Andreas Crivellin

Explaining the LHC flavour anomalies

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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).
- 3.1 σ in $B_s \to \phi\mu\mu$
- Contribution to $C_9^{\mu\mu}$ but not C_9^{ee} gives simultaneously a good fit ⇒ 4.3 σ better than SM
- Explanation:
  - Leptoquarks — 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

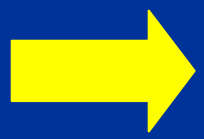
$$\mathrm{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)\%$$ CMS-PAS-HIG-14-005

- 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_μ-L_τ

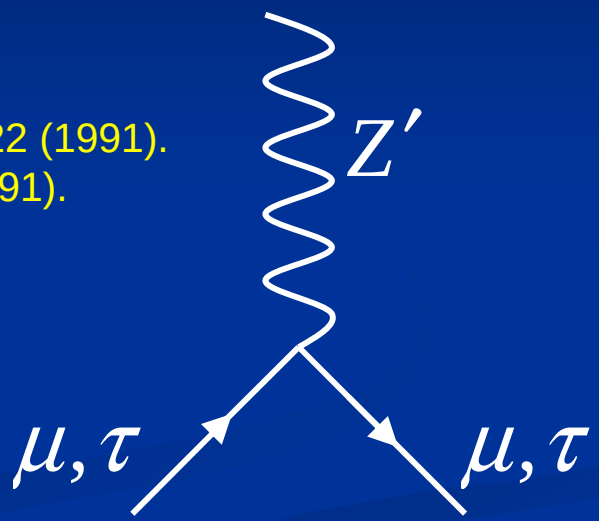
PRL, arXiv:1501.00993.

Gauged $L_\mu - L_\tau$

- Vectorial U(1) gauge group:
  Q(e) = 0, Q(μ) = 1, Q(τ) = -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

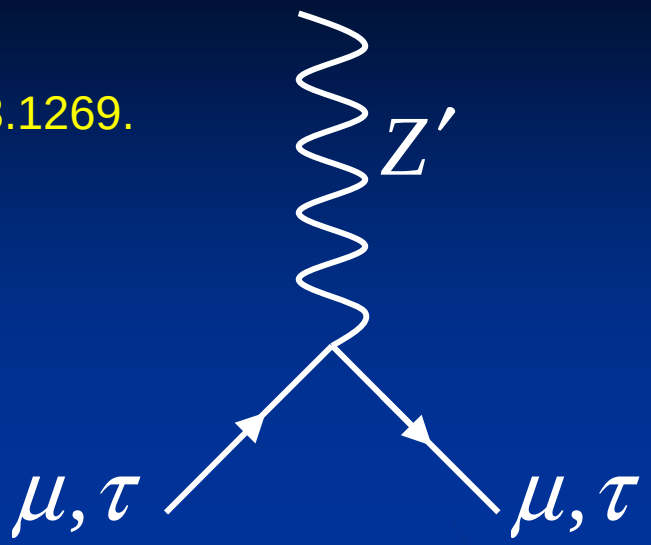
➡ Breaking necessary for a realistic neutrino sector

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 $L_\mu - L_\tau$

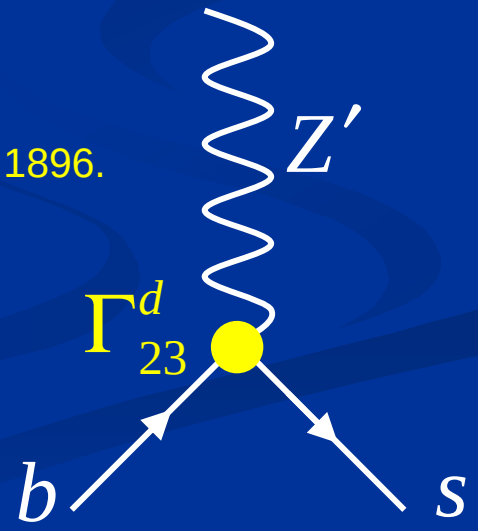
$$m_Q \bar{Q}_L \tilde{Q}_R + m_D \bar{\tilde{D}}_L D_R + m_U \bar{\tilde{U}}_L U_R + \text{h.c.}$$

- Effective Z' quark couplings

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

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

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



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

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

- Two Higgs doublets

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

- 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

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

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

$$\sin\theta_L \simeq 0$$

- Lepton flavour violating Z' couplings

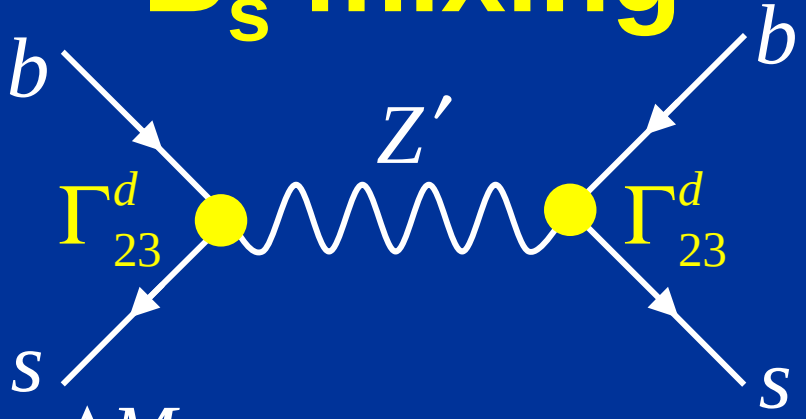
$$g' Z'(\bar{\mu}, \bar{\tau}) \begin{pmatrix} \cos 2\theta_R & \sin 2\theta_R \\ \sin 2\theta_R & -\cos 2\theta_R \end{pmatrix} \gamma^\nu P_R \begin{pmatrix} \mu \\ \tau \end{pmatrix}$$

