Charged Higgs effects in Tauonic B decays and 2HDMs phenomenology

Ahmet KOKULU

Department of Mathematical Sciences, University of Liverpool

in collaboration with

Ch. Greub (Bern U, AEC) and A. Crivellin (CERN, Theory division)

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PLAN OF THE TALK

1. Basics
   - Effective Theory Approach
   - 2HDMs
2. Work

- Flavor phenomenology of 2HDMs
   - $B \to X_{s(d)}\gamma$
   - $B \to (D^{(*)})\tau\nu$ and d_n
   - Upper limits on $B_{s,d} \to \mu e$
   - Correlation between $\mu \to e\gamma$ and $\mu \to 3e$
   - Summary of the constraints

3. Conclusions

1. Basics

Effective Field Theory

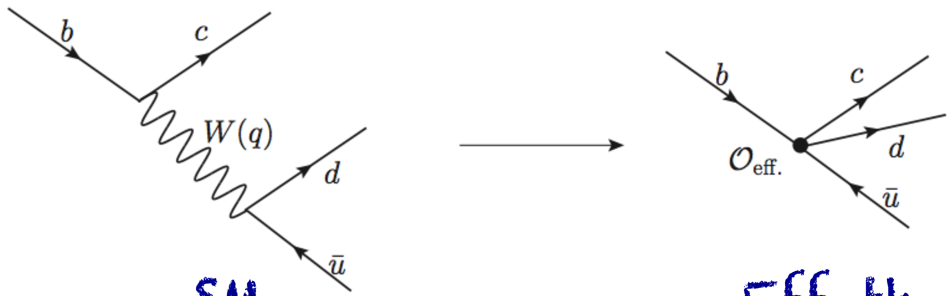
- ET is the theory valid (good) up to some energy scales.
- Applied to Feynman diagrams it means studying the dynamics of the diagram(s) after integrating out the heavy DOF.

– Formally performed within the concept of Operator Product Expansion (OPE) introduced by Wilson in 1969.

– Physics describing short distance effects are absorbed in the so-called Wilson coefficients C_i's, while low energy effects are hidden in matrix el. of effective operators O_i's.

Examples:
Euler-Heisenberg (ET of QED-100MeV), Fermi (ET of Weak int.-90GeV), ChPT (ET of QCD-1Gev) or even SM (ET of a more fund. theory?-1Tev).

e.g. Consider the tree-level $b \to c d \bar{u}$ transition:



SM Eff. th.

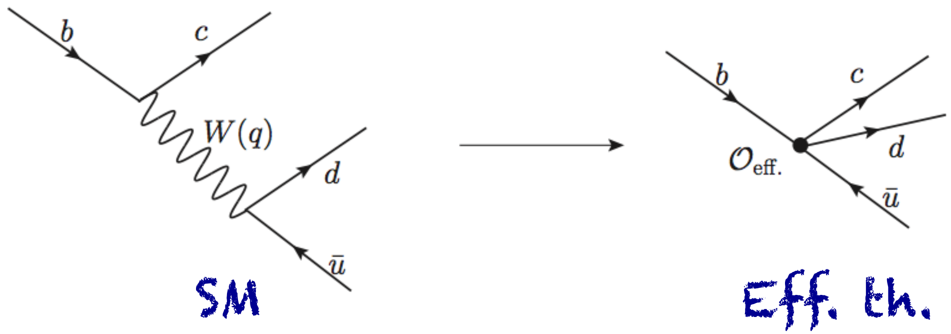
The SM Amplitude:

$$\mathcal{A}_{\text{SM}} = -i\left(\frac{-ig_2}{\sqrt{2}}\right)^2 V_{cb}V_{ud}^*\,\frac{g^{\mu\nu}-\frac{q^\mu q^\nu}{m_W^2}}{q^2-m_W^2}\,(\bar{d}\gamma_\mu L u)\,(\bar{c}\gamma_\nu L b)$$

$q \approx O(m_b) << m_W$, expand in q^2/m_W^2 ; $\quad \frac{g^{\mu\nu}-\frac{q^\mu q^\nu}{m_W^2}}{q^2-m_W^2} = -\frac{g^{\mu\nu}}{m_W^2} + \mathcal{O}\left(\frac{q^2}{m_W^4}\right)$

-> series of local operators with ascending mass dim:

$$\mathcal{A}_{\text{SM}} = \frac{-ig_2^2}{2}V_{cb}V_{ud}^*\left[\frac{1}{m_W^2}\underbrace{(\bar{d}\gamma_\mu L u)\,(\bar{c}\gamma^\mu L b)}_{\text{dim-6 operator}} + \frac{1}{m_W^4}\underbrace{(..........)}_{\text{dim-8 operator}} + \ldots\right]$$



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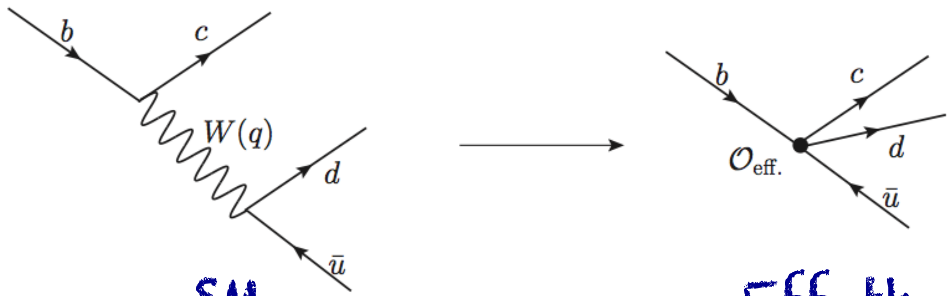

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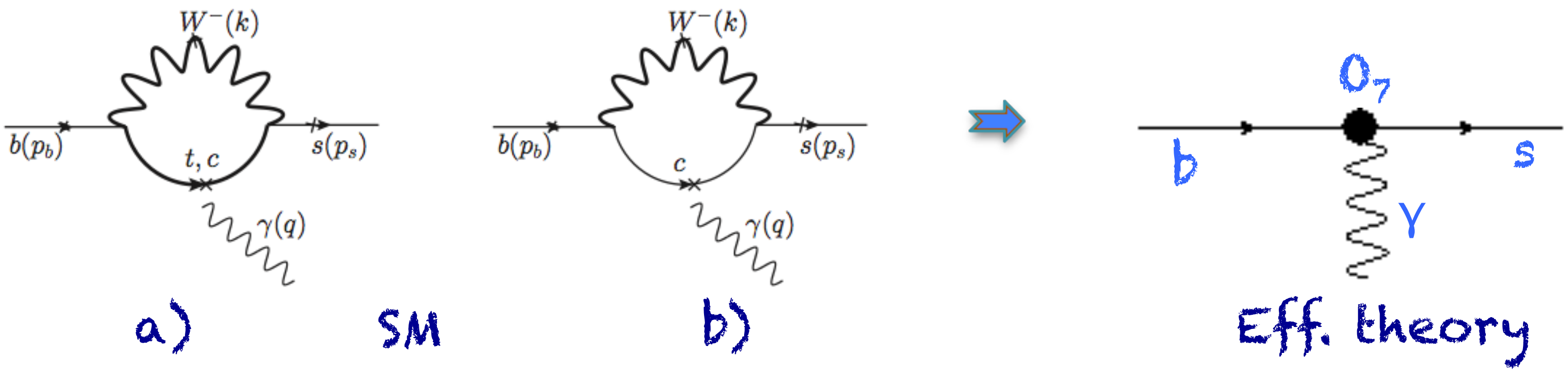
Effective Amplitude:

$$\mathcal{A}_{\text{eff}} = \frac{-ig_2^2}{2} V_{cb}V_{ud}^* \frac{1}{m_W^2}\left(\bar{d}\gamma_\mu L u\right)\left(\bar{c}\gamma^\mu L b\right).$$

➢ Matching procedure

Idea: Calculating a particular process both on the full and ET side then extracting C_i's by confronting both results.

e.g. consider the quark-level $b \to s\gamma$ decay at LO in QCD:



-Diag with u-quark is prop. to $V_{ub}V_{us}^*$ and as $|V_{ub}V_{us}^*| \ll |V_{tb}V_{ts}^*|$ it can be safely neglected.

• Calculation on the full theory side:

Acc. to HME rules by V.A. Smirnov'94 two type of diags to calculate; a) and b)

Diagram a)- top and charm contributions

- for t-quark propagators simply make the expansion (also for p_s)

$$\frac{1}{(k+p_b)^2-m_t^2}=\frac{1}{k^2-m_t^2}\sum_{n\geq 0}\left(-\frac{p_b^2+2kp_b}{k^2-m_t^2}\right)^n$$

- for c-quark propagators additional expansion in m_c (i.e mc=0).

Diagram b)- charm-loop

- treat k as an external momentum and expand the W propagator as

$$\frac{1}{k^2-m_W^2}=-\frac{1}{m_W^2}\left[1+\frac{k^2}{m_W^2}+\mathcal{O}\left(\frac{1}{m_W^4}\right)\right]$$

Diagram a)- top and charm contributions

- for t-quark propagators simply make the expansion (also for p_s)

$$\frac{1}{(k+p_b)^2 - m_t^2} = \frac{1}{k^2 - m_t^2} \sum_{n\geq 0} \left(-\frac{p_b^2 + 2kp_b}{k^2 - m_t^2} \right)^n$$

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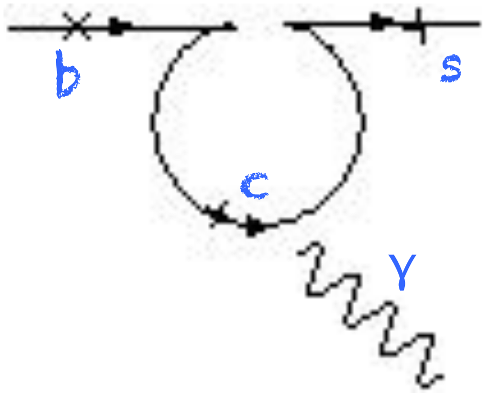
- treat k as an external momentum and expand the W propagator as

$$\frac{1}{k^2 - m_W^2} = -\frac{1}{m_W^2} \left[1 + \frac{k^2}{m_W^2} + \mathcal{O}\left(\frac{1}{m_W^4} \right) \right]$$

⬇

we are then left with



$\propto (q^2\gamma_\mu - \not{q} q_\mu)\varepsilon^\mu = 0$

which just vanishes for an on-shell photon (q^2=0)!

-Hence, the complete SM amplitude reads

$$\mathcal{A}_{\rm full} = i\,\frac{4G_F\,\lambda_t}{\sqrt{2}}\,\frac{e}{16\pi^2}\,\underbrace{\frac{x}{24}\left[\frac{-8x^3+3x^2+12x-7+(18x^2-12x)\ln({\rm x})}{(x-1)^4}\right]}$$

$$\times\quad \bar{u}(p_s)2\left[R(\not{\epsilon}(q)(m_b^2+m_s^2)-2m_b\,p_b.\epsilon(q))+L\,(2m_bm_s\not{\epsilon}(q)-2m_s\,p_b.\epsilon(q))\right]u(p_b$$

where $x=m_t^2/m_W^2$.

