

**Andreas
Crivellin**



Lepton Flavour Universality Violation in B decays and New Physics

Supported by a Marie Curie Intra-European Fellowship of the European Community's 7th Framework Programme under contract number (PIEF-GA-2012-326948).

Outline:

- Introduction: The LHC flavour anomalies
- 2HDM with gauged $L_\mu - L_\tau$ and vector-like quarks
 - $B \rightarrow K^* \mu^+ \mu^-$
 - $B \rightarrow K \mu^+ \mu^- / B \rightarrow K e^+ e^-$
 - $B_s \rightarrow \phi \mu^+ \mu^-$
 - $h \rightarrow \tau \mu$
 - $\tau \rightarrow \mu \mu \mu$
- 2HDM and 3HDM with gauged horizontal charged (no vector-like quarks)
- Conclusions

The LHC flavour anomalies

$B \rightarrow K^* \mu\mu, B_s \rightarrow \phi\mu^+ \mu$ and $R(K)$

See talks of David Straub and Joaquim Matias

- 2-3 σ deviation from the SM mostly in $C5'$
- 2.6 σ deviation from the theoretically rather clean SM expectation for $R(K)$.
- 3.1 σ in $B_s \rightarrow \phi\mu\mu$
- Contribution to $C_9^{\mu\mu}$ but not C_9^{ee} gives simultaneously a good fit  **4.3 σ better than SM**
- Explanation:
 - Leptoquarks e.g. G. Hiller, M. Schmaltz, 1408.1627
 - Extra dimensions C. Niehoff, P. Stangl, D. Straub, arXiv:1503.03865.
 - Flavour non-universal Z' W. Altmannshofer, et al. 1403.1269

$$h \rightarrow \tau\mu$$

- 2.4 σ difference from zero

$$\text{Br}[h \rightarrow \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right) \% \quad \text{CMS-PAS-HIG-14-005}$$

- Can be explained in the effective field theory approach by

$$Q_{e\phi}^{fi} = \ell_f \phi e_i \phi^\dagger \phi$$

R. Harnik, J. Kopp, and J. Zupan, 1209.1397.
G. Blankenburg, J. Ellis, and G. Isidori, 1202.5704.
S. Davidson and P. Verdier, 1211.1248.

- No dominant contribution from vector-like fermions

A. Falkowski, D. M. Straub, and A. Vicente, 1312.5329



Extended
Higgs sector

A. Dery, et. al. 1408.1371.
M. D. Campos, et. al., 1408.1652.
A. Celis, et. al., 1409.4439.
D. Aristizabal Sierra and A. Vicente, 1409.7690.
C.-J. Lee and J. Tandean, 1410.6803.
J. Heeck, et. al., 1412.3671.

2HDM with vector-quarks

Explaining $B \rightarrow K^* \mu \mu$, $B \rightarrow K \mu \mu$ / $B \rightarrow K e e$ and $h \rightarrow \tau \mu$ in a two-Higgs-doublet model with gauged $L_\mu - L_\tau$
PRL, arXiv:1501.00993.

Gauged $L_\mu - L_\tau$

- Vectorial U(1) gauge group:
 $Q(e) = 0, Q(\mu) = 1, Q(\tau) = -1$

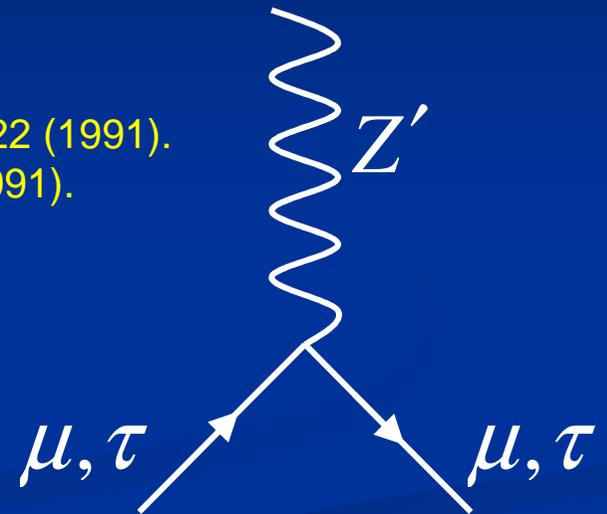
- Anomaly free X. He, G. C. et al., Phys.Rev. **D43**, 22 (1991).
R. Foot, Mod.Phys.Lett. **A6**, 527 (1991).

- Good zero order approximation to the PMNS matrix:

- maximal atmospheric and
- vanishing reactor neutrino mixing angle

$$M_\nu = \begin{pmatrix} X & 0 & 0 \\ 0 & 0 & Y \\ 0 & Y & 0 \end{pmatrix}$$

P. Binetruy, et al., hep-ph/9610481.
N. F. Bell and R. R. Volkas, hep-ph/0008177.
S. Choubey and W. Rodejohann, hep-ph/0411190.
J. Heeck and W. Rodejohann, 1107.5238



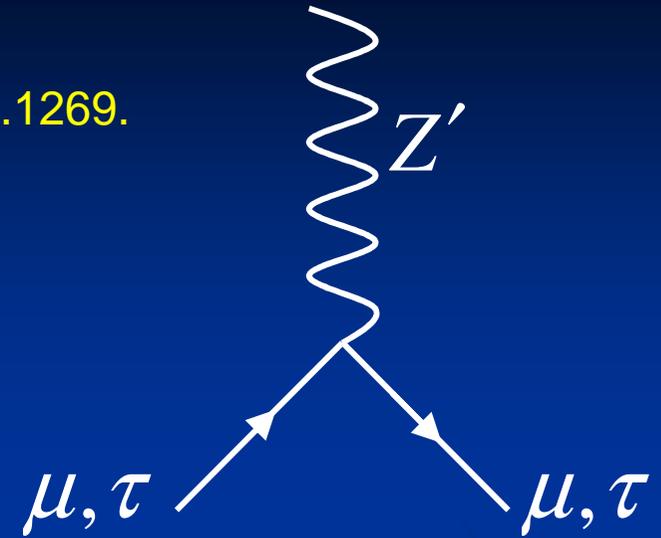
➔ Breaking necessary for a realistic neutrino sector

The Model

W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, 1403.1269.

