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Explaining the LHC flavor anomalies

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Outline:

- Introduction: Flavour anomalies
  - $b \to s\mu^+\mu^-$
  - $B \to D^{(*)}\tau\nu$
  - $h \to \tau\mu$
- Models with gauged $L_\mu - L_\tau$
  - Vector-like quarks
  - Horizontal charges
- $b \to s\mu^+\mu^-$ and $B \to D^{(*)}\tau\nu$ with third generation couplings
- a_μ, $\tau \to \mu\nu\nu$, $R(D^{(*)})$ and $t \to Hc$ in a 2HDM X
- Conclusions

Flavour Anomalies

Global fit to b→sμμ data

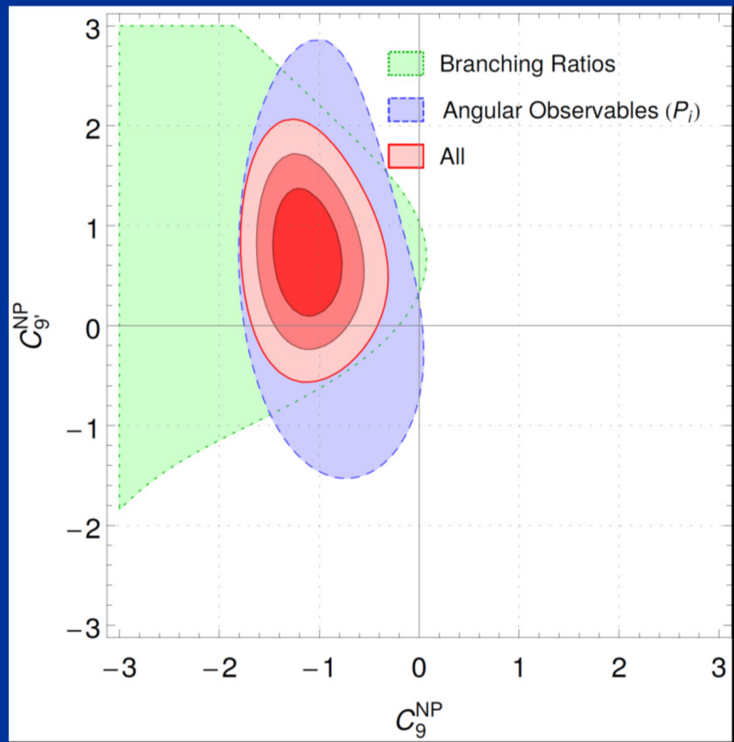
- Global analysis give a very good fit to data

  See talk of Wolfgang Altmannshofer

- Symmetry based solutions give a very good fit to data:
  - C_9
  - $C_9 = -C_{10}$
  - $C_9 = -C_9'$

$$O_9 = \bar{s}\gamma^{\mu} P_L b \bar{\ell}\gamma_{\mu}\ell$$

$$O_{10} = \bar{s}\gamma^{\mu} P_L b \bar{\ell}\gamma_{\mu}\gamma^5 \ell$$



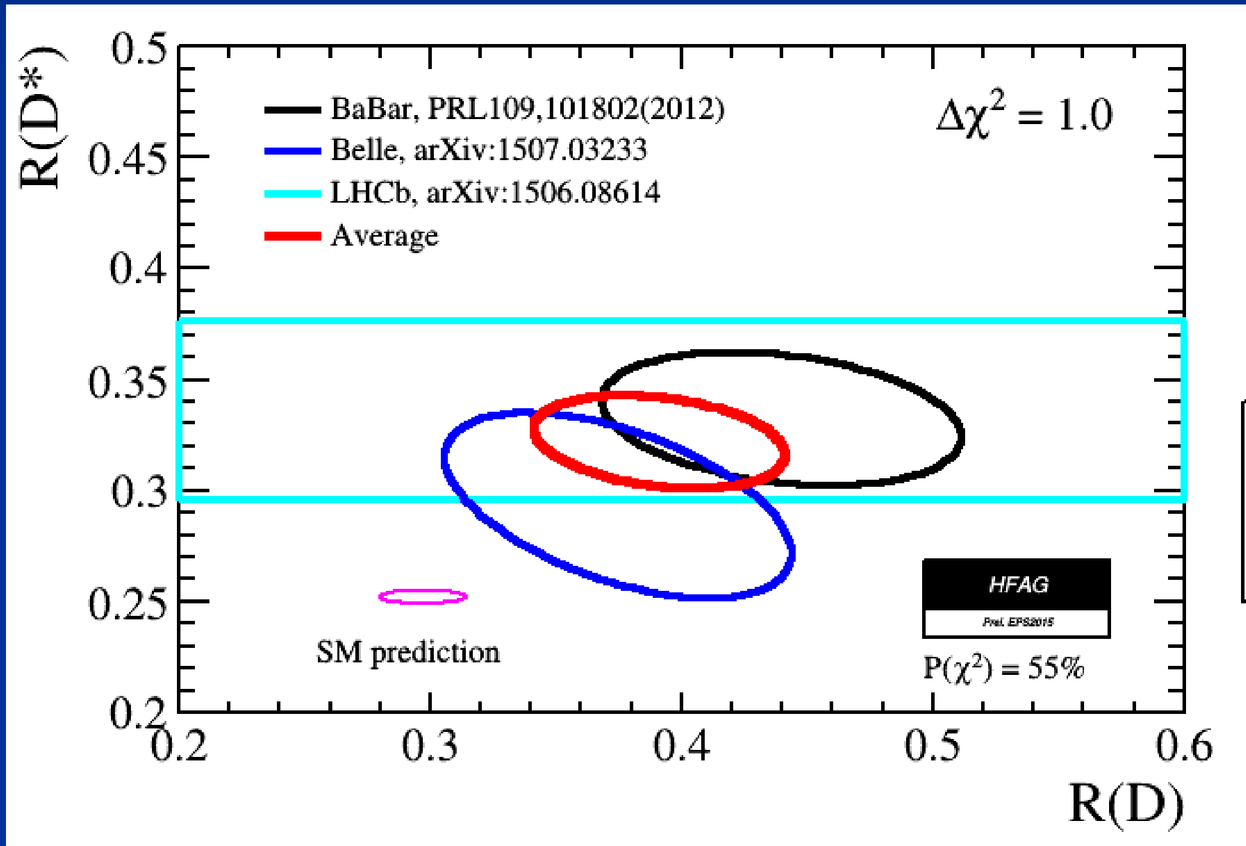
1501.04239

⇒ Fit is 4-5 σ better than in the SM

Tauonic B decays

- Tree-level decays in the SM via W-boson

$$R\left(D^{(*)}\right) = B \to D^{(*)}\tau\nu \big/ B \to D^{(*)}\ell\nu$$

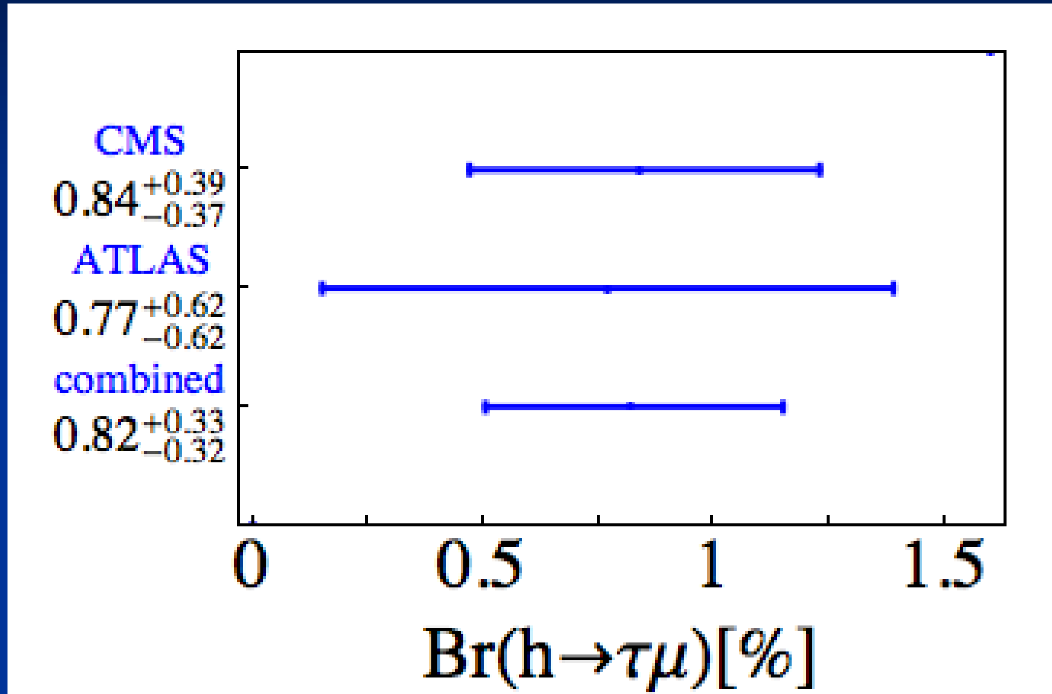


➡ All five measurements above the SM prediction
Combined 3.9 σ deviation

$h \to \tau\mu$

- 2.6 σ difference from zero
- 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

see arXiv:1502.07784 for a model comparison

$\tau \to \mu\nu\nu$ and a_μ

- Tau decays

$$\mathrm{Br}\left[\tau \to \mu\nu\nu\right]_{\exp} = \left(17.41 \pm 0.04\right)\%$$

$$\Delta_{\tau\to\mu\nu\nu} = \frac{\mathrm{Br}\left[\tau \to \mu\nu\nu\right]_{\exp}}{\mathrm{Br}\left[\tau \to \mu\nu\nu\right]_{SM}} - 1 = \left(0.69 \pm 0.29\right)\%$$

