B-physics and other anomalies as hints for new physics

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Based on work in collaboration with Andreas Crivellin, Giancarlo D'Ambrosio, Peter Stoffer, Martin Holthausen, Werner Rodejohann, and Yusuke Shimizu.

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Current flavor anomalies: $h \to \mu\tau$

Lepton flavor violation in Brout–Englert–Higgs boson decay $h \to \mu\tau$:

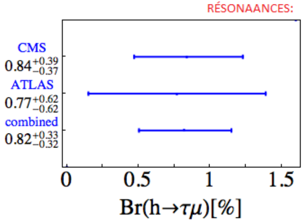
- CMS [1502.07400]: 2.4σ:

$$\mathrm{BR}(h \to \mu\tau) = \left(0.84^{+0.39}_{-0.37}\right)\%\,.$$

- ATLAS [1508.03372]: 1.2σ:

$$\mathrm{BR}(h \to \mu\tau) = (0.77 \pm 0.62)\,\%\,.$$

$\Rightarrow 2.6\sigma$ combined.



- Requires couplings beyond the SM:

$$\mathcal{L} \supset -y_{\mu\tau}\overline{\mu}_L \tau_R h - y_{\tau\mu}\overline{\tau}_L \mu_R h + \text{h.c.} \quad \text{with} \quad \sqrt{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2} \simeq 0.003.$$

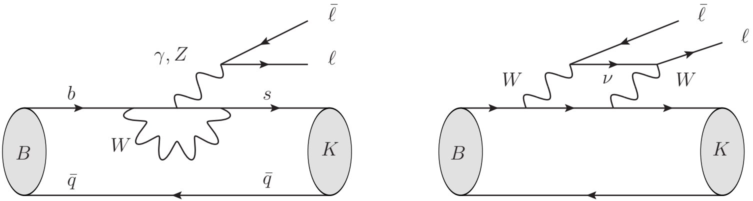
- By itself not in conflict with $\tau \to \mu\gamma$ etc.[1]
- Go-to explanation: extended scalar sector, e.g. (type-III) 2HDM.[2]

[1] Blankenburg, Ellis, Isidori, 1202.5704; Harnik, Kopp, Zupan, 1209.1397; Davidson, Verdier, 1211.1248; Kopp, Nardecchia, 1406.5303.

[2] Campos, Hernandez, Päs, Schumacher, 1408.1652; Celis, Cirigliano, Passemar, 1409.4439; Aristizabal Sierra, Vicente, 1409.7690; **J.H.**, Holthausen, Rodejohann, Shimizu, 1412.3671;. . .

Current flavor anomalies: $b \to s$

- Rare flavor changing decays $B \to K\bar{\ell}\ell$ at loop level in SM.
- Branching ratios of order 10^{-7}.



- $B = \bar{B}^0$ for $q = d$.
- $B = B^-$ for $q = u$.
- $B = \bar{B}_s^0$ for $q = s$ (and $K \to \phi$).

Current flavor anomalies: $b \to s$

- LHCb [1406.6482]: 2.6σ lepton non-universality:

$$R(K) \equiv \frac{B^+ \to K^+\mu\mu}{B^+ \to K^+ee} = 0.745^{+0.090}_{-0.074} \pm 0.036,$$

  SM prediction $R(K) = 1 \pm \mathcal{O}(10^{-4})$
  [Bobeth, Hiller, Piranishvili, 0709.4174].
  (Comes from smaller $\mu\mu$ rate.)

- LHCb [1506.08777]: 3.5σ too small differential branching fraction

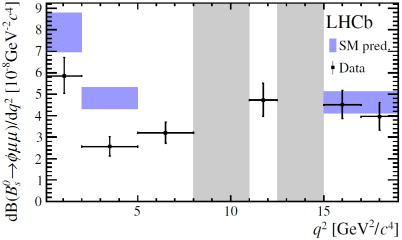
$$B^0_s \to \phi\mu^+\mu^- \to K^+K^-\mu^+\mu^-\,,$$

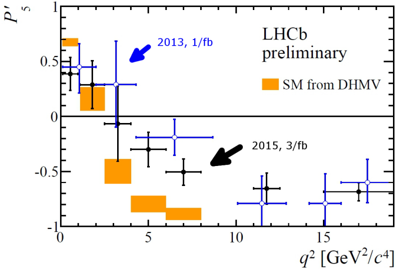
  confirming 1/fb analysis [1305.2168].

- LHCb [LHCb-CONF-2015-002]: 3.7σ deviation in angular observable P_5' of

$$B^0 \to K^*\mu\mu \to K^+\pi^-\mu\mu\,,$$

  confirming 1/fb analysis [1308.1707].





Global fit for $b \to s$

Global fit[3] with effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_{\rm EM}}{4\pi} \left(\sum_{j=9,10} C_j^{\ell\ell} O_j^{\ell\ell} + C_j^{\prime\ell\ell} O_j^{\prime\ell\ell} \right) + \text{h.c.},$$

with

$$O_9^{\ell\ell} = [\bar{s}\gamma^\mu P_L b] \left[\bar{\ell}\gamma_\mu \ell\right], \qquad O_{10}^{\ell\ell} = [\bar{s}\gamma^\mu P_L b] \left[\bar{\ell}\gamma_\mu \gamma^5 \ell\right],$$

$$O_9^{\prime\ell\ell} = [\bar{s}\gamma^\mu P_R b] \left[\bar{\ell}\gamma_\mu \ell\right], \qquad O_{10}^{\prime\ell\ell} = [\bar{s}\gamma^\mu P_R b] \left[\bar{\ell}\gamma_\mu \gamma^5 \ell\right],$$

to all $B \to X\mu^+\mu^-$, $B \to X\gamma$ observables (but not $R(K)$ etc.):

$$3.7\sigma: \quad C_9^{\rm NP} = -1.07 \pm 0.25 \quad (= -25\% C_9^{\rm SM}).$$

[3] Altmannshofer, Straub, 1503.06199, 1411.3161.
Similar results by Descotes-Genon et al.; Hurth, Mahmoudi, Neshatpour, 1410.4545; ...

