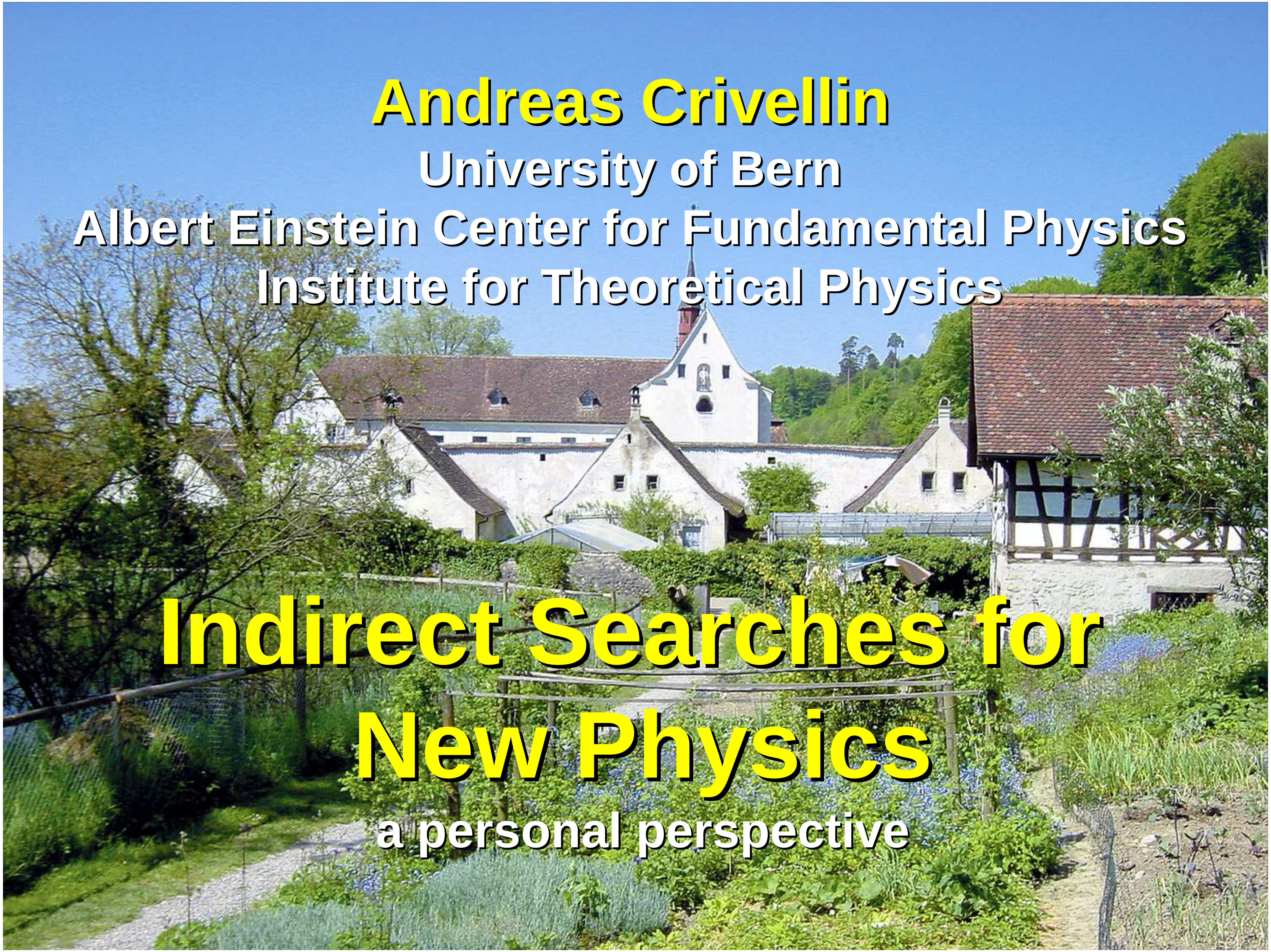

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Indirect Searches for New Physics

a personal perspective

Outline:

- Introduction
  - Indirect searches for New Physics
  - Flavour violation in the Standard Model and the determination of the CKM matrix.
  - Hints for NP?
- Two Higgs Doublet Models
  - Tauonic B decays in a 2HDM III
- Minimal Supersymmetric Standard Model (MSSM)
  - Constraints on the flavour structure and the "SUSY_FLAVOR" code
  - Flavour violation from SUSY-breaking
- Conclusions