$m_D^2 \to \infty$

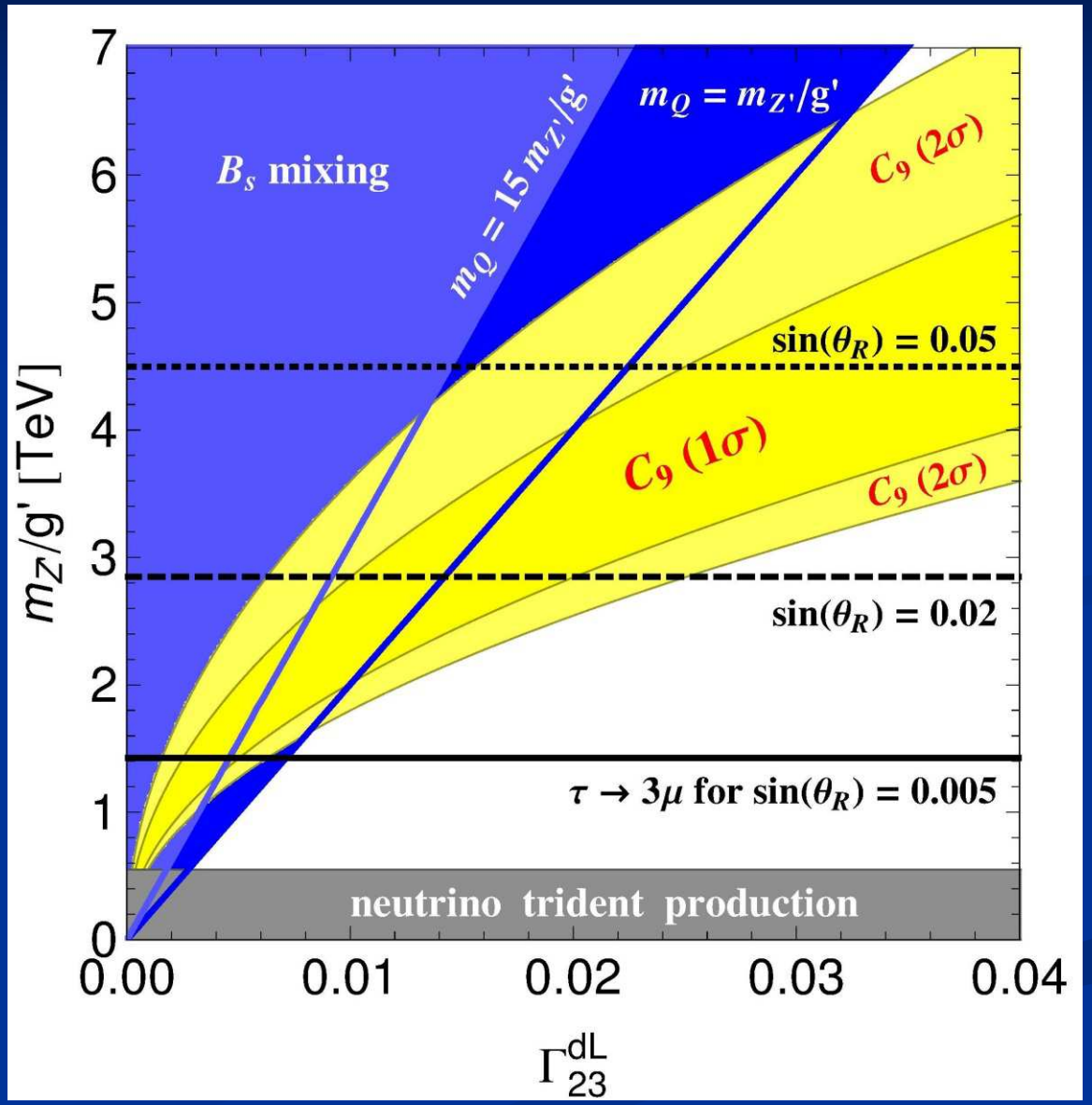
b→sμμ

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

B_s mixing

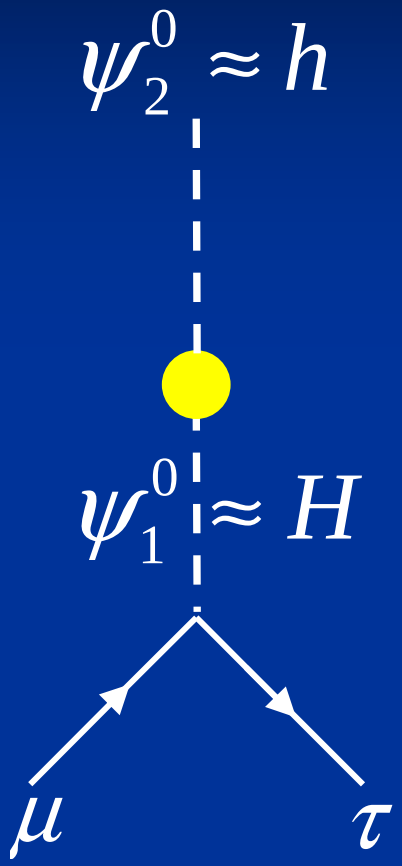


$$\frac{\Delta M_{12}}{M_{12}^{SM}} \propto \left(\Gamma_{23}^{dL}\right)^2 g'^2 / m_{Z'}^2$$

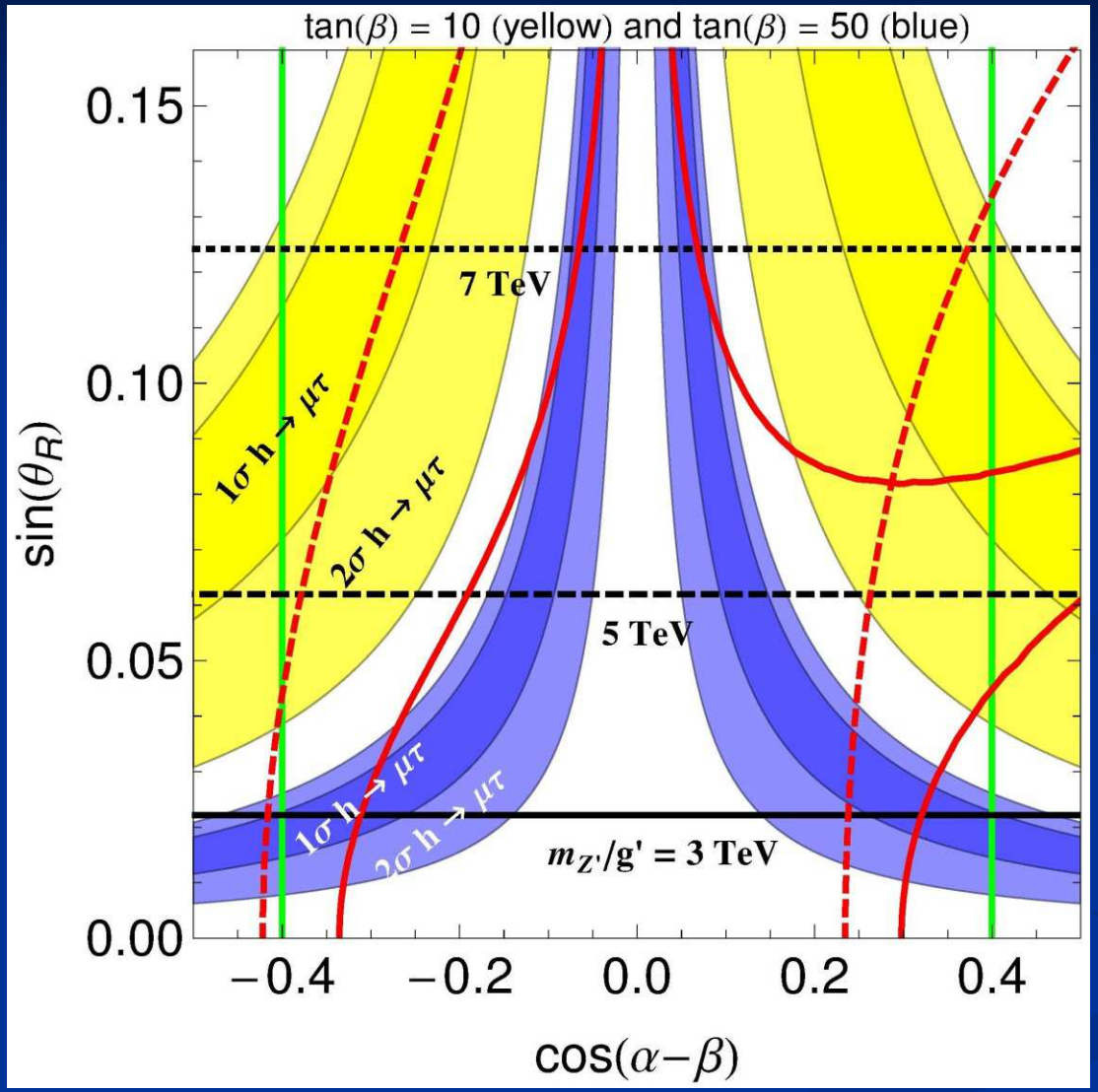


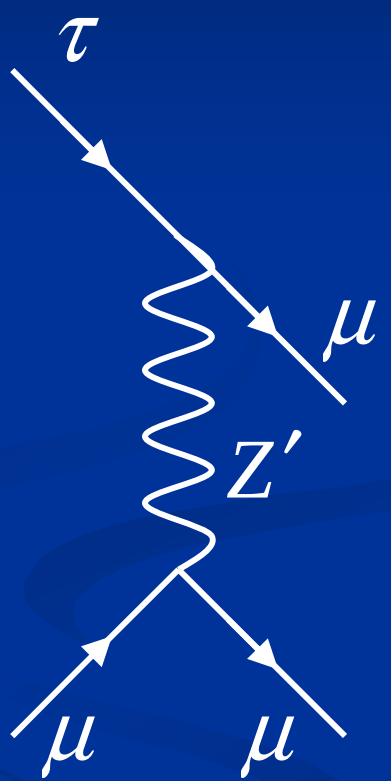
allowed regions

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



$h \to \gamma\gamma$ etc.





