Flavor violation in multi-Higgs-doublet models

Julian Heeck

2nd International Conference on Charged Lepton Flavor Violation

June 20, 2016

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

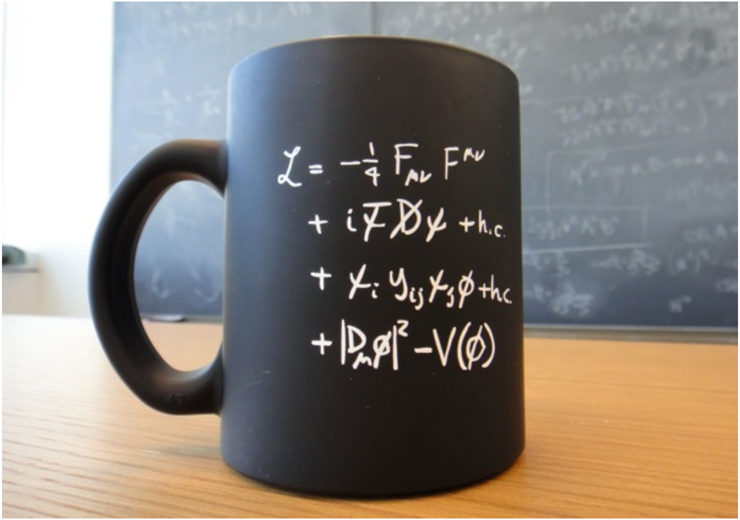
Fundamental Interactions .be

fnrs LA LIBERTÉ DE CHERCHER

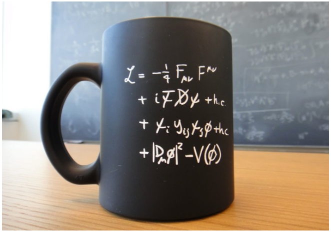
UNIVERSITÉ LIBRE DE BRUXELLES ULB

Standard Model of particle physics

Beautiful and simple:



Standard Model of particle physics



Fine print:

- Gauge group $SU(3)_{\text{color}} \times SU(2)_{\text{isospin}} \times U(1)_{\text{hypercharge}}$
  $\Rightarrow 8 + 3 + 1$ spin-1 bosons with field strength $F_{\mu\nu}$;
- Three copies of spin-$\frac{1}{2}$ Weyl fields (families/generations) in rep.

$$\Psi_{1,2,3} \sim \underbrace{(\mathbf{3}, \mathbf{2}, +\tfrac{1}{6}) \oplus (\mathbf{3}, \mathbf{1}, +\tfrac{2}{3}) \oplus (\mathbf{3}, \mathbf{1}, -\tfrac{1}{3})}_{\text{quarks}} \oplus \underbrace{(\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}) \oplus (\mathbf{1}, \mathbf{1}, -1)}_{\text{leptons}};$$

- One complex spin-0 field $\phi \sim (\mathbf{1}, \mathbf{2}, +\frac{1}{2})$ which breaks
  $SU(2) \times U(1) \to U(1)_{\text{EM}}$ via $\langle \phi \rangle \simeq 250\,\text{GeV}$;
- About 18 free parameters, all measured as of 2013 ($m_{\text{BEH}} \simeq 125\,\text{GeV}!$).

Conserved lepton charges in SM

SM: one scalar doublet $\Phi = \begin{pmatrix} G^+ \\ (v + h + iG)/\sqrt{2} \end{pmatrix}$.

Leptons:

$$\mathcal{L} \supset i\overline{L}_{\alpha,L} \not{D} L_{\alpha,L} + i\overline{\ell}_{\alpha,R} \not{D} \ell_{\alpha,R} - \left(Y^\ell_{\alpha\beta} \overline{L}_{\alpha,L} \Phi \ell_{\beta,R} + \text{h.c.} \right).$$

Singular value decomposition: $Y^\ell = V_L \text{diag}(y_e, y_\mu, y_\tau) V_R^\dagger$.
Rotate lepton fields into mass basis ($m_\alpha = y_\alpha v/\sqrt{2}$):

$$\mathcal{L} \to i\overline{L}_{\alpha,L} \not{D} L_{\alpha,L} + i\overline{\ell}_{\alpha,R} \not{D} \ell_{\alpha,R} - \left(\sum_{\alpha=e,\mu,\tau} y_\alpha \overline{L}_{\alpha,L} \Phi \ell_{\alpha,R} + \text{h.c.} \right).$$

$\Rightarrow$ No flavor-changing couplings.
$\Rightarrow$ Global $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$ symmetry.

Conserved quark charges in SM

Quarks:

$$\mathcal{L} \supset i\overline{Q}_{\alpha,L} \not{D} Q_{\alpha,L} + i\overline{d}_{\alpha,R} \not{D} d_{\alpha,R} + i\overline{u}_{\alpha,R} \not{D} u_{\alpha,R} - \left(Y^d_{\alpha\beta} \overline{Q}_{\alpha,L} \Phi d_{\beta,R} + Y^u_{\alpha\beta} \overline{Q}_{\alpha,L} i\sigma_2 \Phi^* u_{\beta,R} + \text{h.c.} \right)$$

SVD: $Y^d = V^d_L \text{diag}(y_d, y_s, y_b) V^\dagger_R$ and $Y^u = V^u_L \text{diag}(y_u, y_c, y_t) \tilde{V}^\dagger_R$.

Unless $V^d_L = V^u_L$: off-diagonal couplings! (Move to $W^\pm_\mu$ interactions.)

$\Rightarrow$ Flavor-changing couplings $\propto (V^{d,\dagger}_L V^u_L)_{\alpha\beta} \equiv (V_{CKM})_{\alpha\beta}$.

$\Rightarrow$ Only global $U(1)_B$.

