Andreas Crivellin

New Physics in the flavor sector at the LHC

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Outline:

- Introduction: Flavour anomalies

  $b \to s\mu^+\mu^-$ and $h \to \tau\mu$ with gauged $L_\mu - L_\tau$
  - Vector-like quarks
  - Horizontal charges
- $B \to D^{(*)}\tau\nu$
  - EFT analysis
  - 2HDMs
- Lepton flavour violating B decays in Z' models
- $b \to s\mu^+\mu^-$ and $B \to D^{(*)}\tau\nu$ with third generation couplings
- Conclusions

Flavour Anomalies

Global fit to b→sμμ data

See talk of Quim Matias

- Global analysis give a very good fit to data

  W. Altmannshofer, D. M. Straub, arXiv:1503.06199. T. Hurth, F. Mahmoudi, and S. Neshatpour, 1410.4545. Descotes-Genon et al. 1501.04239

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

→ Fit is 4-5 σ better than the SM and is even slightly improved with the assumption LFUV

Tauonic B decays

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

$$R(D)_{\text{BaBar}} = 0.440 \pm 0.058 \pm 0.042$$

$$R(D)_{\text{BELLE}} = 0.375^{+0.064}_{-0.063} \pm 0.026$$

$$R(D)_{SM} = 0.300 \pm 0.008$$

$$R(D^*)_{\text{BaBar}} = 0.332 \pm 0.024 \pm 0.018$$

$$R(D^*)_{\text{BELLE}} = 0.293^{+0.039}_{-0.037} \pm 0.015$$

$$R(D^*)_{\text{LHCb}} = 0.336 \pm 0.027 \pm 0.030$$

$$R(D^*)_{SM} = 0.252 \pm 0.003$$

➡ All five measurements above the SM prediction

Leptoquarks or a charged Higgs?

$h \to \tau\mu$

see Admir Greljo et al. arXiv:1502.07784 for a comparison of different models

- 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

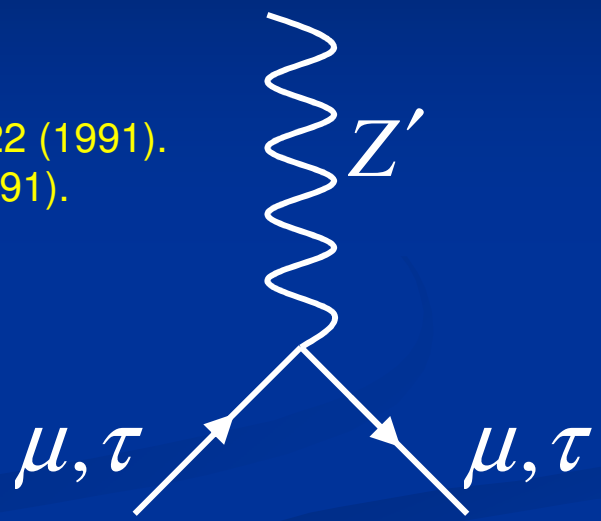
→ Extended Higgs sector

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.

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

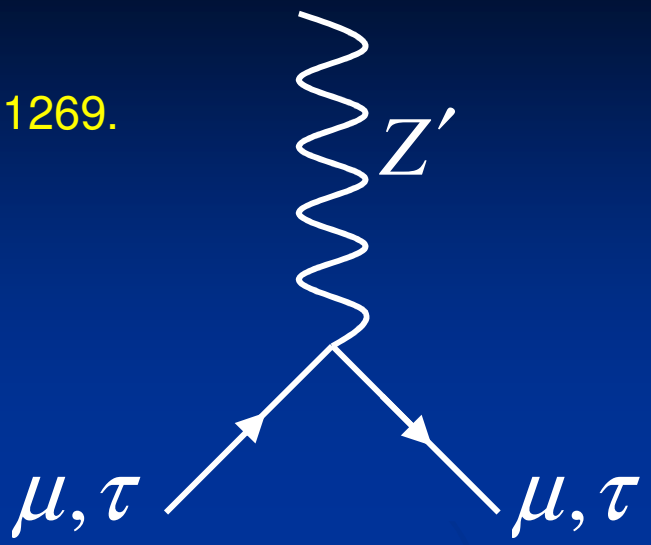
1HDM
with vector-quarks

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 $L_\mu - L_\tau$

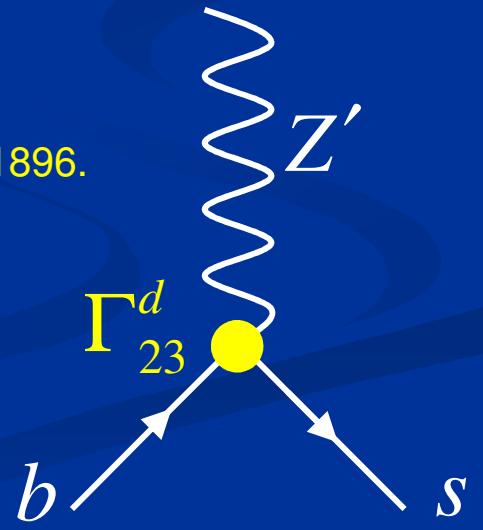
$$m_Q \bar{Q}_L \tilde{Q}_R + m_D \bar{\tilde{D}}_L D_R + m_U \bar{\tilde{U}}_L U_R + \text{h.c.}$$

- Effective Z' quark couplings

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

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

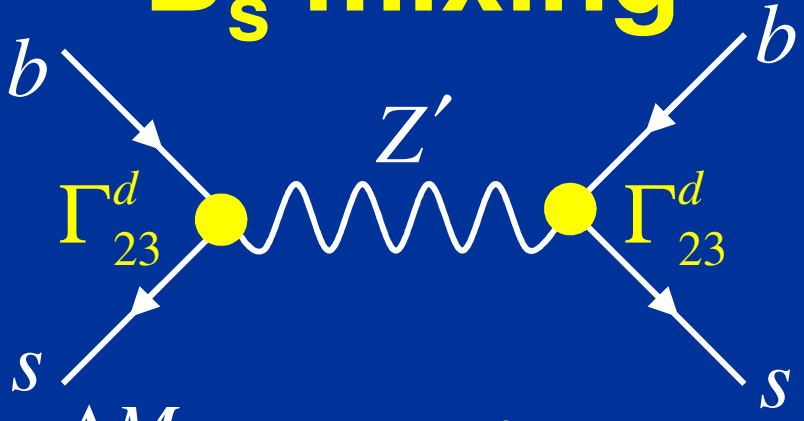
$$\Gamma^{dR}_{ij} \simeq -\frac{v_\Phi^2}{2m_D^2}(Y_i^D Y_j^{D*}), \quad \Gamma^{dL}_{ij} \simeq \frac{v_\Phi^2}{2m_Q^2}(Y_i^Q Y_j^{Q*})$$



$B \to K^* \mu\mu$, R(K)

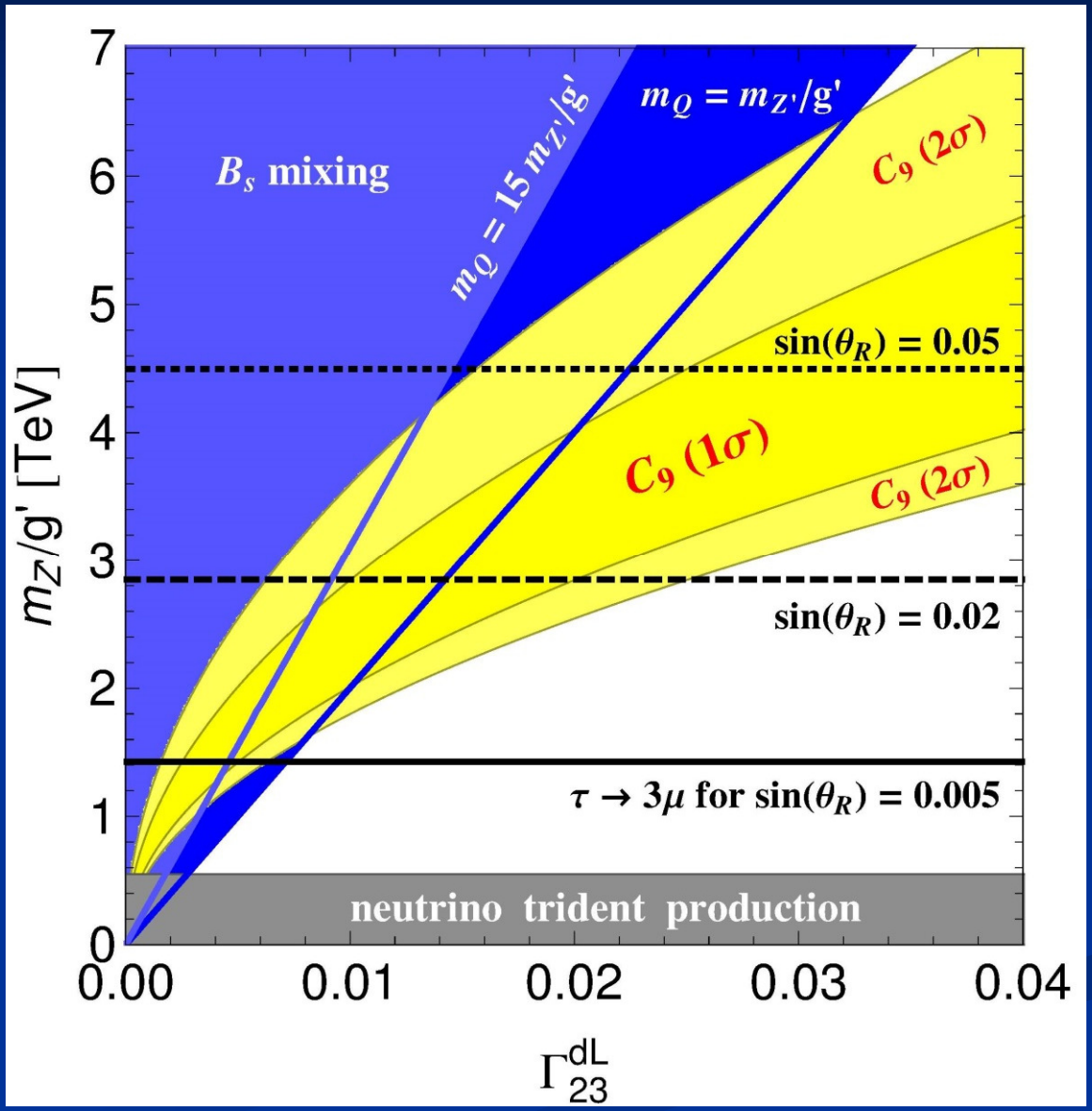
$$C_9^{\mu\mu} \propto \Gamma_{23}^{dL}\, g'^2 / m_{Z'}^2$$