- Calculation on the ET side:

-at the LO in QCD O_7 is the only operator cont. to b->sγ.

$$\mathcal{A}_{\rm eff} = \frac{4iG_F\,\lambda_t}{\sqrt{2}}\,C_7\langle s\gamma|\mathcal{O}_7|b\rangle$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2}\left(\bar{s}\sigma^{\mu\nu}\left[\bar{m}_bR+\bar{m}_sL\right]b\right)F_{\mu\nu}$$

-Decomposing the $\sigma_{\mu\nu}F^{\mu\nu}$ structure in O_7 gives:

$$\begin{aligned}\mathcal{A}_{\rm eff} &= \frac{4iG_F\,\lambda_t}{\sqrt{2}}\,C_7\langle s\gamma|\mathcal{O}_7|b\rangle = \frac{4iG_F C_7\,\lambda_t}{\sqrt{2}}\,\frac{e}{16\pi^2}\\ &\times\ \bar{u}(p_s)2\left[R(\not\epsilon(q)(m_b^2+m_s^2)-2m_b\,p_b.\epsilon(q))+L\left(2m_bm_s\not\epsilon(q)-2m_s\,p_b.\epsilon(q)\right)\right]u(p_b)\end{aligned}$$

-requiring $A_{eff}=A_{full}$ completes the matching and fixes C_7 as:

$$C_7=\frac{x}{24}\left[\frac{-8x^3+3x^2+12x-7+(18x^2-12x)\ln(\mathrm{x})}{(x-1)^4}\right]$$ ✓

Two Higgs doublet models

SM: one Higgs doublet Φ

charged component of Φ becomes the long. component of W

neutral CP-odd component of Φ becomes the long. component of Z

→ only one physical Higgs (neutral CP-even)

2HDMs: H_u and H_d

-five physical Higgses: h^0, H^0, A^0, $H^{\pm}$ (CP consv. Higgs potential)

type-I: H_u couples to up and down-type quarks, H_d does not couple to fermions.

type-II: H_u couples to up and H_d to down-type quarks.
(MSSM at tree-level)

type-III: both H_u and H_d couple to both type of quarks.
(FCNCs at tree-level)

lepton specific, flipped, inert or Aligned [Pich,Tuzon'09] 2HDM etc...

-1st formulation by T.D. Lee in 1973: motivation to find extra sources of CP violation.

MSSM like Higgs potential:

$$V(H_u, H_d) = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + \frac{\lambda_1}{2}\left(H_d^\dagger H_u\right)\left(H_u^\dagger H_d\right) + \frac{\lambda_2}{8}\left(|H_u|^2 - |H_d|^2\right)^2$$

$$+ \left(b\left(\epsilon^T H_d^\star\right)^\dagger H_u + \text{h.c.}\right), \quad \text{with } \lambda_1 = g^2,\ \lambda_2 = g^2 + g'^2, \qquad (*)$$

$$H_d = \begin{pmatrix} H_d^1 \\ H_d^2 \end{pmatrix} = \begin{pmatrix} v_d + H_d^0 \\ H_d^- \end{pmatrix} \text{ with } H_d^0 = \rho_d + i\eta_d\,,$$

$$H_u = \begin{pmatrix} H_u^1 \\ H_u^2 \end{pmatrix} = \begin{pmatrix} H_u^+ \\ v_u + H_u^0 \end{pmatrix} \text{ with } H_u^0 = \rho_u + i\eta_u$$

and $v_u/vd = \tan\beta$.

minimization of (*) gives:

$$m_{H_u}^2 = b\frac{v_d}{v_u} + \frac{\lambda_2}{4}\left(v_d^2 - v_u^2\right)\ ,\quad m_{H_d}^2 = b\frac{v_u}{v_d} + \frac{\lambda_2}{4}\left(v_u^2 - v_d^2\right)$$

Scalar masses: work out the quadratic + mixing terms in V

Guage boson masses: follow from the kinetic terms in the Lagrangian.

Scalar mass terms:

$$m_{H^\pm}^2 = \frac{2b}{\sin 2\beta} + \frac{\lambda_1 v^2}{2}, \quad m_{G^\pm}^2 = 0, \quad m_{A^0}^2 = \frac{2b}{\sin 2\beta}, \quad m_{G^0}^2 = 0\,,$$

$$m_{H^0,h^0}^2 = \frac{1}{2}\left(m_{A^0}^2 + \frac{\lambda_2 v^2}{2} \pm \sqrt{\left(m_{A^0}^2 - \lambda_2 v^2/2\right)^2 + 2\lambda_2 v^2 m_{A^0}^2 \sin^2 2\beta}\right)$$

Gauge bosons mass terms ($v_u^2+v_d^2=v^2=(174\,\mathrm{GeV})^2$):

$$m_W^2 = \frac{g^2(v_u^2+v_d^2)}{2}, \quad m_Z^2 = \frac{(g^2+g'^2)(v_u^2+v_d^2)}{2}, \quad m_\gamma^2 = 0$$

-Also, one can obtain the following relation between α and β:

$$\tan(2\alpha) = \frac{m_{A^0}^2 + m_Z^2}{m_{A^0}^2 - m_Z^2}\tan(2\beta) = \frac{m_{H^0}^2 + m_{h^0}^2}{m_{A^0}^2 - m_Z^2}\tan(2\beta)$$

- for $-\pi/2<\alpha<0$, $0<\beta<\pi/2$, large $\tan\beta$ and $v \ll m_{A^0}$:

$$\boxed{\begin{aligned} &\tan\beta \approx -\cot\alpha\,, \\ &m_{H^0} \approx m_{H^\pm} \approx m_{A^0} \equiv m_H \end{aligned}}$$

-Yukawa Lag. of of type-III model in physical basis:

$$
\begin{aligned}
\mathcal{L}_Y = &- \bar{d}_{f\,L}\left[\left(\frac{m_{d_i}}{v_d}\delta_{fi} - \epsilon^d_{fi}\tan\beta\right)H_d^{0\star} + \epsilon^d_{fi}\,H_u^0\right]d_{i\,R} \\
&- \bar{u}_{f\,L}\left[\left(\frac{m_{u_i}}{v_u}\delta_{fi} - \epsilon^u_{fi}\cot\beta\right)H_u^{0\star} + \epsilon^u_{fi}\,H_d^0\right]u_{i\,R} \\
&+ \bar{u}_{f\,L}V_{fj}\left[\frac{m_{d_i}}{v_d}\delta_{ji} - (\cot\beta + \tan\beta)\,\epsilon^d_{ji}\right]H_d^{2\star}\,d_{i\,R} \\
&+ \bar{d}_{f\,L}V^\star_{jf}\left[\frac{m_{u_i}}{v_u}\delta_{ji} - (\tan\beta + \cot\beta)\,\epsilon^u_{ji}\right]H_u^{1\star}u_{i\,R} + h.c.\ . \qquad \boxed{(**)}
\end{aligned}
$$

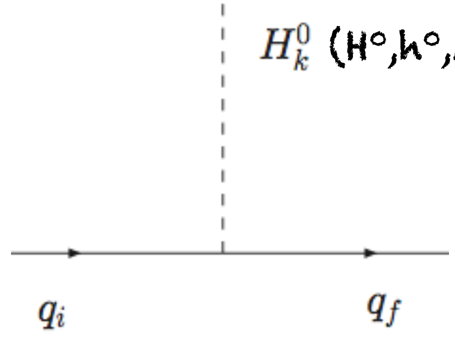
$\tan\beta$, m_H and ε_{ij}^f !

FCNCs at tree-level!

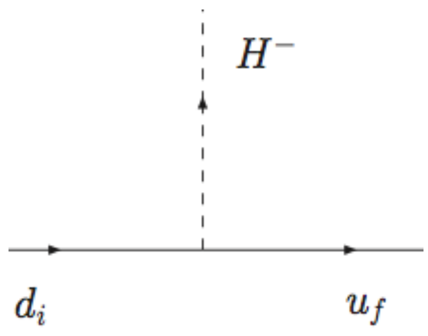
→ Eq. (**) defines:

ε_{ij}^f couplings:

$$
\begin{aligned}
m^d_{ij} &= v_d Y^{d\,\mathrm{ew}}_{ij} + v_u \epsilon^{d\,\mathrm{ew}}_{ij}\,, \\
m^u_{ij} &= v_u Y^{u\,\mathrm{ew}}_{ij} + v_d \epsilon^{u\,\mathrm{ew}}_{ij}\,, \\
m^\ell_{ij} &= v_d Y^{\ell\,\mathrm{ew}}_{ij} + v_u \epsilon^{\ell\,\mathrm{ew}}_{ij}\,.
\end{aligned}
$$



$$i\left(\Gamma^{LR\,H_k^0}_{q_f q_i}P_R + \Gamma^{RL\,H_k^0}_{q_f q_i}P_L\right)$$



$$i\left(\Gamma^{LR\,H^-}_{u_f d_i}P_R + \Gamma^{RL\,H^-}_{u_f d_i}P_L\right)$$

-flavor viol. (beyond type-II) is entirely governed by ε_{ij}^f.

↓

main task is to constrain ε_{ij}^f.

2. Work

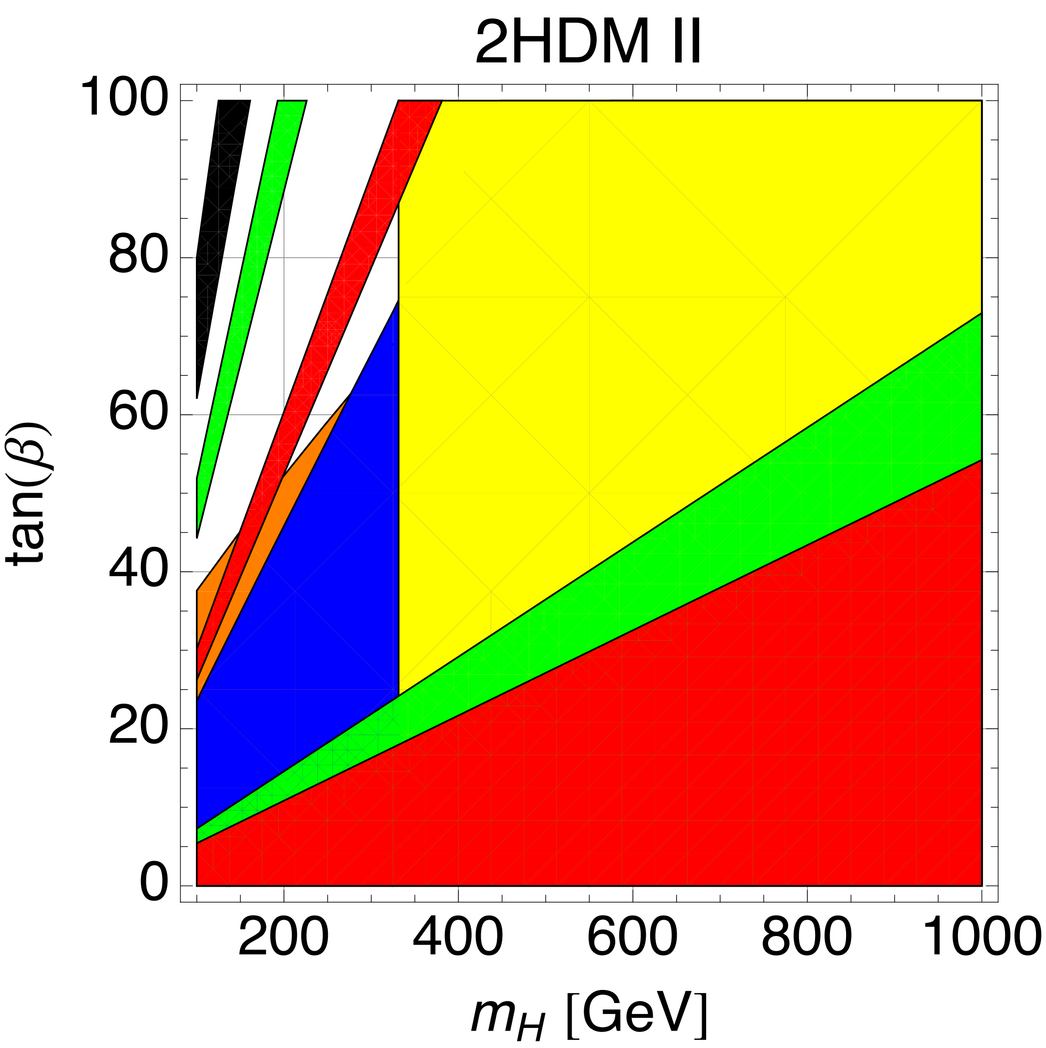
Flavor phenomenology of 2HDMs

- "Explaining $B \to (D^{(*)})\tau\nu$ in a 2HDM of type III"
- "Flavor phenomenology of 2HDMs with generic Yukawa structure"

Crivellin, Greub and A.K.