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$$3.7\sigma: \quad C_9^{\text{NP}} = -1.07 \pm 0.25 \quad (= -25\% C_9^{\text{SM}}).$$

Include $b \to s\, e^+e^-$ ($R(K)$): 4.3σ for $C_9^{\mu\mu}$.

Need $(\bar{s}\gamma_\alpha P_L b)(\overline{\mu}\gamma^\alpha \mu)/(35\,\text{TeV})^2$, but no electrons.

[3] Altmannshofer, Straub, 1503.06199, 1411.3161.
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Current flavor anomalies: $b \to c$

- Lepton non-universality in B decays

$$R(D^{(*)}) \equiv \frac{\bar{B} \to D^{(*)}\tau\bar{\nu}}{\bar{B} \to D^{(*)}\ell\bar{\nu}}\,.$$

- Combination of BaBar, Belle, and LHCb

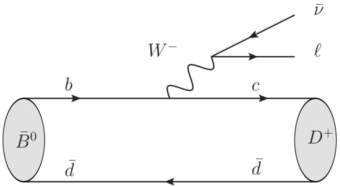
$$R(D)_{\rm exp} = 0.388 \pm 0.047\,,$$
$$R(D^*)_{\rm exp} = 0.321 \pm 0.021\,,$$

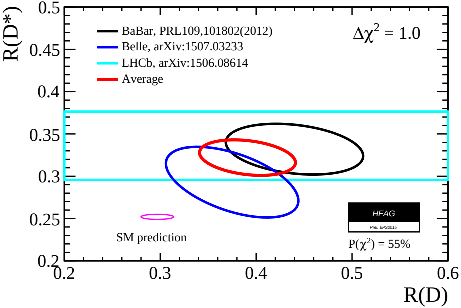
compared to SM prediction (e.g. [Fajfer, Kamenik, Nisandzic, 1203.2654])

$$R(D)_{\rm SM} = 0.297 \pm 0.017\,,$$
$$R(D^*)_{\rm SM} = 0.252 \pm 0.003\,,$$

$\Rightarrow 3.9\sigma$ combined (HFAG).

- Confirms earlier results by BaBar & Belle.





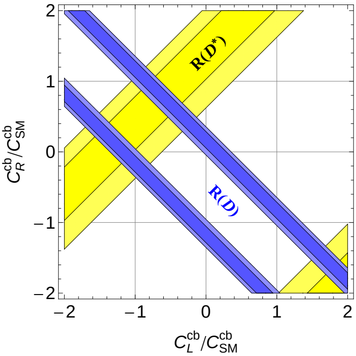
Wilson coefficients for $b \to c$

- Possible new physics explanation of $B \to D^{(*)}\tau\nu$ by charged Higgs.
- Relevant effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = C^{qb}_{\text{SM}} O^{qb}_{\text{SM}} + C^{qb}_{R} O^{qb}_{R} + C^{qb}_{L} O^{qb}_{L} \,,$$
$$O^{cb}_{\text{SM}} = \bar{c}\gamma_\mu P_L b\, \bar{\tau}\gamma_\mu P_L \nu_\tau \,, \quad O^{cb}_{L,R} = \bar{c} P_{L,R} b\, \bar{\tau} P_L \nu_\tau \,.$$

- Need e.g. $C^{cb}_R = 0$ and $C^{cb}_L \simeq -1.2\,|C^{cb}_{\text{SM}}|$.

$$\frac{R(D^*)}{R(D^*)_{\text{SM}}} = 1 + 0.12\,\Re\left[\frac{C^{cb}_R - C^{cb}_L}{C^{cb}_{\text{SM}}}\right] + 0.05\left|\frac{C^{cb}_R - C^{cb}_L}{C^{cb}_{\text{SM}}}\right|^2 .$$



- ($B \to \tau\nu$ depends on *ub* couplings.)
  - Can not explain $R(D)$ and $R(D^*)$ in type-II 2HDM, but works in general type III [Crivellin, Greub, Kokulu, 1206.2634, 1303.5877], or modified type X (also resolving muon's magnetic moment anomaly) [**J.H.**, Crivellin, Stoffer, 1507.07567].

A model for $h \to \mu\tau$

J.H., M. Holthausen, W. Rodejohann, Y. Shimizu,
Nucl. Phys. B896 (2015) 281–310, [arXiv:1412.3671].

Flavor violating Higgs decays

For 2.4σ effect $\text{BR}(h \to \mu\tau) = \left(0.84^{+0.39}_{-0.37}\right)\%$ need

$$\mathcal{L} \supset -y_{\mu\tau}\overline{\mu}_L \tau_R h - y_{\tau\mu}\overline{\tau}_L \mu_R h + \text{h.c.} \quad \text{with} \quad \sqrt{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2} \simeq 0.003.$$

- Go-to explanation: extended scalar sector, e.g. 2HDM.[4]
- Lepton flavor violation $\Leftrightarrow$ connection to flavor symmetries?[5]
  - Non-abelian symmetries A_4 or S_4 have at least 3HDM.
  - Predict $\text{BR}(h \to e\tau) \sim \text{BR}(h \to \mu\tau)$.

[4] de Lima, Machado, Matheus, do Prado, 1501.06923; Dorsner et al, 1502.07784.
[5] Campos, Hernández, Päs, Schumacher, 1408.1652;
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  - Predict $\text{BR}(h \to e\tau) \sim \text{BR}(h \to \mu\tau)$.