- Gauged $L_\mu - L_\tau$: Z' boson with

$$-ig' \bar{l}_f \gamma^\mu Z'_\mu l_i \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}_{fi}$$



- Vector-like quarks charged under $L_\mu - L_\tau$

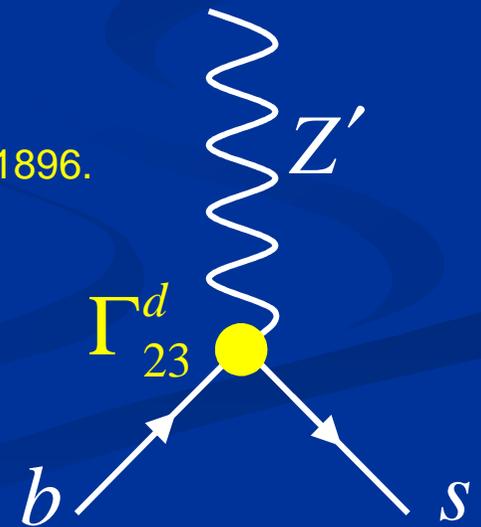
$$m_Q \bar{Q}_L \tilde{Q}_R + m_D \bar{D}_L \tilde{D}_R + m_U \bar{U}_L \tilde{U}_R + \text{h.c.}$$

- Effective Z' quark couplings

P. Langacker, 0801.1345., A. J. Buras, F. De Fazio, and J. Girrbach, 1211.1896.

$$ig' \gamma^\mu d_f \left(\Gamma_{fi}^L P_L + \Gamma_{fi}^R P_R \right) d_i Z'_\mu$$

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



2nd Doublet breaks $L_\mu - L_\tau$

J. Heeck, M. Holthausen, W. Rodejohann and Y. Shimizu, 1412.3671

- Two Higgs doublets

$$Q_{L_\mu - L_\tau}(\Psi_2) = 0 \quad Q_{L_\mu - L_\tau}(\Psi_1) = 2$$

- Yukawa couplings

$$\mathcal{L}_Y \supset -\bar{\ell}_f Y_i^\ell \delta_{fi} \Psi_2 e_i - \xi_{\tau\mu} \bar{\ell}_3 \Psi_1 e_2 - \bar{Q}_f Y_{fi}^u \tilde{\Psi}_2 u_i - \bar{Q}_f Y_{fi}^d \Psi_2 d_i + \text{h.c.}$$

- Flavour changing SM-like Higgs coupling

$$\Gamma_{\tau\mu}^h \bar{\tau} P_R \mu h^0 \approx \frac{m_\tau}{v} \frac{\cos(\alpha - \beta)}{\cos(\beta) \sin(\beta)} \theta_R \bar{\tau} P_R \mu h^0 \quad \sin \theta_R \approx \frac{v}{\sqrt{2} m_\tau} \xi_{\tau\mu} \cos \beta$$