Conserved quark charges in SM

Quarks:

$$\mathcal{L} \supset i\overline{Q}_{\alpha,L}\not{D}Q_{\alpha,L} + i\overline{d}_{\alpha,R}\not{D}d_{\alpha,R} + i\overline{u}_{\alpha,R}\not{D}u_{\alpha,R}$$
$$- \left(Y^d_{\alpha\beta}\overline{Q}_{\alpha,L}\Phi d_{\beta,R} + Y^u_{\alpha\beta}\overline{Q}_{\alpha,L} i\sigma_2\Phi^* u_{\beta,R} + \text{h.c.}\right)$$

SVD: $Y^d = V^d_L \mathrm{diag}(y_d, y_s, y_b) V^\dagger_R$ and $Y^u = V^u_L \mathrm{diag}(y_u, y_c, y_t)\tilde{V}^\dagger_R$.
Unless $V^d_L = V^u_L$: off-diagonal couplings! (Move to $W^\pm_\mu$ interactions.)

⇒ Flavor-changing couplings $\propto (V^{d,\dagger}_L V^u_L)_{\alpha\beta} \equiv (V_{CKM})_{\alpha\beta}$.
⇒ Only global $U(1)_B$.

Global symmetry in SM:

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$
$$= \underbrace{U(1)_{B+L}}_{\text{anomalous}} \times U(1)_{B-L} \times U(1)_{L_e - L_\mu} \times U(1)_{L_\mu - L_\tau}\,.$$

$\Delta B = 3$, $\Delta L_e = 1$, $\Delta L_\mu = 1$, $\Delta L_\tau = 1$, but heavily suppressed.[1]

[1] G. t Hooft, 1976.

Flavor changing effects in SM

Couplings of Brout–Englert–Higgs boson h to fermions:

$$-\mathcal{L} = \sum_{f=e,\mu,\tau,d,s,b,u,c,t} h\left(\frac{m_f}{v}\right)\overline{f}f\,.$$

Flavor violation in SM only for quarks via CKM matrix (charged currents), lepton flavor is conserved.

Even non-zero neutrino masses typically only induce *tiny* LFV. E.g. light Dirac neutrinos:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta\gamma)}{\Gamma(\ell_\alpha \to \ell_\beta\nu_\alpha\overline{\nu}_\beta)} \simeq \frac{3\alpha_{\mathrm{EM}}}{32\pi}\left|\sum_{j=2,3} U_{\alpha j}\frac{\Delta m^2_{j1}}{M_W^2}U^\dagger_{j\beta}\right|^2 < 5\times 10^{-53}\,.$$

LFV = new physics!

Two-Higgs-Doublet Model (2HDM)

Simple extension of SM: add one more scalar doublet.[2]

- Arises often in BSM, e.g. SUSY, axion models.
- New physical scalars: H, A, H^+.
- $\rho = M_W^2/M_Z^2 \cos^2\theta_W = 1$ at tree level; $\langle\Phi_1\rangle/\langle\Phi_2\rangle = \tan\beta$.
- Brings additional CP violation (useful for baryogenesis).
- Generally induces flavor-changing processes (both quarks and leptons), e.g.

$$\ell_\alpha \to \ell_\beta\gamma\,, \qquad h \to \ell_\alpha\bar{\ell}_\beta\,,^3 \qquad Z \to \ell_\alpha\bar{\ell}_\beta\,.$$

- Limits up to $m_{A,H} > 10^3$–$10^5\,\mathrm{TeV}$ for $\mathcal{O}(1)$ $e\mu$ or ds couplings.

[2] Lee, 1973; extensive review of 2HDM in Branco et al, arXiv:1106.0034.

[3] Davidson, Grenier, 2010; Blankenburg, Ellis, Isidori; Harnik, Kopp, Zupan, 2012.

Two-Higgs-Doublet Model (2HDM)

Simple extension of SM: add one more scalar doublet.[2]

- Arises often in BSM, e.g. SUSY, axion models.
- New physical scalars: H, A, H^+.
- $\rho = M_W^2/M_Z^2 \cos^2\theta_W = 1$ at tree level; $\langle\Phi_1\rangle/\langle\Phi_2\rangle = \tan\beta$.
- Brings additional CP violation (useful for baryogenesis).
- Generally induces flavor-changing processes (both quarks and leptons), e.g.

$$\ell_\alpha \to \ell_\beta\gamma\,, \qquad h \to \ell_\alpha\bar{\ell}_\beta\,,^{3} \qquad Z \to \ell_\alpha\bar{\ell}_\beta\,.$$

- Limits up to $m_{A,H} > 10^3$–$10^5\,\mathrm{TeV}$ for $\mathcal{O}(1)$ $e\mu$ or ds couplings.

Why flavor-changing?

[2] Lee, 1973; extensive review of 2HDM in Branco et al, arXiv:1106.0034.
[3] Davidson, Grenier, 2010; Blankenburg, Ellis, Isidori; Harnik, Kopp, Zupan, 2012.

Yukawa couplings for 2HDM:

$$\mathcal{L} \supset i\overline{L}_{\alpha,L}\not{D}L_{\alpha,L} + i\overline{\ell}_{\alpha,R}\not{D}\ell_{\alpha,R} - \left(Y^{\ell,1}_{\alpha\beta}\overline{L}_{\alpha,L}\Phi_1\ell_{\beta,R} + Y^{\ell,2}_{\alpha\beta}\overline{L}_{\alpha,L}\Phi_2\ell_{\beta,R} + \text{h.c.}\right)$$

Not possible to diagonalize both Y^1 and Y^2 $\Rightarrow$ LFV!

[4] Pich & Tuzón, 2009; Ferreira, Lavoura, Silva, 2010.
[5] Paschos, 1977, Weinberg & Glashow, 1977.

LFV in 2HDM

Yukawa couplings for 2HDM:

$$\mathcal{L} \supset i\overline{L}_{\alpha,L}\not{D}L_{\alpha,L} + i\overline{\ell}_{\alpha,R}\not{D}\ell_{\alpha,R} - \left(Y^{\ell,1}_{\alpha\beta}\overline{L}_{\alpha,L}\Phi_1\ell_{\beta,R} + Y^{\ell,2}_{\alpha\beta}\overline{L}_{\alpha,L}\Phi_2\ell_{\beta,R} + \text{h.c.}\right)$$

Not possible to diagonalize both Y^1 and Y^2 $\Rightarrow$ LFV!

