Andreas Crivellin

Albert Einstein Center for Fundamental Physics
Institute for Theoretical Physics
University of Bern

Flavor-changing Higgs Effects in the MSSM and 2HDMs

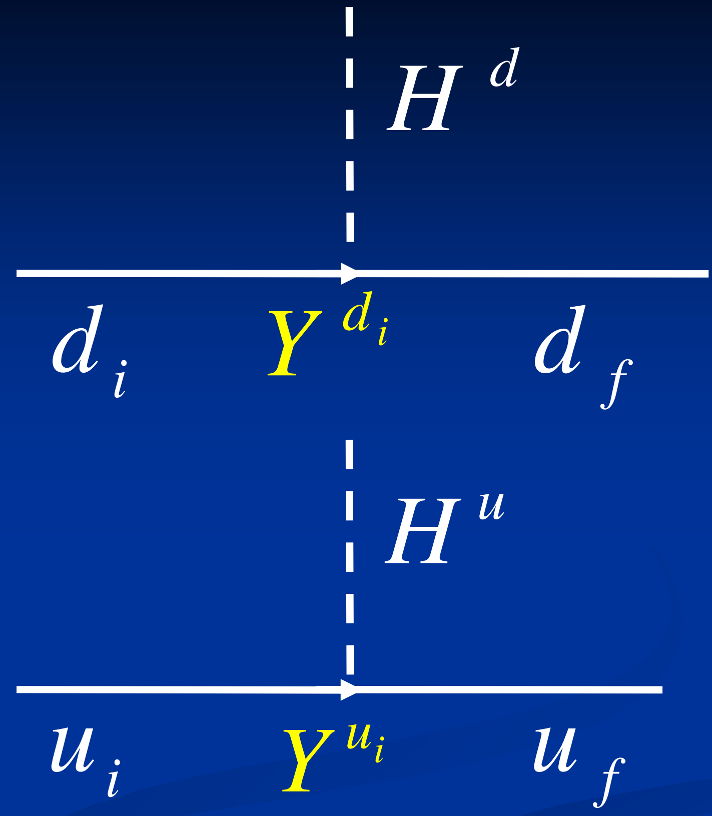
Outline:

- Introductions: Flavor violation in 2HDMs
- Matching on the MSSM on the 2HDM of type III
  - Resummation of chirally enhanced effects
  - 2-loop corrections to Higgs-quark-quark vertices
- Flavor-phenomenology of 2HDMs with generic flavour-structure
  - Constraints from FCNC processes
  - Tauonic B decays
  - Direct CP asymmetry in D->KK,ππ
  - LFV processes
- Conclusions

Introduction

Flavor-violation in 2HDMs

2HDM of type II
(MSSM at tree-level)



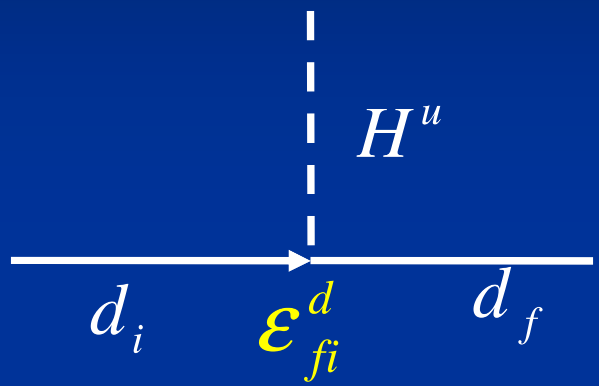
- One Higgs doublet couples only to down-quarks (and charged leptons), the other Higgs doublet couples only to up-quarks.
- 2 additional free parameters: $\tan(\beta)=v_u/v_d$ and the heavy Higgs mass $m_H \approx m_{A^0} \approx m_{H^\pm} \approx m_{H^0}$

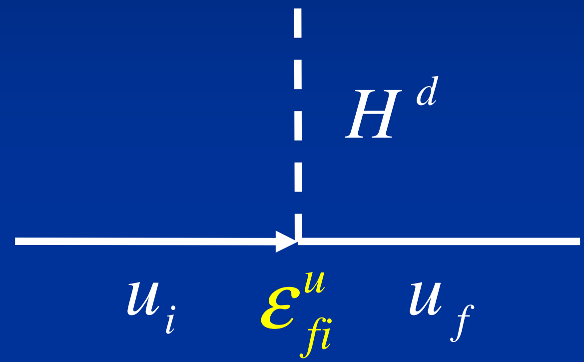
$$m_{q_i} = v_q Y^{q_i}$$

- All flavor-violations is due to the CKM matrix: neutral Higgs-quark couplings are flavor-conserving.

2HDM of type III

- Both Higgs doublets couple simultaneously to up and down quarks.





$$m^d_{ij} = v_d Y^d_{ij} + v_u \varepsilon^d_{ij} \qquad m^u_{ij} = v_u Y^u_{ij} + v_d \varepsilon^u_{ij}$$

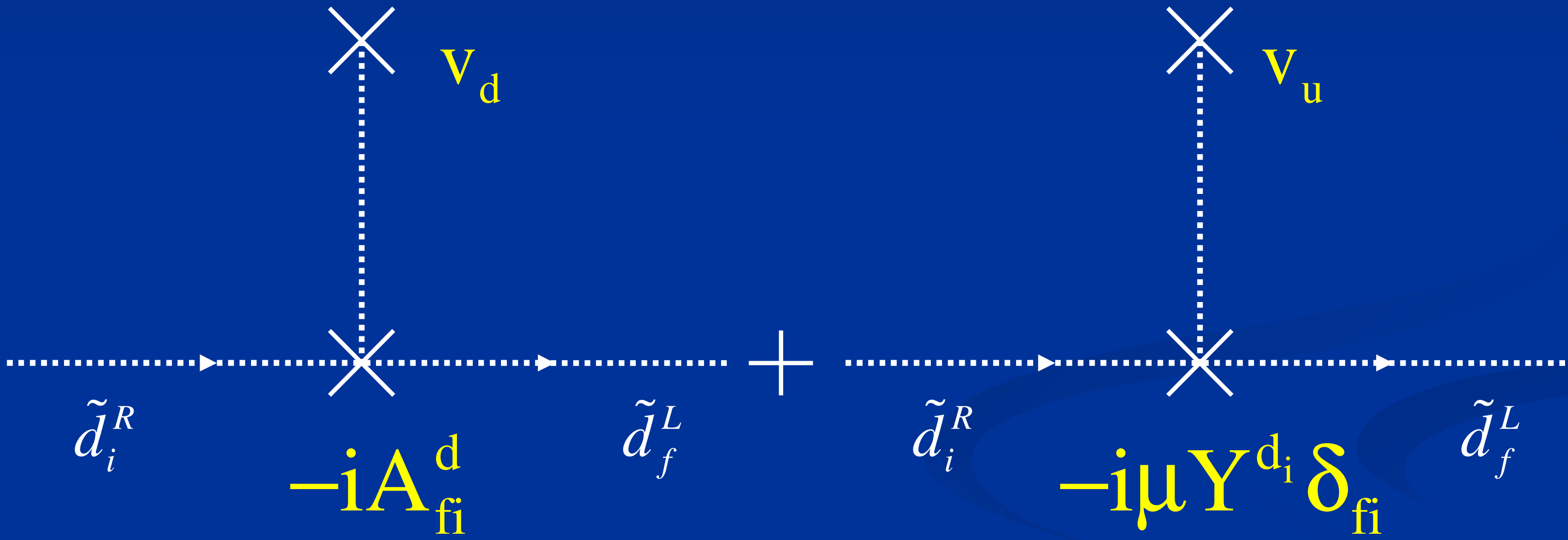
- The parameters $\varepsilon^{u,d}_{ij}$ describe flavor-changing neutral Higgs interactions