- Anomalous magnetic moment of the muon

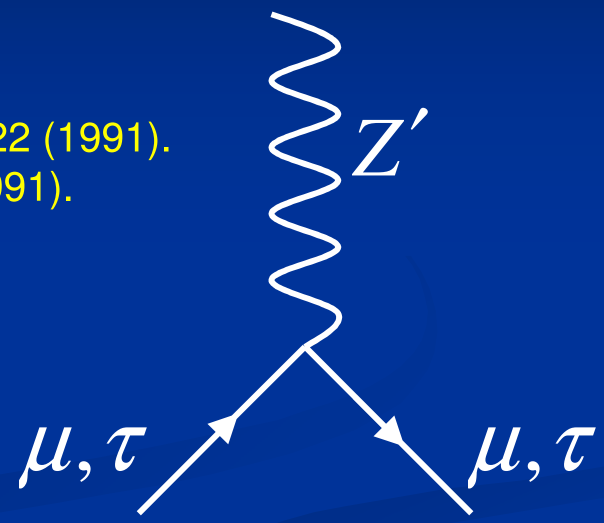
$$\Delta a_\mu = \left(236 \pm 87\right) \times 10^{-11}$$

⇨ $2-3\,\sigma$ deviations in the lepton sector

Z' models with gauged $L_\mu - L_\tau$

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

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

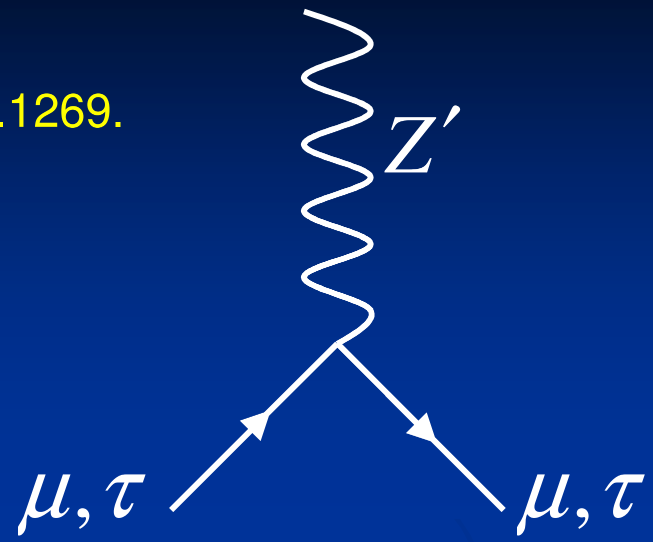
P. Binetruy, et al., hep-ph/9610481.
N. F. Bell and R. R. Volkas, hep-ph/0008177.
S. Choubey and W. Rodejohann, hep-ph/0411190.
J. Heeck and W. Rodejohann, 1107.5238

➡ Breaking necessary for a realistic neutrino sector

1HDM
with vector-quarks

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 $L_\mu - L_\tau$

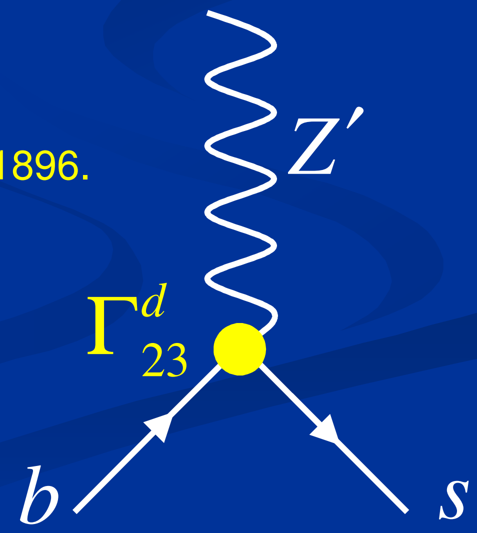
$$m_Q\bar{Q}_L\tilde{Q}_R + m_D\bar{\tilde{D}}_L D_R + m_U\bar{\tilde{U}}_L U_R + \text{h.c.}$$

- Effective Z' quark couplings

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

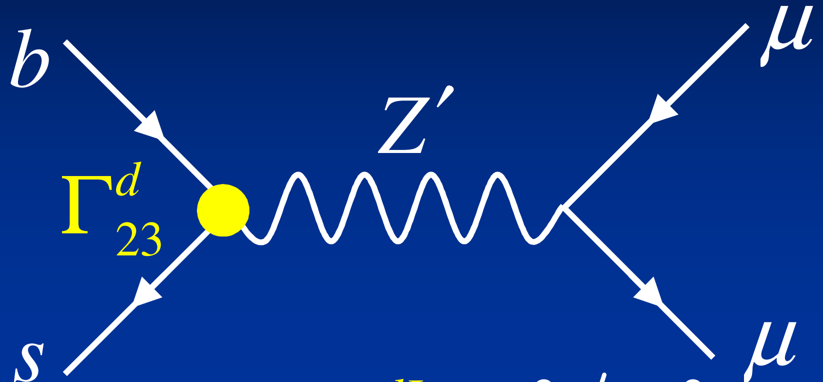
$$ig'\gamma^\mu d_f\left(\Gamma^L_{fi}P_L + \Gamma^R_{fi}P_R\right)d_i Z'_\mu$$

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



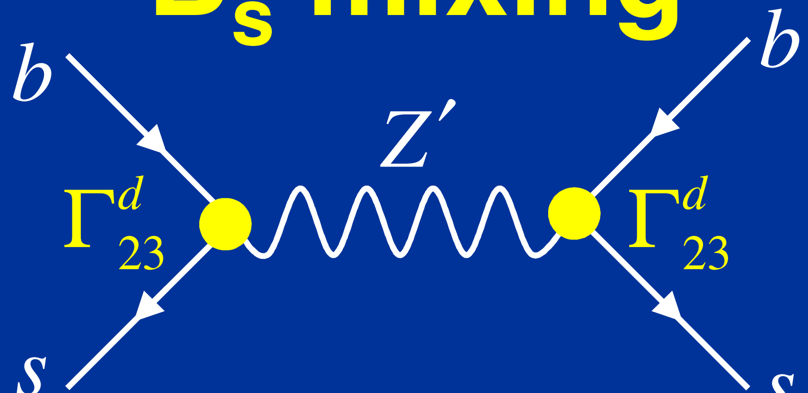
B→K*μμ, R(K)

$$m_D^2 \to \infty$$

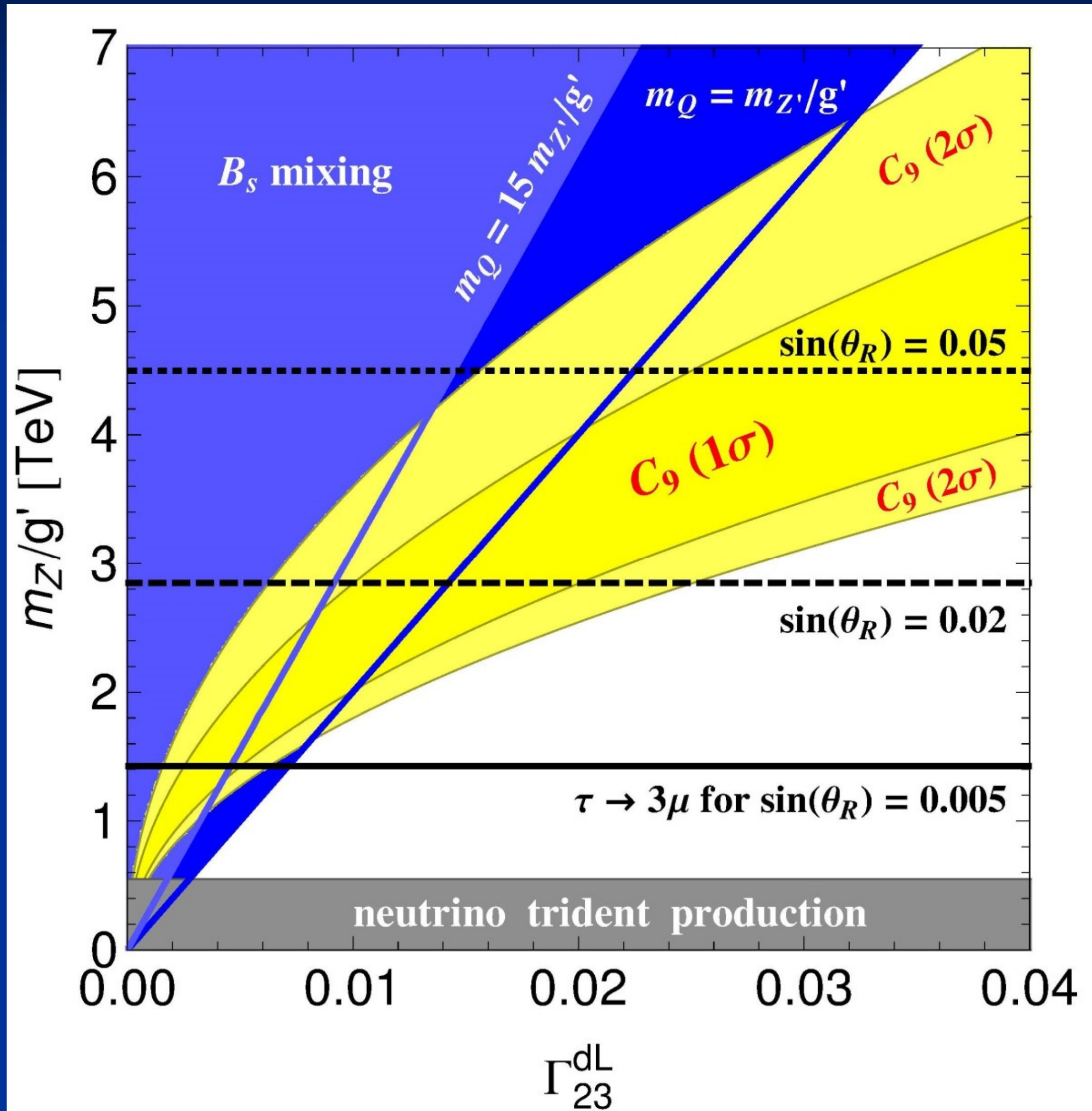


$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL}\, g'^2 / m_{Z'}^2$$

B_s mixing



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



allowed regions

2HDM with vector-quarks

A.C., G. D'Ambrosio and Julian Heeck

Explaining $B\to K^*\mu\mu$, R(K) and $h\to\tau\mu$ in a two-Higgs-doublet model with gauged L_μ-L_τ