Introduction

Indirect searches for New Physics

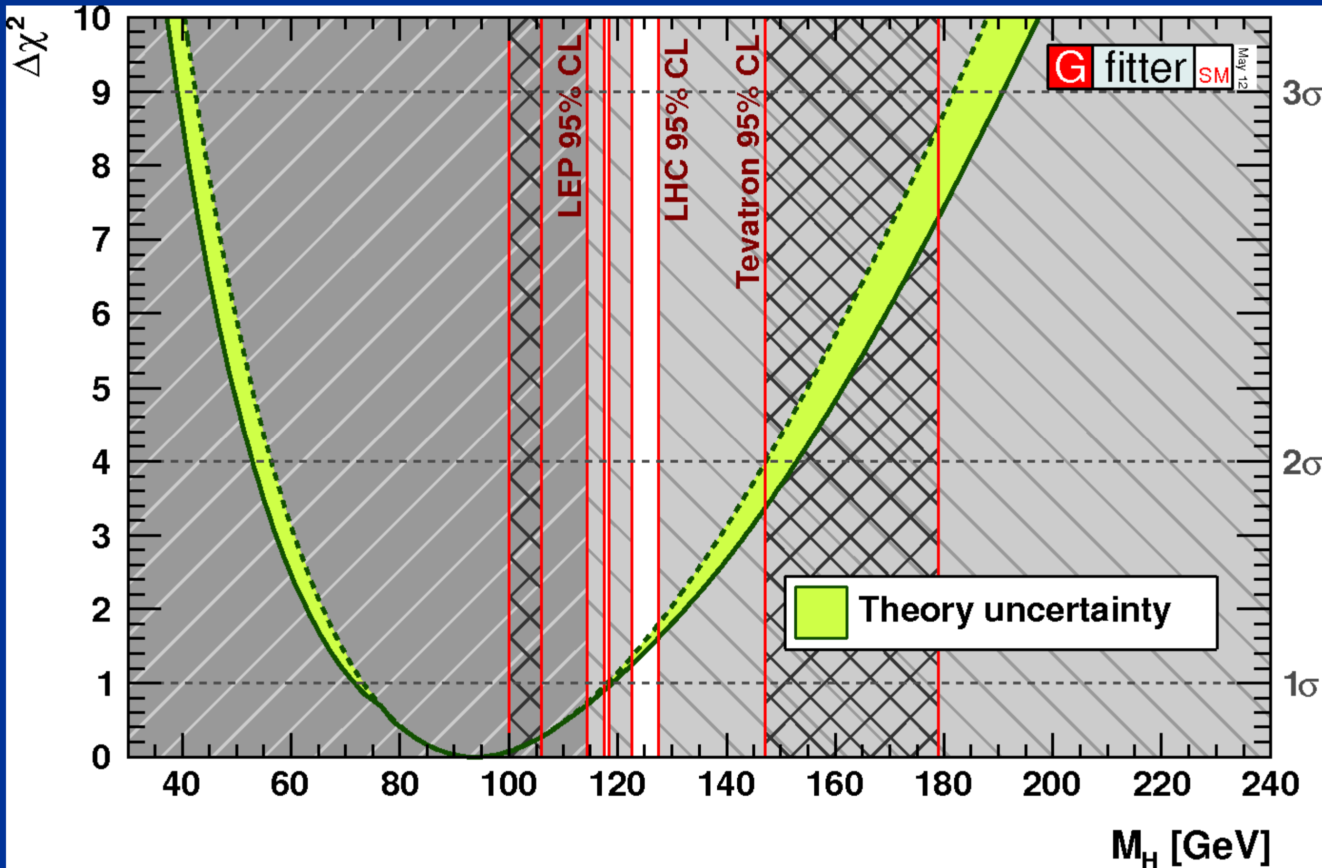
Indirect Searches for New Physics

Do low-energy observables which are sensitive to new (virtual) particles agree with the SM predictions?

- Tests of conservation laws
  - Proton decay (Baryon/Lepton number violation)
  - CPT violation
  - Neutrinoless double beta decay (lepton number violation)
- Electroweak precision observables
- Flavour observables
  - Anomalous Magnetic Moments
  - Electric dipole moments
  - Flavour-changing processes

Electroweak precision observables

- Higgs mass of 125 GeV fits well with the EW-precision data



Flavour-observables

- Anomalous magnetic moments (g-2) sensitive to chirality violating New Physics
- Electric dipole moments (test flavour-blind CP violation)
- Lepton flavour violation
  - Neutrino oscillations

    ➡ SM+ (with massive neutrinos)
  - Charged lepton flavour-violation

  $\mu \to e\gamma,\ \tau \to \mu\gamma,\ \tau \to e\gamma,\ \mu \to e$ conversion (forbidden in the SM)
- Quark flavour violation and CP violation
  - (Semi-) leptonic B and Kaon decays
  - Indirect determinations of the CKM matrix $\Delta F = 2$ processes
  - Rare decays $B_{d,s} \to \mu^+\mu^-, B_{d,s} \to \tau^+\tau^-, B \to \tau\nu, K \to \pi\nu\nu$

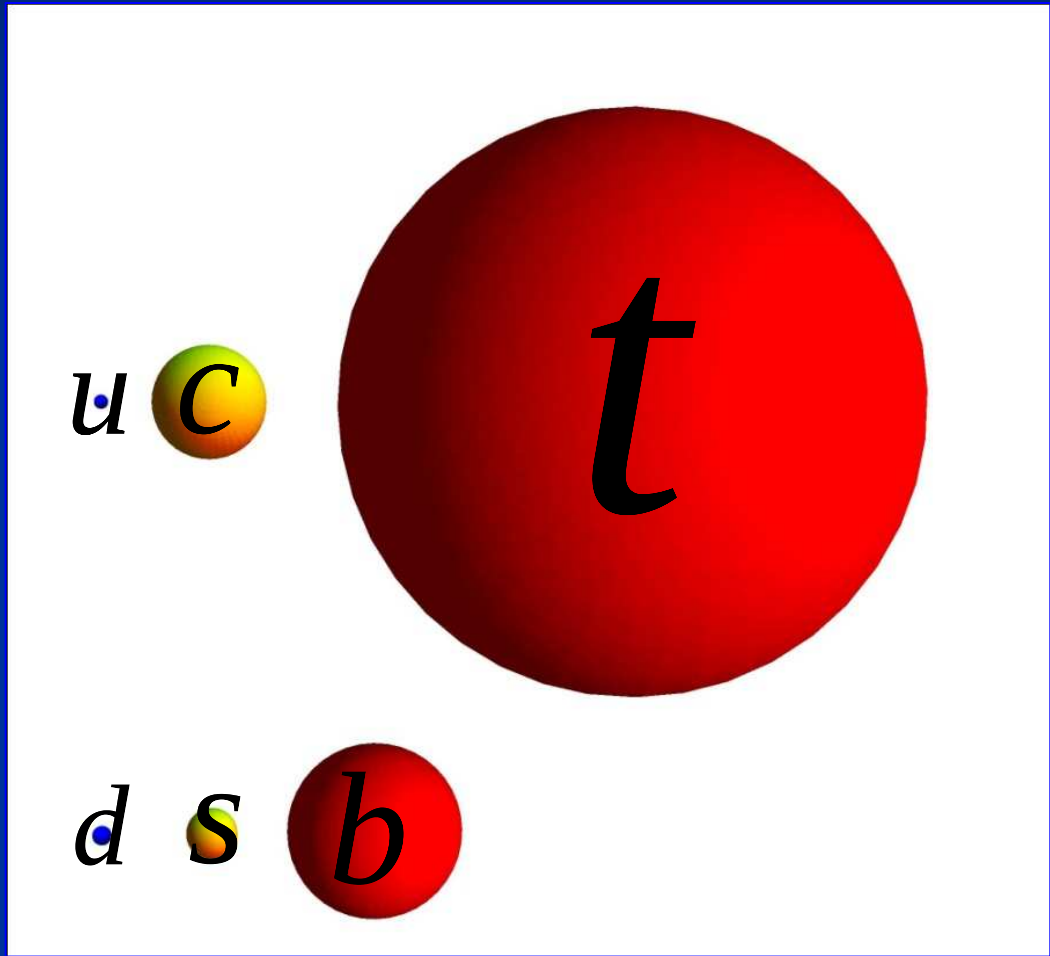
    $B \to X_{s,d}\gamma$

Quark flavour violation and the CKM matrix

Quark masses

- Coupling to the Higgs proportional to the mass.
- Bottom quark rather light, but Y^b can be big at large tan(β) in the MSSM or a 2HDM
- All other quark masses are very small

➡ sensitive to radiative corrections



CKM matrix

- CKM matrix is the only source of flavour and CP violation in the SM.
- No tree-level FCNCs
- Off-diagonal CKM elements are small

➡ Flavour-violation is suppressed in the Standard Model.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The Unitary Triangle

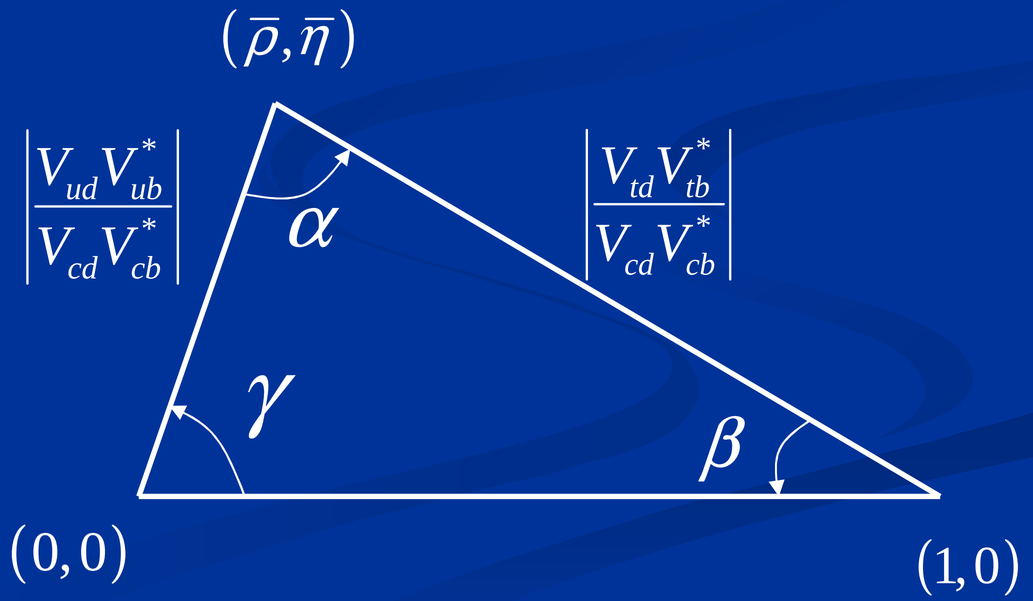
- 4 free parameter: 3 angles and 1 complex phase

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Unitary relation

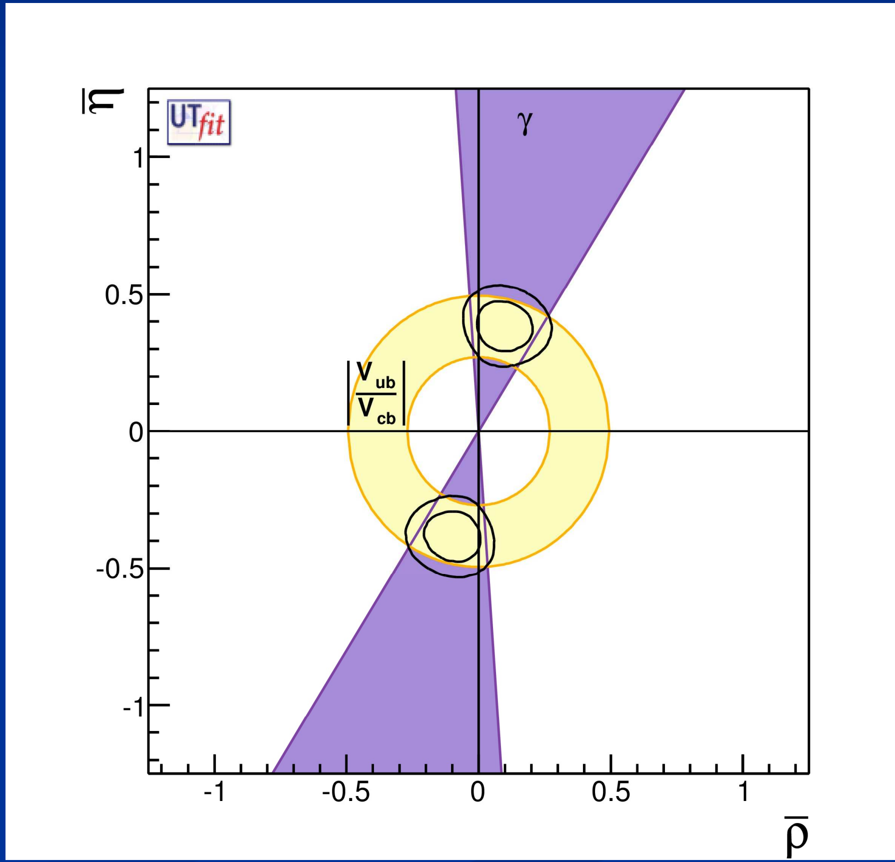
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$$\Rightarrow -\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} - \frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}} = 1$$



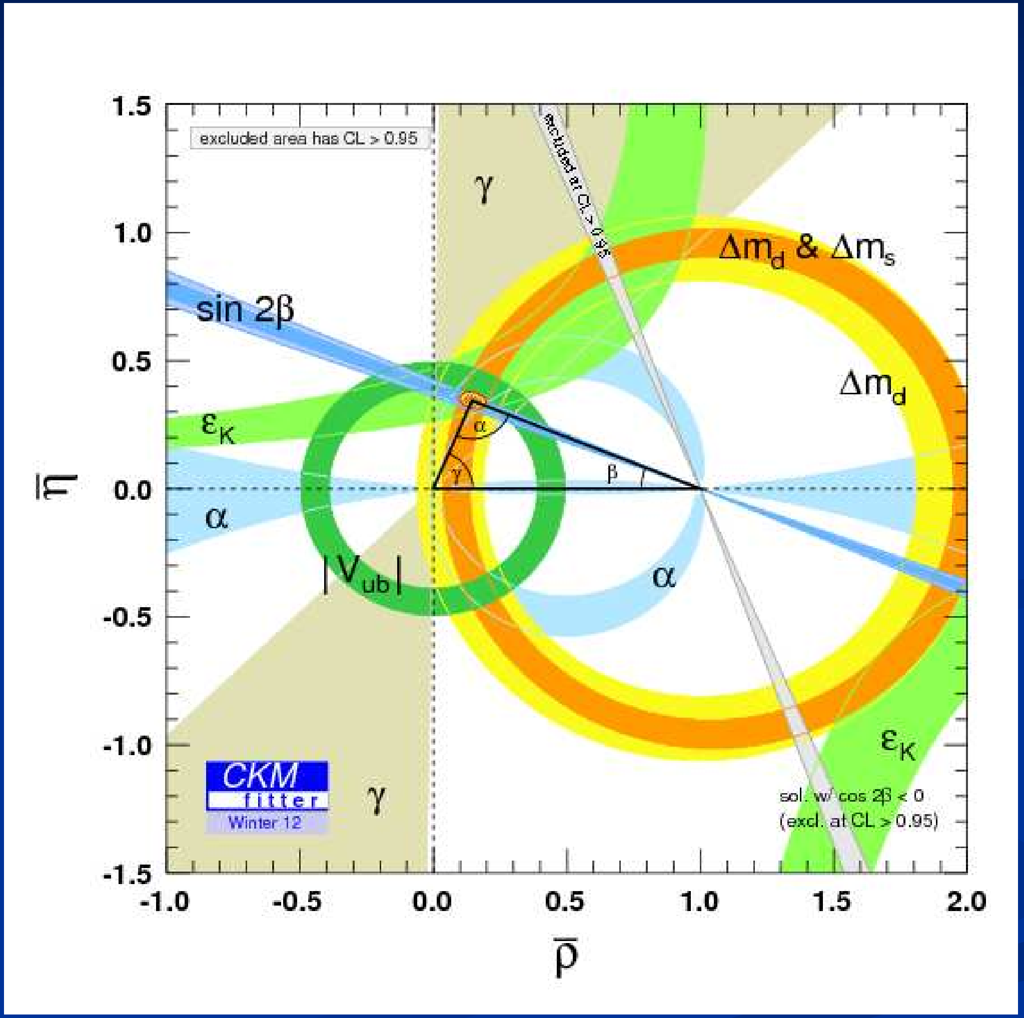
Determination of the CKM elements from tree-level decays

