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Outline:

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

The LHC flavour anomalies

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

See talk of Wolfgang Altmannshofer

- 2-3 σ deviation from the SM mostly in C5'
- 2.6 σ deviation from the theoretically rather clean SM expectation for R(K).
- 3.5 σ in $B_s \to \phi\mu\mu$
- Contribution to $C_9^{\mu\mu}$ but not C_9^{ee} gives simultaneously a good fit ⇒ more than 4.3 σ better than SM
- Explanation:
  - Leptoquarks — see talk of Sophie Renner and Gudrun Hiller
  - Extra dimensions — C. Niehoff, P. Stangl, D. Straub, arXiv:1503.03865.
  - Flavour non-universal Z' — W. Altmannshofer, et al. 1403.1269

$h \to \tau\mu$

- 2.4 σ difference from zero

$$\mathrm{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)\%$$ 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

Andreas Crivellin, Giancarlo D'Ambrosio and Julian Heeck

Explaining $B \to K^* \mu\mu$, $B \to K\mu\mu$/ $B \to Kee$ and $h \to \tau\mu$ in a two-Higgs-doublet model with gauged $L_\mu - L_\tau$

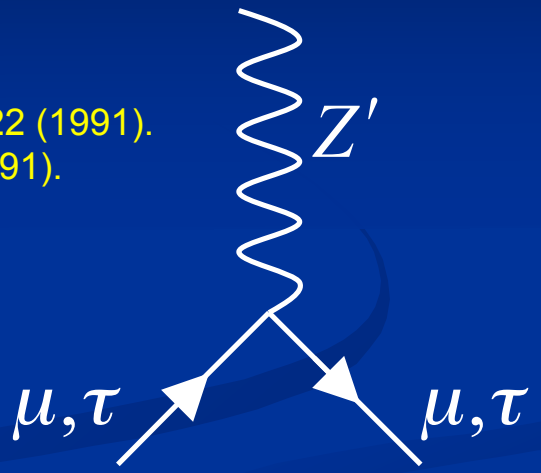
PRL, arXiv:1501.00993.

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

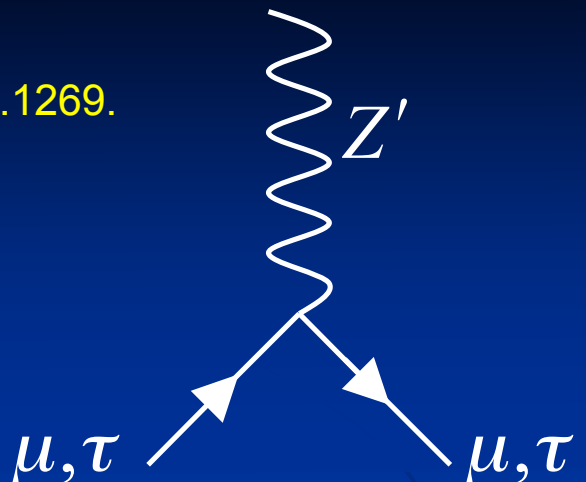
➡ Breaking necessary for a realistic neutrino sector

The Model

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

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

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



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

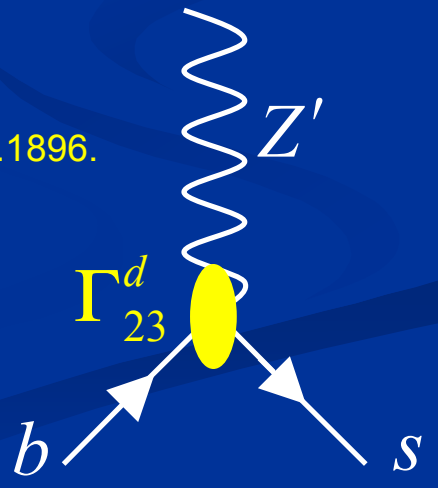
$$m_Q \bar{Q}_L \tilde{Q}_R + m_D \bar{\tilde{D}}_L D_R + m_U \bar{\tilde{U}}_L U_R + \text{h.c.}$$

- Effective Z' quark couplings

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

$$ig'\gamma^\mu d_f \left(\Gamma^L_{fi} P_L + \Gamma^R_{fi} P_R\right) d_i Z'_\mu$$

$$\Gamma^{dR}_{ij} \quad -\frac{v_\Phi^2}{2m_D^2}(Y_i^D Y_j^{D*}), \quad \Gamma^{dL}_{ij} \quad \frac{v_\Phi^2}{2m_Q^2}(Y_i^Q Y_j^{Q*})$$