arXiv:1501.00993, PRL 114 (2015) 151801

2^{nd} 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

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

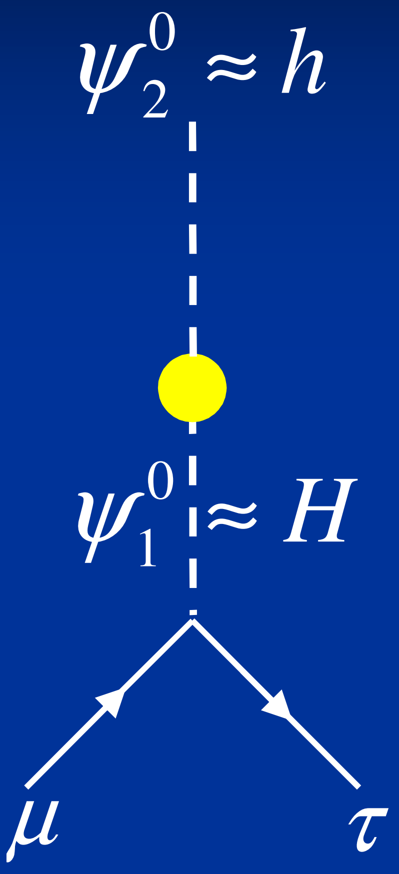
- θ_R diagonalizes the τ-μ block of the mass matrix
- Flavour changing SM-like Higgs coupling

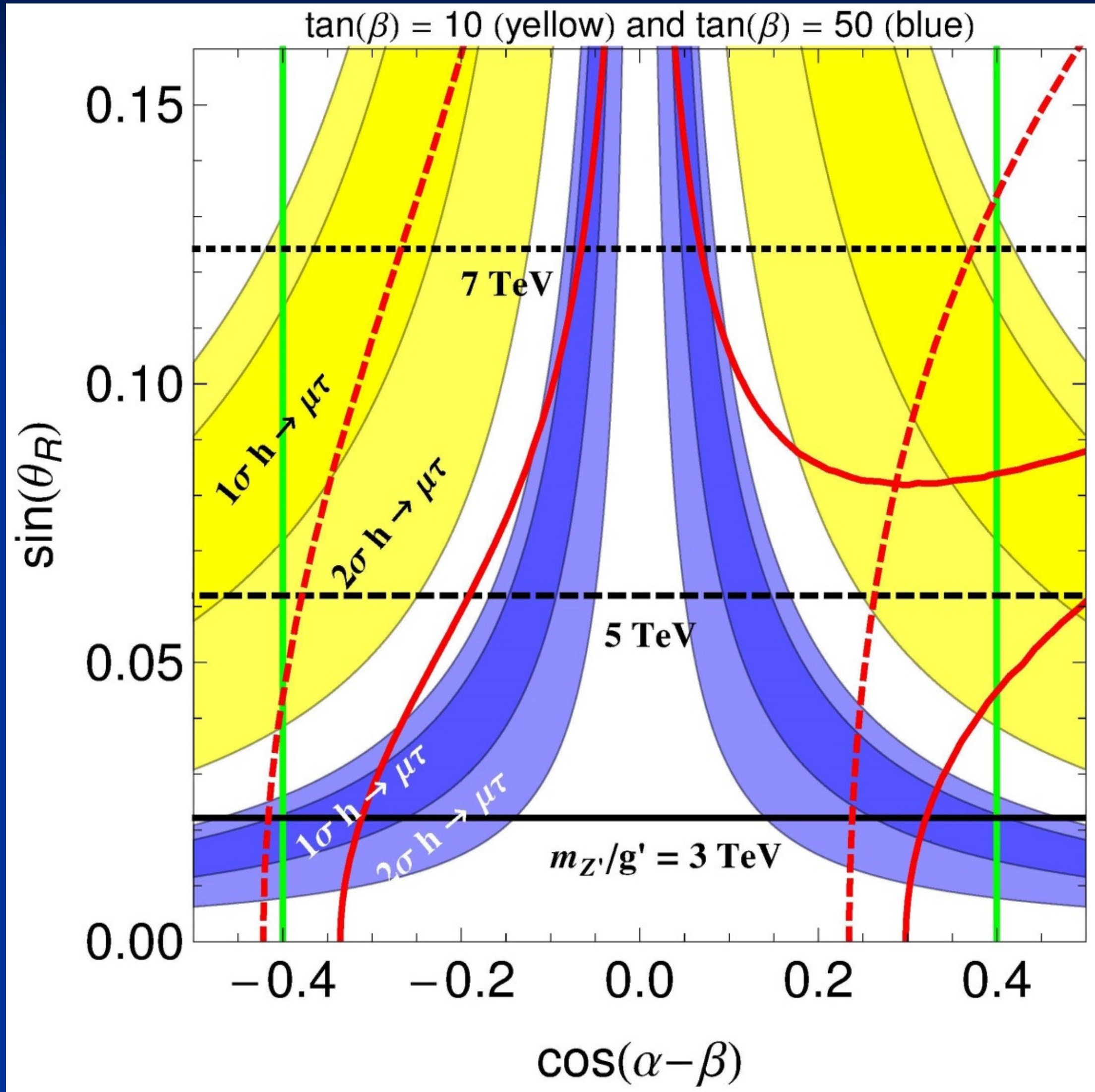
$$\overline{\tau} P_R \mu h^0 \sim \cos(\alpha - \beta)\theta_R \qquad \sin\theta_R \simeq \frac{v}{\sqrt{2} m_\tau} \xi_{\tau\mu} \cos\beta, \quad \sin\theta_L \simeq 0$$

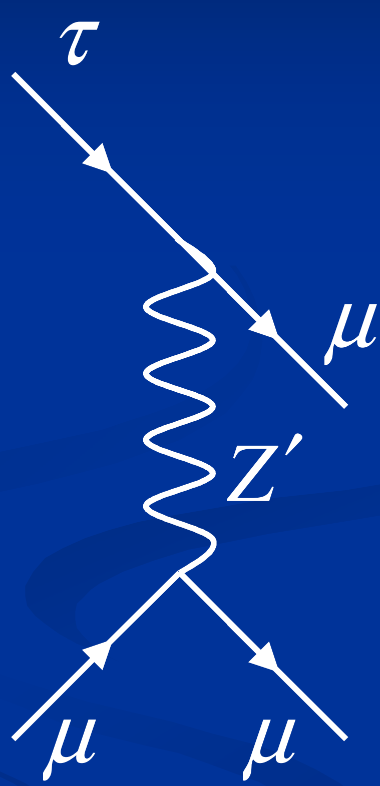
- Lepton flavour violating Z' couplings

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

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







$h \to \gamma\gamma$ etc.

