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Flavour-Phenomenology of Two-Higgs-Doublet Models

Supported by a Marie Curie Intra-European Fellowship of the European Community's 7th Framework Programme under contract number (PIEF-GA-2012-326948).

Outline:

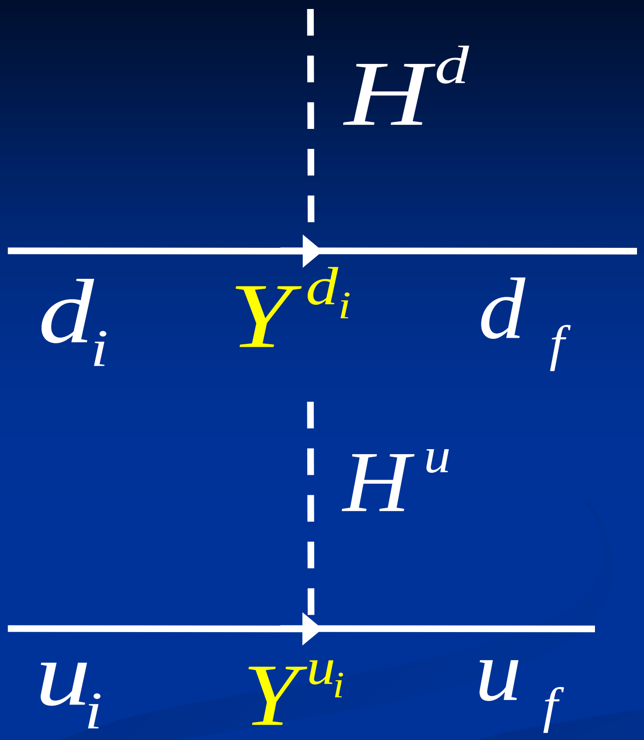
- Introduction
- Flavour constraints
  - Tree-level contributions to FCNC processes
  - Loop-contributions to FCNC processes
- Tauonic B decays
- Connection to the MSSM
- Conclusions

Introduction

Yukawa interactions

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 (MSSM like Higgs potential)
  $m_H \approx m_{A^0} \approx m_{H^\pm} \approx m_{H^0}$

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

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

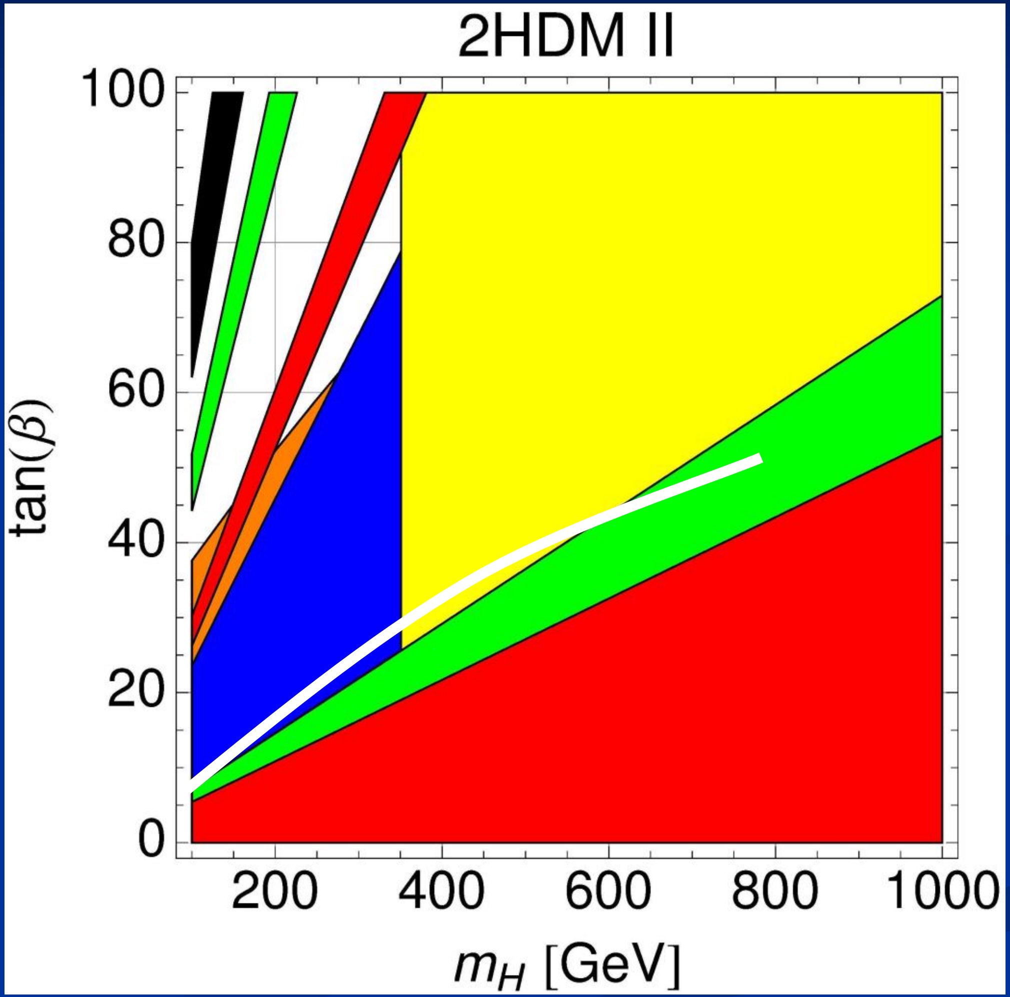
Type-II 2HDM

- Allowed

  2σ regions from:

  (superimposed)

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	$B \to D^*\tau\nu$
white	LHC



⇨ Tension from $B \to D^*\tau\nu$

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

Phenomenology of the 2HDM with generic Yukawa structure

Strategy

Constrains

- ‘t Hooft’s naturelness agrument
  (order of magnitude)
- Tree-level contributions to FCNC processes
- Loop-effects
- Charged current processes

Where are large effects still possible?