$h \to \tau\tau$

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

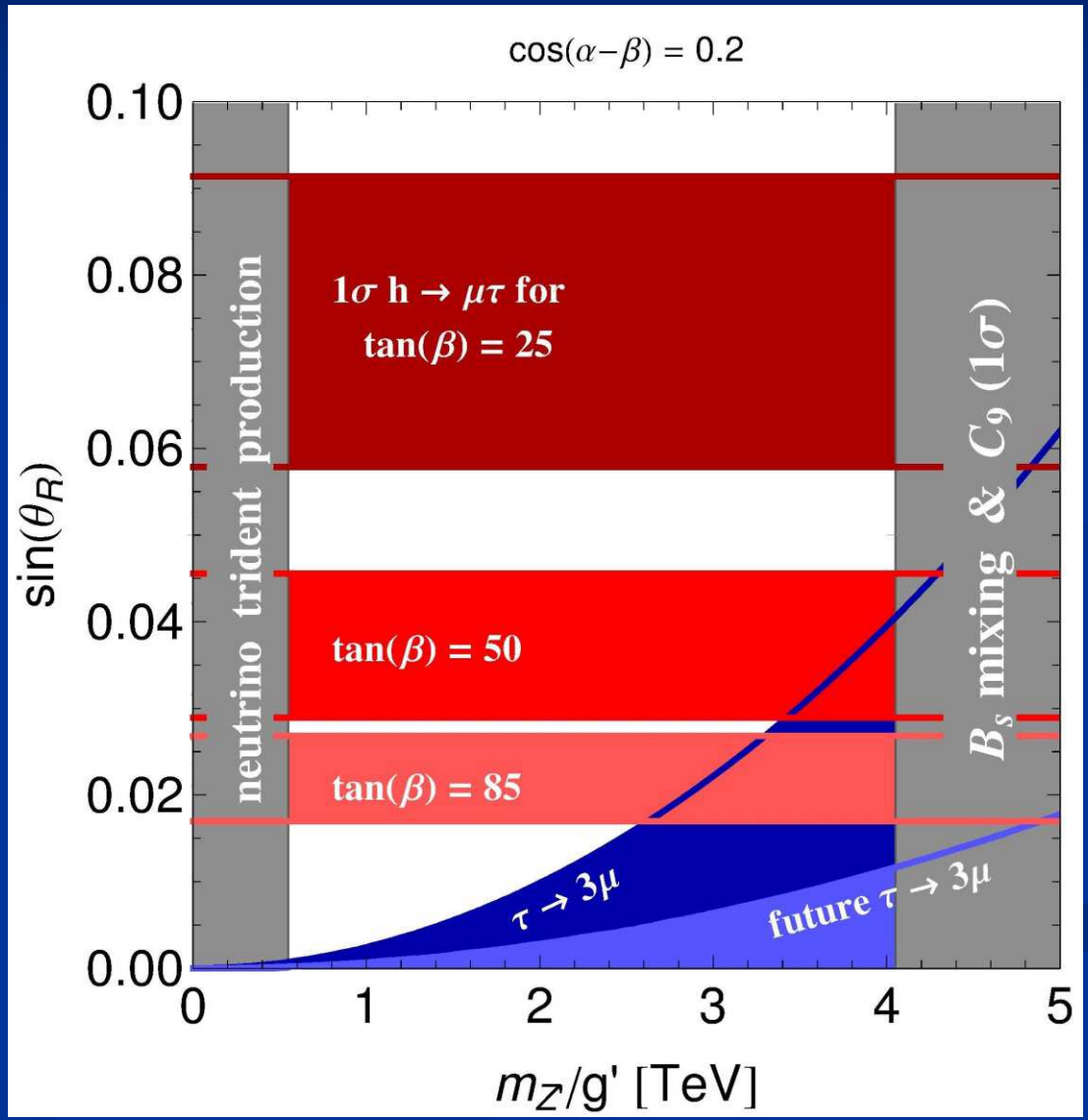
$h \to \mu\tau \ (\tan\beta = 10)$

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

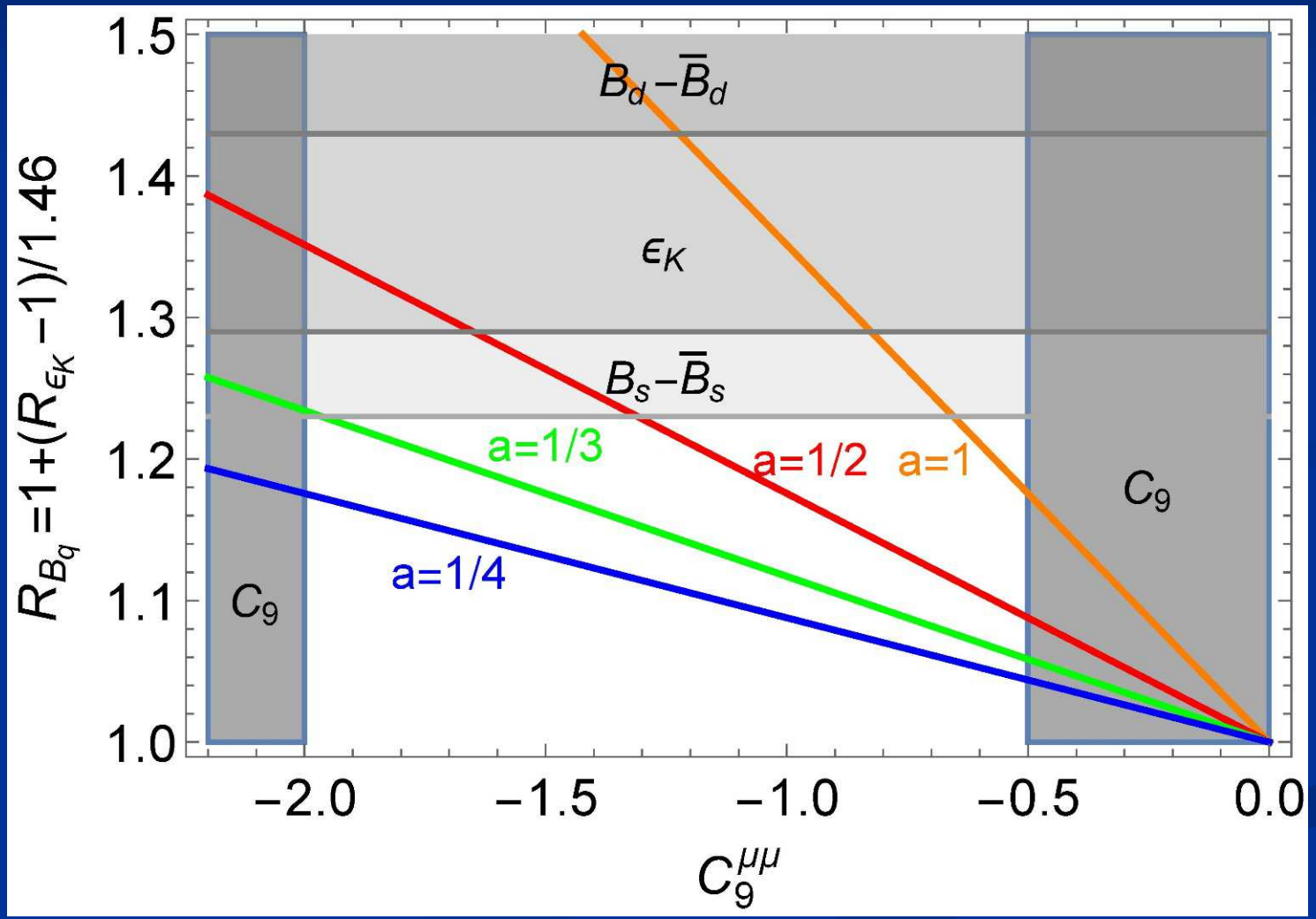
- First two quark generations must have the same charges because the large Cabibbo angle would lead to huge effect in Kaon mixing
- Anomaly free