$h \to \tau\tau$

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

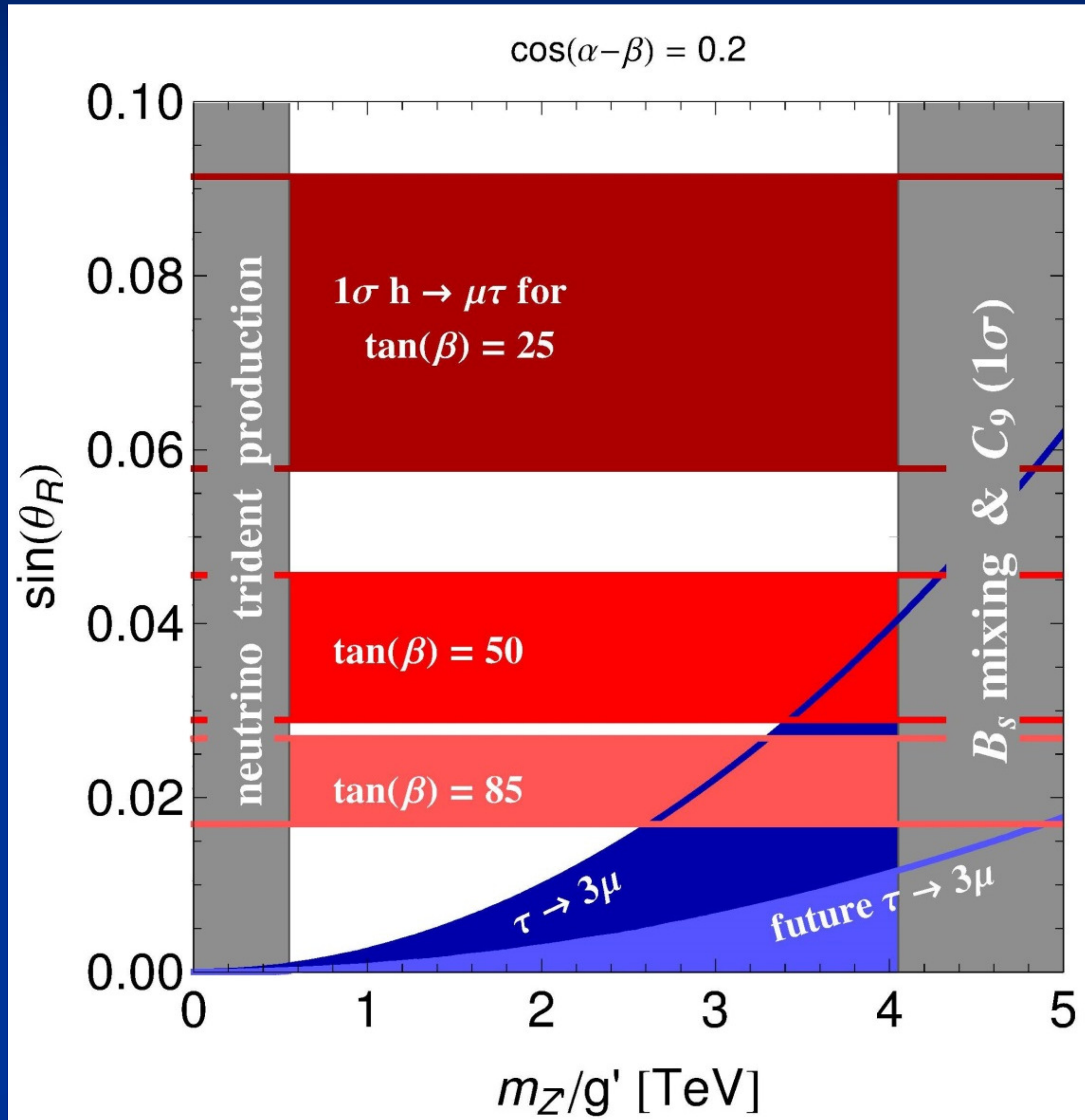
$h \to \mu\tau \ (\tan\beta = 10)$

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

excluded

allowed by $h \to \tau\mu$

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



Horizontal charges

A.C., Giancarlo D'Ambrosio and Julian Heeck

Adressing the LHC flavour anomalies with horizontal gauge symmetries

Phys.Rev. D91 (2015) 7, 075006

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}

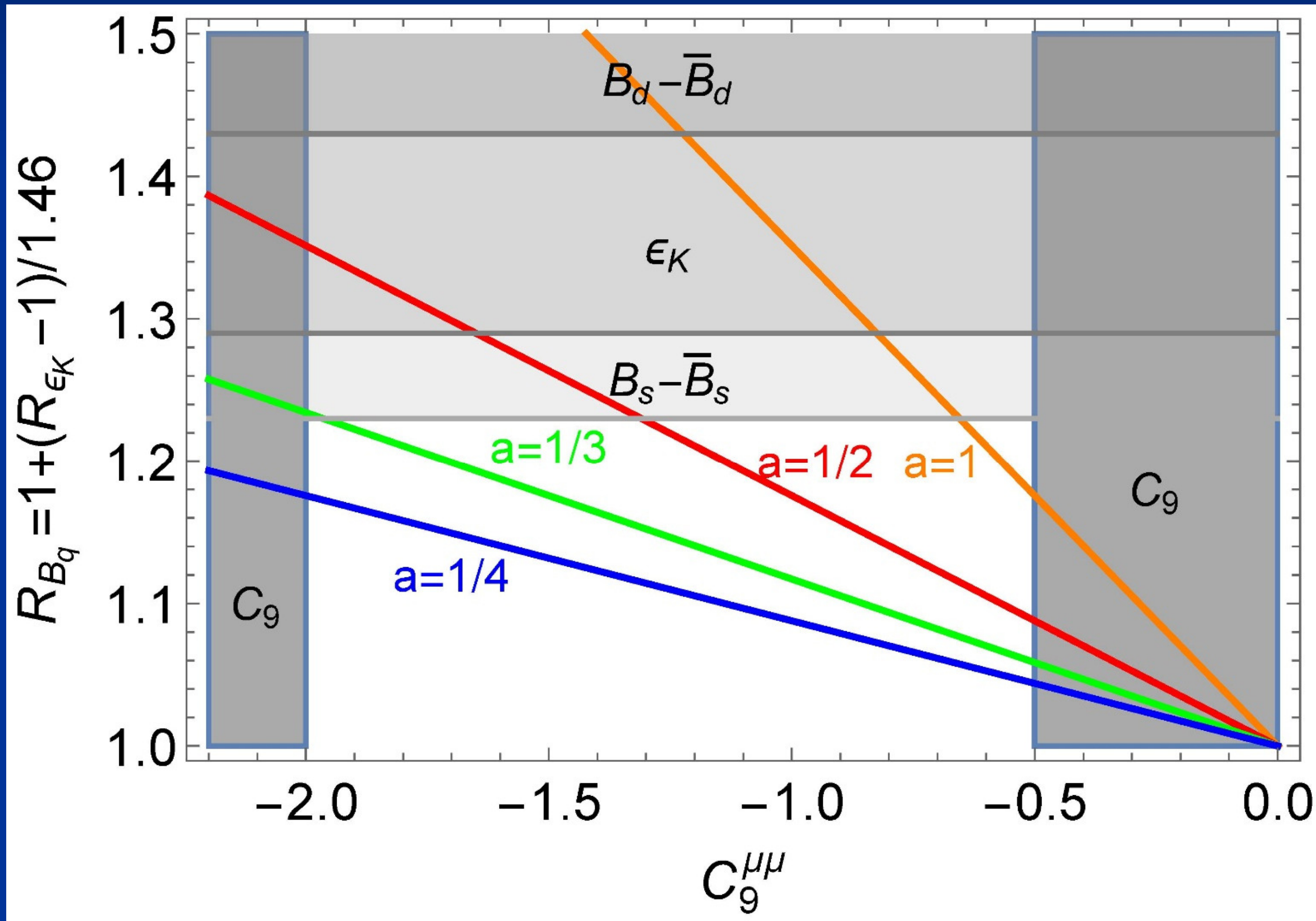
- First two quark generations must have the same charges because the large Cabibbo angle would lead to huge effect in Kaon mixing
- Anomaly free