Unless:

- $Y^{\ell,1}_{\alpha\beta} = 0$ or $Y^{\ell,2}_{\alpha\beta} = 0$.
- $Y^{\ell,1}_{\alpha\beta} = c \times Y^{\ell,2}_{\alpha\beta}$ (more general *alignment*, RGE unstable).[4]

Formally:[5]

> No tree-level FCNC if fermions of the same electric charge get mass from just *one* scalar doublet.

Impose $\mathbb{Z}_2$ symmetry: $\Phi_{1,2} \to \pm\Phi_{1,2}$, $\ell_R \to -\ell_R$ gives $Y^{\ell,1}_{\alpha\beta} = 0 \neq Y^{\ell,2}_{\alpha\beta}$.

[4] Pich & Tuzón, 2009; Ferreira, Lavoura, Silva, 2010.

[5] Paschos, 1977, Weinberg & Glashow, 1977.

2HDM with $\mathbb{Z}_2$

2HDM without tree-level scalar-mediated FCNC via $\mathbb{Z}_2$:[6]

type	Φ_1	Φ_2	Q_L, L_L	u_R	d_R	ℓ_R
I	+	−	+	−	−	−
II (MSSM like)	+	−	+	−	+	+
X (lepton specific)	+	−	+	−	−	+
Y (flipped)	+	−	+	−	+	−

- (More choices if we add ν_R, e.g. neutrinophilic 2HDM.[7])
- (If type-I Φ_1 has no VEV: Inert Doublet Model for dark matter.[8])
- ($\mathbb{Z}_2$ can be promoted to $U(1)_H$.[9])
- Most general 2HDM (*without* $\mathbb{Z}_2$, *with* FCNC): type III.

[6] Barger, Hewett, Phillips, 1990; Aoki, Kanemura, Tsumura, Yagyu, 2009.
[7] Ma, 2001, Wang, Wang, Yang, 2006, Gabriel, Nandi, 2007, Davidson, Logan, 2009.
[8] Deshpande, Ma, 1978.
[9] Ko, Omura, Yu, 2012, 2013, 2014.

2HDM potential

Scalar potential for 2HDM, $\Phi_j = \begin{pmatrix} \phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix}$:

$$V = \sum_{j=1,2} \left[m_{jj}^2 \Phi_j^\dagger \Phi_j + \tfrac{1}{2}\lambda_j (\Phi_j^\dagger \Phi_j)^2 \right]$$
$$- \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$
$$+ \left[\tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \lambda_6 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_1^\dagger \Phi_2\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\left(\Phi_1^\dagger \Phi_2\right) + \text{h.c.} \right]$$

In $\mathbb{Z}_2$ models:

- $\lambda_6 = \lambda_7 = 0$
- $m_{12}^2 \neq 0$: softly broken $\mathbb{Z}_2$ to avoid domain wall problem.
- If CP conserved:

$$h = \sin\alpha\, \rho_1 - \cos\alpha\, \rho_2 \,, \qquad A = \sin\beta\, \eta_1 - \cos\beta\, \eta_2 \,,$$
$$H = -\cos\alpha\, \rho_1 - \sin\alpha\, \rho_2 \,, \qquad H^+ = \sin\beta\, \phi_1^+ - \cos\beta\, \phi_2^+ \,.$$

2HDM with $\mathbb{Z}_2$: couplings

Yukawa couplings,[10] no FCNC by construction:

$$\mathcal{L} = - \sum_{f=u,d,\ell} \left(\frac{m_f}{v} \xi_h^f \overline{f} f\, h + \frac{m_f}{v} \xi_H^f \overline{f} f\, H - i \frac{m_f}{v} \xi_A^f \overline{f} \gamma_5 f\, A \right)$$
$$- \left\{ \frac{\sqrt{2} V_{ud}}{v} \overline{u} \left(m_u \xi_A^u \mathrm{P}_L + m_d \xi_A^d \mathrm{P}_R \right) d\, H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v} \overline{\nu_L} \ell_R H^+ + \text{h.c.} \right\}$$

type	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

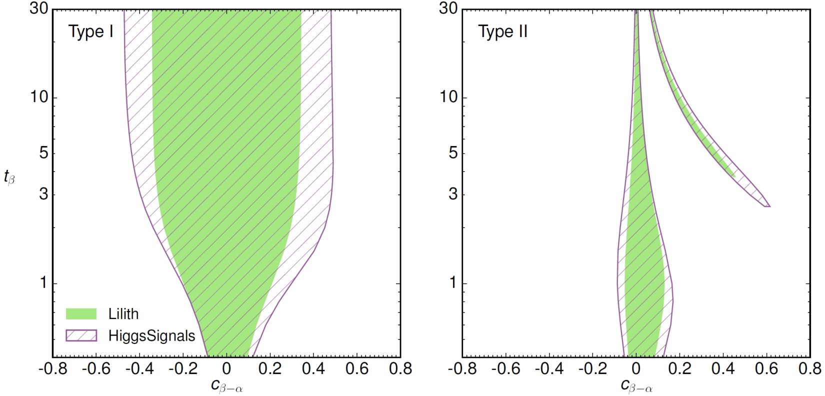
Experimental limits on $\tan\beta$, $\cos(\alpha-\beta)$, M_{A,H,H^+}.

[10] Aoki, Kanemura, Tsumura, Yagyu, 2009.

Constraints from h couplings

Define $m_h = 125\,\mathrm{GeV}$; h has SM couplings for $\cos(\alpha-\beta) \to 0$.[11]

$\tan\beta$ vs. $\cos(\alpha-\beta)$:

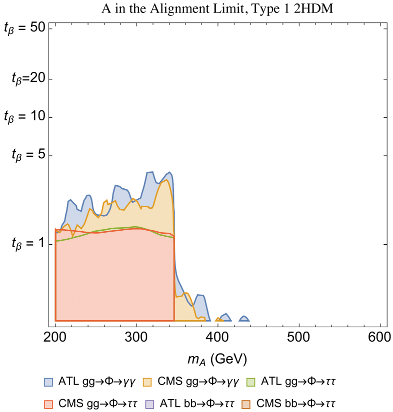


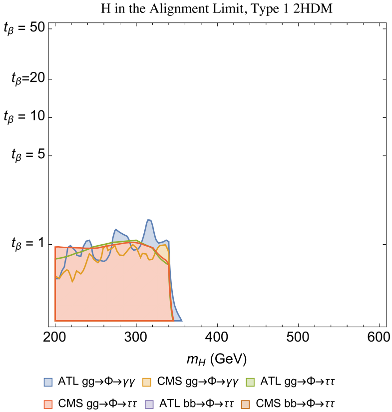
Dorsch, Huber, Mimasu, No, arXiv:1601.04545.