B_s mixing



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

$$m_D^2 \to \infty$$



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 $L_\mu - L_\tau$

arXiv:1501.00993, PRL 114 (2015) 151801

2nd Doublet breaks $L_\mu - L_T$

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

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

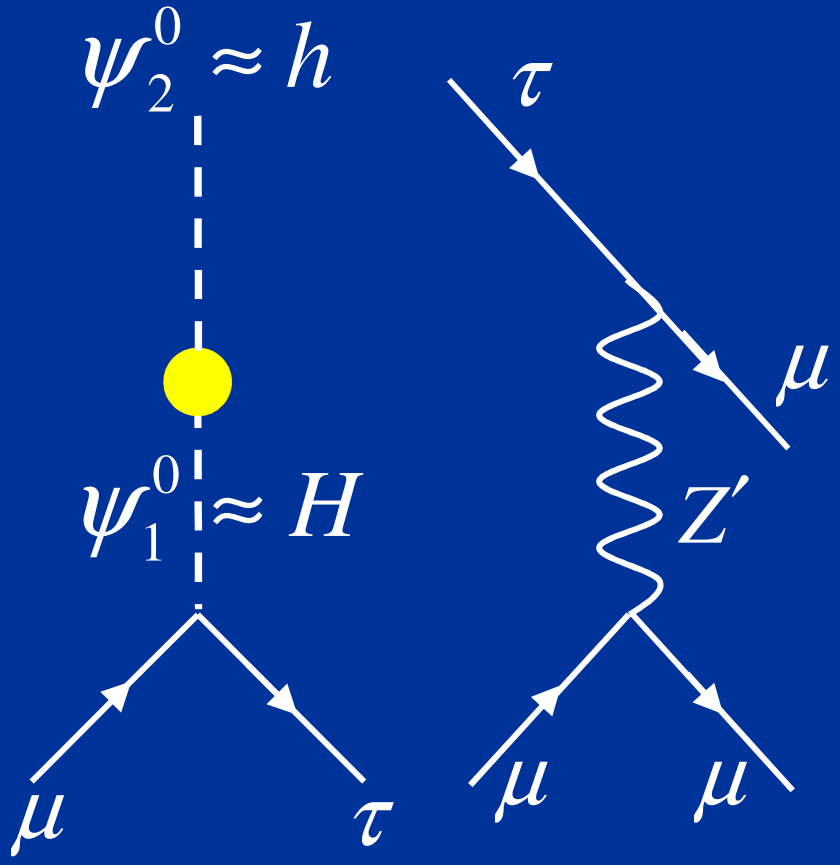
$$\sin\theta_R \simeq \frac{v}{\sqrt{2} m_\tau} \xi_{\tau\mu} \cos\beta$$

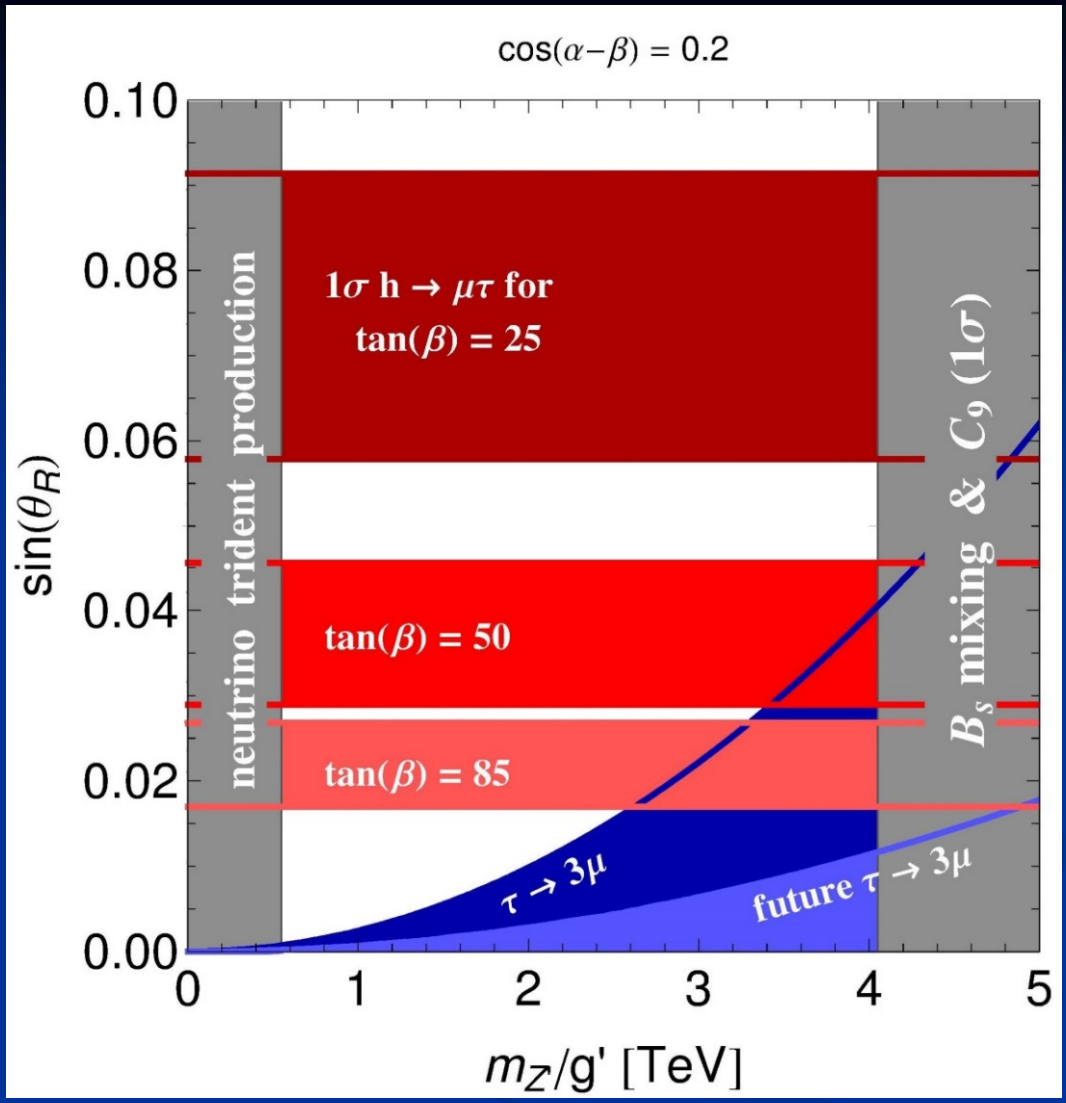
$$\sin\theta_L \simeq 0$$

- Lepton flavour violating Z' couplings

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

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





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}

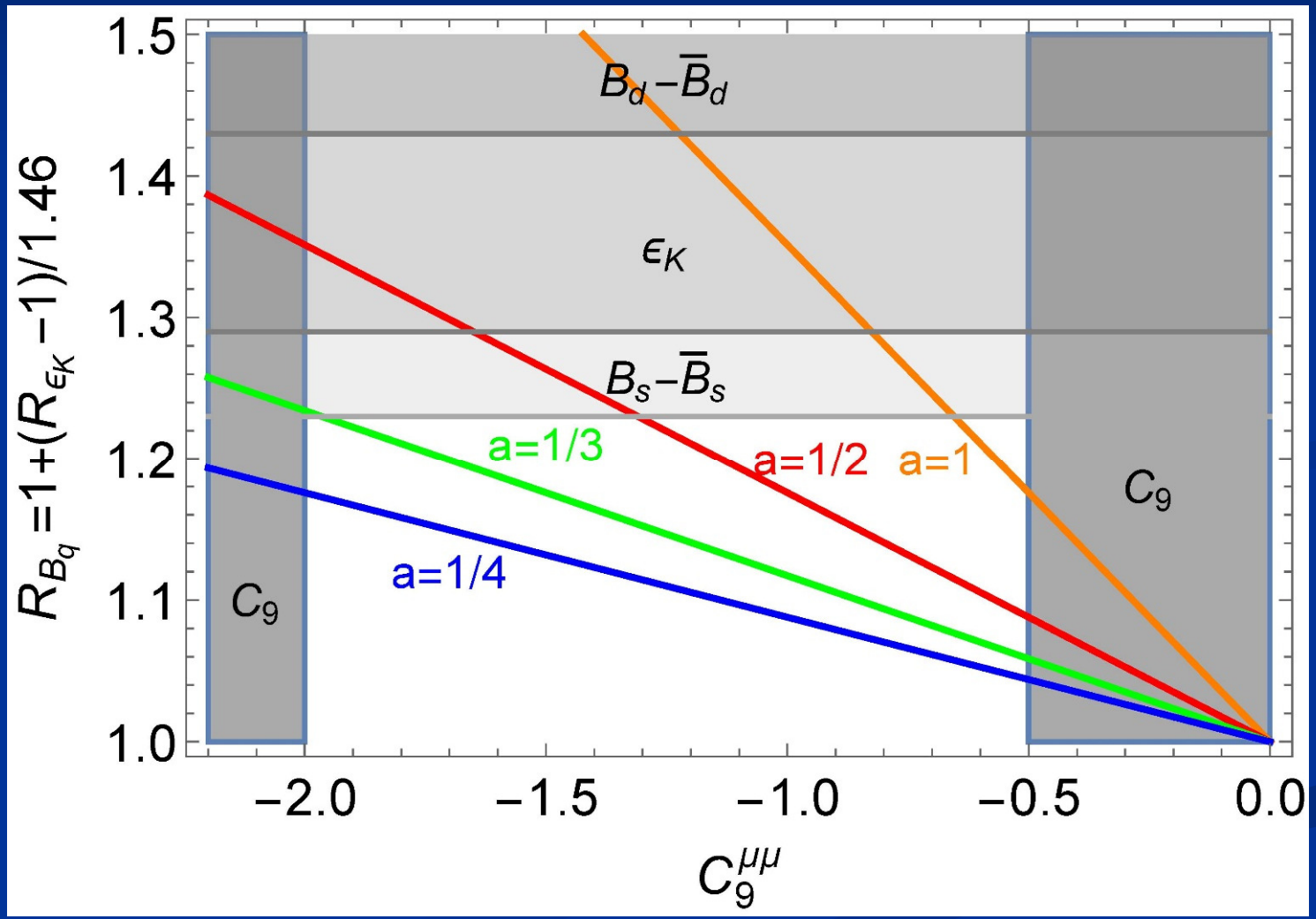
- First two quark generations must have the same charges because the large Cabibbo angle would lead to huge effect in Kaon mixing
- Anomaly free

