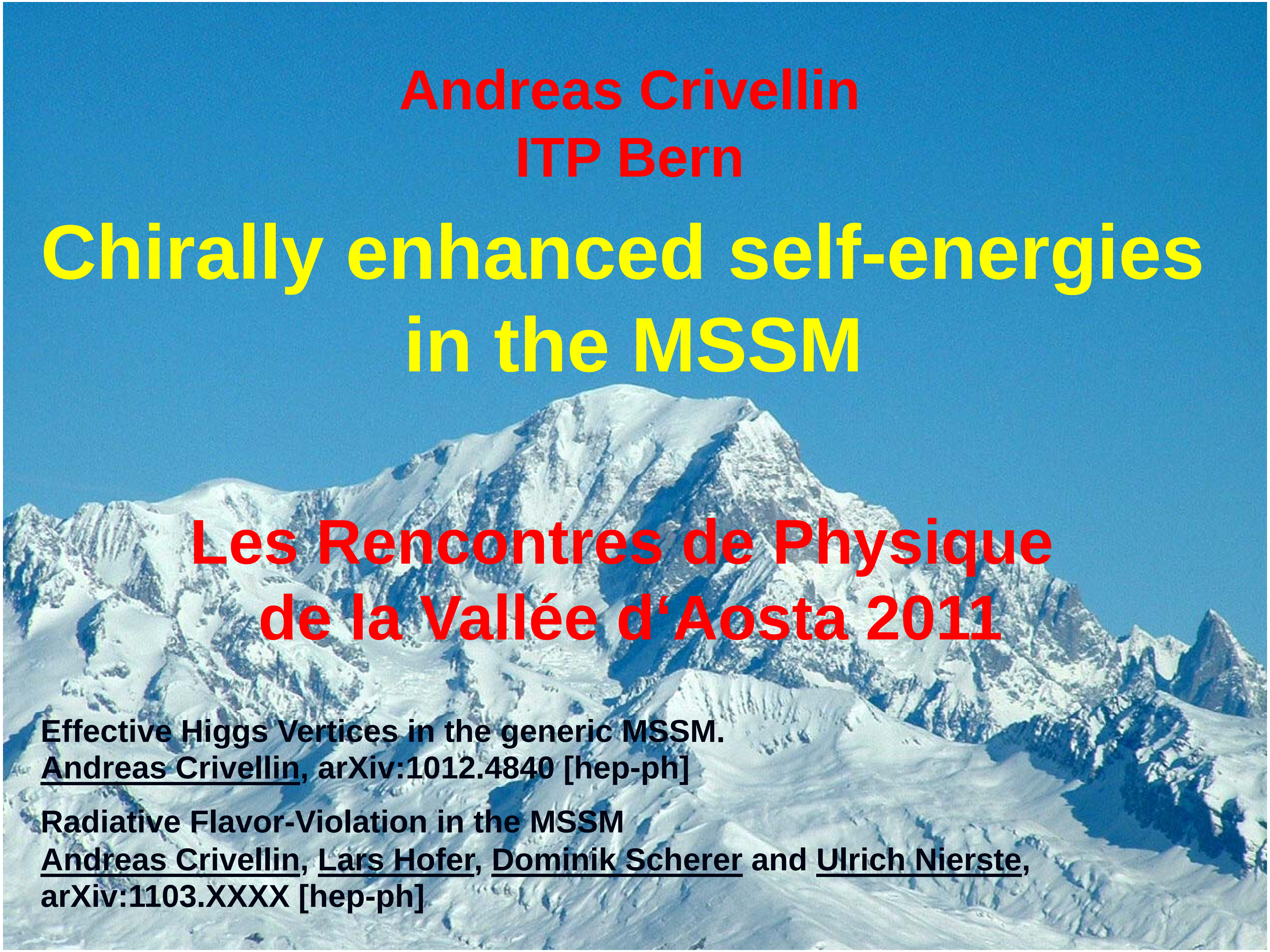

Andreas Crivellin
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Chirally enhanced self-energies in the MSSM

Les Rencontres de Physique de la Vallée d'Aosta 2011

Effective Higgs Vertices in the generic MSSM.
Andreas Crivellin, arXiv:1012.4840 [hep-ph]

Radiative Flavor-Violation in the MSSM
Andreas Crivellin, Lars Hofer, Dominik Scherer and Ulrich Nierste, arXiv:1103.XXXX [hep-ph]

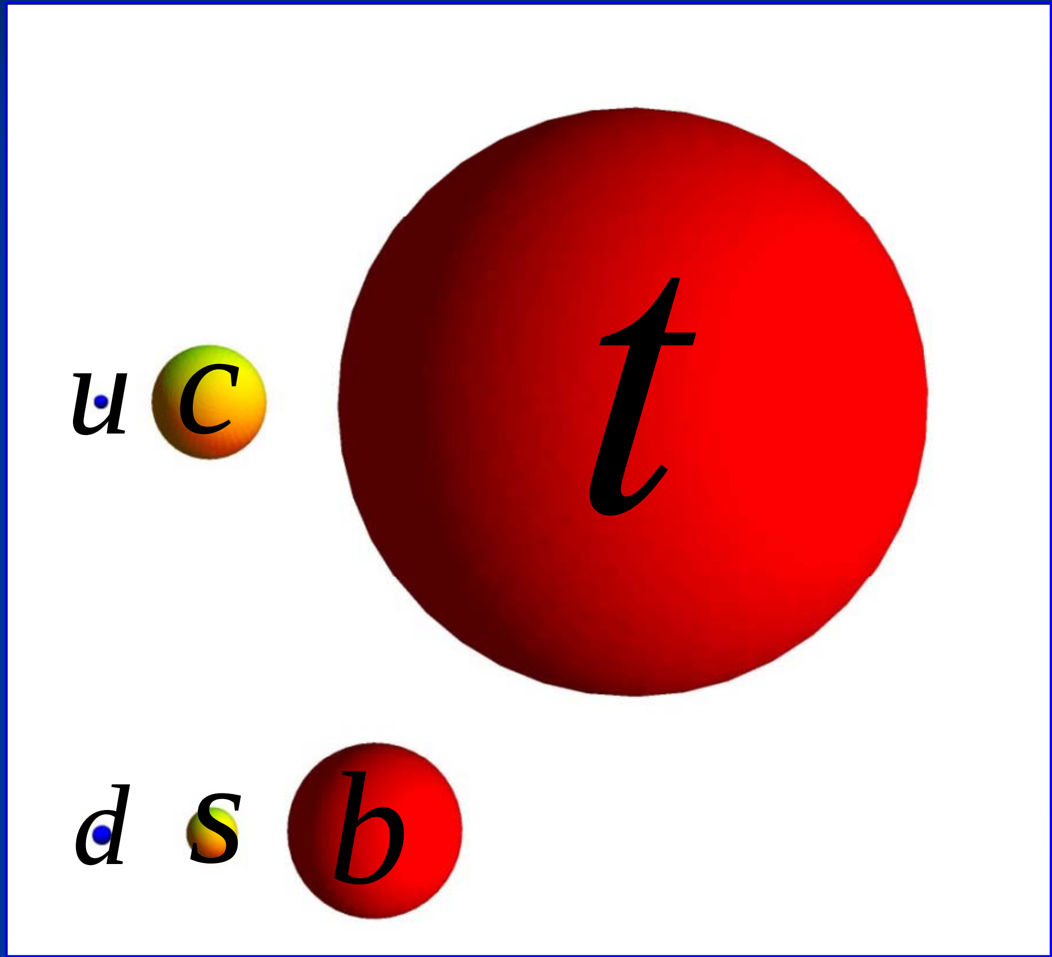
Outline:

- The SUSY flavor-problem
- Self-energies and the origin of chiral enhancement
- Renormalization and tan(β) resummation.
- Flavor-changing neutral Higgs vertices
- Radiative flavor-violation in the MSSM

Quark masses

- Top quark is very heavy. $m_t \approx v$
- Bottom quark rather light, but Y^b can be big at large tan(β)
- All other quark masses are very small

➡ sensitive to radiative corrections

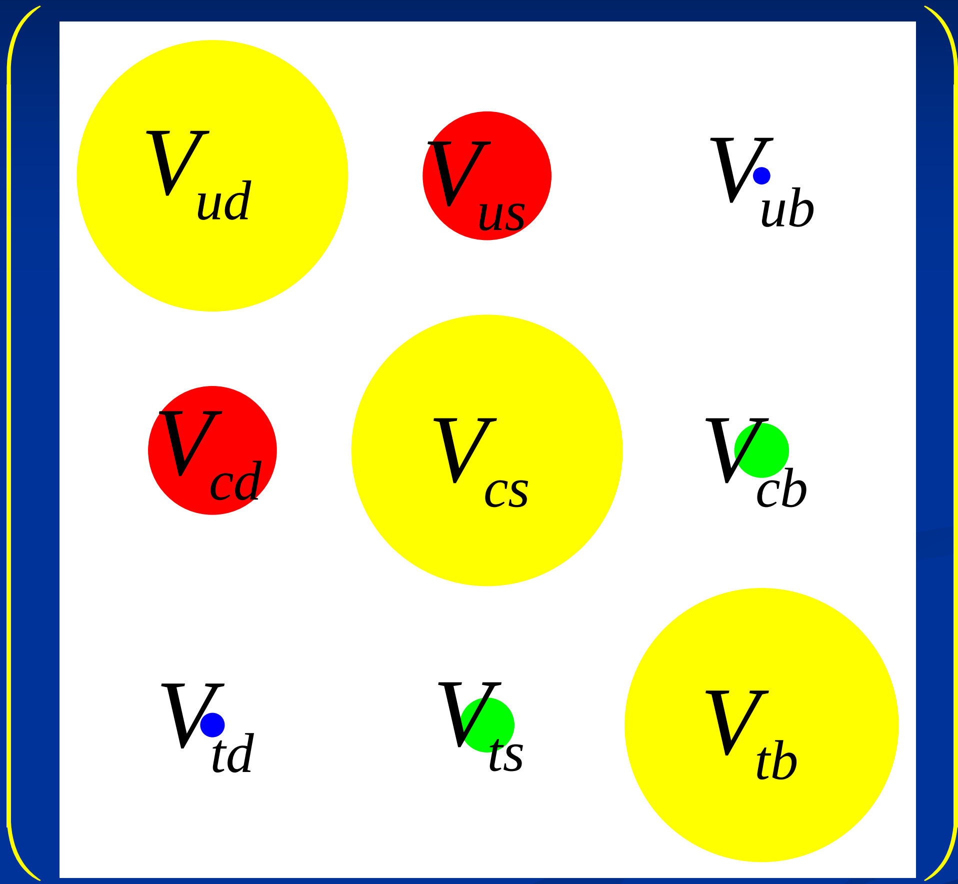


CKM matrix

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

➡ Flavor-violation is suppressed in the SM.

$V_{CKM} =$



SUSY flavor (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 flavor-mixing (and complex phases) since they don’t necessarily posses the suppression of the SM.
- The MSSM possesses two Higgs-doublets: Flavour-changing charged and (loop-induced) neutral Higgs interactions.
- Possible solutions:

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

  - effective SUSY Barbieri et at hep-ph/10110730

  - Radiative flavour violation

Squark mass matrix

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

hermitian: ➡ $W^{\tilde{q}\dagger} M_{\tilde{q}}^2 W^{\tilde{q}} = M_{\tilde{q}}^{2(D)}$

$M_{LL,RR}^{\tilde{q}\,2}$ involves only bilinear terms (in the decoupling limit)

The chirality-changing elements are proportional to a vev

$$\Delta_{ij}^{d\,LR} = -v_d\left(\mu \tan(\beta)\, Y_i^{d(0)} \delta_{ij} + A_{ij}^d\right)$$

$$\Delta_{ij}^{u\,LR} = -v_u\left(\mu \cot(\beta)\, Y_i^{u(0)} \delta_{ij} + A_{ij}^u\right)$$

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

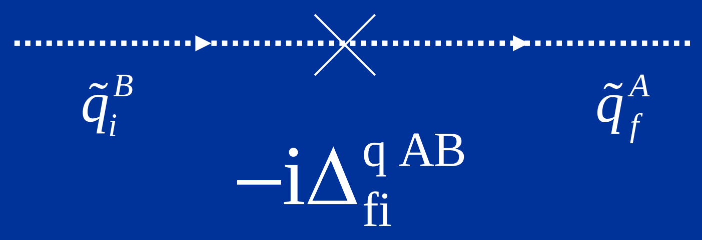
Mass insertion approximation

(L.J. Hall, V.A. Kostelecky and S. Raby, Nucl. Phys. B 267 (1986) 415.)