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

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

- Two Higgs doublets

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

- 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

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

$$\sin\theta_L \quad 0$$

- Lepton flavour violating Z' couplings

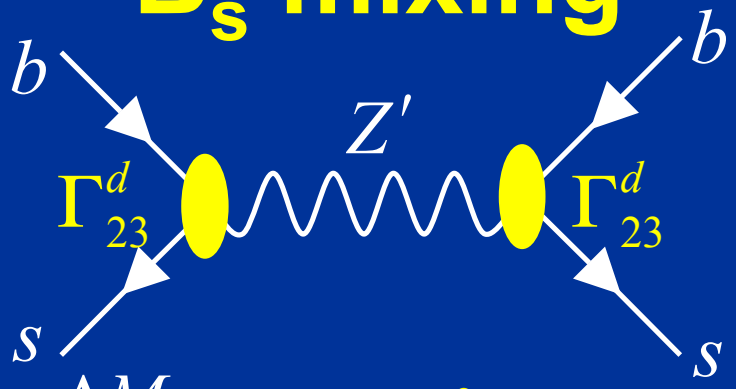
$$g' Z'(\bar{\mu}, \bar{\tau}) \begin{pmatrix} \cos 2\theta_R & \sin 2\theta_R \\ \sin 2\theta_R & -\cos 2\theta_R \end{pmatrix} \gamma^\nu P_R \begin{pmatrix} \mu \\ \tau \end{pmatrix}$$