➡ $Q(B) = (-a, \quad -a, \quad 2a)$

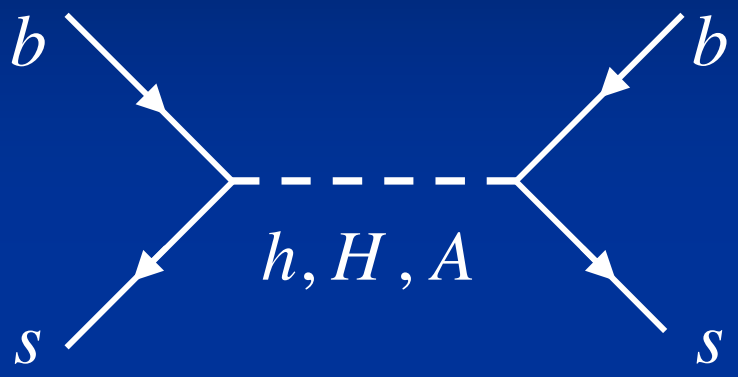
ΔF=2: Z' contribution

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

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



ΔF=2: Higgs contributions

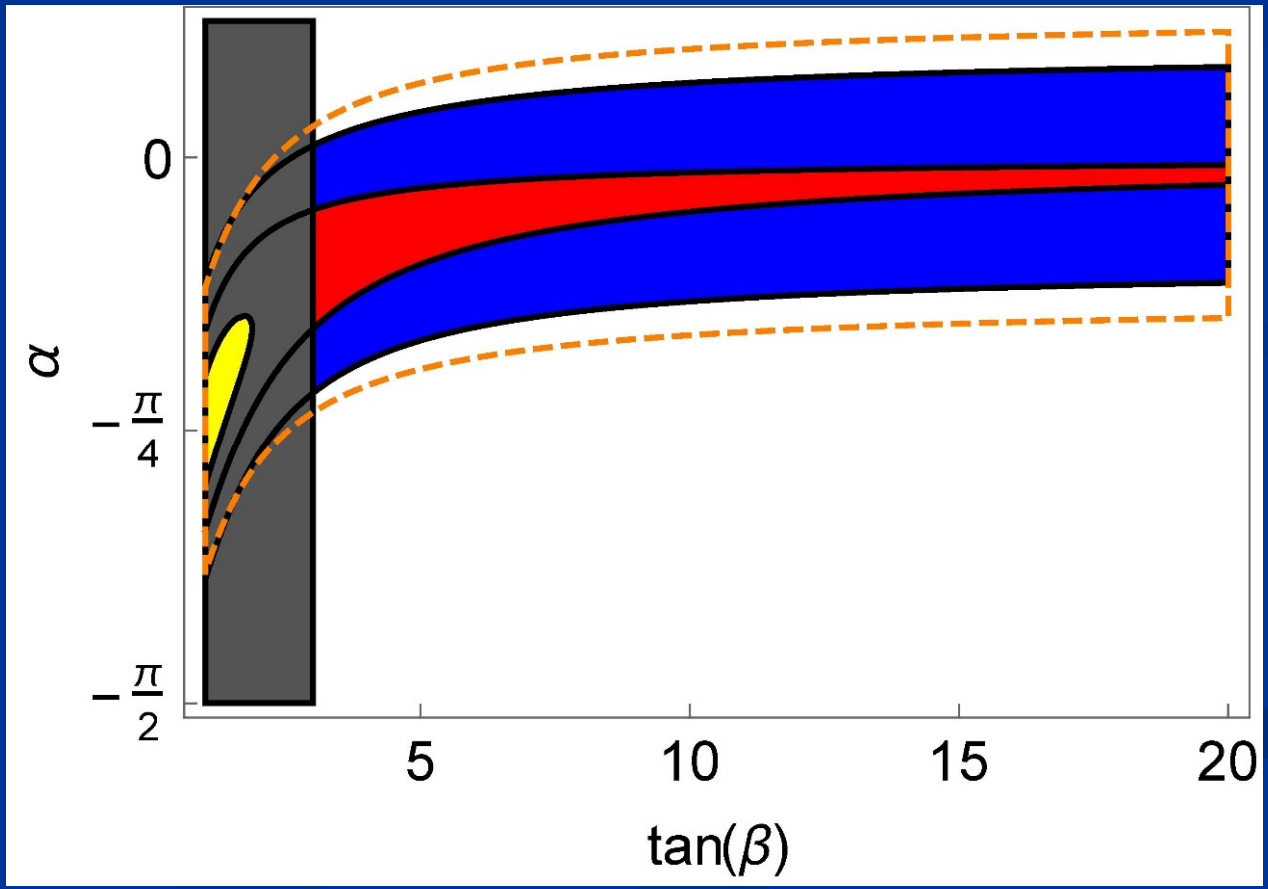


$m_H = 300\ \text{GeV}, \quad C_9^{\mu\mu} = -1.3$

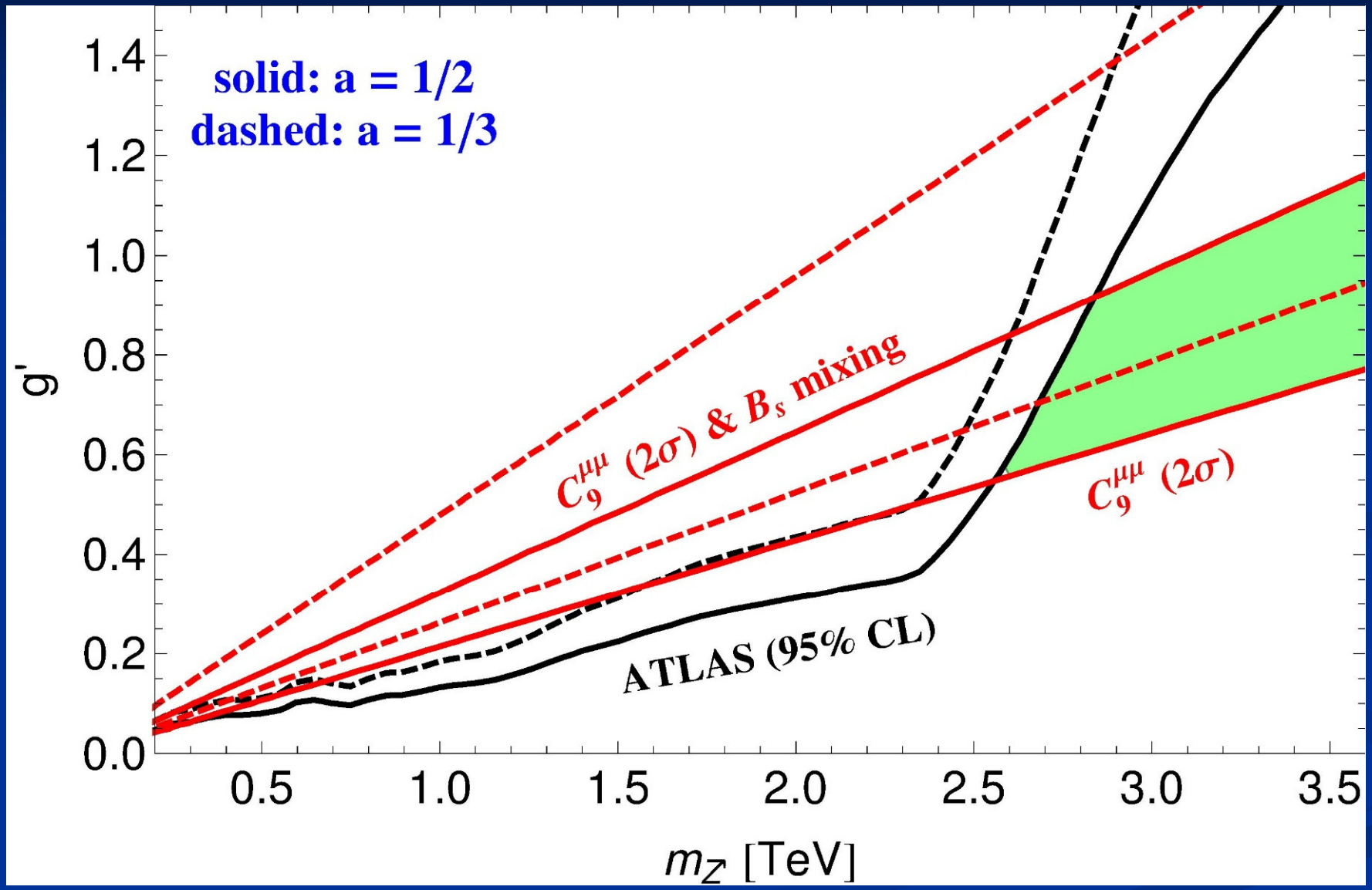
$m_A = 350\ \text{GeV}$

$m_A = 300\ \text{GeV}$

$m_A = 250\ \text{GeV}$



LHC limits



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

3HDM

- Same effect in

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

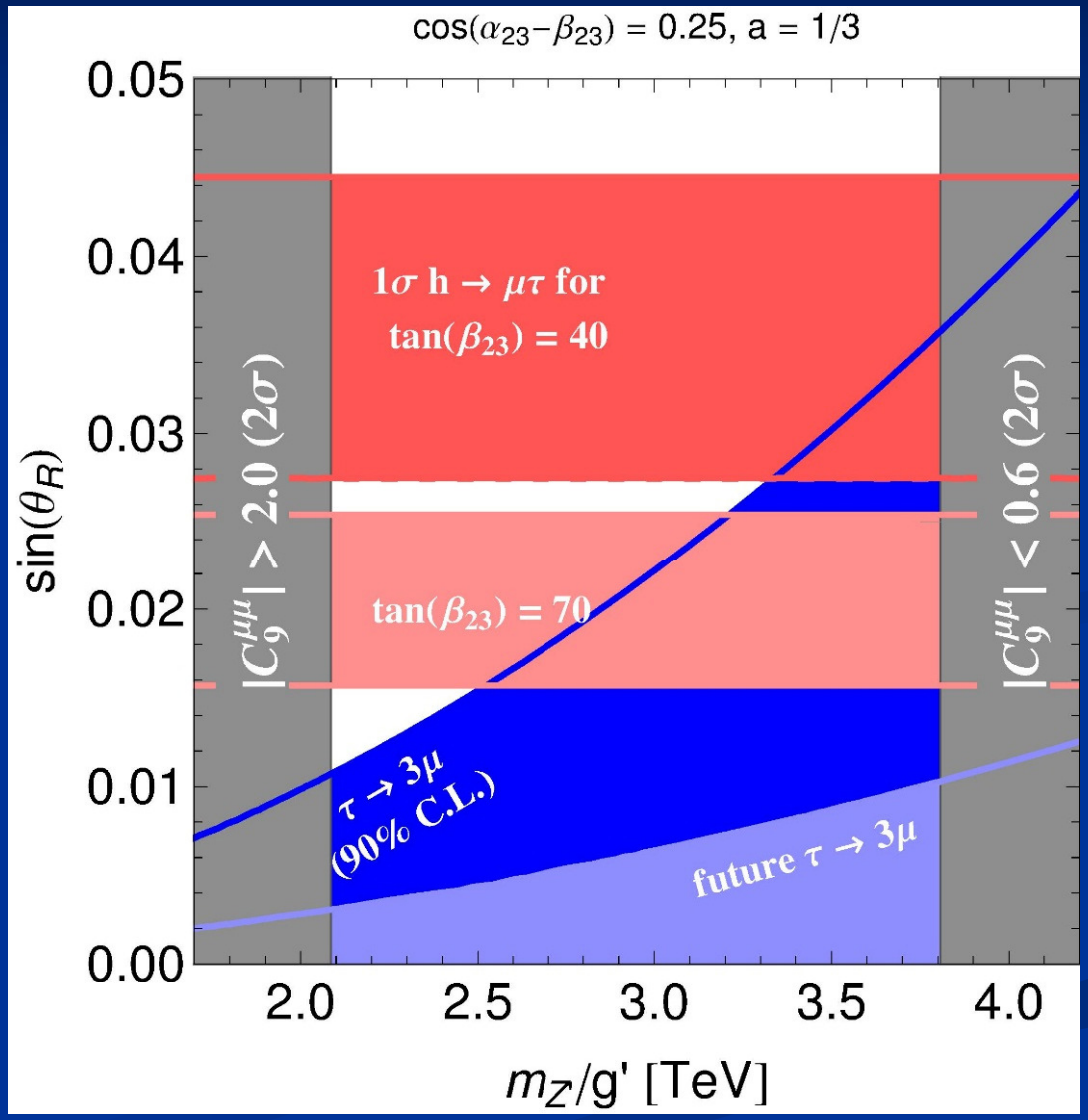
$h \to \mu\tau$

provided that the mixing among the doublets is small

excluded

allowed by $h \to \tau\mu$

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



Lepton Flavour Violating B decays in Z' models

AC, Lars Hofer, Joaquim Matias, Ulrich Nierste, Stefan Pokorski, Janusz Rosiek. arXiv:1504.07928 [hep-ph].

