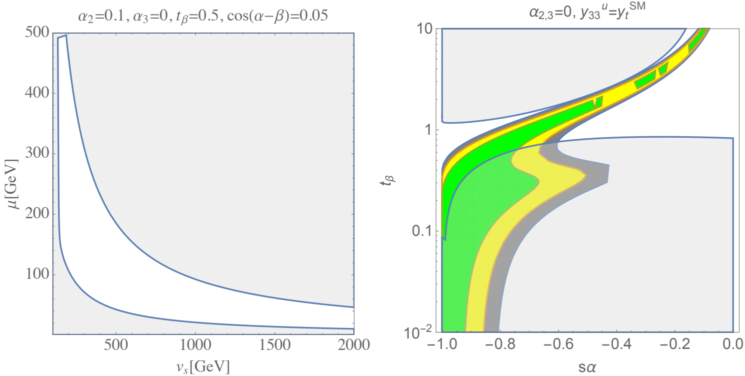
with

$$M_D = \begin{pmatrix} y^\nu_{11}\langle \tilde{H}_1\rangle & 0 & 0 \\ 0 & y^\nu_{22}\langle \tilde{H}_1\rangle & 0 \\ 0 & 0 & y^\nu_{33}\langle \tilde{H}_1\rangle \end{pmatrix}, \quad M_R = \begin{pmatrix} M_{11} & z^{(1)}_{12}\langle\Phi_1\rangle & z^{(2)}_{13}\langle\Phi_2\rangle \\ z^{(1)}_{21}\langle\Phi_1\rangle & 0 & z^{(3)}_{23}\langle\Phi_3\rangle \\ z^{(2)}_{31}\langle\Phi_2\rangle & z^{(3)}_{32}\langle\Phi_3\rangle & 0 \end{pmatrix}.$$

- The neutrino masses arise via the seesaw mechanism, $m_\nu \simeq -M_D M_R^{-1} M_D^T$.

Constraints on the Higgs sector

Theoretical bounds from the perturbative unitarity and stability and experimental bounds from the Higgs data at the LHC

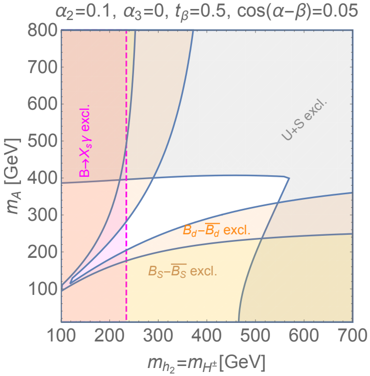


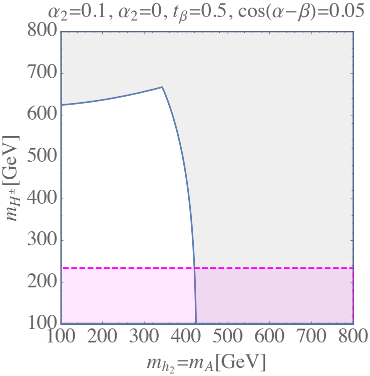
The EWPT constraint (assuming negligible kinetic mixing):

$$\Delta\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} - 1 \simeq 10^{-4}\left(\frac{x}{0.05}\right)^2 g_{Z'}^2 \sin^4\beta \left(\frac{400\ \mathrm{GeV}}{m_{Z'}}\right)^2 .$$

Constraints on the Higgs sector

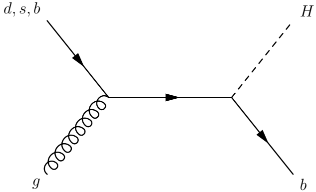
B-physics bounds: $B_s \to \mu^+\mu^-$, $B_s - \bar{B}_s$ mixing, $B \to X_s\gamma$ for the heavy Higgses as well as Z'

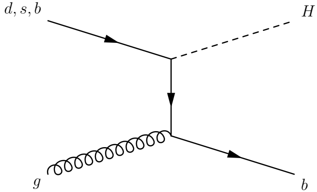




Higgs productions and decays at the LHC: neutral

- The standard channels for neutral Higgs production are $gg \to H$ and $b\bar{b} \to H$.
- Productions through the flavor-violating couplings, $b\bar{d}_i/d_i\bar{b} \to H$ ($d_i = d, s$).
- b-quark associated productions: $bg \to bH$ and $d_ig \to bH$.