b→sμμ

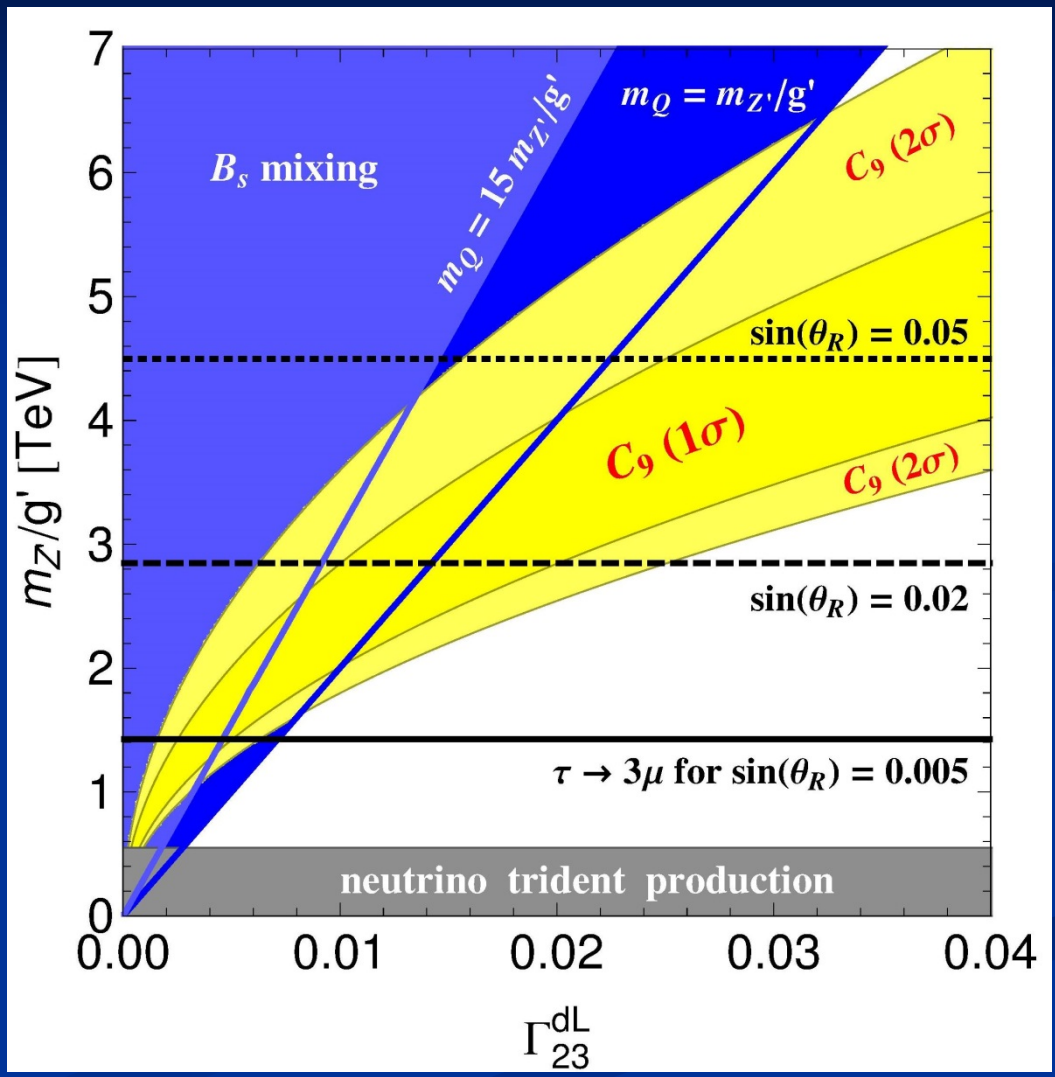
$$m_D^2 \to \infty$$

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

B_s mixing

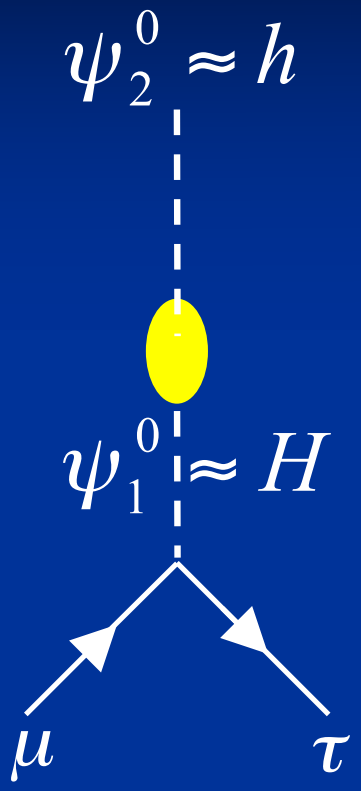


$$\frac{\Delta M_{12}}{M_{12}^{\rm SM}} \propto \left(\Gamma_{23}^{dL}\right)^2 g'^2 / m_{Z'}^2$$