- In the MSSM, $\varepsilon^{u,d}_{ij}$ are induced via loops

Matching of the MSSM on the 2HDM

Squark-Higgs couplings

- The off-diagonal elements $\Delta_{ij}^{q\,LR}$ of the squark mass matrices originate from squark-Higgs couplings



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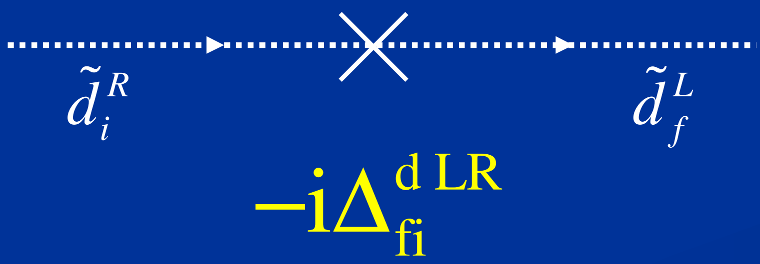


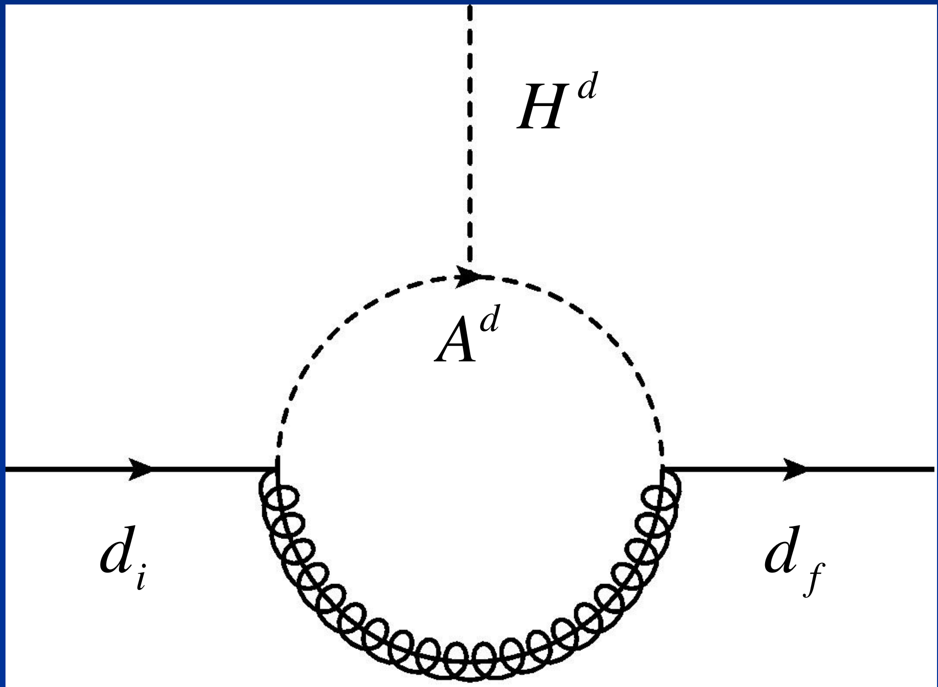
≙ Mass insertion approximation

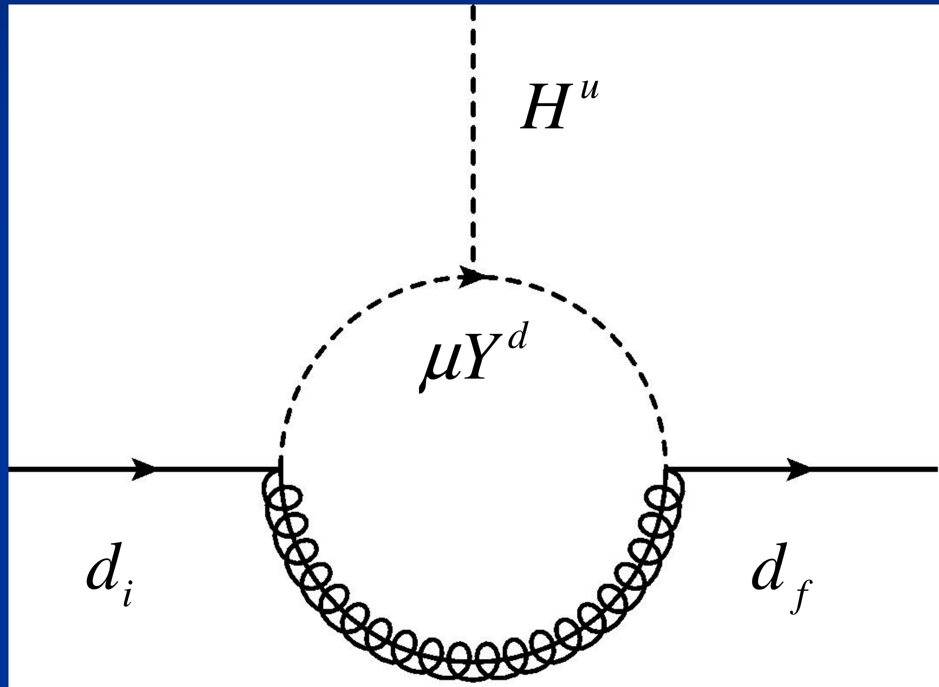
$$\delta_{fi}^{\tilde{q}\,LR} \equiv \frac{\Delta_{fi}^{\tilde{q}\,LR}}{\hat{m}_{\tilde{q}}^2}$$