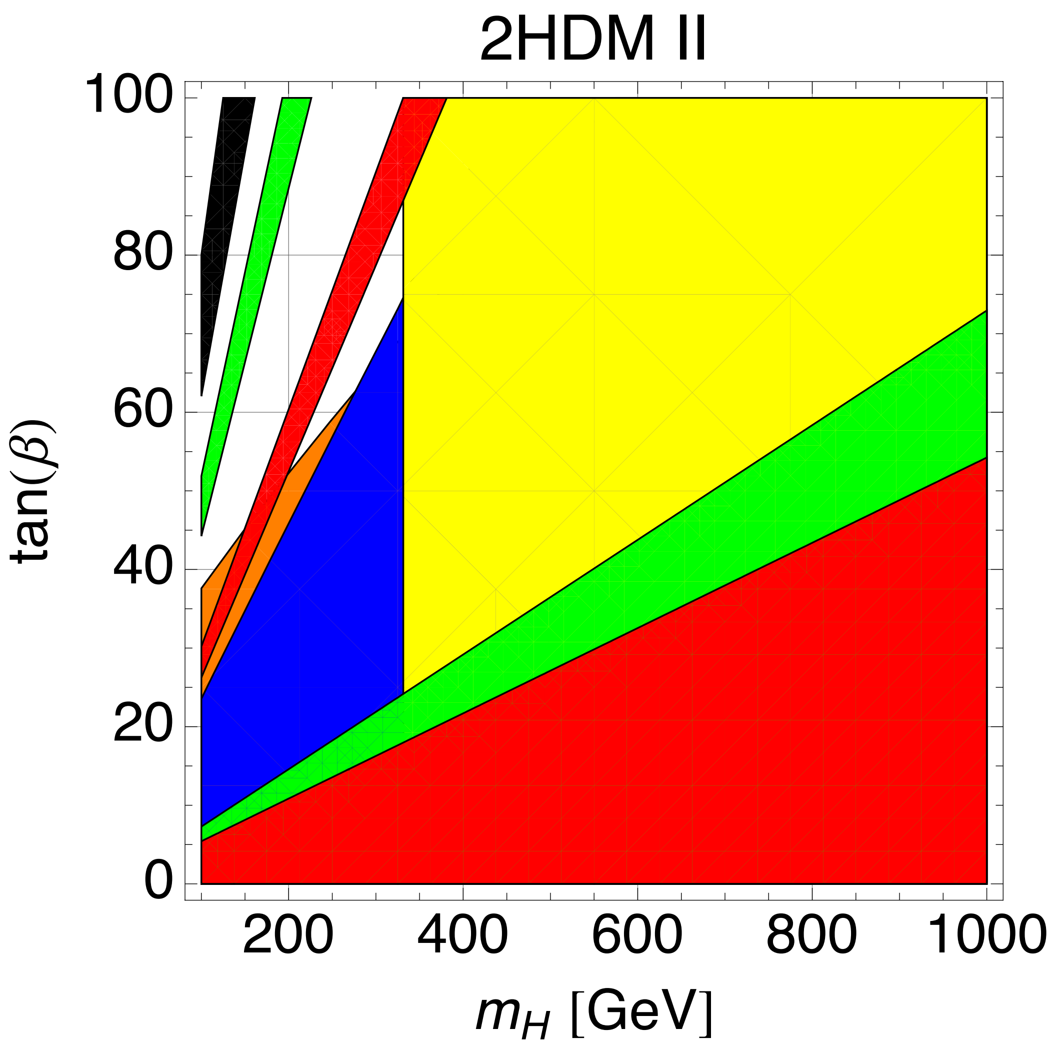
- Phys. Rev. D86, 054014, 2012
- Phys. Rev. D87, 094031, 2013

Updated constraints on 2HDM II



- Allowed 2σ regions
  (+ th. uncertainties superimposed)

Updated constraints on 2HDM II



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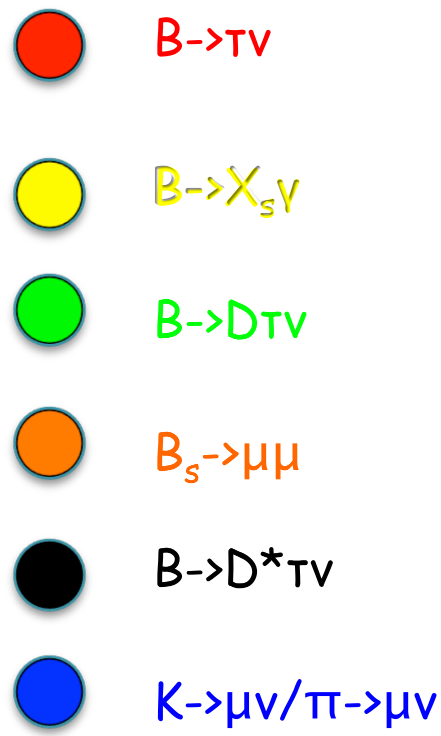
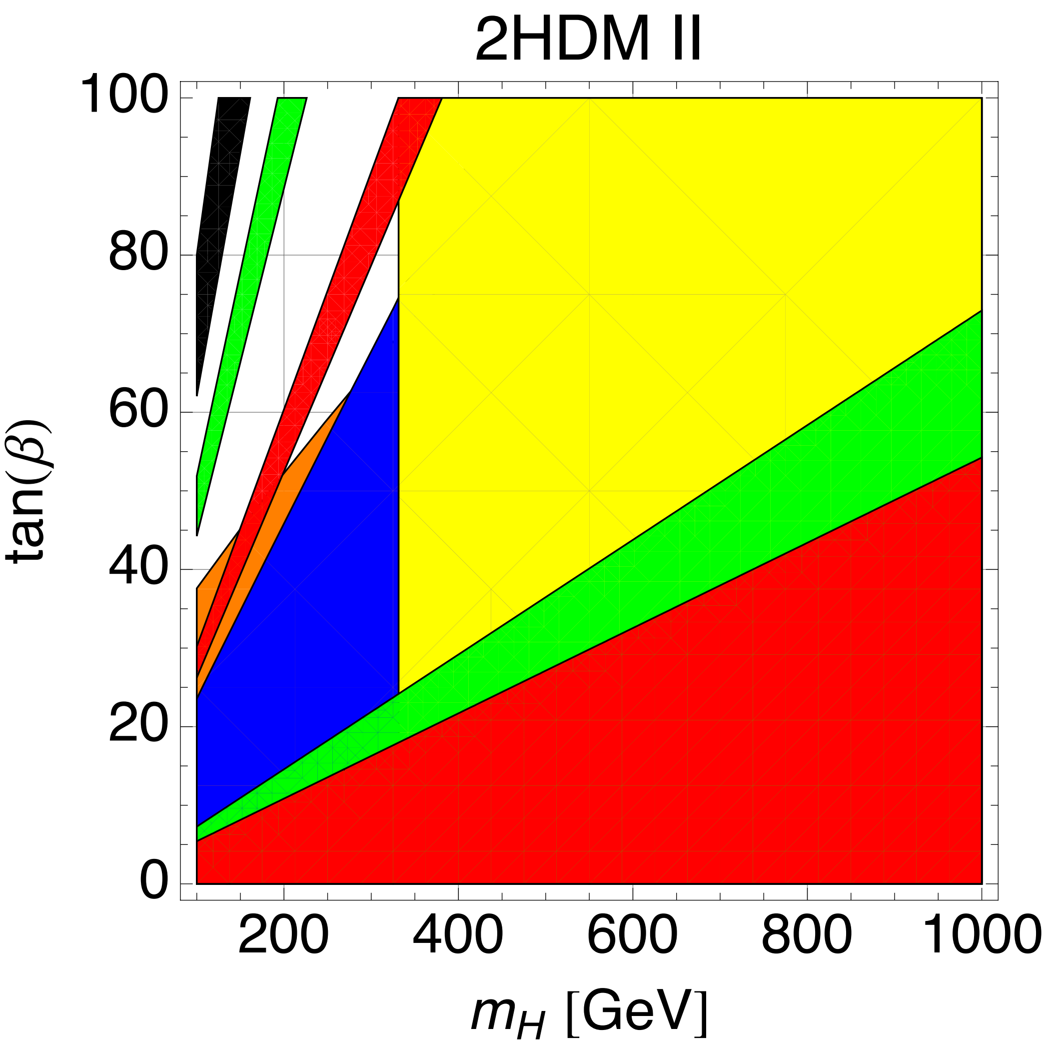


➢ Tension from B->D*τν !

