Rare $B_s \to l^+ l^-$ decays in a two-Higgs-doublet model with three spurions

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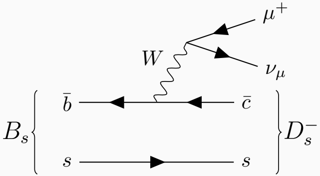
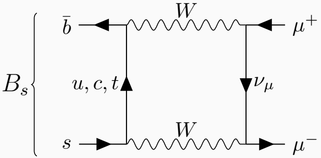
TTP KIT / TP1 Siegen

Introduction: Leptonic decays of neutral B mesons



$\mathcal{B} \approx 2.5\,\%$



$\mathcal{B} \approx 3 \cdot 10^{-9}$

Why are rare leptonic decays interesting?

- loop-suppressed within the Standard Model $\Rightarrow$ even tiny effects of New Physics can have significant impact on partial decay widths
- non-perturbative QCD is well controlled $\Rightarrow$ small uncertainties via f_{B_s}
- momentum scale $p^2 \sim M_{B_s}^2 \ll M_W^2, m_t^2$ $\Rightarrow$ we can integrate out heavy particles!

Introduction: Effective theory description

Effective operators

$$\mathcal{H}_{\rm eff} = N \sum_{i=A,S,P} \left(C_i Q_i + C_i' Q_i'\right) , \qquad N = \frac{G_F^2 M_W^2 V_{tb}^* V_{ts}}{\pi^2}$$

$$\begin{aligned}
\boldsymbol{Q_A} &= \left(\bar{b}\gamma_\mu P_L s\right)\left(\bar{\mu}\gamma^\mu\gamma_5\mu\right) , & Q_A' &= \left(\bar{b}\gamma_\mu P_R s\right)\left(\bar{\mu}\gamma^\mu\gamma_5\mu\right) , \\
Q_S &= \left(\bar{b}P_L s\right)\left(\bar{\mu}\mu\right) , & Q_S' &= \left(\bar{b}P_R s\right)\left(\bar{\mu}\mu\right) , \\
Q_P &= \left(\bar{b}P_L s\right)\left(\bar{\mu}\gamma_5\mu\right) , & Q_P' &= \left(\bar{b}P_R s\right)\left(\bar{\mu}\gamma_5\mu\right) ,
\end{aligned}$$

- the operator matrix elements are computed in terms of f_{B_s}
- we are interested in the *Wilson coefficients* $C_i^{(\prime)} = C_i^{(\prime)(0)} + \frac{\alpha_s}{4\pi} C_i^{(\prime)(1)} + \ldots$

$$\overline{\mathcal{B}}^1 = |N|^2 \frac{M_{B_s}^3 f_{B_s}^2}{32\pi\Gamma_H^s}\beta\left[\left|r\left(C_A - C_A'\right) - u\left(C_P - C_P'\right)\right|^2 F_P + \left|u\beta\left(C_S - C_S'\right)\right|^2 F_S\right]$$

[1] Hermann et al., 2013

Yukawa Lagrangian

$$\mathcal{L}_Y = -\overline{Q}' \left[\overline{Y}^d H_d + \overline{\epsilon}^d H_u \right] d'_R \; - \; \overline{Q}' \left[\overline{Y}^u \epsilon H_u^* + \overline{\epsilon}^u \epsilon H_d^* \right] u'_R + \text{h.c.} + \text{leptons}$$

with two Higgs doublets $H_{u,d}^T = \left(H_{u,d}^+ , H_{u,d}^0 \right)$ with vacuum expectation values

$\langle H_u^0 \rangle = v_u = v \sin\beta \, , \langle H_d^0 \rangle = v_d = v \cos\beta \, ,$ $\boxed{\tan\beta := \frac{v_u}{v_d} \, , v := \sqrt{v_u^2 + v_d^2} = 174\,\text{GeV}}$