- Useful to visualize flavor-changes in the squark sector

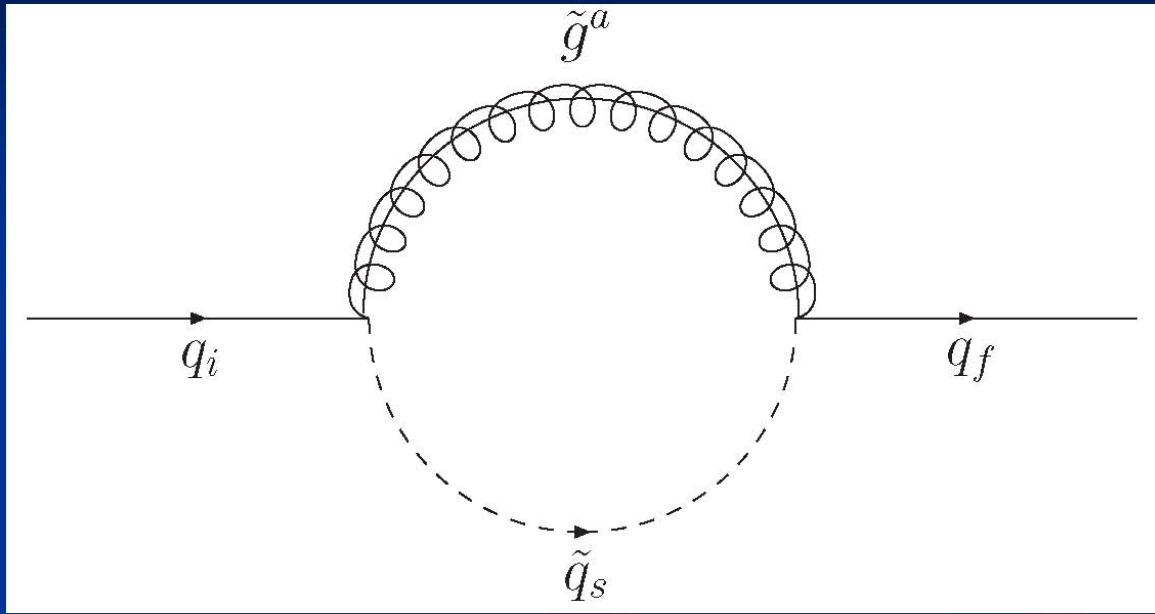
  $\Delta_{ij}^{q\ AB}$ off-diagonal element of the squark mass matrix

- $q = u, d$
- i, j flavor indices 1,2,3
- A, B chiralitys L,R



SQCD self-energy:

$$-i\Sigma(0)_{fi}^{q\,LR} =$$



$$\Sigma_{fi}^{q\,LR} = \alpha_s \frac{2}{3\pi} m_{\tilde{g}} W_{fs} W_{i+3,s}^{*} B_0\left(m_{\tilde{g}}{}^2, m_{\tilde{q}_s}^2\right)$$

Finite and proportional to at least one power of $\Delta_{fi}^{q\,LR}$

$$\Sigma_{fi}^{q\,LR} = \alpha_s \frac{2}{3\pi} m_{\tilde{g}} W_{fs}^{q} W_{js}^{q*} \Delta_{jl}^{q\,LR} W_{lt}^{q} W_{it}^{q*} C_0\left(m_{\tilde{g}}{}^2, m_{\tilde{q}_s}^2, m_{\tilde{q}_t}^2\right)$$

decoupling limit

Decomposition of the self-energy

Decompose the self-energy

$$\Sigma_{ii}^{d\,LR} = \Sigma_{ii\,A}^{d\,LR} + \Sigma_{ii\,Y}^{d\,LR}$$

into a holomorphic part proportional to an A-term

$$\Sigma_{fi\,A}^{d\,LR} = -v_d \alpha_s \frac{2}{3\pi} m_{\tilde{g}} W_{fs}^{d} W_{js}^{d*} A_{jl}^{q} W_{lt}^{d} W_{it}^{d*} C_0\left(m_{\tilde{g}}^{2}, m_{\tilde{q}_s}^{2}, m_{\tilde{q}_t}^{2} \right)$$

non-holomorphic part proportional to a Yukawa

$$\Sigma_{fi\,Y}^{d\,LR} = -v_u \mu \alpha_s \frac{2}{3\pi} m_{\tilde{g}} W_{fs}^{d} W_{js}^{d*} Y^{d_j} W_{jt}^{d} W_{it}^{d*} C_0\left(m_{\tilde{g}}^{2}, m_{\tilde{q}_s}^{2}, m_{\tilde{q}_t}^{2} \right)$$

Define dimensionless quantity $\varepsilon_i^d = \dfrac{\Sigma_{ii\,Y}^{d\,LR}}{v_u Y^{d_i}}$

which is dimensionless and independent of a Yukawa coupling

Renormalization I

- All corrections are finite; counter-term not necessary.
- Minimal renormalization scheme is simplest.