Updated constraints on 2HDM II



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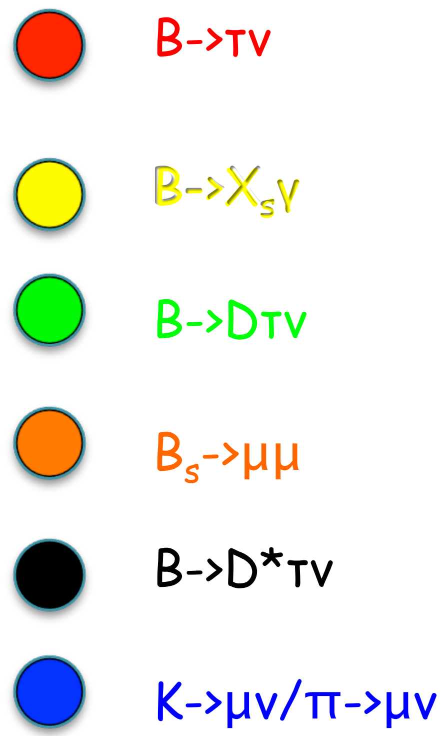
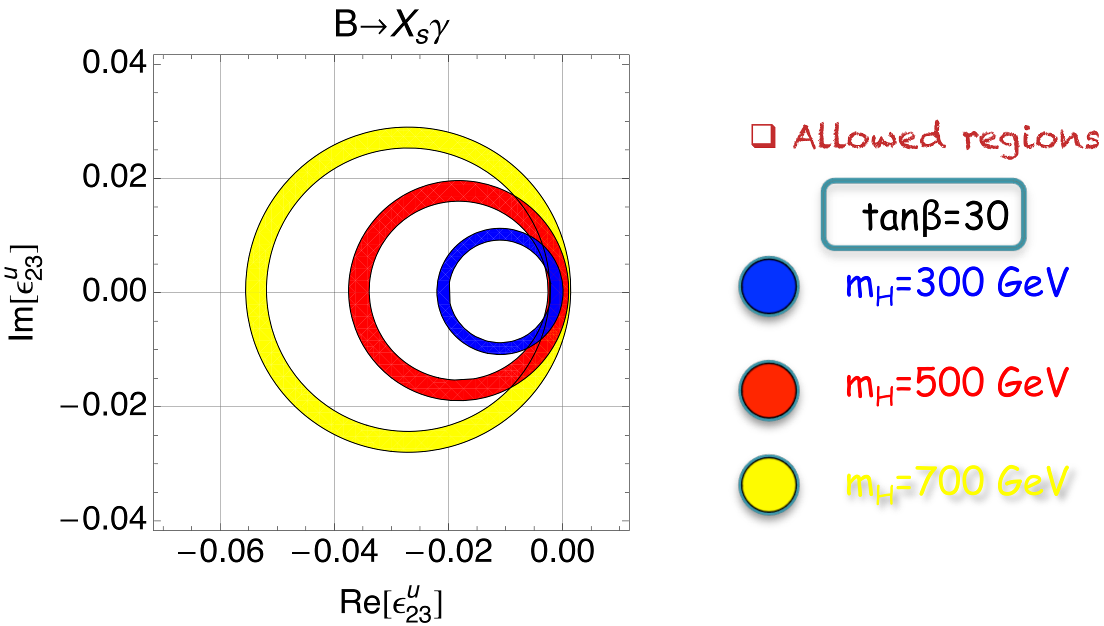
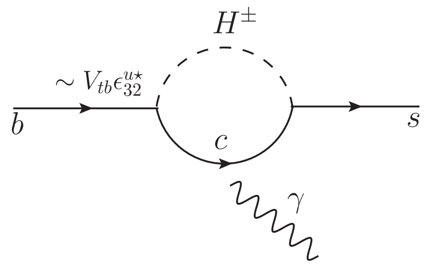


- Tension from B->D*τν !
- The current best lower bound on the charged Higgs mass (from $B\to X_s\gamma$) is $m_H > 360$ GeV [Hermann,Misiak,Steinhauser'12].

B->$X_s\gamma$ in 2HDM III





- stringent constraints on ε^u_{23}, while loose ones on ε^u_{32}!

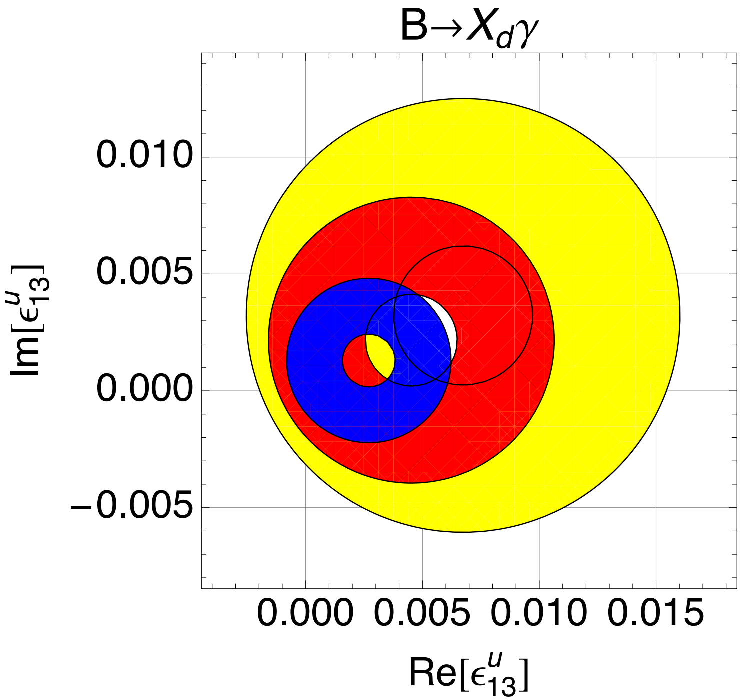
B->$X_s\gamma$ (ε^u_{23})

$$\mathcal{B}\,[B \to X_s\gamma]|^{\rm exp}_{E_\gamma > 1.6\,{\rm GeV}} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$ [Babar+Belle Av. '12]

$$\mathcal{B}\,[B \to X_s\gamma]^{\rm SM} = (3.15 \pm 0.23) \times 10^{-4}$$ [Greub, Gorbahn, Misiak et al. '07 -NNLO]

require: SM + 2HDM-III lies within 2σ experimental range + th. uncertainty

B->$X_d\gamma$ in 2HDM III



- Allowed regions

tanβ=30

m_H=300 GeV

m_H=500 GeV

m_H=700 GeV

B->$X_d\gamma$ ($\varepsilon^u{}_{13}$)

$\mathcal{B}\,[B \to X_d\gamma]|^{\rm exp}_{E_\gamma>1.6\,{\rm GeV}} = (1.41 \pm 0.57) \times 10^{-5}$ [Babar CP Av. '11]

$\mathcal{B}\,[B \to X_d\gamma]|^{\rm SM}_{E_\gamma>1.6\,{\rm GeV}} = (1.54^{+0.26}_{-0.31}) \times 10^{-5}$ [Crivellin et al. '11-NLL]

demand: SM + 2HDMIII lies within 2σ experimental range + th. uncertainty

Tauonic B decays and d_n

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

BABAR '13 meas.

$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042\,,$$
$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018\,.$$

SM pred. [Aubert et al. '12]

$$\mathcal{R}_{\rm SM}(D) = 0.297 \pm 0.017\,,$$
$$\mathcal{R}_{\rm SM}(D^*) = 0.252 \pm 0.003$$

➢ 2σ for R(D) and 2.7σ for R(D*). Combined 3.4σ dev. from the SM!

BABAR+BELLE '12 Av.

$$\mathcal{B}_{exp}[B \to \tau\nu] = (1.15 \pm 0.23) \times 10^{-4}$$

SM pred. [Charles et al. '05]

$$\mathcal{B}_{\rm SM}[B \to \tau\nu] = (0.796^{+0.088}_{-0.087}) \times 10^{-4}$$

➢ Disagrees with SM pred. by 1.6σ using V_{ub} from global fit!

evidence for LFU violation -> which model of NP to explain?

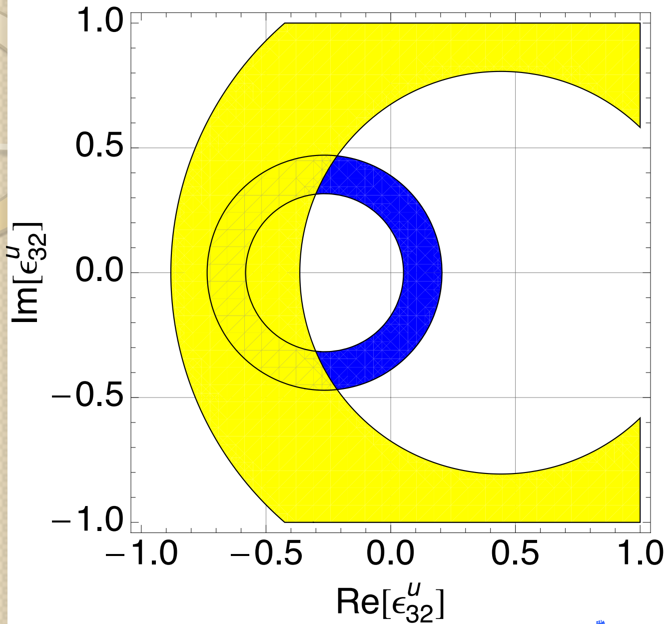
- 2HDM II is not capable of removing these tensions! (destructive interference with SM for B->τν and cannot simultaneously satisfy R(D) and R(D*).)

Possibilities:

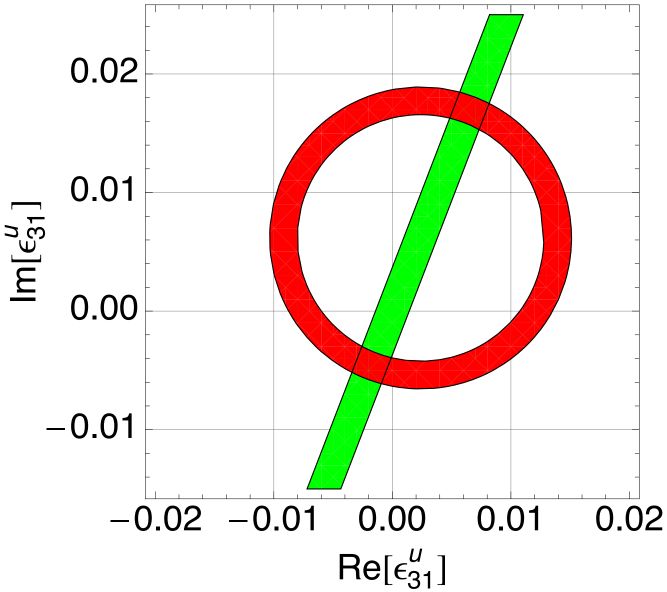
- NP in B mixing (bigger values for V_{ub})
- 2HDM-III with flavor viol. in the up sector
- RH W-couplings etc.

