Andreas Crivellin

Challenges for New Physics in the Flavour Sector

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-physics vs LHC searches
- Flavor observables and implications for NP
  - $B_q \to \mu^+\mu^-$
  - Meson mixing
  - Radiative B decays
  - $B \to K^*\mu^+\mu^-$
  - Lepton flavour violation
  - Tauonic B decays
- Radiative flavour violation in the MSSM
- Conclusions

Flavor-Physics vs LHC

- **Direct searches**

  probe the scale of NP Λ

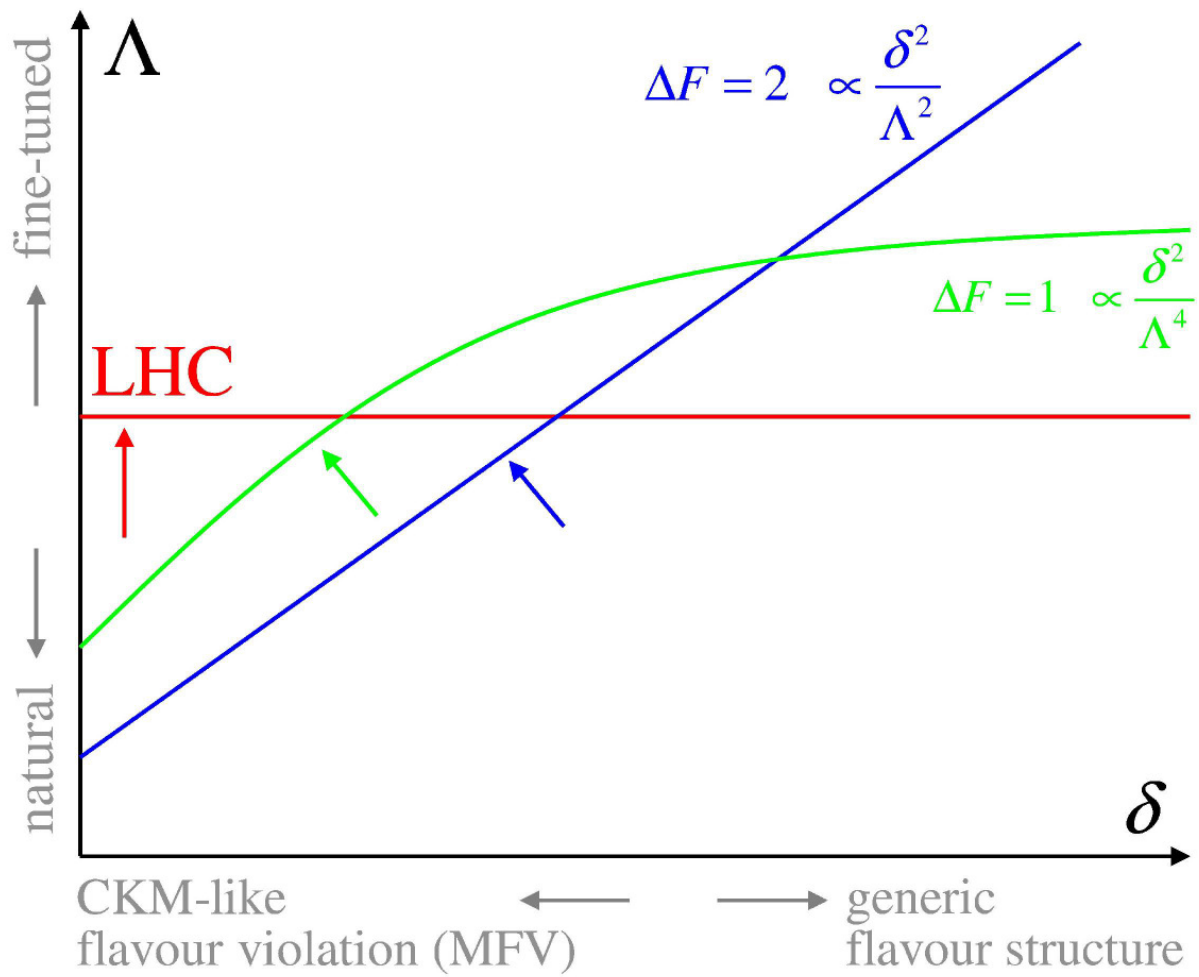
➡ Limited by available energy

- **Flavor physics**

  probes NP indirectly through loop effects

➡ Limited by the size of flavor violation δ and the available statistics/precision

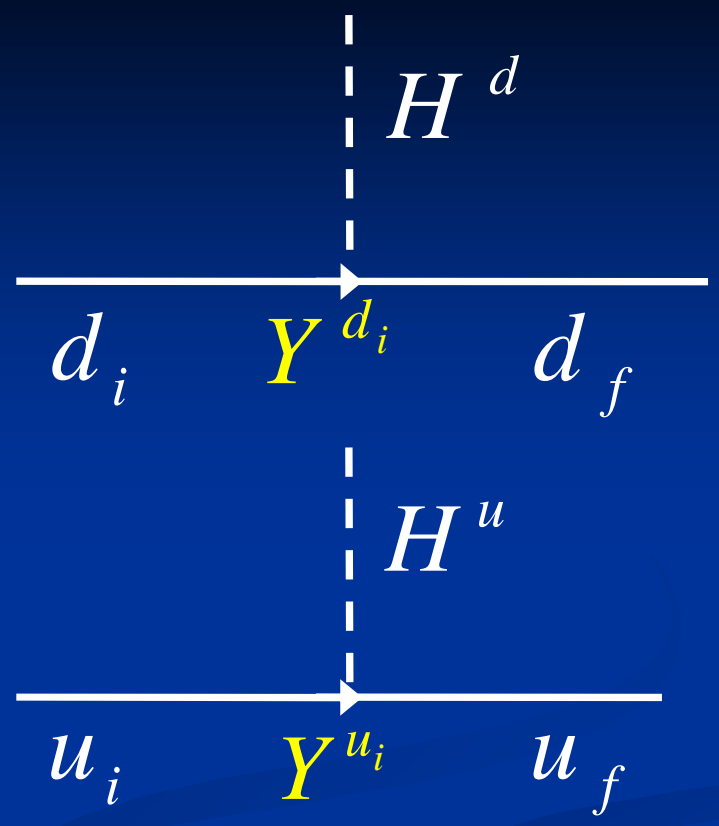
Flavour-Physics vs LHC



Challenges for New Physics in the Flavour Sector

- If new physics is natural, why is flavour-violation so small?
  - Minimal Flavour Violation D'Ambrosio et al. hep-ph/0207036, Buras et al., …
  - SPILT SUSY Giudice, Romanino et al. hep-ph/0406088
  - MSSM with Radiative Flavour Violation Lahanas *et al.* Phys.Lett. B122. Buchmüller *et al.* Phys.Lett. B121, Masiero *et al.* Phys.Lett. B126 Borzumati et al., hep-ph/9902443 Crivellin 11052818….
  - ….
- Can deviations from the SM be explained with a model of physics beyond the SM?

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)

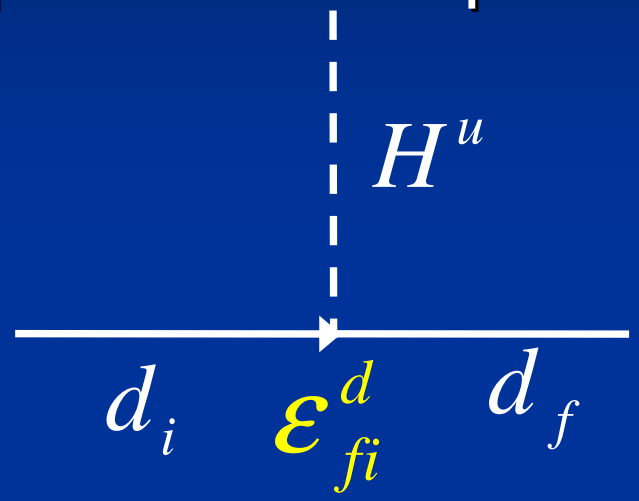
$$m_{q_i} = v_q Y^{q_i}$$

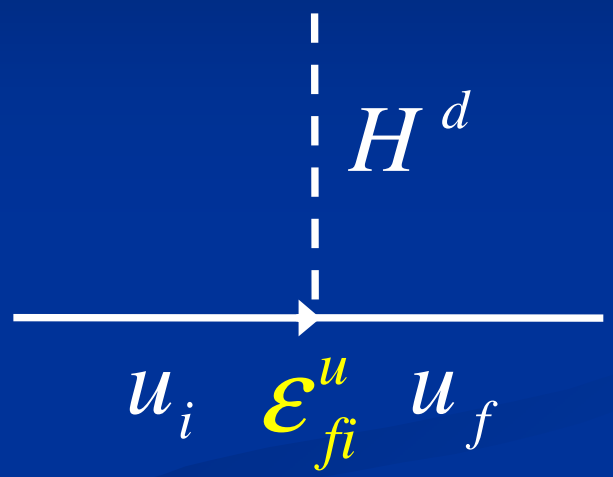
$$m_H \approx m_{A^0} \approx m_{H^\pm} \approx m_{H^0}$$

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

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.