- Tauonic B decays
- LFV B decays

‘t Hooft’s naturelness argument

Large accidental cancelations which are not enforced by a symmetry should be avoided.

$$\varepsilon_{ij}^{d} \leq \frac{\max\left[m_{d_i}, m_{d_j}\right]}{v\tan\beta}$$

$$\varepsilon_{ij}^{u} \leq \frac{\max\left[m_{u_i}, m_{u_j}\right]}{v}\tan\beta$$

Tree-level FCNC constraints

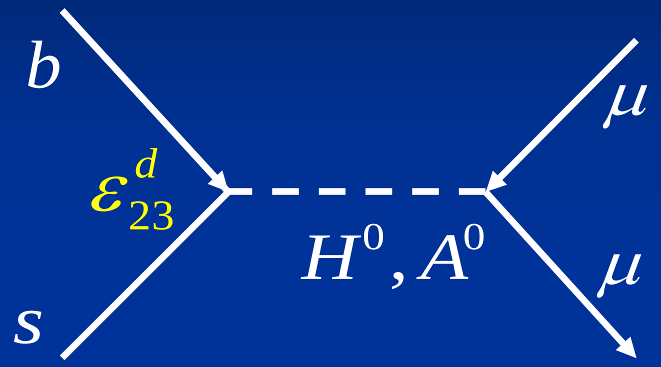
$\tan(\beta) = 50$

$m_H = 700$ GeV

$m_H = 500$ GeV

$m_H = 300$ GeV

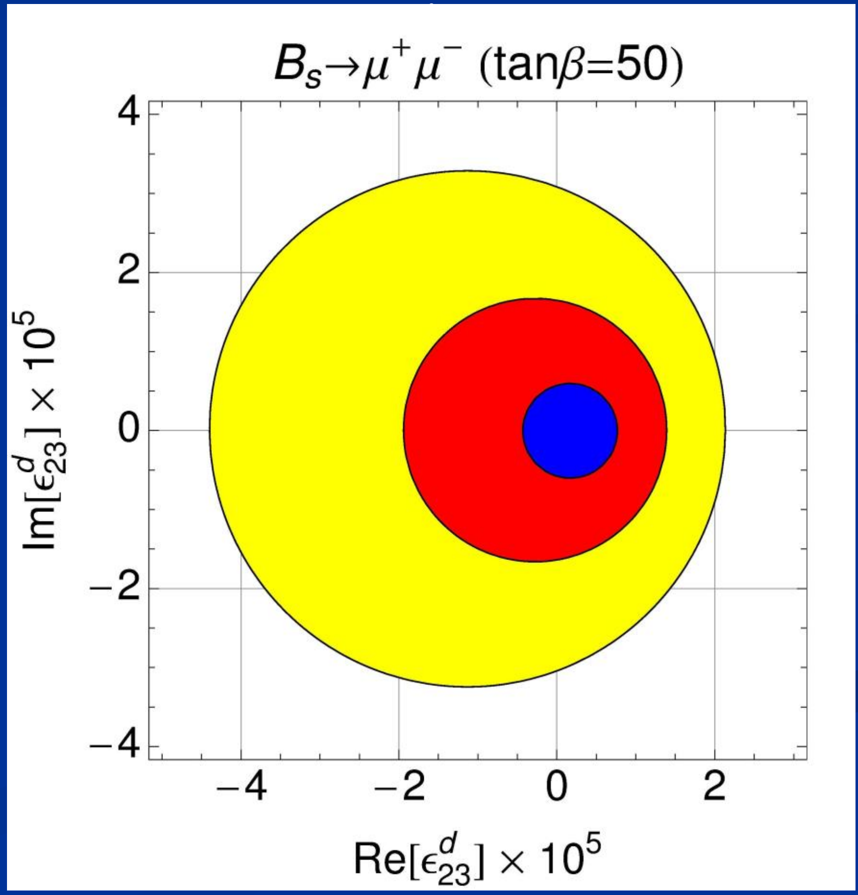
$M \to \mu^+\mu^-$



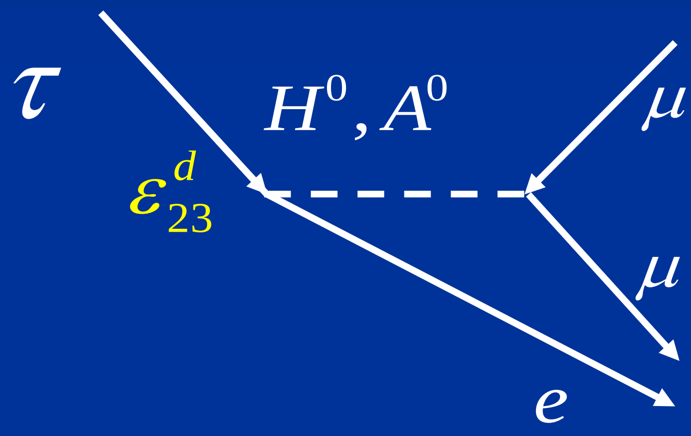
- $B \to \mu^+\mu^-$ constrains $\varepsilon^d_{13,31}$
- $B_s \to \mu^+\mu^-$ constrains $\varepsilon^d_{23,32}$
- $K_L \to \mu^+\mu^-$ constrains $\varepsilon^d_{12,21}$
- $D \to \mu^+\mu^-$ constrains $\varepsilon^u_{12,21}$