Mass renormalization

$$m_{d_i} = v_d Y^{d_i(0)} + \Sigma_{ii}^{d\,LR}$$
$$= v_d Y^{d_i(0)} + \Sigma_{ii\,A}^{q\,LR} + v_d \tan(\beta) Y^{d_i(0)} \varepsilon_i^d$$

$$\Rightarrow \quad Y^{d_i(0)} = \frac{m_{d_i} - \Sigma_{ii\,A}^{q\,LR}}{v_d \left(1 + \tan(\beta)\varepsilon_i^d\right)}$$

- tan(β) is automatically resummed to all orders

Renormalization II

- Corrections to the CKM matrix:

$$V_{fi}^{CKM} = U_{jf}^{u\,L*} V_{jk}^{CKM\,(0)} U_{ki}^{d\,L}$$

$$U^{q\,L} = \begin{pmatrix} 1-\frac{\left|\Sigma_{12}^{q\,LR}\right|^2}{2m_{q_2}^2} & \frac{1}{m_{q_2}}\Sigma_{12}^{q\,LR} & \frac{1}{m_{q_3}}\Sigma_{13}^{q\,LR} \\ \frac{-1}{m_{q_2}}\Sigma_{21}^{q\,RL} & 1-\frac{\left|\Sigma_{12}^{q\,LR}\right|^2}{2m_{q_2}^2} & \frac{1}{m_{q_3}}\Sigma_{23}^{q\,LR} \\ \frac{-1}{m_{q_3}}\Sigma_{31}^{q\,RL} + \frac{\Sigma_{32}^{q\,RL}\Sigma_{21}^{q\,RL}}{m_{q_2} m_{q_3}} & \frac{-1}{m_{q_3}}\Sigma_{32}^{q\,RL} & 1 \end{pmatrix}$$

important two-loop corrections

A.C. Jennifer Girrbach 2010

Chiral enhancement

$$\Sigma_{fi}^{d\,LR} \approx \frac{1}{50}\frac{\Delta_{fi}^{q\,LR}}{M_{SUSY}} = \frac{-v_d}{50}\left(\tan(\beta)\,Y_i^{d(0)}\delta_{ij} + \frac{A_{ij}^{d}}{M_{SUSY}}\right)$$

- For the bottom quark only the term proportional to tan(β) is important.

$$\Sigma_{33\,Y}^{d\,LR} = \frac{-1}{50} v_d \tan(\beta)\,Y^{b(0)} \square\ m_b$$

➡ tan(β) enhancement

$$O\left(\frac{\tan(\beta)}{50}\right)$$

Blazek, Raby, Pokorski, hep-ph/9504364

- For the light quarks also the part proportional to the A-term is relevant.

$$\Sigma_{22\,A}^{d\,LR} = O(1) \square\ A_{22}^{d} \approx M_{SUSY}$$

$$\Sigma_{11\,A}^{d\,LR} = O(1) \square\ A_{11}^{d} \approx \frac{1}{50} M_{SUSY}$$

Flavour-changing corrections

$$\frac{\Sigma_{fi}^{q\,LR}}{m_{q_{\max(f,i)}}} \sim V_{fi}^{CKM}$$

$$V_{cb}^{CKM}: \quad A_{23}^{q} \approx M_{SUSY}$$

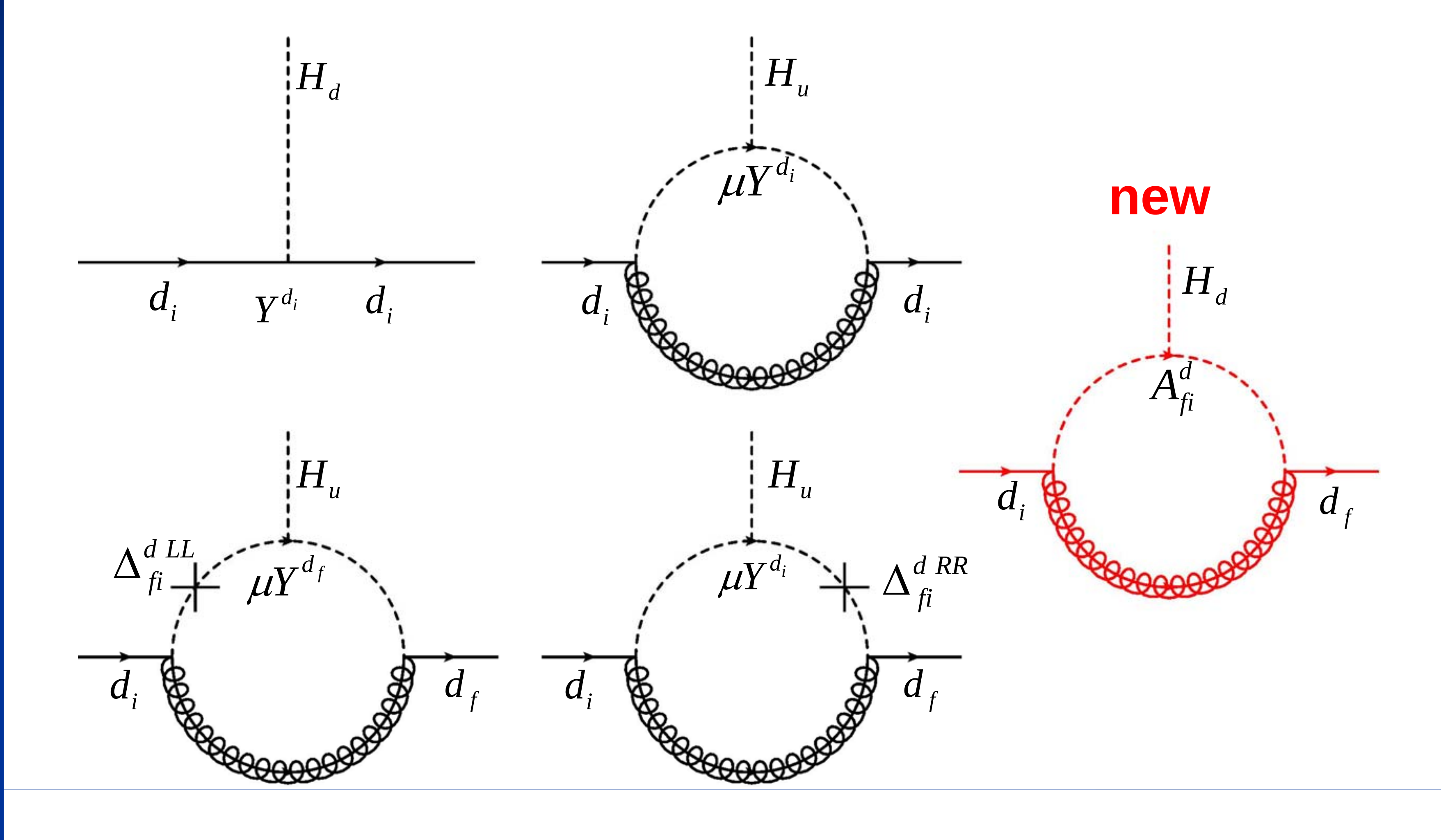
$$V_{ub}^{CKM}: \quad A_{13}^{q} \approx M_{SUSY} \times 10^{-1}$$

$$V_{us}^{CKM}: \quad A_{12}^{q} \approx M_{SUSY} \times 10^{-1}$$

- Flavor-changing A-term can easily lead to order one correction.

