Squark Flavor Implications from $B \to K^{(*)} l^+ l^-$

Stefan Schacht

technische universität dortmund

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in collaboration with
Arnd Behring, Christian Gross and Gudrun Hiller

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SM and SUSY Flavor Puzzle

SM Flavor Puzzle

- Origin of hierarchy of Yukawa couplings?
  $\lambda_{\text{Top}} \sim 1,\ \lambda_b,\ \ldots,\ \lambda_e \sim 10^{-2}, \ldots, 10^{-6}$

SUSY Flavor Problem

- SUSY says nothing about flavor violation in SUSY breaking
  $\Rightarrow$ SUSY flavor violation (FV) generically large
- FCNCs: partly drastic constraints on SUSY FV
  $\Rightarrow$ Non-generic structure necessary here $\Rightarrow$ SUSY flavor problem

Flavor and CP Violation in SUSY

- Many new sources of FV in SUSY soft breaking terms
- Parallel rotation of squarks and quarks (super-CKM basis)
  $\Rightarrow 6 \times 6$ squark mass matrices in general not diagonal.
- In $\bar{B} \to \bar{K}^{(*)} l^+ l^-$: Most sensitive to $(\Delta^u_{23})_{LR}$

$$M^2_{\tilde{u}} = \begin{pmatrix} & & & L & & & & R & \\ & & \tilde{u} & \tilde{c} & \tilde{t} & & \tilde{u} & \tilde{c} & \tilde{t} \\ & \tilde{u} & m^2_{\tilde{u}_L} & (\Delta^u_{12})_{LL} & (\Delta^u_{13})_{LL} & | & (\Delta^u_{11})_{LR} & (\Delta^u_{12})_{LR} & (\Delta^u_{13})_{LR} \\ L & \tilde{c} & (\Delta^u_{12})^*_{LL} & m^2_{\tilde{c}_L} & (\Delta^u_{23})_{LL} & | & (\Delta^u_{21})_{LR} & (\Delta^u_{22})_{LR} & (\Delta^u_{23})_{LR} \\ & \tilde{t} & (\Delta^u_{13})^*_{LL} & (\Delta^u_{23})^*_{LL} & m^2_{\tilde{t}_L} & | & (\Delta^u_{31})_{LR} & (\Delta^u_{32})_{LR} & (\Delta^u_{33})_{LR} \\ & & --- & --- & --- & --- & --- & --- & --- \\ & \tilde{u} & & & & | & m^2_{\tilde{u}_R} & (\Delta^u_{12})_{RR} & (\Delta^u_{13})_{RR} \\ R & \tilde{c} & & h.c. & & | & (\Delta^u_{12})^*_{RR} & m^2_{\tilde{c}_R} & (\Delta^u_{23})_{RR} \\ & \tilde{t} & & & & | & (\Delta^u_{13})^*_{RR} & (\Delta^u_{23})^*_{RR} & m^2_{\tilde{t}_R} \end{pmatrix}$$

Parametrization of Flavor Violation and FCNC bounds

- Normalization of off-diagonal elements:
  Mass Insertion (MI) parameters

$$\delta_{ij} = \frac{\Delta_{ij}}{M_{av}^2}$$

- FCNC bounds on δ_{ij} parameter: [Artuso et. al. 2008]

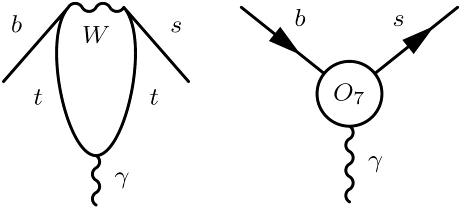
$\lvert(\delta_{12}^d)_{LL,RR}\rvert$	$\lvert(\delta_{12}^d)_{LR}\rvert$	$\lvert(\delta_{12}^d)_{RL}\rvert$
$1 \cdot 10^{-2}$	$5 \cdot 10^{-4}$	$5 \cdot 10^{-4}$
$\lvert(\delta_{12}^u)_{LL,RR}\rvert$	$\lvert(\delta_{12}^u)_{LR}\rvert$	$\lvert(\delta_{12}^u)_{RL}\rvert$
$3 \cdot 10^{-2}$	$6 \cdot 10^{-3}$	$6 \cdot 10^{-3}$
$\lvert(\delta_{13}^d)_{LL,RR}\rvert$	$\lvert(\delta_{13}^d)_{LR}\rvert$	$\lvert(\delta_{13}^d)_{RL}\rvert$
$7 \cdot 10^{-2}$	$1 \cdot 10^{-2}$	$1 \cdot 10^{-2}$
$\lvert(\delta_{23}^d)_{LL}\rvert$	$\lvert(\delta_{23}^d)_{RR}\rvert$	$\lvert(\delta_{23}^d)_{LR,RL}\rvert$
$2 \cdot 10^{-1}$	$7 \cdot 10^{-1}$	$5 \cdot 10^{-3}$