Higgs basis

For flavour processes it is convenient to change to a basis in which one of the doublets is the SM doublet ⇒ the other doublet has zero vev:

$$\begin{pmatrix} \phi_{\text{new}} \\ \phi_{\text{SM}} \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} H_u \\ H_d \end{pmatrix} \, , \quad \phi_{\text{SM}} = \begin{pmatrix} G^+ \\ v + \frac{\phi^0 + \mathrm{i}G^0}{\sqrt{2}} \end{pmatrix} \, , \quad \phi_{\text{new}} = \begin{pmatrix} H^+ \\ \frac{\phi^{0\prime} + \mathrm{i}A^0}{\sqrt{2}} \end{pmatrix}$$

Introduction: The 3-Spurion 2HDM

- diagonalise the mass matrix as usual
- eliminate $Y^{u,d}$ for a linear combination of the diagonal mass matrix and $\epsilon^{u,d}$

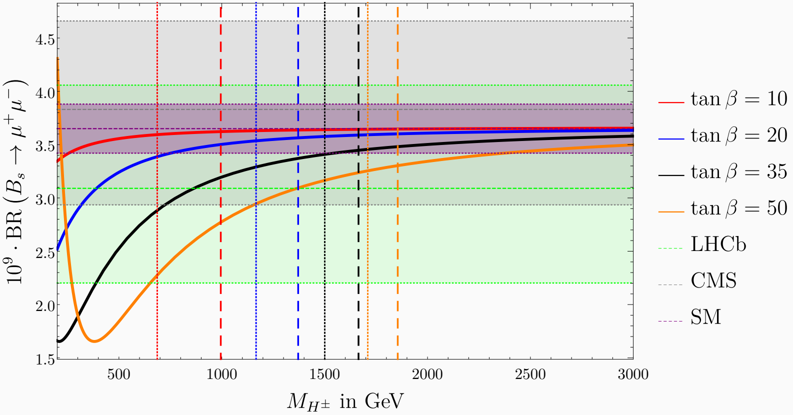
Lagrangian

$$\mathcal{L}_Y^{\text{phys}} = -\bar{u}_L \left[\frac{\hat{M}^u}{v} \cot\beta + g^u \right] u_R \frac{\phi^{0\prime} - \mathrm{i}A^0}{\sqrt{2}} + \bar{d}_L \left[\frac{\hat{M}^d}{v} \tan\beta + g^d \right] d_R \frac{\phi^{0\prime} + \mathrm{i}A^0}{\sqrt{2}}$$
$$+ \bar{u}_L V \left[\frac{\hat{M}^d}{v} \tan\beta + g^d \right] d_R H^+ + \bar{d}_L V^\dagger \left[\frac{\hat{M}^u}{v} \cot\beta + g^u \right] u_R H^-$$
$$- \bar{d}_L \frac{\hat{M}^d}{v} d_R \left(v + \frac{\phi^0}{\sqrt{2}} \right) - \bar{u}_L \frac{\hat{M}^u}{v} u_R \left(v + \frac{\phi^0}{\sqrt{2}} \right) + \text{h.c.} + \text{leptons}$$

with $g^d = -\epsilon^d \sin\beta\,(\tan\beta + \cot\beta)$, $\qquad g^u = -\epsilon^u \cos\beta\,(\tan\beta + \cot\beta)$

The 2HDM of type II

the 2HDM of **type II** has $g^u = g^d = 0 \Rightarrow$ at leading power in $\tan\beta$ the Wilson coefficients only depend on $x_t := \frac{m_t^2}{M_W^2}$, $r_H := \frac{m_t^2}{M_{H^\pm}^2}$, $\tan\beta$, but **not** on any parameters of the neutral Higgs sector!