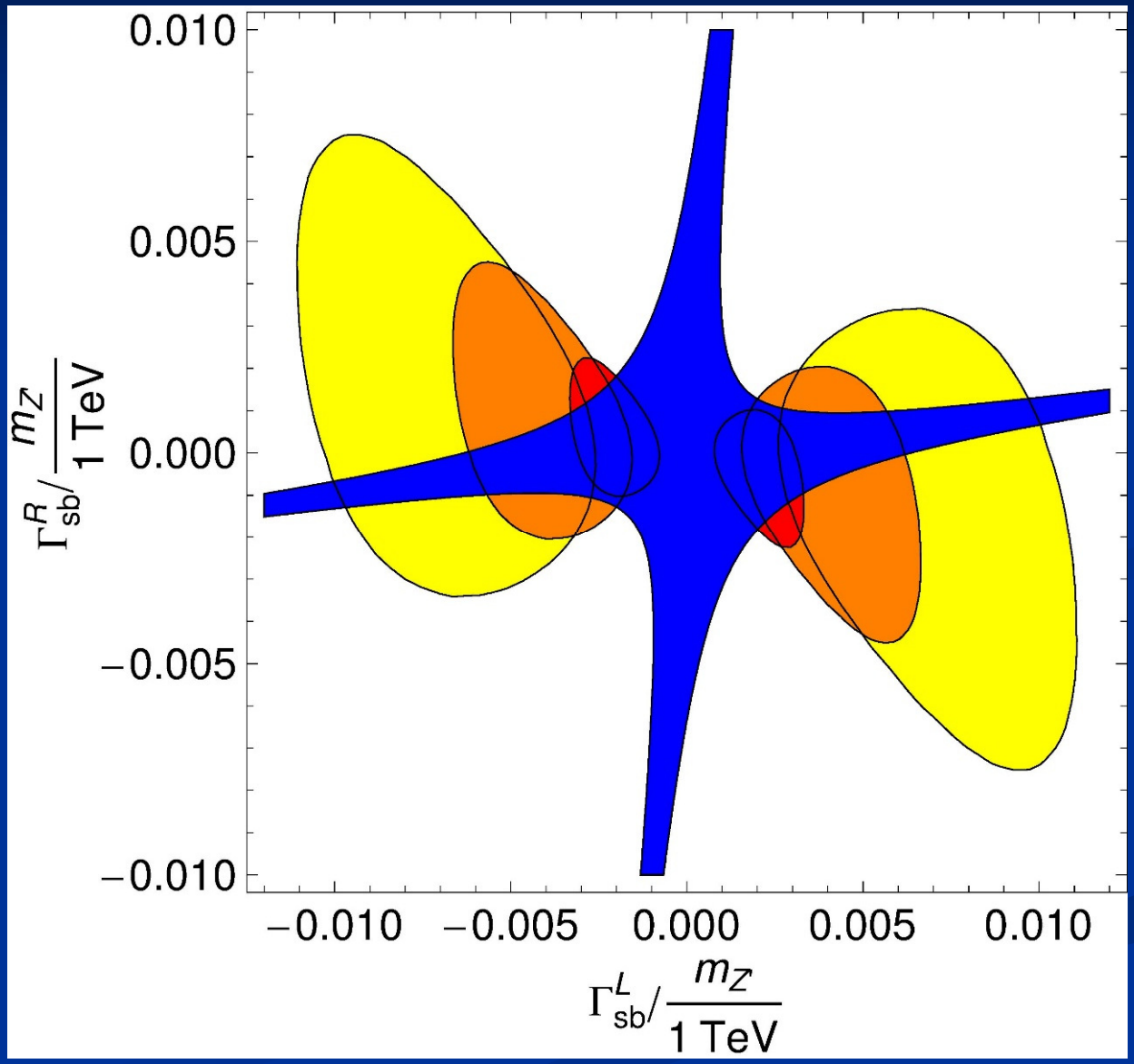
Constraints in the quark sector

C_9 for $\Gamma^V_{\mu\mu} = 0.3$

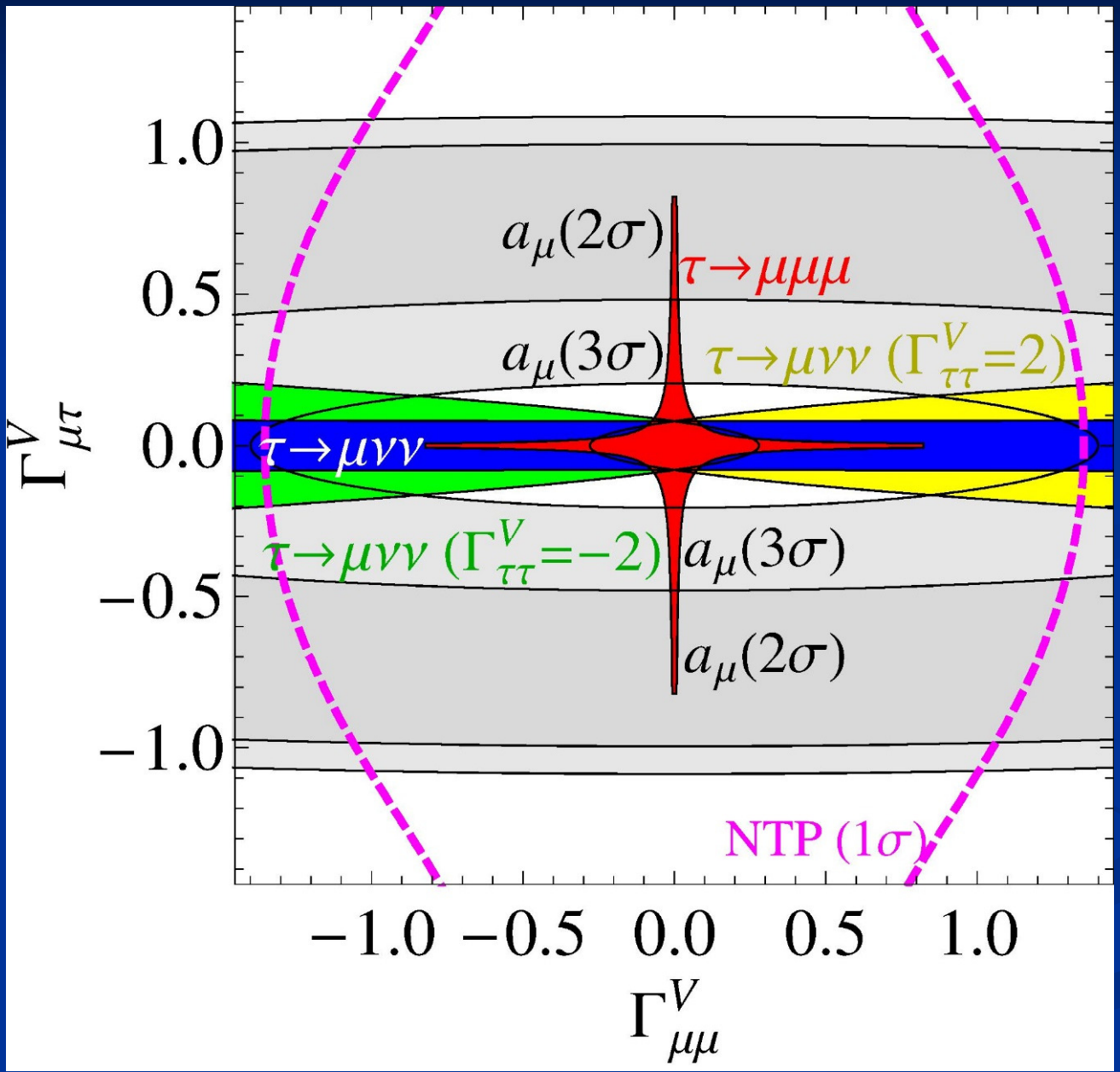
C_9 for $\Gamma^V_{\mu\mu} = 0.5$

C_9 for $\Gamma^V_{\mu\mu} = 1$

$B_s - \bar{B}_s$ mixing



Lepton sector



$B \to K^{(*)} \tau\mu$ and $B_s \to \tau\mu$

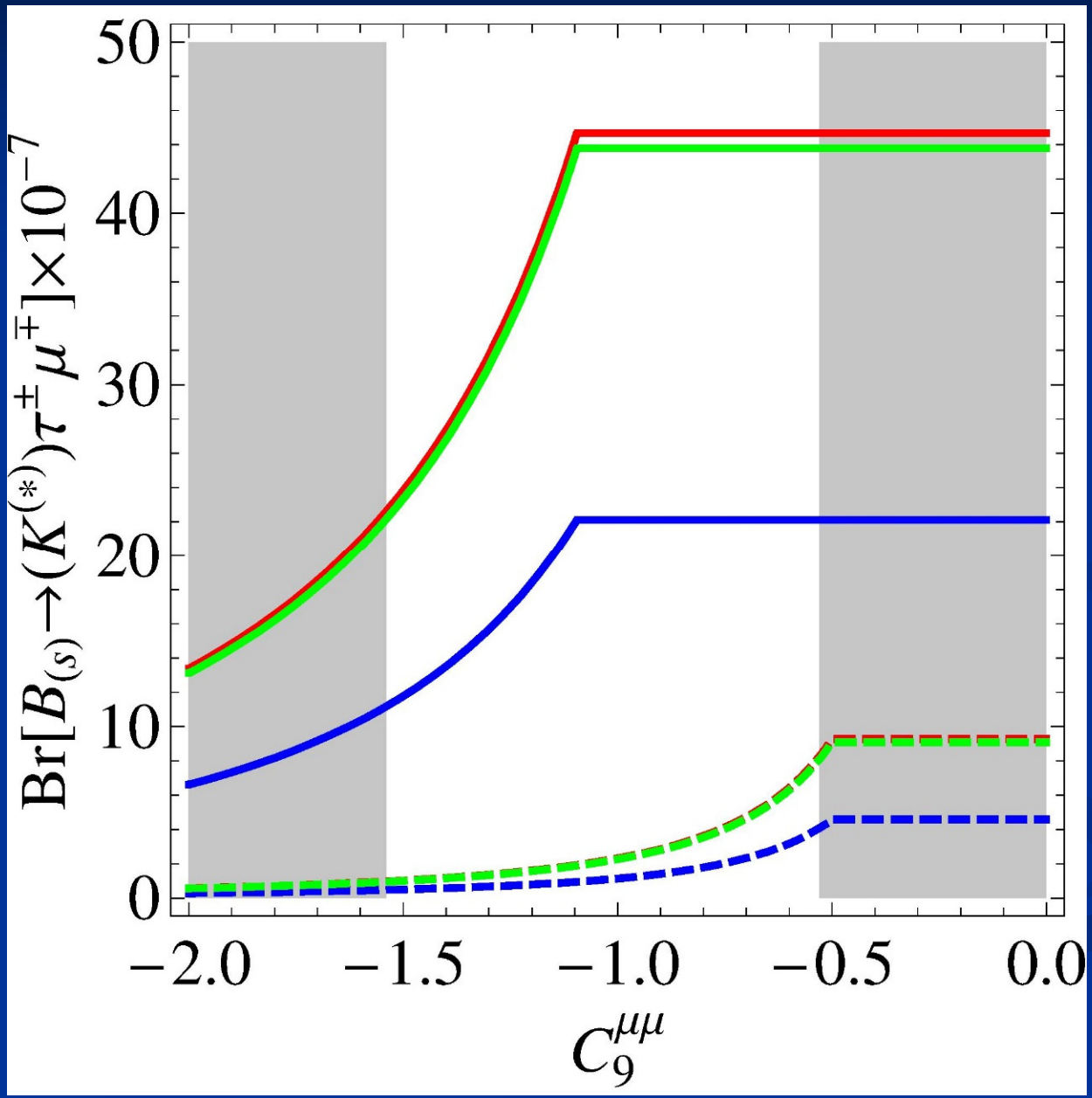