Higgs productions and decays at the LHC: neutral

$$-\mathcal{L}_Y^H \supset \frac{\lambda_t^H}{\sqrt{2}}\bar{t}_R t_L H + \frac{\lambda_b^H}{\sqrt{2}}\bar{b}_R b_L H + \frac{\sin(\alpha-\beta)}{\sqrt{2}\cos\beta}\bar{b}_R\left(\tilde{h}_{13}^{d*}d_L + \tilde{h}_{23}^{d*}s_L\right)H + \text{h.c.},$$

where

$$\lambda_t^H = \frac{\sqrt{2}m_t\cos\alpha}{v\cos\beta} + \frac{\tilde{h}_{33}^u\sin(\alpha-\beta)}{\cos\beta}, \quad \lambda_b^H = \frac{\sqrt{2}m_b\cos\alpha}{v\cos\beta} + \frac{\tilde{h}_{33}^d\sin(\alpha-\beta)}{\cos\beta}$$

with

$$\tilde{h}_{13}^d = \frac{\sqrt{2}m_b}{v\sin\beta}\left(V_{ud}^* V_{ub} + V_{cd}^* V_{cb}\right), \quad \tilde{h}_{23}^d = \frac{\sqrt{2}m_b}{v\sin\beta}\left(V_{us}^* V_{ub} + V_{cs}^* V_{cb}\right),$$

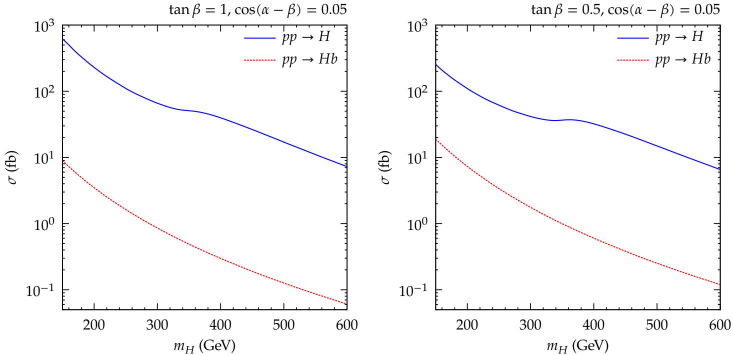
$$\tilde{h}_{33}^d = \frac{\sqrt{2}m_b}{v\sin\beta}\left(|V_{ub}|^2 + |V_{cb}|^2\right), \quad \tilde{h}_{33}^u = \frac{\sqrt{2}m_t}{v\sin\beta}\left(1 - \frac{v^2\cos^2\beta}{2m_t^2}\left|y_{33}^u\right|^2\right).$$

If $y_{33}^u = y_t^{\rm SM}$,

$$\lambda_t^H = y_t^{\rm SM}\cos(\alpha-\beta) \xrightarrow{\alpha=\beta-\pi/2} 0.$$

The gluon-fusion process is suppressed compared to the SM case.

Higgs productions and decays at the LHC: neutral



For $m_H = 200$ GeV and $\tan\beta = 1$ (0.5), $\sigma_{pp\to H} \simeq 225.2$ (110.5) fb.

$$(\sigma_{b\bar{d}_i\to H} + \sigma_{d_i\bar{b}\to H})/\sigma_{gg\to H} \simeq 0.62\%(1.6\%),$$
$$(\sigma_{b\bar{d}_i\to H} + \sigma_{d_i\bar{b}\to H})/\sigma_{b\bar{b}\to H} \simeq 1.6\%(10.9\%).$$

- The gluon-fusion process is still the most dominant.