$\Rightarrow$ SUSY flavor problem

- At present: bound for $(\delta_{23}^u)_{LR} \sim \mathcal{O}(1)$

Low Energy Effective Field Theory

- $\Delta B = 1$-Hamiltonian: $\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu) + \text{h.c.}$



Most important operators for semileptonic process $b \to s l^+ l^-$

$$O_7 = \frac{e}{16\pi^2} m_b \left(\bar{s}_{L\alpha} \sigma_{\mu\nu} b_{R\alpha}\right) F^{\mu\nu} \qquad O_9 = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b\right) \left(\bar{l}\gamma^\mu l\right)$$

$$O_{10} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b\right) \left(\bar{l}\gamma^\mu \gamma_5 l\right)$$

New Physics (NP) [1 loop MSSM: Cho, Misiak, Wyler, 1996, 2 loop SM: Bobeth, Misiak, Urban, 2000]

- MSSM contributions to $C_i \Rightarrow C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$ here: $i = 7, 9, 10$

Comparison of SUSY Predictions with Data

- C_7 heavily constrained by $\bar{B} \to X_s \gamma$
- New theoretical and experimental results on $\bar{B} \to \bar{K}^{(*)} l^+ l^-$
  - New constraints on C_9 and C_{10} [Bobeth, Hiller, van Dyk, Wacker 2010, 2011]
- Higgs mass bounds, including NMFV with FeynHiggs [Heinemeyer, Hahn et. al.]

Vary SUSY parameters at EW scale, allowing for flavor violation

$$300\,\text{GeV} \le m_{H^\pm} \le 1000\,\text{GeV} \qquad 100\,\text{GeV} \le M_2 \le 1000\,\text{GeV}$$

$$80\,\text{GeV} \le |\mu| \le 1000\,\text{GeV} \qquad 3 \le \tan\beta \le 15$$

$$m_{\tilde{q}} = 1000\,\text{GeV} \qquad 170\,\text{GeV} \le m_{\tilde{t}_R} \le 800\,\text{GeV}$$

$$-3000\,\text{GeV} \le A_t \le 3000\,\text{GeV} \qquad m_{\tilde{\nu}} = 100\,\text{GeV}$$

- Calculation with EOS: Tool for calculation of flavor observables
  http://project.het.physik.tu-dortmund.de/eos/

SUSY with Flavor Violation against Data

- Measure New Physics effect with:

$$R_i \equiv \left| C_i^{\mathrm{NP}} / C_i^{\mathrm{SM}} \right|$$

BEFORE applying the semileptonic bounds

- $R_9(\mu_b) \lesssim 4\%$ $R_{10}(\mu_b) \lesssim 47\%$ Large effect in C_{10}

AFTER applying the semileptonic bounds

- $R_9(\mu_b) \lesssim 4\%$ $R_{10}(\mu_b) \lesssim 16\%$ at 68% C.L. NEW!

SUSY with Flavor Violation against Data

- Solutions for $C_7 > 0$ disfavored by zero of $A_{\mathrm{FB}}(\bar{B} \to K^* \mu^+ \mu^-)$
- Strong correlation between C_9 and C_{10} due to Z penguin dominance in SUSY

$$\frac{C_{10}^{\mathrm{SUSY}}}{C_9^{\mathrm{SUSY}}} \simeq \frac{1}{4s_w^2 - 1}$$

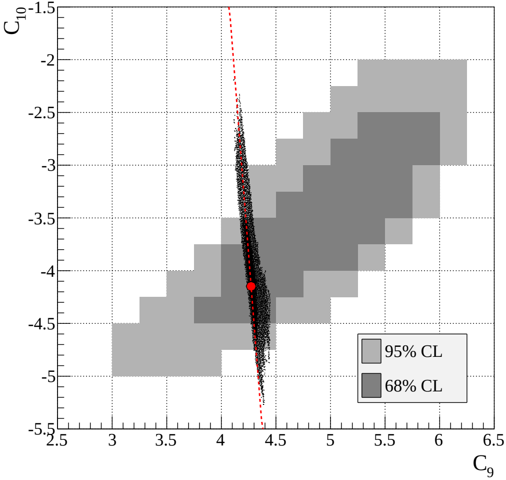
➥ Bounds stronger than model independent ones

- Black: **SUSY points**

[Behring,Gross,Hiller,StS 2012]

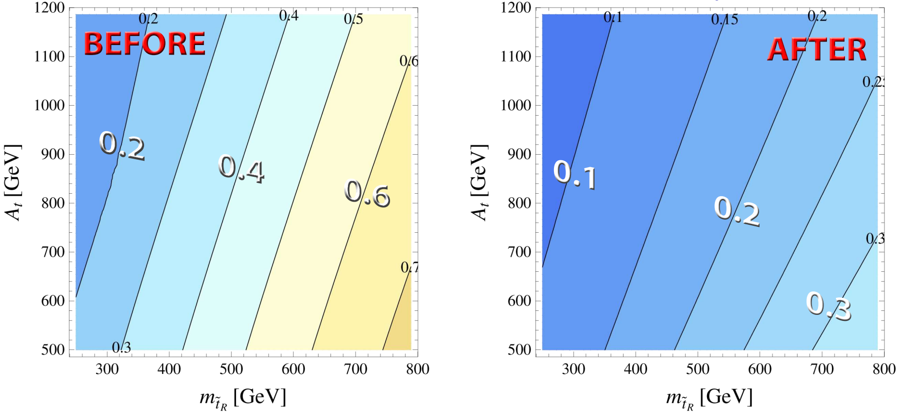
- Gray: Data

[Bobeth,Hiller,van Dyk,Wacker 2011]



MFV ranges: $R_9(\mu_b) \lesssim 3\%$, $R_{10}(\mu_b) \lesssim 11\%$.

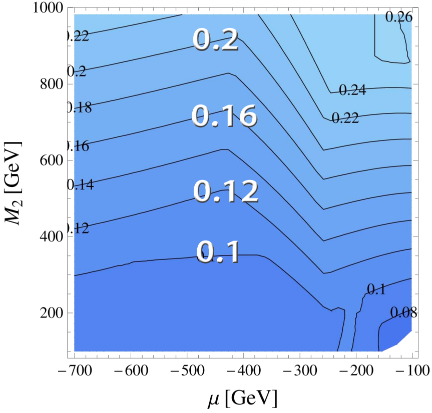
Improvement of bound on $|(\delta^u_{23})_{LR}|$



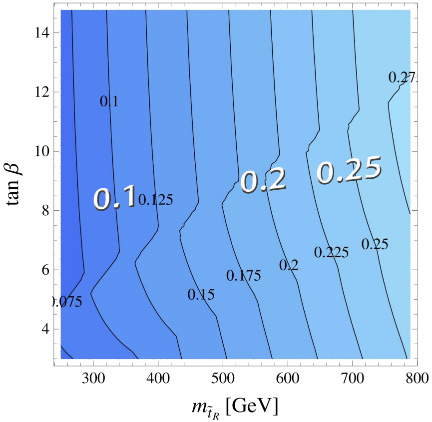
- Part of parameter space: significantly improved bound.
- Stronger than vacuum stability bounds at $m_{\tilde{q}} = m_{\tilde{l}} = 1$ TeV, $m_{\tilde{t}_R} = 300$ GeV: $(\delta^u_{23})_{LR} \lesssim 0.3$.

SUSY point: $m_{\tilde{\nu}} = 100\,\text{GeV},\ m_{H^\pm} = 300\,\text{GeV},\ \tan\beta = 4,\ M_2 = 150\,\text{GeV},\ \mu = -300\,\text{GeV},\ m_{\tilde{q}} = 1000\,\text{GeV}$

Improvement of bound on $|(\delta^u_{23})_{LR}|$, cont'd.



μ-M_2 plane



$m_{\tilde{t}_R}$-$\tan\beta$ plane

- Stronger bounds for $|\mu| \gg M_2$
  Somewhat weaker bounds for larger $\tan\beta$

Implications for $\mathcal{B}(B_s \to \mu^+\mu^-)$

- Current exp. upper limit at 95% (90%) C.L. [R. Aaij et al. (LHCb) 2012]

$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) < 4.5\,(3.8) \times 10^{-9}$$

- SM value
  using lattice data for f_{B_s} (2011)

$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) = (3.1 \pm 0.6) \times 10^{-9}$	$f_{B_s} = 231(15)(4)\,\mathrm{MeV}$	(HPQCD)
$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) = (3.8 \pm 0.4) \times 10^{-9}$	$f_{B_s} = 256(6)(6)\,\mathrm{MeV}$	(MILC)

  assuming SM-like ΔM_s: [Buras 2011]