$B_s \to \tau\mu$

$B \to K^* \tau\mu$

$B \to K \tau\mu$

Solid:
Fine-tuning 100

Dashed:
Fine-tuning 20



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

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

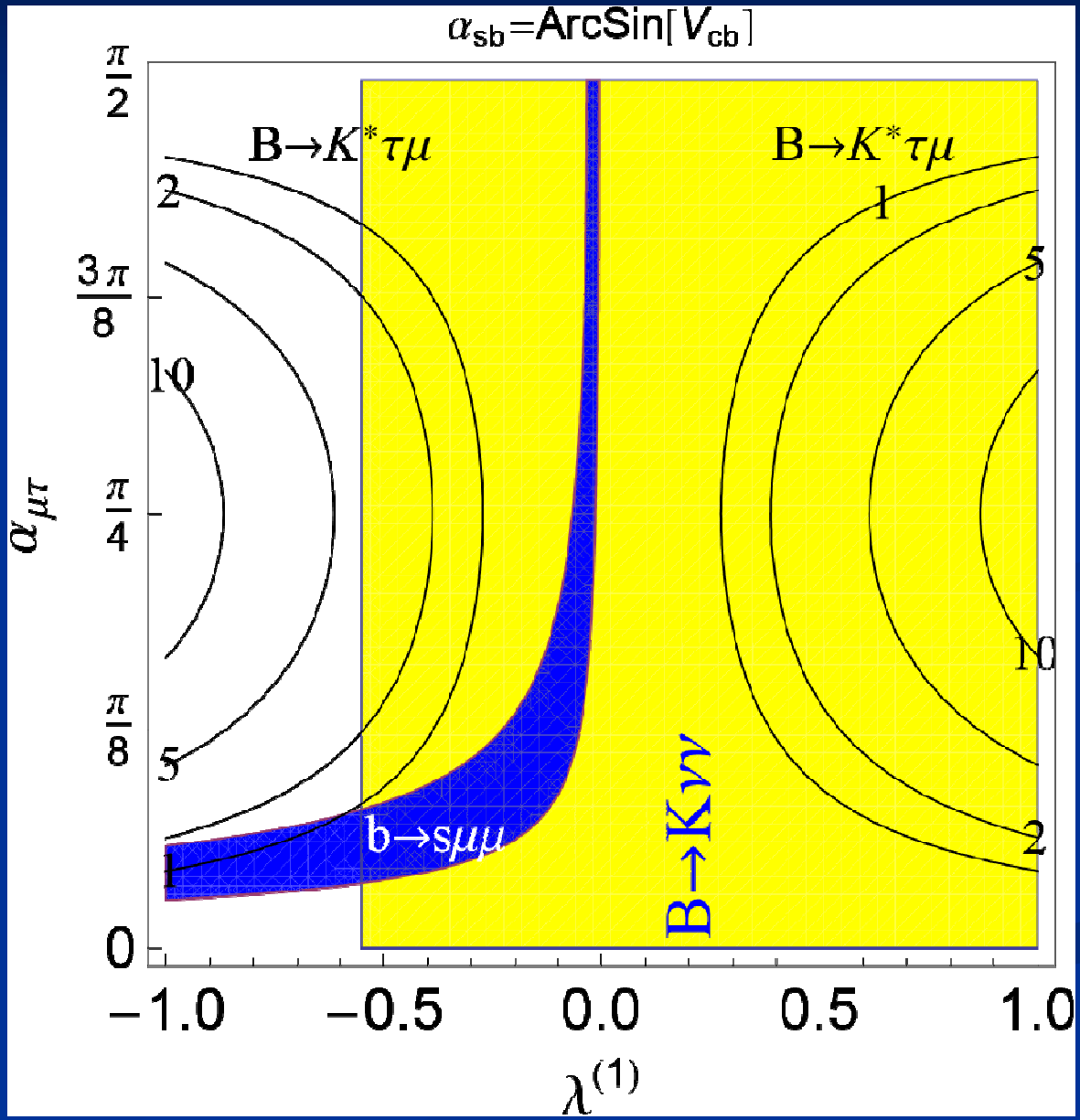
$$H_{eff} = C^{(1)} Q^{(1)}_{llqq} = C^{(1)} L\gamma^{\mu} P_L L Q\gamma^{\mu} P_L Q$$