Higgs productions and decays at the LHC: neutral

The most important decay modes of the heavy neutral Higgs are $H \to b\bar{d}_i$ and $H \to hh$.

$$\Gamma(H \to b\bar{d}_i) = \Gamma(H \to d_i\bar{b}) = \frac{3|\tilde{h}^d_{i3}|^2 \sin^2(\alpha-\beta)}{32\pi\cos^2\beta} m_H \left(1 - \frac{m_b^2}{m_H^2}\right)^2,$$

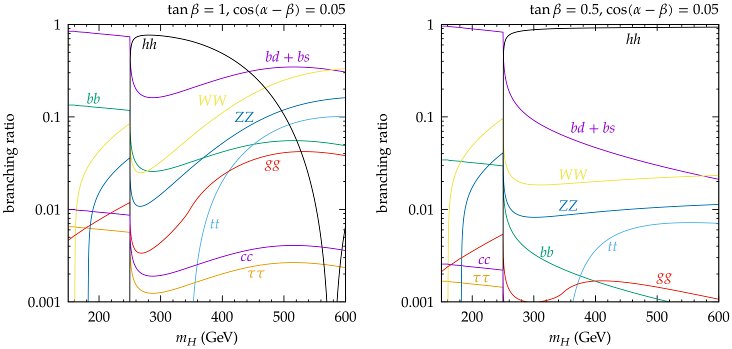
$$\Gamma(H \to hh) = \frac{g_{Hhh}^2 v^2}{32\pi m_H}\left(1 - \frac{4m_h^2}{m_H^2}\right)^{1/2},$$

where

$$\tilde{h}^d_{13} = 1.80 \times 10^{-2}\left(\frac{m_b}{v\sin\beta}\right), \quad \tilde{h}^d_{23} = 5.77 \times 10^{-2}\left(\frac{m_b}{v\sin\beta}\right),$$

$$g_{Hhh} = 3(\lambda_1 \sin\alpha\cos\beta + \lambda_2\cos\alpha\sin\beta)\sin(2\alpha) + (\lambda_3+\lambda_4)\left[3\cos(\alpha+\beta)\cos(2\alpha) - \cos(\alpha-\beta)\right].$$

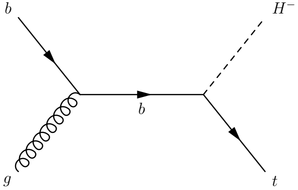
Higgs productions and decays at the LHC: neutral

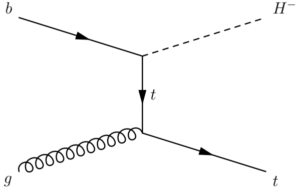


- If $m_H < 2m_{hh}$, $H \to bq$ is the most dominant channel.
- If $m_H > 2m_{hh}$, $H \to hh$ up to accidental cancellation in the trilinear coupling g_{Hhh}.

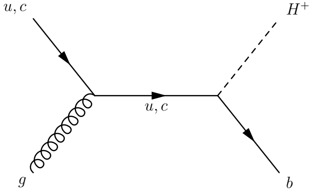
Higgs productions and decays at the LHC: charged

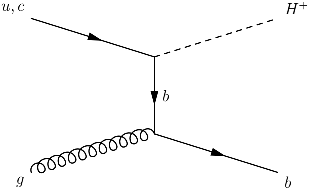
- The standard channels for charged Higgs production are top quark associated process, $bg \to tH^-$.





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





Higgs productions and decays at the LHC: charged

$$-\mathscr{L}_Y^{H^-} \supset \bar{b}(\lambda_{t_L}^{H^-} P_L + \lambda_{t_R}^{H^-} P_R) t H^- + \bar{b}(\lambda_{c_L}^{H^-} P_L + \lambda_{c_R}^{H^-} P_R) c H^- + \lambda_{u_L}^{H^-} \bar{b} P_L u H^- + \text{h.c.},$$

where

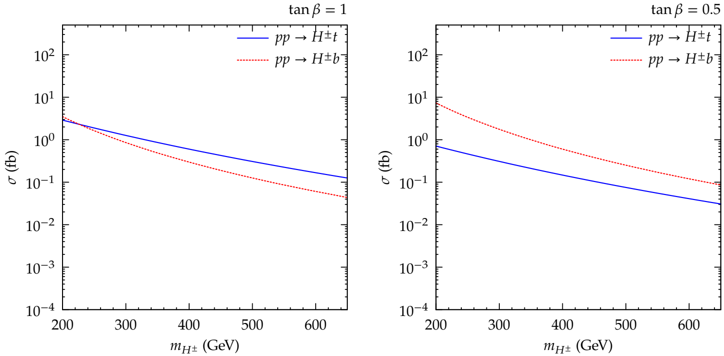
$$\lambda_{t_L}^{H^-} = \frac{\sqrt{2} m_b \tan\beta}{v} V_{tb}^* - \frac{(V_{\rm CKM} \tilde{h}^d)^*_{33}}{\cos\beta}, \quad \lambda_{t_R}^{H^-} = -\left(\frac{\sqrt{2} m_t \tan\beta}{v} - \frac{\tilde{h}^u_{33}}{\cos\beta}\right) V_{tb}^*,$$