$B_s \to \mu^+\mu^-$

- **New SM predictions**
  - Effect of Γ_s included
    De Bruyn et al. 1204.1737
  - New lattice result for f_{B_s}
    HPQCD, FLAG
  - NLO electroweak corrections
    Bobeth et al. 1311.1348
  - NNLO QCD corrections
    Hermann et al. 1311.1347

$$Br[B_s \to \mu\mu]_{LHCb+CMS} = (2.9 \pm 0.7) \times 10^{-9}$$

$$Br[B_s \to \mu\mu]_{SM} = (3.65 \pm 0.23) \times 10^{-9}$$

- Stringent constraints on scalar operators (e.g. Higgs induced flavour-violation)
- Starting to probe vector operators

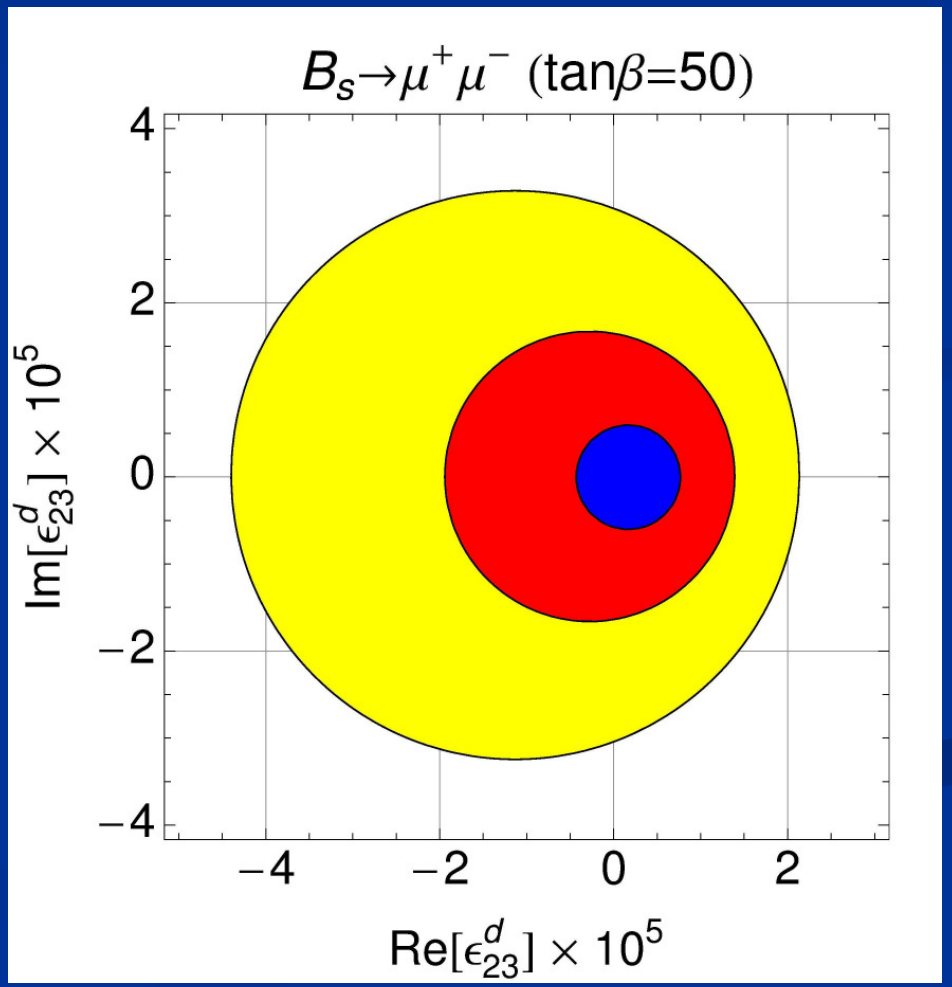
More in the talk of Tobias Hurt

$\tan(\beta) = 50$

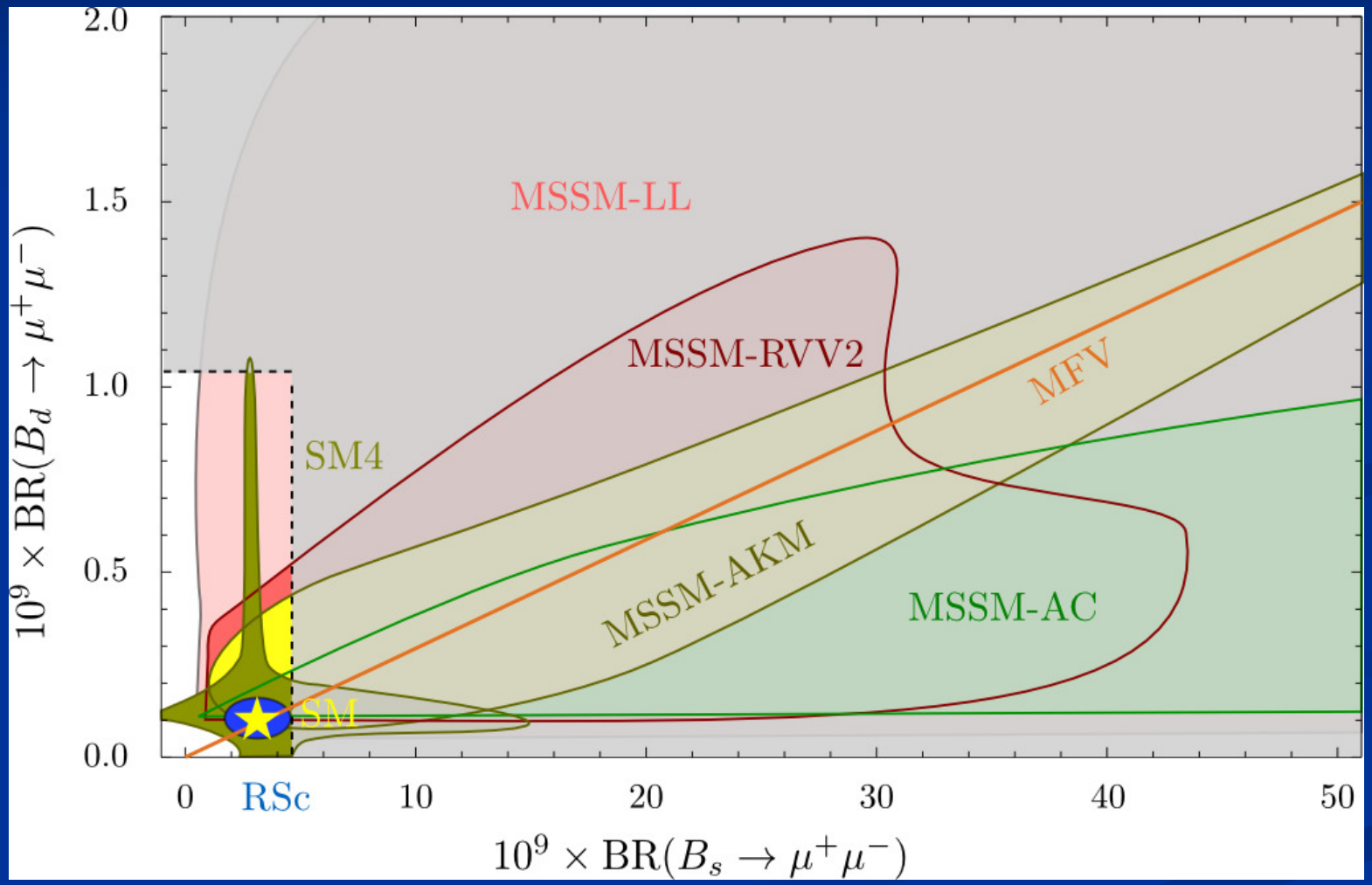
$m_H = 700$ GeV

$m_H = 500$ GeV

$m_H = 300$ GeV



Constraints on NP models from $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$



Plot from a talk of David Straub

$B \to X_q \gamma$

$\tan(\beta) = 50$

$m_H = 700$ GeV

$m_H = 500$ GeV

$m_H = 300$ GeV

$b \to s\gamma$

- NNLO QCD corrections

$Br[b \to s\gamma]_{\exp} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$

$Br[b \to s\gamma]_{SM} = (3.15 \pm 0.23) \times 10^{-4}$

M. Misiak et al. hep-ph/0609232

- Best constraints on the charged Higgs mass $m_H \geq 380$ GeV

Hermann et al. 1208.2788

$b \to d\gamma$

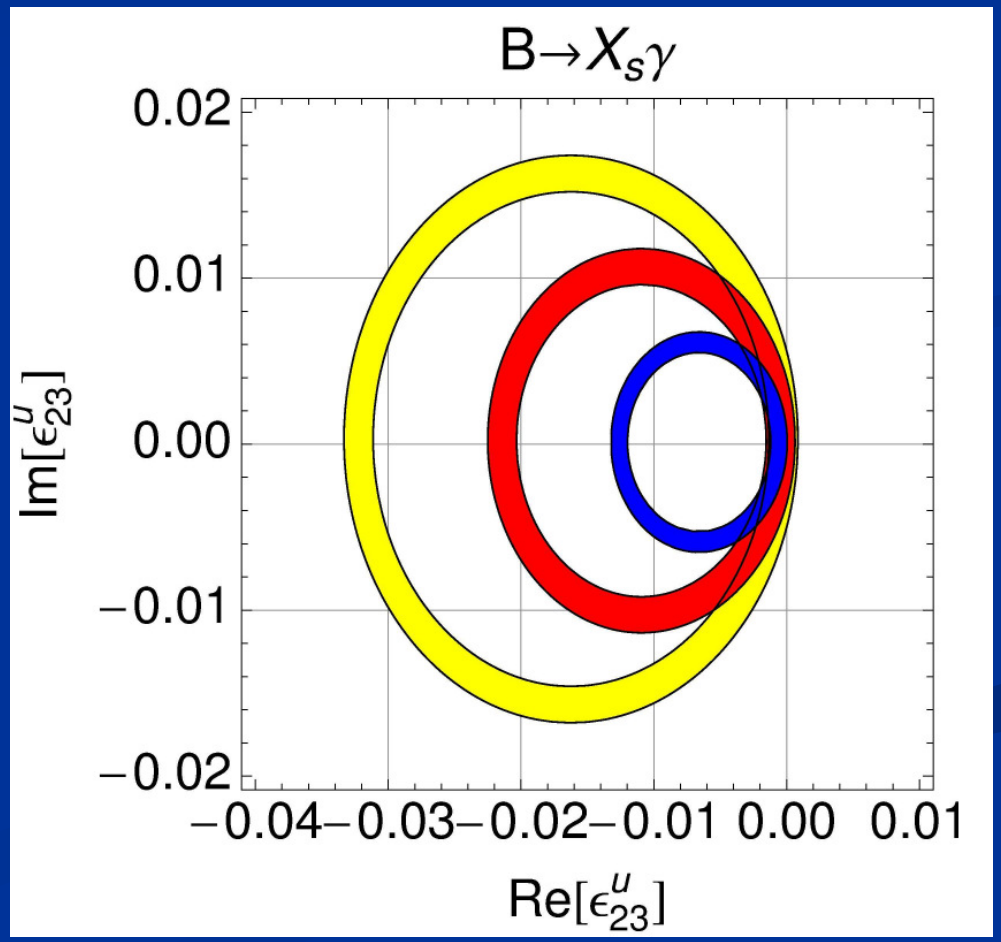
- Hadronic uncertainties largely drop out in the CP averaged BR

Benzke et al. 1003.5012, Hurth et al. 1005.1224

$Br[b \to d\gamma]_{\exp} = (1.41 \pm 0.57) \times 10^{-5}$

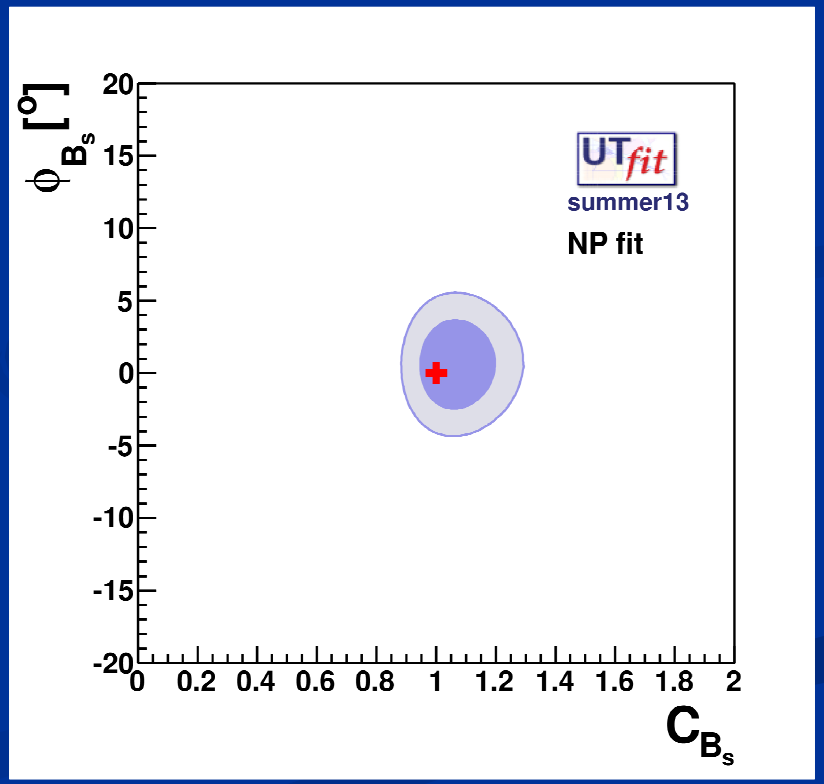
$Br[b \to d\gamma]_{SM} = 1.54^{+0.26}_{-0.31} \times 10^{-5}$

AC, L. Mercolli 1106.5499



Meson mixing

- Kaon mixing
  - Very sensitive to NP with additional phases
    generic NP > 10^5 TeV
    Most stringent constraints on extra dimensions
- B_s, B_d mixing
  - Now in good agreement with the SM
- D mixing
  - Poor SM prediction for the mass difference due to non-perturbative effects
  - No sign for additional phases



See for example A. Lenz et al. arXiv:1008.1593 for a review for B mixing

Squark mass splitting in the MSSM: Constraints from Kaon and D mixing

- Cancellations between different contributions

Non-degenerate squark masses are allowed

- Interesting for LHC benchmark scenarios.

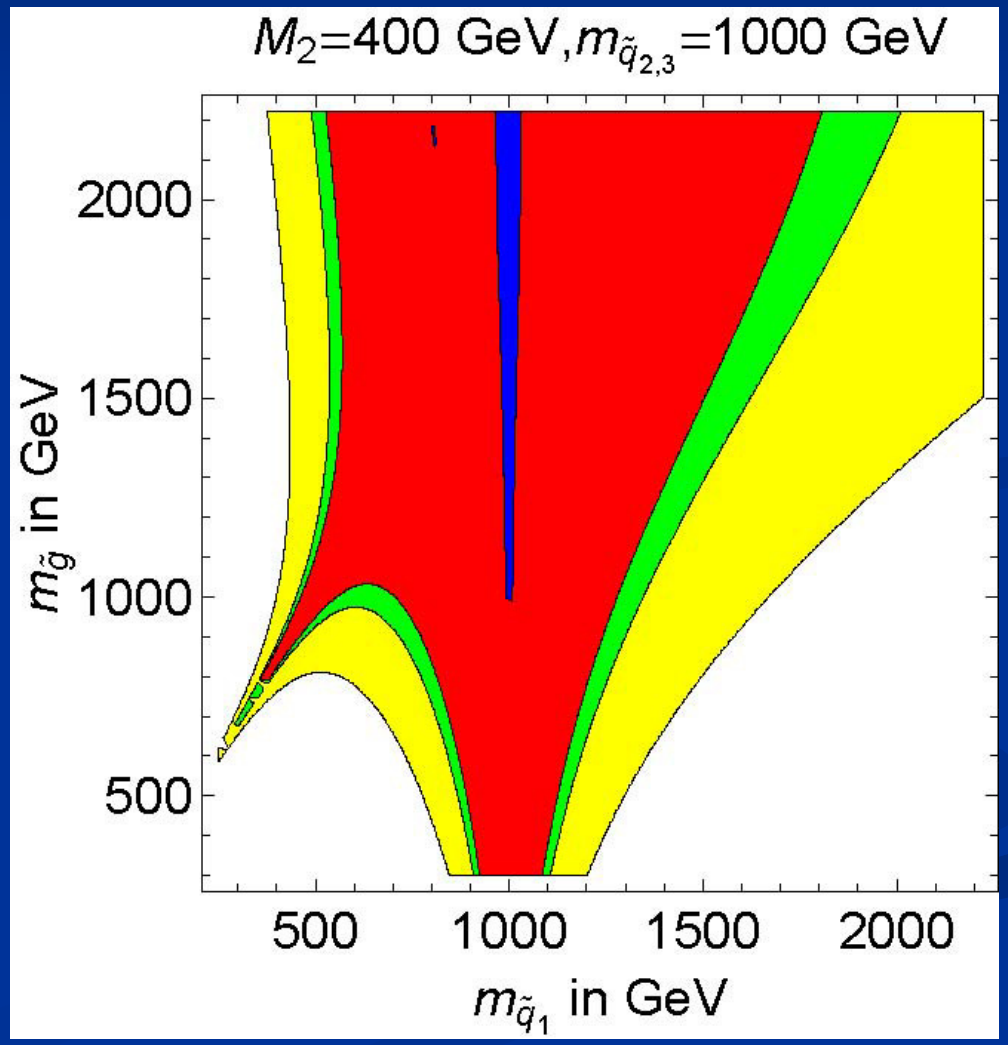
Maximally allowed mass-splitting

Alignment to $(Y^d)^2$
Constraints from D mixing

Alignment to $(Y^u)^2$
Constraints from Kaon mixing

Minimally allowed mass-splitting

Breaking of $SU(2)_F$, see talk by Jernej

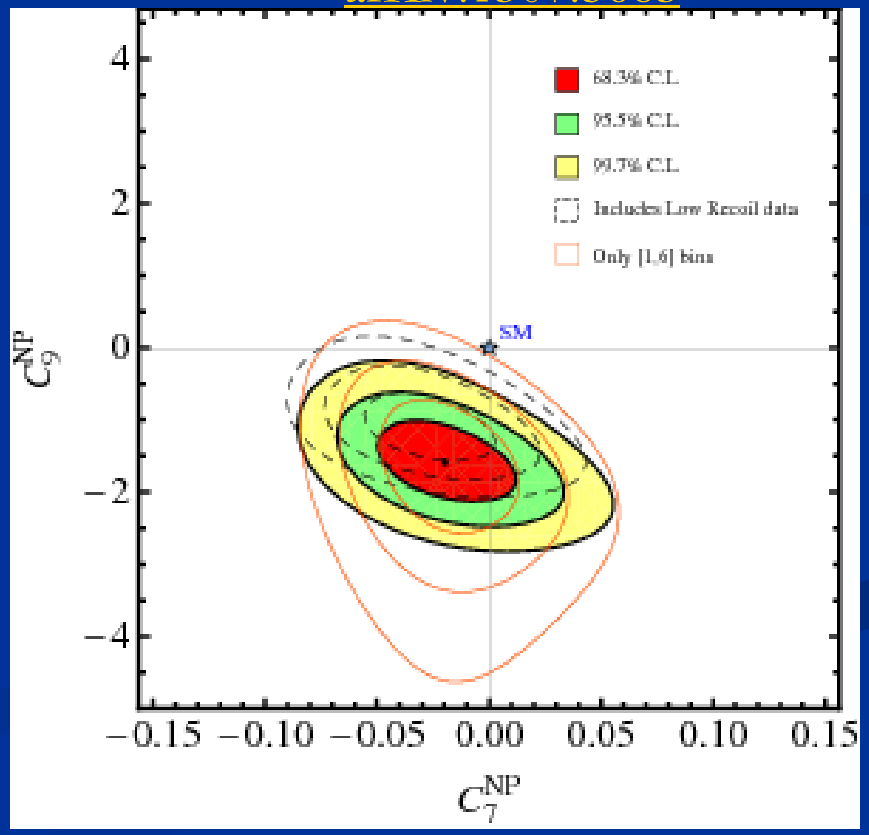


AC, M. Davidkov 1002:2653

B→K*μμ

- Several 2-3 σ deviations from the SM
- Can be explained by $O_9 = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \ell$
  Descotes-Genon et al. 1307.5683, Altmannshofer and DS 1308.1501, Beaujean et al. 1310.2478
- New physics explanation is hard
  (MSSM, 2HDM, extra dimensions not possible).
- Most natural explenation: Z'
  Gauld et al. 1310.1082,
  Buras et al. 1311.6729, ...
- Subleading hadronic effects might be langer than expected.

arXiv:1307.5683



Lepton Flavour Violation

- **In the SM with massive neutrinos EXTREMELY small O(10^{-50})**

Observation of LFV would establish physics beyond the SM

- $\mu \to e\gamma$ best constraints on generic NP
- $\mu \to e$ conversion talk by *Kyle Knoepfel*

excellent experimental prospects

sensitive to Higgs mediated flavour-violation

new predictions for the scalar-nucleon couplings
AC, M. Procura, M. Hoferichter arXiv:1404.7134

- $\tau \to \mu\mu\mu, \tau \to e\mu\mu, \tau \to eee, \mu \to eee$

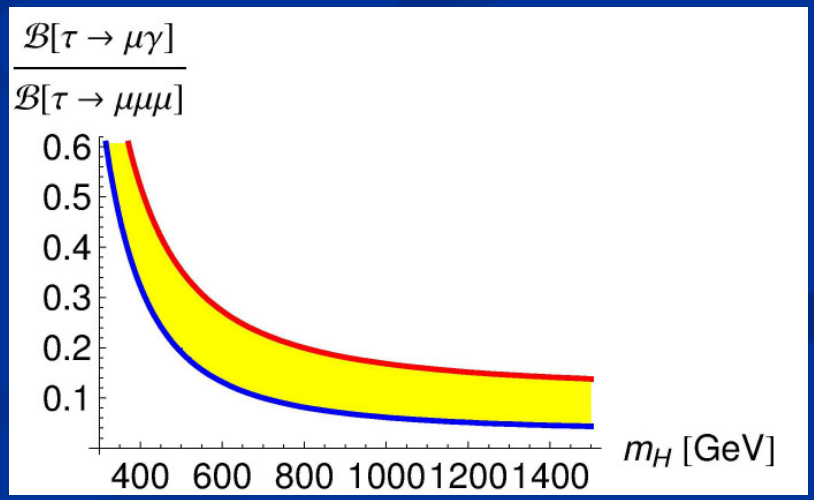
Sensitive to flavour-changing Z effects

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

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

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

Predicted ratio in the 2HDM



More in the talk by Asmaa Abada

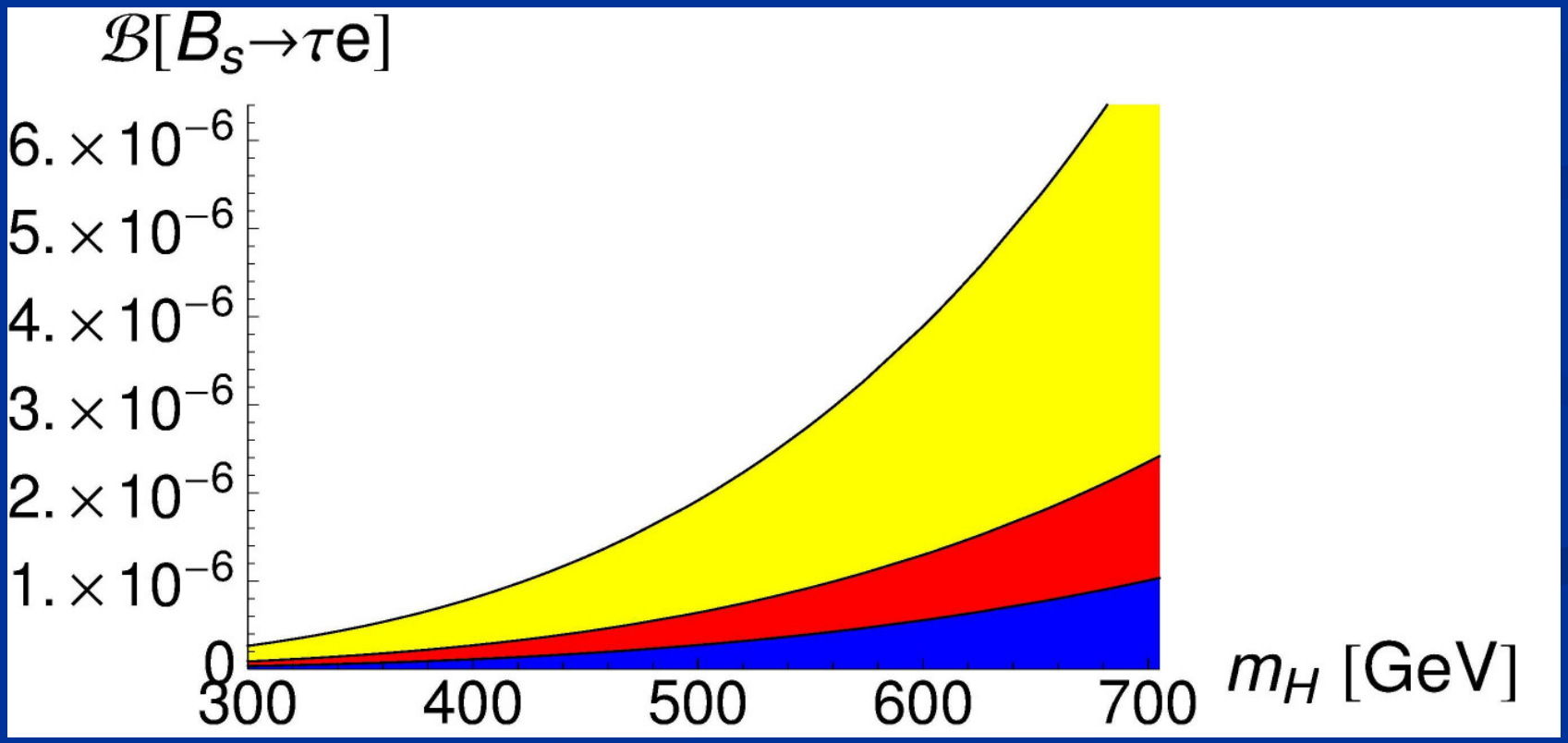
Lepton flavour violating B decays

$\tan(\beta) = 30$

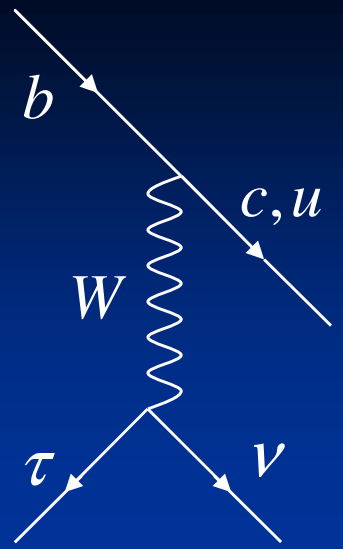
$\tan(\beta) = 40$

$\tan(\beta) = 50$

Allowed regions respecting the constraints from $\tau \to e\mu\mu$ **and** $B_s \to \mu^+\mu^-$



Tauonic B decays



see also talk by Jernej

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

More details in the talk by Ryoutaro Watanabe

Observable	SM	Experiment	Significance
$\mathrm{Br}[B \to \tau\nu]$	$(0.719^{+0.115}_{-0.076})\times 10^{-4}$	$(1.15 \pm 0.23)\times 10^{-4}$	$1.6\,\sigma$
$\mathrm{Br}[B \to D\tau\nu]/\mathrm{Br}[B \to D\ell\nu]$	0.297 ± 0.017	0.440 ± 0.072	$2.0\,\sigma$
$\mathrm{Br}[B \to D^*\tau\nu]/\mathrm{Br}[B \to D^*\ell\nu]$	0.252 ± 0.003	0.332 ± 0.030	$2.7\,\sigma$

➡ All three observables are above the SM prediction

Type-II 2HDM

- Allowed 2σ regions from: (superimposed)

$b \to s\gamma$

$B \to \tau\nu$

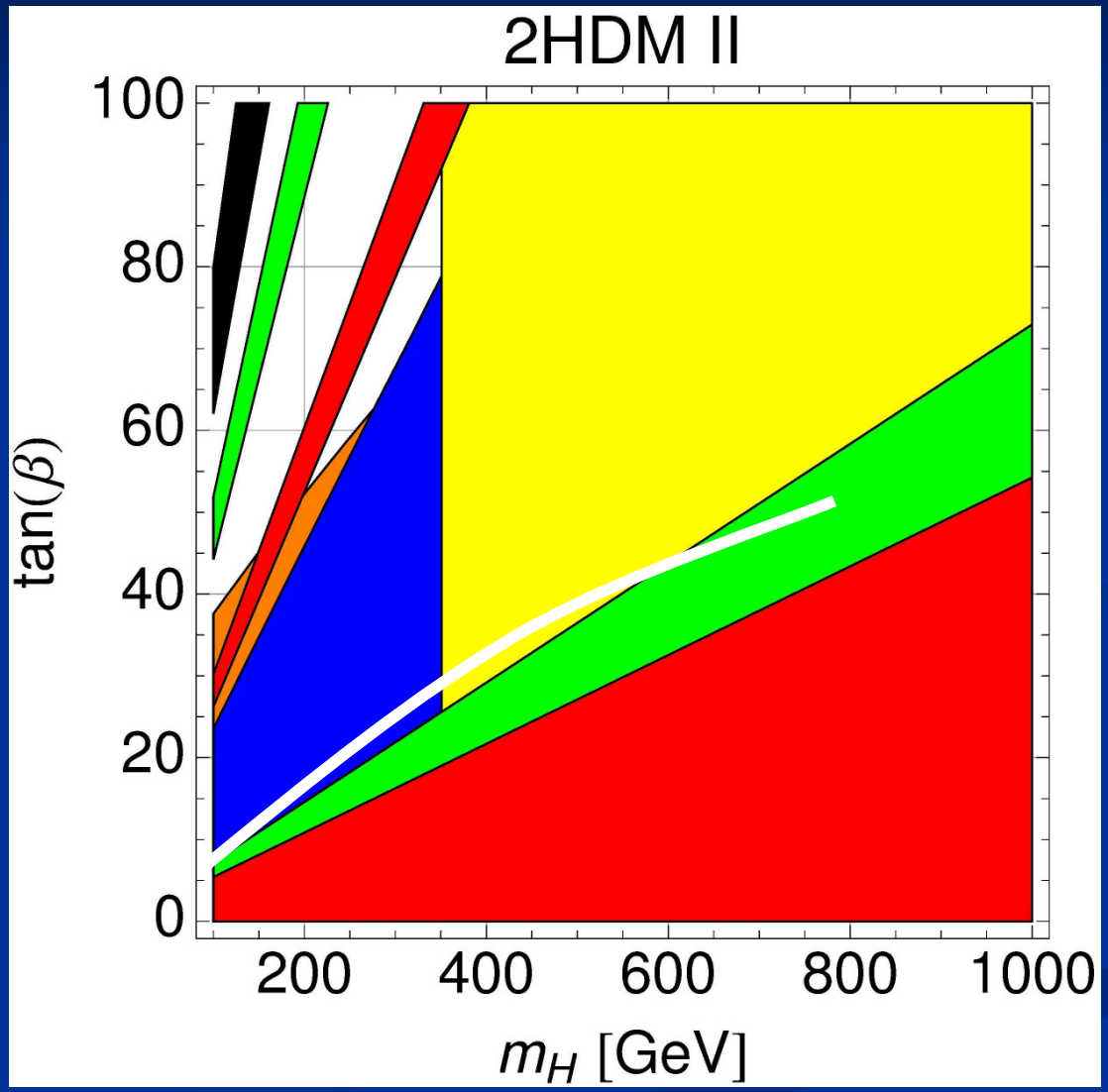
$K \to \mu\nu / \pi \to \mu\nu$

$B \to D\tau\nu$

$B_s \to \mu^+\mu^-$

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

LHC



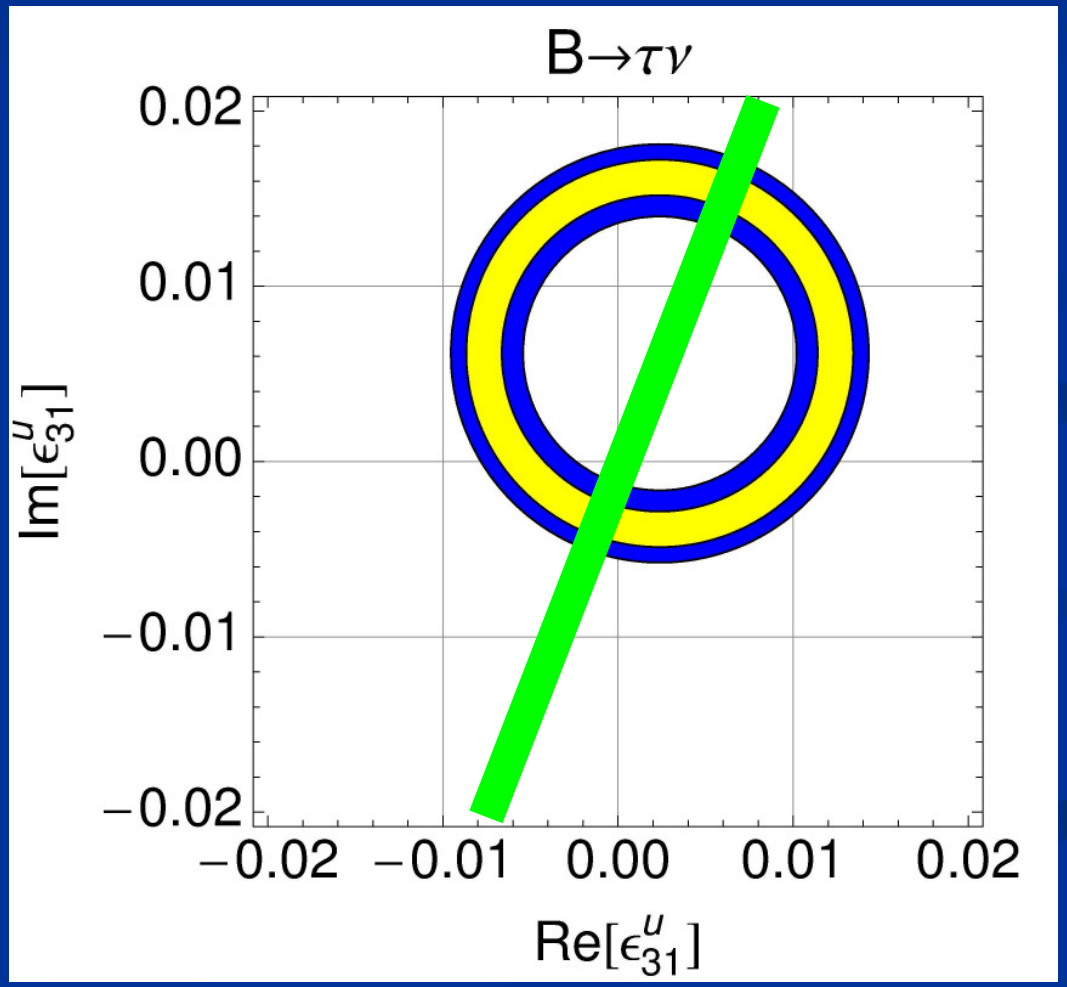
➡ Tension from $B \to D^*\tau\nu$

B→τν in the 2HDM III

- Constructive contribution to B→τν using ε_{31}^{u} is possible while satisfying the constraints from FCNC processes.

Allowed regions from:

- $B \to \tau\nu\ 1\sigma$
- $B \to \tau\nu\ 2\sigma$
- 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_{32}^{u} without violating bounds from FCNC processes.

Allowed regions from:

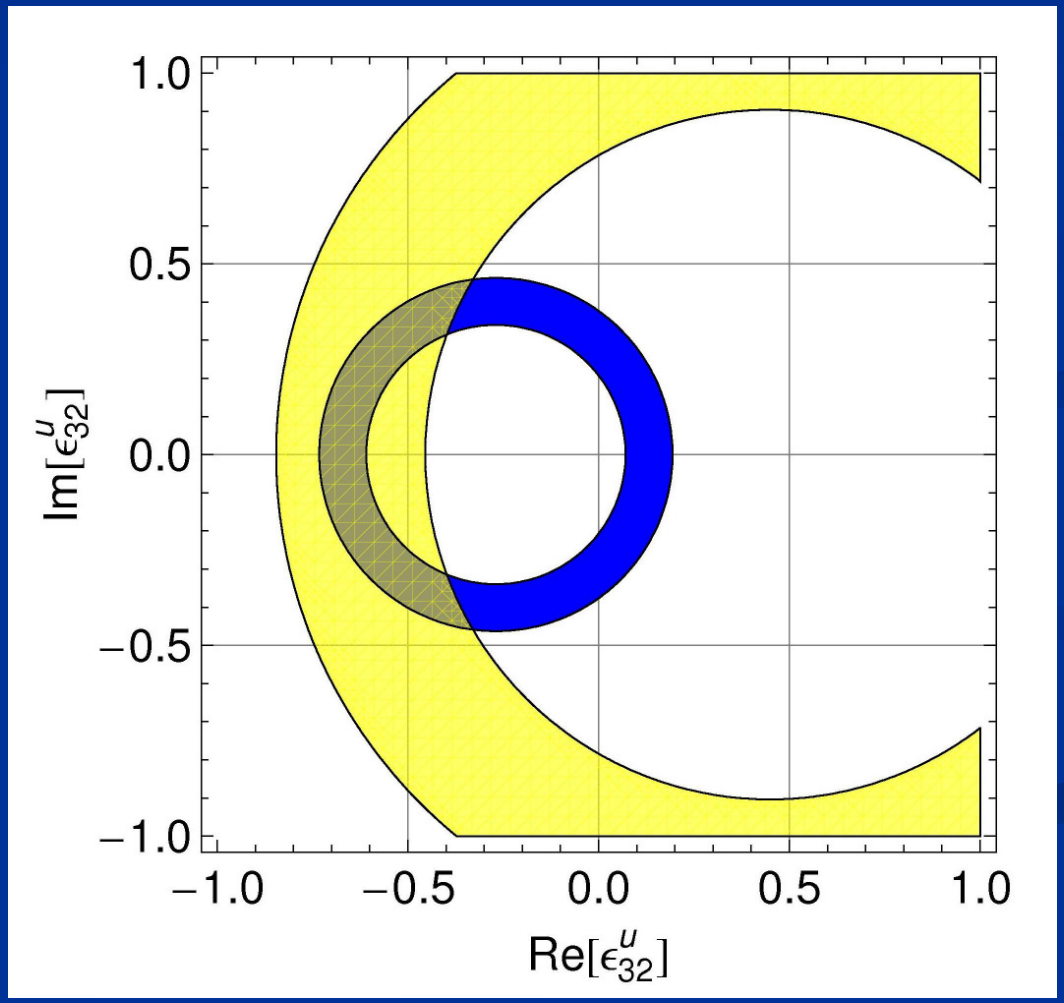
$B \to D\tau\nu$

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

Check model via

$H^0, A^0 \to \bar{t}c$

$t \to h^0 c$



Radiative flavour violation in the MSSM

CKM generation in the down-sector:

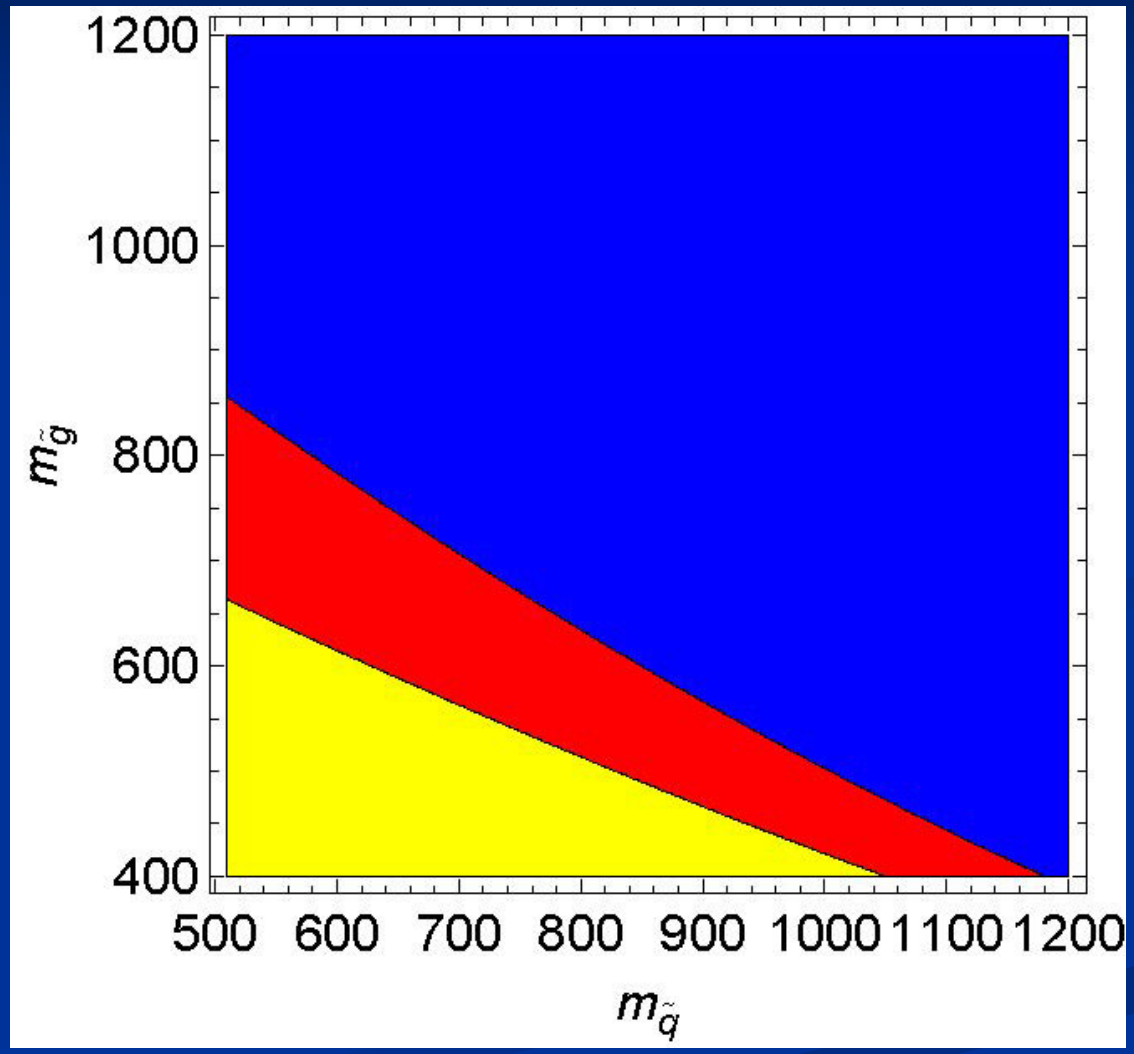
$$\Sigma_{13}^{d\,LR} \overset{!}{=} m_b V_{ub}$$

$$\Sigma_{23}^{d\,LR} \overset{!}{=} m_b V_{cb}$$

- Allowed regions from b→sγ.

  Chirally enhanced corrections must be taken into account.

  A.C., Ulrich Nierste 2009



$m_b \mu \tan(\beta) = 0.12\ \mathrm{TeV}^2$

$m_b \mu \tan(\beta) = 0\ \mathrm{TeV}^2$

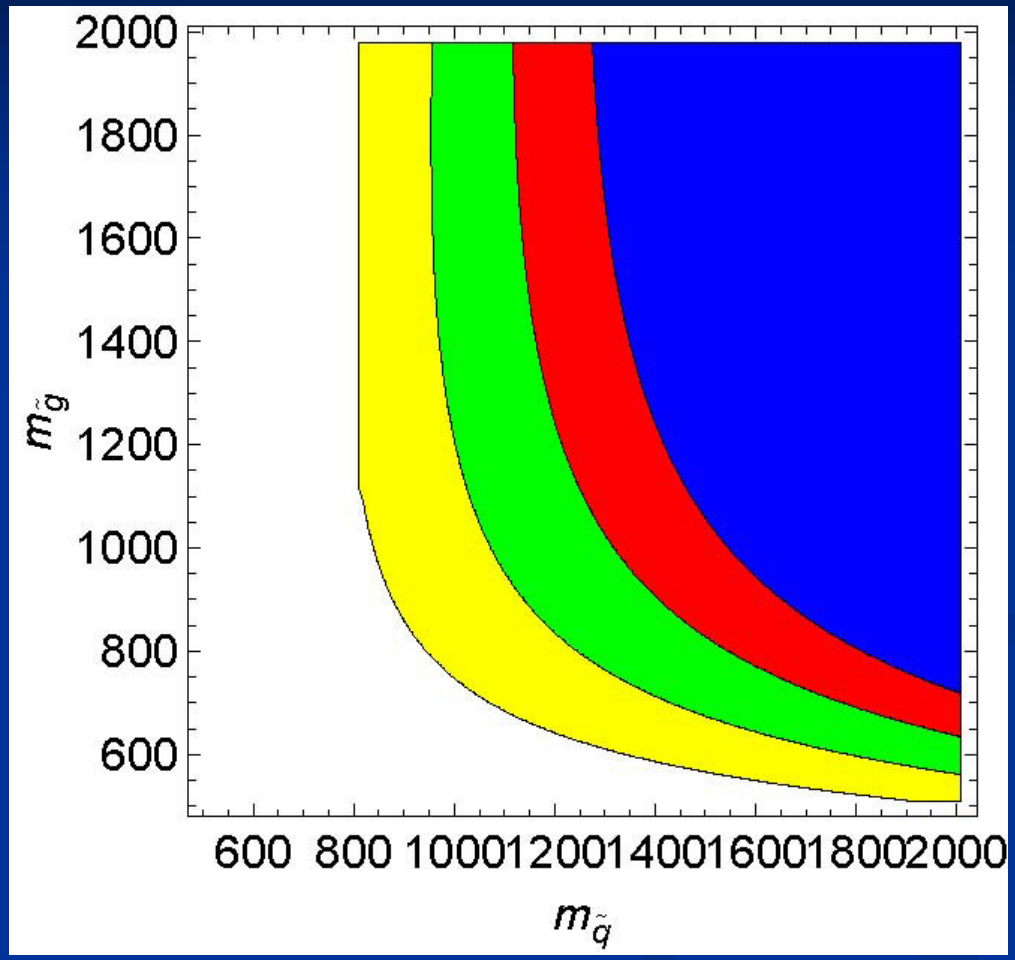
$m_b \mu \tan(\beta) = 0.12\ \mathrm{TeV}^2$

CKM generation in the up-sector:

$$\Sigma_{13}^{u\,LR} \overset{!}{=} m_t V_{td}^*$$

$$\Sigma_{23}^{u\,LR} \overset{!}{=} m_t V_{cb}^*$$

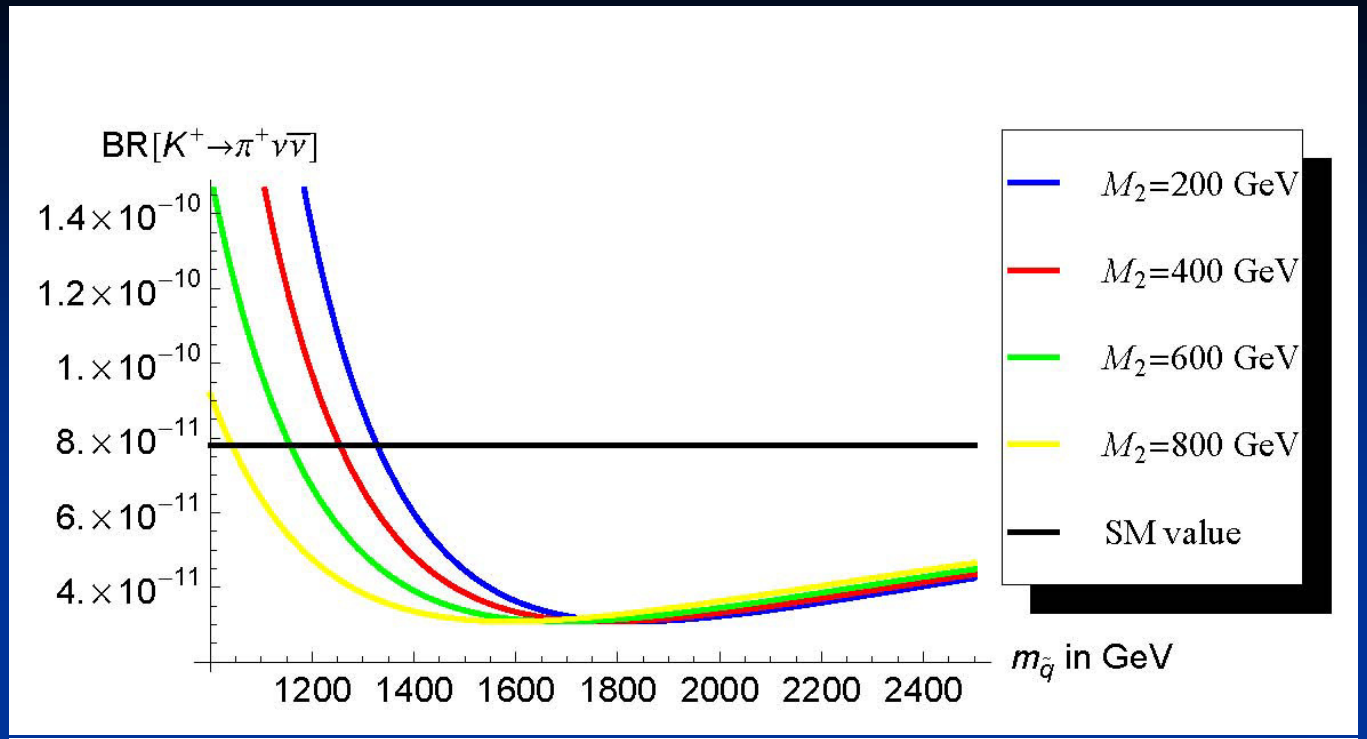
- Constraints from Kaon mixing.
- $\delta_{31}^{u\,LR}, \delta_{32}^{u\,LR}$ unconstrained from FCNC processes.
- $\delta_{31}^{u\,LR}$ can induce a sizable right-handed W coupling.

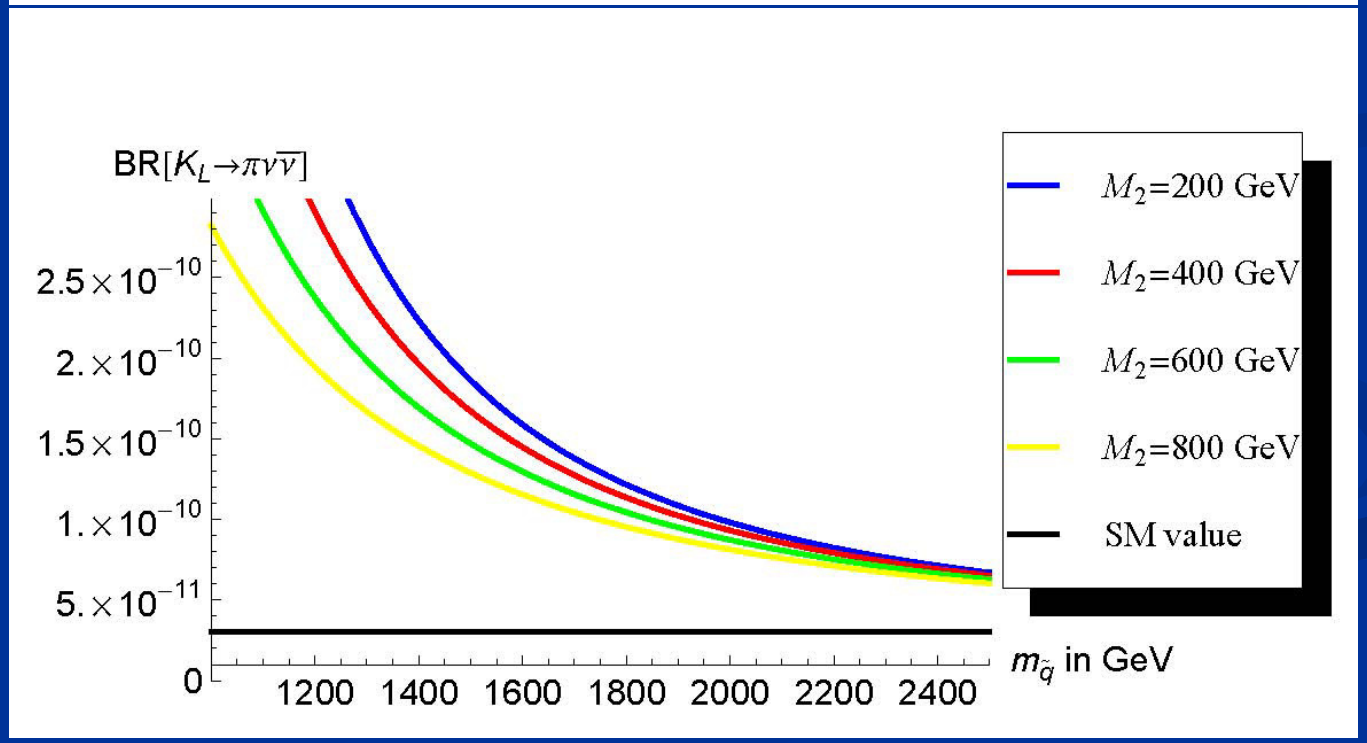


$M_2 = 200\text{GeV}$ $M_2 = 400\text{GeV}$

$M_2 = 400\text{GeV}$ $M_2 = 800\text{GeV}$

- Effects in K→πνν
- Verifiable predictions for NA62





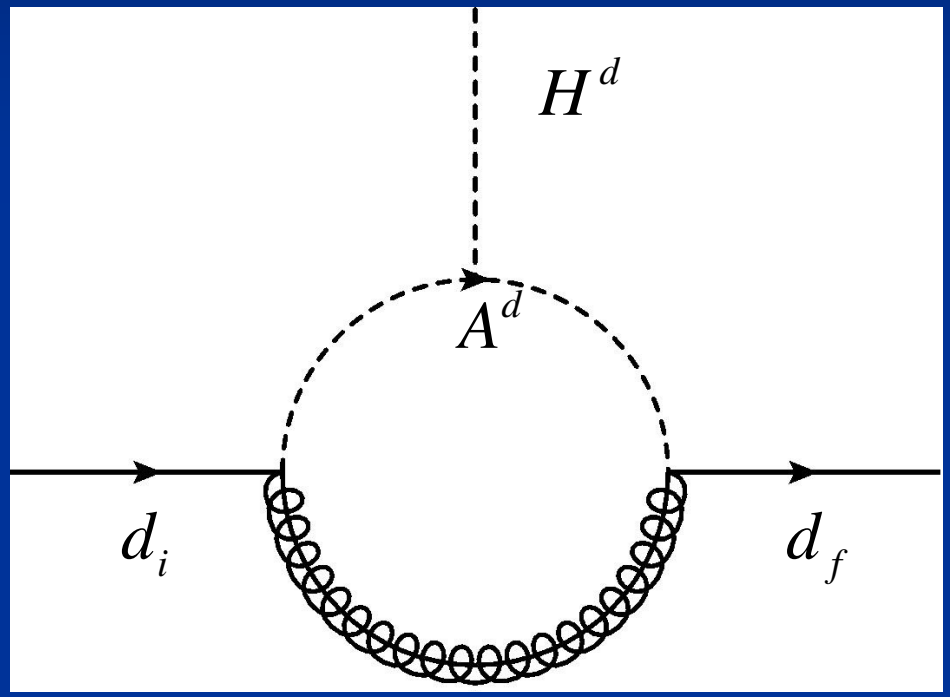
Challenges for New Physics in the flavour sector

1. Explain why is flavour-violation small in
   - $B_q \to \mu^+\mu^-$
   - $b \to q\gamma$
   - $\Delta F = 2$
   - EDMs
   - LFV
2. Explain possible deviations from the SM in
   - $B \to \tau\nu,\ B \to D^{(*)}\tau\nu$
   - a_μ
   - $B \to K^*\mu^+\mu^-$
   - See what the future brings…

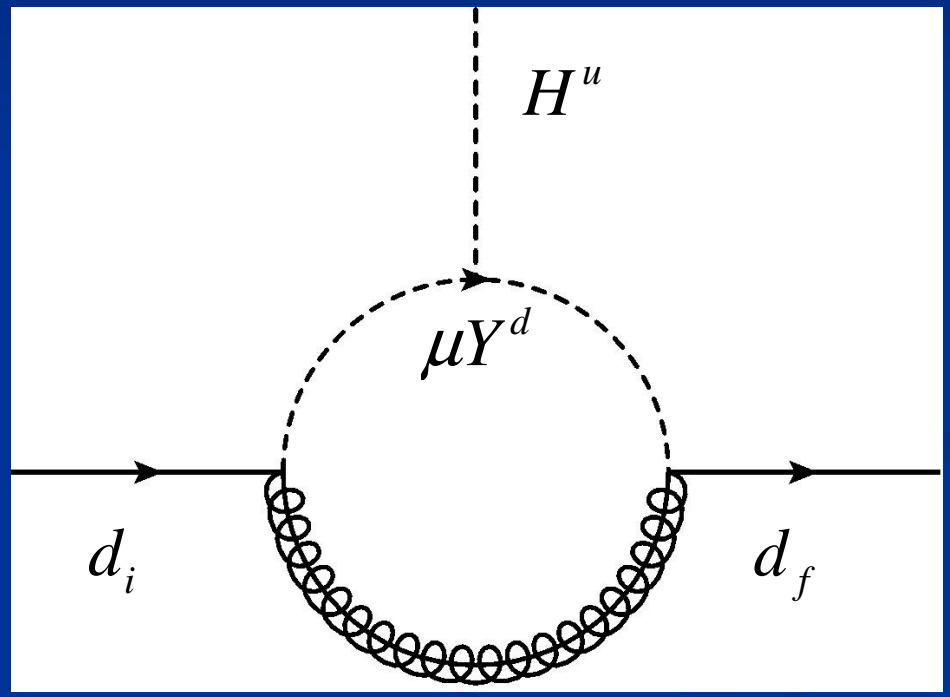
Backup

Loop corrections to Higgs-quark couplings in the MSSM

- Before electroweak symmetry breaking



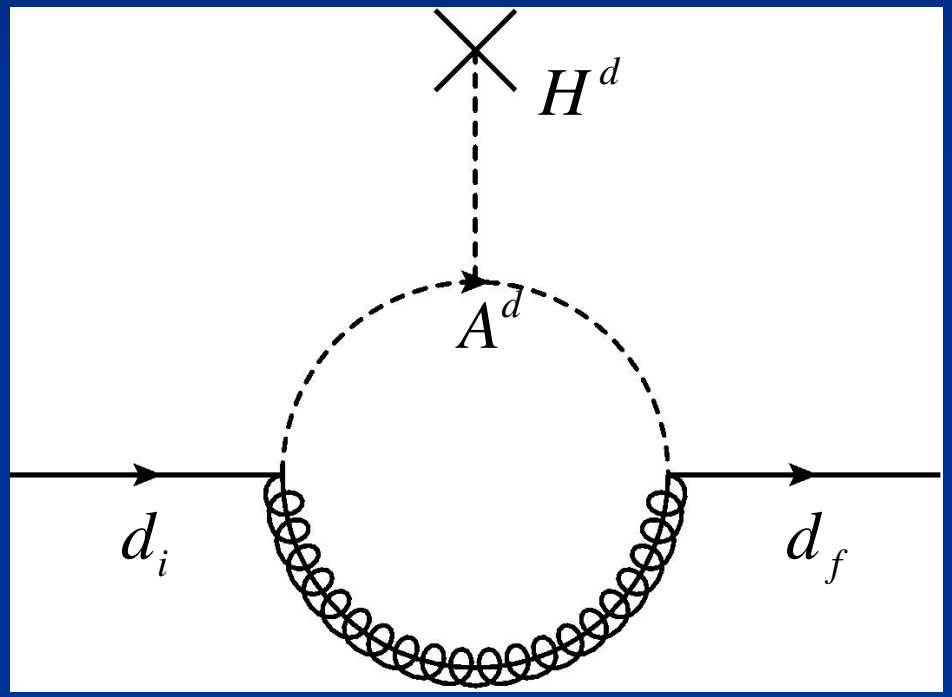
$$\Gamma^{H^d}_{d_f d_i}$$

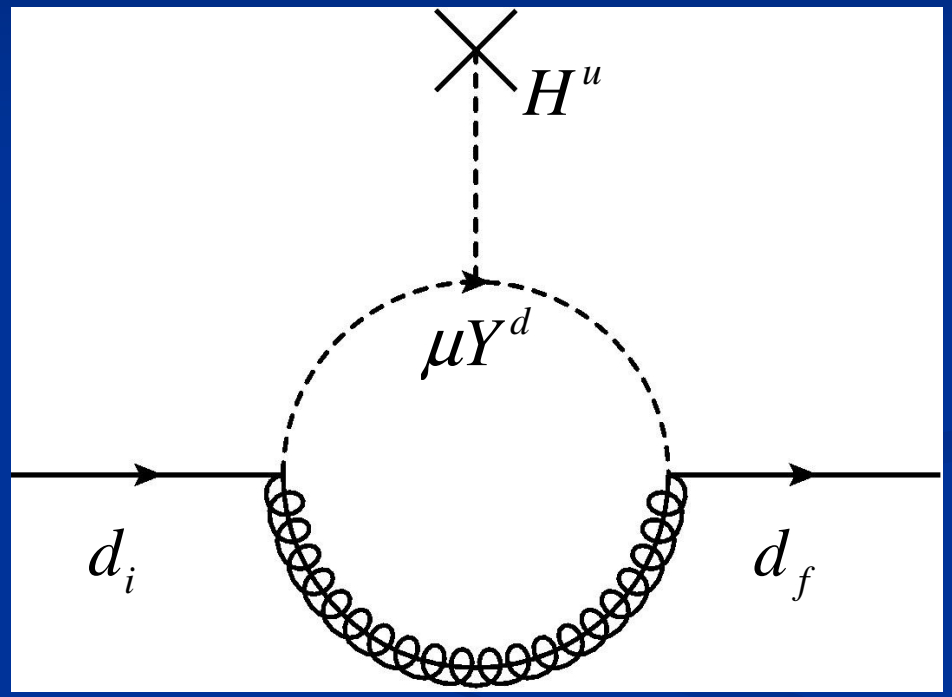


$$\Gamma^{H^u}_{d_f d_i}$$

Loop corrections to Higgs-quark couplings in the MSSM

- After electroweak symmetry breaking



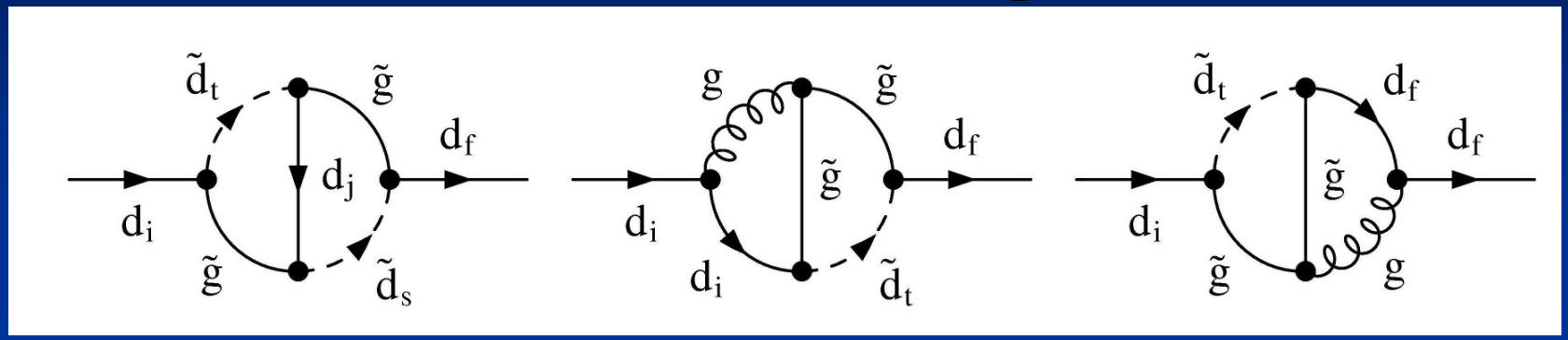


$$\Sigma^{d\,LR}_{fi\,A} = v_d \Gamma^{H^d}_{d_f d_i}$$

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

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

NLO calculation of the quark self-energies

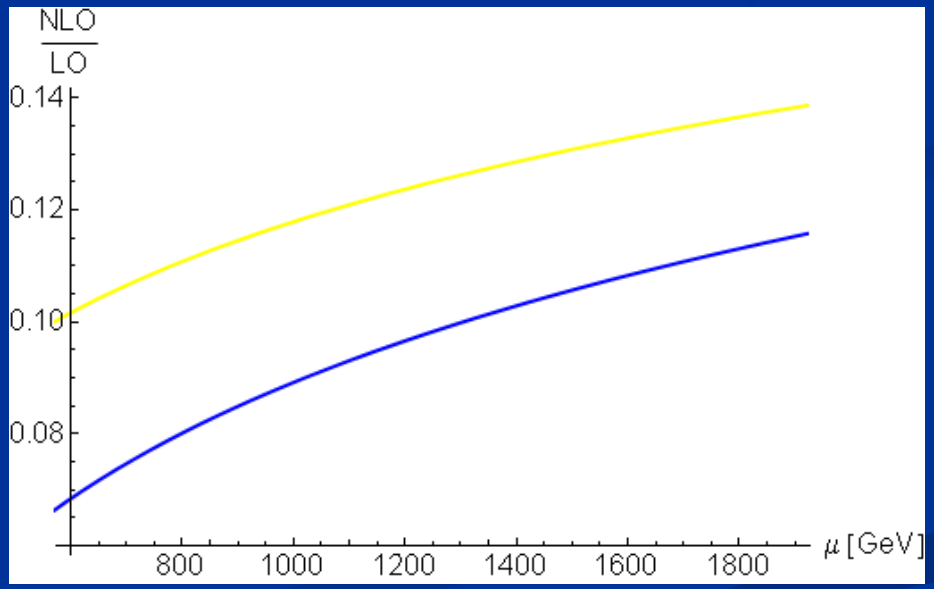


Example diagrams

NLO calculation is important for:

- Computation of effective Higgs-quark vertices.
- Determination of the Yukawa couplings of the MSSM superpotential.

Reduction of the matching scale dependence



$\overline{DR}$

on − shell