Third generation couplings

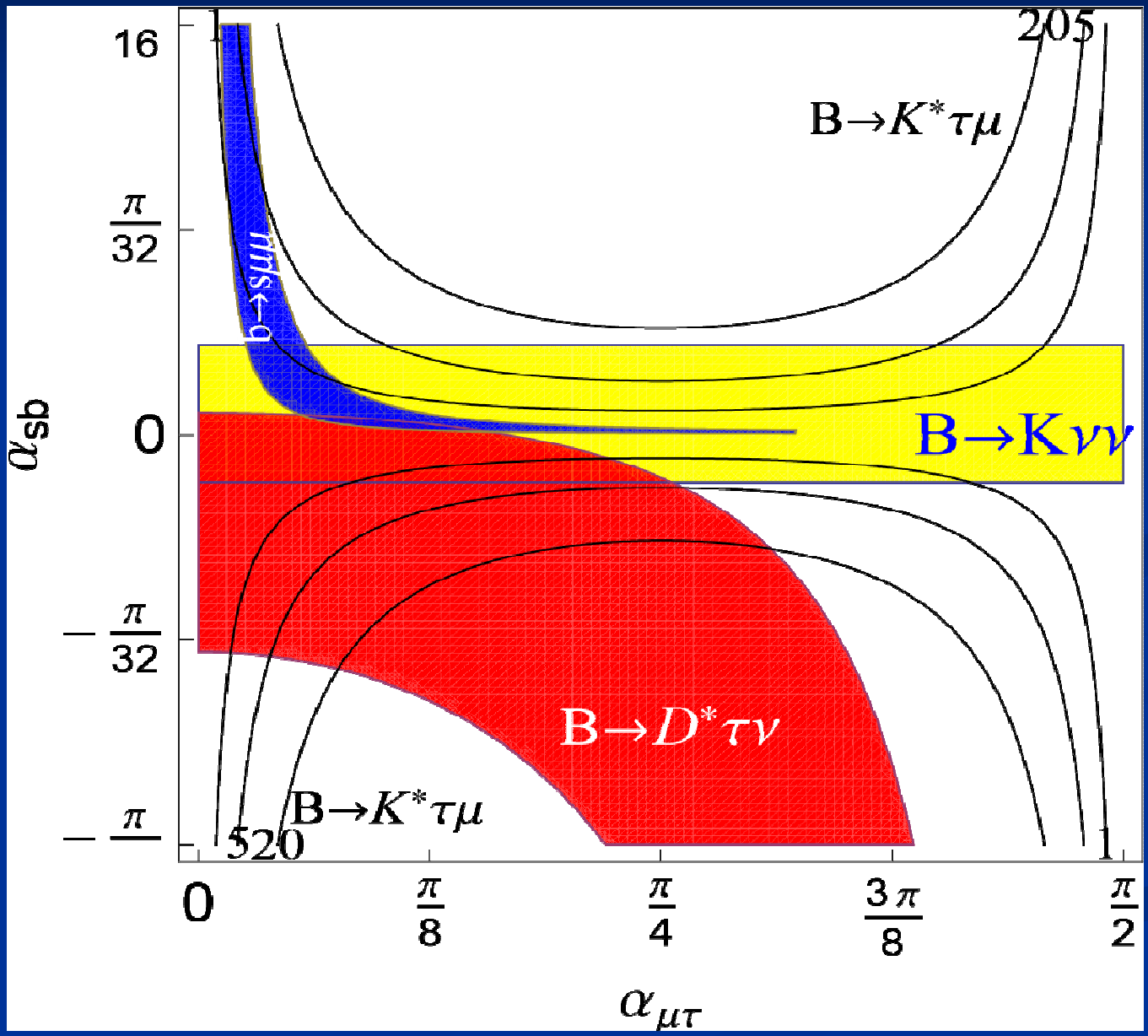
$$C^{(1)} = \lambda^{(1)} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\alpha_{\mu\tau}$ Misalignment between

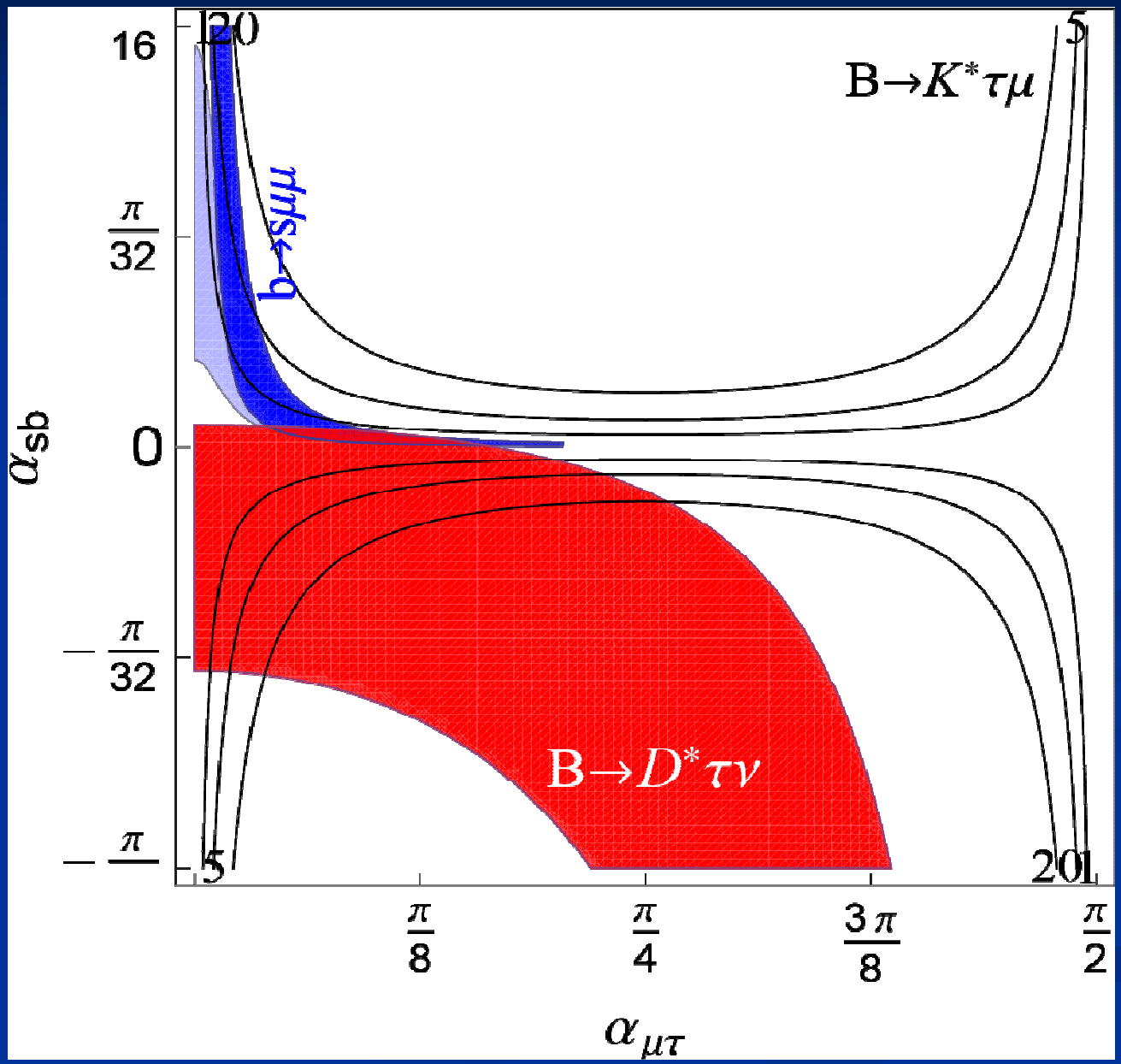
α_{sb} interaction and mass basis



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



$$C^{(1)}_{llqq} = C^{(3)}_{llqq}$$



UV realizations (single mediator)

- Vector SU(2) triplet
- Vector-leptoquark SU(2) singlet

- 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!

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

Leptoquarks could explain R(D) and R(K)

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?