➡ $Q(B) = (-a, \quad -a, \quad 2a)$

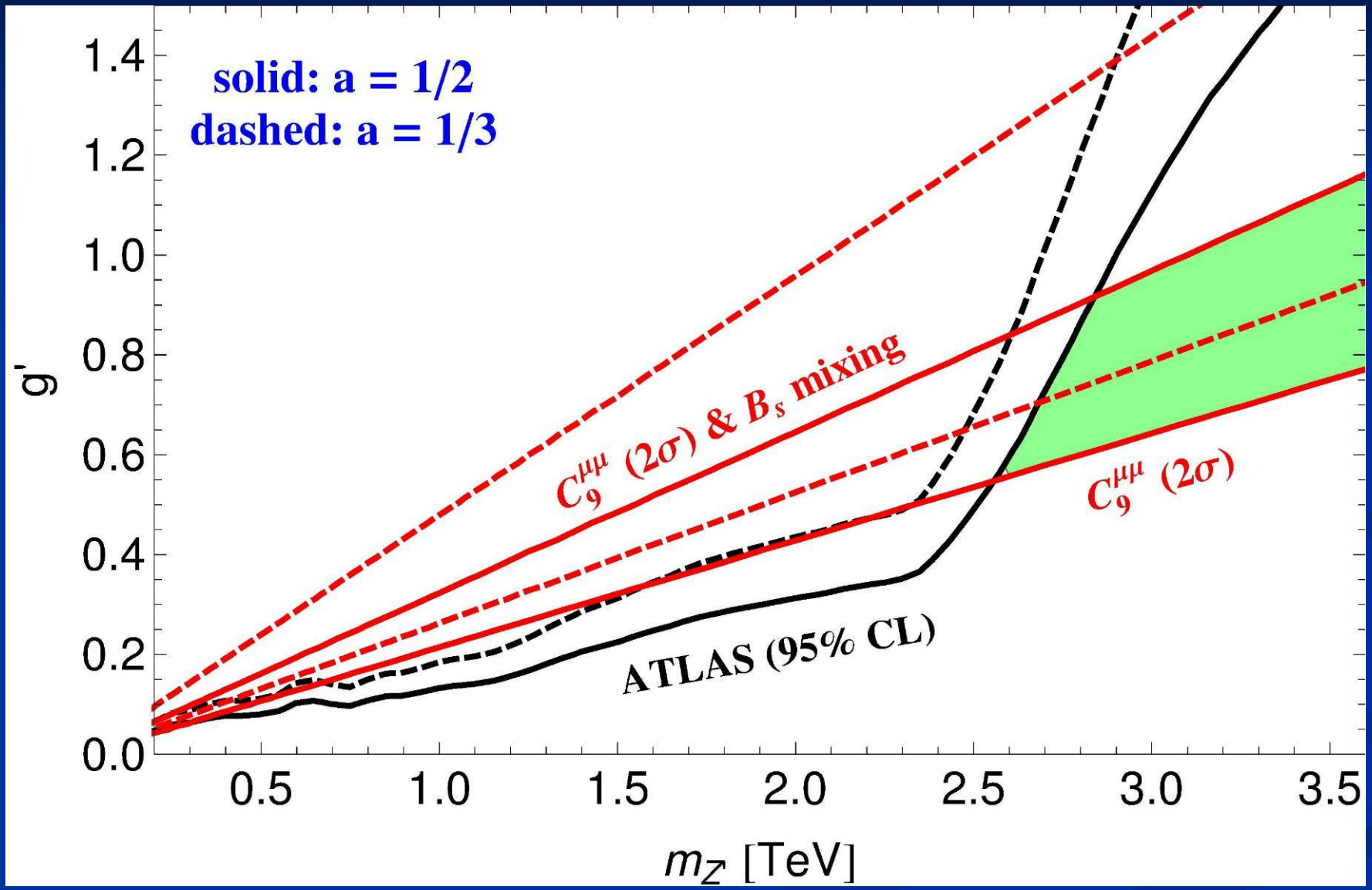
ΔF=2: Z' contribution

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

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



LHC limits



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

3HDM

- Same effect in

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