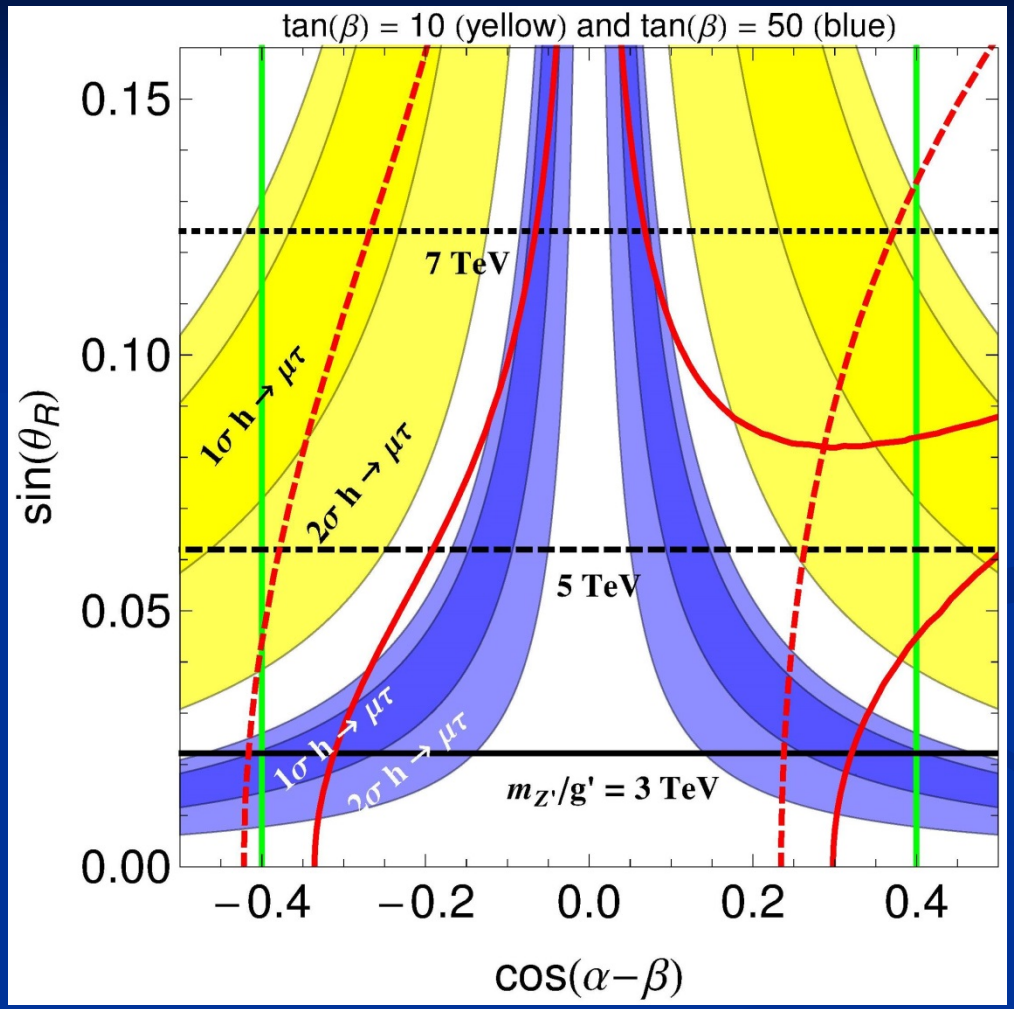


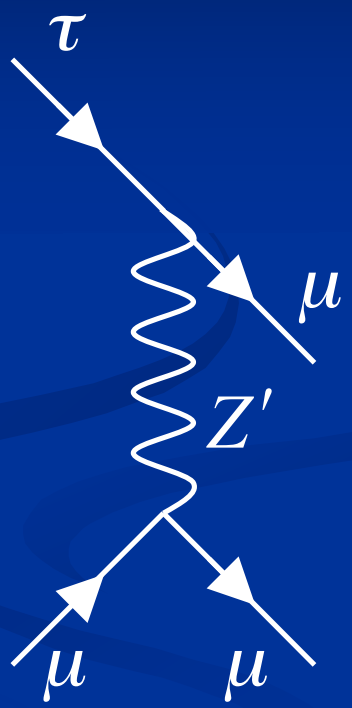
allowed regions

$h \to \mu\tau$ and $\tau \to \mu\mu\mu$



$h \to \gamma\gamma$ etc.