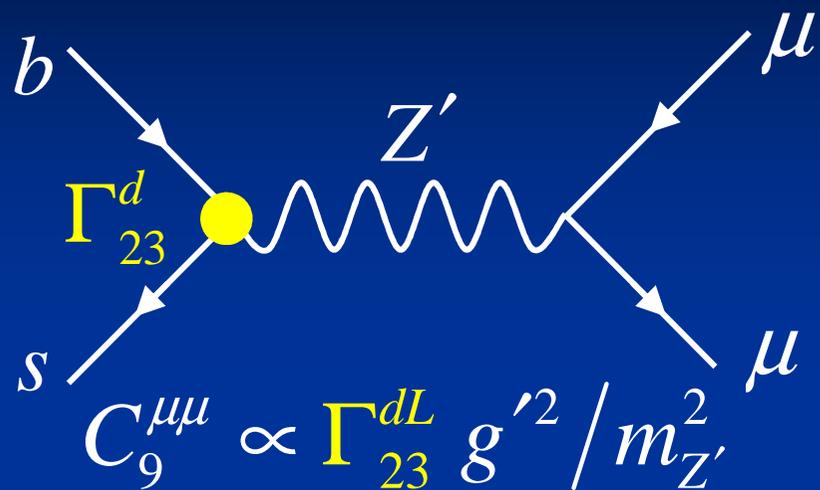
$$\sin \theta_L \approx 0$$

- Lepton flavour violating Z' couplings

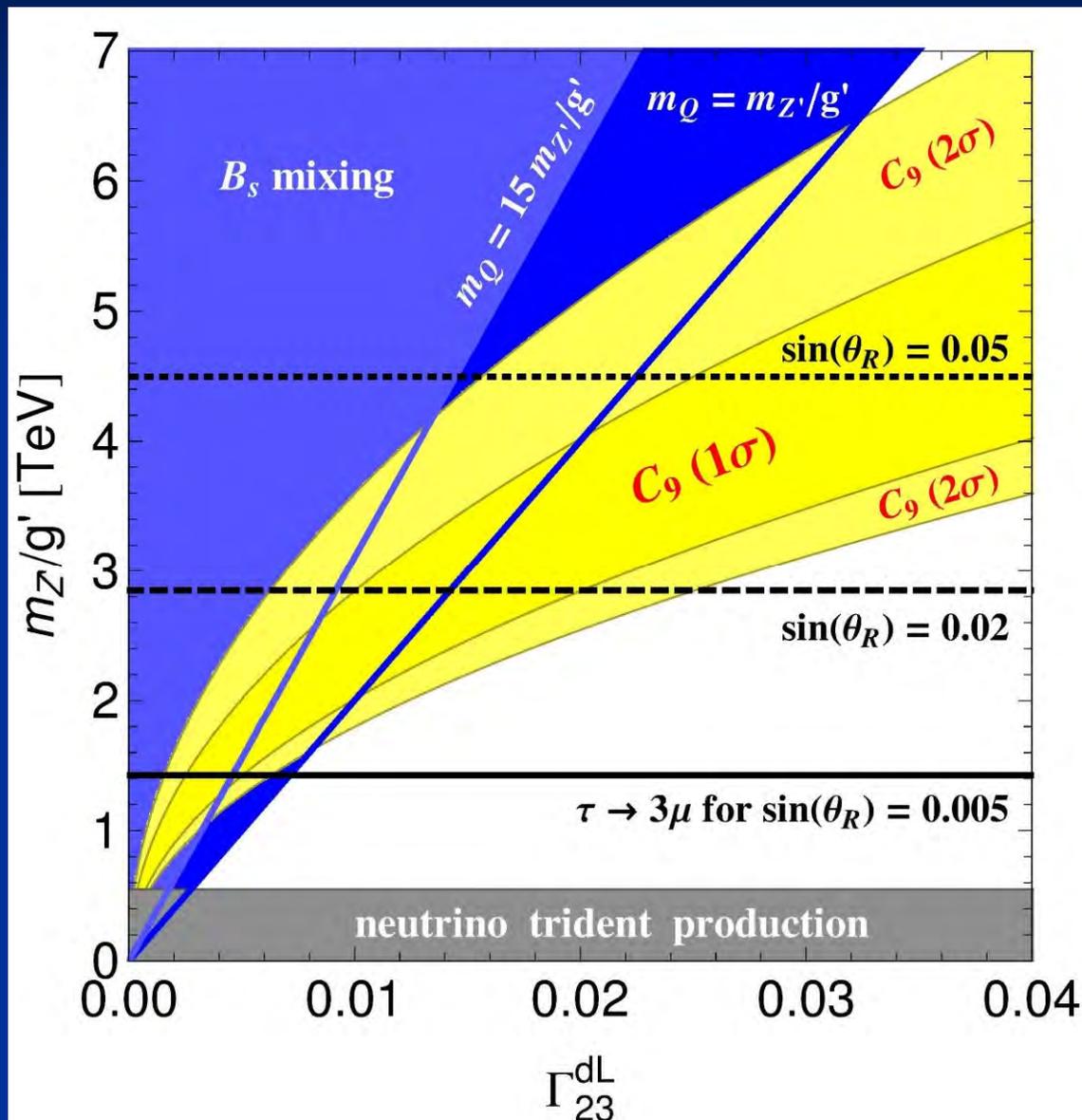
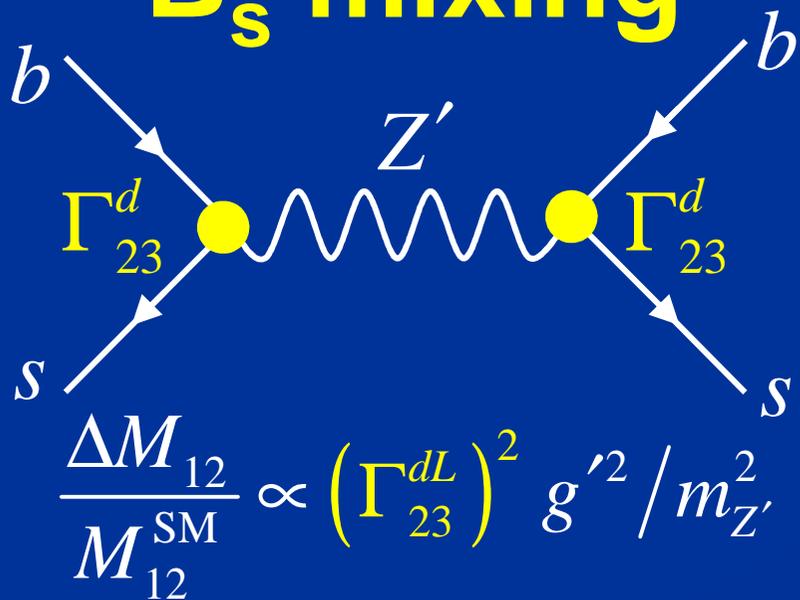
$$g' Z'(\bar{\mu}, \bar{\tau}) \begin{pmatrix} \cos 2\theta_R & \sin 2\theta_R \\ \sin 2\theta_R & -\cos 2\theta_R \end{pmatrix} \gamma^\nu P_R \begin{pmatrix} \mu \\ \tau \end{pmatrix}$$