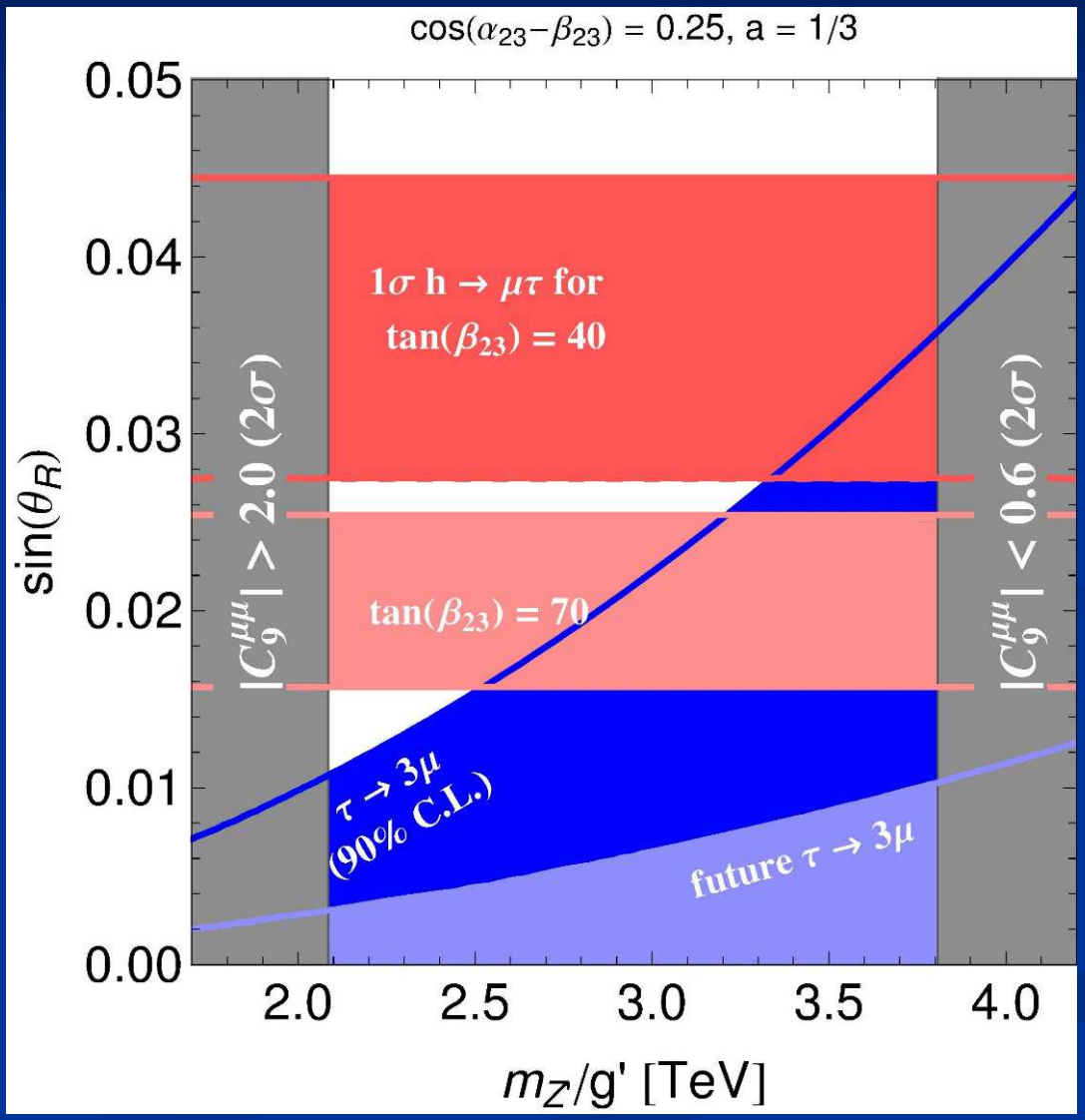
$h \to \mu\tau$

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
  - $h \to \tau\mu$
  - $\mathrm{B} \to \mathrm{K}^{*} \mu^{+} \mu^{-}$
  - $\mathrm{B} \to \mathrm{K} \mu^{+} \mu^{-} / \mathrm{B} \to \mathrm{K} e^{+} e^{-}$
  - $\mathrm{B}_{s} \to \phi \mu^{+} \mu^{-}$
- All four 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?