$$\lambda_{c_L}^{H^-} = \frac{\sqrt{2} m_b \tan\beta}{v} V_{cb}^* - \frac{(V_{\rm CKM} \tilde{h}^d)^*_{23}}{\cos\beta}, \quad \lambda_{c_R}^{H^-} = -\frac{\sqrt{2} m_c \tan\beta}{v} V_{cb}^*,$$

$$\lambda_{u_L}^{H^-} = \frac{\sqrt{2} m_b \tan\beta}{v} V_{ub}^* - \frac{(V_{\rm CKM} \tilde{h}^d)^*_{13}}{\cos\beta}.$$

- If $y_{33}^u = y_t^{\rm SM}$, $\lambda_{t_R}^{H^-} = 0$.

Higgs productions and decays at the LHC: charged



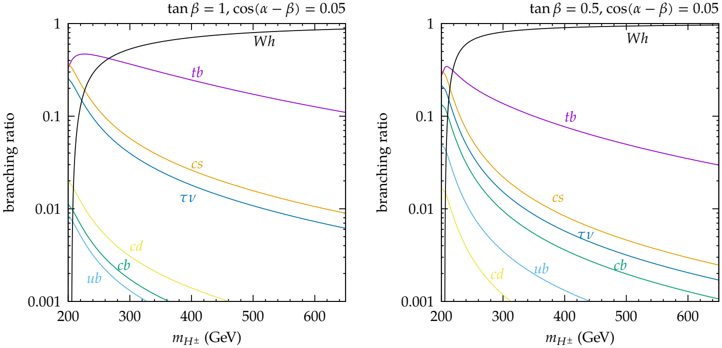
- The bottom-quark associated production can be dominant process for the charged Higgs if $\tan\beta$ is small.

Higgs productions and decays at the LHC: charged

The most important decay modes of the heavy charged Higgs are $H^+ \longrightarrow W^+ h$ and $H^+ \longrightarrow t\bar{b}$.

$$\Gamma(H^+ \longrightarrow W^+ h) = \Gamma(H^- \longrightarrow W^- h)$$
$$= \frac{g^2 \cos^2(\alpha - \beta) m_{H^\pm}^3}{64\pi m_W^2} \left[\left(1 - \frac{m_W^2}{m_{H^\pm}^2} - \frac{m_h^2}{m_{H^\pm}^2} \right)^2 - \frac{4 m_W^2 m_h^2}{m_{H^\pm}^4} \right]^{3/2},$$
$$\Gamma(H^+ \longrightarrow t\bar{b}) = \Gamma(H^- \longrightarrow b\bar{t})$$
$$= \frac{3|\lambda_{t_L}^{H^-}|^2 m_{H^\pm}}{16\pi} \left[\left(1 - \frac{(m_t + m_b)^2}{m_{H^\pm}^2} \right) \left(1 - \frac{(m_t - m_b)^2}{m_{H^\pm}^2} \right) \right]^{1/2}$$
$$\times \left(1 - \frac{m_t^2 + m_b^2}{m_{H^\pm}^2} \right) \qquad (y_{33}^u = y_t^{\rm SM},\ \lambda_{t_R}^{H^-} = 0).$$

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.

Summary and conclusion

- The B-meson anomalies at LHCb indicate BSM, which could be the flavored Z'.
  - We studied $U(1)'_{y(L_\mu - L_\tau)+x(B_3-L_3)}$.
- Various theoretical and experimental bounds are important.
  - Perturbative unitarity and stability, electroweak precision and Higgs data, B-meson mixing, $B_s \to \mu^+\mu^-$, $b \to s\gamma$, rare decays, …
- Direct signals can be probed via $Z' \to \mu\mu$ and flavor-violating decays of heavy Higgs bosons at the LHC.
  - $pp \to H^\pm + b \to W^\pm h + b$ will be the smoking gun signal.