Here: take abelian symmetry.

- Lepton numbers in $h \to \bar{\mu}\tau, \mu\bar{\tau}$:

$$\Delta L_e = 0 = \Delta(L_\mu + L_\tau), \text{ but } \Delta(L_\mu - L_\tau) = \pm 2\,.$$

[4] de Lima, Machado, Matheus, do Prado, 1501.06923; Dorsner et al, 1502.07784.
[5] Campos, Hernández, Päs, Schumacher, 1408.1652;
J.H., Holthausen, Rodejohann, Shimizu, 1412.3671.

Gauged $U(1)_{L_\mu - L_\tau}$ flavor symmetry

$L_\mu - L_\tau$ well known symmetry:

- Current $j'_\alpha = \bar{\mu}\gamma_\alpha\mu - \bar{\tau}\gamma_\alpha\tau + \bar{\nu}_\mu\gamma_\alpha P_L\nu_\mu - \bar{\nu}_\tau\gamma_\alpha P_L\nu_\tau$.
- Anomaly free in SM.[6]
- Light Z' could resolve $(g-2)_\mu$ anomaly.[7]
- Good zeroth order approximation to neutrino mixing with quasi-degenerate masses ($m_{1,2,3} \simeq 1\,\mathrm{eV}$ and $\beta = \pi/2$):

$$\mathcal{M}_\nu = U_{\mathrm{PMNS}}\,\mathrm{diag}(m_1, m_2, m_3) U^T_{\mathrm{PMNS}} \simeq \begin{pmatrix} 0.96 & -0.20 & -0.22 \\ \cdot & 0.11 & -0.97 \\ \cdot & \cdot & -0.07 \end{pmatrix} \mathrm{eV} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & 0 & \times \\ 0 & \times & 0 \end{pmatrix} \leftarrow L_\mu - L_\tau$$

- $L_\mu - L_\tau$ gives $\theta_{23} = \pi/4$ and $\theta_{13} = 0$.[8]

[6] He, Joshi, Lew, Volkas, PRD 1991; Foot, MPLA 1991.
[7] Altmannshofer, Gori, Pospelov, Yavin, PRL 2014, 1406.2332.
[8] Binetruy, Lavignac, Petcov, Ramond, NPB 1997; Bell, Volkas, PRD 2001; Choubey, Rodejohann, EPJC 2005.

$L_\mu - L_\tau$ in a 2HDM

- 2HDM: $\Phi_1 \sim -2$, $\Phi_2 \sim 0$ under $U(1)_{L_\mu - L_\tau}$.[9]
- Plus scalar singlet $S \sim 1$ and three $\nu_R \sim (0, 1, -1)$ for seesaw.
- $S \to \langle S \rangle$ generates $\Delta \mathcal{M}_R$ for valid PMNS, $M_{Z'}/g' = \langle S \rangle$, and $S^2 \Phi_2^\dagger \Phi_1 \to m_3^2 \Phi_2^\dagger \Phi_1$.
  $\Rightarrow$ small VEV $\langle \Phi_1 \rangle$ induced! ($\leftarrow$ large $\tan\beta$ region.)
- Lepton Yukawa couplings:[10]

$$Y_{\ell_2} = \mathrm{diag}(y_e, y_\mu, y_\tau)\,, \qquad Y_{\ell_1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \xi_{\tau\mu} & 0 \end{pmatrix}.$$

$\Rightarrow$ Gauge symmetry sets all other LFV couplings zero!

Coupling $h\mu\tau$ now generated by scalar mixing and lepton mixing.

[9] **J.H.**, Rodejohann, PRD 2011, see Dutta, Joshipura, Vijaykumar, PRD 1994, for $L_e - L_{\mu,\tau}$.
[10] **J.H.**, Holthausen, Rodejohann, Shimizu, 1412.3671.

Charged lepton masses

- Diagonalization of M_e requires small μ_R–τ_R rotation

$$s_R \equiv \sin\theta_R \simeq \frac{v}{m_\tau}\frac{\xi_{\tau\mu}}{\sqrt{2}}\cos\beta\,.$$

- SM-like scalar h couples

$$y^h \simeq \underbrace{\mathrm{diag}(m_e, m_\mu, m_\tau)\frac{c_\alpha}{v s_\beta}}_{\text{type-I 2HDM}} - s_R \frac{m_\tau}{v}\frac{\cos(\alpha-\beta)}{c_\beta s_\beta}\begin{pmatrix} 0 & & \\ & 0 & 0 \\ & c_R & s_R \end{pmatrix}.$$

- Z' couples to (e, μ, τ) via

$$\begin{pmatrix} 0 & & \\ & 1 & \\ & & -1 \end{pmatrix} P_L + \begin{pmatrix} 0 & & \\ & \cos 2\theta_R & \sin 2\theta_R \\ & \sin 2\theta_R & -\cos 2\theta_R \end{pmatrix} P_R,$$

leads to $\tau \to 3\mu$; need $\theta_R \lesssim 4 \times 10^{-3} (M_{Z'}/g'/1\,\mathrm{TeV})^2$.

Only LFV in μ–τ sector, quarks and electrons save!