$h \to \tau\tau$

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

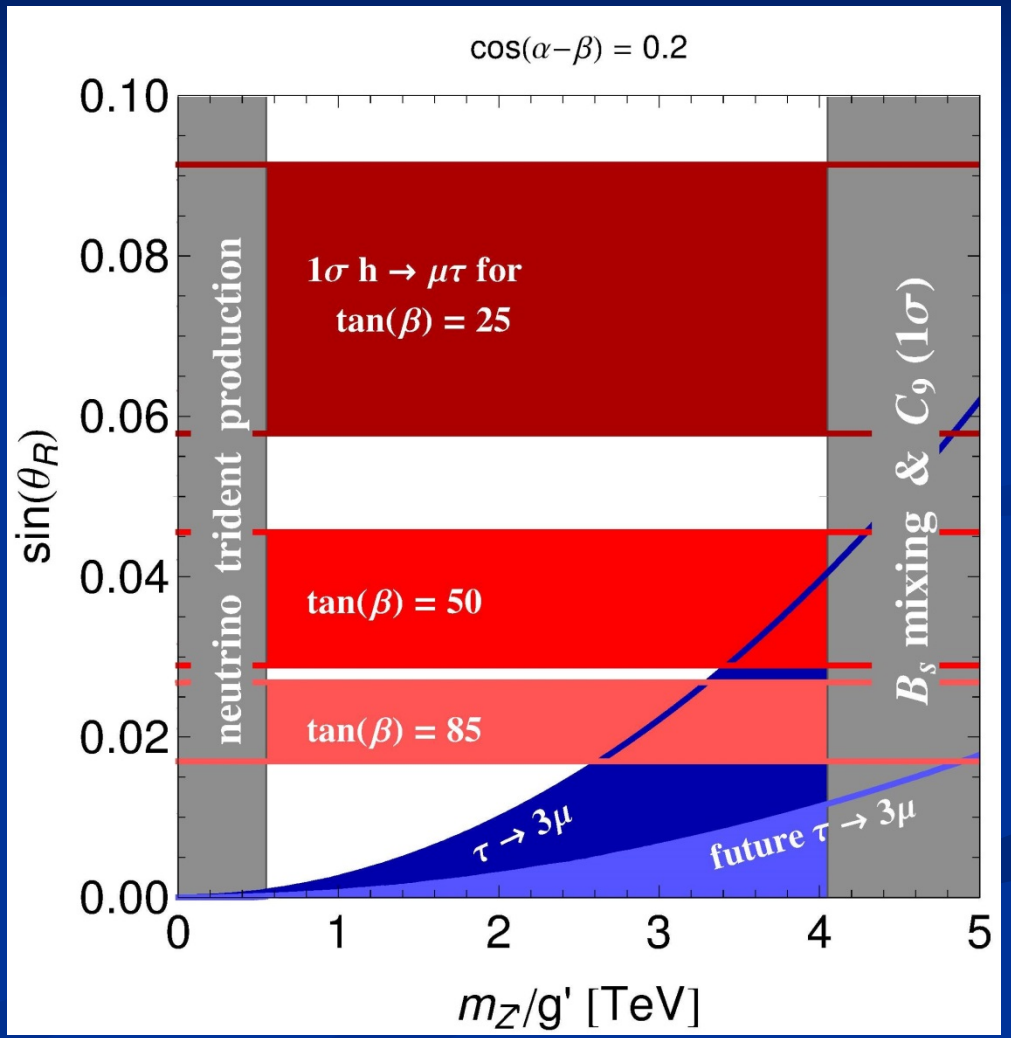
$h \to \mu\tau \ (\tan\beta = 10)$

$\tau \to \mu\mu\mu$ and $h \to \mu\tau$

excluded

allowed by $h \to \tau\mu$

allowed by $\tau \to \mu\mu\mu$



Horizontal charges