A.C., Ulrich Nierste, hep-ph/08101613

Higgs vertices in the EFT I



Higgs vertices in the EFT II

$$\mathcal{L}_Y^{\text{eff}} = \bar{Q}^a_{f\,L}\left(\left(Y_i^d\delta_{fi} + E_{fi}^d\right)\varepsilon_{ba}H_d^b + E_{fi}'^d H_u^{a*}\right)d_{i\,R}$$

- Non-holomorphic corrections $E_{fi}'^d = \dfrac{\Sigma_{fi\,Y}^{d\,LR}}{v_u}$
- Holomorphic corrections $E_{fi}^d = \dfrac{\Sigma_{fi\,A}^{d\,LR}}{v_u}$
- The quark mass matrix $m_{fi}^d = v_d\left(Y^{d_i}\delta_{fi} + E_{fi}^d\right) + v_u E_{fi}'^d$ is no longer diagonal in the same basis as the Yukawa coupling

➡ Flavour-changing neutral Higgs couplings

Effective Yukawa couplings

- Final result:

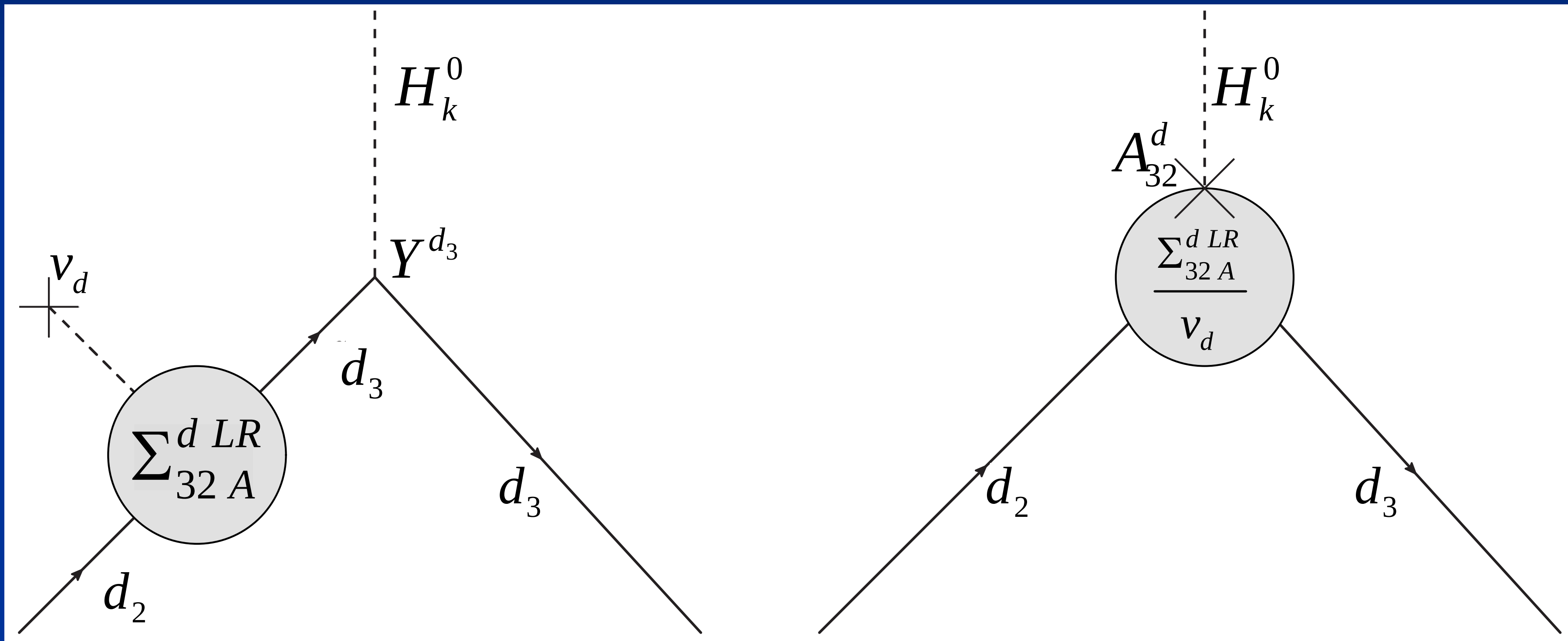
$$Y_{ij}^{d\,eff} = \frac{1}{v_d}\left(m_{d_i}\delta_{ij} - \tilde{\Sigma}_{ij\,Y}^{d\,LR}\right)$$

with

$$\tilde{\Sigma}_{jk\,Y}^{d\,LR} = U_{jf}^{d\,L*}\Sigma_{jk\,Y}^{d\,LR}U_{ki}^{d\,R} \approx \Sigma_{fi\,Y}^{d\,LR} - \begin{pmatrix} 0 & \frac{\Sigma_{22\,Y}^{d\,LR}}{m_{d_2}}\Sigma_{12}^{d\,LR} & \frac{\Sigma_{33\,Y}^{d\,LR}}{m_{d_3}}\Sigma_{13}^{d\,LR} \\ \frac{\Sigma_{22\,Y}^{d\,LR}}{m_{d_2}}\Sigma_{21}^{d\,LR} & 0 & \frac{\Sigma_{33\,Y}^{d\,LR}}{m_{q_3}}\Sigma_{23}^{d\,LR} \\ \frac{\Sigma_{33\,Y}^{d\,LR}}{m_{d_3}}\Sigma_{31}^{d\,LR} & \frac{\Sigma_{33\,Y}^{d\,LR}}{m_{q_3}}\Sigma_{32}^{d\,LR} & 0 \end{pmatrix}$$

Diagrammatic explanation in the full theory:

Higgs vertices in the full theory



- Cancellation incomplete since $v_d Y^{d_3} \neq m_{d_3}$
  Part proportional to $\Sigma^{d\,LR}_{33\,Y}$ is left over.