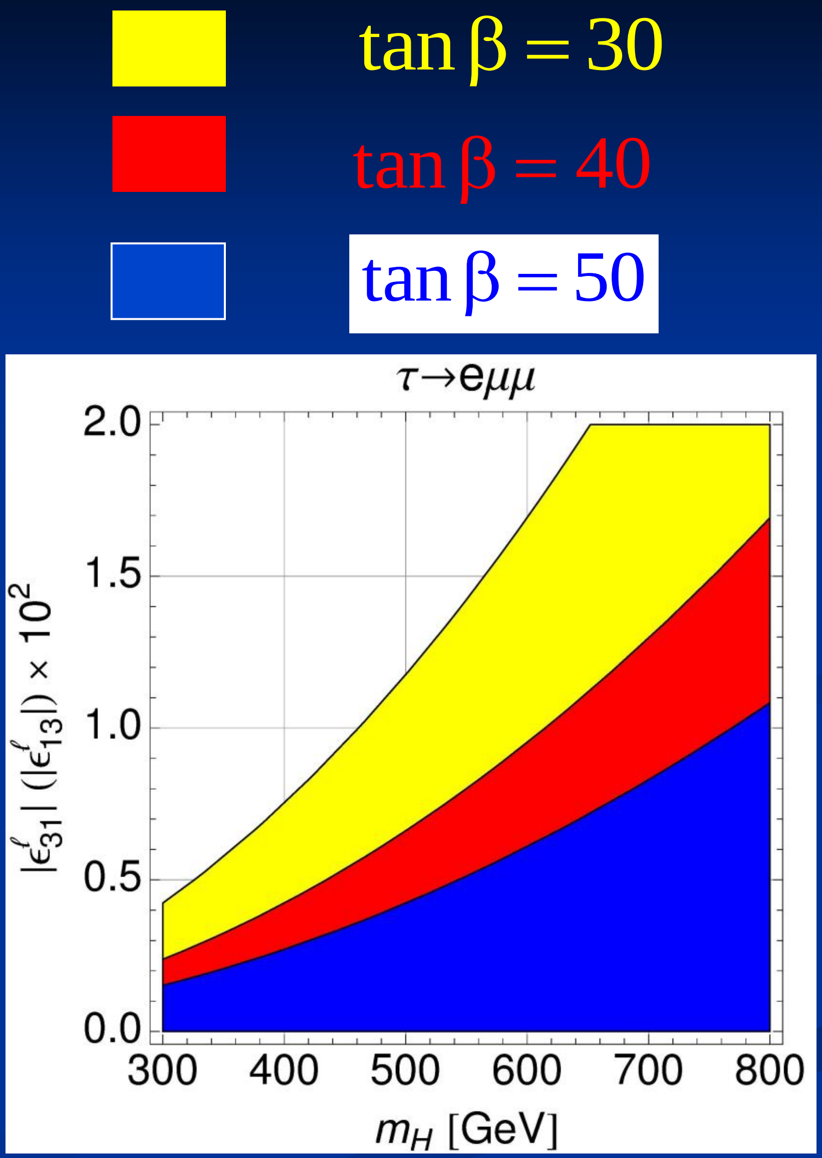
$\varepsilon^u_{32,23}$ and $\varepsilon^u_{13,31}$ unconstrained

⇒ from tree-level FCNCs



$$\ell_i \to \ell_f \ell_j \ell_j$$





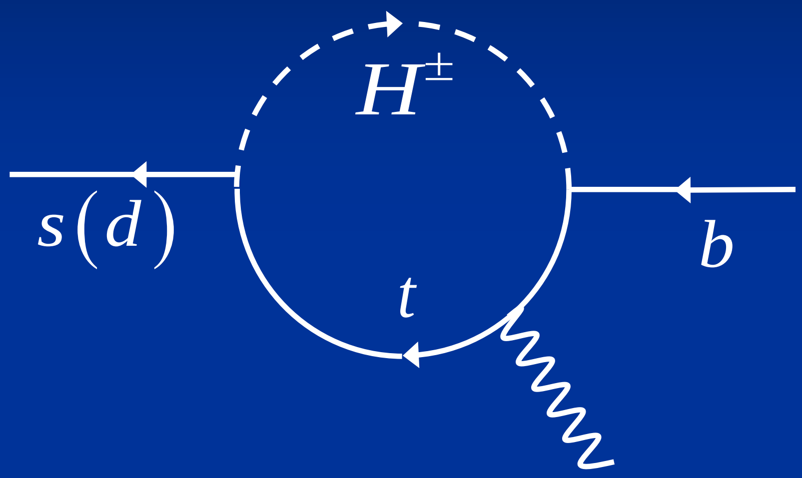
- $\tau \to e\mu\mu$ constrains $\varepsilon^{\ell}_{13,31}$
- $\tau \to \mu\mu\mu$ constrains $\varepsilon^{\ell}_{23,32}$