$\tau \to \mu\nu\nu$ and a_μ

- Tau decays

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

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

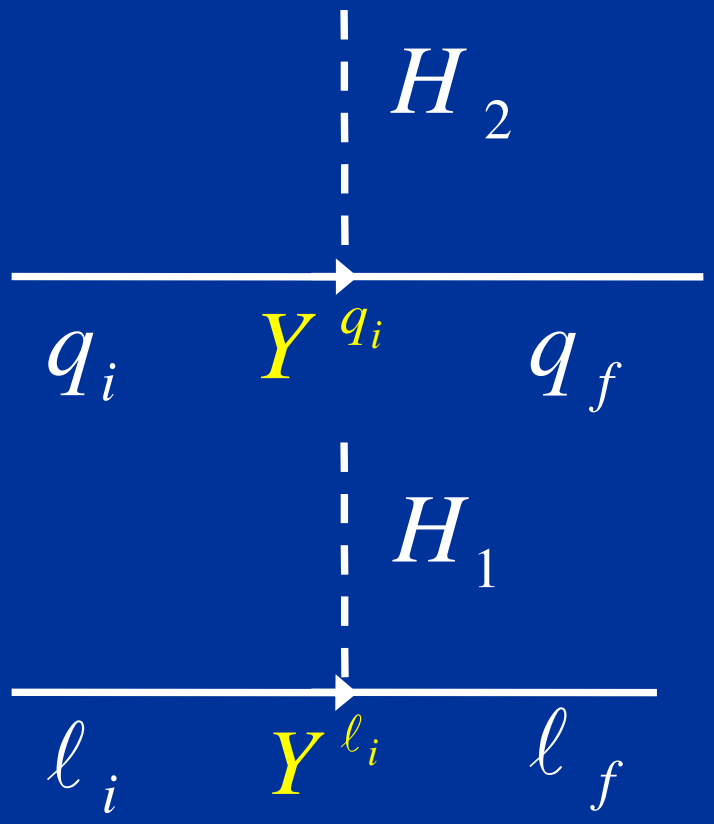
- Anomalous magnetic moment of the muon

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

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

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

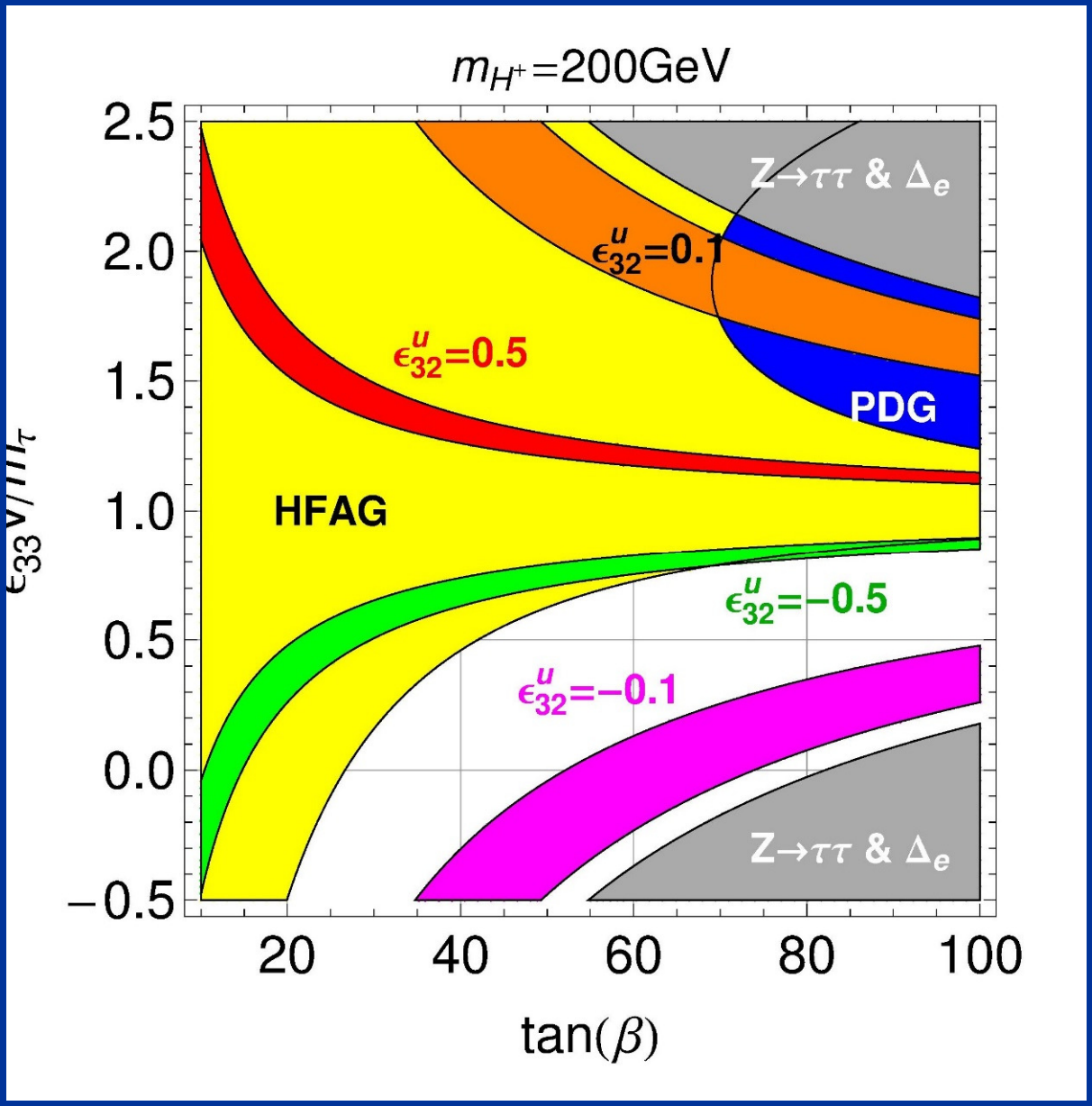
2HDM of type X + corrections

- Allow for additional couplings

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

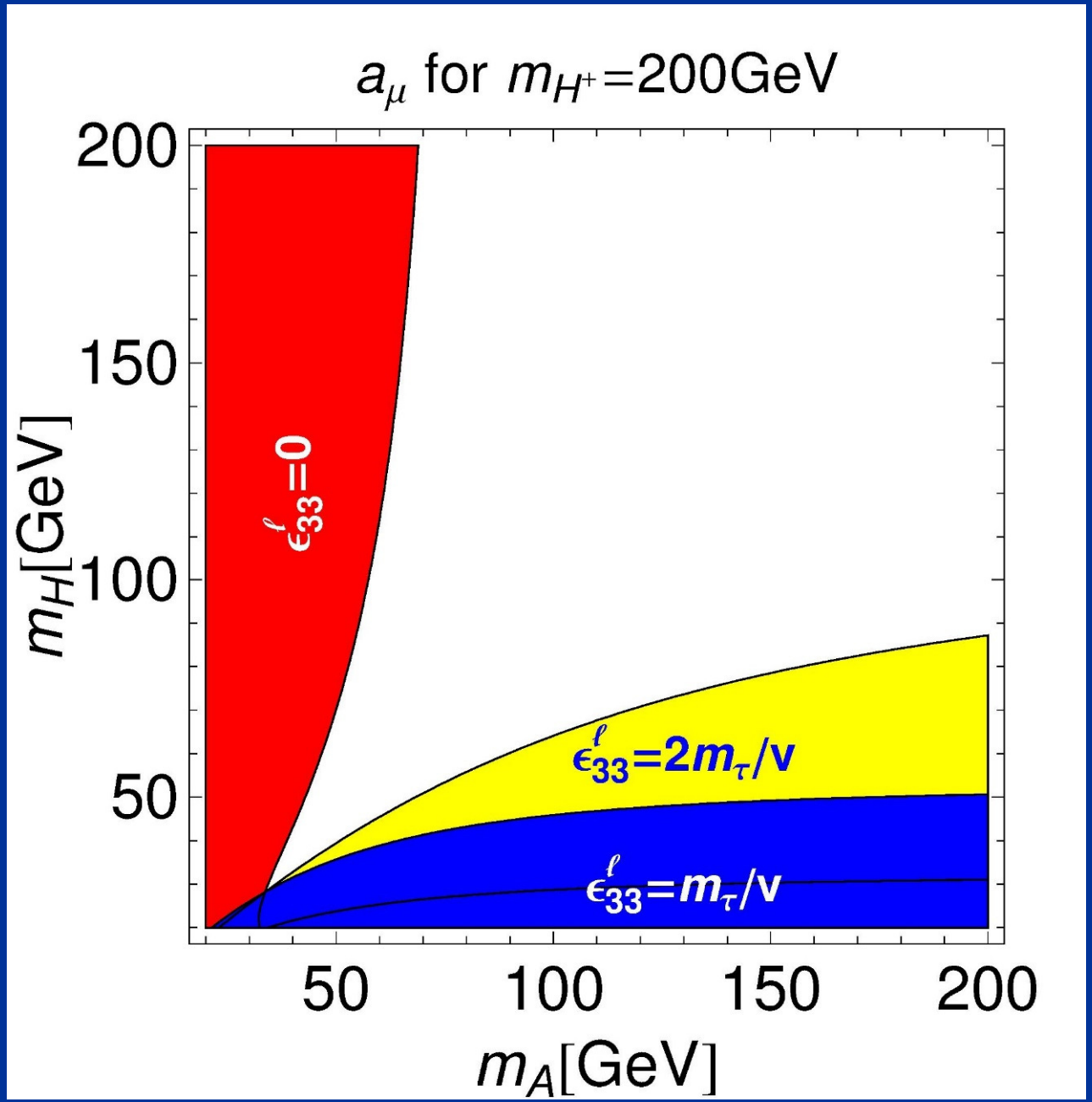
$$\varepsilon^d_{fi} = 0 \qquad \varepsilon^{u,\ell}_{fi} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \varepsilon^{u,\ell}_{32} & \varepsilon^{u,\ell}_{33} \end{pmatrix}$$