$h \to \mu\tau$

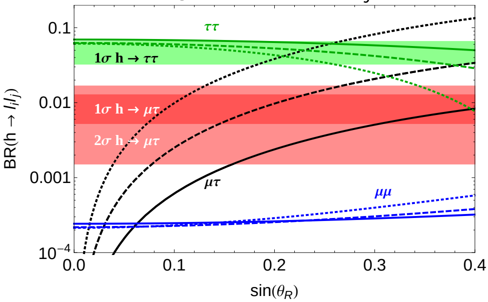
- CMS 2.4σ excess in $h \to \mu\tau$ for

$$|y^h_{\tau\mu}| = \frac{m_\tau}{v} \left| \frac{\cos(\alpha - \beta)}{c_\beta s_\beta} c_R s_R \right|$$
$$\overset{!}{\simeq} 3 \times 10^{-3}\,.$$

- $c_\beta \sim s_R \ll 1$ and $\xi_{\tau\mu} c_{\alpha-\beta} \simeq 0.004$.
- (slightly) modified $h \to \tau\tau$.
- Otherwise just type-I 2HDM.
- Expect $\tau \to 3\mu$ (see later).

$h \to \mu\tau$ resolved.

CMS allowed regions for $h \to \ell_i \ell_j$:



solid:	$\tan\beta = 3$,	$\cos(\alpha - \beta) = -0.3$,
dashed:	$\tan\beta = 10$,	$\cos(\alpha - \beta) = -0.2$,
dotted:	$\tan\beta = 20$,	$\cos(\alpha - \beta) = -0.2$.

J.H., Holthausen, Rodejohann, Shimizu, 1412.3671.

A model for $b \to s$

J.H., A. Crivellin, G. D'Ambrosio,

Phys. Rev. Lett. 114 (2015) 151801 [arXiv:1501.00993];

Phys. Rev. D91 (2015), 075006, [arXiv:1503.03477].

$b \to s$ model building

For 4.3σ improvement, need

- $(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)/(35\,\mathrm{TeV})^2$,
- no coupling to electrons.

Obvious solution: flavor-non-universal Z'.[11]

Perfect candidate: $U(1)_{L_\mu - L_\tau}$ (remember?).
Just need flavor- changing coupling to quarks:

- via heavy vector-like quarks,[12]
- via an additional scalar doublet.[13]

[11] Altmannshofer, Straub, 1503.06199, 1411.3161; Gauld, Goertz, Haisch, 1308.1959, 1310.1082; Buras, Girrbach et al., 1309.2466, 1311.6729; Aristizabal Sierra, Staub, Vicente, 1503.06077; Crivellin et al., 1504.07928; Celis et al., 1505.03079.

[12] Altmannshofer, Gori, Pospelov, Yavin, PRD 2014, 1403.1269; **J.H.**, Crivellin, D'Ambrosio, PRL 2015, 1501.00993.

[13] **J.H.**, Crivellin, D'Ambrosio, PRD 2015, 1503.03477.

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[13] **J.H.**, Crivellin, D'Ambrosio, PRD 2015, 1503.03477.

$b \to s$ without vector-quarks

Instead of vector-like quarks with ad-hoc structure, extend $L_\mu - L_\tau$ to

$$Q' = (L_\mu - L_\tau) - a(B_1 + B_2 - 2B_3) \text{ with } a \in \mathbb{Q}\,.$$

with two scalar doublets $\Phi_1 \sim -a$, $\Phi_2 \sim 0$ and some singlets.

$$Y_{d_2} = \begin{pmatrix} y^d_{11} & y^d_{12} & \\ y^d_{21} & y^d_{22} & \\ & & y^d_{33} \end{pmatrix}, \qquad Y_{d_1} = \begin{pmatrix} 0 & 0 & \xi_{db} \\ 0 & 0 & \xi_{sb} \\ 0 & 0 & 0 \end{pmatrix}.$$

- $L_\mu - L_\tau$ in lepton sector. ✓
- Cabibbo angle & Kaon mixing constraints. ✓
- Mixing of third quark generation by $\langle \Phi_1 \rangle$ induces $Z'bs$ coupling. ✓
- (Later: introduce third doublet $\Phi_3 \sim 2$ to induce $h \to \mu\tau$.)

Flavor violating couplings

Diagonalization of quark mass matrices (focus on down quarks):

$$-\bar{d}\left(\frac{\cos\alpha}{v\sin\beta} m_d^D - \frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta}\tilde{\xi}^d\right) P_R d\, h - \bar{d}\left(\frac{\sin\alpha}{v\sin\beta} m_d^D - \frac{\sin(\alpha-\beta)}{\sqrt{2}\sin\beta}\tilde{\xi}^d\right) P_R d\, H$$
$$+ i\bar{d}\left(\frac{m_d^D}{v\tan\beta} - \frac{1}{\sqrt{2}\sin\beta}\tilde{\xi}^d\right) P_R d\, A - \bar{u}\left(\frac{\sqrt{2}}{v\tan\beta} V m_d^D - \frac{1}{\sin\beta} V\tilde{\xi}^d\right) P_R d\, H^+ .$$

Type-I 2HDM plus perturbations specified by CKM:

$$\tilde{\xi}^d \simeq V^\dagger Y_{d_1} \simeq \frac{\sqrt{2}}{\cos\beta}\frac{m_b}{v}\begin{pmatrix} 0 & 0 & -V_{td}^* V_{tb} \\ 0 & 0 & -V_{ts}^* V_{tb} \\ 0 & 0 & 1-|V_{tb}|^2 \end{pmatrix} .$$

Z' couplings:

$$\Gamma^{dL} \simeq a\begin{pmatrix} |V_{td}|^2 - \frac{1}{3} & V_{ts}V_{td}^* & V_{tb}V_{td}^* \\ V_{td}V_{ts}^* & |V_{ts}|^2 - \frac{1}{3} & V_{tb}V_{ts}^* \\ V_{td}V_{tb}^* & V_{ts}V_{tb}^* & |V_{tb}|^2 - \frac{1}{3} \end{pmatrix}, \quad \Gamma^{dR} \simeq a\begin{pmatrix} -\frac{1}{3} & 0 & 0 \\ 0 & -\frac{1}{3} & 0 \\ 0 & 0 & \frac{2}{3} \end{pmatrix}.$$