Andreas Crivellin, Giancarlo D'Ambrosio and Julian Heeck

Adressing 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}

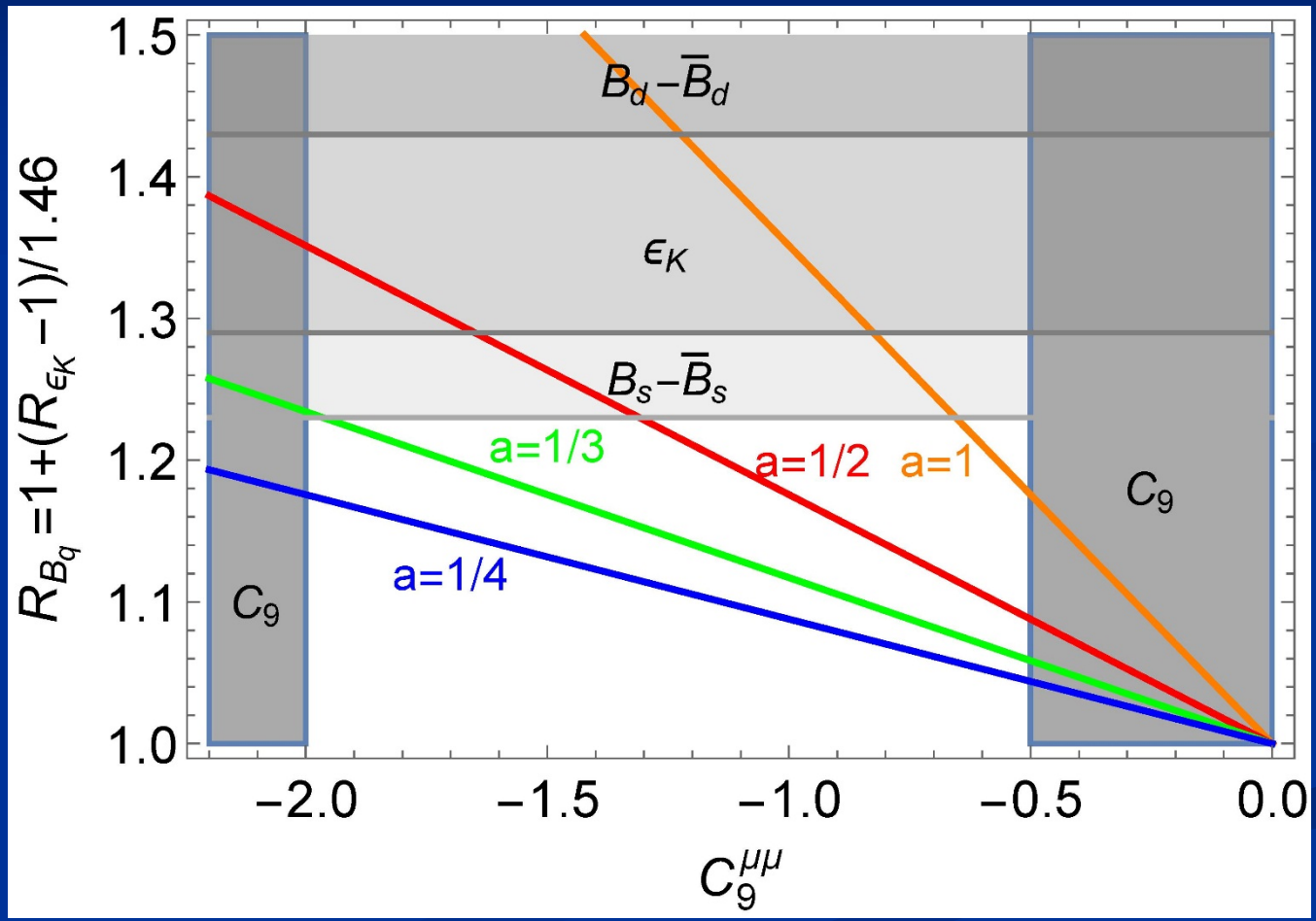
- First two quark generations must have the same charges because the large Cabibbo angle would lead to huge effect in Kaon mixing
- Anomaly free