The 3-spurion 2HDM

ideally, we would like $g^u \neq 0$, but $g^d = 0$ to comply with constraints from mixing of neutral kaons and B mesons $\Rightarrow$ **renormalisability??**

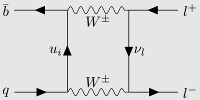
we construct the minimal renormalisable theory by keeping $Y^{u,d}$ and ϵ^u as the **spurions** breaking the global $SU(3)^5$ flavour symmetry of the gauge sector

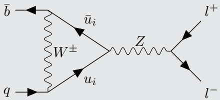
$$\epsilon^d = cY^d + c_{11} Y^d Y^{d\dagger} Y^d + b_{11} \epsilon^u \epsilon^{u\dagger} Y^d + b_{12} \epsilon^u Y^{u\dagger} Y^d + b_{21} Y^u \epsilon^{u\dagger} Y^d + b_{22} Y^u Y^{u\dagger} Y^d + \ldots$$

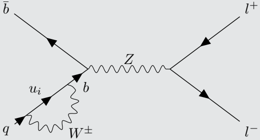
$\Rightarrow$ g^d (ϵ^d) provides the necessary Yukawa-type counterterms to cure the divergences!

Diagram classes

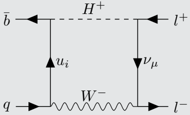
Standard Model

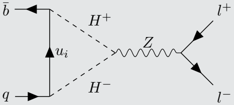


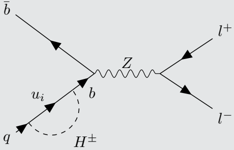


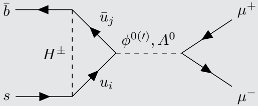


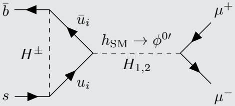
2HDM

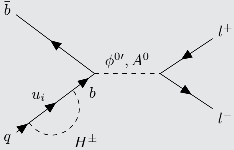












Method of computation

we computed all Wilson coefficients through next-to-leading order in QCD (2-loop)

$\Rightarrow$ several hundreds of box, penguin and flavour-changing self-energy diagrams

Method of computation

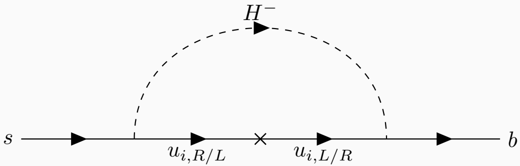
- Feynman rules for the general 2HDM: `FeynRules` + `UFO` Alloul et al., '09, '11, '13, '13
  $\rightarrow$ converted into `FORM` notation using `tapir`
- Feynman diagram generation: `qgraf` Nogueira, '93
- conversion to symbolic `FORM` expressions: `tapir` Gerlach et al., '23
- mapping onto tadpole integral topologies: `exp` Seidensticker et al. '97, '99
- integration: in-house `FORM` setup Vermaseren, '17
  using `MATAD` topologies Steinhauser, '00, Davydychev, Tausk, '93 Salomon, '12

Higgs-mediated flavour-changing self-energy diagrams

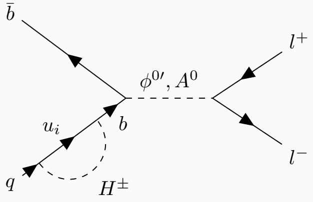
- an additional $t\bar{c}\phi^{0\prime}(A^0)$ coupling (non-diagonal element of g^u) can lift the CKM suppression
- decomposing the flavour-changing self-energy diagram as

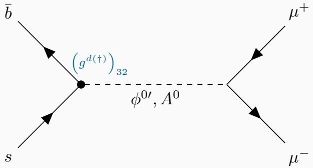
$$\Sigma^{H^\pm} = \Sigma_{LL}^{H^\pm} P_R \not{q} + \Sigma_{RR}^{H^\pm} P_L \not{q} + \Sigma_{LR}^{H^\pm} P_R + \Sigma_{RL}^{H^\pm} P_L \,,$$

  the $\Sigma_{LR}^{H^\pm}$ and $\Sigma_{RL}^{H^\pm}$ parts receive corrections enhanced by $\tan\beta$
- the chirality-flipping $q \to b$ transition is linear in g^u