- Direct determination of $|V_{cb}|$ and $|V_{ub}|$ ($|V_{us}|$) from inclusive and exclusive semileptonic B (Kaon) decays.
  - In- and exclusive determinations of $|V_{cb}|$ agree reasonably (2.1 σ)
  - New Belle result makes the $|V_{ub}|$- problem from $B \to \tau\nu$ less severe. arxiv:1208.4678
- Determination of γ from $B^- \to D^0 K^-, B^- \to \bar{D}^0 K^-$



Global fit to the CKM matrix

- Determine UT including in addition constraints from loop-observables:
  - B_s mixing
  - B_d mixing
  - Kaon mixing
  - CP violation in B decays
- All determinations agree rather well



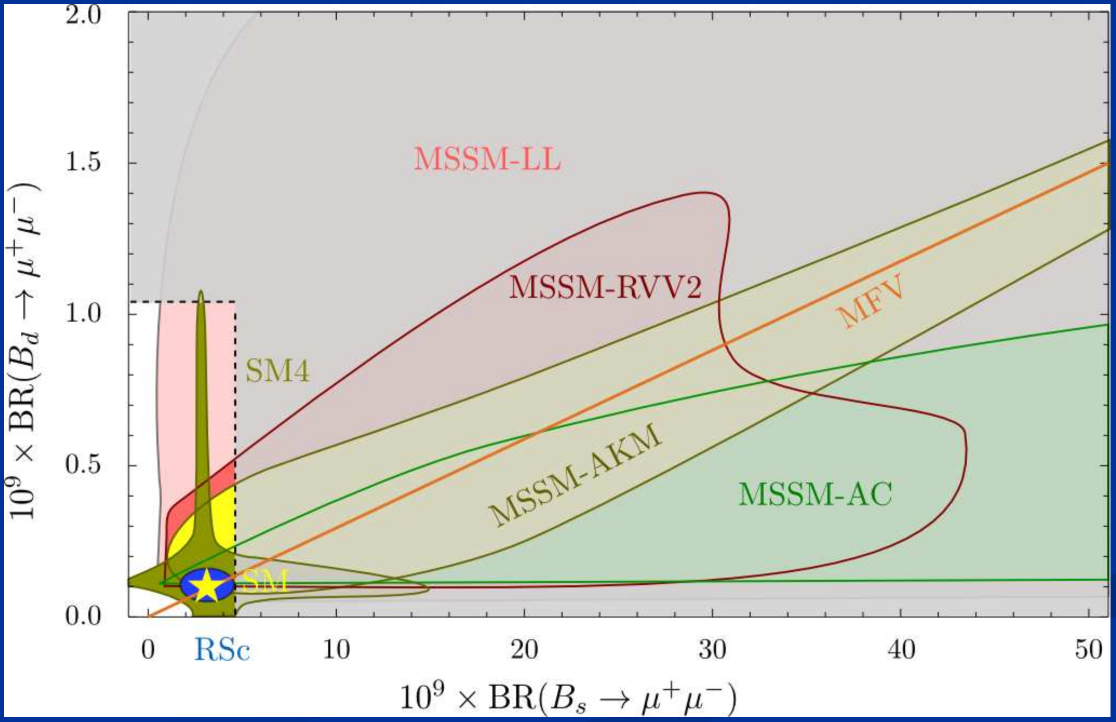
⟹ CKM mechanism of flavour violation works very well

Rare decays

- $B \to X_s \gamma$ perfectly compatible with the SM
- $B_s \to \mu^+\mu^-$ CDF found an excess but LHCb and CMS didn't confirm this. New upper bound close to the SM expectation.
- $B_d \to \mu^+\mu^-$ new LHCb bound
- $K \to \pi\nu\nu$ waiting for Na62
- $B_d \to \tau^+\tau^-$, $B \to K\nu\nu$ SuperB, Belle II

⟹ No sign of NP (yet)

Constraints on NP models



Plot from David Straub's talk at Moriond EW 2012

Hints for New Physics?

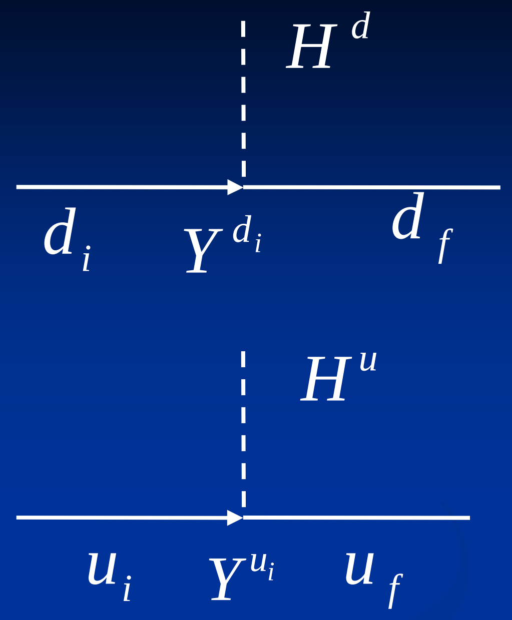
- CP violation in $\mathrm{D} \to \mathrm{K}^+\mathrm{K}^-,\ \mathrm{D} \to \pi^+\pi^-$
  3.8 σ but large hadronic uncertainties.
- Anomalous magnetic moment of the muon
  ~ 3.6 σ above the SM prediction
- Tauonic B decays

Observable	SM	Experiment	Significance
$\mathrm{Br}[B \to \tau\nu]$	$\left(0.757^{+0.098}_{-0.061}\right)\times 10^{-4}$	$(1.15 \pm 0.23)\times 10^{-4}$	$1.3\,\sigma$
$\mathrm{Br}[B \to D\tau\nu]/\mathrm{Br}[B \to D\ell\nu]$	0.297 ± 0.017	0.440 ± 0.072	$2.0\,\sigma$
$\mathrm{Br}\left[B \to D^*\tau\nu\right]/\mathrm{Br}\left[B \to D^*\ell\nu\right]$	0.252 ± 0.003	0.332 ± 0.030	$2.7\,\sigma$

⇒ All three observables are above the SM prediction

Two Higgs Doublet Models (2HDMs)

2HDM of type II



- One Higgs doublet couples only to down-quarks the other Higgs doublet only to up-quarks.
- 2 additional free parameters: $\tan(\beta)=v_u/v_d$ and the heavy Higgs mass M_H
- Neutral Higgs-quark couplings are flavour-conserving.
- Charged Higgs contribution to $b \to s\gamma$ requires $m_H > 380$ GeV T. Hermann, M. Misiak and M. Steinhauser 1208.2788
- Contribution to $B \to \tau\nu$ necessarily destructive.
- Cannot explain $B \to D^{(*)}\tau\nu$ and $B \to D\tau\nu$ simultaneously. BaBar collaboration 1205.5442

⟹ Disfavored by current data

2HDM of type III

- Both Higgs doublets couple simultaneously to up and down quarks

➡ Flavour-changing neutral Higgs couplings

- All flavour-changing elements ε^d_{fi} and $\varepsilon^u_{12,21}$ are constrained from FCNCs processes.
- Also $\varepsilon^u_{13,23}$ constrained from charged Higgs diagrams, but $\varepsilon^u_{31,32}$ is unconstrained.
- 2HDM III with MFV cannot explain B→τν, B→D$^{(*)}$τν and B→Dτν

2HDM of type III with flavour-violation in the up-sector

A.C., C. Greub, A. Kokulu 1208.2788

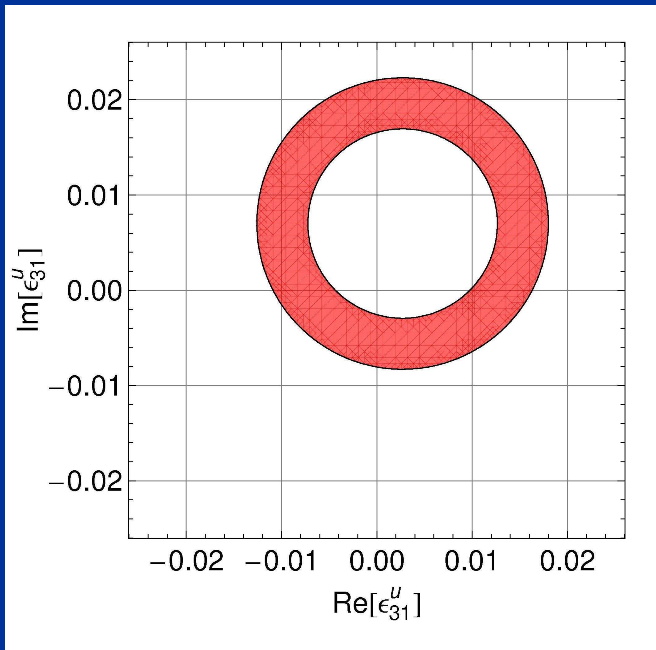
- Constructive contribution to B→τν using ε_{31}^{u} is possible.
- B→D(*)τν and B→Dτν can be explained simultaneously using ε_{32}^{u}. ➡ Check model via $H^0, A^0 \to \bar{t}c$

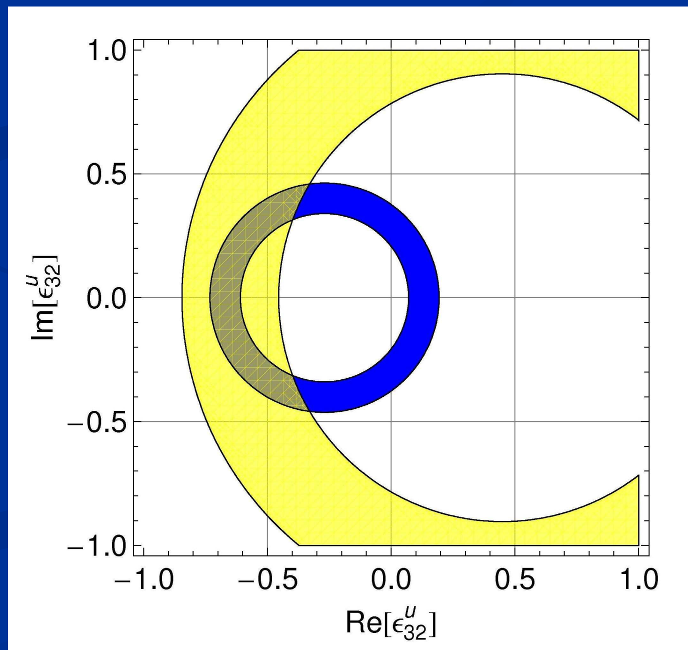
Allowed regions from:

$B \to D\tau\nu$

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

$B \to \tau\nu$





Constraints on the MSSM Flavour Structure

SUSY flavour (CP) problem

- The squark mass matrices are not necessarily diagonal (and real) in the same basis as the quark mass matrices.
- Especially the trilinear A-terms can induce dangerously large flavour-mixing (and complex phases) since they don't necessarily respect hierarchy of the SM.
- The MSSM possesses two Higgs-doublets: Flavour-changing charged and (loop-induced) neutral Higgs interactions.

➡ Why is the observed flavour violation so small?

- Possible solutions:

  - MFV D'Ambrosio, Giudice, Isidori, Strumia hep-ph/0207036

  - Flavour-symmetries

  - effective SUSY Barbieri et at hep-ph/10110730

  - Radiative flavour violation

Squark mass matrix

$$M_{\tilde{q}}^2 = \begin{pmatrix} M_{LL}^{\tilde{q}\,2} & \Delta^{\tilde{q}\,LR} \\ \Delta^{\tilde{q}\,LR\dagger} & M_{RR}^{\tilde{q}\,2} \end{pmatrix}$$

$M_{LL,RR}^{\tilde{q}\,2}$ and $\Delta_{ij}^{q\,LR}$ are 3x3 matrices in flavour-space

$M_{LL,RR}^{\tilde{q}\,2}$ are chirality conserving

$\Delta_{ij}^{q\,LR}$ chirality changing

$$\tan(\beta) = \frac{v_u}{v_d}$$

$$\Delta_{ij}^{d\,LR} = -v_d\left(\mu\tan(\beta)\,Y_i^d\delta_{ij} + A_{ij}^d\right)$$

$$\Delta_{ij}^{u\,LR} = -v_u\left(\mu\cot(\beta)\,Y_i^u\delta_{ij} + A_{ij}^u\right)$$

$$\delta_{ij}^q = \frac{\Delta_{ij}^q}{\tilde{m}_{\tilde{q}}^2}$$

Constraints on the off-diagonal elements of the sfermion mass matrices

Except $\delta^{u\,RR,RL}_{23,13}$ all elements are stringently constrained.

SUSY_FLAVOUR 2.0
A.C., J. Rosiek et al, arXiv:1203.5023
can calculate these observables including the numerically important resummation of all chirally enhanced corrections.
L. Hall, R. Rattazzi, U. Sarid hep-ph/9306309,
A.C., L. Hofer, J. Rosiek, arXiv:1103.4272

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

Radiative Flavour Violation in the MSSM

Radiative Flavour Violation (RFV)

SU(2)³ flavour-symmetry in the MSSM superpotential:

- CKM matrix is the unit matrix.
- Only the third generation Yukawa coupling is different from zero.

$$V_{CKM}^{(0)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$Y^{q} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & Y^{q_3} \end{pmatrix}$$

All other elements are generated radiatively using the trilinear A-terms!

Features of the model

- Additional flavour symmetries in the superpotential.
- Explains small masses and mixing angles via a loop-suppression.
- Deviations from MFV if the third generation is involved.
- Solves the SUSY CP problem via a mandatory phase alignment. (Phase of μ enters only at two loops) Borzumati, Farrar, Polonsky, Thomas 1999.
- The SUSY flavour problem reduces to the elements $\delta_{32}^{q\,LR}, \delta_{31}^{q\,LR}$

CKM generation in the down-sector:

CKM elements generate by the self-energies:

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

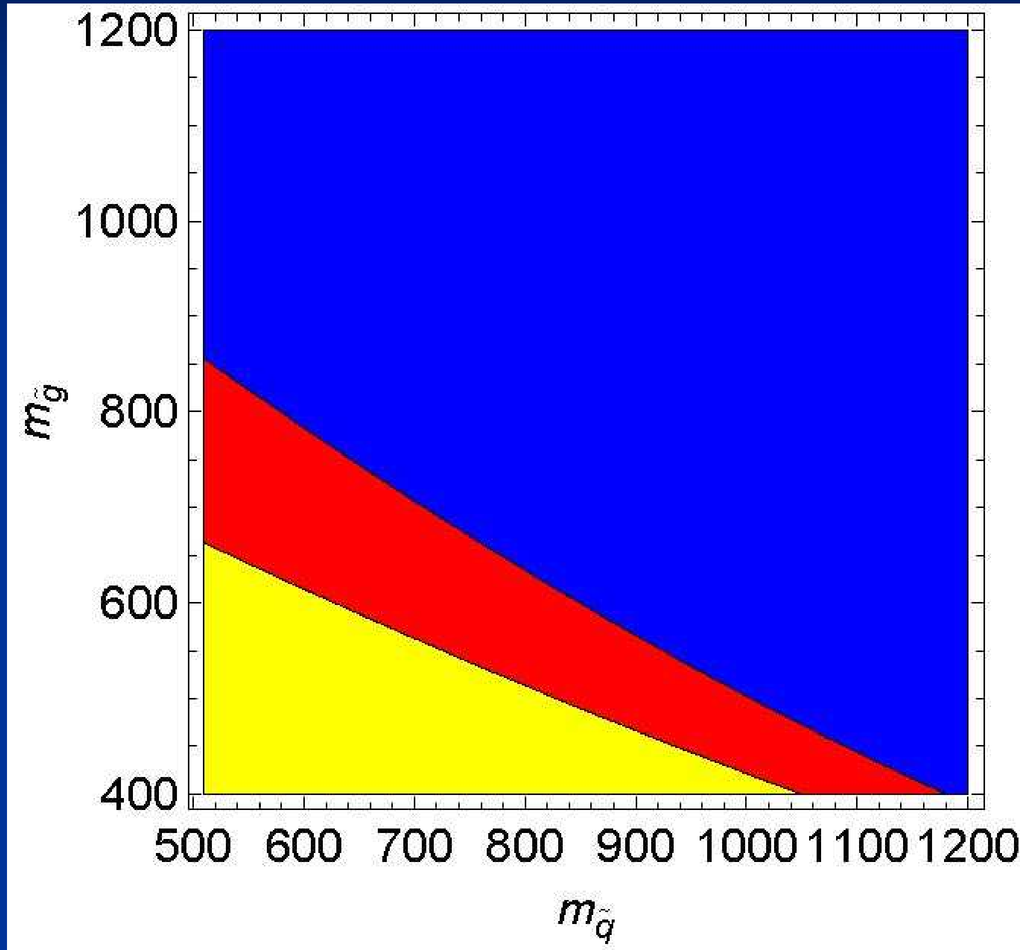
$$\Sigma_{23}^{d\,LR} \stackrel{!}{=} m_b V_{cb}$$

Allowed regions from $b \to s\gamma$

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

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

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



Higgs effects: $B_s \to \mu^+ \mu^-$

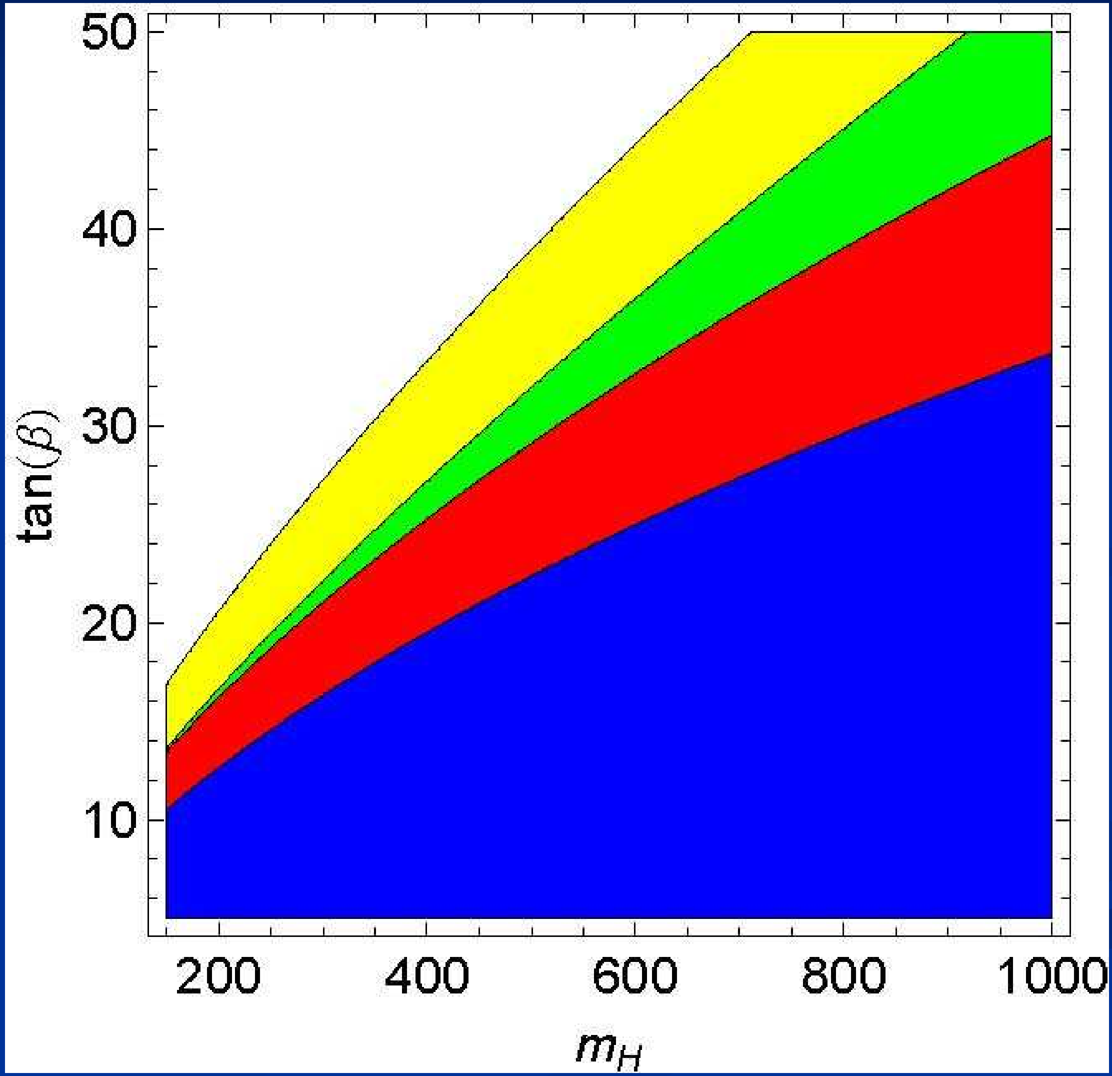
- Constructive and destructive contribution depending on the sign of μ

$\varepsilon_b = 0.005$

$\varepsilon_b = 0.01$

$\varepsilon_b = -0.005$

$\varepsilon_b = -0.01$

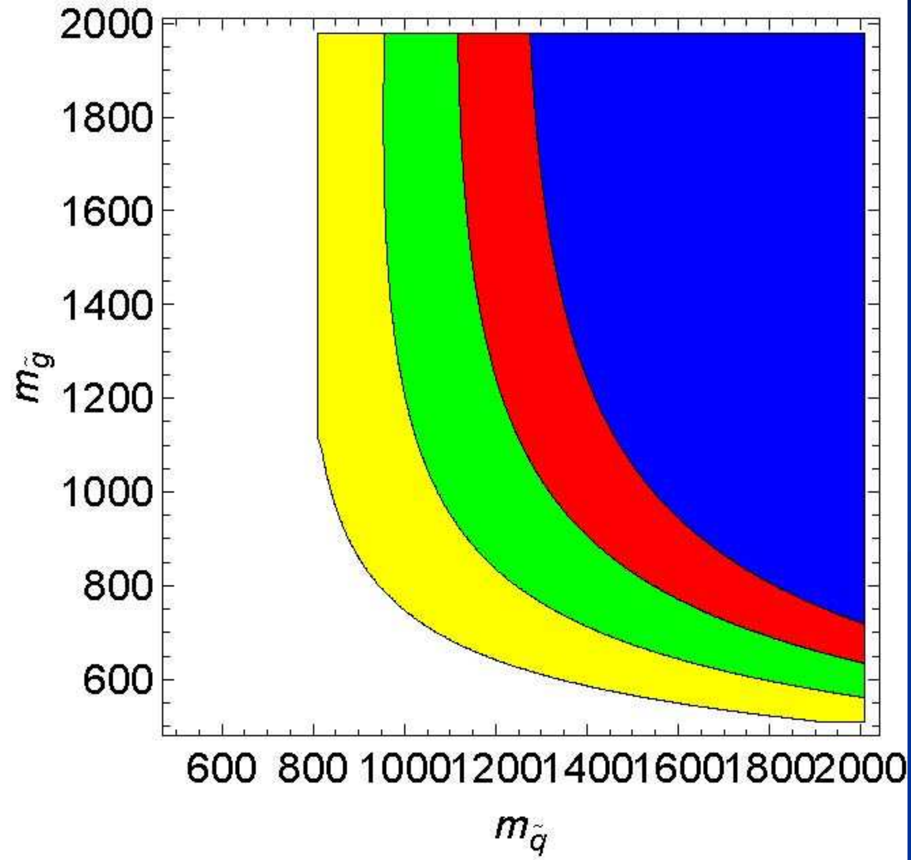


CKM generation in the up-sector:

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

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

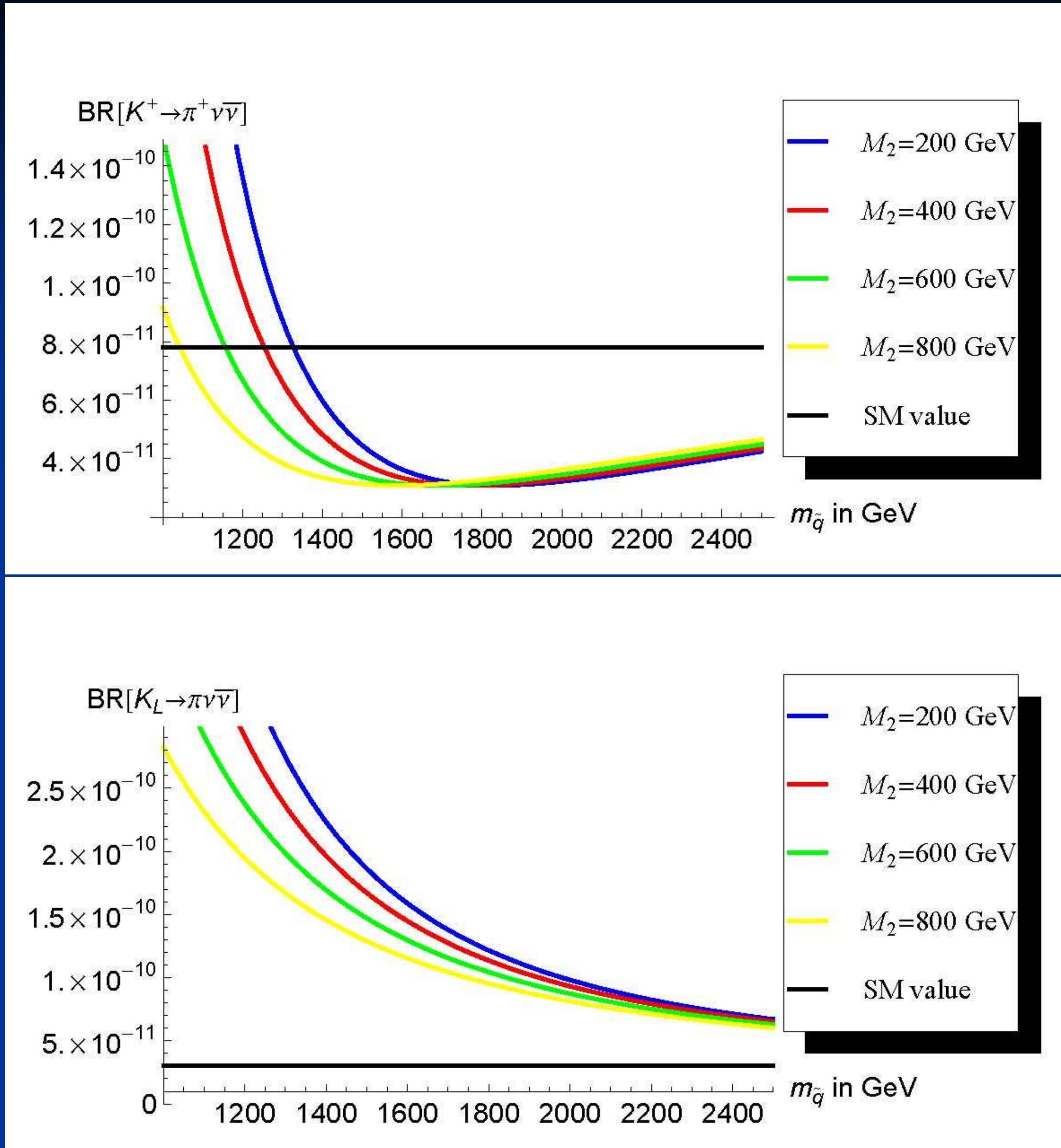
- Constraints from Kaon mixing.
- $\delta_{31}^{u\,LR}, \delta_{32}^{u\,LR}$ unconstrained from FCNC processes.
- $\delta_{31}^{u\,LR}$ can induce a sizable right-handed W-coupling.