$b \rightarrow s \mu \mu$

$m_D^2 \rightarrow \infty$



B_s mixing

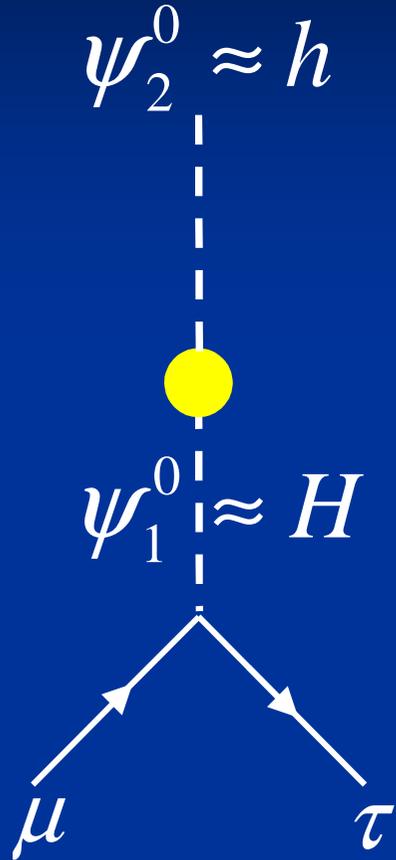


allowed regions

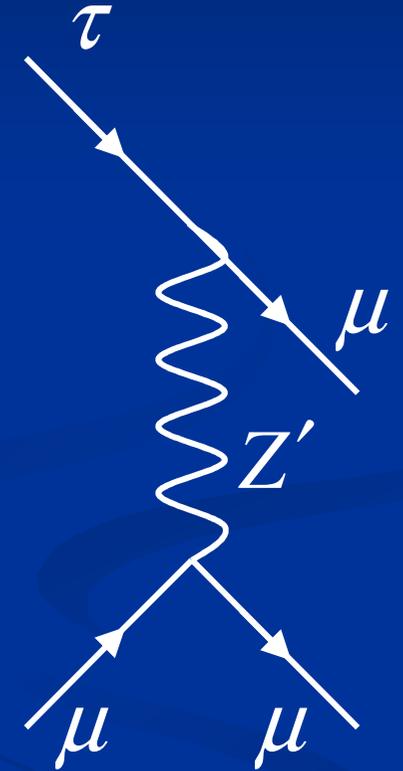
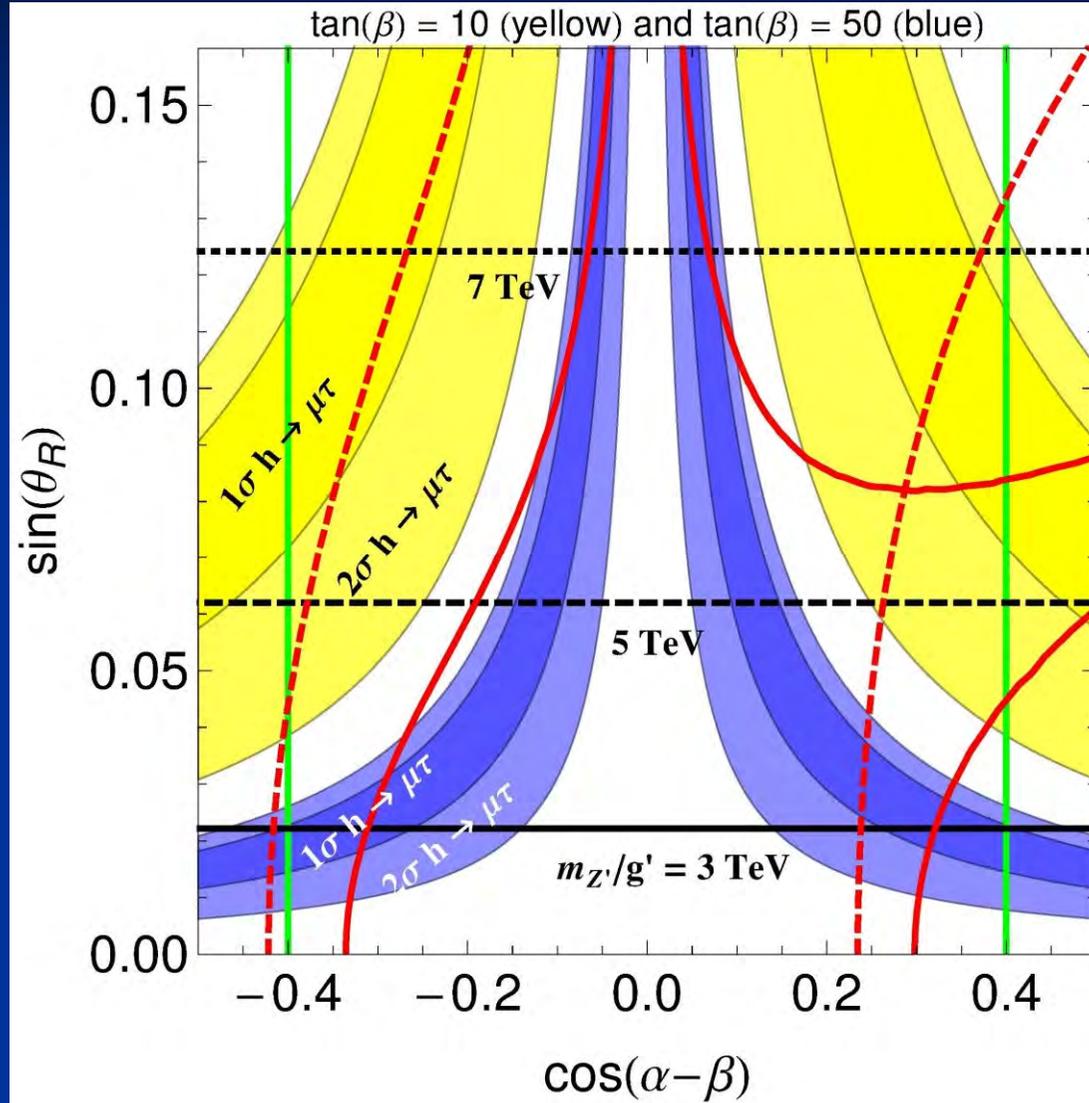
$h \rightarrow \mu\tau$

and

$\tau \rightarrow \mu\mu\mu$



$h \rightarrow \gamma\gamma$ etc.