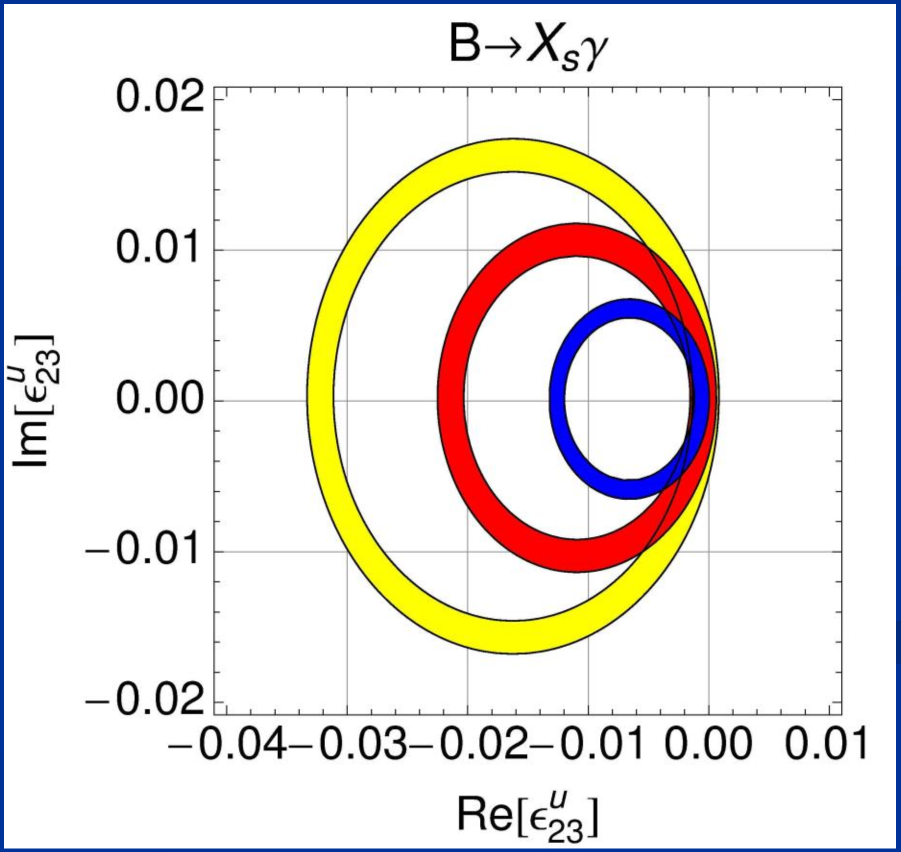
Loop induced FCNC constraints

Constraints from $b\to s(d)\gamma$

$\tan(\beta)=50$

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





- $b\to s\gamma$ constrains ε^{u}_{23}
- $b\to d\gamma$ constrains ε^{u}_{13}
- $\mu\to e\gamma$ constrains $\varepsilon^{\ell}_{12,21}$

Where are sizable effects still possible?

- All flavour changing elements in the down sector are stringently constrained from leptonic decays of neutral mesons
- $\varepsilon^{u}_{23,13}$ constrained from $b \to s, d\, \gamma$
- Only $\varepsilon^{u}_{32,31}$ can be large

⇒ **Tauonic B decays**

Also LFV B decays can still be sizable

Tauonic B decays

- Tree-level decays in the SM via W-boson
- Sensitive to a charged Higgs due to the heavy tau lepton in the final state.

Observable	SM	Experiment	Significance
$\mathrm{Br}\left[B\to\tau\nu\right]$	$\left(0.719^{+0.115}_{-0.076}\right)\times10^{-4}$	$\left(1.15\pm0.23\right)\times10^{-4}$	$1.6\,\sigma$
$\mathrm{Br}\left[B\to D\tau\nu\right]/\mathrm{Br}\left[B\to D\ell\nu\right]$	0.297 ± 0.017	0.440 ± 0.072	$2.0\,\sigma$
$\mathrm{Br}\left[B\to D^{*}\tau\nu\right]/\mathrm{Br}\left[B\to D^{*}\ell\nu\right]$	0.252 ± 0.003	0.332 ± 0.030	$2.7\,\sigma$

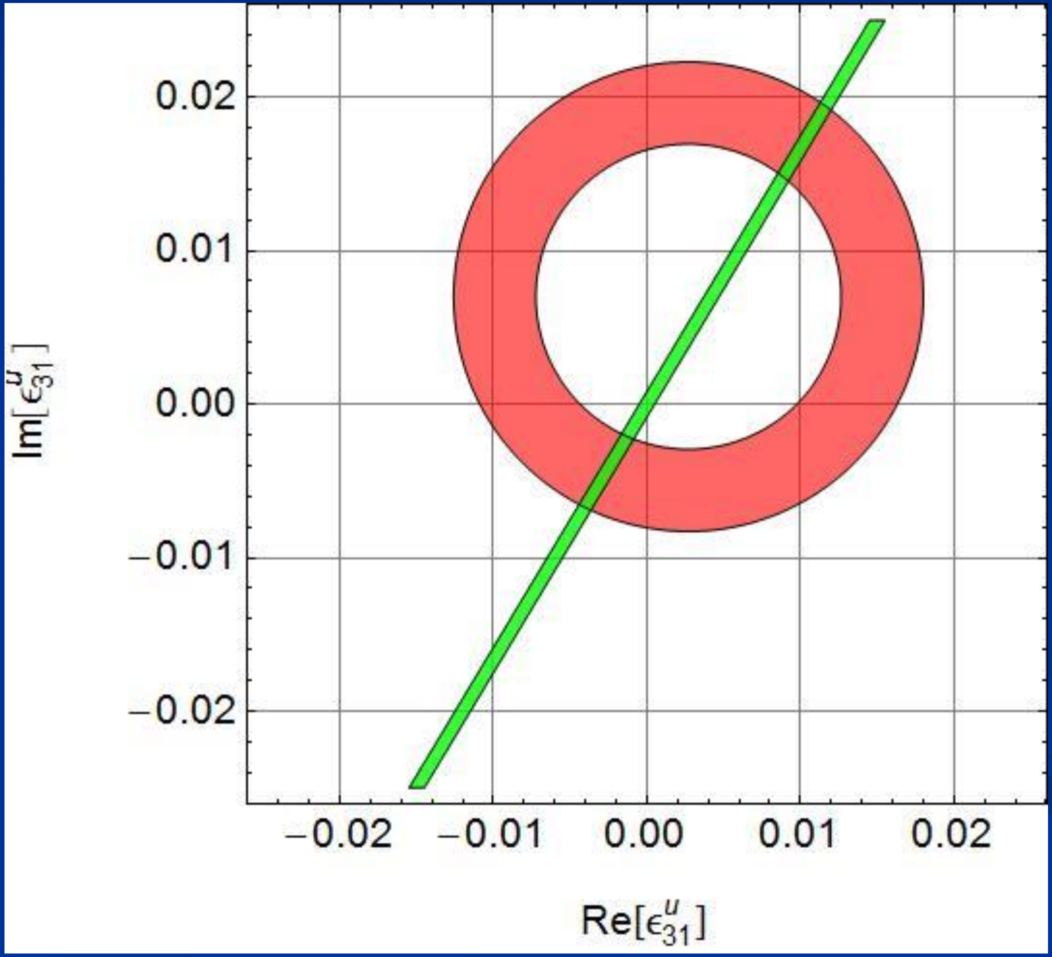
⇒ All three observables are above the SM prediction

B→τν in the 2HDM III

- Constructive contribution to B→τν using ε_{31}^{u} is possible.