⇒ $Q(B) = (-a, \quad -a, \quad 2a)$

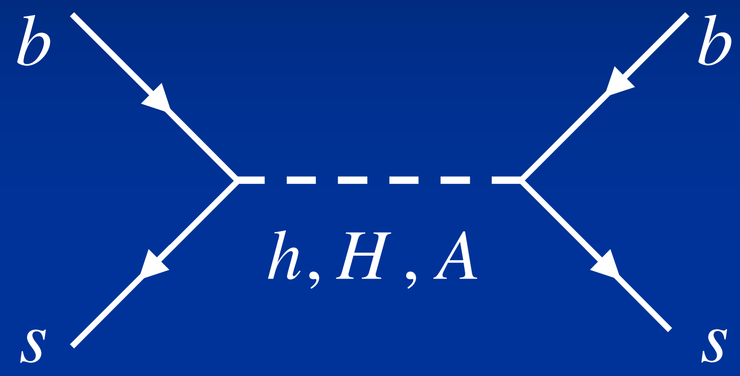
ΔF=2: Z' contribution

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

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



ΔF=2: Higgs contributions

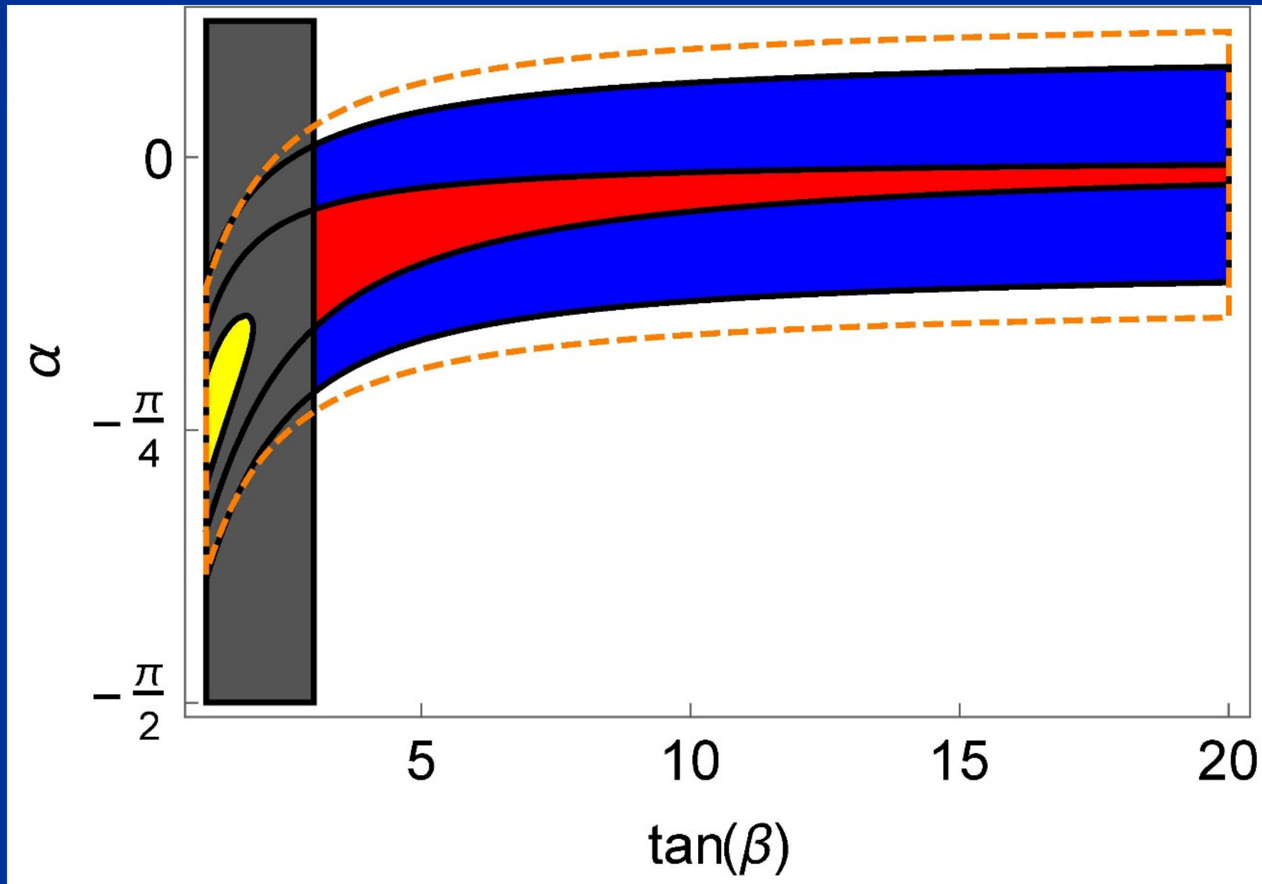


$m_H = 300\ \text{GeV}, \quad C_9^{\mu\mu} = -1.3$

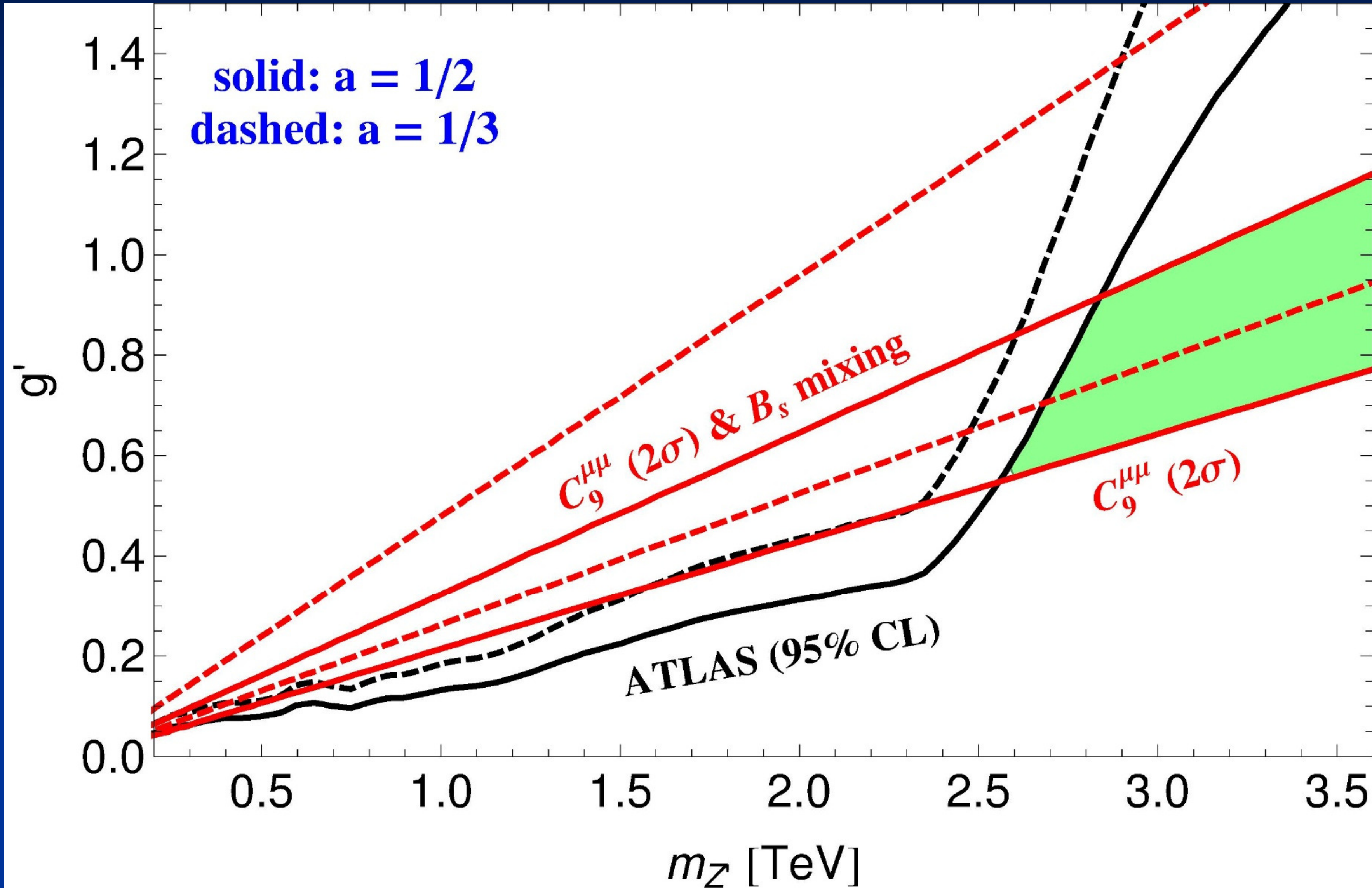
$m_A = 350$ GeV (yellow)

$m_A = 300$ GeV (red)

$m_A = 250$ GeV (blue)