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

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

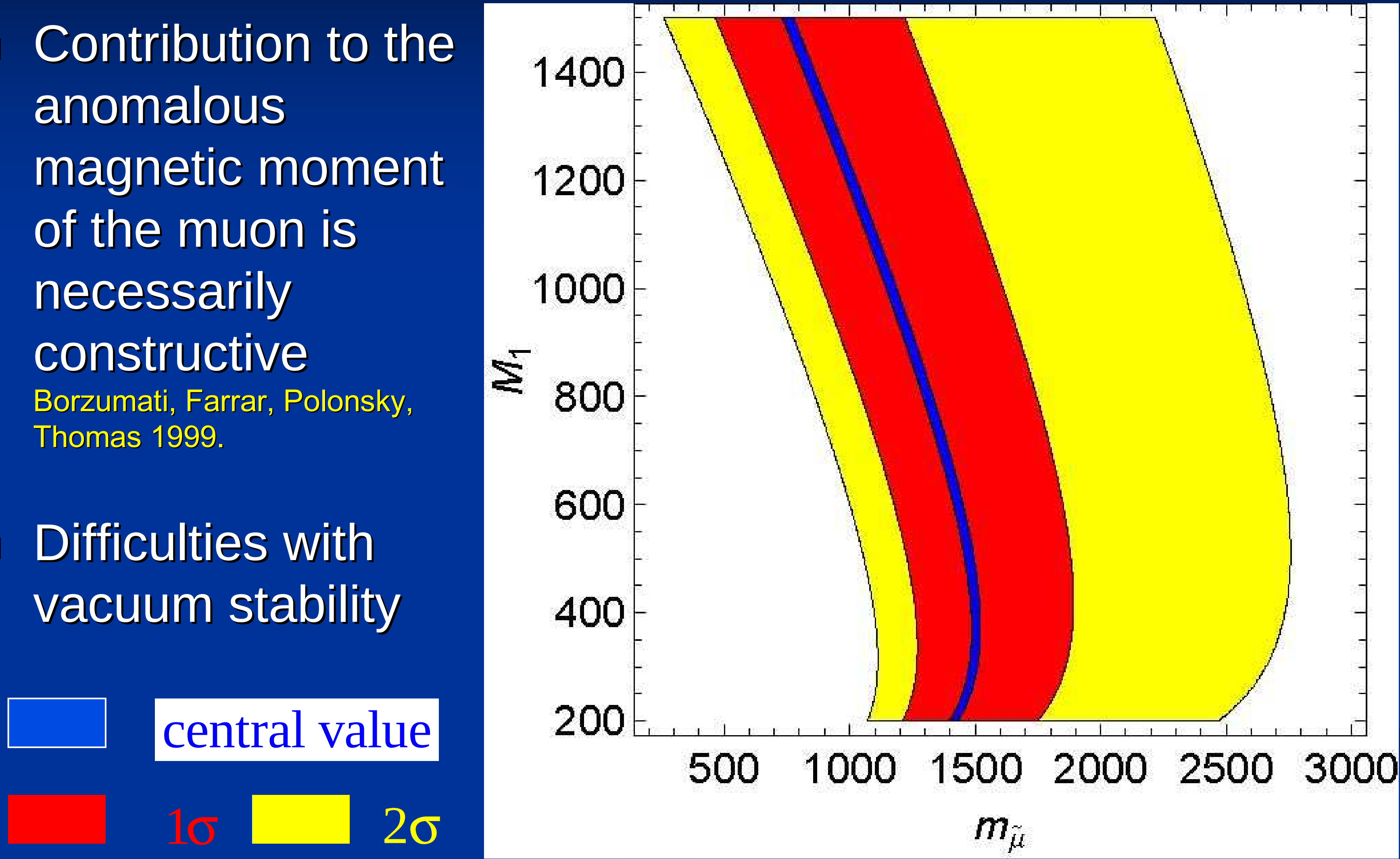
- Effects in $K \to \pi\nu\nu$
- Verifiable predictions for NA62



Radiative Lepton Mass Generation

- Contribution to the anomalous magnetic moment of the muon is necessarily constructive
  Borzumati, Farrar, Polonsky, Thomas 1999.

- Difficulties with vacuum stability



Conclusions

- Indirect searches for NP probe energy scales much higher than the one of the LHC.
- The CKM mechanism of flavour-violation in the SM works very well. $\Rightarrow$ Stringent constraints on physics beyond the SM.
- Hints for new physics: The anomalous magnetic moment of the muon and tauonic B decays?
- 2HDM of type III with flavour-violation in the up-sector can explain the $B\to\tau\nu$, $B\to D^{(*)}\tau\nu$ and $B\to D\tau\nu$.
- Flavour structure of the MSSM stringently constrained from flavour observables.
- RFV solves the SUSY flavour and the SUSY CP problem and can explain the anomalous magnetic moment of the muon.