Allowed regions from:

- (red) $B \to \tau\nu$
- (green) d_n

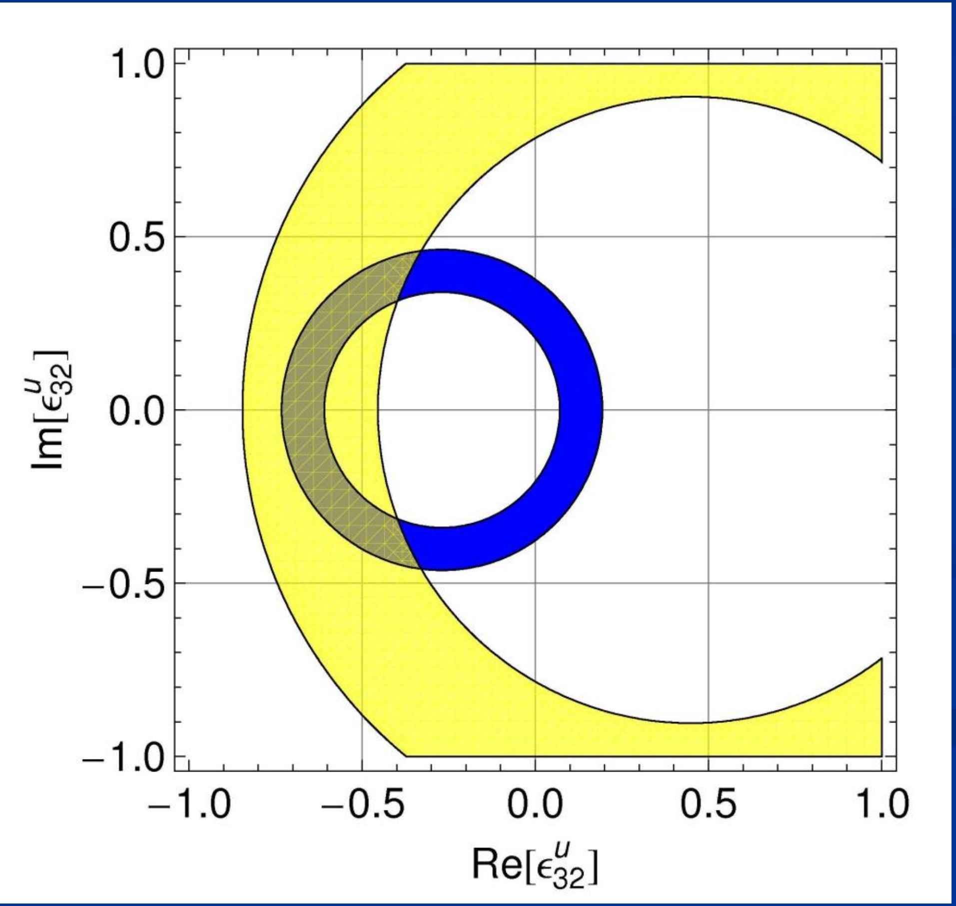


$B \to D^{(*)}\tau\nu$ in the 2HDM III

- $B \to D^{(*)}\tau\nu$ and $B \to D\tau\nu$ can be explained simultaneously using ε^u_{32}. ➡ Check model via $H^0, A^0 \to \bar{t}c$

Allowed regions from:

- Blue: $B \to D\tau\nu$
- Yellow: $B \to D^*\tau\nu$



Lepton Flavour violating B decays

Lepton flavour violating B decays

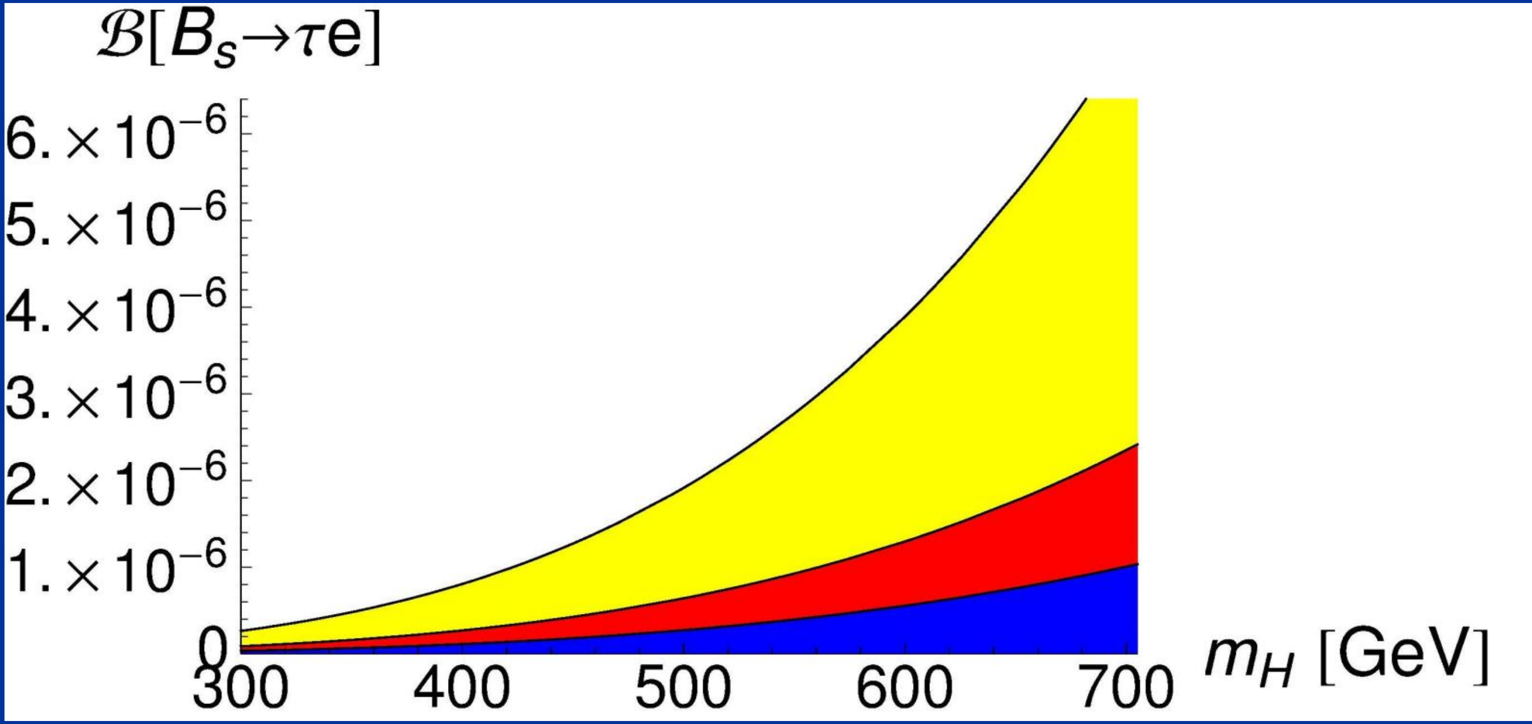
$\tan(\beta) = 30$

$\tan(\beta) = 40$

$\tan(\beta) = 50$

Allowed regions respecting

the constraints from $t \to e\mu\mu$ **and** $B_s \to \mu^+\mu^-$



Lepton Flavor violation

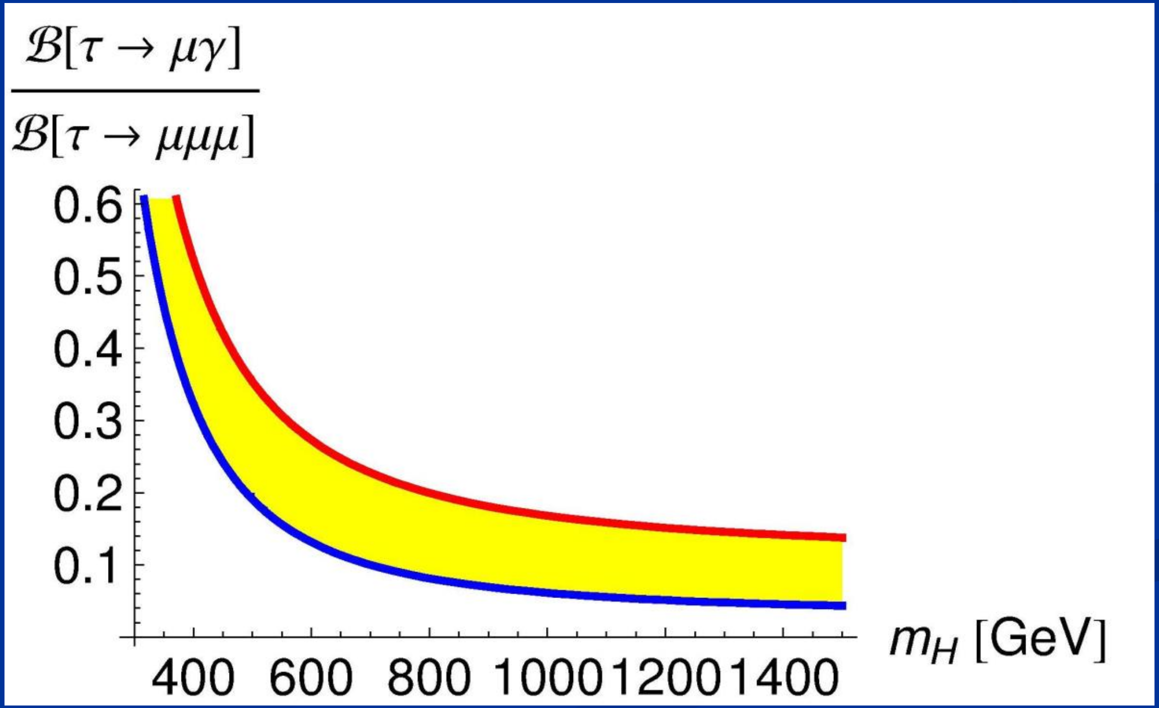
- Correlations between $\tau \to \mu\mu\mu$ and $\tau \to \mu\gamma$

Predicted ratio in the 2HDM of type III

$\varepsilon_{23}^{\ell} \neq 0, \varepsilon_{32}^{\ell} \neq 0$

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

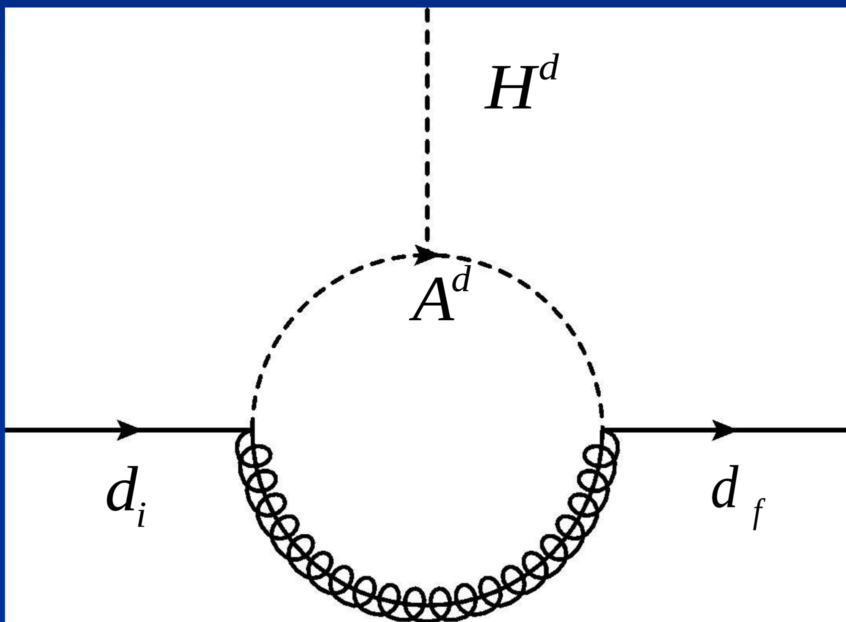
$\varepsilon_{32}^{\ell} \neq 0, \varepsilon_{23}^{\ell} = 0$