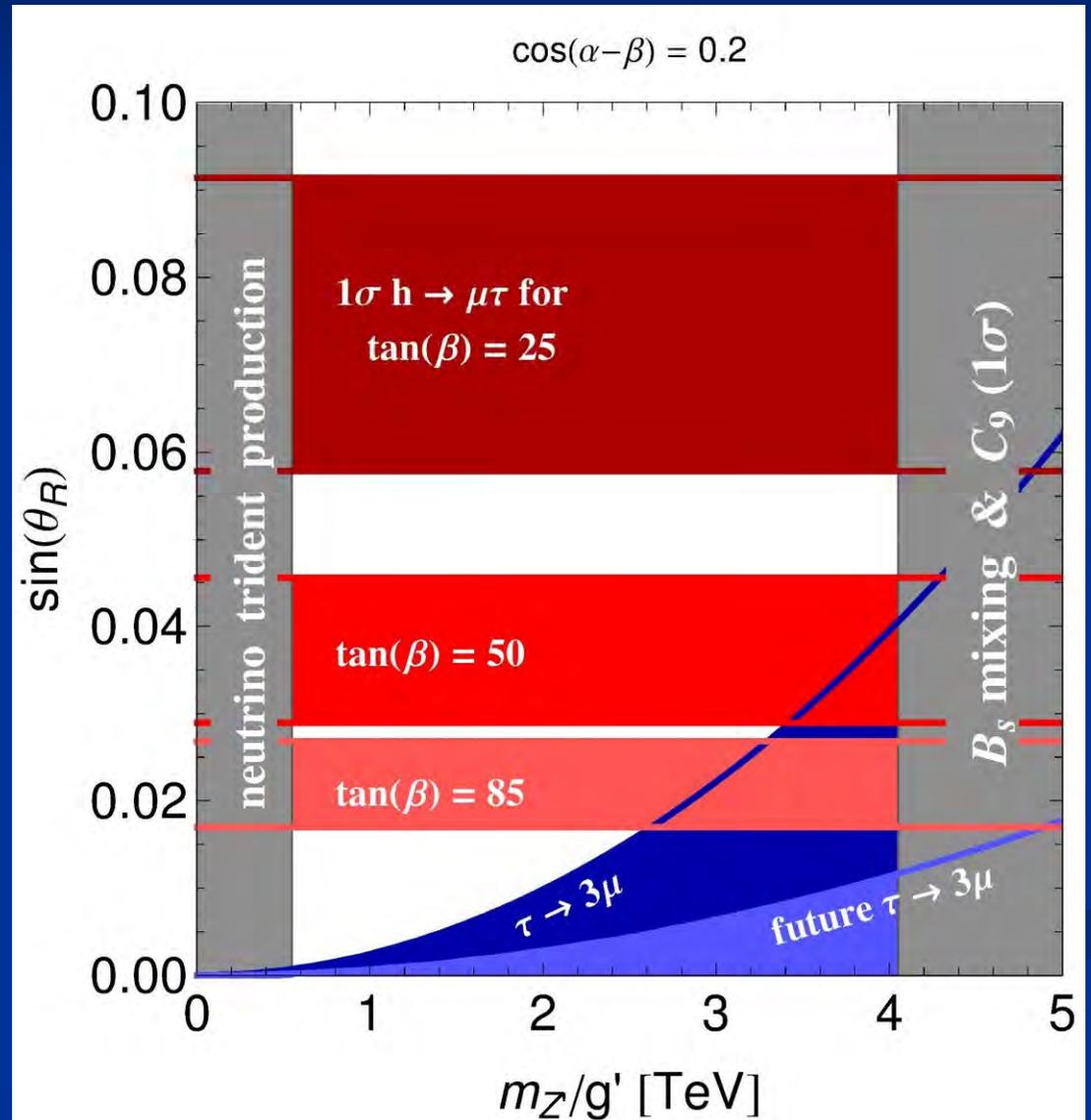
$h \rightarrow \tau\tau$

$h \rightarrow \mu\tau$ ($\tan\beta = 50$)

$h \rightarrow \mu\tau$ ($\tan\beta = 10$)

$\tau \rightarrow \mu\mu\mu$ and $h \rightarrow \mu\tau$

- excluded
- allowed by $h \rightarrow \tau\mu$
- allowed by $\tau \rightarrow \mu\mu\mu$



Horizontal charges

Andreas Crivellin, Giancarlo D'Ambrosio and Julian Heeck

Addressing the LHC flavour anomalies with horizontal gauge symmetries (arXiv:1503.03477)

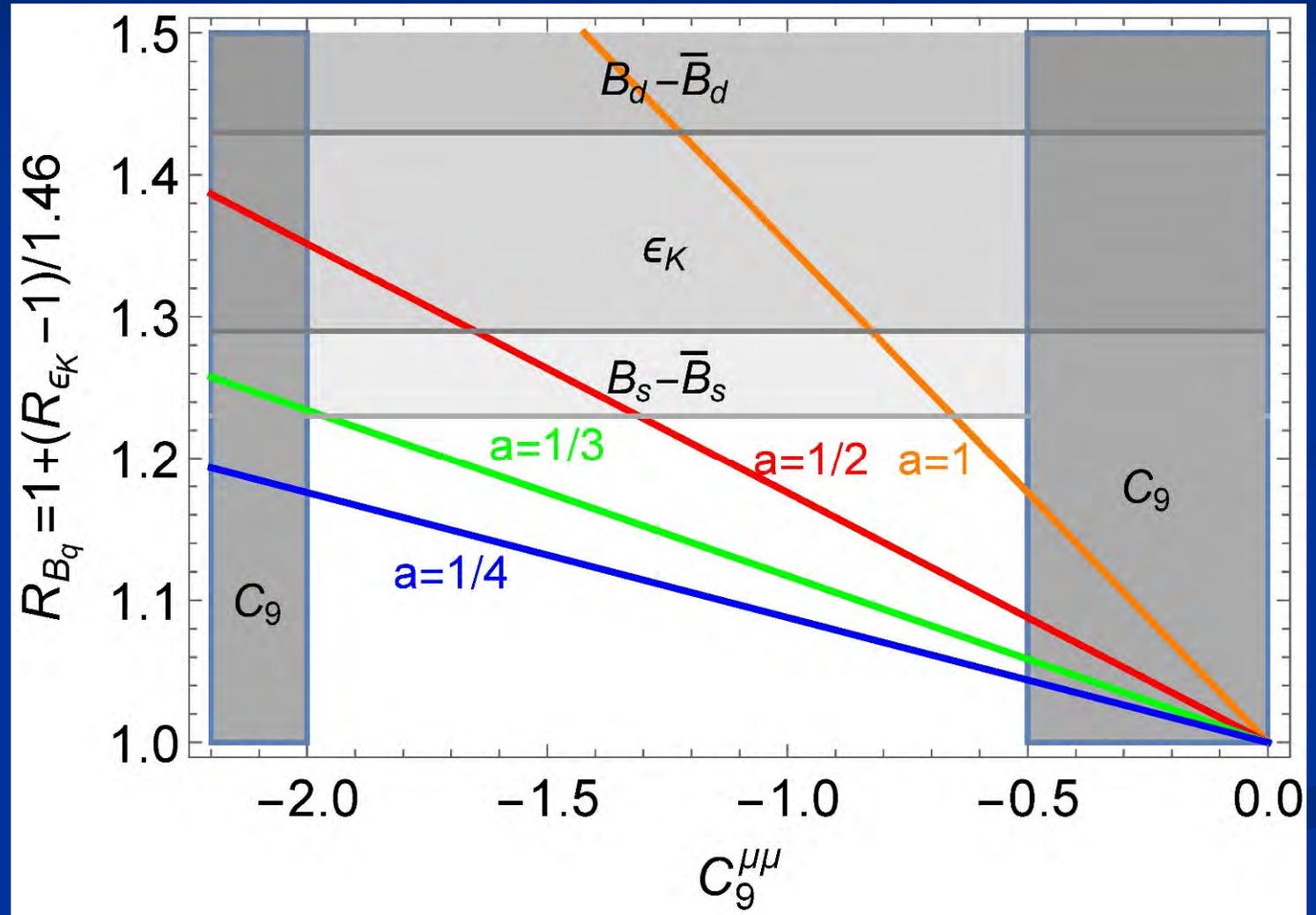
Charge assignment

- Avoid vector-like quarks by assigning charges to baryons as well
 - ➔ same mechanism in the quark and lepton sector
- Use $L_\mu - L_\tau$ in the lepton sector
 - good symmetry for the PMNS matrix
 - ➔ effect in $C_9^{\mu\mu}$ but not C_9^{ee}
- First two quark generations must have the same charges because the large Cabibbo angle would lead to huge effect in Kaon mixing
- Anomaly free
 - ➔ $Q(B) = (-a, -a, 2a)$