Allowed 1σ regions for tanβ=50, m_H=500 GeV

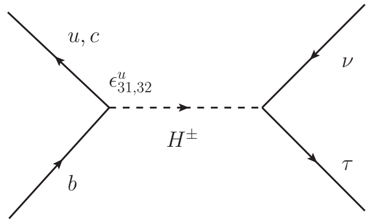
R(D), R(D*)



B->τν, d_n



2HDM III



type-III 2HDM

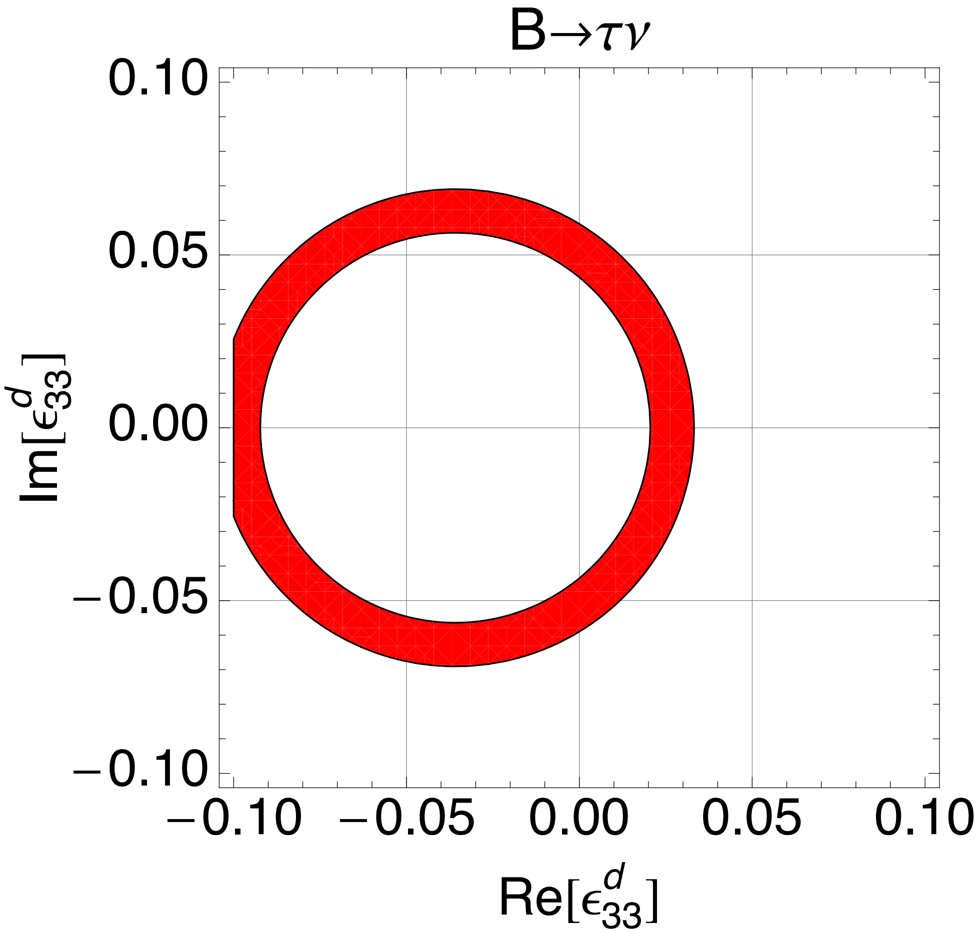
- R(D) and R(D*) can simultaneously be explained by ε^u_{32}.
- Also, B->τν can be brought into agreement with exp. using ε^u_{31}.

[Crivellin, Greub and AK]
(PRD 86, 054014, 2012)

- We propose searches for A°,H°->tc(u) or t->h°c(u) at the LHC to test the model.

--> related work is in progress!

Allowed 1σ region for $\tan\beta=50$, $m_H=500$ GeV



- Explaining the (slight) discrepancy in B->τν by ε^d_{33} violates Naturalness criterion!

LFV transitions

- Neutral meson decays: $B_{s,d}\to\mu e$ ($B_{s,d}\to\tau\mu$, $B_{s,d}\to\tau e$)

- In the SM (massless neutrinos) Br's of these decays are zero!

- In the 2HDM-II they are also not possible (no FCNH interactions)!

- In the 2HDM-III they are possible if $\varepsilon^{l}_{ij}\neq 0$, and even a tree-level neutral Higgs contribution exist when also $\varepsilon^{d}_{32,23}\neq 0$ ($\varepsilon^{d}_{31,13}\neq 0$).

- for large $\tan\beta$ and $v \ll m_H$ we obtain: [Crivellin, Greub and AK] (PRD 87, 094031, 2013)

$$\mathcal{B}\left[B_q \to \ell_i^+\ell_j^-\right] \approx N_{ij}^q \left(\frac{\tan\beta/50}{m_H/500\,\mathrm{GeV}}\right)^4 2\left[\left|\epsilon^\ell_{ji}\right|^2\left|\epsilon^d_{q3}\right|^2 + \left|\epsilon^\ell_{ij}\right|^2\left|\epsilon^d_{3q}\right|^2\right]$$

with

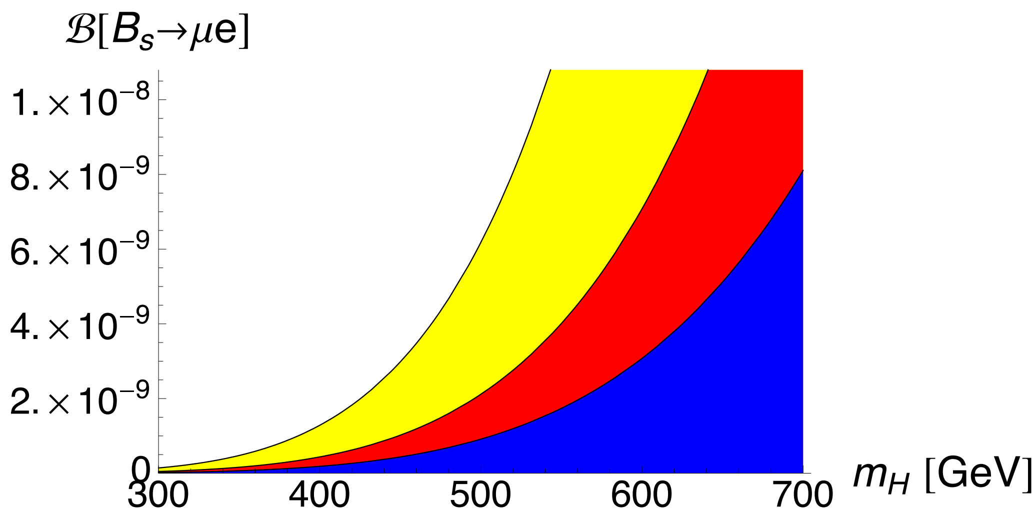
$$N^s_{21} \approx 2.1\times 10^7 \frac{f_{B_s}}{0.229\,\mathrm{GeV}},$$
$$N^d_{21} \approx 1.6\times 10^7 \frac{f_{B_d}}{0.196\,\mathrm{GeV}},$$
$$N^s_{31,32} \approx 1.7\times 10^7 \frac{f_{B_s}}{0.229\,\mathrm{GeV}},$$
$$N^d_{31,32} \approx 1.2\times 10^7 \frac{f_{B_d}}{0.196\,\mathrm{GeV}}.$$

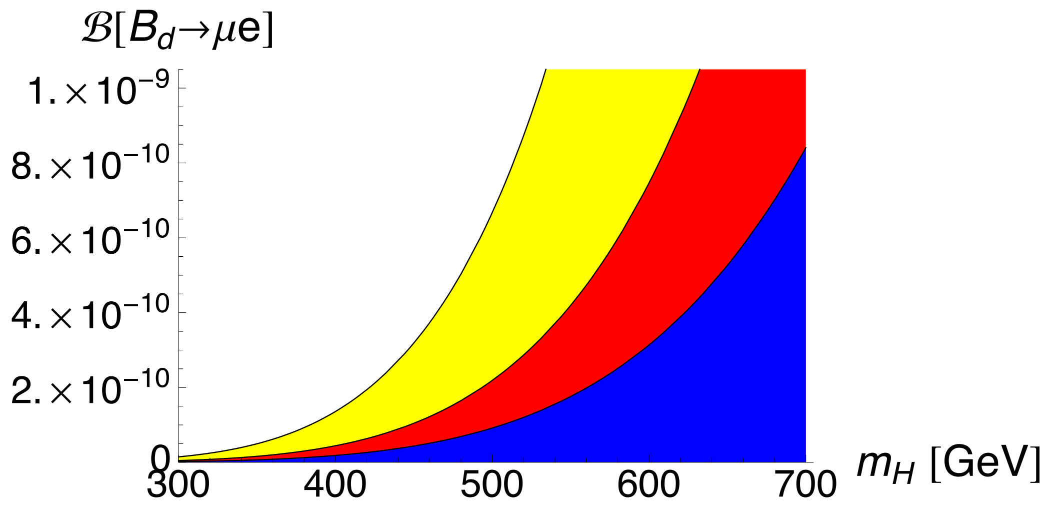
Upper limits in 2HDM-III

-biggest allowed values for $|\varepsilon^{d}_{32,23}|$ ($|\varepsilon^{d}_{31,13}|$) from $B_{s(d)}\to\mu^+\mu^-$
-biggest allowed values for $|\varepsilon^{l}_{21,12}|$ from $\mu\to e\gamma$
-biggest allowed values for $|\varepsilon^{l}_{32,23}|$ ($|\varepsilon^{l}_{31,13}|$) from $\tau\to 3\mu$ ($\tau\to e\mu^+\mu^-$)

respecting these bounds we obtain:

$\tan\beta=30$ (yellow), $\tan\beta=40$ (red), $\tan\beta=50$ (blue)





◆ Correlations among $l_i \to l_f \gamma$ and $l_i^- \to l_f^- l_j^+ l_j^-$

-In the 2HDM-III for large tanβ and $v \ll m_H$ one has

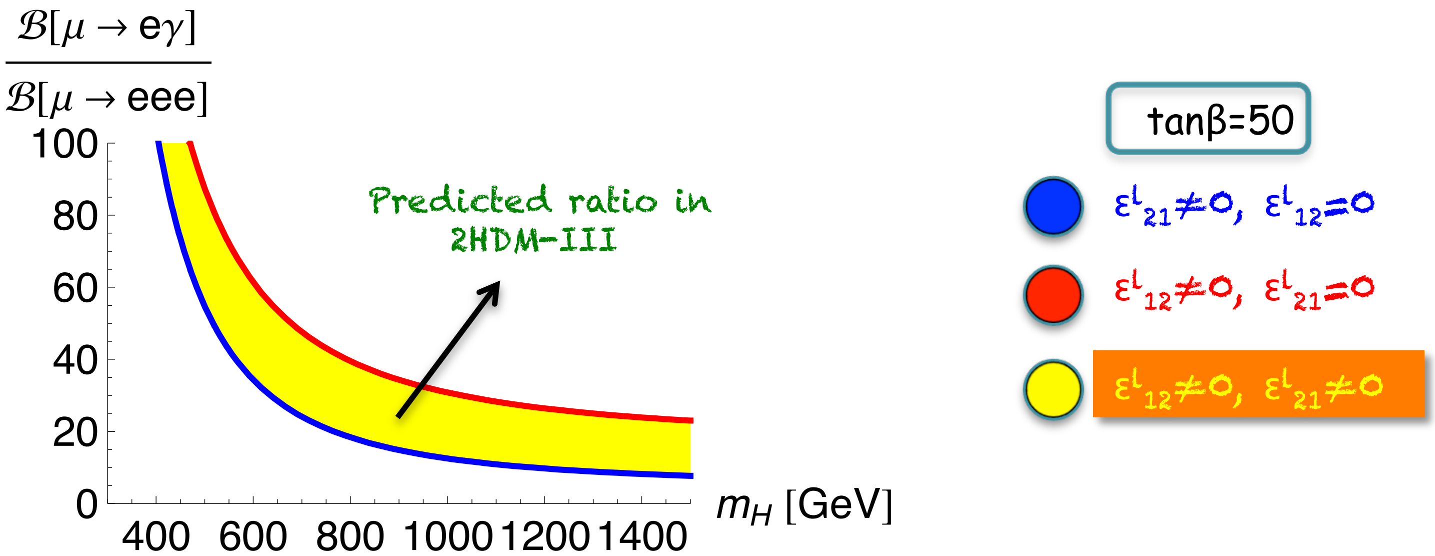
$$\frac{\mathcal{B}\left[\ell_i \to \ell_f \gamma\right]}{\mathcal{B}\left[\ell_i^- \to \ell_f^- \ell_j^+ \ell_j^-\right]} = \frac{\alpha_{em}}{24\pi} \frac{\left|m_{\ell_i}/v - \epsilon^\ell_{ii}\right|^2}{\left|m_{\ell_j}/v - \epsilon^\ell_{jj}\right|^2} \frac{\left(\left|\epsilon^\ell_{if}\right|^2 + 4\left|\epsilon^\ell_{fi}\right|^2\right)}{\left(\left|\epsilon^\ell_{if}\right|^2 + \left|\epsilon^\ell_{fi}\right|^2\right)}$$