➡ A-terms generate flavor-changing Higgs couplings

Radiative flavor-violation

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

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

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

$$Y^q = \frac{1}{v_q} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_{q_3} \end{pmatrix}$$

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

Features of the model

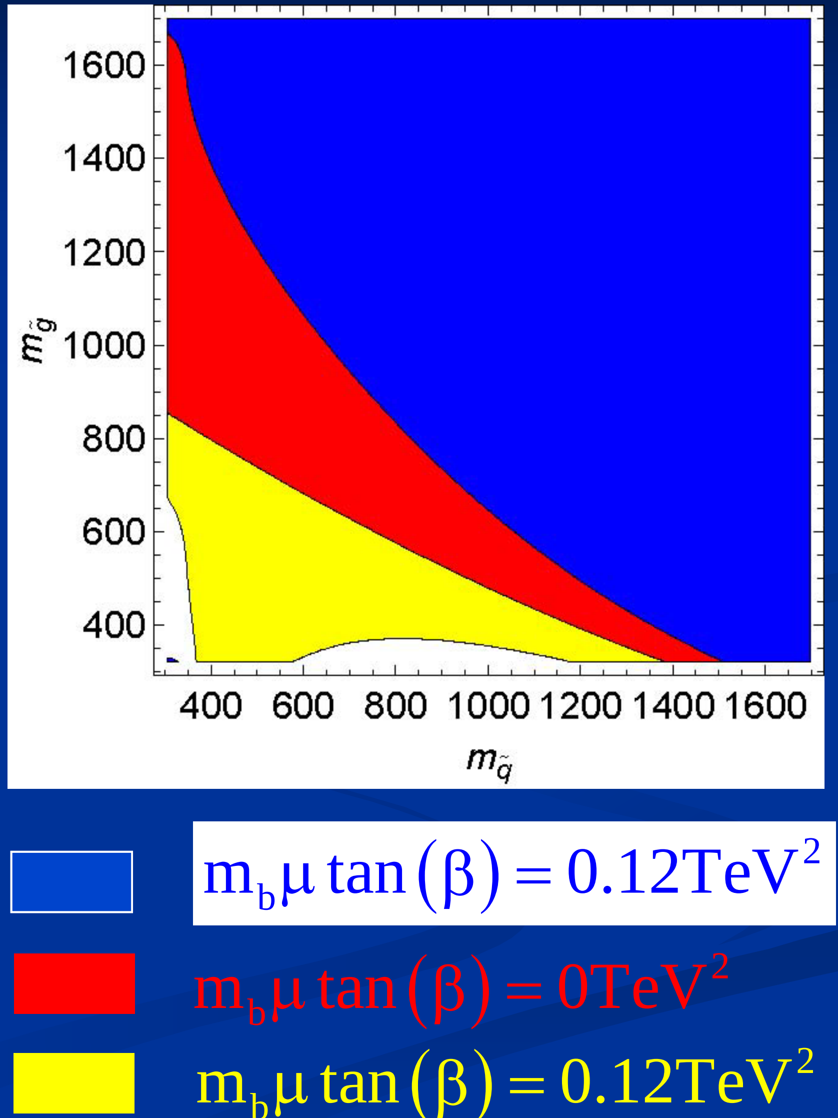
- Additional flavor symmetries in the superpotential.
- Explains small masses and mixing angles via a loop-suppression.
- Deviations from MFV if the third generation is involved.
- Solves the SUSY CP problem via a mandatory phase alignment. (Phase of μ enters only at two loops)
  Borzumati, Farrar, Polonsky,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

CKM generation in the down-sector:

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

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

- Constraints from b→sγ. Chirally enhanced corrections must be taken into account.
  A.C., Ulrich Nierste 2009
- $\delta_{31}^{d\,LR}, \delta_{32}^{d\,LR}$ less constrained since they contribute to C7',C8'.
- $\delta_{32}^{d\,LR}$ can explain the CP phase in B_s mixing. (not possible in MFV)