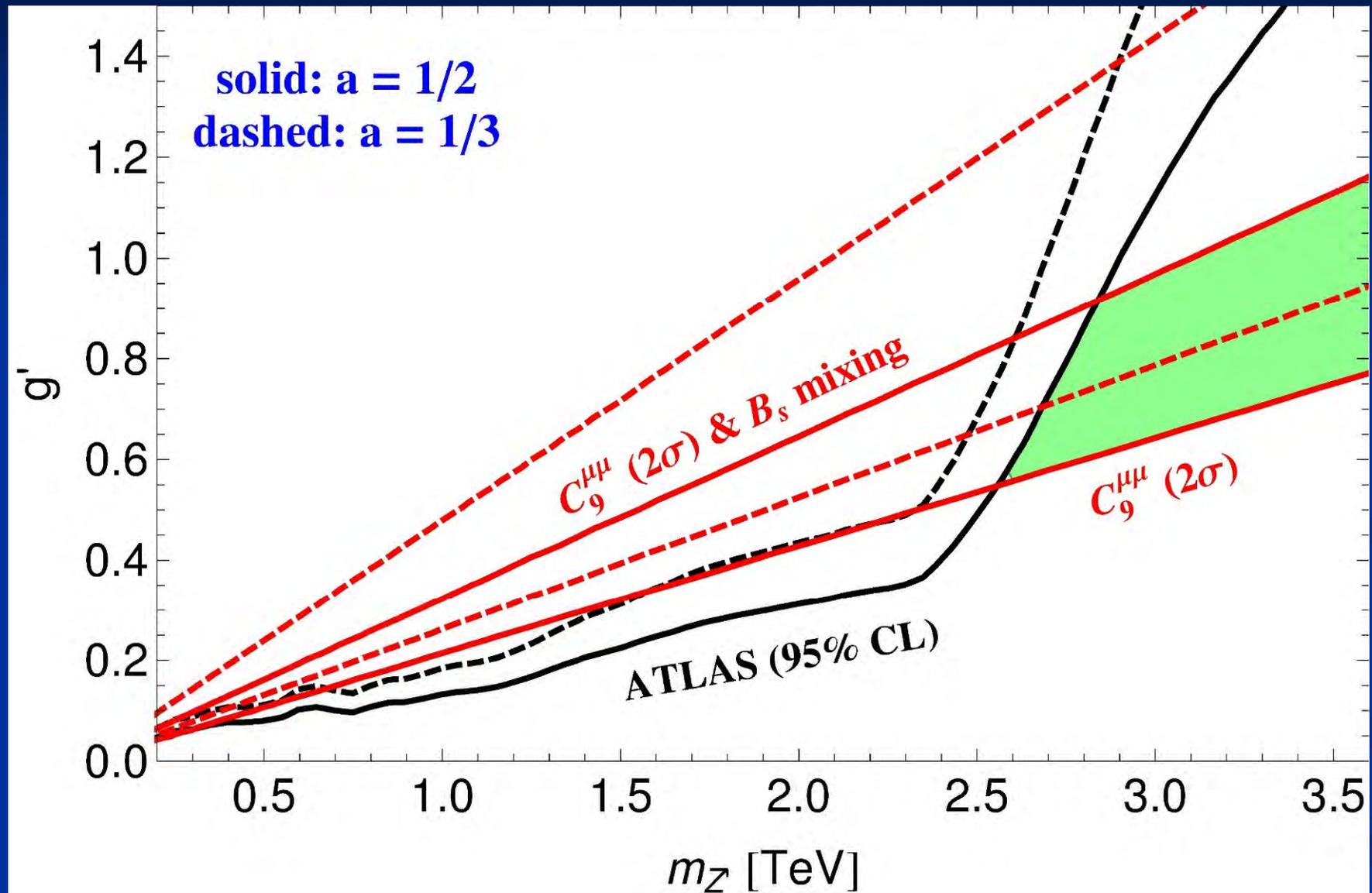
$\Delta F=2$: Z' contribution

$$R_{B_q} = \frac{\Delta m_{B_q}}{\Delta m_{B_q}^{SM}}$$

$$R_{\epsilon_K} = \frac{\epsilon_K}{\epsilon_K^{SM}}$$



LHC limits



ATLAS



$C_9^{\mu\mu} \& B_s - \bar{B}_s$



$a = 1/2$ allowed

3HDM

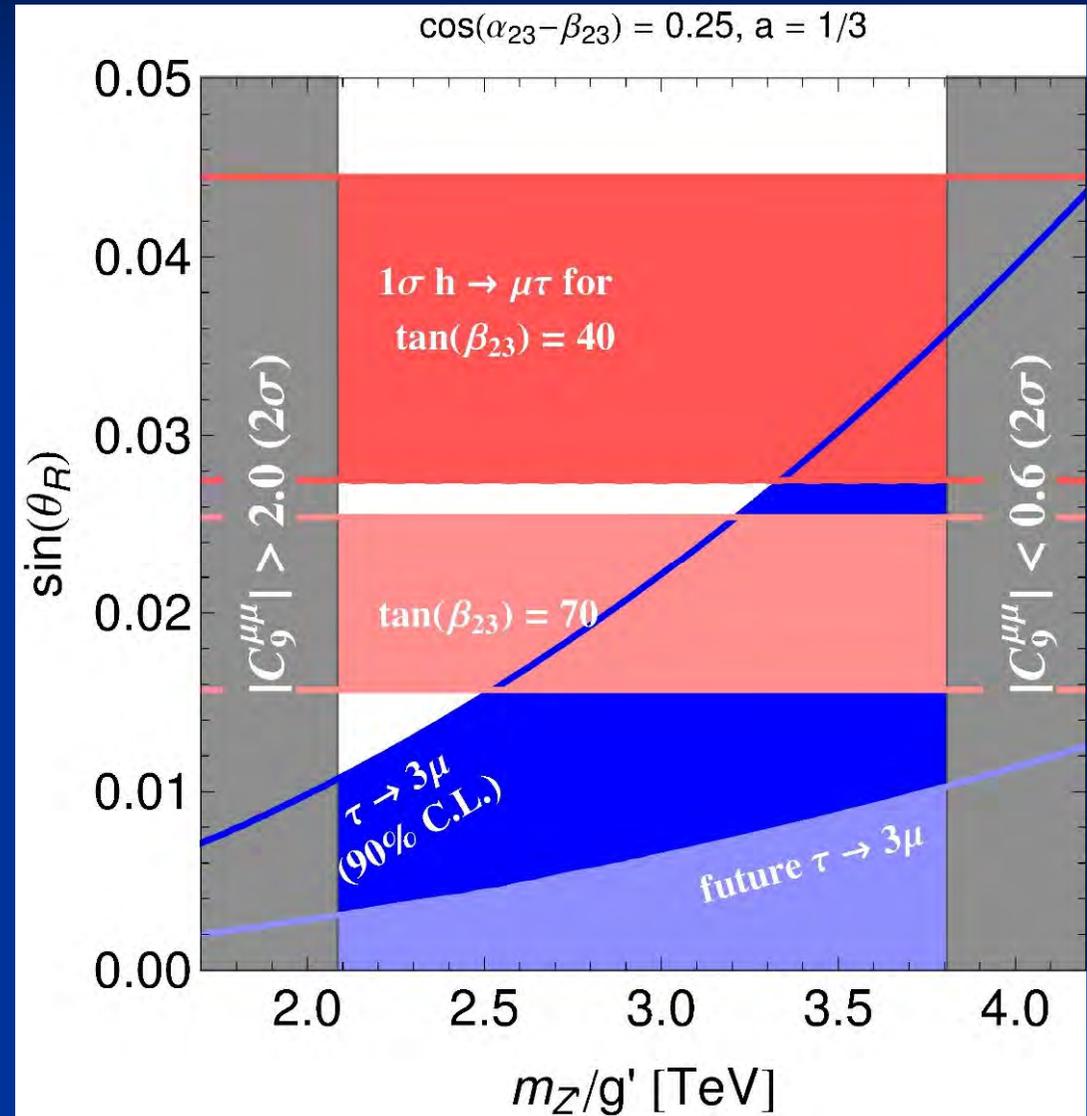
- Same effect in

$$\tau \rightarrow \mu\mu\mu$$

$$h \rightarrow \mu\tau$$

provided that the mixing among the doublets is small

- excluded
- allowed by $h \rightarrow \tau\mu$