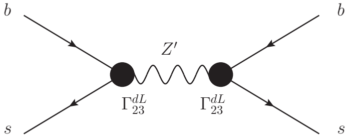
$b \to s$

- Dominant off-diagonal: $Z' bs$.
- Structure perfect for $b \to s$:

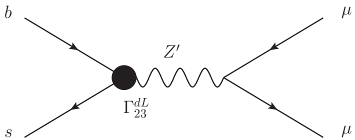
$$C_9^{\mu\mu} \simeq -\left(\frac{a}{1/3}\right)\left(\frac{3\text{TeV}}{m_{Z'}/g'}\right)^2 ,$$

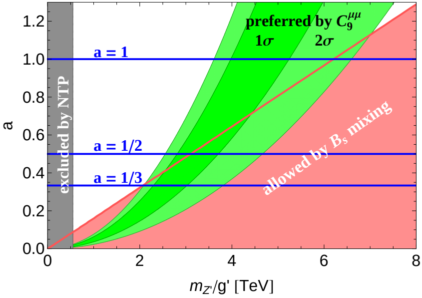
$$C_9^{ee} = C_9^{\prime\ell\ell} = C_{10}^{\ell\ell} = C_{10}^{\prime\ell\ell} = 0 .$$

- $a < 1$ to satisfy B_s mixing.



$$\Delta M_{12}/M_{12}^{\text{SM}} \propto a^2 g'^2/m_{Z'}^2 .$$





$b \to s$ anomalies resolved!

LHC constraints

Z' couples to first-gen. quarks $\Rightarrow$ direct detection via $pp \to Z' \to \mu^+\mu^-$.

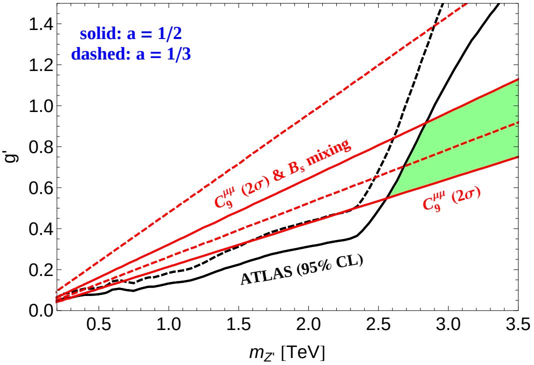
- For $m_t \ll m_{Z'} < 2m_{\nu_R}$:

  $$\text{BR}(Z' \to \mu\mu) \simeq \frac{1}{3+4a^2}\,,$$

  and

  $$ee : \mu\mu : \tau\tau : uu : dd : ss : cc : bb : tt$$
  $$= 0 : 1 : 1 : \frac{a^2}{3} : \frac{a^2}{3} : \frac{a^2}{3} : \frac{a^2}{3} : \frac{4a^2}{3} : \frac{4a^2}{3}\,.$$

- Can rescale $B-L$ limits from ATLAS [1405.4123].
- Flavor violating decays $Z' \to bs$ suppressed.

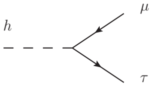


Look forward to new LHC run!

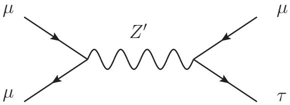
Add third scalar doublet for $h \to \mu\tau$

Put in third scalar doublet $\Phi_3 \sim 2$ for $h \to \mu\tau \Rightarrow \tau \to 3\mu$:

- $\mathrm{BR}(h \to \mu\tau) \propto \sin^2\theta_R \cos^2(\alpha - \beta) \tan^2\beta$:

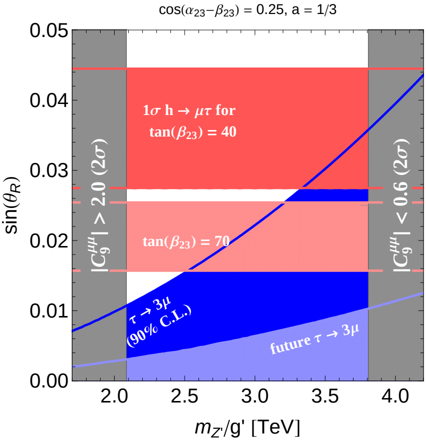


- $\mathrm{BR}(\tau \to 3\mu) \propto \sin^2\theta_R g'^4 / m_{Z'}^4$:



- Correlation:

$$\mathrm{BR}(\tau \to 3\mu) \propto \frac{(C_9^{\mu\mu})^2 \mathrm{BR}(h \to \mu\tau)}{a^2 \tan^2\beta} \,.$$



At 2σ predict: $\mathrm{BR}(\tau \to 3\mu) \gtrsim 9.3 \times 10^{-9} (10/\tan\beta)^2$.

Partial summary

Tantalizing hints for new physics in flavor sector:

- $h \to \mu\tau$ at 2.6σ,
- $b \to s$ plus $R(K)$ at $4.3\sigma \Leftarrow (\bar{s}\gamma_\alpha P_L b)(\overline{\mu}\gamma^\alpha \mu)/(35\,\mathrm{TeV})^2$.

New physics explanation:

- $U(1)_{L_\mu - L_\tau}$ gauge symmetry.
  - Flavor non-universal.
  - Good for quasi-degenerate neutrinos.
- Z' couplings to quarks can give $C_9^{\mu\mu}$ for $b \to s$.
  - $Z'qq$ via mixing with vector-like quarks.
  - $Z'qq$ via new scalar doublet $\sim$ type-I 2HDM. $\Leftarrow$ Z' at LHC.
- New doublet $\Phi \sim 2$ gives $\Delta(L_\mu - L_\tau)$ decay $h \to \mu\tau$ via mixing.
  $\Rightarrow$ Always $\mathrm{BR}(\tau \to 3\mu) \propto (C_9^{\mu\mu})^2 \mathrm{BR}(h \to \mu\tau)/\tan^2\beta$.