$\hat{m}_{\tilde{q}}^2$ average squark mass

Loop corrections to Higgs quark couplings

- Before electroweak symmetry breaking

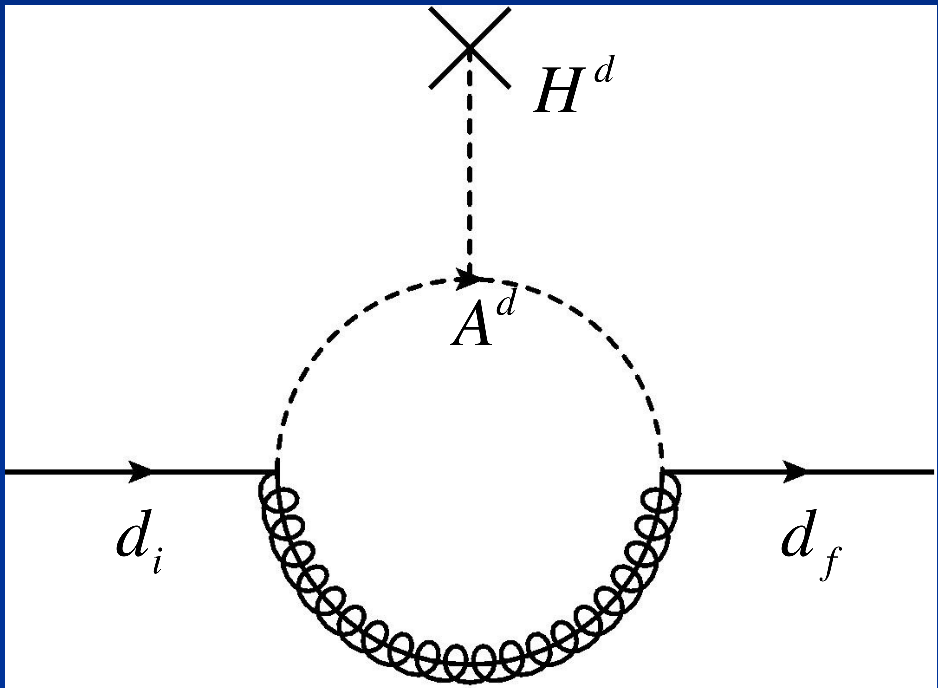


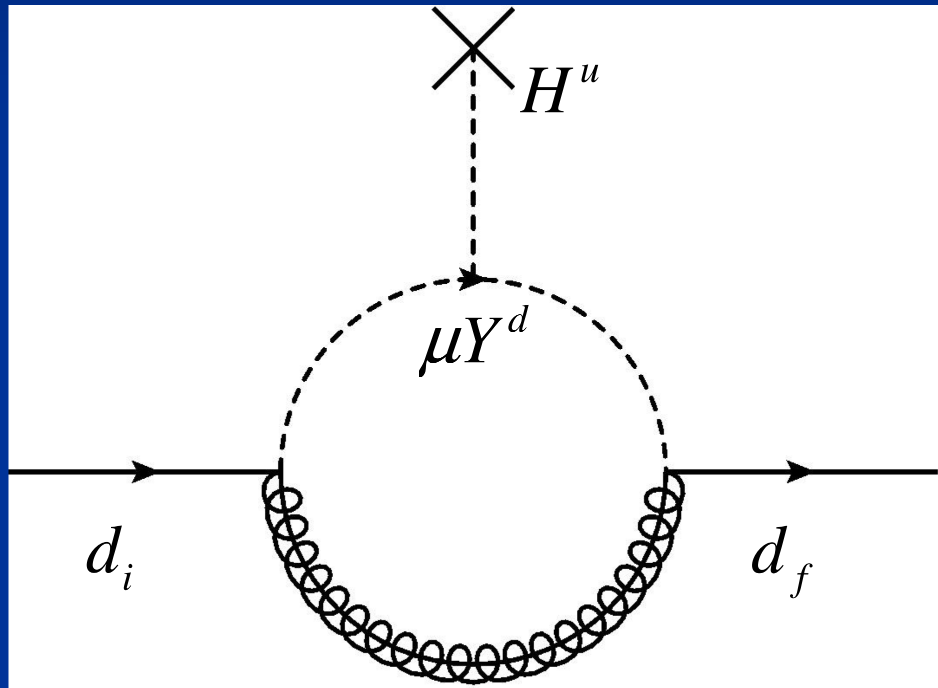


$\Gamma^{H^d}_{d_f d_i}$ $\Gamma^{H^u}_{d_f d_i}$

Loop corrections to Higgs quark couplings

- After electroweak symmetry breaking





$$\Sigma^{d\ LR}_{fi\ A} = v_d \Gamma^{H^d}_{d_f d_i}$$

$$\Sigma^{d\ LR}_{fi\ Y} = v_u \Gamma^{H^u}_{d_f d_i}$$

➡ One-to-one correspondence between Higgs-quark couplings and chirality changing self-energies. (In the decoupling limit)

Determination of the MSSM Yukawa coupling

- All corrections are finite and are non-decoupling

Matching condition:

$$
\begin{aligned}
m_{d_i} &= v_d Y^{d_i} + \Sigma_{ii}^{d\,LR} \\
&= v_d Y^{d_i} + \Sigma_{ii\,A}^{q\,LR} + v_d \tan(\beta) Y^{d_i} \varepsilon_{d_i}
\end{aligned}
$$

$$
\Rightarrow \quad Y^{d_i} = \frac{m_{d_i} - \Sigma_{ii\,A}^{q\,LR}}{v_d \left(1 + \tan(\beta)\,\varepsilon_i^d\right)}
$$

- tan(β) is automatically resummed to all orders

Carena et al, hep-ph/9912516

Complete resummation of all chirally enhanced corrections

A.C., L. Hofer and J. Rosiek, 1103.4272

Including:

- Most general MSSM flavor structure
- SQCD and electroweak contributions
- Threshold corrections to the CKM matrix
- Effective Higgs-quark-quark vertices
- Effective quark-squark-gaugino vertices

Using these vertices, all chirally enhanced corrections can be automatically included.

Implemented in SUSY_FLAVOR 2.0

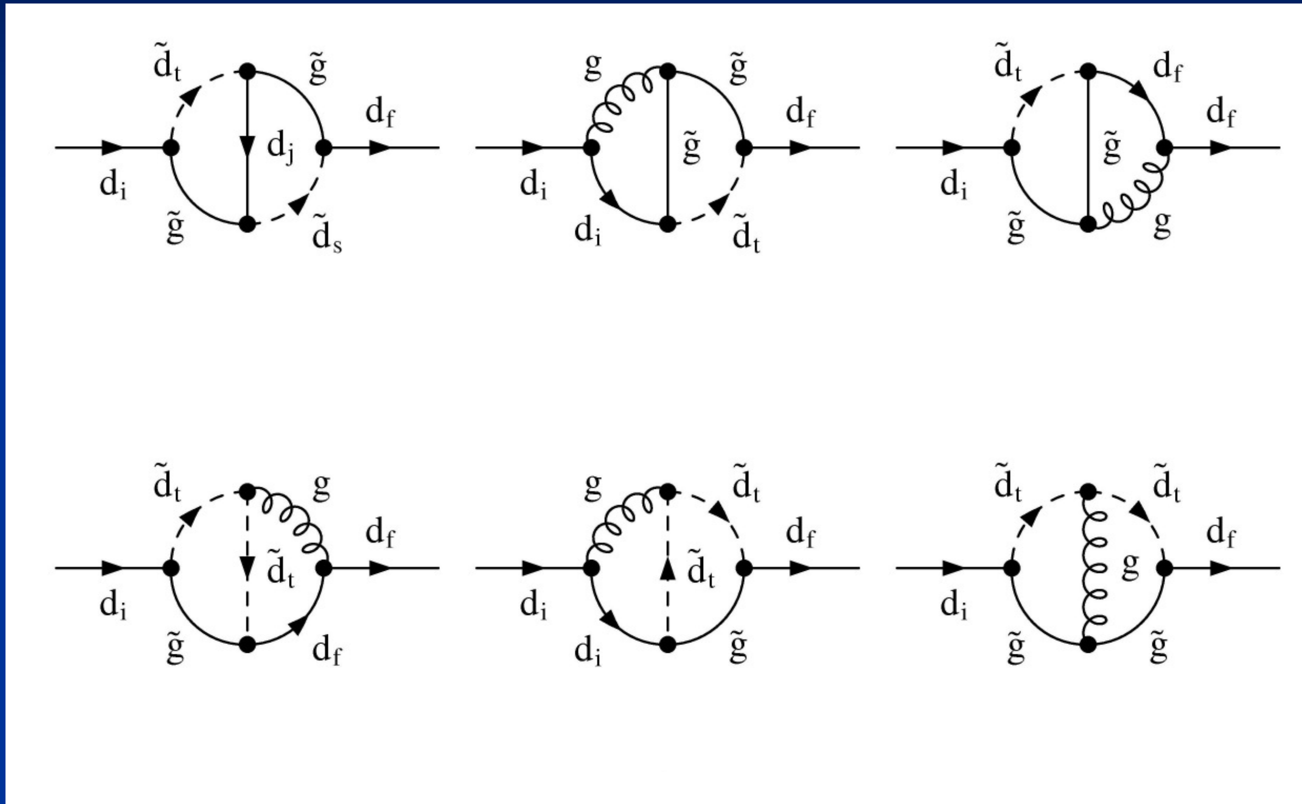
NLO calculation of the quark self-energies

NLO calculation is important for:

- Computation of effective Higgs-quark vertices.
- Determination of the Yukawa couplings of the MSSM superpotential (needed for the study of Yukawa unification in GUTs).
- NLO calculation of FCNC processes in the MSSM at large tan(β).