[11] Or for $m_{A,H,H^+} \gg m_h$, see Haber, 1994, Gunion, Haber, 2002, Haber et al. . . .

Alignment limit $\cos(\alpha - \beta) = 0$.

$\tan\beta$ vs. m_A and m_H for type I:



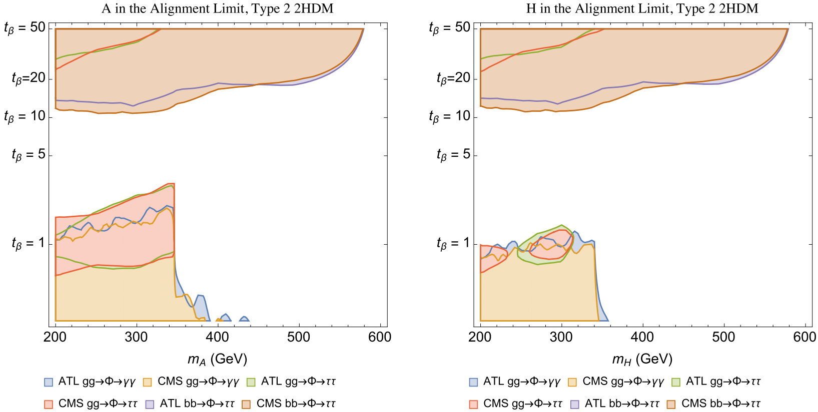


Craig, D'Eramo, Draper, Thomas, Zhang, arXiv:1504.04630.

Constraints from direct searches

Alignment limit $\cos(\alpha - \beta) = 0$.

$\tan\beta$ vs. m_A and m_H for type II:



Craig, D'Eramo, Draper, Thomas, Zhang, arXiv:1504.04630.

2HDM *with* flavor violation

General type-III 2HDM:

- No symmetry distinguishing Φ_1 and $\Phi_2 \Rightarrow \tan\beta$ unphysical.[12]
- Rotate to Georgi basis, only $\Phi_1 = \begin{pmatrix} G^+ \\ (v + h_1 + iG)/\sqrt{2} \end{pmatrix}$ has VEV.[13]
- SM-like Φ_1 still mixes with Φ_2 with angle $\alpha_H \mathrel{\widehat{=}} \beta - \alpha$.
- Φ_2 has arbitrary (off-diagonal) couplings ρ to fermions.

Yukawa couplings (CP conserving case):[14]

$$\begin{aligned} \bar{f} P_R f' h &: \frac{m_f}{v} \sin(\alpha_H) \delta_{ff'} + \cos(\alpha_H) \rho_{ff'} \,, \\ \bar{f} P_R f' H &: \frac{m_f}{v} \cos(\alpha_H) \delta_{ff'} - \sin(\alpha_H) \rho_{ff'} \,, \\ \bar{f} P_R f' A &: \pm i \rho_{ff'} \,. \end{aligned}$$

Simply pick ρ to explain e.g. $h \to \mu\tau$ & $g - 2$. Talk by Kazuhiro Tobe.

[12] Davidson, Haber, 2005; Haber, O'Neil, 2006.
[13] Georgi, Nanopoulos, 1979.
[14] Davidson, Grenier, 2010.

2HDM *with* flavor violation

General type-III 2HDM:

- No symmetry distinguishing Φ_1 and $\Phi_2 \Rightarrow \tan\beta$ unphysical.[12]
- Rotate to Georgi basis, only $\Phi_1 = \begin{pmatrix} G^+ \\ (v + h_1 + iG)/\sqrt{2} \end{pmatrix}$ has VEV.[13]
- SM-like Φ_1 still mixes with Φ_2 with angle $\alpha_H \mathrel{\widehat{=}} \beta - \alpha$.
- Φ_2 has arbitrary (off-diagonal) couplings ρ to fermions.

Yukawa couplings (CP conserving case):[14]

$$\begin{aligned} \overline{f} P_R f' h &: \frac{m_f}{v} \sin(\alpha_H) \delta_{ff'} + \cos(\alpha_H) \rho_{ff'} \,, \\ \overline{f} P_R f' H &: \frac{m_f}{v} \cos(\alpha_H) \delta_{ff'} - \sin(\alpha_H) \rho_{ff'} \,, \\ \overline{f} P_R f' A &: \pm i \rho_{ff'} \,. \end{aligned}$$

Any guesses for ρ?

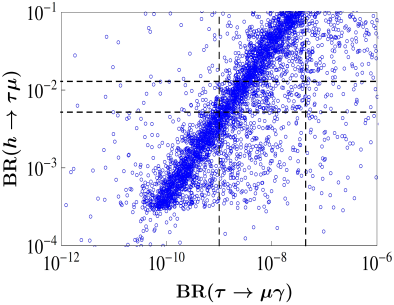
---

[12] Davidson, Haber, 2005; Haber, O'Neil, 2006.
[13] Georgi, Nanopoulos, 1979.
[14] Davidson, Grenier, 2010.

Cheng–Sher Ansatz

Popular Ansatz:[15] hierarchical $\rho_{ij} = \sqrt{m_i m_j}/v \times \mathcal{O}(1)$.

- Automatically suppresses first-gen. couplings.
- m_{A,H,H^+} down to $\mathcal{O}(200\,\mathrm{GeV})$ allowed.
- Only leptons: can give large $\tau \to \mu\gamma$ or $h \to \mu\tau$ (but not $g-2$).[16]
- Large $H, A \to \mu\tau$.[17]



[15] Cheng, Sher, 1987.
[16] Davidson, Grenier, 2010; Kopp, Nardecchia, 2014; Aristizabal Sierra, Vicente, 2014.
[17] Sher, Thrasher, arXiv:1601.03973.