Partial summary

Tantalizing hints for new physics in flavor sector:

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H^+ coupling too small to also explain $\bar{B} \to D^{(*)}\tau\bar{\nu}/\bar{B} \to D^{(*)}\ell\bar{\nu}$.

A model for $b \to c$

J.H., A. Crivellin, P. Stoffer,
arXiv:1507.07567.

Modified type-X 2HDM

- Lepton-specific 2HDM (type X):

$$\mathcal{L}_Y = -\overline{Q}_L Y^u \tilde{\Phi}_2 u_R - \overline{Q}_L Y^d \Phi_2 d_R - \overline{L}_L Y^\ell \Phi_1 e_R + \text{h.c.}$$

- Add breaking terms for more freedom (type X $\to$ type III):

$$\Delta\mathcal{L}_Y = -\overline{Q}_L \xi^u \tilde{\Phi}_1 u_R - \overline{Q}_L \xi^d \Phi_1 d_R - \overline{L}_L \xi^\ell \Phi_2 e_R + \text{h.c.}$$

- For large $\tan\beta$ ($\varepsilon^\ell \equiv L_L^\dagger \xi^\ell L_R$ etc.):

$$\Gamma^{hLR}_{q_i q_j} \simeq -\frac{1}{\sqrt{2}}\left(\frac{m_{q_i}}{v}\delta_{ij}\cos\alpha - \varepsilon^q_{ij}\sin\alpha\right), \qquad \Gamma^{HLR}_{q_i q_j} \simeq -\frac{1}{\sqrt{2}}\left(\frac{m_{q_i}}{v}\delta_{ij}\sin\alpha + \varepsilon^q_{ij}\cos\alpha\right),$$

$$\Gamma^{H^+LR}_{u_i d_j} \simeq V_{ij'}\varepsilon^d_{j'j}, \qquad \Gamma^{H^+RL}_{u_i d_j} \simeq -\varepsilon^{u*}_{j'i} V_{j'j},$$

$$\Gamma^{hLR}_{\ell_f \ell_i} \simeq \frac{\sin\alpha\tan\beta}{\sqrt{2}}\left(\frac{m_{\ell_i}}{v}\delta_{fi} - \varepsilon^\ell_{fi}\right), \qquad \Gamma^{HLR}_{\ell_f \ell_i} \simeq -\frac{\cos\alpha\tan\beta}{\sqrt{2}}\left(\frac{m_{\ell_i}}{v}\delta_{fi} - \varepsilon^\ell_{fi}\right),$$

$$\Gamma^{ALR}_{\ell_f \ell_i} \simeq -i\frac{\tan\beta}{\sqrt{2}}\left(\frac{m_{\ell_i}}{v}\,\delta_{fi} - \varepsilon^\ell_{fi}\right), \qquad \Gamma^{H^+LR}_{\nu_f \ell_i} \simeq \tan\beta\left(\frac{m_{\ell_i}}{v}\delta_{fi} - \varepsilon^\ell_{fi}\right).$$

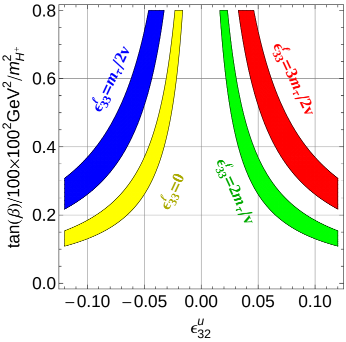
- $\varepsilon^\ell_{33} > m_\tau/v$ flips sign of coupling.

Modified type-X 2HDM

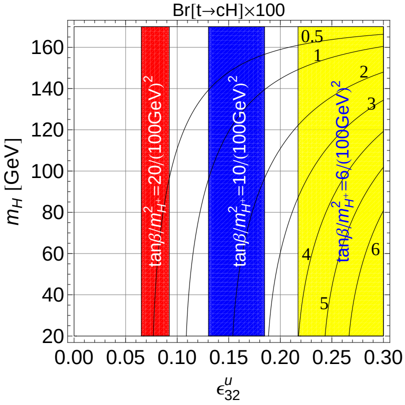
- To generate $b \to c$ and $h \to \mu\tau$, use structure $\varepsilon^d = 0$,

$$\varepsilon^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \times & \times \end{pmatrix}, \quad \varepsilon^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \times & \times \end{pmatrix}.$$

- Easily resolve $R(D^{(*)})$ using ε^u_{32}.

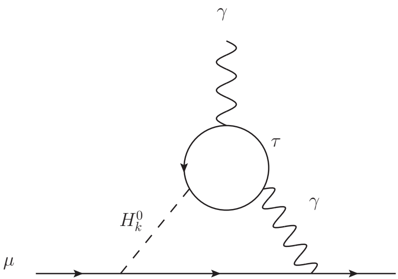


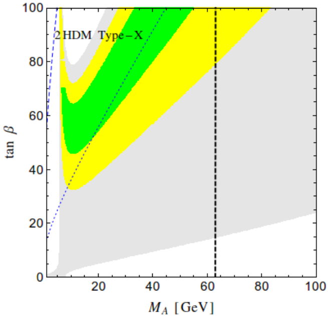
- If H (or A) are light, this induces $t \to Hc$, followed by $H \to \tau\tau$.



Why light H or A?