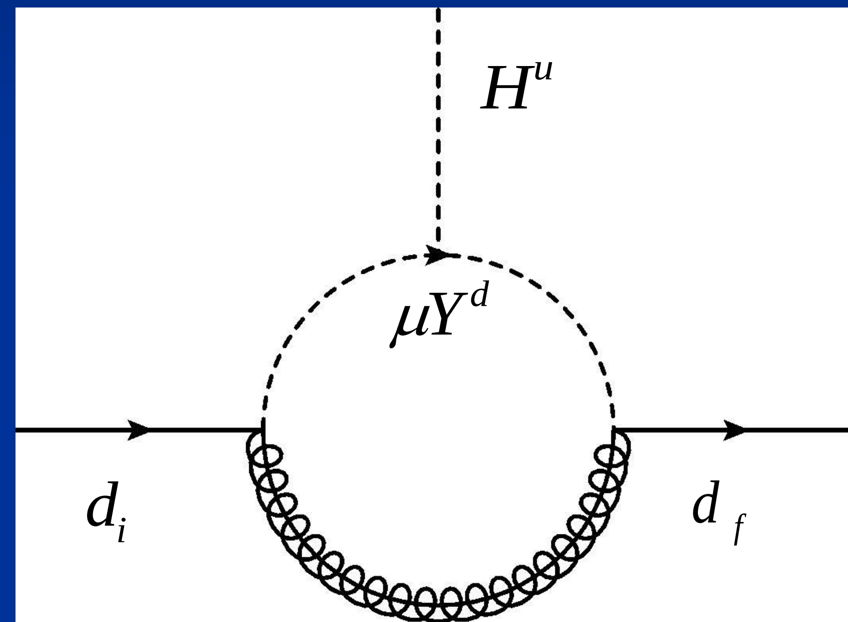


Connection to the MSSM

Loop corrections to Higgs quark couplings

- Before electroweak symmetry breaking
- After electroweak symmetry breaking





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

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

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

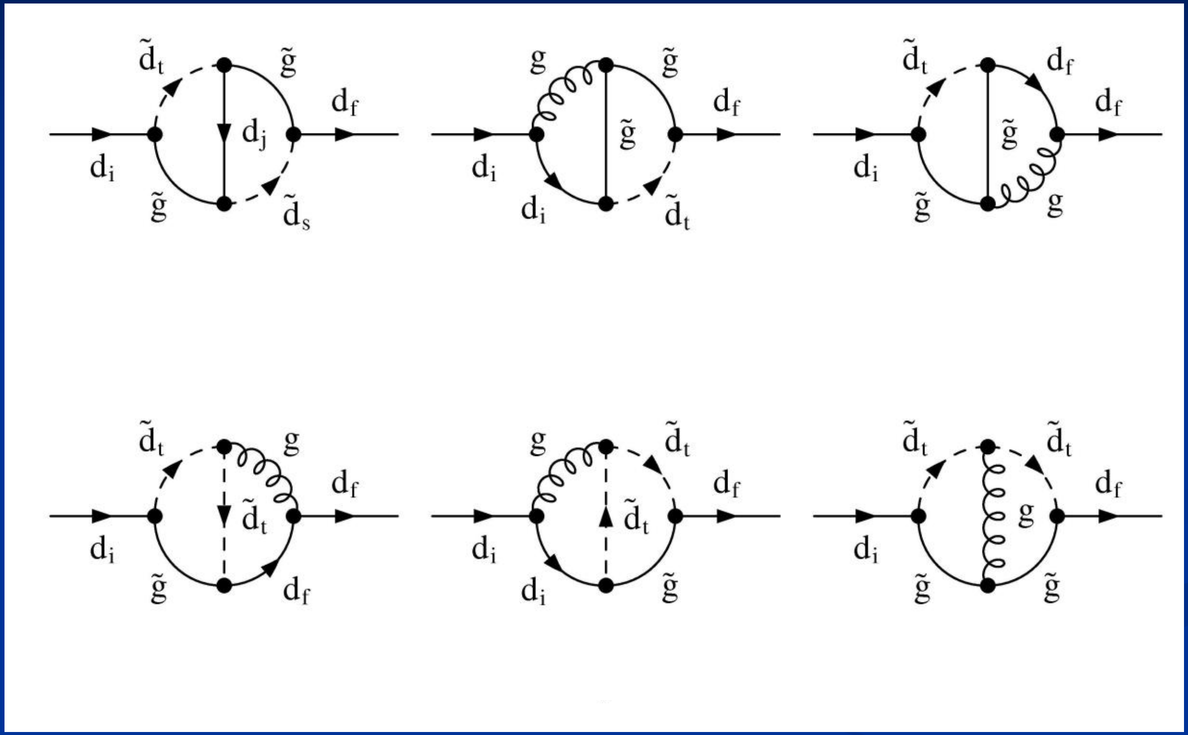
NLO calculation of the quark self-energies