LHC limits



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

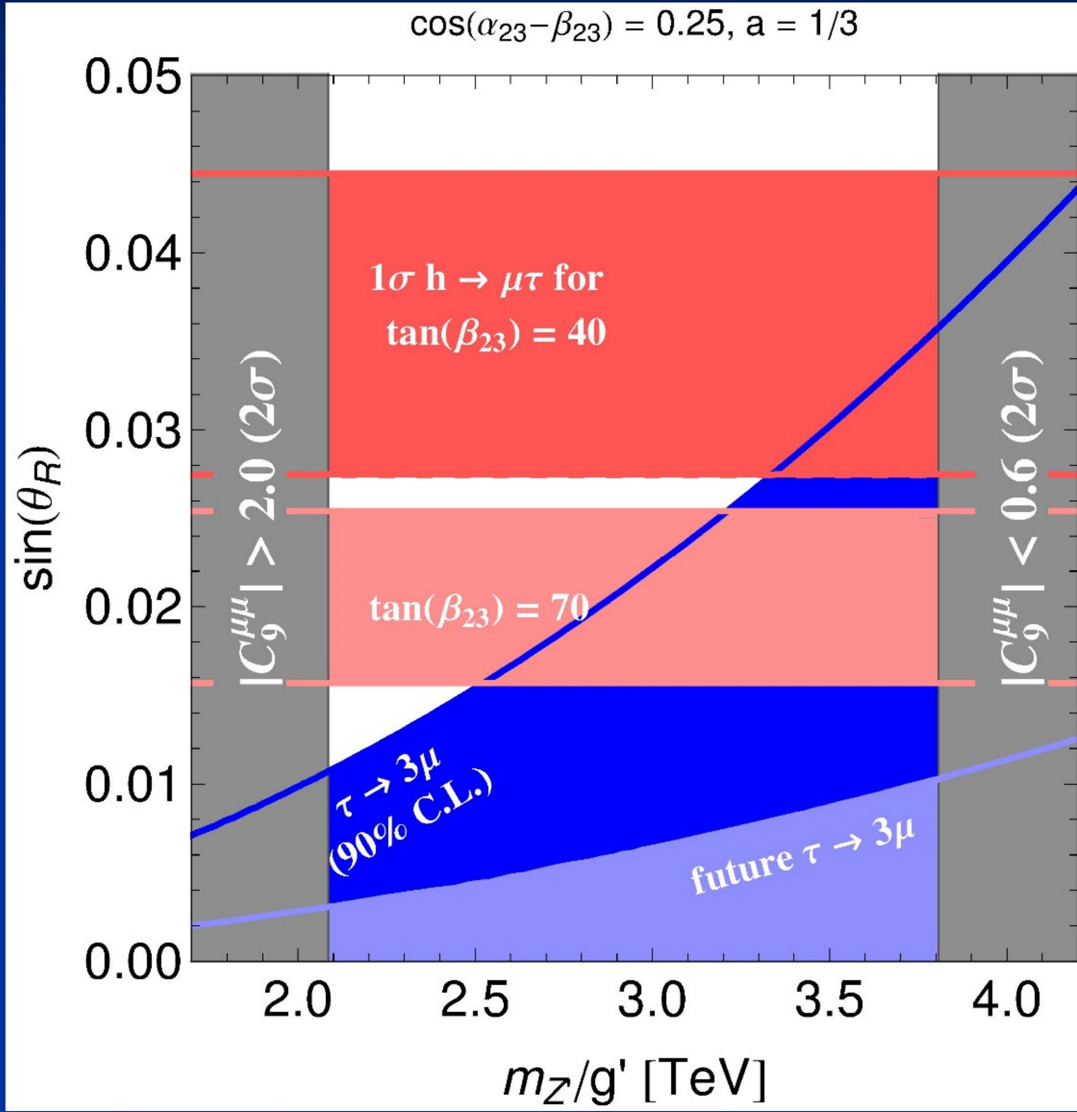
3HDM

- Same effect in

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

$h \to \mu\tau$

provided that the mixing among the doublets is small



excluded

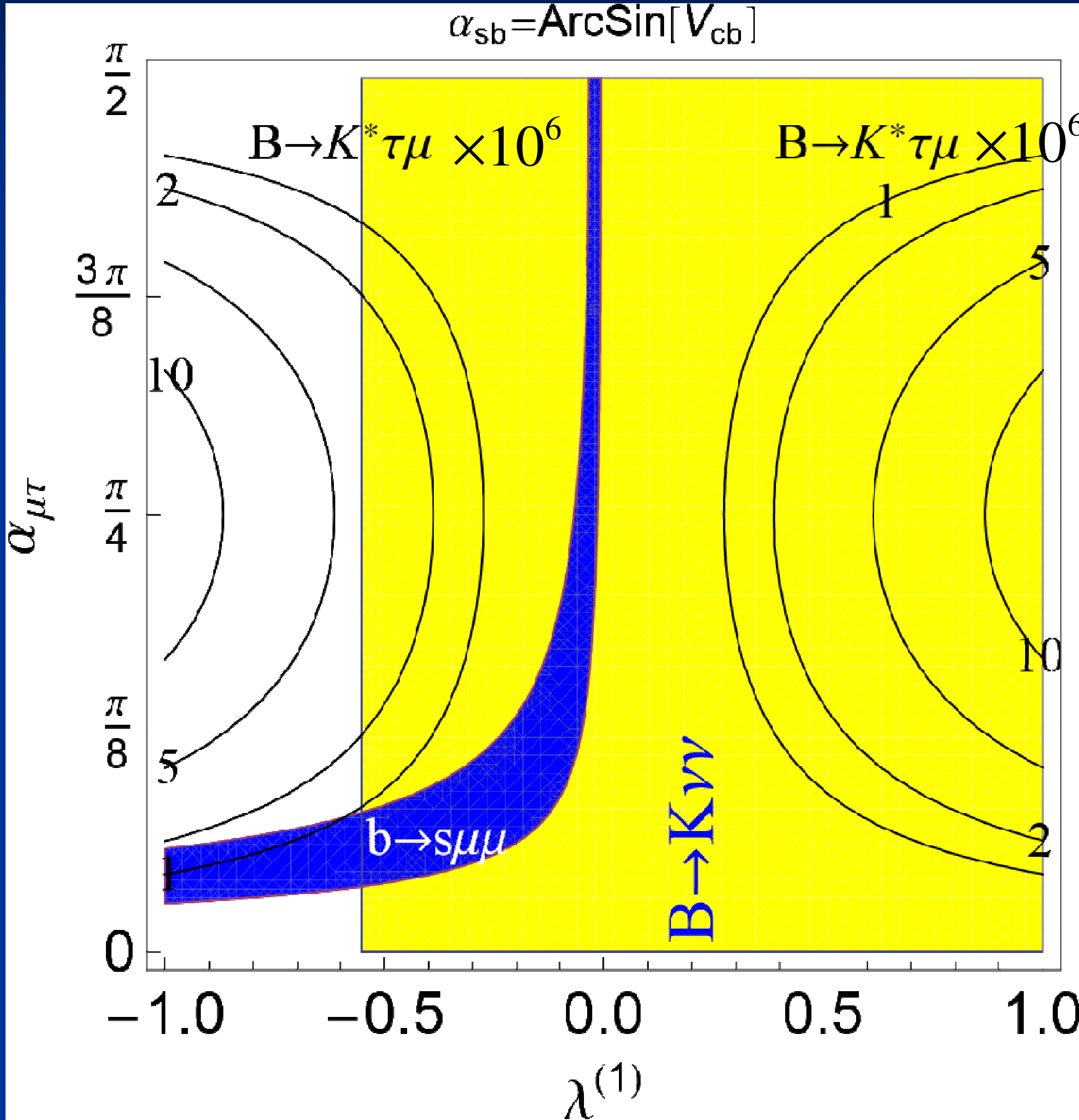
allowed by $h \to \tau\mu$

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

Combining $b \to s\mu\mu$ with $B \to D^{(*)}\tau\nu$

L. Calibbi, A.C. and T. Ota, PRL, arXiv:1506.02661

$$Q_{llqq}^{(1)} = L\gamma^{\mu} P_L L Q \gamma^{\mu} P_L Q$$

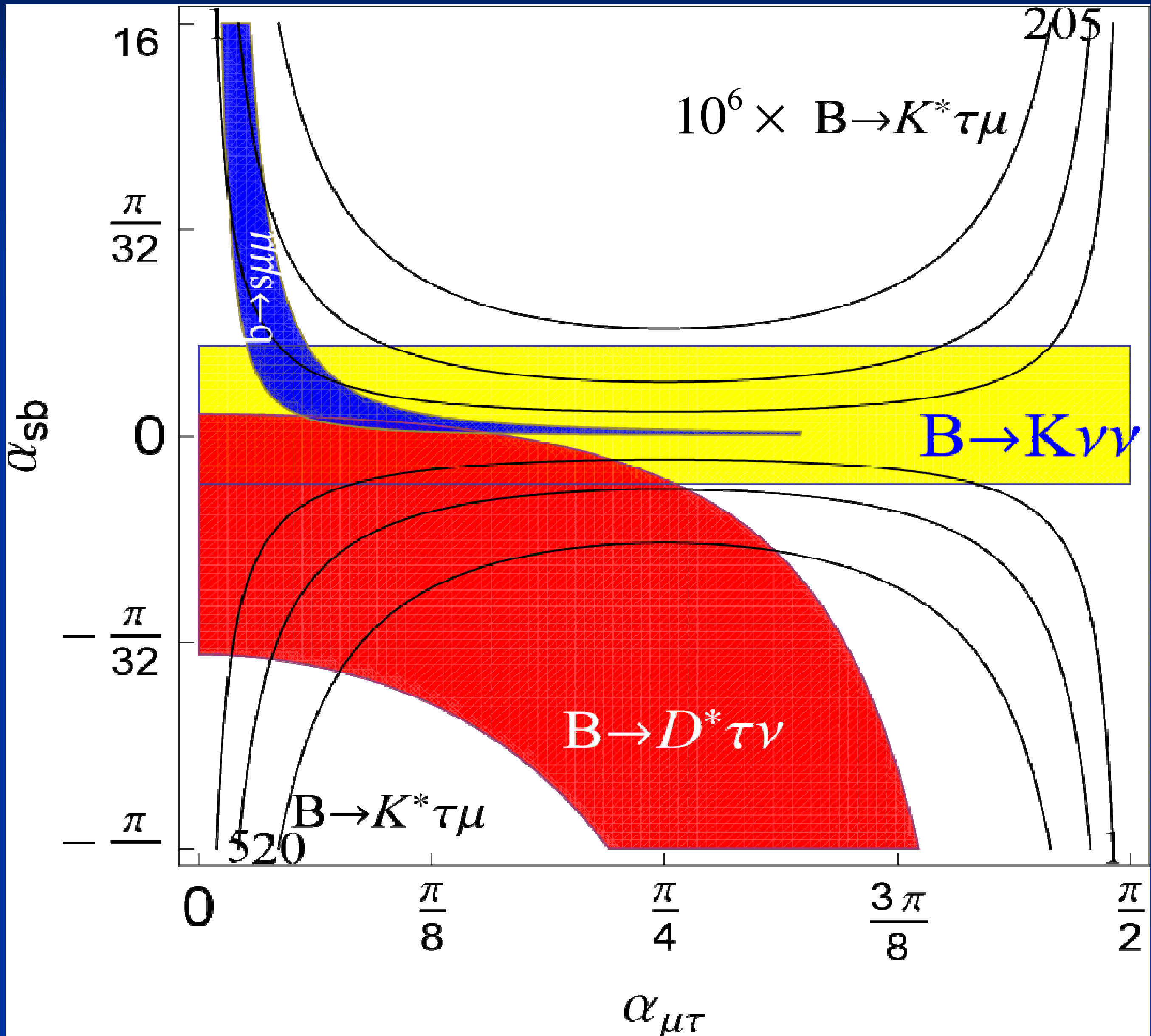


Third generation couplings

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\alpha_{\mu\tau}$ Misalignment between interaction and mass basis

$$Q_{llqq}^{(3)} = L\gamma^{\mu} P_L \tau^I L Q\gamma^{\mu} \tau_I P_L Q$$



UV realizations (single mediator)

- Vector SU(2) triplet
- Vector-leptoquark SU(2) singlet
- Skalar-leptoquark
  (without third gerneration couplings)
  M. Bauer, M. Neubert arXiv:1511.01900
- Could be generated in
  - Composite Higgs models
  - Models with extra dimensions

More than a single mediator?