Higgs-mediated flavour-changing self-energy diagrams





- leading contributions to $C_{S,P}^{(\prime)}$ starting at $\tan^3\beta$
- divergent $\Rightarrow$ the spurion expansion provides the necessary counterterm via g_{bs}

$$C_{P,\tan^3\beta}^{(0),\mathrm{III}} = -\frac{1}{8} Y_{\tan^3\beta}^{(\mathrm{III})} \left[\log\left(\frac{\mu^2}{m_t^2}\right) - \frac{\log(r_H)}{r_H - 1} + 1\right]$$

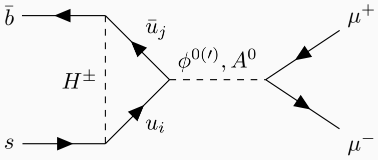
$$Y_{\tan^3\beta}^{(\mathrm{III})} \equiv \frac{1}{M_{A^0}^2} \frac{m_b m_\mu m_t \tan^3\beta}{G_F M_W^2 \sqrt{2} v V_{ts}} \left(g_{ct}^* V_{cs} + g_{tt}^* V_{ts} + g_{ut}^* V_{us}\right),$$

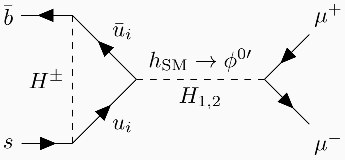
$$C_{P,\tan^3\beta}^{(1),\mathrm{III}} = -\frac{1}{6} Y_{\tan^3\beta}^{(\mathrm{III})} \left[\left(\frac{2(4r_H - 7)}{r_H - 1} + \frac{6\log(r_H)}{(r_H - 1)^2}\right)\log\left(\frac{\mu^2}{m_t^2}\right) + 3\log^2\left(\frac{\mu^2}{m_t^2}\right) - 6\mathrm{Li}_2\left(\frac{r_H - 1}{r_H}\right) + \frac{8(r_H - 2)}{r_H - 1} + \frac{(14 - 6r_H)\log(r_H)}{(r_H - 1)^2}\right]$$

Lang, Nierste, '22

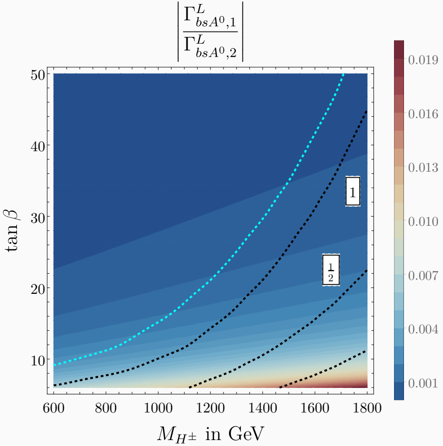
First subleading power $\tan^2\beta$

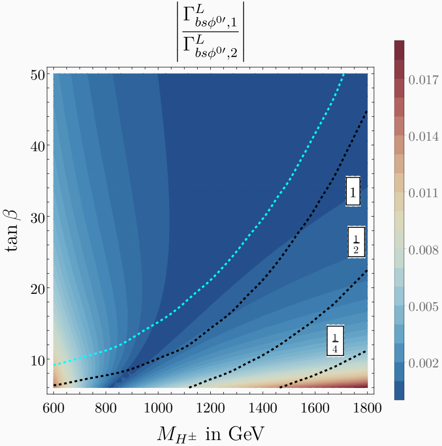
- at the next lower power of $\tan\beta$ the Yukawa structure becomes much richer
- many different Feynman diagrams contribute at this order
- however, mixed $W^{\pm}$–$H^{\mp}$ box diagrams are the same as in the type II 2HDM
- the $\mathcal{O}\left(\tan^2\beta\right)$ Wilson coefficients depend on parameters of the Higgs potential
- computed at NLO QCD for generic (CP-conserving) Higgs potential, taking mixing between h_{SM} and $\phi^{0\prime}$ into account