- allowed by $\tau \rightarrow \mu\mu\mu$



Conclusions

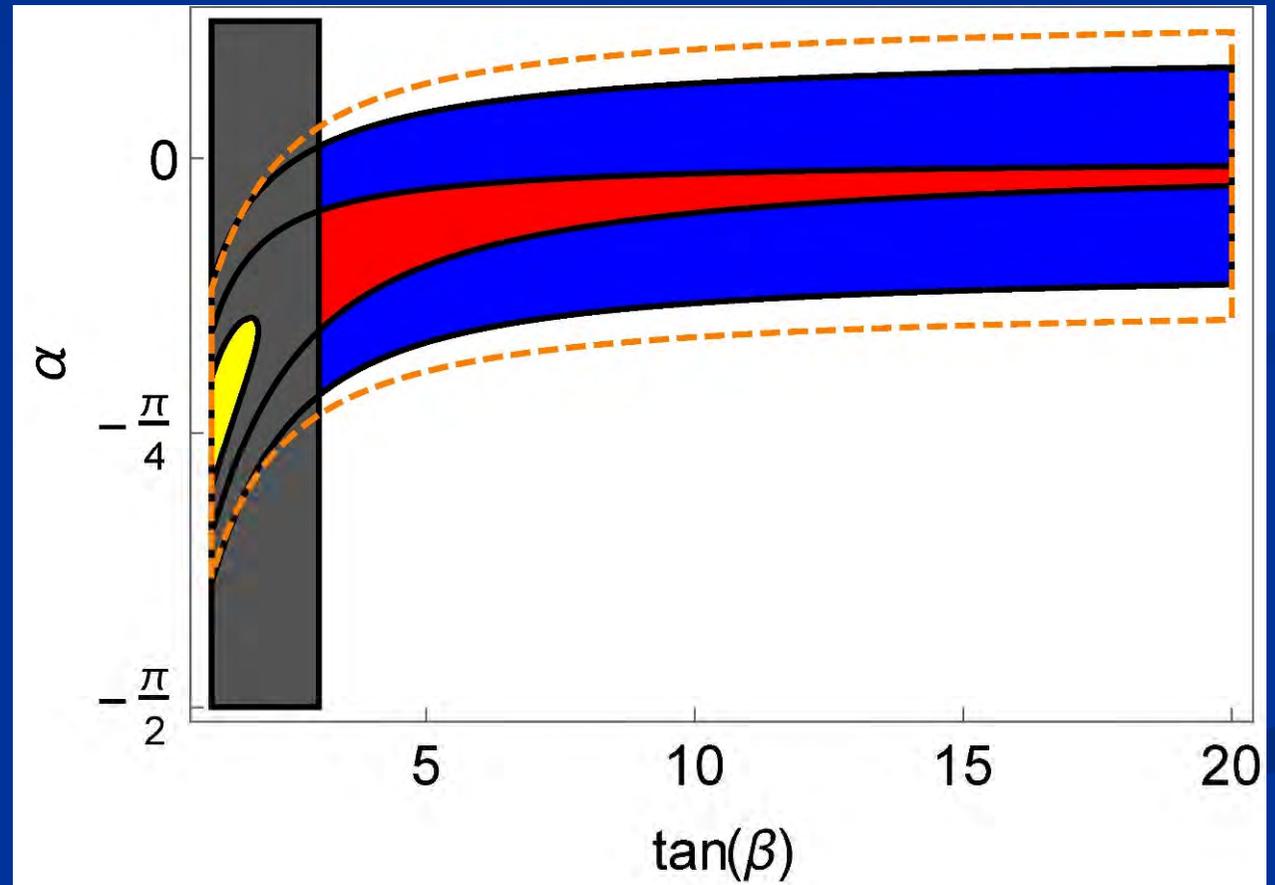
- The LHC found four anomalies in the flavour sector
 - $h \rightarrow \tau\mu$
 - $B \rightarrow K^* \mu^+ \mu^-$
 - $B \rightarrow K \mu^+ \mu^- / B \rightarrow K e^+ e^-$
 - $B_s \rightarrow \phi \mu^+ \mu^-$
- All three anomalies can be explained in a model with gauged $L_\mu - L_\tau$
 - 2HDM with vector-like quarks
 - 3HDM with gauged flavour dependent B-L charges