Reduction of the matching scale dependence

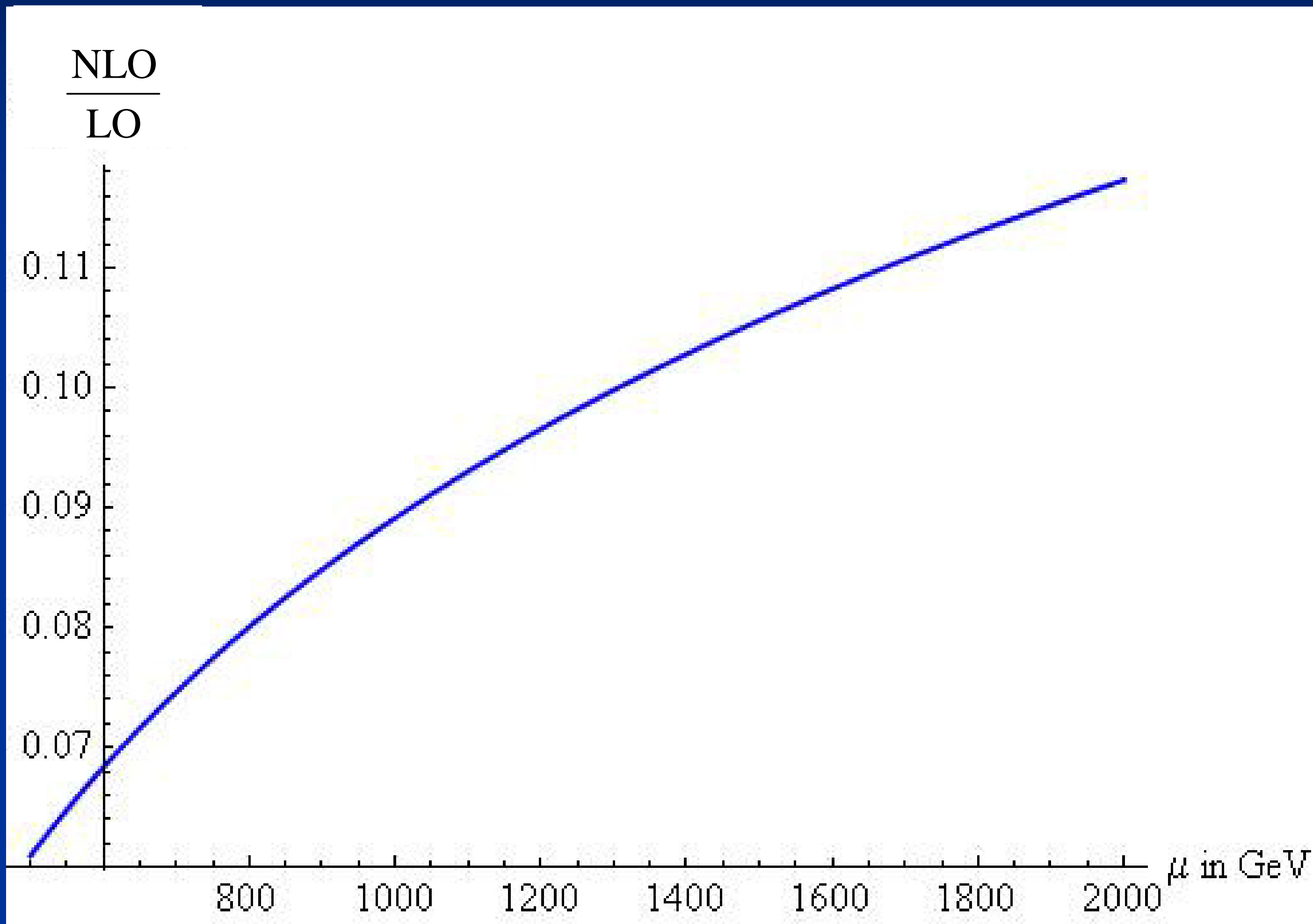
NLO calculation



Examples of 2-loop diagrams

- NLO calculation includes analytic results and tan(β) resummation in the generic MSSM. Δ_b at order α_s^2

NLO results

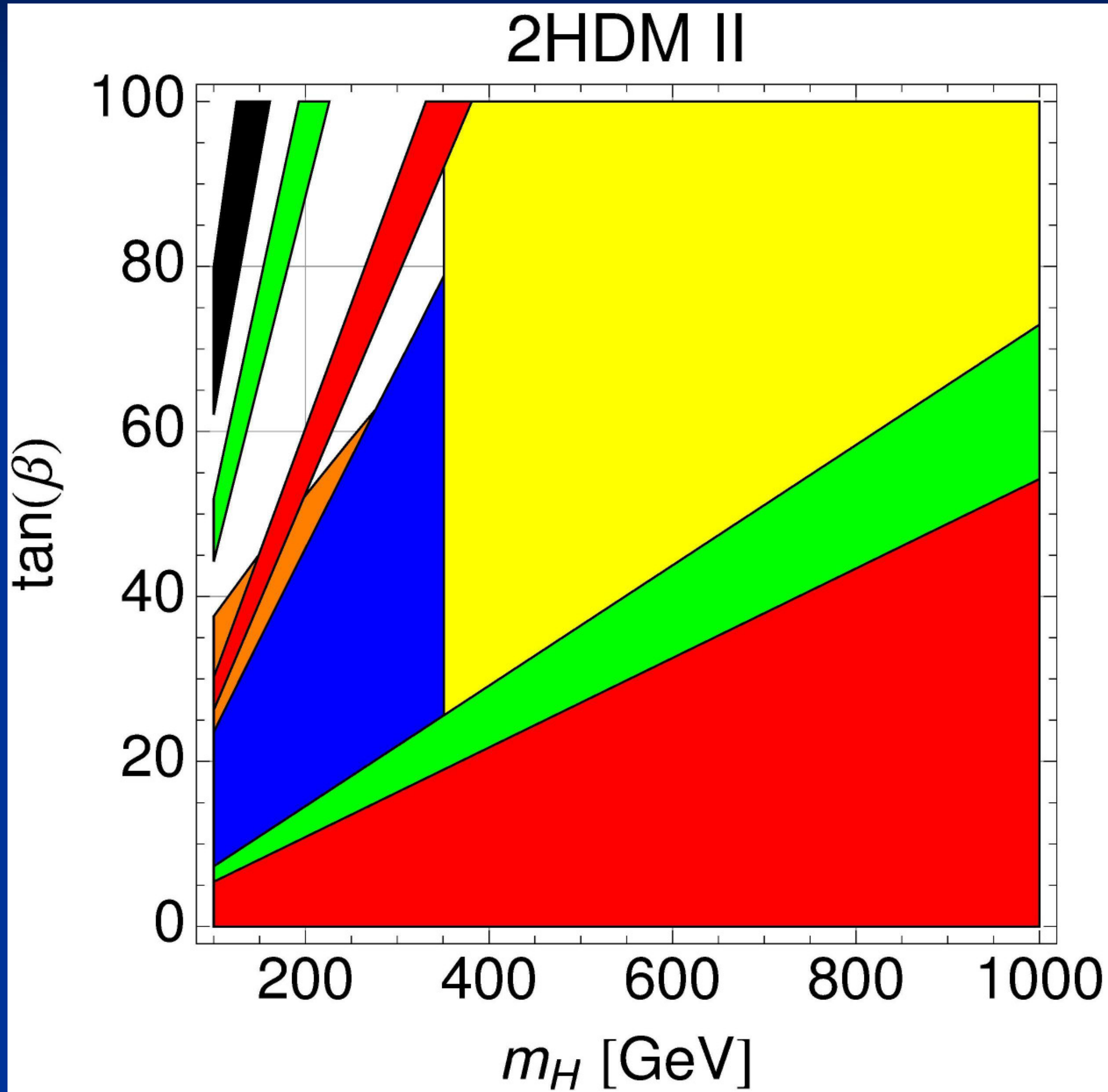


Relative importance of the 2-loop corrections approximately 9%

Flavor-phenomenology of two-Higgs-doublet models

Type-II 2HDM

- Allowed regions from:



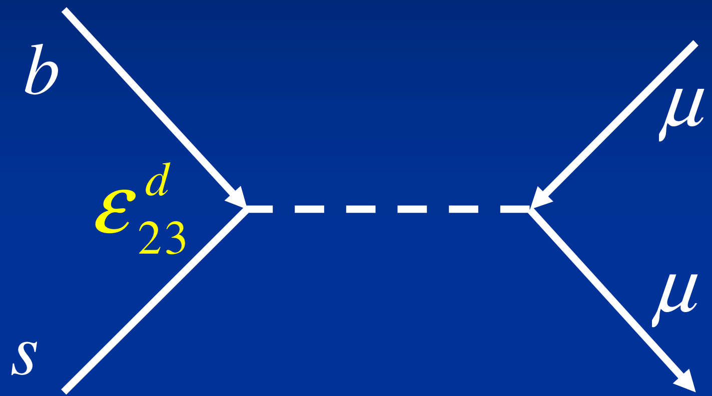
yellow	$b \to s\gamma$
red	$B \to \tau\nu$
blue	$K \to \mu\nu / \pi \to \mu\nu$
green	$B \to D\tau\nu$
orange	$B_s \to \mu^+\mu^-$
black	$B \to D^*\tau\nu$

➡ Tension from $B \to D^*\tau\nu$

Type-III: constraints from $M \to \mu^+\mu^-$

$\tan(\beta) = 50$

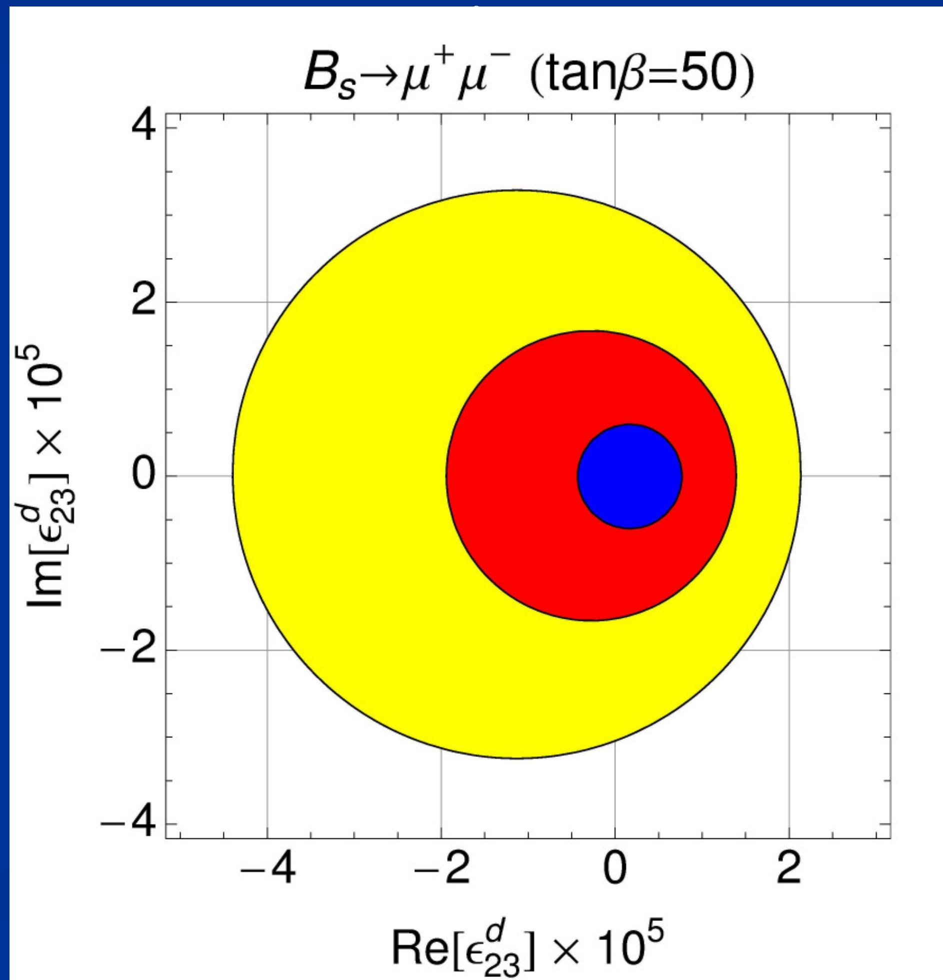
- $m_H = 700$ GeV
- $m_H = 500$ GeV
- $m_H = 300$ GeV



- $B \to \mu^+\mu^-$ constrains $\varepsilon^d_{13,31}$
- $B_s \to \mu^+\mu^-$ constrains $\varepsilon^d_{23,32}$
- $K_L \to \mu^+\mu^-$ constrains $\varepsilon^d_{12,21}$
- $D \to \mu^+\mu^-$ constrains $\varepsilon^u_{12,21}$