- for very large m_H, the expression reduces to (when $\varepsilon^l_{jj}/\varepsilon^l_{ii} = m_{lj}/m_{li}$)

$$\frac{\mathcal{B}\left[\ell_i \to \ell_f \gamma\right]}{\mathcal{B}\left[\ell_i^- \to \ell_f^- \ell_j^+ \ell_j^-\right]} = \frac{\alpha_{em}}{24\pi} \frac{m^2_{\ell_i}}{m^2_{\ell_j}} \quad \text{for} \quad \epsilon^\ell_{if} \neq 0$$

$$\frac{\mathcal{B}\left[\ell_i \to \ell_f \gamma\right]}{\mathcal{B}\left[\ell_i^- \to \ell_f^- \ell_j^+ \ell_j^-\right]} = \frac{\alpha_{em}}{6\pi} \frac{m^2_{\ell_i}}{m^2_{\ell_j}} \quad \text{for} \quad \epsilon^\ell_{fi} \neq 0$$

- for light m_H values, the expression gets modified as (for the 2->1 case):



Summary of the constraints

Table-I

Observable	Results
Neutral meson decays to muons	
$B_s \to \mu^+\mu^-$	$\left\|\epsilon^d_{32}\right\| \lesssim 3.0\times10^{-5}$, $\left\|\epsilon^d_{23}\right\| \lesssim 1.9\times10^{-5}$, $\left\|\epsilon^\ell_{22}\right\| \lesssim 2.0\times10^{-3}$
$B_d \to \mu^+\mu^-$	$\left\|\epsilon^d_{31}\right\| \lesssim 1.1\times10^{-5}$, $\left\|\epsilon^d_{13}\right\| \lesssim 9.4\times10^{-6}$
$K_L \to \mu^+\mu^-$	$\left\|\epsilon^d_{21}\right\| \lesssim 1.6\times10^{-6}$, $\left\|\epsilon^d_{12}\right\| \lesssim 1.6\times10^{-6}$
$\bar{D}^0 \to \mu^+\mu^-$	$\|\epsilon^u_{21}\| \lesssim 3.0\times10^{-2}$, $\|\epsilon^u_{12}\| \lesssim 3.0\times10^{-2}$
$\Delta F = 2$ processes	
$B_s - \overline{B}_s$ mixing	$\left\|\epsilon^d_{23}\epsilon^{d\star}_{32}\right\| \lesssim 9.2\times10^{-10}$, $\|\epsilon^u_{23}\| \lesssim 0.18$, $\|\epsilon^u_{32}\| \lesssim 1.7$, $\|\epsilon^u_{33}\| \lesssim 0.7$
$B_d - \overline{B}_d$ mixing	$\left\|\epsilon^d_{13}\epsilon^{d\star}_{31}\right\| \lesssim 3.9\times10^{-11}$, $\|\epsilon^u_{23}\| \lesssim 0.2$, $\|\epsilon^u_{13}\| \lesssim 0.04$, $\|\epsilon^u_{31}\| \lesssim 1.9$
$K - \overline{K}$ mixing	$\left\|\epsilon^d_{12}\epsilon^{d\star}_{21}\right\| \lesssim 1.0\times10^{-12}$, $\|\epsilon^u_{22}\| \lesssim 0.25$, $\|\epsilon^u_{23}\| \lesssim 0.14$
$D - \overline{D}$ mixing	$\|\epsilon^u_{12}\epsilon^{u\star}_{21}\| \lesssim 2.0\times10^{-8}$, $\|\epsilon^u_{32}\epsilon^{u\star}_{31}\| \lesssim 0.02$
Radiative B decays	
$b \to s\gamma$	$\|\epsilon^u_{23}\| \lesssim 0.024$, $\|\epsilon^u_{33}\| \lesssim 0.55$
$b \to d\gamma$	$\|\epsilon^u_{13}\| \lesssim 7.0\times10^{-3}$
Radiative lepton decays	
$\mu \to e\gamma$	$\left\|\epsilon^\ell_{12}\right\| \lesssim 1.7\times10^{-4}$, $\left\|\epsilon^\ell_{21}\right\| \lesssim 2.2\times10^{-4}$, $55 \lesssim \frac{\mathcal{B}[\mu\to e\gamma]}{\mathcal{B}[\mu^-\to e^-e^+e^-]} \lesssim 86$
$\tau \to e\gamma$	$0.19 \lesssim \frac{\mathcal{B}[\tau\to e\gamma]}{\mathcal{B}[\tau^-\to e^-\mu^+\mu^-]} \lesssim 0.35$
$\tau \to \mu\gamma$	$0.19 \lesssim \frac{\mathcal{B}[\tau\to \mu\gamma]}{\mathcal{B}[\tau^-\to \mu^-\mu^+\mu^-]} \lesssim 0.35$
Neural current lepton decays	
$\mu^- \to e^-e^+e^-$	$\left\|\epsilon^\ell_{12,21}\right\| \lesssim 2.3\times10^{-3}$
$\tau^- \to e^-\mu^+\mu^-$	$\left\|\epsilon^\ell_{13,31}\right\| \lesssim 4.2\times10^{-3}$
$\tau^- \to \mu^-\mu^+\mu^-$	$\left\|\epsilon^\ell_{23,32}\right\| \lesssim 3.7\times10^{-3}$

Table-II

Observable	Results
Charged current processes	
$B \to \tau\nu$	$2.7 \times 10^{-3} \leq \lvert\epsilon^{u}_{31}\rvert \leq 2.0 \times 10^{-2}$, $\lvert\epsilon^{\ell}_{i3}\rvert \leq 6.0 \times 10^{-2}$
$B \to D\tau\nu$ & $B \to D^{\star}\tau\nu$	$0.43 \leq \lvert\epsilon^{u}_{32}\rvert \leq 0.74$
$D_s \to \tau\nu$ & $D_{(s)} \to \mu\nu$	$\lvert\mathrm{Re}\,[\epsilon^{u}_{22}]\rvert \leq 0.2$
$D \to \tau\nu$	–
$K \to \mu(e)\nu/\pi \to \mu(e)\nu$	$\lvert\mathrm{Re}\,[\epsilon^{d}_{22}]\rvert \leq 1.0 \times 10^{-3}$
$K(\pi) \to e\nu/K(\pi) \to \mu\nu$	$\lvert\mathrm{Re}\,[\epsilon^{\ell}_{i1}]\rvert \leq 2.0 \times 10^{-6}$, $\lvert\mathrm{Re}\,[\epsilon^{\ell}_{i2}]\rvert \leq 5.0 \times 10^{-4}$
$\tau \to K(\pi)\nu/K(\pi) \to \mu\nu$	$-4.0 \times 10^{-2} \leq \mathrm{Re}\,[\epsilon^{\ell}_{i3}] \leq 2.0 \times 10^{-2}$
$\tau \to K\nu/\tau \to \pi\nu$	$\lvert\epsilon^{\ell}_{i3}\rvert \leq 0.14$
EDMs and anomalous magnetic moments	
d_e	$\lvert\mathrm{Im}\,[\epsilon^{\ell}_{12}\epsilon^{\ell}_{21}]\rvert \leq 2.5 \times 10^{-8}$, $\lvert\mathrm{Im}\,[\epsilon^{\ell}_{13}\epsilon^{\ell}_{31}]\rvert \leq 2.5 \times 10^{-9}$
d_μ	–
d_τ	–
d_n	$\lvert\mathrm{Im}\,[\epsilon^{u}_{11}]\rvert \leq 2.2 \times 10^{-2}$, $\lvert\mathrm{Im}\,[\epsilon^{u}_{22}]\rvert \leq 1.1 \times 10^{-1}$, $\mathrm{Arg}[\epsilon^{u}_{31}] = \mathrm{Arg}[V_{ub}] \pm \pi$
a_μ	Deviation from the SM cannot be explained
LVF B meson decays	
$B_s \to \tau\mu$	$\mathcal{B}\,[B_s \to \tau\mu] \leq 2.0 \times 10^{-7}$
$B_s \to \mu e$	$\mathcal{B}\,[B_s \to \mu e] \leq 9.2 \times 10^{-10}$
$B_s \to \tau e$	$\mathcal{B}\,[B_s \to \tau e] \leq 2.8 \times 10^{-7}$
$B_d \to \tau\mu$	$\mathcal{B}\,[B_d \to \tau\mu] \leq 2.1 \times 10^{-8}$
$B_d \to \mu e$	$\mathcal{B}\,[B_d \to \mu e] \leq 9.2 \times 10^{-11}$
$B_d \to \tau e$	$\mathcal{B}\,[B_d \to \tau e] \leq 2.8 \times 10^{-8}$

-Combining the constraints from Table-I and II we obtain

$$\left|\epsilon^u_{ij}\right| \leq \begin{pmatrix} 3.4\times10^{-4} & 3.0\times10^{-2} & 7.0\times10^{-3} \\ 3.0\times10^{-2} & \underline{1.4\times10^{-1}} & 2.4\times10^{-2} \\ 2.0\times10^{-2} & \underline{7.4\times10^{-1}} & \underline{5.5\times10^{-1}} \end{pmatrix}_{ij}$$

$$\left|\epsilon^d_{ij}\right| \leq \begin{pmatrix} 1.3\times10^{-4} & 1.6\times10^{-6} & 9.4\times10^{-6} \\ 1.6\times10^{-6} & 2.6\times10^{-4} & 2.0\times10^{-5} \\ 1.1\times10^{-5} & 3.0\times10^{-5} & 1.4\times10^{-2} \end{pmatrix}_{ij}$$

$$\left|\epsilon^\ell_{ij}\right| \leq \begin{pmatrix} 2.9\times10^{-6} & 1.7\times10^{-4} & 4.2\times10^{-3} \\ 2.2\times10^{-4} & 6.1\times10^{-4} & 3.7\times10^{-3} \\ 4.2\times10^{-3} & 3.7\times10^{-3} & 1.0\times10^{-2} \end{pmatrix}_{ij}$$

-for the benchmark point of $\tan\beta=50$ and $m_H=500$ GeV.

3. Conclusions

- Type-II 2HDM is not capable of explaining the 2012 exp. data on the tauonic B decays.

- In the general 2HDM (of type III) it is possible to explain B->(D$^{(*)}$)τν simultaneously without fine-tuning.

- In the 2HDM-III all the epsilon parameters except $\varepsilon^u_{22,32,33}$ are found to be small.

- 2HDM-III provides stringent upper limits for LFV neutral B-meson decays.

- Interesting correlations exist in 2HDM-III among the LFV radiative lepton decays and the 3-body LFV lepton decays.

- Searches for A°,H°->tc(u) at the LHC can test the model.


THANK
YOU
FOR
LISTENING !!!