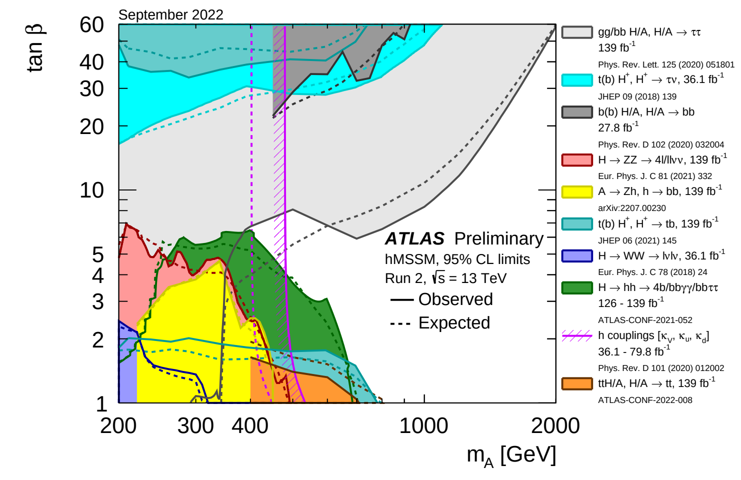


We find these $\tan\beta$-suppressed terms to be indeed **small**





Experimental constraints: collider



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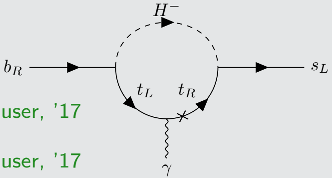
+ perturbativity bounds on scalar and Yukawa couplings

Experimental constraints

$b \to s\gamma$

- loop process, mediated in the SM by $W^\pm$, in the 2HDM additionally by $H^\pm$
- $\approx$ independent of $\tan\beta$ in the type-II 2HDM
- use the ratio $R_\gamma \equiv \frac{\mathcal{B}(b\to s\gamma)+\mathcal{B}(b\to d\gamma)}{\mathcal{B}(b\to c l\nu)}$



- $R_{\gamma,\mathrm{SM}} = (3.31 \pm 0.22)\cdot 10^{-3}$ Misiak, Steinhauser, '17

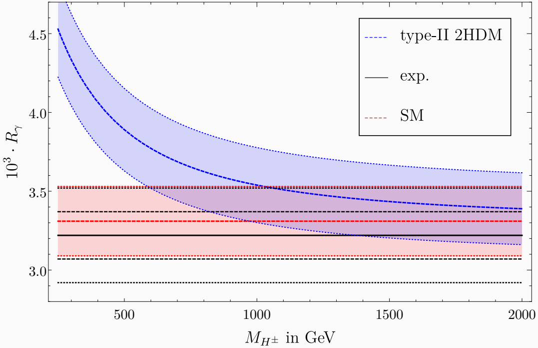
  $R_{\gamma,\mathrm{exp.}} = (3.22 \pm 0.15)\cdot 10^{-3}$ Misiak, Steinhauser, '17
- sensitive to the same combination of Yukawa couplings

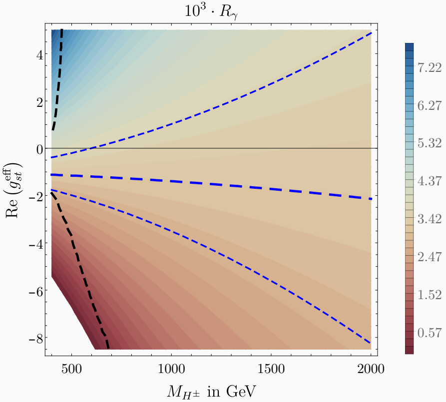
$$\left(\frac{m_b \tan\beta\, V_{tb}}{v}\right)\left(\frac{m_t\, V_{ts}^*}{v\tan\beta} + V_{ts}^*\, g_{tt} + V_{cs}^*\, g_{ct} + V_{us}^*\, g_{ut}\right) \equiv \frac{m_b m_t\, V_{tb} V_{ts}^*}{v^2}\left(1 + g_{st}^{\mathrm{eff}}\right)$$

- **caution:** $g_{st}^{\mathrm{eff}} = 0$ is the type-II 2HDM, the SM is $g_{st}^{\mathrm{eff}} = -1$