➡ $Q(B) = (-a, \quad -a, \quad 2a)$

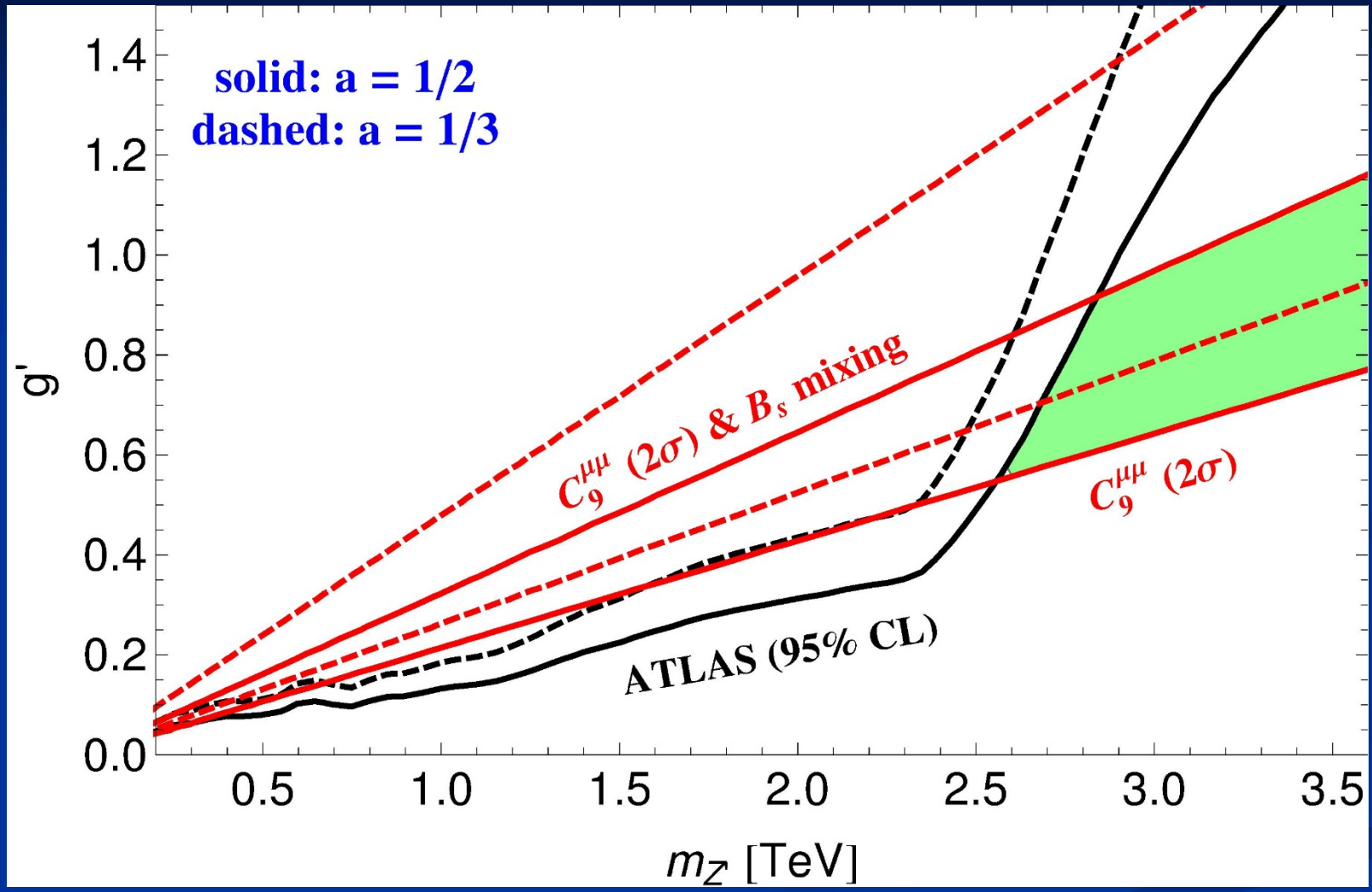
ΔF=2: Z' contribution

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

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



LHC limits



ATLAS $C_9^{\mu\mu}$ & $B_s - \overline{B}_s$ a = 1 / 2 allowed

3HDM

- Same effect in

$\tau \to \mu\mu\mu$

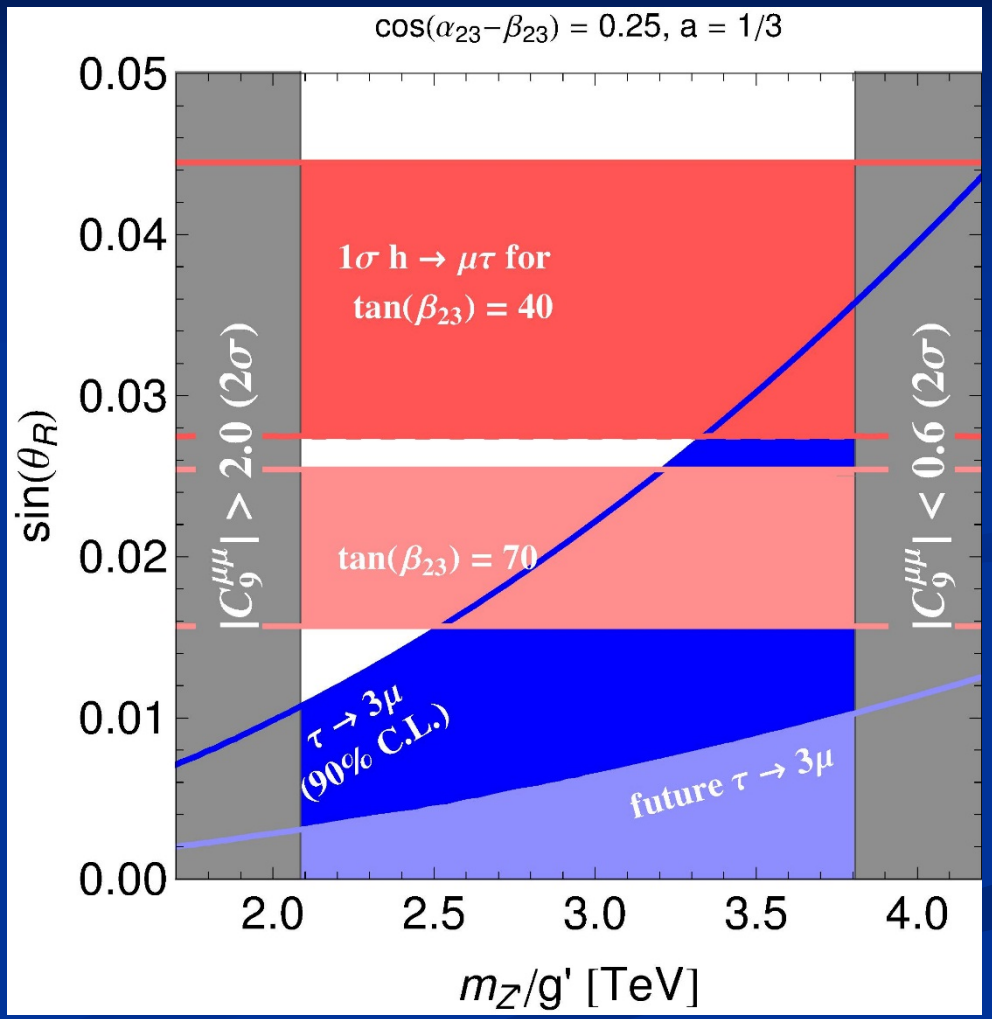
$h \to \mu\tau$

provided that the mixing among the doublets is small

excluded

allowed by $h \to \tau\mu$

allowed by $\tau \to \mu\mu\mu$



Conclusions

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

Relation to LFUV in tauonic B decays?