Relation to LFUV in tauonic B decays?

$\Delta F=2$: Higgs contributions

$$m_H = 300 \text{ GeV}, \quad C_9^{\mu\mu} = -1.3$$

- $m_A = 350 \text{ GeV}$
- $m_A = 300 \text{ GeV}$
- $m_A = 250 \text{ GeV}$



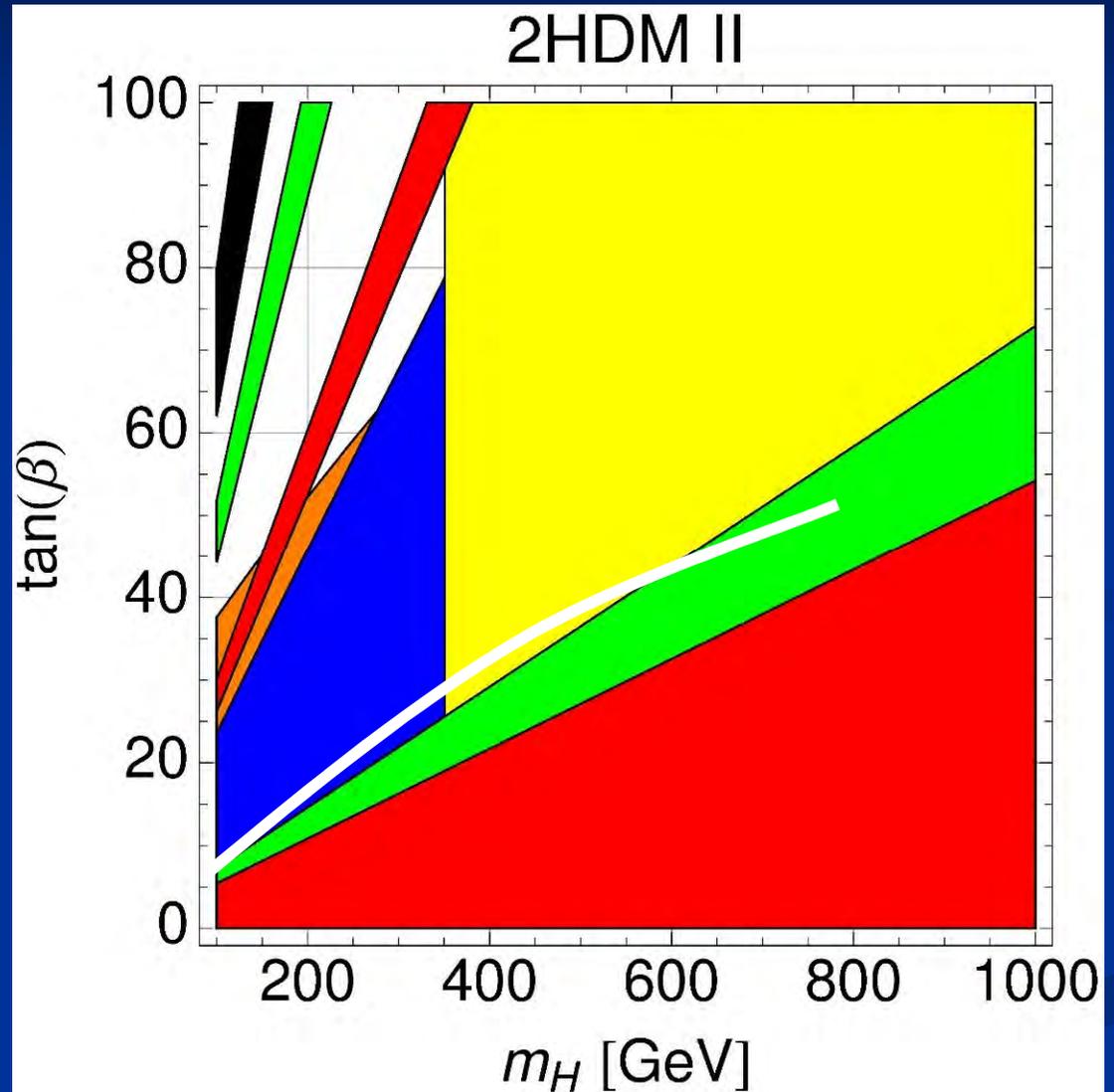
Type-II 2HDM

■ Allowed

2σ regions from:

(superimposed)

- $b \rightarrow s\gamma$
- $B \rightarrow \tau\nu$
- $K \rightarrow \mu\nu / \pi \rightarrow \mu\nu$
- $B \rightarrow D\tau\nu$
- $B_s \rightarrow \mu^+\mu^-$
- $B \rightarrow D^*\tau\nu$
- LHC



➔ Tension from $B \rightarrow D^*\tau\nu$

$B \rightarrow D^{(*)} \tau \nu$ in the 2HDM III

- $B \rightarrow D^{(*)} \tau \nu$ and $B \rightarrow D \tau \nu$ can be explained simultaneously using \mathcal{E}_{32}^u . \rightarrow Check model via $H^0, A^0 \rightarrow \bar{t}c$

Allowed regions from:

