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Flavour Phenomenology of 2HDMs with generic Yukawa couplings

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

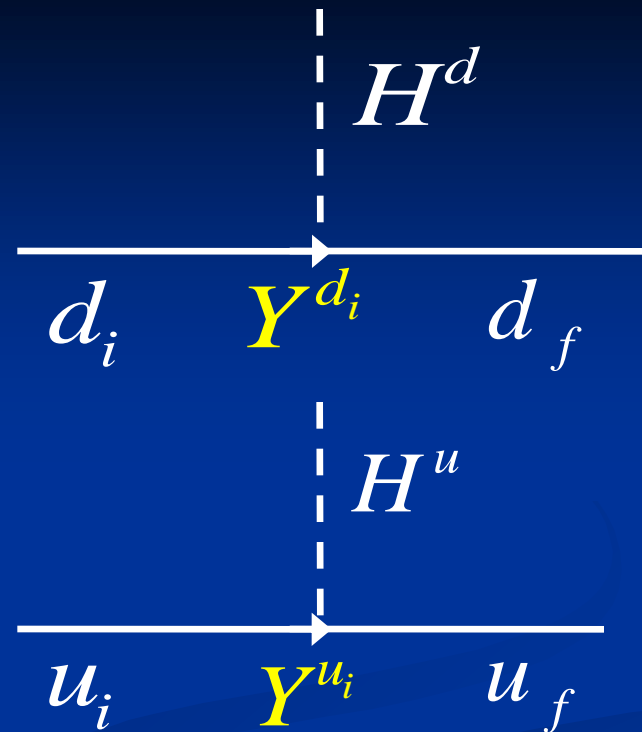
Yukawa interactions

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)

$$m_H \approx m_{A^0} \approx m_{H^\pm} \approx m_{H^0}$$

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



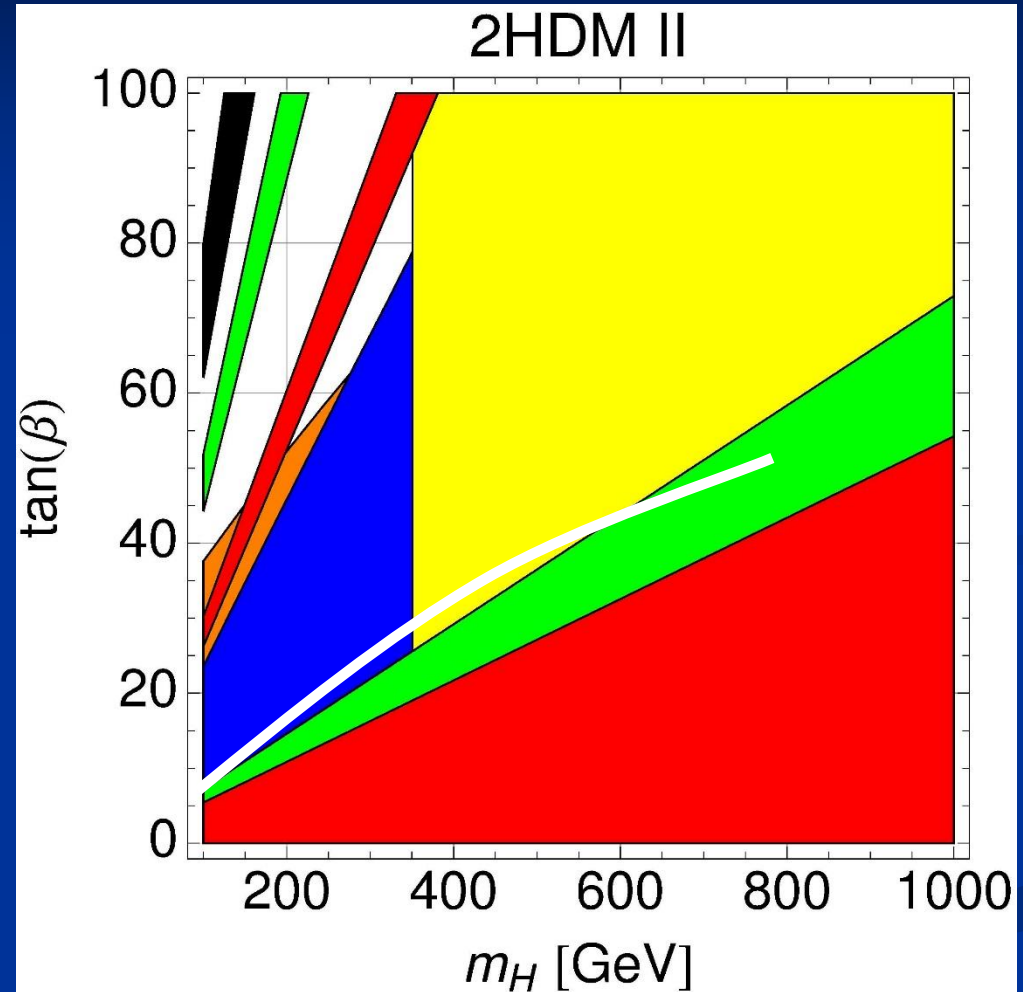
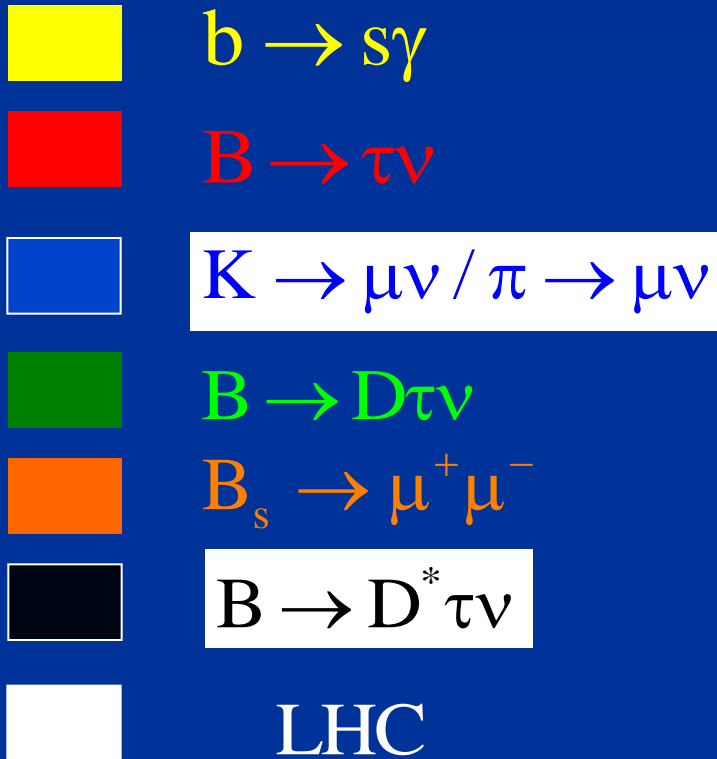
$$m_{q_i} = v_q Y^{q_i}$$

Type-II 2HDM

■ Allowed

2 σ regions from:

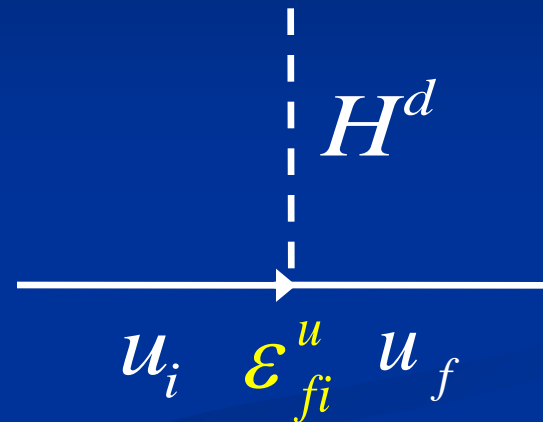
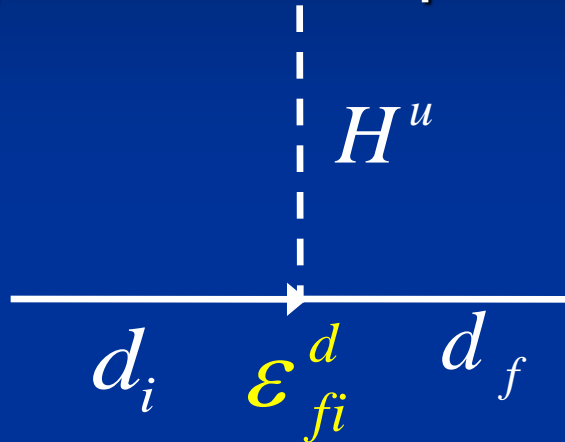
(superimposed)



➔ Tension from $B \rightarrow D^*\tau\nu$

2HDM of type III

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



$$m_{ij}^d = v_d Y_{ij}^d + v_u \epsilon_{ij}^d$$

$$m_{ij}^u = v_u Y_{ij}^u + v_d \epsilon_{ij}^u$$

- The parameters $\epsilon_{ij}^{u,d}$ describe flavor-changing neutral Higgs interactions
- In the MSSM, $\epsilon_{ij}^{u,d}$ 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

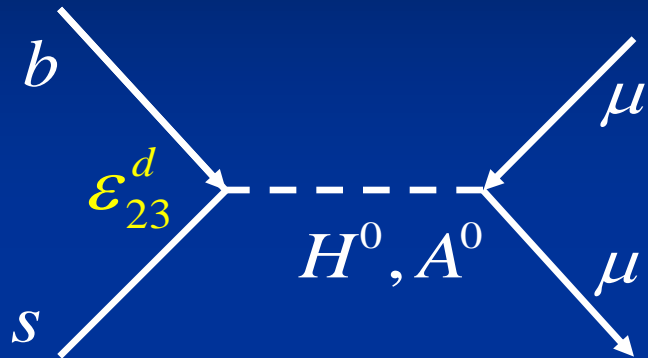
't Hooft's naturelness argument

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

$$\mathcal{E}_{ij}^d \leq \frac{\max[m_{d_i}, m_{d_j}]}{v \tan \beta}$$
$$\mathcal{E}_{ij}^u \leq \frac{\max[m_{u_i}, m_{u_j}]}{v} \tan \beta$$

Tree-level FCNC constraints

$M \rightarrow \mu^+ \mu^-$



- $B \rightarrow \mu^+ \mu^-$ constrains $\epsilon_{13,31}^d$
- $B_s \rightarrow \mu^+ \mu^-$ constrains $\epsilon_{23,32}^d$
- $K_L \rightarrow \mu^+ \mu^-$ constrains $\epsilon_{12,21}^d$
- $D \rightarrow \mu^+ \mu^-$ constrains $\epsilon_{12,21}^u$

$\epsilon_{32,23}^u$ and $\epsilon_{13,31}^u$ unconstrained

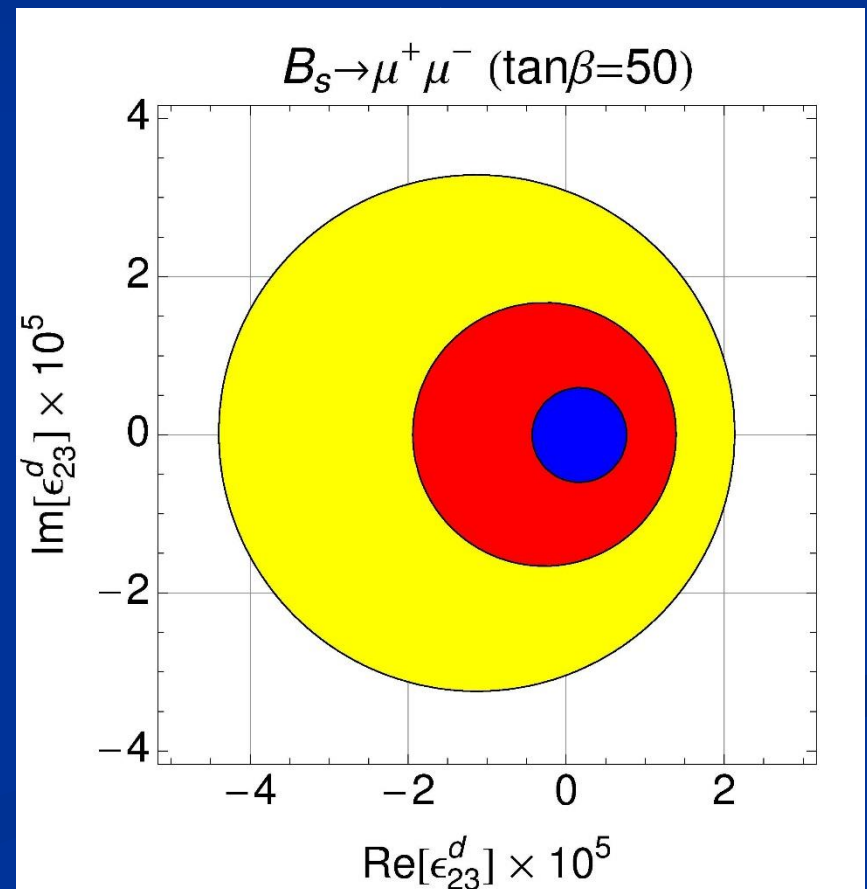
→ from tree-level FCNCs

$$\tan(\beta) = 50$$

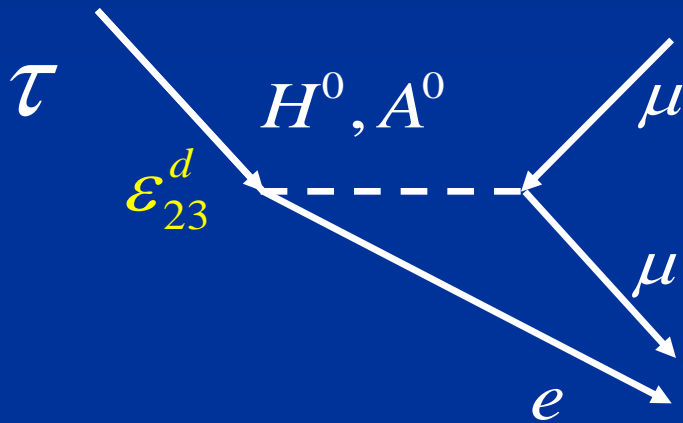
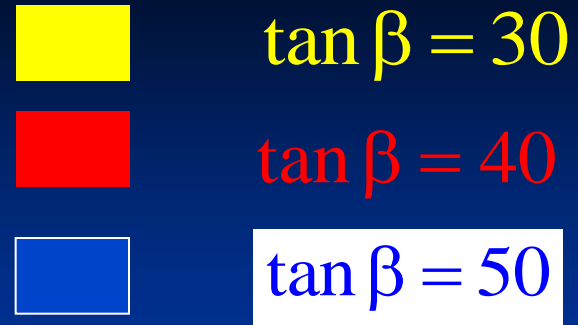
■ $m_H = 700 \text{ GeV}$

■ $m_H = 500 \text{ GeV}$

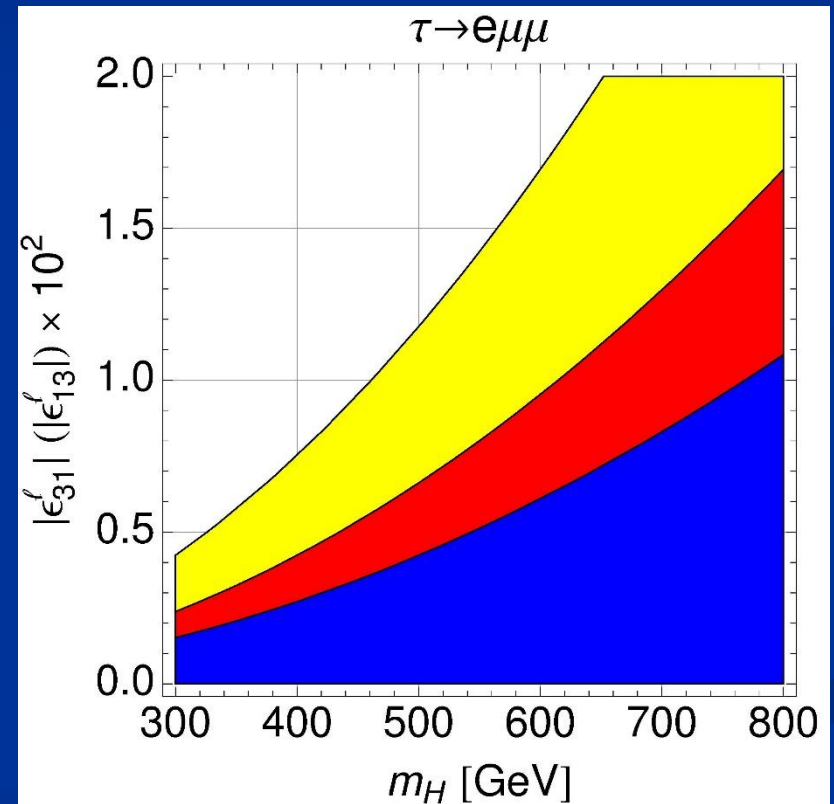
■ $m_H = 300 \text{ GeV}$



$$l_i \rightarrow l_f l_j l_j$$



- $\tau \rightarrow e \mu \mu$ constrains $\epsilon_{13,31}^l$
- $\tau \rightarrow \mu \mu \mu$ constrains $\epsilon_{23,32}^l$



Loop induced FCNC constraints

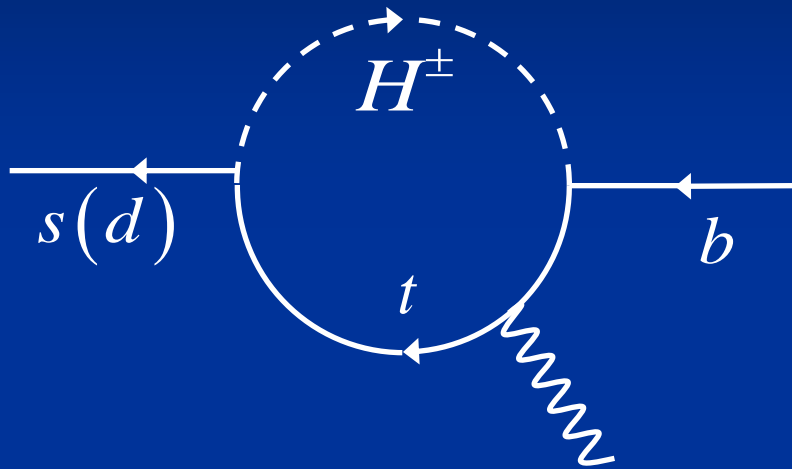
Constraints from $b \rightarrow s(d)\gamma$

$$\tan(\beta) = 50$$

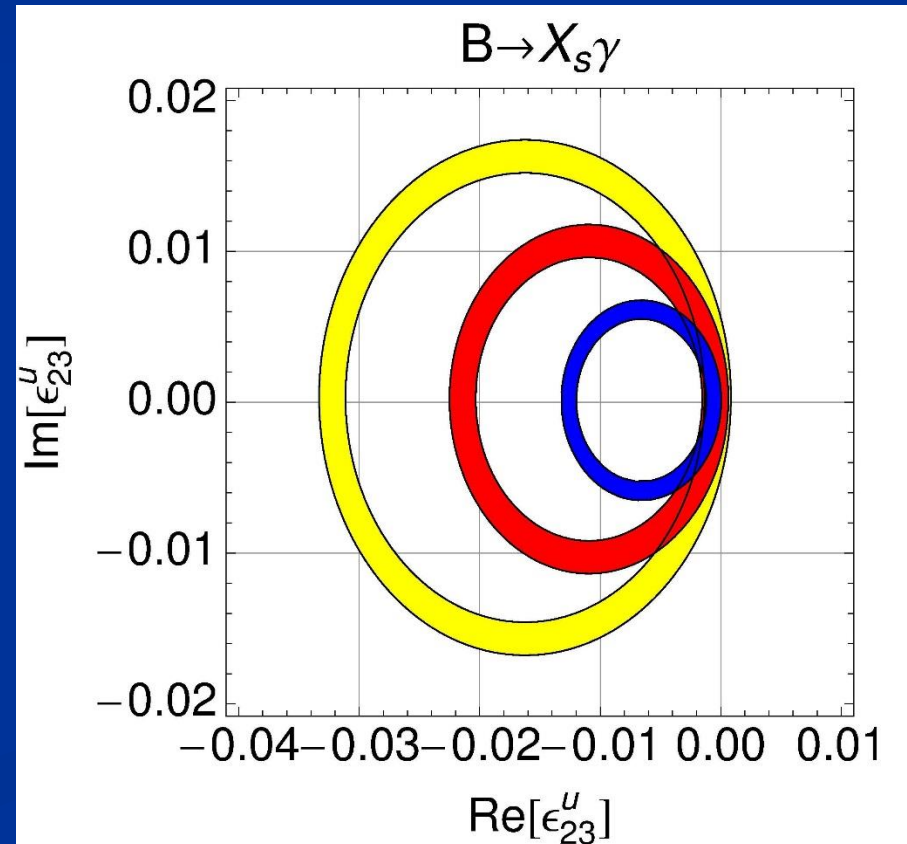
■ $m_H = 700 \text{ GeV}$

■ $m_H = 500 \text{ GeV}$

■ $m_H = 300 \text{ GeV}$

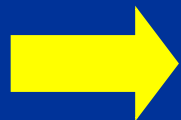


- $b \rightarrow s\gamma$ constrains ϵ_{23}^u
- $b \rightarrow d\gamma$ constrains ϵ_{13}^u
- $\mu \rightarrow e\gamma$ constrains $\epsilon_{12,21}^\ell$



Where are sizable effects still possible?

- All flavour changing elements in the down sector are stringently constrained from leptonic decays of neutral mesons
- $\epsilon_{23,13}^u$ constrained from $b \rightarrow s, d \gamma$
- Only $\epsilon_{32,31}^u$ 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
$\text{Br}[B \rightarrow \tau \nu]$	$(0.719^{+0.115}_{-0.076}) \times 10^{-4}$	$(1.15 \pm 0.23) \times 10^{-4}$	1.6σ
$\text{Br}[B \rightarrow D \tau \nu] / \text{Br}[B \rightarrow D \ell \nu]$	0.297 ± 0.017	0.440 ± 0.072	2.0σ
$\text{Br}[B \rightarrow D^* \tau \nu] / \text{Br}[B \rightarrow D^* \ell \nu]$	0.252 ± 0.003	0.332 ± 0.030	2.7σ

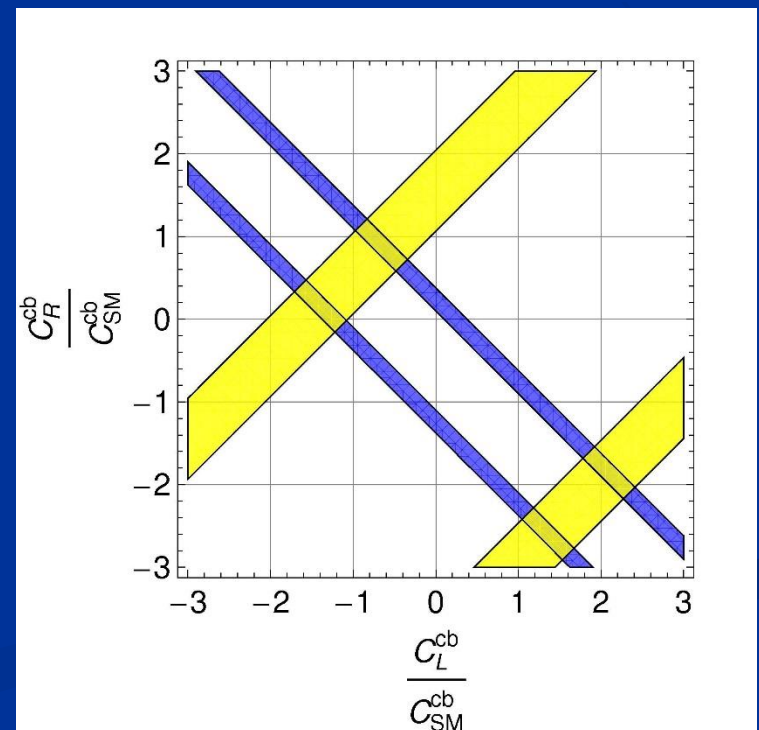
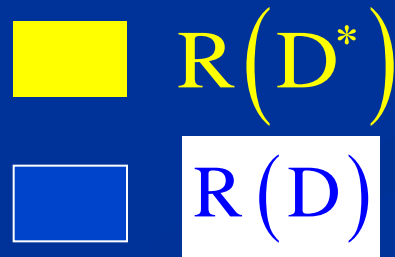
➡ All three observables are above the SM prediction

B → D(*) TV

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

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

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



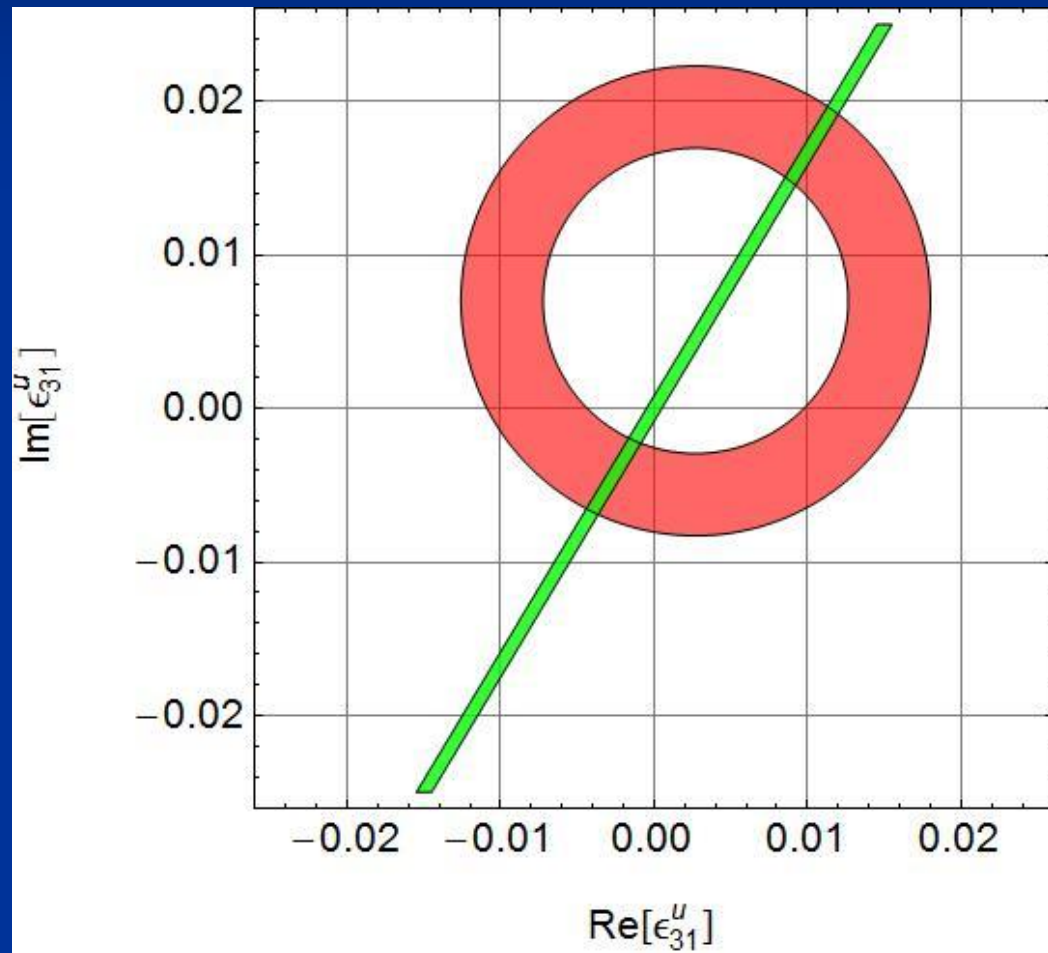
$B \rightarrow \tau \nu$ in the 2HDM III

- Constructive contribution to $B \rightarrow \tau \nu$ using ϵ_{31}^u is possible.

Allowed regions from:

 $B \rightarrow \tau \nu$

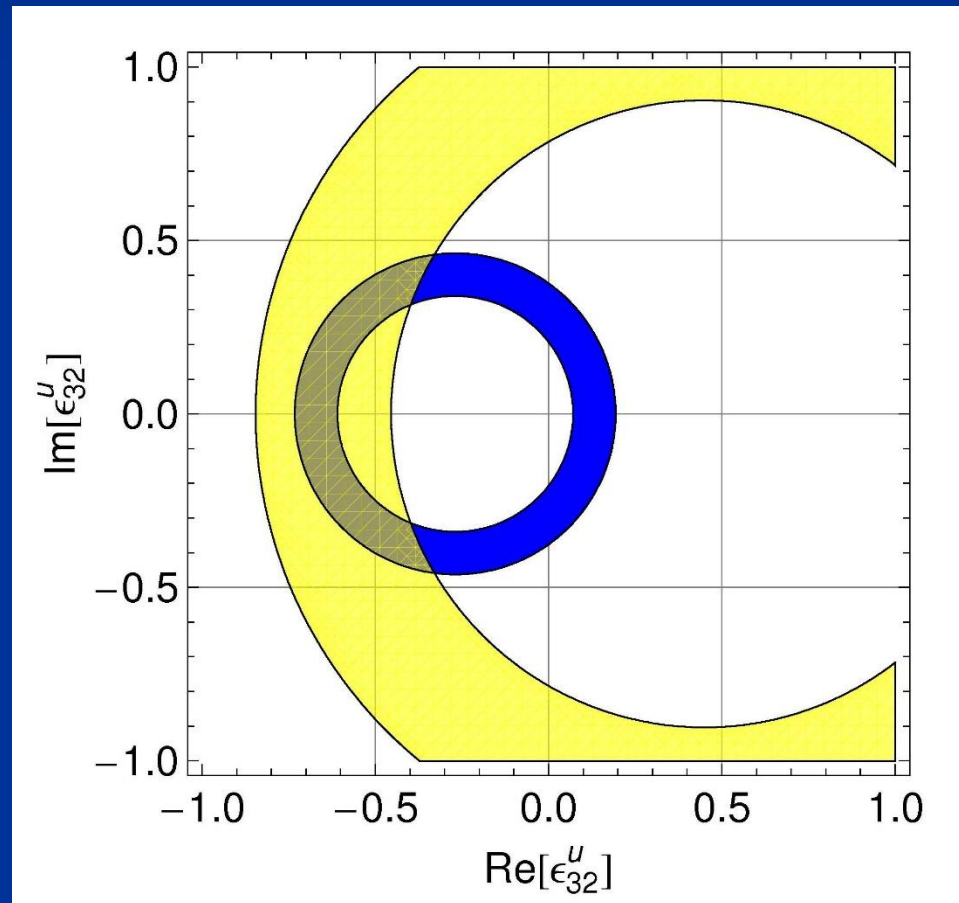
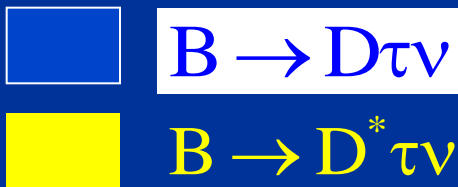
 d_n