Type-? 2HDM + perturbations

Different Ansatz for ρ:

- Start with familiar 2HDM of type I/II/X/Y.
- Add (off-diagonal) perturbations.

Example 1: type I + pert. from flavor symmetry to explain $h \to \mu\tau$.[18]

[18] **J.H.**, M. Holthausen, W. Rodejohann, Y. Shimizu, NPB (2015), arXiv:1412.3671.
[19] Campos, Hernández, Päs, Schumacher, PRD 2015.

Type-? 2HDM + perturbations

Different Ansatz for ρ:

- Start with familiar 2HDM of type I/II/X/Y.
- Add (off-diagonal) perturbations.

Example 1: type I + pert. from flavor symmetry to explain $h \to \mu\tau$.[18]

Lepton flavor violation $\Leftrightarrow$ connection to flavor symmetries?

[18] **J.H.**, M. Holthausen, W. Rodejohann, Y. Shimizu, NPB (2015), arXiv:1412.3671.
[19] Campos, Hernández, Päs, Schumacher, PRD 2015.

Type-? 2HDM + perturbations

Different Ansatz for ρ:

- Start with familiar 2HDM of type I/II/X/Y.
- Add (off-diagonal) perturbations.

Example 1: type I + pert. from flavor symmetry to explain $h \to \mu\tau$.[18]

Lepton flavor violation $\Leftrightarrow$ connection to flavor symmetries?

- Non-abelian symmetries A_4 or S_4[19] have at least 3HDM.
- Predict $\text{BR}(h \to \mu\tau) \sim \text{BR}(h \to e\tau)$.
- CMS-PAS-HIG-14-040: $\text{BR}(h \to e\tau) < 0.69\%$ at 95%CL.

[18] **J.H.**, M. Holthausen, W. Rodejohann, Y. Shimizu, NPB (2015), arXiv:1412.3671.
[19] Campos, Hernández, Päs, Schumacher, PRD 2015.

Type-? 2HDM + perturbations

Different Ansatz for ρ:

- Start with familiar 2HDM of type I/II/X/Y.
- Add (off-diagonal) perturbations.

Example 1: type I + pert. from flavor symmetry to explain $h \to \mu\tau$.[18]

Lepton flavor violation $\Leftrightarrow$ connection to flavor symmetries?

- Non-abelian symmetries A_4 or S_4[19] have at least 3HDM.
- Predict $\mathrm{BR}(h \to \mu\tau) \sim \mathrm{BR}(h \to e\tau)$.
- CMS-PAS-HIG-14-040: $\mathrm{BR}(h \to e\tau) < 0.69\%$ at 95%CL.

Here: take abelian symmetry.

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

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

[18] **J.H.**, M. Holthausen, W. Rodejohann, Y. Shimizu, NPB (2015), arXiv:1412.3671.
[19] Campos, Hernández, Päs, Schumacher, PRD 2015.

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.[20]
- Light Z' could resolve $(g-2)_\mu$ anomaly.[21]
- Good zeroth order approximation to neutrino mixing with quasi-degenerate masses ($m_{1,2,3} \simeq 1\,\mathrm{eV}$ and $\beta = \pi/2$):

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

- $L_\mu - L_\tau$ gives $\theta_{23} = \pi/4$ and $\theta_{13} = 0$.[22]

---

[20] He, Joshi, Lew, Volkas, PRD 1991; Foot, MPLA 1991.

[21] Baek et al, PRD 2001; Altmannshofer et al, PRL 2014; Baek, 1510.02168.

[22] 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 $U(1)_{L_\mu - L_\tau}$.[23]
- 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 $S^2 \Phi_2^\dagger \Phi_1 \to m_{12}^2 \Phi_2^\dagger \Phi_1$.
  $\Rightarrow$ small VEV $\langle \Phi_1 \rangle$ induced! ($\leftarrow$ large $\tan\beta$ region.)
- Lepton Yukawa couplings:[24]

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

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

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

[23] **J.H.**, Rodejohann, PRD 2011, see Dutta, Joshipura, Vijaykumar, PRD 1994, for $L_e - L_{\mu,\tau}$.
[24] **J.H.**, Holthausen, Rodejohann, Shimizu, NPB (2015), 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!

$h \to \mu\tau$

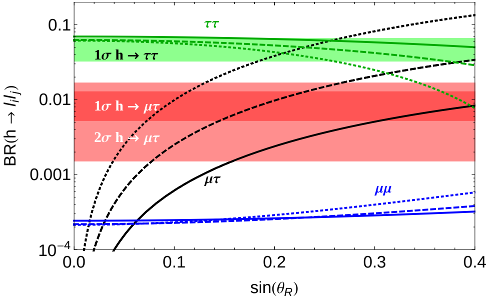
- CMS 2.4σ excess in $h \to \mu\tau$ for

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

- $c_\beta \sim s_R \ll 1$ 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 $h \to \ell_i \ell_j$:



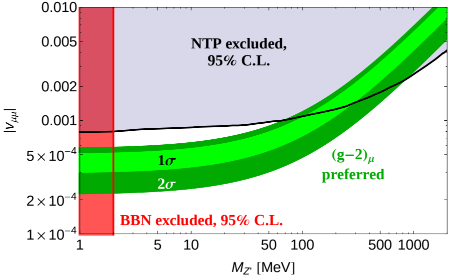
solid:	$\tan\beta = 3$,	$\cos(\alpha-\beta) = -0.3$,
dashed:	$\tan\beta = 10$,	$\cos(\alpha-\beta) = -0.2$,
dotted:	$\tan\beta = 20$,	$\cos(\alpha-\beta) = -0.2$.

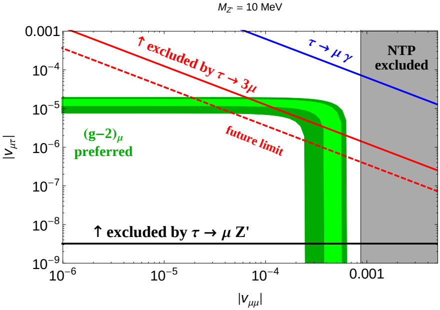
J.H., Holthausen, Rodejohann, Shimizu, 1412.3671.