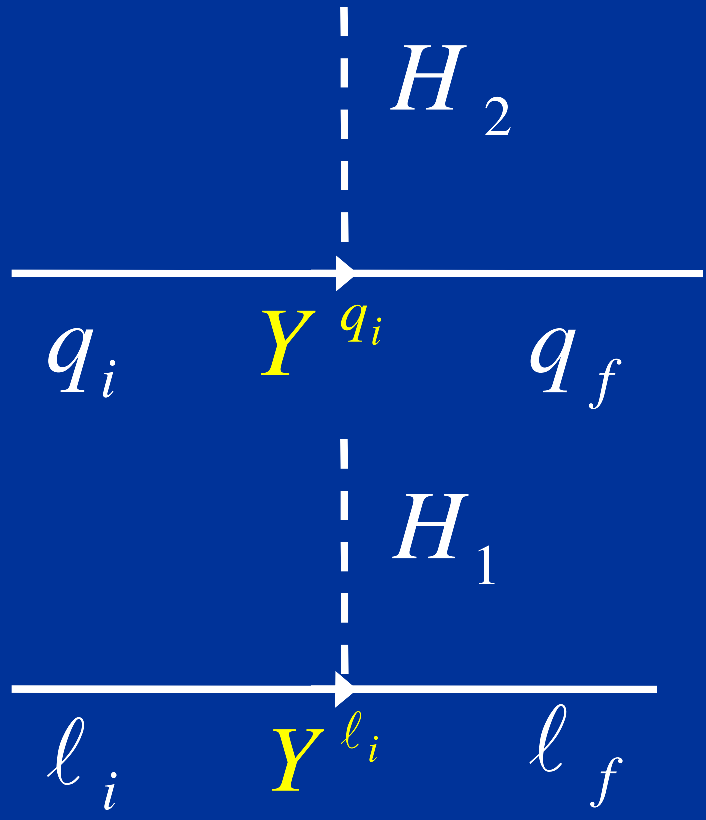
Only possible if $B_s \to \mu\mu$ is below the SM value!

Perturbed 2HDM X

AC, Julian Heeck, Peter Stoffer. arXiv:1507.07567.

2HDM of type X

- One Higgs doublet couples only to quarks the other Higgs doublet to leptons.
- Additional free parameters:
  $\tan\beta = v_1 / v_2$
  $m_H, m_{A^0}, m_{H^\pm}, m_{H^0}$
- All flavor-violations is due to the CKM matrix.



$$m_{q_i} = v_2 Y^{q_i}$$

$$m_{\ell_i} = v_1 Y^{\ell_i}$$

⇒ Neutral Higgs-quark couplings are flavor-conserving
Couplings to leptons are tan(β) enhanced

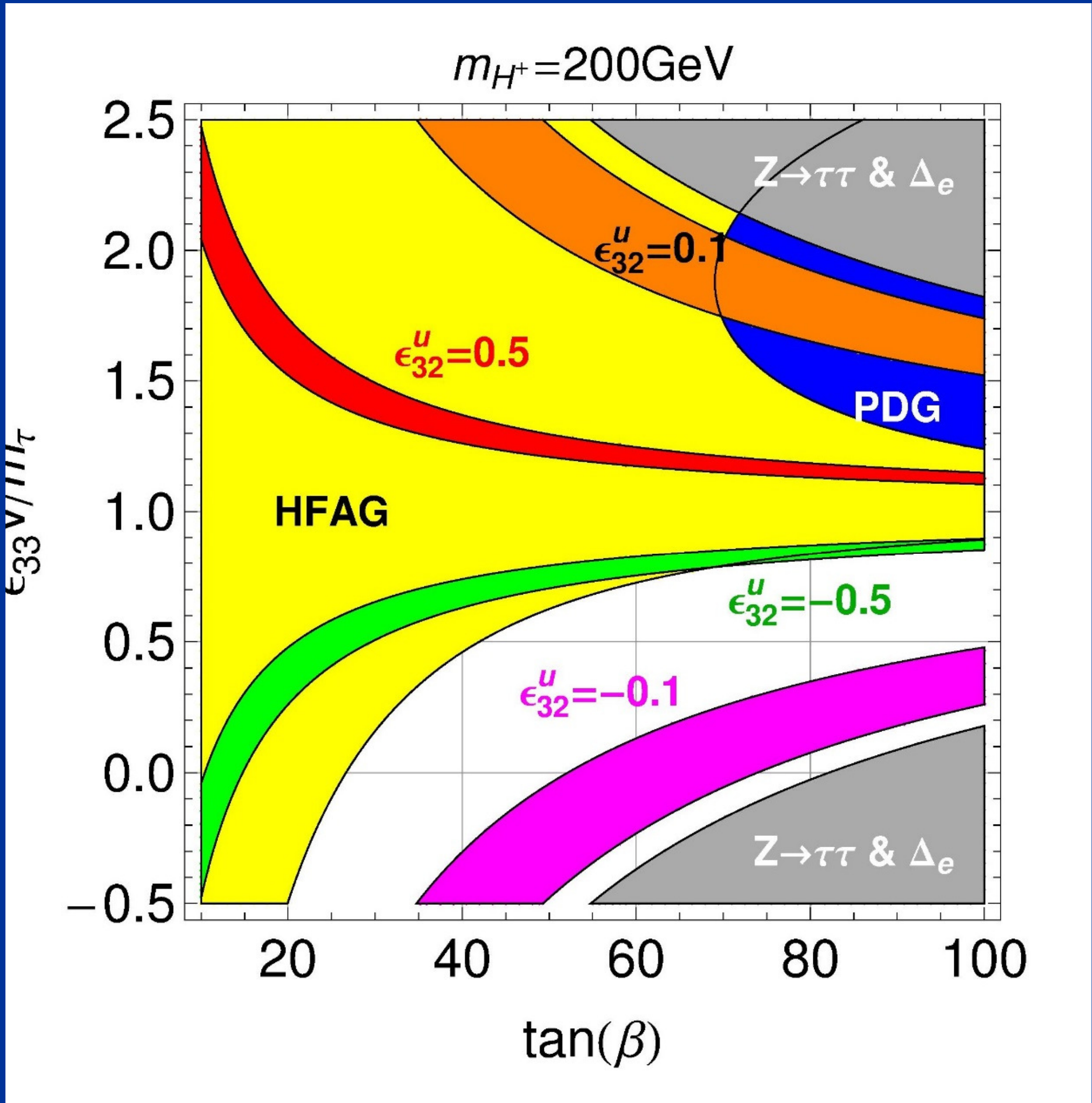
2HDM of type X + corrections

- Allow for additional couplings

- The parameters ε_{fi} describe flavor-changing neutral Higgs interactions which we assume to be of the form

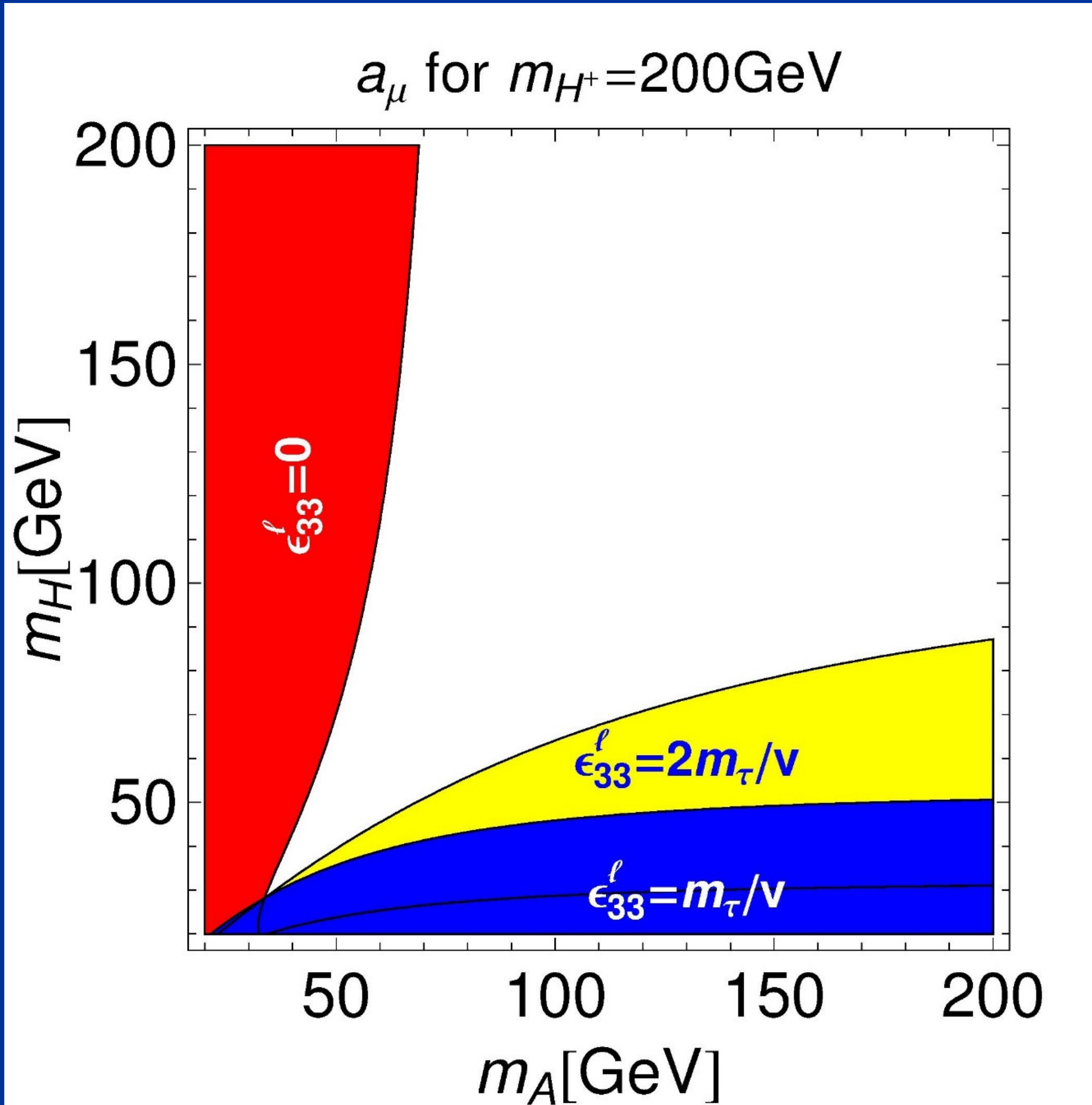
$$\varepsilon^d_{fi} = 0 \qquad \varepsilon^{u,\ell}_{fi} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \varepsilon^{u,\ell}_{32} & \varepsilon^{u,\ell}_{33} \end{pmatrix}$$