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

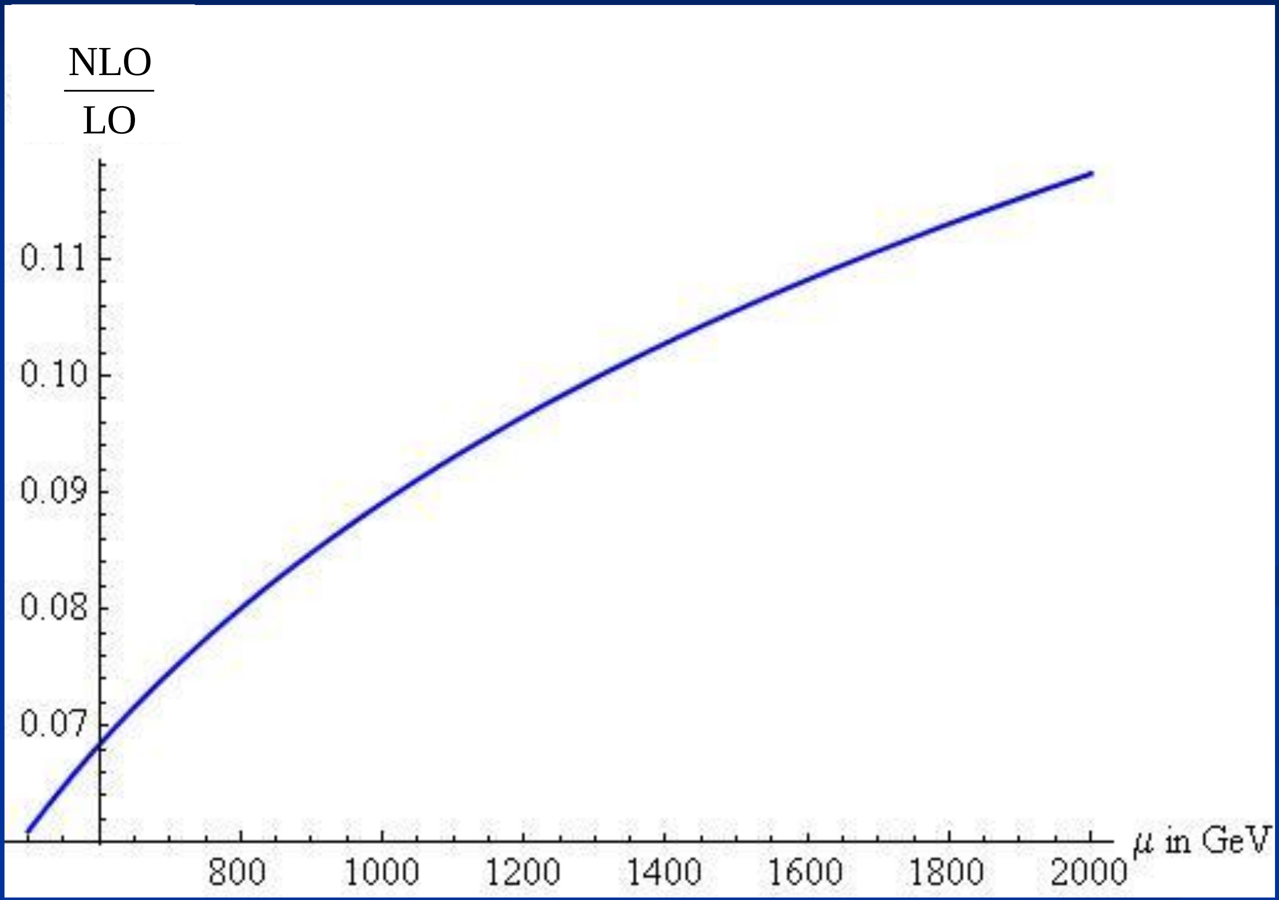


Examples of 2-loop diagrams

- 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%

Conclusions

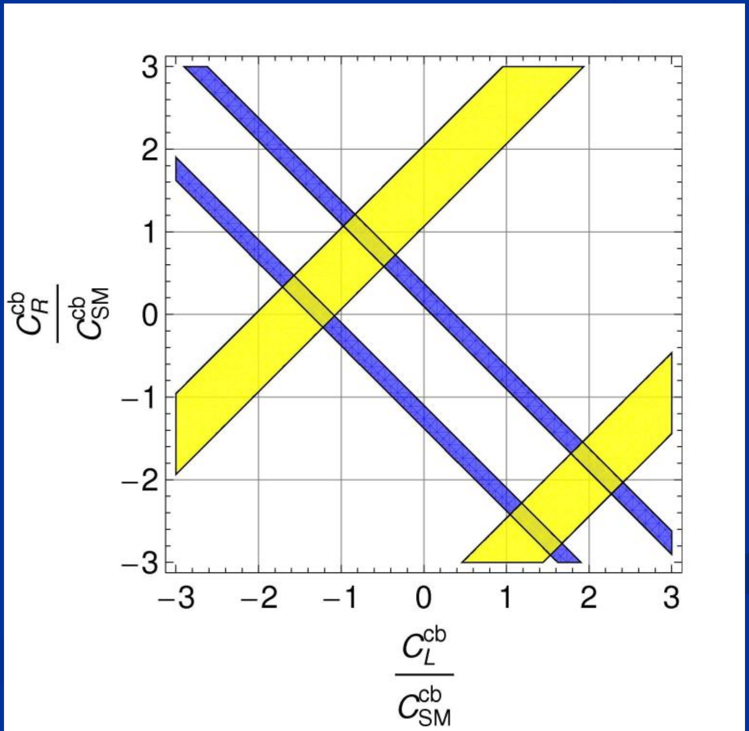
- The parameter space of the 2HDM with generic flavour-structure is stringently constrained from:
  - Neutral Meson decays to muons
  - Radiative B decays
  - LFV observables
- A 2HDM of type III with flavour violation in the up-sector can still explain $B \to \tau\nu$, $B \to D\tau\nu$ and $B \to D^*\tau\nu$.
- Sizable effects in LFV B decays still possible.
- The decoupling limit of the MSSM is the 2HDM of type III.
- 2-loop calculation of Higgs-quark couplings in the MSSM significantly reduces the matching scale dependence.

$B \to D^{(*)}\tau\nu$

$$R(D)=\frac{\mathrm{Br}[B\to D\tau\nu]}{\mathrm{Br}[B\to D\ell\nu]}=R_{SM}(D)\left(1+1.5\,\mathrm{Re}\left[\frac{C_R^{cb}+C_L^{cb}}{C_{SM}^{cb}}\right]+1.0\left|\frac{C_R^{cb}+C_L^{cb}}{C_{SM}^{cb}}\right|^2\right)$$

$$R(D^*)=\frac{\mathrm{Br}[B\to D^*\tau\nu]}{\mathrm{Br}[B\to D^*\ell\nu]}=R_{SM}(D^*)\left(1+0.12\,\mathrm{Re}\left[\frac{C_R^{cb}-C_L^{cb}}{C_{SM}^{cb}}\right]+0.05\left|\frac{C_R^{cb}-C_L^{cb}}{C_{SM}^{cb}}\right|^2\right)$$

- Form factors uncertainties drop out to a large extend in the rations R(D) and R(D*).
- C_R cannot explain R(D) and R(D*) simultaneously but C_L can.



$R(D^*)$

$R(D)$