Lepton flavor violation with light bosons

As an aside:[25]

- Same $L_\mu - L_\tau$ model, make $g' \ll 1 \Rightarrow$ Light Z'.
- $Z'\mu\mu$ coupling constrained by Neutrino Trident Production.[26]
- $Z'\mu\tau$ coupling gives two-body $\tau \to \mu Z'$, followed by $Z' \to \nu\nu$.[27]
- ARGUS (1995): $\mathrm{Br}(\tau \to \mu Z') < 5 \times 10^{-3}$ from 5×10^5 τs.





[25] **J.H.**, Phys. Lett. B (2016), arXiv:1602.03810.
[26] Altmannshofer, Gori, Pospelov, Yavin, PRL 2014.
[27] Foot, He, Lew, Volkas, 1994; McDonald, McKellar, 2006.

Type-? 2HDM + perturbations

Different Ansatz for ρ:

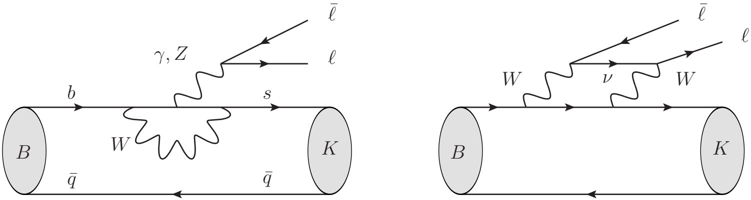
- Start with familiar 2HDM of type I/II/X/Y.
- Add (off-diagonal) perturbations.

Example 1: type I + pert. from flavor symmetry to explain $h \to \mu\tau$.

Example 2: type I + pert. from flavor symmetry to explain $R(K)$ etc.[28]

[28] **J.H.**, A. Crivellin, G. D'Ambrosio, Phys. Rev. Lett. (2015) [arXiv:1501.00993]; **J.H.**, A. Crivellin, G. D'Ambrosio, Phys. Rev. D (2015), [arXiv:1503.03477].

- 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.)

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

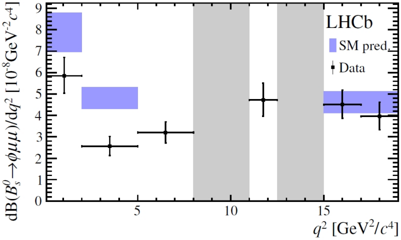
$$B_s^0 \to \phi\mu^+\mu^- \to K^+K^-\mu^+\mu^- ,$$

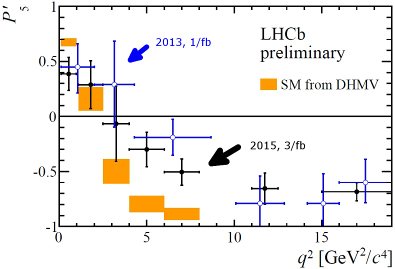
  confirming 1/fb analysis [1305.2168].

- 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[29] with effective Hamiltonian

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

with

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

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

[29] Descotes-Genon, Hofer, Matias, Virto, 1510.04239. Similar results by Hurth, Mahmoudi, Neshatpour, 1410.4545; Altmannshofer, Straub, 1503.06199, 1411.3161; ...

Global fit[29] with effective Hamiltonian

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

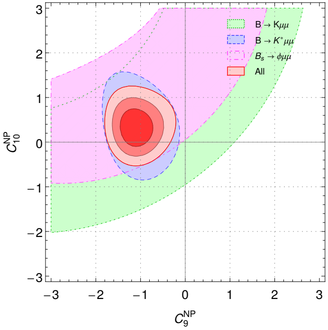
with

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

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

to all $B \to X\mu^+\mu^-$, $B \to X\gamma$, and $R(K)$:

4.9σ : $\quad (C_9^{\rm NP})^{\mu\mu} = -1.14 \pm 0.20$ $(\simeq -25\% C_9^{\rm SM})$.



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

[29] Descotes-Genon, Hofer, Matias, Virto, 1510.04239. Similar results by Hurth, Mahmoudi, Neshatpour, 1410.4545; Altmannshofer, Straub, 1503.06199, 1411.3161; ...

Z' coupled to bs

For 4.9σ improvement, need $(\bar{s}\gamma_\alpha P_L b)(\overline{\mu}\gamma^\alpha\mu)/(35\,\mathrm{TeV})^2$.

$\Rightarrow Z'$ coupled to $\overline{\mu}\gamma^\alpha\mu$ and $\bar{s}\gamma_\alpha P_L b$.[30]

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

Z' coupled to bs

For 4.9σ improvement, need $(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)/(35\,\mathrm{TeV})^2$.

$\Rightarrow$ Z' coupled to $\bar{\mu}\gamma^\alpha \mu$ and $\bar{s}\gamma_\alpha P_L b$.[30]

Extend $L_\mu - L_\tau$ to $U(1)_{Q'}$:

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

with *three* scalar doublets $\Phi_1 \sim -a$, $\Phi_2 \sim 0$, $\Phi_3 \sim 2$ 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. ✓

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

Flavor violating quark 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:

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

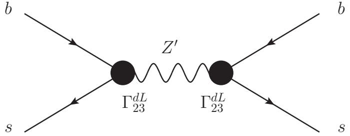
Z' couplings:

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

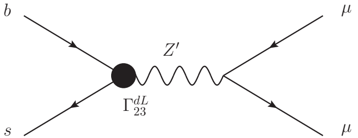
- Dominant off-diagonal: $Z' bs$.
- Structure perfect for $b \to s$:

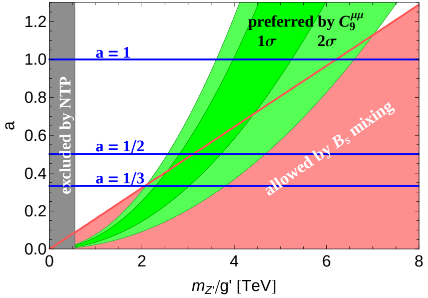
$$C_9^{\mu\mu} \simeq -\left(\frac{a}{1/3}\right)\left(\frac{3\text{TeV}}{m_{Z'}/g'}\right)^2,$$
$$C_9^{ee} = C_9'^{\ell\ell} = C_{10}^{\ell\ell} = C_{10}'^{\ell\ell} = 0\,.$$

- $a < 1$ 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 $pp \to Z' \to \mu^+\mu^-$.