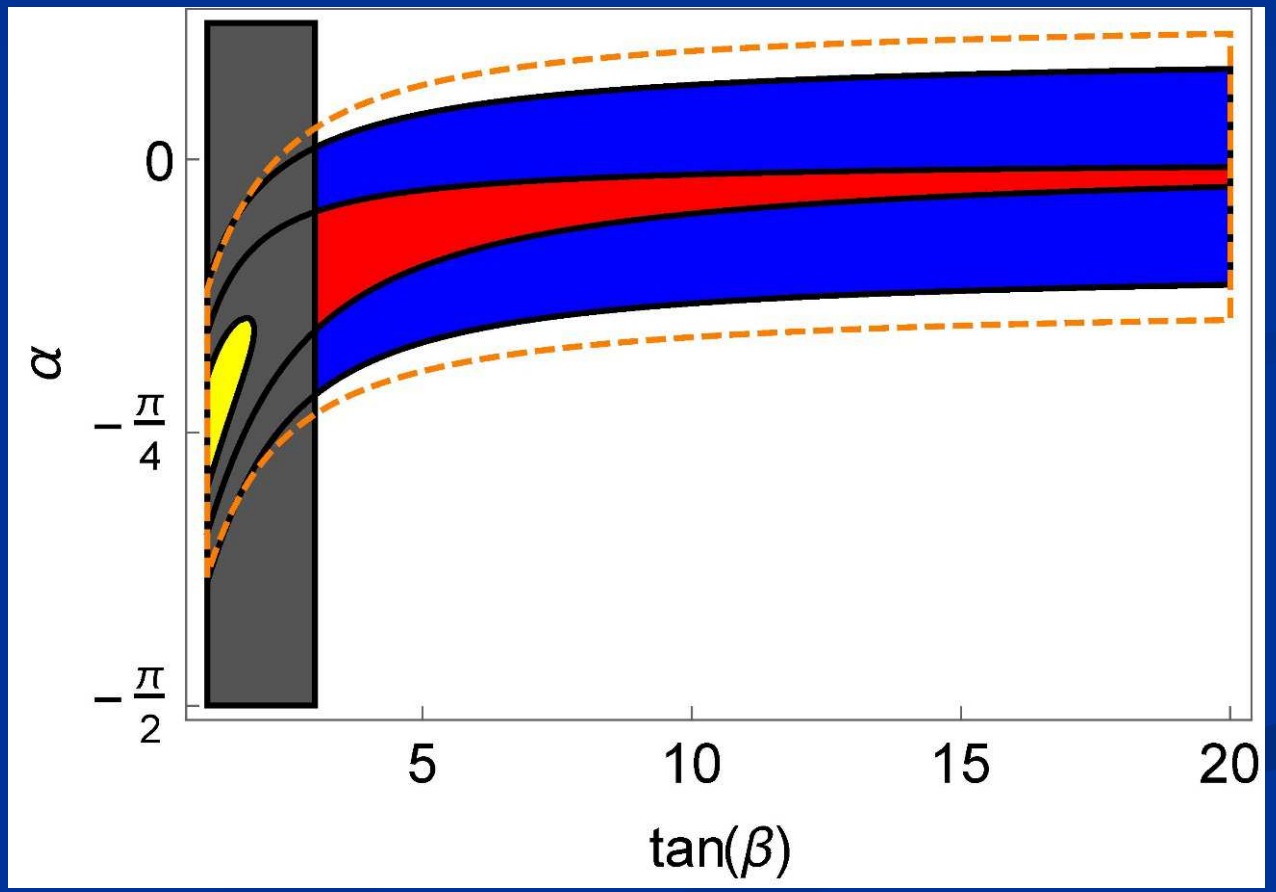
ΔF=2: Higgs contributions

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

$m_A = 350\ \text{GeV}$

$m_A = 300\ \text{GeV}$

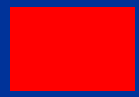
$m_A = 250\ \text{GeV}$



Type-II 2HDM

- Allowed 2σ regions from: (superimposed)


$b \to s\gamma$


$B \to \tau\nu$

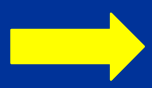

$K \to \mu\nu \,/\, \pi \to \mu\nu$