$\varepsilon^u_{32,23}$ and $\varepsilon^u_{13,31}$ unconstrained

➡ from tree-level FCNCs



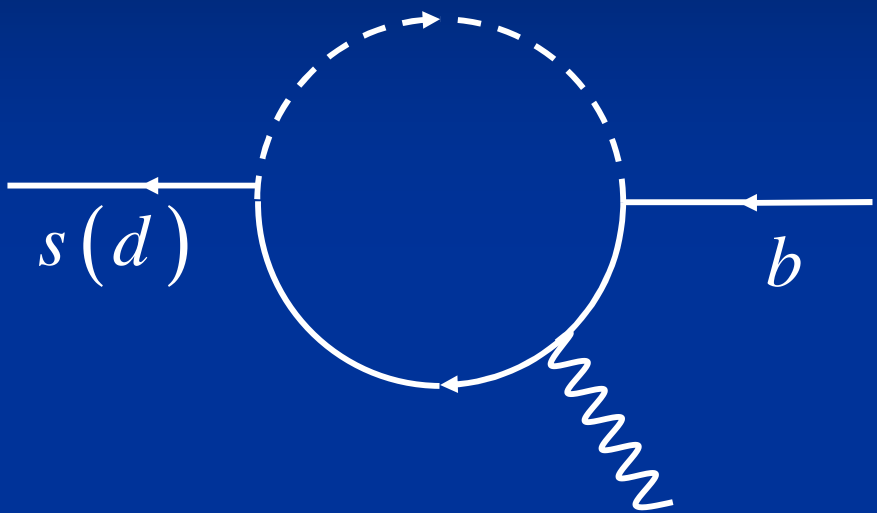
Type-III: Constraints from b→s(d) γ

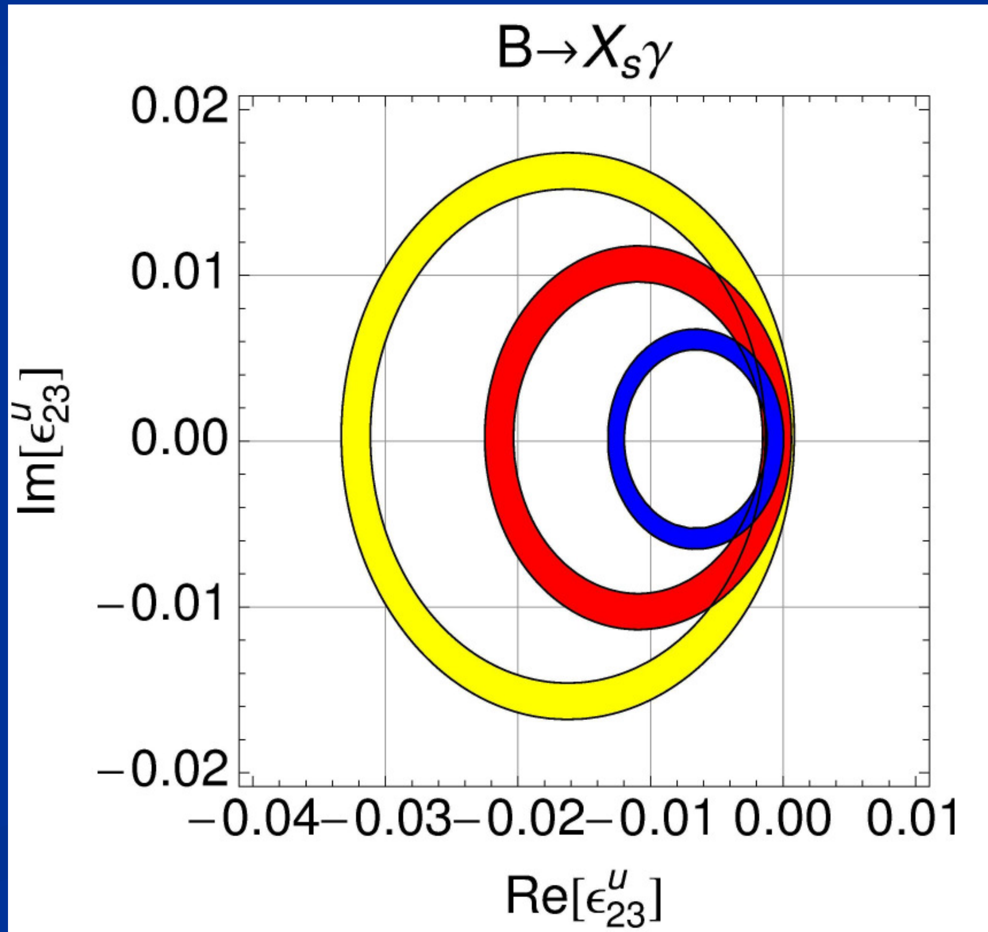
$\tan(\beta) = 50$

$m_H = 700$ GeV

$m_H = 500$ GeV

$m_H = 300$ GeV





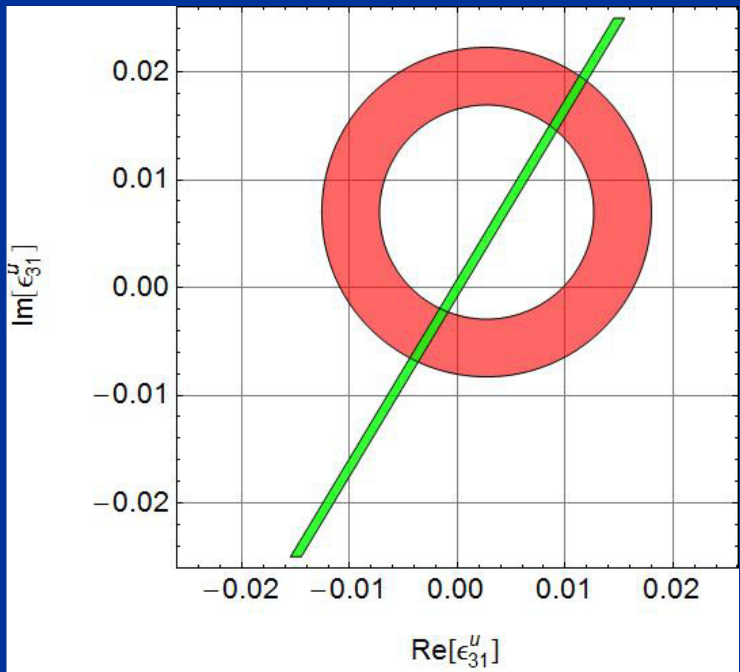
- b→sγ constrains ε^{u}_{23}
- b→dγ constrains ε^{u}_{13}
- $\varepsilon^{u}_{31,32}$ still unconstrained

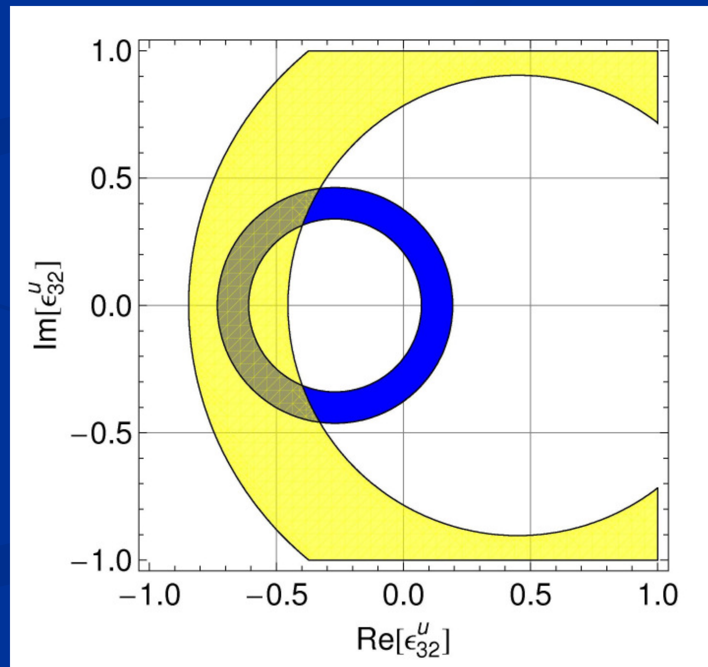
Tauonic B decays

- Constructive contribution to B→τν using ε_{31}^{u} is possible.
- B→D(*)τν and B→Dτν can be explained simultaneously using ε_{32}^{u}. ➡ Check model via $H^0, A^0 \to \overline{t}c$

Allowed regions from:

- (blue) $B \to D\tau\nu$
- (yellow) $B \to D^{*}\tau\nu$
- (red) $B \to \tau\nu$





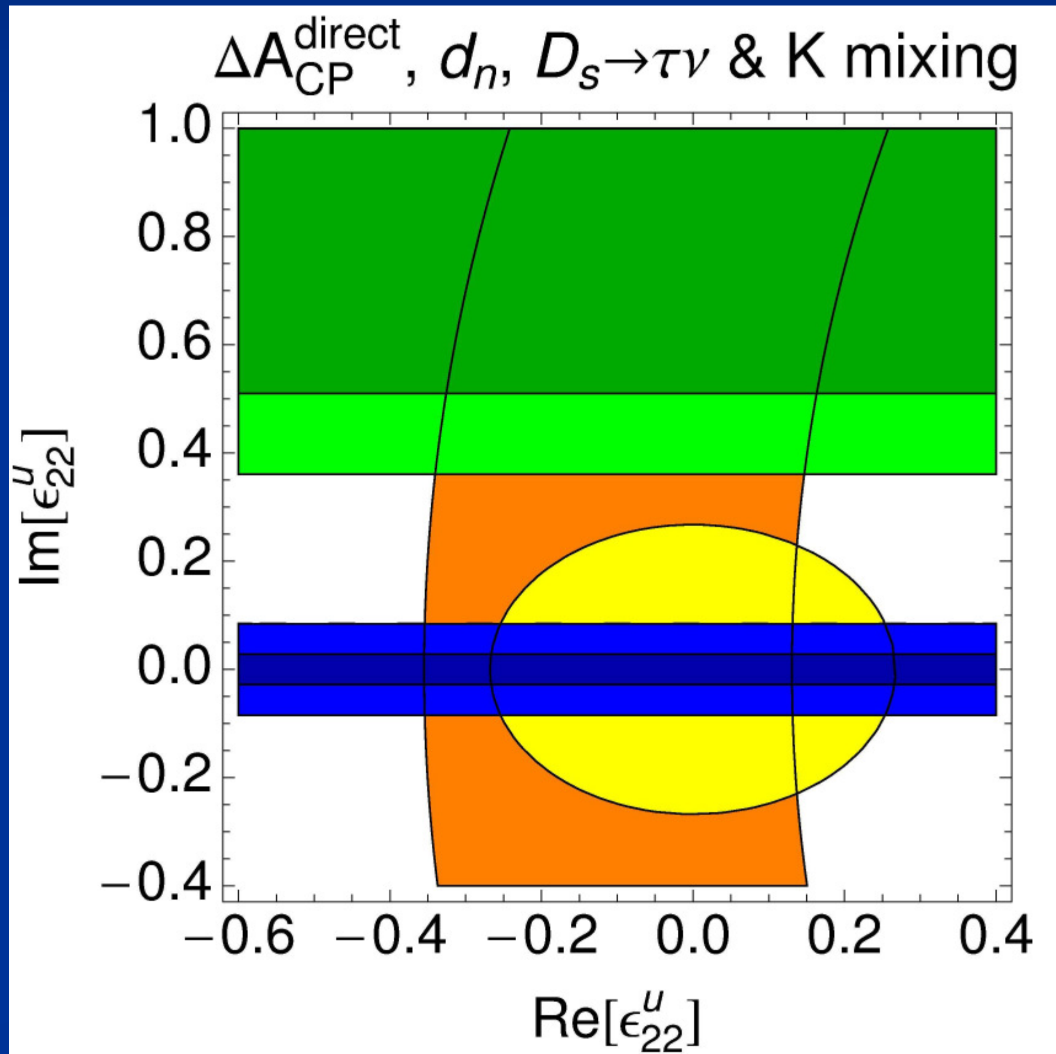
Direct CP asymmetry in

- Cannot be explained in the 2HDM III

Allowed regions from:

- $D \to KK, \pi\pi$
- Neutron EDM
- $K - \bar{K}$ mixing
- $D_{(s)} \to \mu\nu$

$\tan(\beta) = 50,\ m_H = 500\ \mathrm{GeV}$



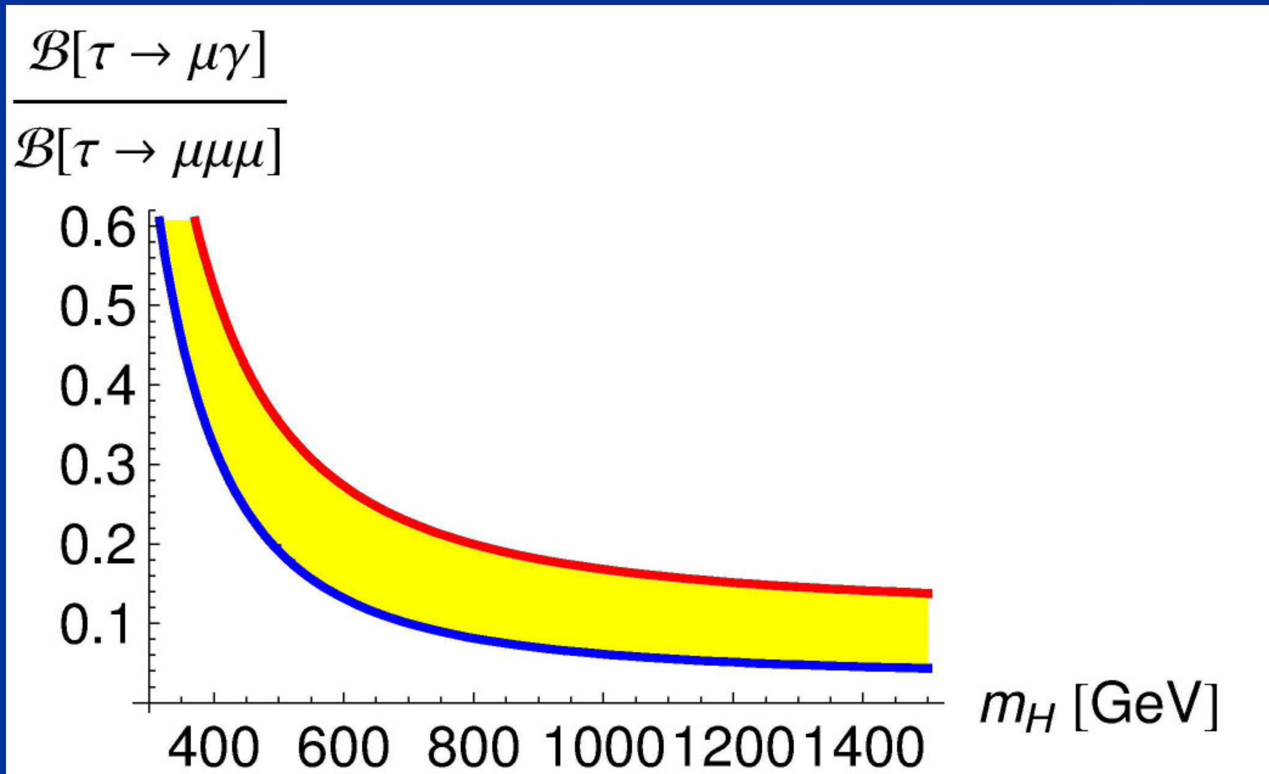
Lepton Flavor violation

- Correlations between $\tau \to \mu\mu\mu$ and $\tau \to \mu\gamma$

$\varepsilon^{\ell}_{23} \neq 0, \varepsilon^{\ell}_{32} \neq 0$

$\varepsilon^{\ell}_{32} = 0, \varepsilon^{\ell}_{23} \neq 0$

$\varepsilon^{\ell}_{32} \neq 0, \varepsilon^{\ell}_{23} = 0$



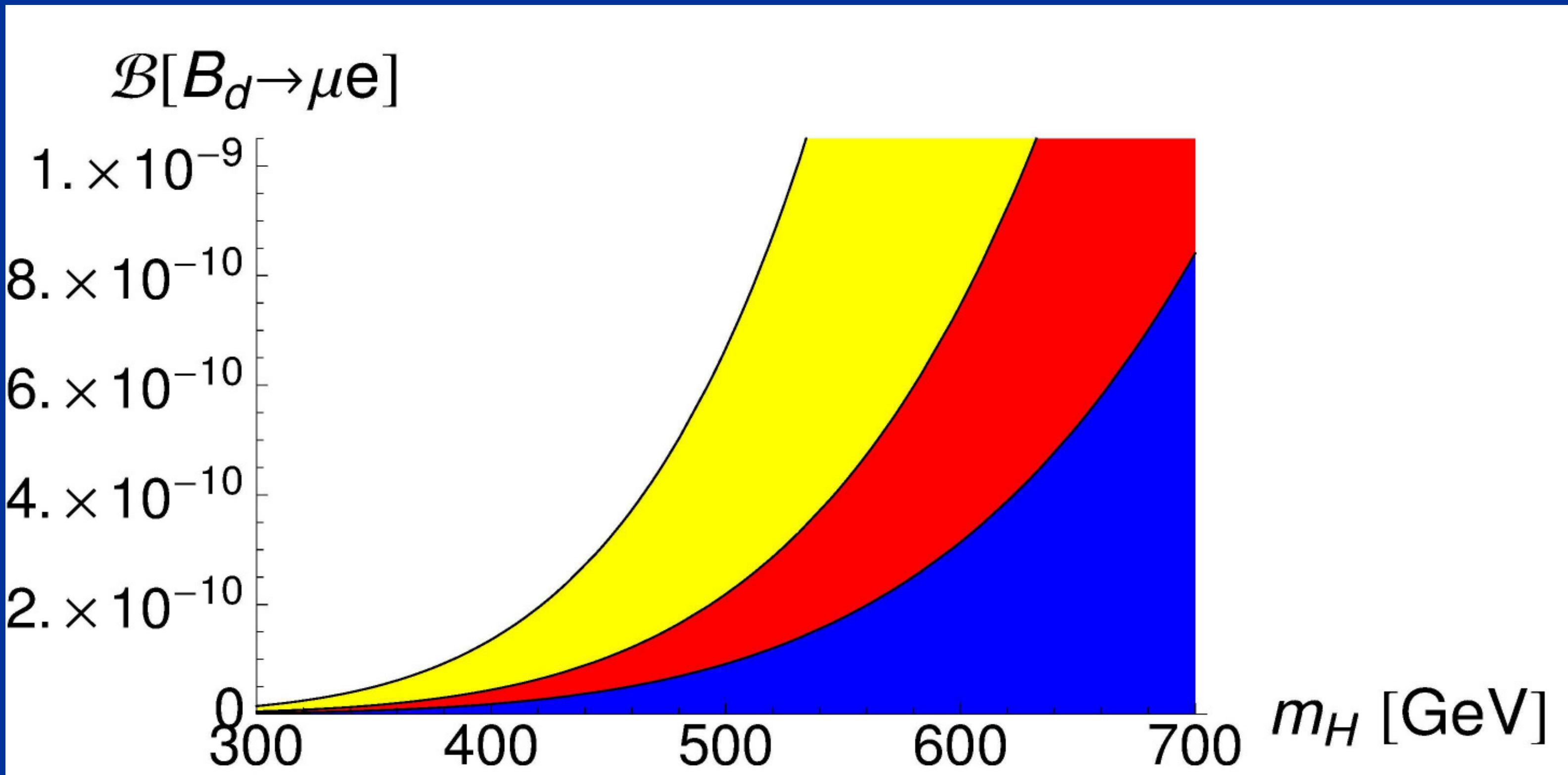
Upper limits on lepton flavour violating B decays