- Grandmother of anomalies: magnetic moment of muon $(g-2)_\mu$, at $\sim 3\sigma$.
- Light A in type-X 2HDM can resolve $(g-2)_\mu$ using Barr–Zee diagram.[14]





[14] Broggio et al, 1409.3199; Wang, Han, 1412.4874; Chun, Kang, Takeuchi, Tsai, 1507.08067.

Last anomaly...

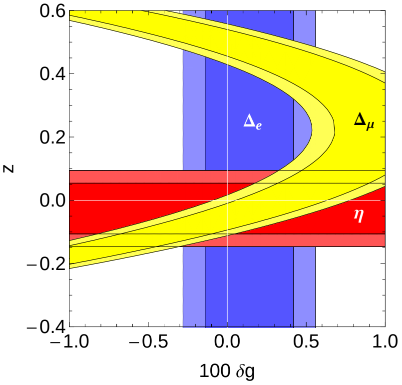
- Problem: Leads to wrong $\tau \to \ell\nu\nu$ rates! [Krawczyk, Temes, hep-ph/0410248; Abe, Sato, Yagyu, 1504.07059]
- Define

$$\Delta_\ell \equiv \frac{\mathrm{BR}(\tau \to \ell\overline{\nu}\nu)_{\mathrm{exp}}}{\mathrm{BR}(\tau \to \ell\overline{\nu}\nu)_{\mathrm{SM}}} - 1$$

  then Δ_μ is 2.4σ above SM expectation.
- Relevant for Michel parameter η:

$$z \equiv \frac{v^2}{m_{H^+}^2} \Gamma^{LR\,H^+}_{\nu_\tau \tau} \Gamma^{LR\,H^+\star}_{\nu_\mu \mu} .$$

- For type-X: δg negative and z positive.
- Negative z possible for $\varepsilon^\ell_{33} > m_\tau / v$!



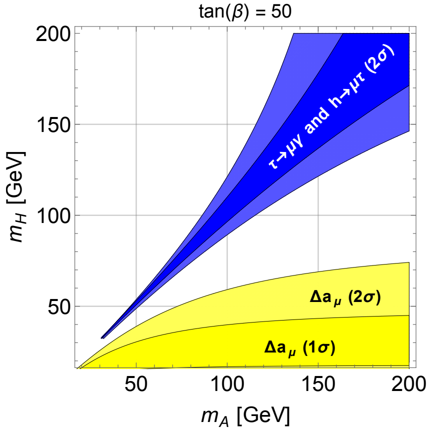
Flip τ coupling of A and H $\Rightarrow$ light H resolves $(g-2)_\mu$ *and* $\tau \to \mu\nu\nu$.

$h \to \mu\tau$ vs. $(g-2)_\mu$

- Light H resolves $(g-2)_\mu$ and $\tau \to \mu\nu\nu$, H^+ resolves $R(D^{(*)})$.
- Using ε^ℓ_{32}, can we also get $h \to \mu\tau$?

$h \to \mu\tau$ vs. $(g-2)_\mu$

- Light H resolves $(g-2)_\mu$ and $\tau \to \mu\nu\nu$, H^+ resolves $R(D^{(*)})$.
- Using ε^ℓ_{32}, can we also get $h \to \mu\tau$?
- No, large $\tau \to \mu\gamma$.
- Same Barr–Zee diagrams for $(g-2)_\mu$ and $\tau \to \mu\gamma$.



Can explain *either* $(g-2)_\mu$ *or* $h \to \mu\tau$ together with $R(D^{(*)})$ in our 2HDM.

Summary

Tantalizing hints for new physics in flavor sector:

- Lepton flavor violation: $h \to \mu\tau$ at 2.6σ.
  - 2HDM?
- Lepton flavor non-universality: $R(K)$ at 2.6σ.
- $b \to s$ (plus $R(K)$) at 4.3σ.
  - Flavored Z'?
- Lepton flavor non-universality: $R(D^{(*)})$ at 3.9σ.
  - Charged scalar of 2HDM?
- Magnetic moment: $(g-2)_\mu$ at $\sim 3\sigma$.
  - Light neutral scalar of 2HDM?

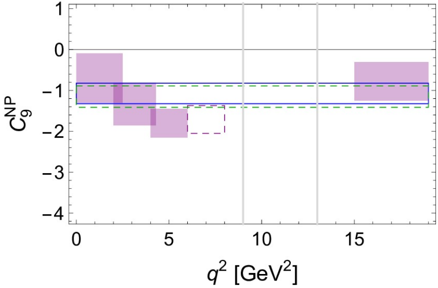
Wait for new data, new calculations, and new physics.

Backup

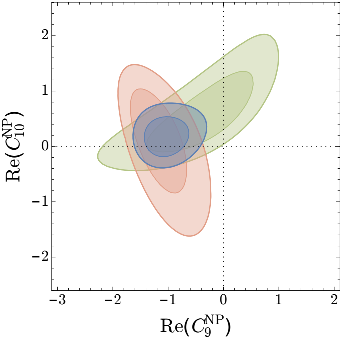
New physics vs. QCD in $b \to s$

Check C_9 in $B \to K^* \mu^+ \mu^-$ as function of $\mu\mu$ mass q^2:

- New physics $\to$ flat.
- Hadronic effect $\to$ not flat.



Inconclusive as of yet.



Altmannshofer, Straub, 1503.06199.

If it's QCD (non-factorizable charm loop), it's much larger than expected!