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

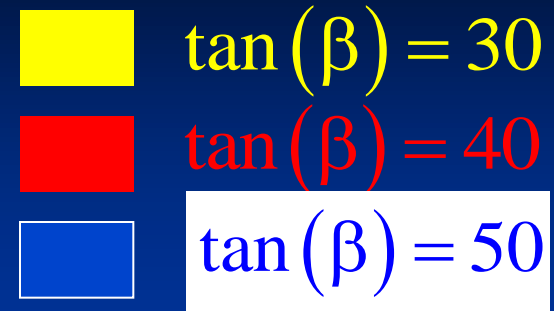
- $B \rightarrow D^{(*)} \tau \nu$ and $B \rightarrow D \tau \nu$ can be explained simultaneously using ϵ_{32}^u . \rightarrow Check model via $H^0, A^0 \rightarrow \bar{t}c$

Allowed regions from:

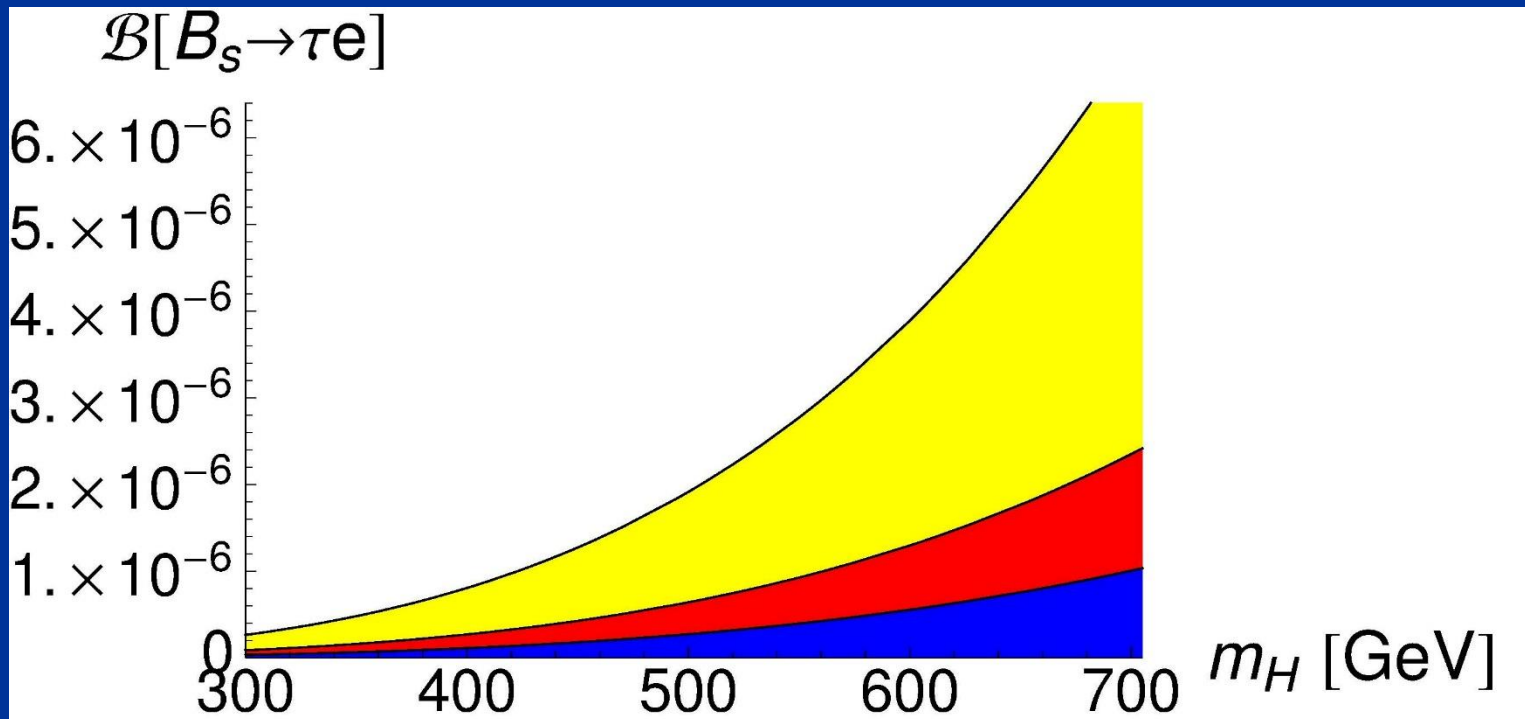


Lepton Flavour violating B decays

Lepton flavour violating B decays



Allowed regions respecting the constraints from $t \rightarrow e\mu\mu$ and $B_s \rightarrow \mu^+\mu^-$