Excluded by experiment

$\tan(\beta) = 30$

$\tan(\beta) = 40$

$\tan(\beta) = 50$



Conclusions

- The decoupling limit of the MSSM is the 2HDM of type III
- Sizable non-holomorphic Higgs couplings are generated via loops, 2-loop calculation of Higgs-quark couplings significantly reduces the matching scale dependence.
- In the 2HDM III all off-diagonal elements ε_{ij}^{q} except $\varepsilon_{31,32}^{u}$ must be small.
- A 2HDM of type III with flavour violation in the up-sector can explain B→τν, B→Dτν and B→D*τν simultaneously.
- The direct CP asymmetry in D → KK,ππ cannot be explained
- Interesting correlations between among lepton flavor violating observables.

SUSY_FLAVOR 2.0

A.C., J. Rosiek et al, arXiv:1203.5023

Calculates a large set of flavour observables including the complete resummation of all chirally enhanced corrections and the effective Higgs vertices.

Observable	Most stringent constraints on	Experiment
$\Delta F = 0$		
$\frac{1}{2}(g-2)_e$	$\mathrm{Re}\left[\delta_{11}^{\ell\,\mathrm{LR,RL}}\right]$	$(1159652188.4 \pm 4.3) \times 10^{-12}$
$\frac{1}{2}(g-2)_\mu$	$\mathrm{Re}\left[\delta_{22}^{\ell\,\mathrm{LR,RL}}\right]$	$(11659208.7 \pm 8.7) \times 10^{-10}$
$\frac{1}{2}(g-2)_\tau$	$\mathrm{Re}\left[\delta_{33}^{\ell\,\mathrm{LR,RL}}\right]$	$< 1.1 \times 10^{-3}$
$\lvert d_e\rvert(\mathrm{ecm})$	$\mathrm{Im}\left[\delta_{11}^{\ell\,\mathrm{LR,RL}}\right]$	$< 1.6 \times 10^{-27}$
$\lvert d_\mu\rvert(\mathrm{ecm})$	$\mathrm{Im}\left[\delta_{22}^{\ell\,\mathrm{LR,RL}}\right]$	$< 2.8 \times 10^{-19}$
$\lvert d_\tau\rvert(\mathrm{ecm})$	$\mathrm{Im}\left[\delta_{33}^{\ell\,\mathrm{LR,RL}}\right]$	$< 1.1 \times 10^{-17}$
$\lvert d_n\rvert(\mathrm{ecm})$	$\mathrm{Im}\left[\delta_{11}^{\mathrm{d\,LR,RL}}\right]$, $\mathrm{Im}\left[\delta_{11}^{\mathrm{u\,LR,RL}}\right]$	$< 2.9 \times 10^{-26}$
$\Delta F = 1$		
$\mathrm{Br}(\mu \to e\gamma)$	$\delta_{12,21}^{\ell\,LR,RL}$, $\delta_{12}^{\ell\,LL,RR}$	$< 2.8 \times 10^{-11}$
$\mathrm{Br}(\tau \to e\gamma)$	$\delta_{13,31}^{\ell\,LR,RL}$, $\delta_{13}^{\ell\,LL,RR}$	$< 3.3 \times 10^{-8}$
$\mathrm{Br}(\tau \to \mu\gamma)$	$\delta_{23,32}^{\ell\,LR,RL}$, $\delta_{23}^{\ell\,LL,RR}$	$< 4.4 \times 10^{-8}$
$\mathrm{Br}(K_L \to \pi^0\nu\nu)$	$\delta_{23}^{u\,LR}, \delta_{13}^{u\,LR} \times \delta_{23}^{u\,LR}$	$< 6.7 \times 10^{-8}$
$\mathrm{Br}(K^+ \to \pi^+\nu\nu)$	sensitive to $\delta_{13}^{u\,LR} \times \delta_{23}^{u\,LR}$	$17.3^{+11.5}_{-10.5} \times 10^{-11}$
$\mathrm{Br}(B_d \to ee)$	$\delta_{13}^{d\,LL,RR}$	$< 1.13 \times 10^{-7}$
$\mathrm{Br}(B_d \to \mu\mu)$	$\delta_{13}^{d\,LL,RR}$	$< 1.8 \times 10^{-8}$
$\mathrm{Br}(B_d \to \tau\tau)$	$\delta_{13}^{d\,LL,RR}$	$< 4.1 \times 10^{-3}$
$\mathrm{Br}(B_s \to ee)$	$\delta_{23}^{d\,LL,RR}$	$< 7.0 \times 10^{-5}$
$\mathrm{Br}(B_s \to \mu\mu)$	$\delta_{23}^{d\,LL,RR}$	$< 1.08 \times 10^{-8}$
$\mathrm{Br}(B_s \to \tau\tau)$	$\delta_{23}^{d\,LL,RR}$	$--$
$\mathrm{Br}(B_s \to \mu e)$	$\delta_{23}^{d\,LL,RR} \times \delta_{12}^{\ell\,LL,RR}$	$< 2.0 \times 10^{-7}$
$\mathrm{Br}(B_s \to \tau e)$	$\delta_{23}^{d\,LL,RR} \times \delta_{13}^{\ell\,LL,RR}$	$< 2.8 \times 10^{-5}$
$\mathrm{Br}(B_s \to \mu\tau)$	$\delta_{23}^{d\,LL,RR} \times \delta_{23}^{\ell\,LL,RR}$	$< 2.2 \times 10^{-5}$
$\mathrm{Br}(B^+ \to \tau^+\nu)$	–	$(1.65 \pm 0.34) \times 10^{-4}$
$\mathrm{Br}(B_d \to D\tau\nu)/\mathrm{Br}(B_d \to Dl\nu)$	–	$(0.407 \pm 0.12 \pm 0.049)$
$\mathrm{Br}(B \to X_s\gamma)$	$\delta_{23}^{d\,LL,RR}$ for large $\tan\beta$, $\delta_{23,32}^{d\,LR}$	$(3.52 \pm 0.25) \times 10^{-4}$
$\Delta F = 2$		
$\lvert\epsilon_K\rvert$	$\mathrm{Im}\left[(\delta_{12}^{\mathrm{d\,LL,RR}})^2\right]$, $\mathrm{Im}\left[(\delta_{12,21}^{\mathrm{d\,LR}})^2\right]$	$(2.229 \pm 0.010) \times 10^{-3}$
ΔM_K	$\delta_{12}^{d\,LL,RR}$, $\delta_{12,21}^{d\,LR}$	$(5.292 \pm 0.009) \times 10^{-3}\ \mathrm{ps}^{-1}$
ΔM_D	$\delta_{12}^{u\,LL,RR}$, $\delta_{12,21}^{u\,LR}$	$(2.37^{+0.66}_{-0.71}) \times 10^{-2}\ \mathrm{ps}^{-1}$
ΔM_{B_d}	$\delta_{13}^{d\,LL,RR}$, $\delta_{13,31}^{d\,LR}$	$(0.507 \pm 0.005)\ \mathrm{ps}^{-1}$
ΔM_{B_s}	$\delta_{23}^{d\,LL,RR}$, $\delta_{23,32}^{d\,LR}$	$(17.77 \pm 0.12)\ \mathrm{ps}^{-1}$