Vector-like quarks for $b \to s$

- Again singlet scalar $S \sim 1$ under $U(1)_{L_\mu - L_\tau}$ and three ν_R for seesaw.
- $Q_L \equiv (U_L, D_L)$, D_R^c, U_R^c and partners $\tilde{Q}_R$, $\tilde{D}_L^c$, $\tilde{U}_L^c$ with $L_\mu - L_\tau = 1$:

$$m_Q \overline{Q}_L \tilde{Q}_R + m_D \overline{\tilde{D}}_L D_R + m_U \overline{\tilde{U}}_L U_R + \text{h.c.}$$

- Yukawas

$$S \sum_{j=1}^{3} \left(\overline{\tilde{D}}_R Y_j^Q P_L d_j + \overline{\tilde{U}}_R Y_j^Q P_L u_j \right) + S^\dagger \sum_{j=1}^{3} \left(\overline{\tilde{D}}_L Y_j^D P_R d_j + \overline{\tilde{U}}_L Y_j^U P_R u_j \right) + \text{h.c.}$$

induce mixing with SM quarks and Z' couplings[15]

$$g' \left(\bar{d}_i \gamma^\mu P_L d_j Z'_\mu \Gamma_{ij}^{dL} + \bar{d}_i \gamma^\mu P_R d_j Z'_\mu \Gamma_{ij}^{dR} \right),$$

with

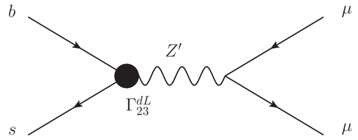
$$\Gamma_{ij}^{dR} \simeq -\frac{v_\Phi^2}{2 m_D^2} (Y_i^D Y_j^{D*}), \qquad \Gamma_{ij}^{dL} \simeq \frac{v_\Phi^2}{2 m_Q^2} (Y_i^Q Y_j^{Q*}).$$

[15] Langacker, 0801.1345; Altmannshofer, Gori, Pospelov, Yavin, 1403.1269.

Vector-like quarks II

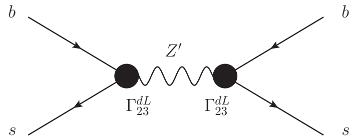
Focus on Γ_{23}^{dL}:

$b \to s\mu\mu$:

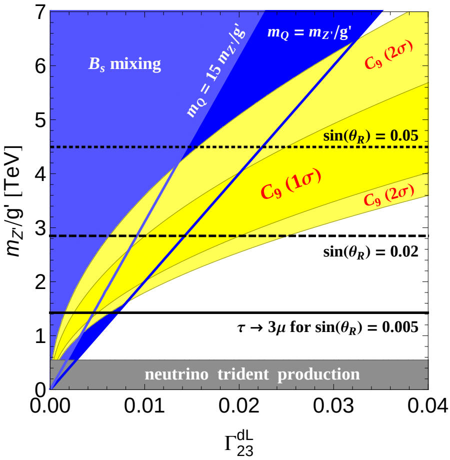


$C_9^{\mu\mu} \propto \Gamma_{23}^{dL} g'^2 / m_{Z'}^2$.

B_s mixing:



$\Delta M_{12} / M_{12}^{\mathrm{SM}} \propto (\Gamma_{23}^{dL})^2 g'^2 / m_{Z'}^2$.

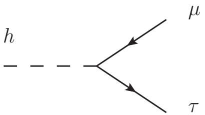


J.H., Crivellin, D'Ambrosio, PRL 2015, 1501.00993.

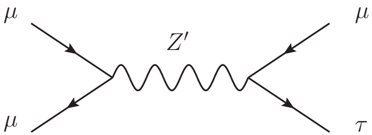
Vector-like quarks + $h \to \mu\tau$

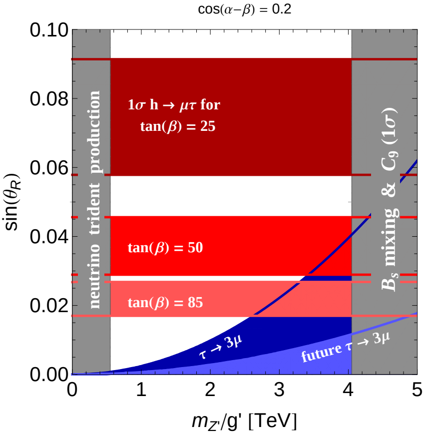
Put in the second scalar doublet for $h \to \mu\tau \Rightarrow$ correlation with $\tau \to 3\mu$:

$\text{BR}(h \to \mu\tau) \propto \sin^2\theta_R \cos^2(\alpha - \beta)\tan^2\beta$.



$\text{BR}(\tau \to 3\mu) \propto \sin^2\theta_R g'^4 / m_{Z'}^4$:





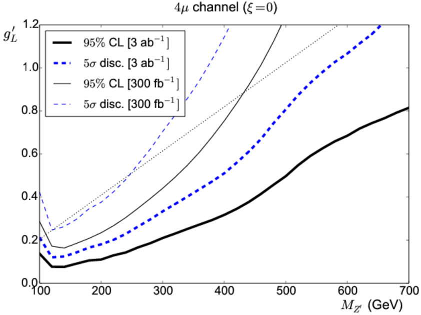
At 1σ predict: $\text{BR}(\tau \to 3\mu) \gtrsim 3.8 \times 10^{-8}(10/\tan\beta)^2$.

$L_\mu - L_\tau$ at LHC

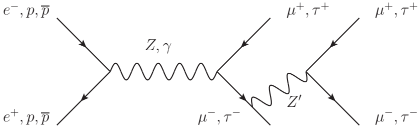
Even without Z' couplings to quarks:

$$pp \to \mu\mu Z' \to 4\mu\,.$$

Ma, Roy, Roy, PLB 2002.



del Aguila, Chala, Santiago, Yamamoto, JHEP 2015 [1411.7394].



Currently weaker than limits from neutrino trident production

$$\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$$

(← thin dotted line).
Altmannshofer, Gori, Pospelov, Yavin, PRL 2014.