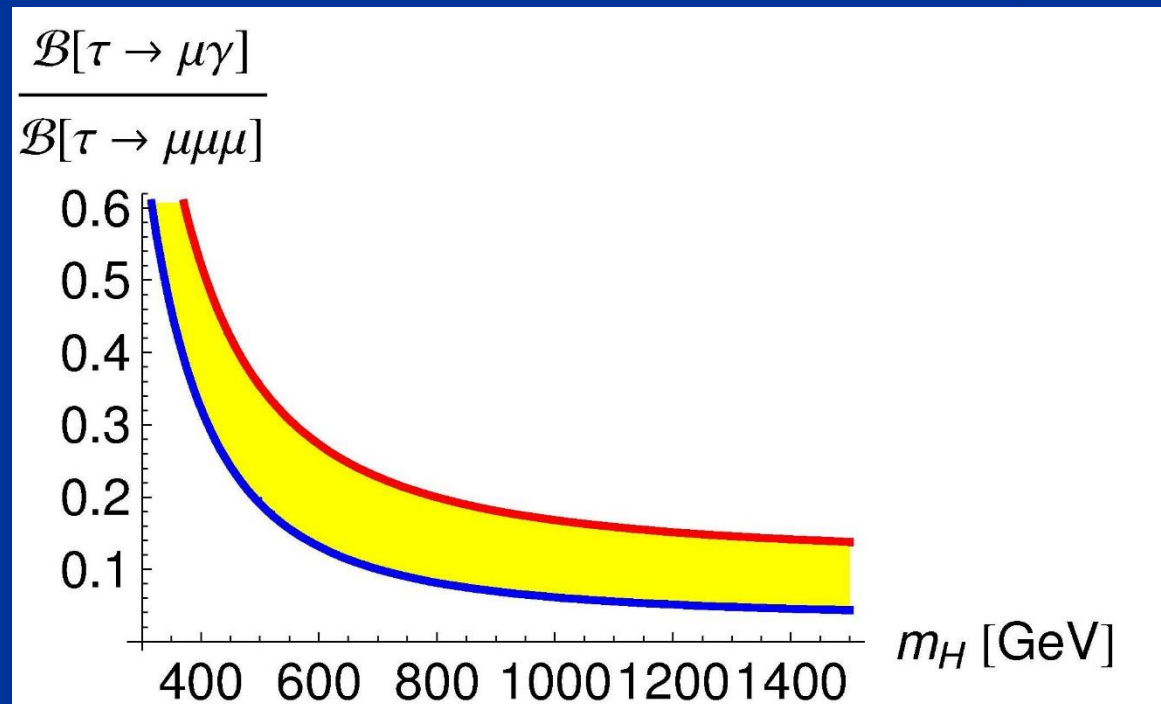


Lepton Flavor violation

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

Predicted ratio in the 2HDM of type III

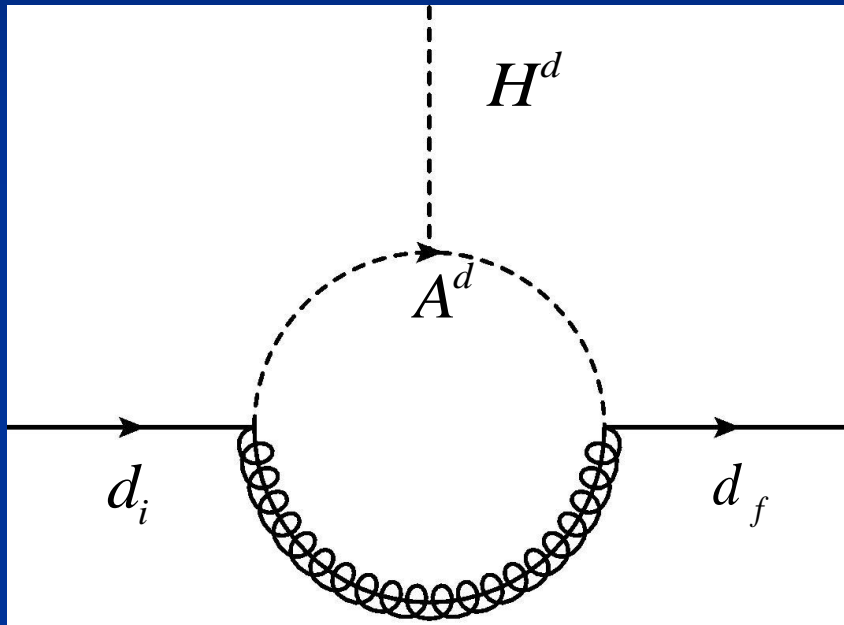
- $\varepsilon_{23}^l \neq 0, \varepsilon_{32}^l \neq 0$
- $\varepsilon_{32}^l = 0, \varepsilon_{23}^l \neq 0$
- $\varepsilon_{32}^l \neq 0, \varepsilon_{23}^l = 0$