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



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

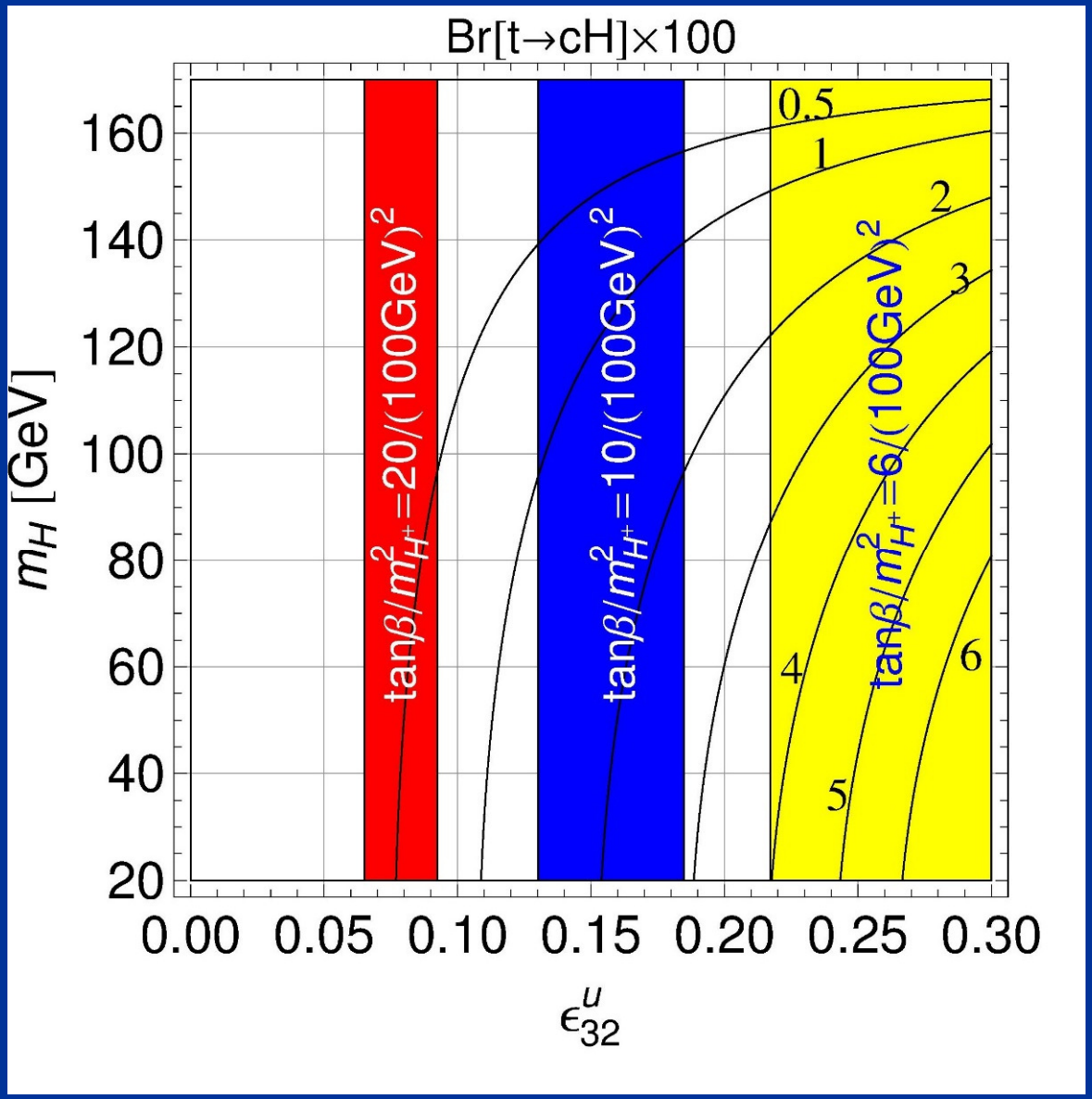
a_μ



$m_H < m_A$

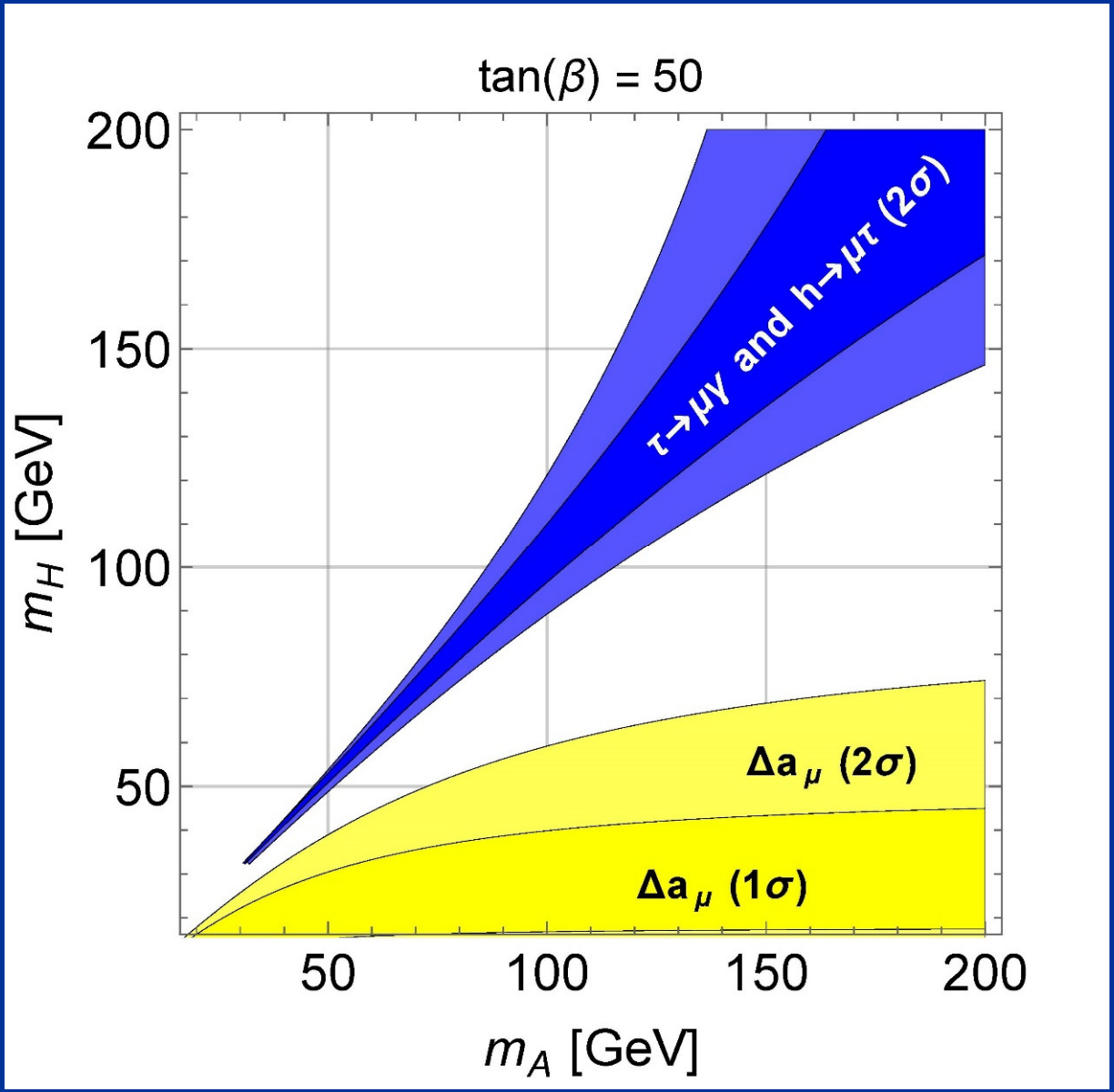
for $\varepsilon^{\ell}_{33} > 0$

$t \to Hc$



Branching ratio can even reach the percent level

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

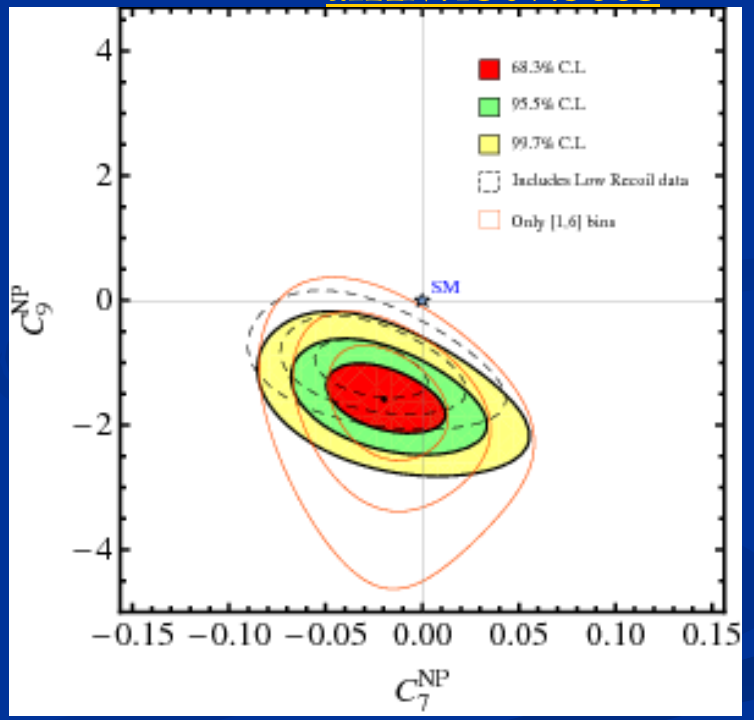


$a_\mu \sim \tau \to \mu\gamma$

No simultaneous explanation without fine-tuning

$B \to K^* \mu\mu$

- 2-3 σ deviation from the SM mostly in P5'
- Can be explained by $O_9 = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \ell$
  Descotes-Genon et al. 1307.5683, Altmannshofer and DS 1308.1501, Beaujean et al. 1310.2478
- New physics explanation is not easy (MSSM, 2HDM).
- Most natural explanation: Z'
  Gauld et al. 1310.1082,
  Buras et al. 1311.6729, …
- Subleading hadronic effects might be larger than expected…
- Further supported by $B_s \to \phi\mu\mu$
  R. Horgan, Z. Liu, S. Meinel, and M. Wingate (2015), 1501.00367.



R(K) = B→Kμμ/B→Kee

- Lepton flavour universality violation
- 2.6 σ deviation from the theoretically rather clean SM expectation

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$

C. Bobeth, G. Hiller, and G. Piranishvili, 0709.4174

$$R_K^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

LHCb 1406.6482

- Explanation:
  - Leptoquarks — Talk of Ivan Nisandzic and Ivo de Medeiros
  - Extra dimensions
  - flavour non-universal Z' — Talk of Alejandro Celis

➡ Also LFV in B decays?