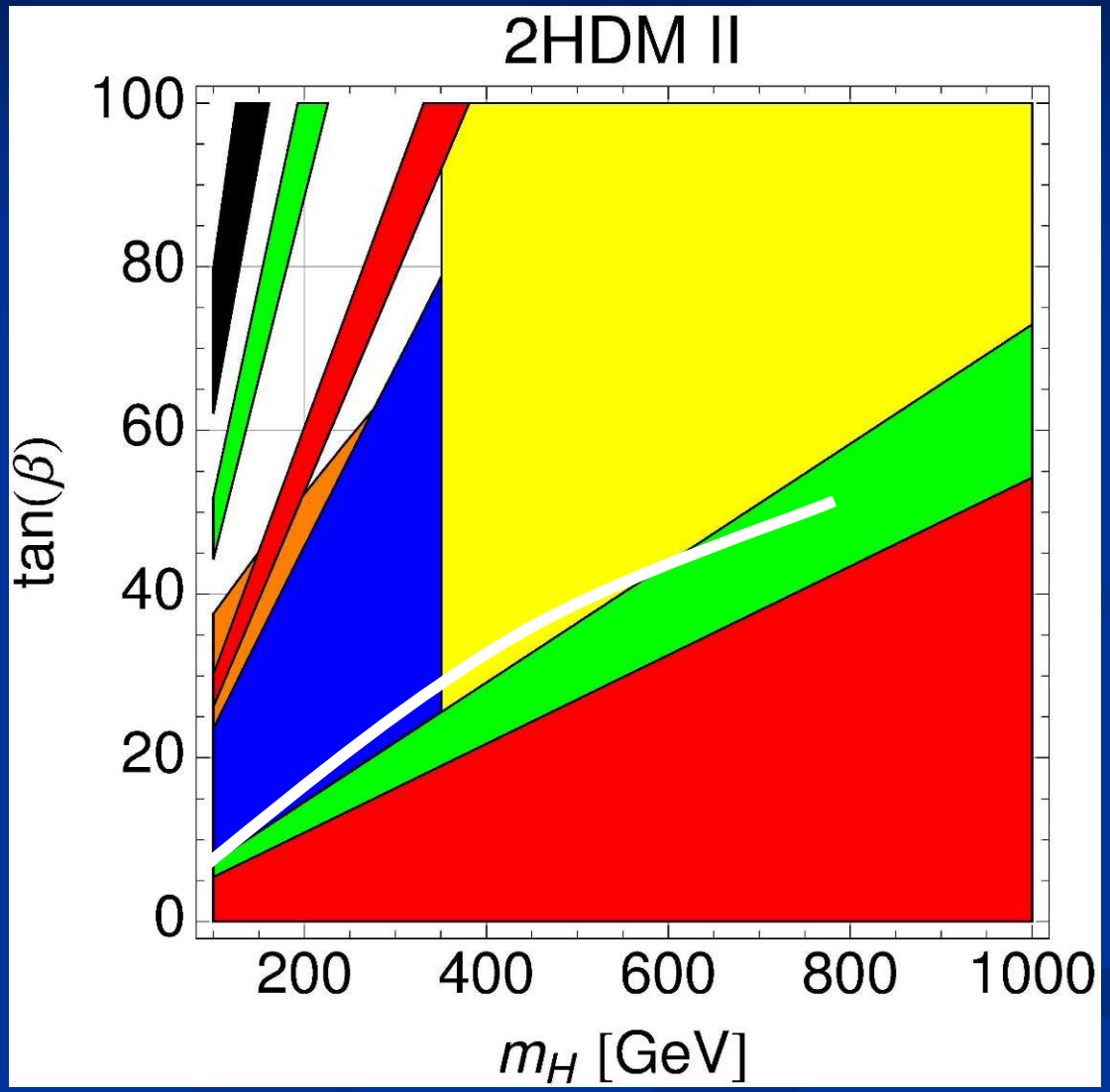

$B \to D\tau\nu$


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


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


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 $\mathcal{E}^{u}_{32}$. ➡ Check model via $H^0, A^0 \to \bar{t}c$

Allowed regions from:

$B \to D\tau\nu$

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