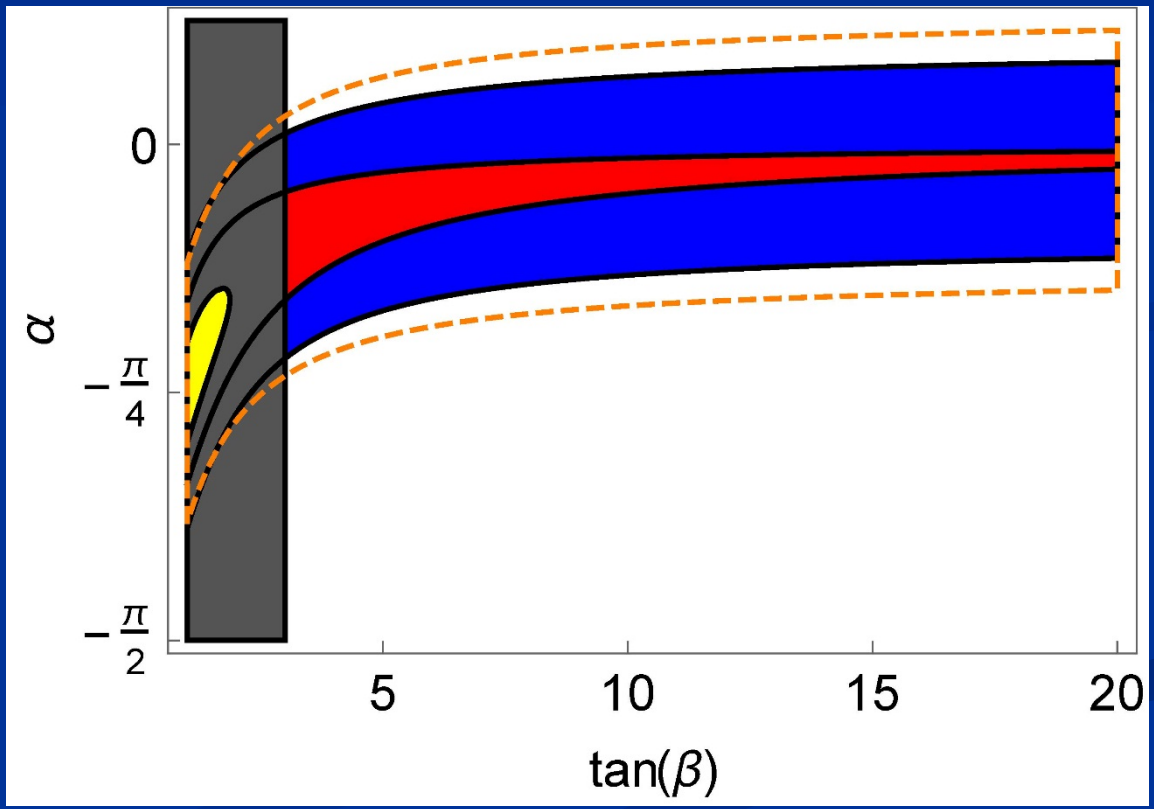
ΔF=2: Higgs contributions

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

$m_A = 350\ \text{GeV}$

$m_A = 300\ \text{GeV}$

$m_A = 250\ \text{GeV}$



Type-II 2HDM

- Allowed 2σ regions from:
  (superimposed)

$b \to s\gamma$

$B \to \tau\nu$

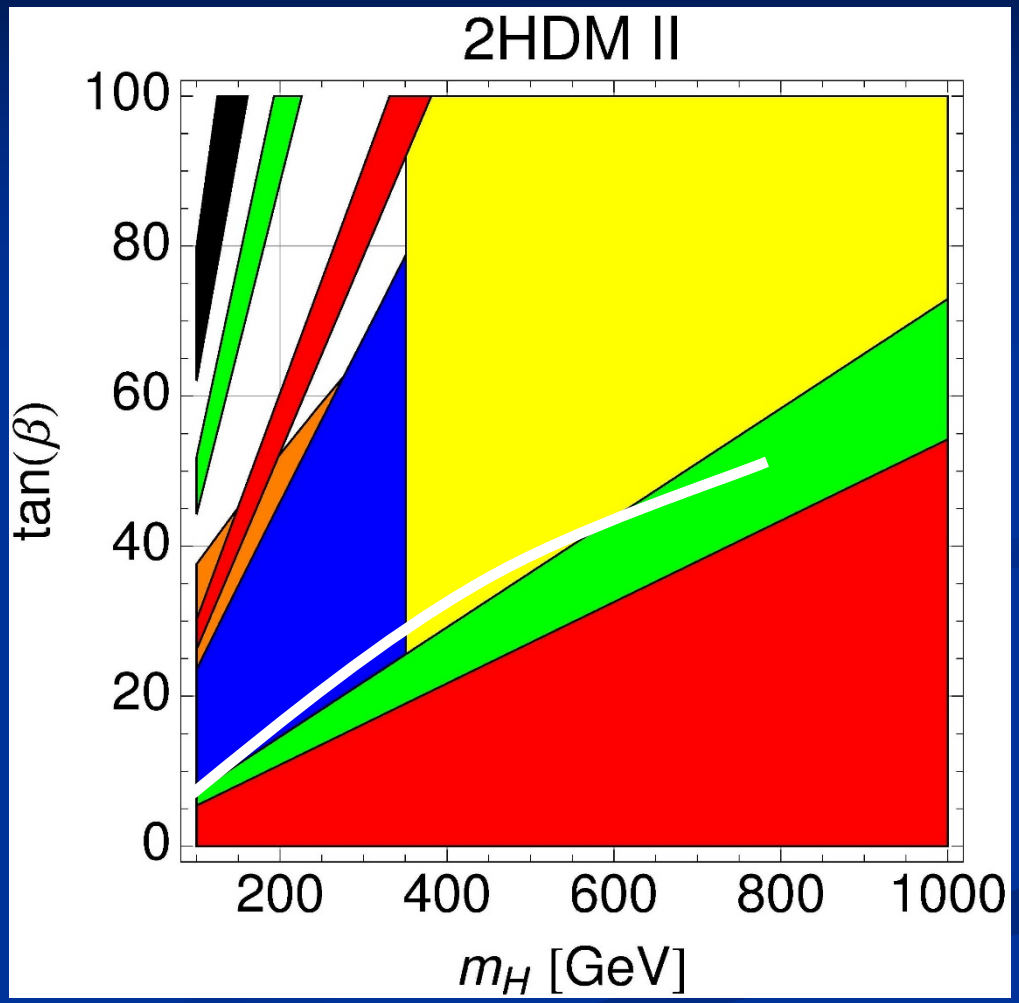
$K \to \mu\nu \,/\, \pi \to \mu\nu$

$B \to D\tau\nu$

$B_s \to \mu^+\mu^-$

$B \to D^*\tau\nu$

LHC



➡ Tension from $B \to D^*\tau\nu$

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

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

Allowed regions from:

$B \to D\tau\nu$

$B \to D^{*}\tau\nu$