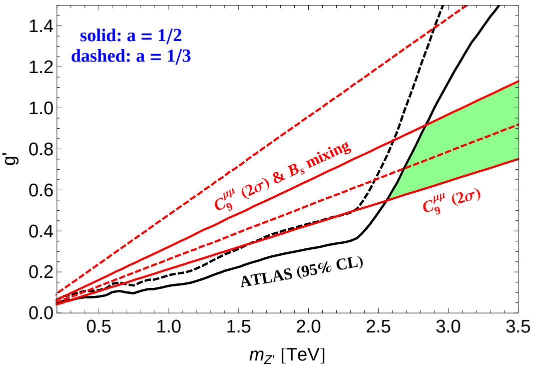
- For $m_t \ll m_{Z'} < 2m_{\nu_R}$:

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

and

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

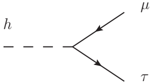
- Can rescale $B-L$ limits from ATLAS [1405.4123].
- Flavor violating decays $Z' \to bs$ suppressed.



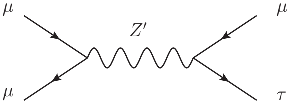
Look forward to new LHC run!

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

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

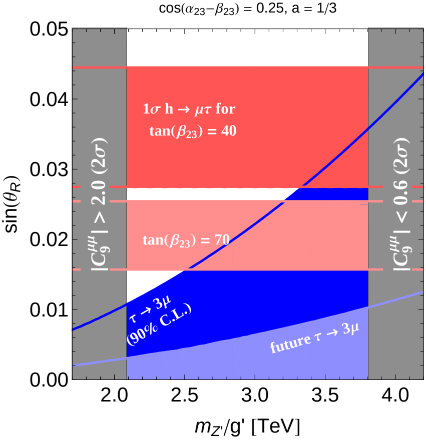


- $\text{BR}(\tau \to 3\mu) \propto \sin^2\theta_R g'^4/m_{Z'}^4$:



- Correlation:

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



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

Type-? 2HDM + perturbations

Different Ansatz for ρ:

- Start with familiar 2HDM of type I/II/X/Y.
- Add (off-diagonal) perturbations.

Example 1: type I + pert. from flavor symmetry to explain $h \to \mu\tau$.

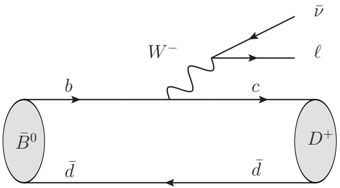
Example 2: type I + pert. from flavor symmetry to explain $R(K)$ etc.

Example 3: type X + pert. to explain $R(D^{(*)})$, $h \to \mu\tau / g-2$.[31]

[31] **J.H.**, A. Crivellin, P. Stoffer, Phys. Rev. Lett. (2016) [arXiv:1507.07567].

- Lepton non-universality in B decays

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



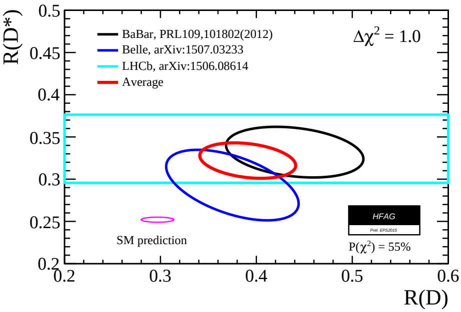
- Combination of BaBar, Belle, and LHCb

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

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

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

$\Rightarrow$ 3.9σ combined (HFAG).



- Confirms earlier results by BaBar & Belle.

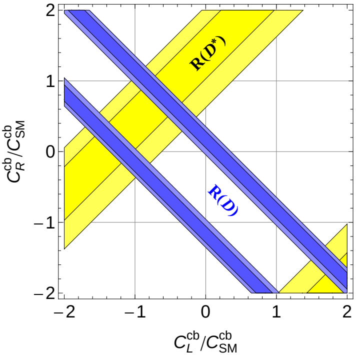
Wilson coefficients for $b \to c$

- 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 [Fajfer, Kamenik, Nišandžić, Zupan, 1206.1872; Crivellin, Greub, Kokulu, 1206.2634, 1303.5877] or type I/X/Y 2HDM [recent: Enomoto, Watanabe, 1511.05066].
  - Need general type III, or modified type X (also resolving muon's magnetic moment anomaly) [**J.H.**, Crivellin, Stoffer, 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 $\rightarrow$ 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.):

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

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

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

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

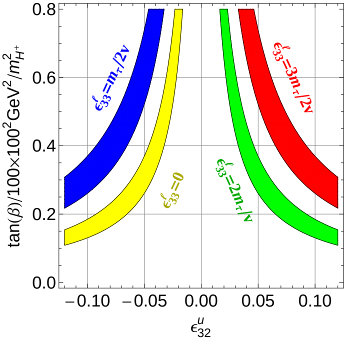
- $\varepsilon^\ell_{33} > m_\tau/v$ flips sign of coupling.