Back-up slides

Higgs Potential in 2HDMs

Explicit form (MSSM like):

$$
\begin{aligned}
V &= m_{H_d}^2\left[(v_d+\rho_d+i\eta_d)(v_d+\rho_d-i\eta_d)+H_d^+H_d^-\right] \\
&+ m_{H_u}^2\left[(v_u+\rho_u+i\eta_u)(v_u+\rho_u-i\eta_u)+H_u^+H_u^-\right] \\
&+ \frac{\lambda_1}{2}\left[\left((v_d+\rho_d-i\eta_d)H_u^+ +(v_u+\rho_u+i\eta_u)H_d^+\right)\left((v_d+\rho_d+i\eta_d)H_u^- +(v_u+\rho_u-i\eta_u)H_d^-\right)\right] \\
&+ \frac{\lambda_2}{8}\left[H_u^+H_u^- - H_d^+H_d^- +(v_u+\rho_u+i\eta_u)(v_u+\rho_u-i\eta_u)-(v_d+\rho_d+i\eta_d)(v_d+\rho_d-i\eta_d)\right]^2 \\
&+ b\left[H_u^+H_d^- + H_u^-H_d^+ -(v_u+\rho_u+i\eta_u)(v_d+\rho_d+i\eta_d)-(v_u+\rho_u-i\eta_u)(v_d+\rho_d-i\eta_d)\right] .
\end{aligned}
$$

Couplings defining the Higgs-fermion interactions (type-III):

$$\Gamma^{LR\,H_k^0}_{u_f u_i} = x_u^k\left(\frac{m_{u_i}}{v_u}\delta_{fi}-\epsilon^u_{fi}\cot\beta\right)+x_d^{k\star}\epsilon^u_{fi}\,,$$

$$\Gamma^{LR\,H_k^0}_{d_f d_i} = x_d^k\left(\frac{m_{d_i}}{v_d}\delta_{fi}-\epsilon^d_{fi}\tan\beta\right)+x_u^{k\star}\epsilon^d_{fi}\,,$$

$$\Gamma^{LR\,H^\pm}_{u_f d_i} = \sum_{j=1}^{3}\sin\beta\,V_{fj}\left(\frac{m_{d_i}}{v_d}\delta_{ji}-\epsilon^d_{ji}\tan\beta\right)\,,$$

$$\Gamma^{LR\,H^\pm}_{d_f u_i} = \sum_{j=1}^{3}\cos\beta\,V^\star_{jf}\left(\frac{m_{u_i}}{v_u}\delta_{ji}-\epsilon^u_{ji}\tan\beta\right)\,.$$

$$\Gamma^{LR\,H_k^0}_{\ell_f \ell_i} = x_d^k\left(\frac{m_{\ell_i}}{v_d}\delta_{fi}-\epsilon^\ell_{fi}\tan\beta\right)+x_u^{k\star}\epsilon^\ell_{fi}\,,$$

$$\Gamma^{LR\,H^\pm}_{\nu_f \ell_i} = \sum_{j=1}^{3}\sin\beta\,V^{\mathrm{PMNS}}_{fj}\left(\frac{m_{\ell_i}}{v_d}\delta_{ji}-\epsilon^\ell_{ji}\tan\beta\right)$$

$$x_u^k = \left(-\frac{1}{\sqrt{2}}\sin\alpha,\,-\frac{1}{\sqrt{2}}\cos\alpha,\,\frac{i}{\sqrt{2}}\cos\beta\right)\,,$$

$$x_d^k = \left(-\frac{1}{\sqrt{2}}\cos\alpha,\,\frac{1}{\sqrt{2}}\sin\alpha,\,\frac{i}{\sqrt{2}}\sin\beta\right)\,.$$

The covariant derivative is defined to be

$$D_\mu = \left(\partial_\mu+\frac{ig}{2}\begin{pmatrix} W^3_\mu & \sqrt{2}W^-_\mu \\ \sqrt{2}W^+_\mu & -W^3_\mu\end{pmatrix}+\frac{ig'}{2}B_\mu\right)$$

Higgs mass terms in 2HDMs

$$\mathcal{L}^{\rm Higgs}_{\rm mass} = \mathcal{L}^{\rm H_u^\pm, H_d^\pm}_{\rm mass} + \mathcal{L}^{\rho_u,\rho_d}_{\rm mass} + \mathcal{L}^{\eta_u,\eta_d}_{\rm mass} \,,$$

$$\begin{aligned}
\mathcal{L}^{\rm H_u^\pm, H_d^\pm}_{\rm mass} &= -\left(b + \frac{\lambda_1 v^2}{4}\sin(2\beta)\right)(H_u^-, H_d^-)\begin{pmatrix}\cot\beta & 1\\ 1 & \tan\beta\end{pmatrix}\begin{pmatrix}H_u^+\\ H_d^+\end{pmatrix}\,,\\
\mathcal{L}^{\rho_u,\rho_d}_{\rm mass} &= -(\rho_u\,,\rho_d)\underbrace{\begin{pmatrix} b\cot\beta + \frac{\lambda_2 v^2}{2}\sin^2\beta & -b - \frac{\lambda_2 v^2}{4}\sin(2\beta)\\ -b - \frac{\lambda_2 v^2}{4}\sin(2\beta) & b\tan\beta + \frac{\lambda_2 v^2}{2}\cos^2\beta\end{pmatrix}}_{\mathcal{M}^{\rho_u,\rho_d}}\begin{pmatrix}\rho_u\\ \rho_d\end{pmatrix}\,,\\
\mathcal{L}^{\eta_u,\eta_d}_{\rm mass} &= -(\eta_u\,,\eta_d)\begin{pmatrix} b\cot\beta & b\\ b & b\tan\beta\end{pmatrix}\begin{pmatrix}\eta_u\\ \eta_d\end{pmatrix}\,.
\end{aligned}$$

Diagonalization via orthogonal matrices →field trans. of the form:

$$\begin{aligned}
\begin{pmatrix}H_u^1\\ H_d^{2\star}\end{pmatrix} &= \begin{pmatrix}H_u^+\\ H_d^+\end{pmatrix} = \begin{pmatrix}\cos\beta & -\sin\beta\\ \sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}H^+\\ G^+\end{pmatrix}\\
\begin{pmatrix}\rho_u\\ \rho_d\end{pmatrix} &= \frac{1}{\sqrt{2}}\begin{pmatrix}\cos\alpha & \sin\alpha\\ -\sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}h^0\\ H^0\end{pmatrix}\,,\\
\begin{pmatrix}\eta_u\\ \eta_d\end{pmatrix} &= \frac{1}{\sqrt{2}}\begin{pmatrix}\cos\beta & -\sin\beta\\ \sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}A^0\\ G^0\end{pmatrix}\,.
\end{aligned}$$

→ The physical (h^0,H^0,A^0,$H^\pm$) and GB (G^0,$G^\pm$) mass eigenstates:

$$\begin{aligned}
H_u^0 &= \rho_u + i\eta_u = \frac{1}{\sqrt{2}}\left(H^0\sin\alpha + h^0\cos\alpha + iA^0\cos\beta - i\sin\beta G^0\right)\,,\\
H_d^0 &= \rho_d + i\eta_d = \frac{1}{\sqrt{2}}\left(H^0\cos\alpha - h^0\sin\alpha + iA^0\sin\beta + i\cos\beta G^0\right)\,,\\
H_u^1 &= H_u^+ = \cos\beta\, H^+ - \sin\beta G^+\,,\\
H_d^2 &= H_d^- = \sin\beta\, H^- + \cos\beta G^-\,,
\end{aligned}$$

Explicit expressions for tauonic B-decays

$$\mathcal{B}_{SM}\left[M \to \ell_j \nu\right] = \frac{m_M}{8\pi} G_F^2 m_{\ell_j}^2 \tau_M f_M^2 \left|V_{u_f d_i}\right|^2 \left(1 - \frac{m_{\ell_j}^2}{m_M^2}\right)^2 \left(1 + \delta_{EM}^{M\ell_j}\right)$$

$$\mathcal{B}_{NP} = \mathcal{B}_{SM} \left| 1 + \frac{m_M^2}{\left(m_{u_f} + m_{d_i}\right) m_{\ell_j}} \frac{C_R^{u_f d_i, \ell_j} - C_L^{u_f d_i, \ell_j}}{C_{SM}^{u_f d_i, \ell_j}} \right|^2$$

$$C_{SM}^{u_f d_i, \ell_j} = 4 G_F V_{u_f d_i} / \sqrt{2} .$$

$$\mathcal{R}(D) = \mathcal{R}_{SM}(D) \left(1 + 1.5 \Re \left[\frac{C_R^{cb,\tau} + C_L^{cb,\tau}}{C_{SM}^{cb,\tau}} \right] + 1.0 \left| \frac{C_R^{cb,\tau} + C_L^{cb,\tau}}{C_{SM}^{cb,\tau}} \right|^2 \right)$$

$$\mathcal{R}(D^*) = \mathcal{R}_{SM}(D^*) \left(1 + 0.12 \Re \left[\frac{C_R^{cb,\tau} - C_L^{cb,\tau}}{C_{SM}^{cb,\tau}} \right] + 0.05 \left| \frac{C_R^{cb,\tau} - C_L^{cb,\tau}}{C_{SM}^{cb,\tau}} \right|^2 \right)$$

$$C_R^{u_f d_i, \ell_j} = -\frac{\tan^2\beta}{m_{H^\pm}^2} \left(V_{fi} \frac{m_{d_i}}{v} - \sum_{j=1}^{3} V_{fj} \epsilon_{ji}^{d} \right) \left(\frac{m_{\ell_j}}{v} - \sum_{k=1}^{3} \epsilon_{kj}^{\ell\star} \right) ,$$

$$C_L^{u_f d_i, \ell_j} = \frac{\tan\beta}{m_{H^\pm}^2} \sum_{j=1}^{3} V_{ji} \epsilon_{jf}^{\star u} \left(\frac{m_{\ell_j}}{v} - \sum_{k=1}^{3} \epsilon_{kj}^{\ell\star} \right) .$$

t' Hooft's naturalness criterion

$$m^d_{ij} = v_d Y^{d\,\mathrm{ew}}_{ij} + v_u \epsilon^{d\,\mathrm{ew}}_{ij}\,, \qquad \left|v_{u(d)}\epsilon^{d(u)}_{ij}\right| \le \left|V^{\mathrm{CKM}}_{ij}\right| \times \max\left[m_{d_i(u_i)}, m_{d_j(u_j)}\right] \text{ for } i<j\,,$$

$$m^u_{ij} = v_u Y^{u\,\mathrm{ew}}_{ij} + v_d \epsilon^{u\,\mathrm{ew}}_{ij}\,, \qquad \left|v_{u(d)}\epsilon^{d(u)}_{ij}\right| \le \max\left[m_{d_i(u_i)}, m_{d_j(u_j)}\right] \text{ for } i\ge j\,,$$

$$m^\ell_{ij} = v_d Y^{\ell\,\mathrm{ew}}_{ij} + v_u \epsilon^{\ell\,\mathrm{ew}}_{ij}\,. \qquad \left|v_u\epsilon^{\ell}_{ij}\right| \le \max\left[m_{\ell_i}, m_{\ell_j}\right]\,.$$

for large tanβ limit and mq(500GeV)

$$\left|\epsilon^d_{ij}\right| \le \begin{pmatrix} 1.3\times10^{-4} & 5.8\times10^{-5} & 5.1\times10^{-5} \\ 2.6\times10^{-4} & 2.6\times10^{-4} & 5.9\times10^{-4} \\ 1.4\times10^{-2} & 1.4\times10^{-2} & 1.4\times10^{-2} \end{pmatrix}_{ij}\,,$$

$$\left|\epsilon^u_{ij}\right| \le (\tan\beta/50) \begin{pmatrix} 3.4\times10^{-4} & 3.2\times10^{-2} & 1.6\times10^{-1} \\ 1.4\times10^{-1} & 1.4\times10^{-1} & 1.9 \\ - & - & - \end{pmatrix}_{ij}$$

$$\left|\epsilon^\ell_{ij}\right| \le \begin{pmatrix} 2.9\times10^{-6} & 6.1\times10^{-4} & 1.0\times10^{-2} \\ 6.1\times10^{-4} & 6.1\times10^{-4} & 1.0\times10^{-2} \\ 1.0\times10^{-2} & 1.0\times10^{-2} & 1.0\times10^{-2} \end{pmatrix}_{ij}\,.$$