Experimental constraints: $b \to s\gamma$

good agreement between SM and experiment $\Rightarrow$ small 2HDM contributions $\Rightarrow$ consider only interference between SM and 2HDM $\Rightarrow$ constraint only on $\mathrm{Re}\left(g_{st}^{\mathrm{eff}}\right)$



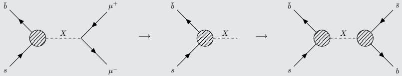


using the available NNLO QCD corrections (for the type-II 2HDM) Hermann et al., '12

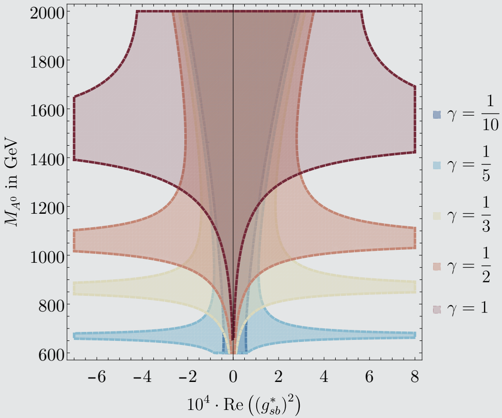
Experimental constraints: B_s–$\bar{B}_s$ mixing

B_s–$\bar{B}_s$ mixing

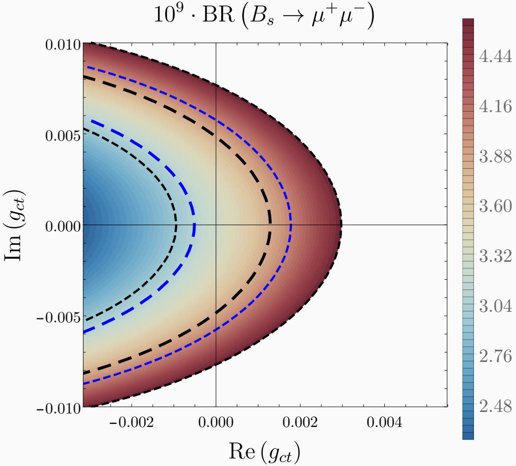
- use the mixing of neutral B_s mesons to constrain g_{sb}
- effective $|\Delta B| = |\Delta S| = 1$ vertices

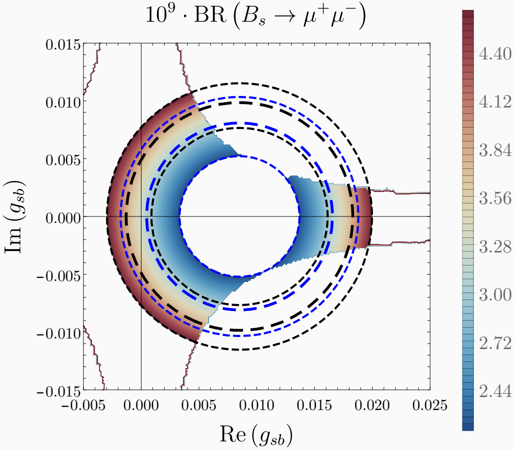


  $\Rightarrow$ construct the **effective** $\mathcal{H}^{\Delta M_s}_{\mathrm{eff,2HDM}}$ Hamiltonian
- crucial dependence on the mass difference $M^2_{\phi^{0\prime}} - M^2_{A^0} \equiv -4\gamma v^2$
- spurion expansion provides $|g_{bs}| \sim \frac{m_s}{m_b} |g_{sb}|$
- phase of M^s_{12} constrains $\mathrm{Im}\left({g_{sb}}^2\right)$



we work in the experimentally favoured **alignment limit** $\cos(\beta - \alpha) = 0$





blue: LHCb LHCb, '22, black: CMS CMS; '22

Conclusion

- the 2HDM with scalar FCNC coupling in the up-type quark sector can have profound consequences on rare leptonic and radiative B decays
- we computed all relevant Wilson coefficients for $B_s \to l^+ l^-$ in NLO QCD in an expansion in large $\tan\beta$
- in the interesting region of large $\tan\beta$ the additional Higgs bosons must be heavy
- $B_s \to l^+ l^-$, $b \to s\gamma$, and B_s–$\bar{B}_s$ mixing give complementary constraints!
- without the CKM suppression and an additional enhancement by $\tan\beta$, the most prominent FCNC coupling g_{ct} can be restricted to $|g_{ct}| \lesssim 0.01$

Thank you for your attention!