$\tau \to \mu\nu\nu + R(D)$



$$\varepsilon_{33}^{\ell} > 0$$

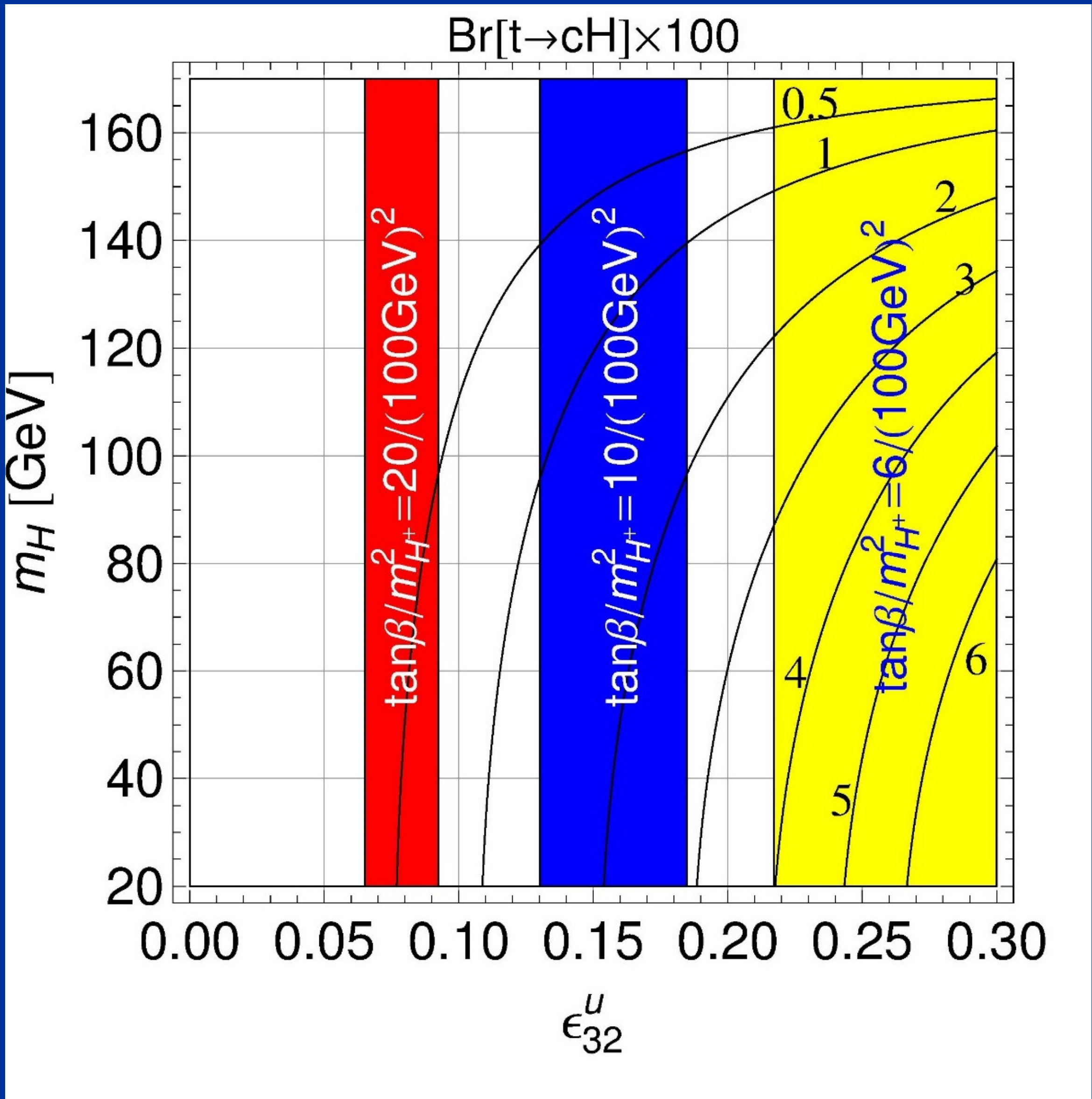
a_μ



$m_H < m_A$

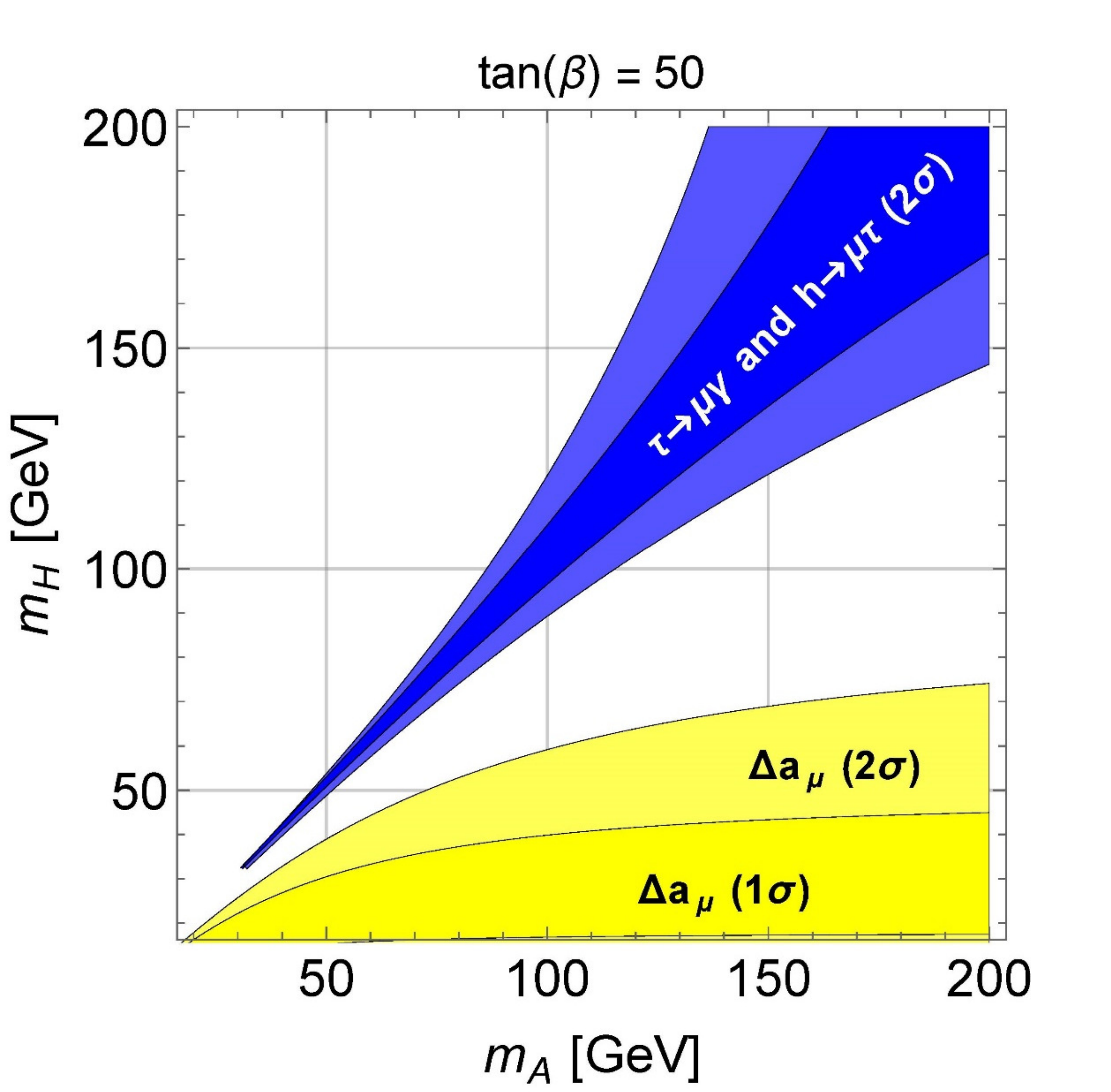
for $\varepsilon^\ell_{33} > 0$

$t \to Hc$



Branching ratio can even reach the percent level

a_μ, $h \to \tau\mu$, $\tau \to \mu\gamma$



$a_\mu \sim \tau \to \mu\gamma$

No simultaneous explanation without fine-tuning

Conclusions

- Rather solid evidence for NP in

➡ Consistent explanation with C_9 or C_9=-C_{10}

Z' model can explain also $b \to s\mu\mu$

- Tauonic B decays seem promising

➡ 2HDM with generic Yukawa couplings

- $b \to s\mu\mu$ and $B \to D^{(*)}\tau\nu$ can be explained simultaniously

➡ Leptoquarks or SU(2) triplet vector-particles?

- a_μ ,$\tau \to \mu\nu\nu$ and $B \to D^{(*)}\tau\nu$ can be explained in a 2HDM X

➡ $t \to Hc$

NP?

$b \to s\mu^+\mu^-$

$b \to c\tau\nu$

$h \to \tau\mu$

Additional neutral gauge bosons (Z’)

Leptoquarks

Extended Higgs sector