Wave func. rotations to arrive at phys. basis with diag. quark mass matrices

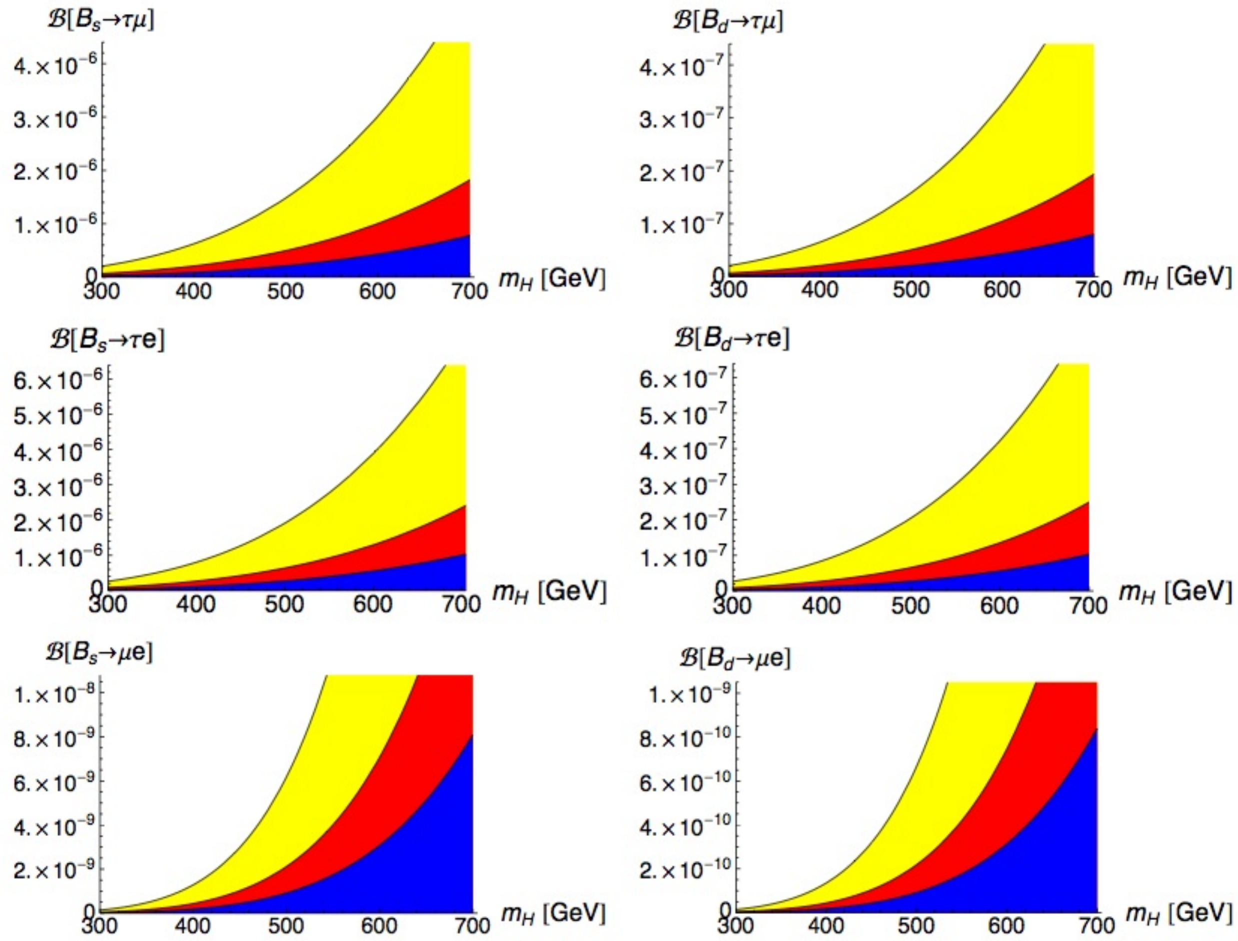
$$U^{q\,L*}_{jf}\, m^q_{jk}\, U^{q\,R}_{ki} = m_{q_i}\delta_{fi}$$

CKM matrix

$$V_{fi} = U^{u\,L*}_{jf}\, U^{d\,L}_{ji}$$

Upper limits in type-III 2HDM

tanβ=30 (yellow), tanβ=40 (red), tanβ=50 (blue)

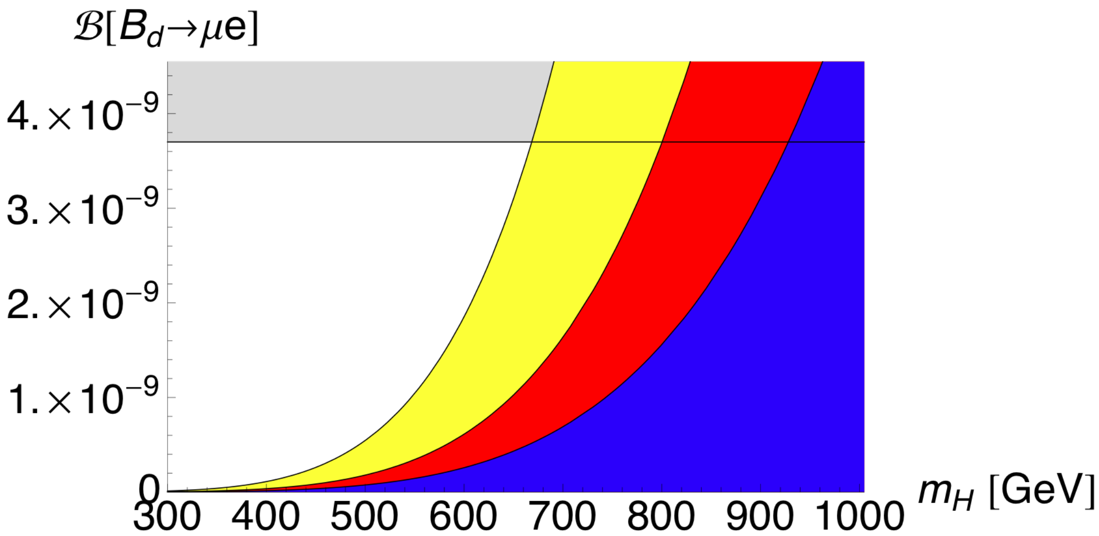


Updated values and plots

$Br[B_s \to \mu\mu] = 2.9^{+1.1}_{-1.0} \times 10^{-9}$ 95% CL, LHCb'July13
$Br[B_d \to \mu\mu] < 7.4 \times 10^{-10}$ 95% CL, LHCb'July13

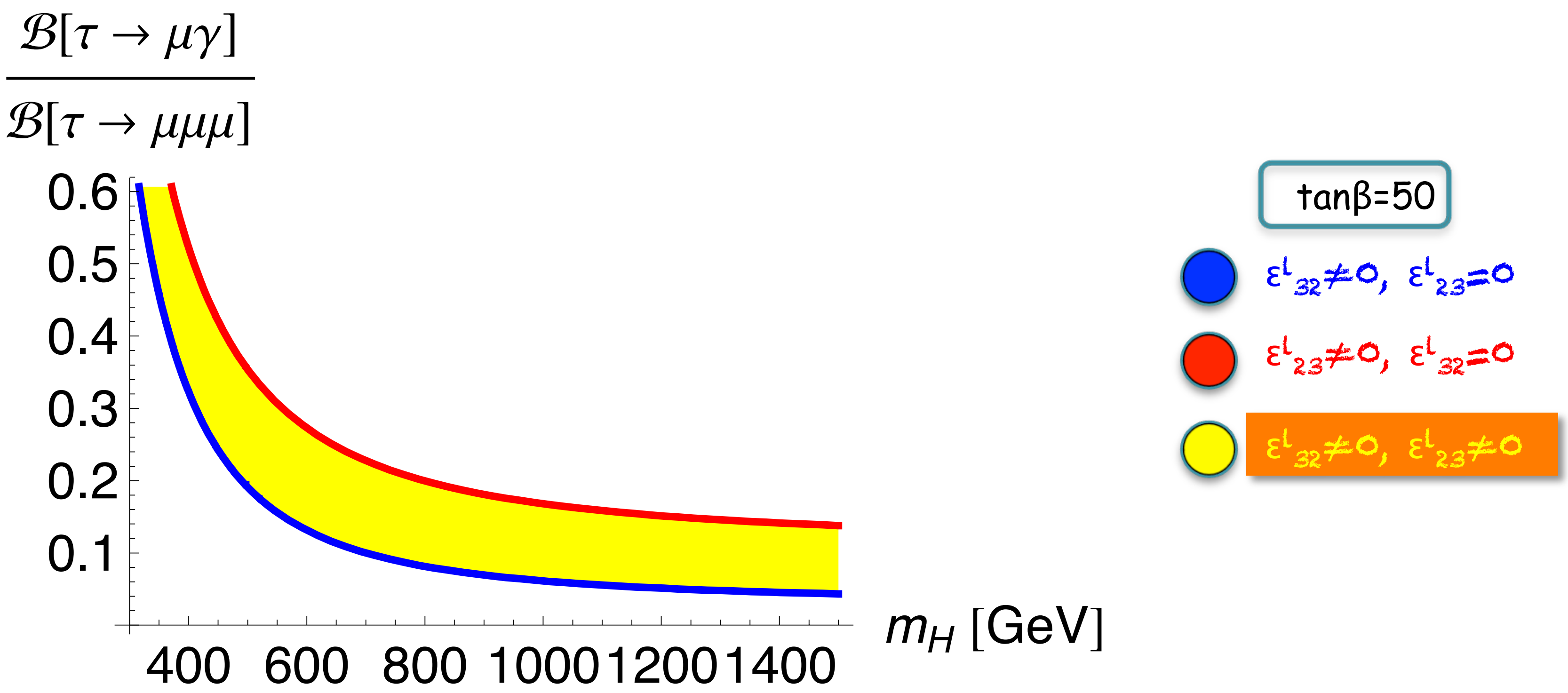
New!

$Br[B_s \to \mu e] < 1.4 \times 10^{-8}$ 95% CL, LHCb'July13
$Br[B_d \to \mu e] < 3.7 \times 10^{-9}$ 95% CL, LHCb'July13



The gray region is excluded by experiment.

Predicted ratio in 2HDM-III



- The behavior of 3->1 transitions is very similar to 3->2 transitions shown here.