Higgs effects: $B_s \to \mu\mu$

- Constructive contribution due to

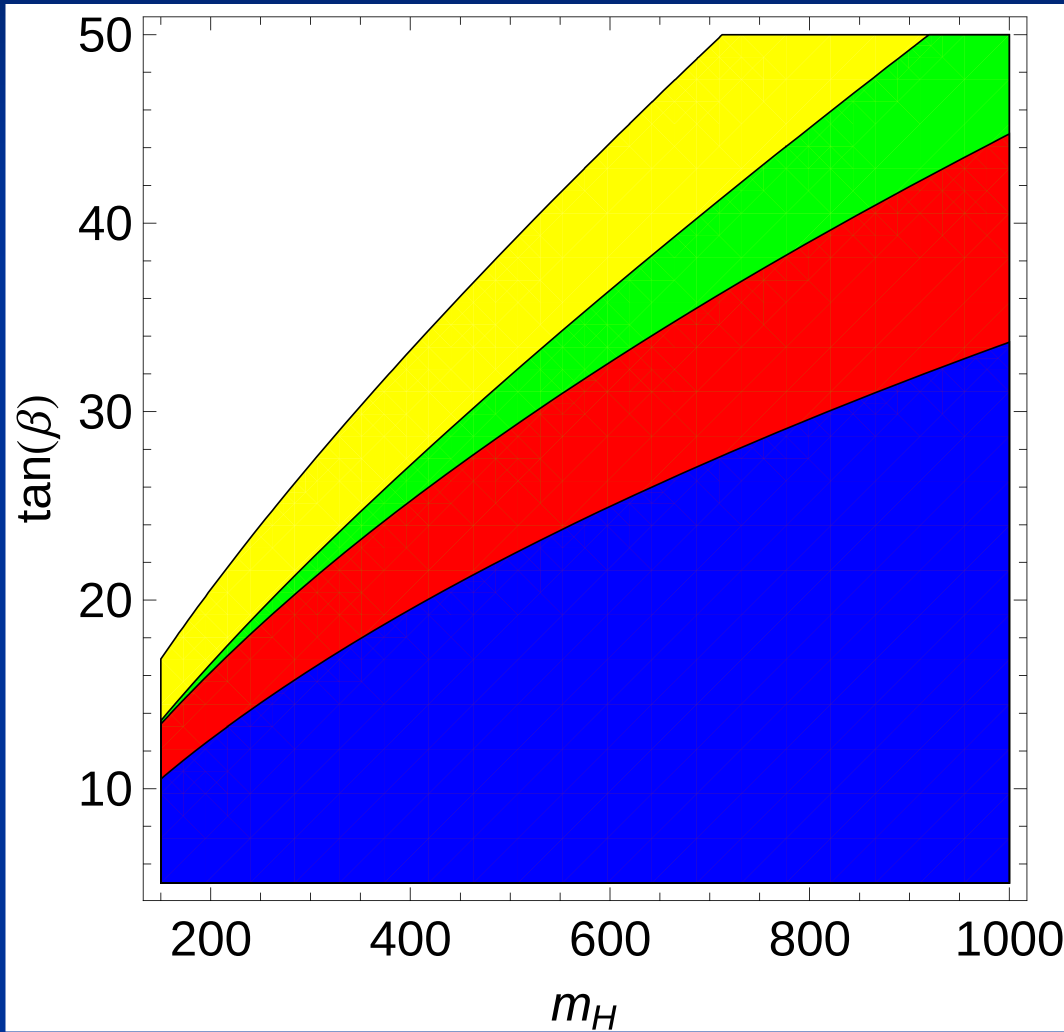
$$\Sigma_{23}^{d\,LR} = m_b V_{cb}$$

$\varepsilon_b = 0.005$

$\varepsilon_b = 0.01$

$\varepsilon_b = -0.005$

$\varepsilon_b = -0.01$



Higgs effects: B_s mixing

- Contribution only if

$$V^R_{23} = \frac{\Sigma^{d\,RL}_{23}}{m_b} \neq 0$$

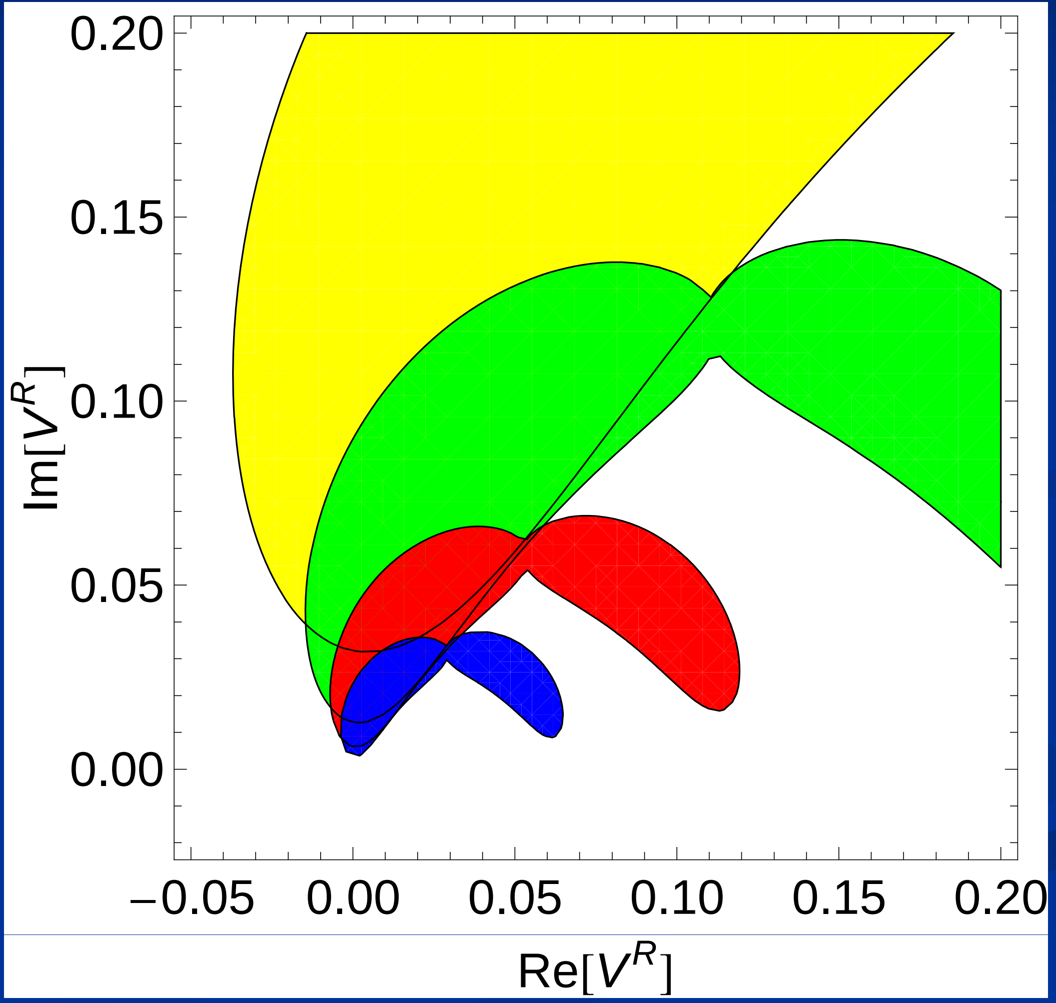
due to Pecci-Quinn symmetry

$\tan(\beta) = 11$

$\tan(\beta) = 14$

$\tan(\beta) = 17$

$\tan(\beta) = 20$



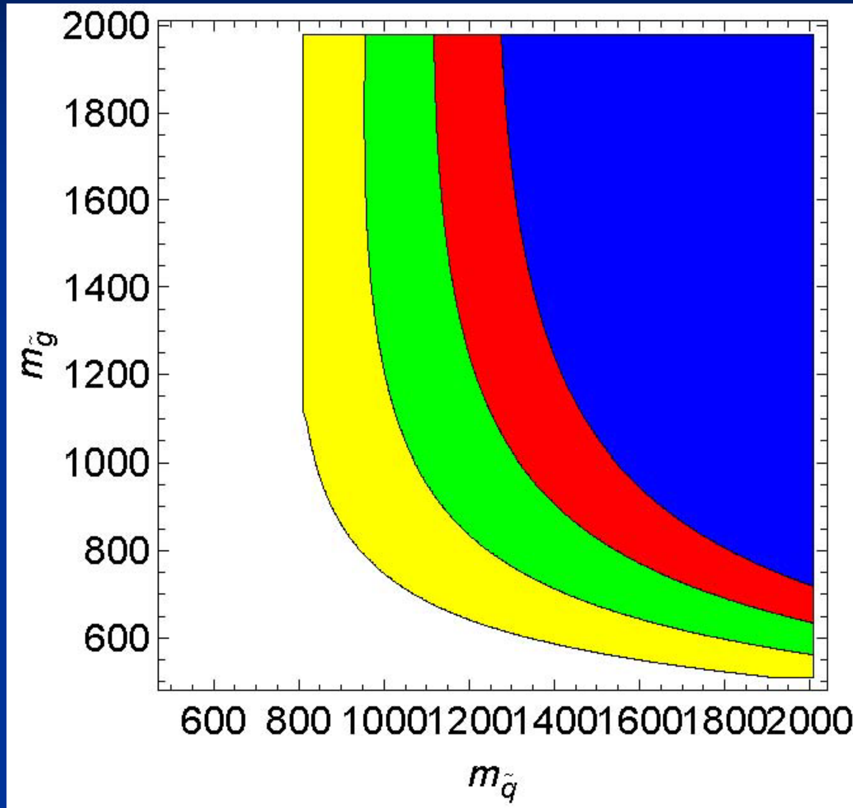
CKM generation in the up-sector:

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

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

- 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.

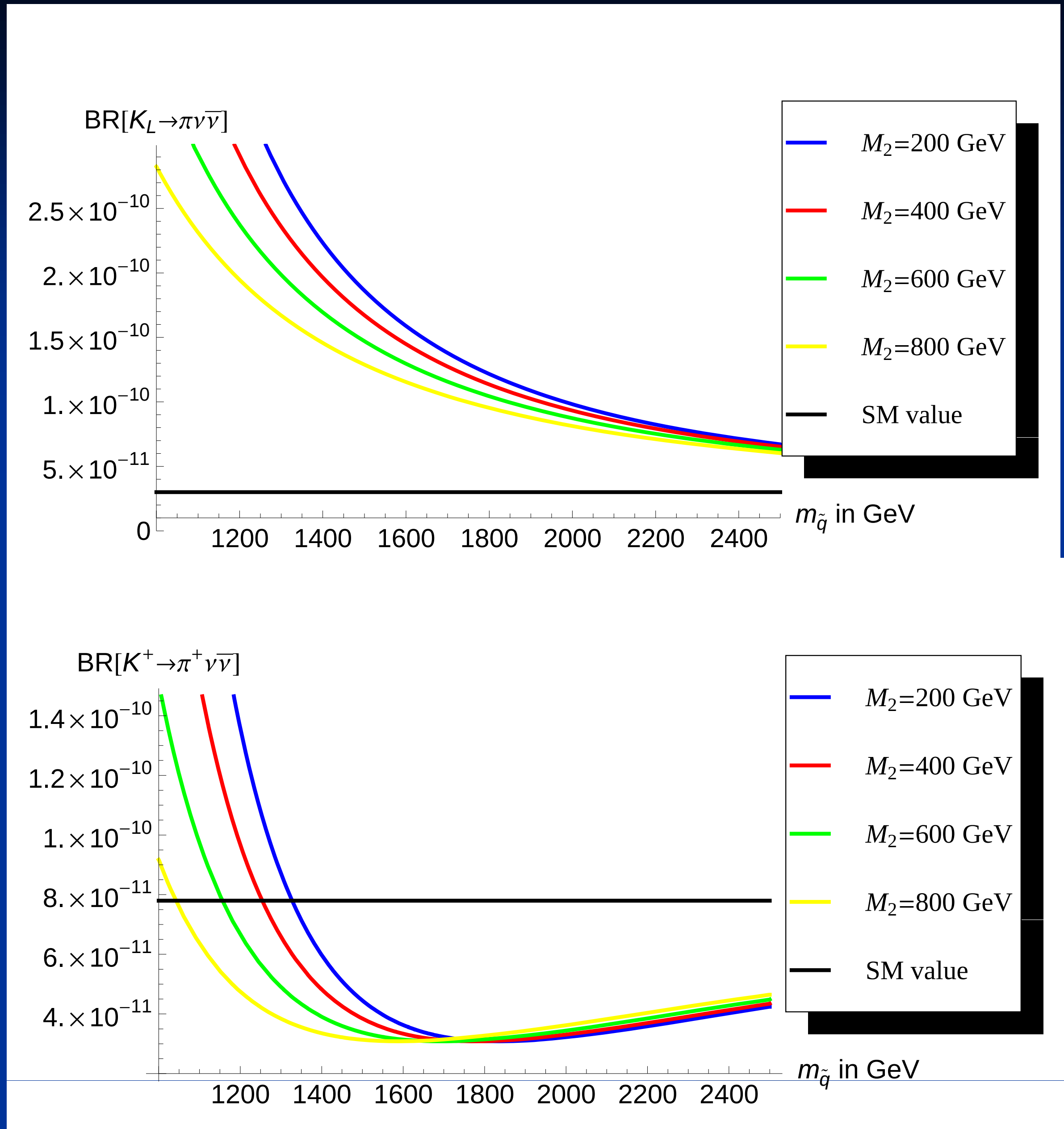
A.C. 2009



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

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

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



Conclusions

- The MSSM possesses many new sources of flavor and CP violation
- Self-energies can be chirally enhanced and of order one.
- Flavour-conserving non-holomorphic corrections induce flavour-changing neutral Higgs couplings proportional to A-terms.

  ➡ Self-energies have physical effects.
- Radiative flavor-violation in the MSSM is a interesting solution to the SUSY CP and SUSY flavor problem.
- Constraints from $b \to s\gamma$ and Kaon mixing are satisfied for SUSY masses O(1TeV).
- Large effects in $K \to \pi\nu\nu$ are possible.
- B_s mixing phase can be explained.