Modified type-X 2HDM

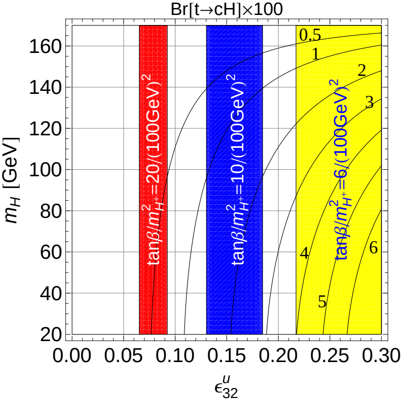
- To generate $b \to c$ and $h \to \mu\tau$, use structure $\varepsilon^d = 0$,

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

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

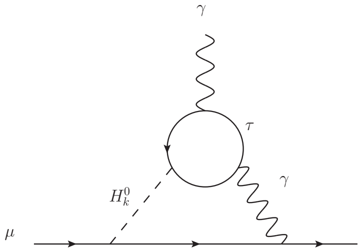


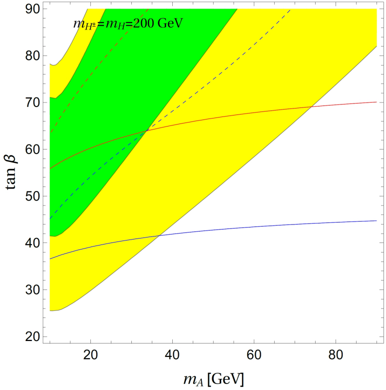
- If H (or A) are light, this induces $t \to Hc$, followed by $H \to \tau\tau$.



Why light H or A?

- Grandmother of anomalies: magnetic moment of muon $(g-2)_\mu$, at $\sim 3\sigma$.
  $\Rightarrow$ **see talk by Joe Price.**
- Light A in type-X 2HDM can resolve $(g-2)_\mu$ using Barr–Zee diagram.[32]





[32] Broggio, Chun, Passera, Patel, Vempati, 1409.3199; Wang, Han, 1412.4874; Chun, Kang, Takeuchi, Tsai, 1507.08067; Chun, Kim, 1605.06298.

$\tau \to \ell\nu\nu$

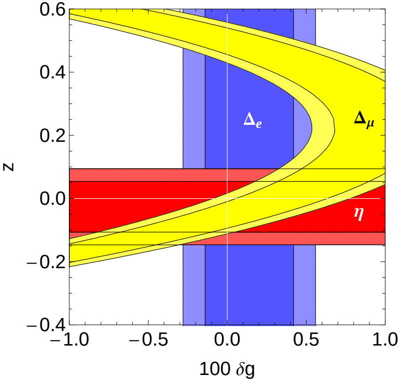
- Problem: Leads to wrong $\tau \to \ell\nu\nu$ rates! [Krawczyk, Temes, hep-ph/0410248; Abe, Sato, Yagyu, 1504.07059]
- Define

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

  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 $\varepsilon^\ell_{33} > m_\tau / v$!



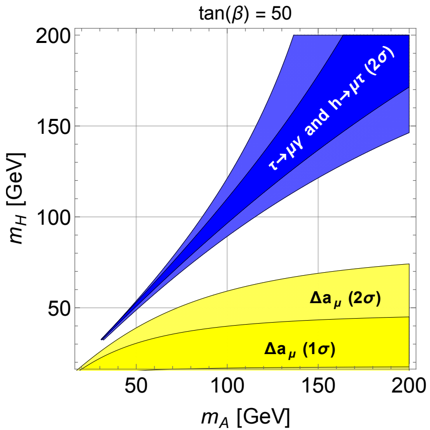
Flip τ coupling of A and H ⇒ light H resolves $(g-2)_\mu$ *and* H^+ solves $\tau \to \mu\nu\nu$.

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

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

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

- Light H resolves $(g-2)_\mu$, H^+ explains $R(D^{(*)})$ and $\tau \to \mu\nu\nu$.
- 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 $\tau \to \mu\gamma$.
- (Finetuning might be possible in general 2HDM. **See talk by Kazuhiro Tobe.**)



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

Summary

General nHDM perfect environment for flavor:

- Flavor non-universality & violation.
- Potentially large $h \to \ell_i \bar{\ell}_j$ & $\ell_i \to \ell_j \gamma$.
- Light A/H could solve $(g-2)_\mu$.
- H^+ could solve $R(D^{(*)})$.

Controlled flavor violation via $U(1)'$:

- Z' could solve $b \to s$ anomalies.
- Light Z' could induce $\ell_i \to \ell_j Z'$.

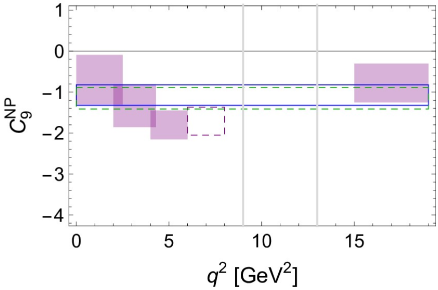
Wait for new ~~data~~ physics.

Backup

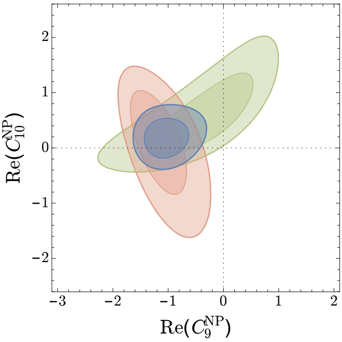
New physics vs. QCD in $b \to s$

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.

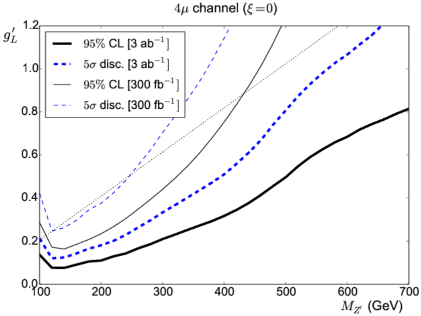
If it's QCD (non-factorizable charm loop), it's much larger than expected!

$L_\mu - L_\tau$ at LHC

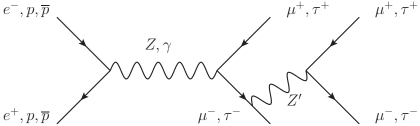
Even without Z' couplings to quarks:

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

Ma, Roy, Roy, PLB 2002.



del Aguila, Chala, Santiago, Yamamoto, JHEP 2015 [1411.7394].
Harigaya, Igari, Nojiri, Takeuchi, Tobe, JHEP 2014 [1311.0870].



Currently weaker than limits from neutrino trident production

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

($\leftarrow$ thin dotted line).
Altmannshofer, Gori, Pospelov, Yavin, PRL 2014.