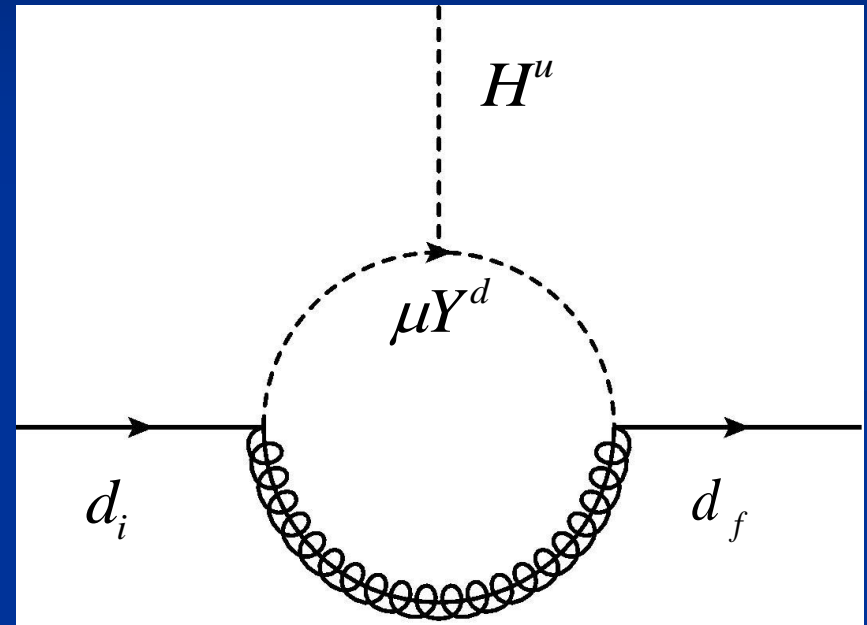
Connection to the MSSM

Loop corrections to Higgs quark couplings

- Before electroweak symmetry breaking



$$\sum_{fi}^{d LR} \Gamma_{d_f d_i}^{H^d} \Gamma_{d_f d_i}^{H^d}$$



$$\sum_{fi}^{d LR} \Gamma_{d_f d_i}^{H^u} \Gamma_{d_f d_i}^{H^u}$$

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

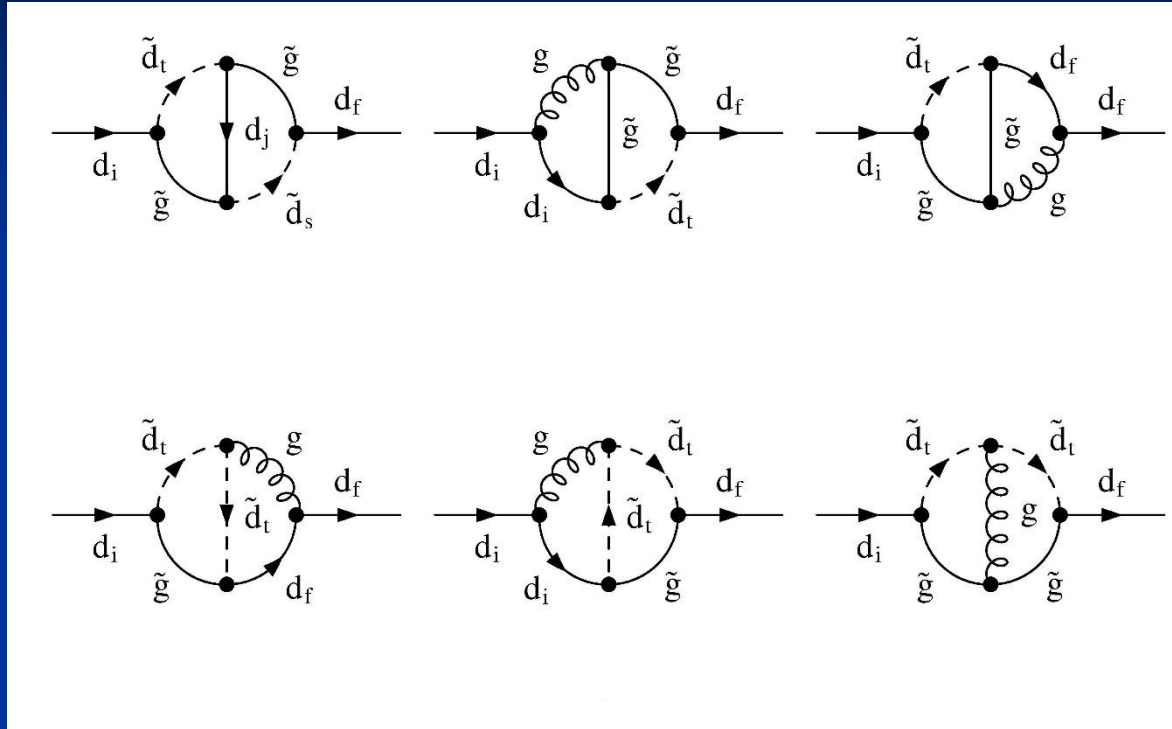
NLO calculation of the quark self-energies

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 $\tan(\beta)$.

Reduction of the matching scale dependence

NLO calculation

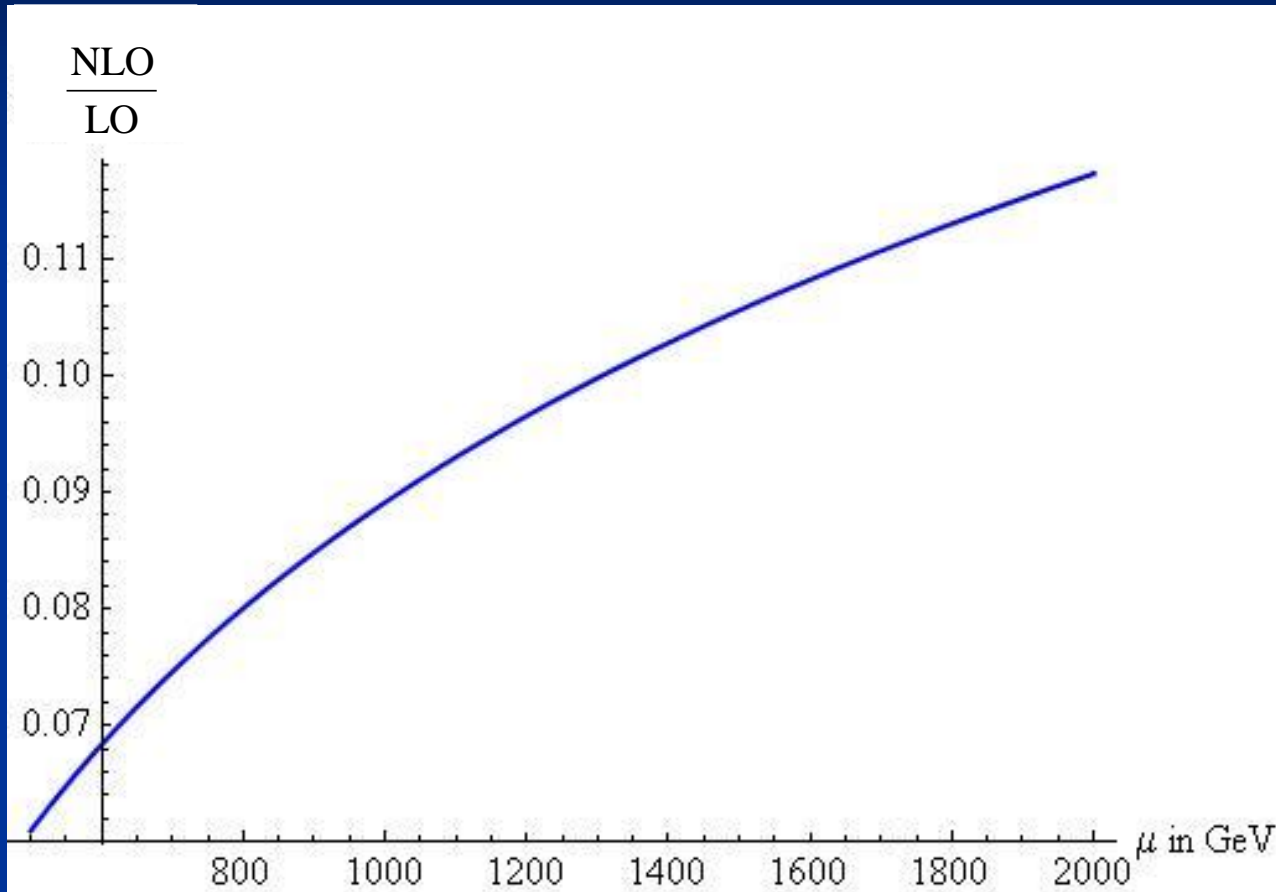


Examples of 2-loop diagrams

- NLO calculation includes analytic results and $\tan(\beta)$ 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 $B \rightarrow \tau \nu$, $B \rightarrow D \tau \nu$ and $B \rightarrow D^* \tau \nu$.
- 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.