Backup

Branching ratio

time averaged branching ratio

$$\overline{\mathcal{B}} = |N|^2 \frac{M_{B_s}^3 f_{B_s}^2}{8\pi\Gamma_H^s} \beta \left[\left| r \left(C_A - C_A' \right) - u \left(C_P - C_P' \right) \right|^2 F_P + \left| u\beta \left(C_S - C_S' \right) \right|^2 F_S \right]$$

with $r = \frac{2m_\mu}{M_{B_s}}$, $\beta = \sqrt{1 - r^2}$, $u = \frac{M_{B_s}}{m_b + m_s}$

In the SM only C_A contributes significantly!

$$\overline{\mathcal{B}}_{\mathrm{SM}} = (3.65 \pm 0.23) \cdot 10^{-9}$$ Bobeth et al., '13

$$\overline{\mathcal{B}}_{\mathrm{LHCb}} = 3.09^{+0.46+0.15}_{-0.43-0.11} \cdot 10^{-9}$$ LHCb, '22

$$\overline{\mathcal{B}}_{\mathrm{CMS}} = 3.83^{+0.38+0.24}_{-0.36-0.21} \cdot 10^{-9}$$ CMS; '22

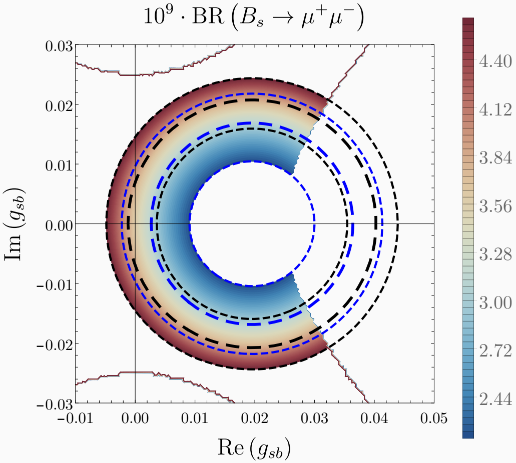
2HDM Yukawa sector

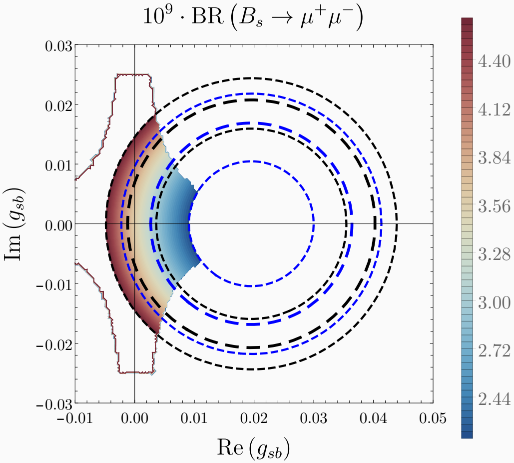
diagonaling mass matrices:

$$\frac{\hat{M}_d}{v} = Y^d \cos\beta + \epsilon^d \sin\beta \,, \frac{\hat{M}_u}{v} = V \left(Y^u \sin\beta + \epsilon^u \cos\beta \right) .$$

$$L_Y \equiv -\overline{Q}\Big[Y^d H_d + \epsilon^d H_u \Big] d_R \; - \; \overline{Q} \Big[Y^u \epsilon H_u^* + \epsilon^u \epsilon H_d^* \Big] u_R + \mathrm{h.c.}$$

Constraints from mixing





Scale dependence