$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$

- Lower limit in the MSSM NEW!
  no scalar/pseudoscalar contributions: $\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) \propto f_{B_s}^2 |C_{10}|^2$

$$\Rightarrow 1 \times 10^{-9} \lesssim \mathcal{B}(\bar{B}_s \to \mu^+\mu^-) < 5\,(6) \times 10^{-9}$$

Implications for Rare Top Decays

- Constraints on $(\delta^u_{23})_{LR} \Rightarrow$ upper bounds on $t \to c\gamma, g, Z$ in MSSM
- Contribution from squark gluino loops
- SM: GIM suppression $\Rightarrow$ negligible contribution

Compare to **requisite BRs** for 5σ observations at LHC [Veloso 2008]

	ATLAS $10\,\mathrm{fb}^{-1}$	ATLAS $100\,\mathrm{fb}^{-1}$	our bound at 68%
$t \to c\gamma$	9.4×10^{-5}	3.0×10^{-5}	$\lesssim 2.1 \times 10^{-8}$
$t \to cg$	4.3×10^{-3}	1.4×10^{-3}	$\lesssim 7.2 \times 10^{-7}$
$t \to cZ$	4.4×10^{-4}	1.4×10^{-4}	$\lesssim 1.0 \times 10^{-7}$

- $m_{\tilde{g}} = 700$ GeV fixed, for $m_{\tilde{g}} > 700$ GeV $\Rightarrow$ upper bound decreases
- Bounds also from squark, gluino and and Higgs mass constraints
- Too small to be observed within foreseeable future

Expectations for $(\delta^u_{23})_{LR}$ in SUSY models

- Minimal Flavor Violation models: $A_u = A\left(a\mathbb{1} + bY_d Y_d^\dagger\right) Y_u$

$$\Rightarrow (\delta^u_{23})_{LR} \sim \lambda_b^2 V_{cb} V_{tb}^* (m_t/m_{\tilde{q}})$$

$\Rightarrow$ Suppression by λ_b^2 and V_{cb} [D'Ambrosio, Giudice, Isidori, Strumia 2002, Hiller, Nir 2008]

- Models with horizontal flavor symmetries [Seiberg, Nir 1993]

$$(\delta^u_{23})_{LR} \sim V_{cb} (m_t/m_{\tilde{q}})$$

$\Rightarrow$ Order of magnitude below limits

Models with large predictions for $(\delta^u_{23})_{LR}$?

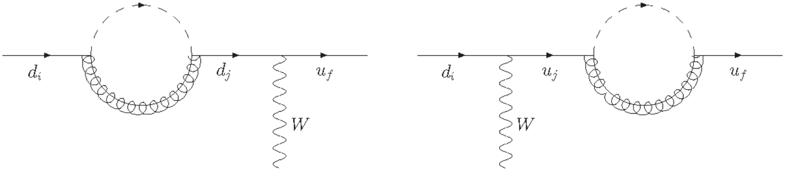
Radiative Flavor Violation (RFV)

[Weinberg 1972, Borzumati, Farrar, Polonsky, Thomas, 1999, Crivellin, Nierste, 2009, Crivellin, Hofer, Nierste, Scherer, 2011]

- Tracing back the SM flavor puzzle to the SUSY flavor puzzle
- "Bare" Yukawa und CKM matrix

$$Y^{f(0)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y^f \end{pmatrix} \qquad V^{(0)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- But: Trilinear SUSY breaking couplings not diagonal
- $\Rightarrow$ Quantum corrections induce hierarchy

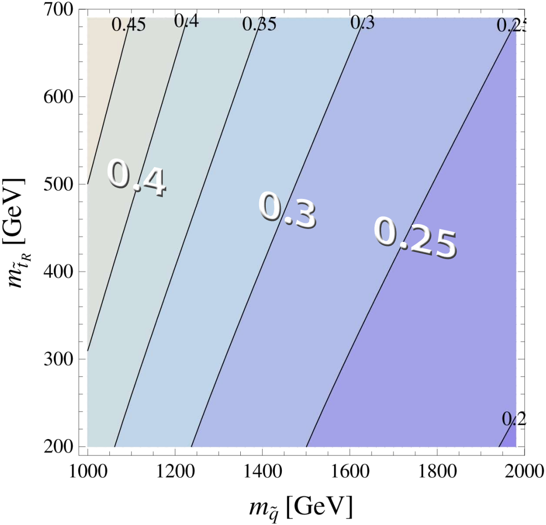


[Feynman diagrams from Crivellin, Hofer, Nierste, Scherer, 2011, arXiv:1105.2818]

Requisite $(\delta^u_{23})_{LR}$ for generating V_{cb}

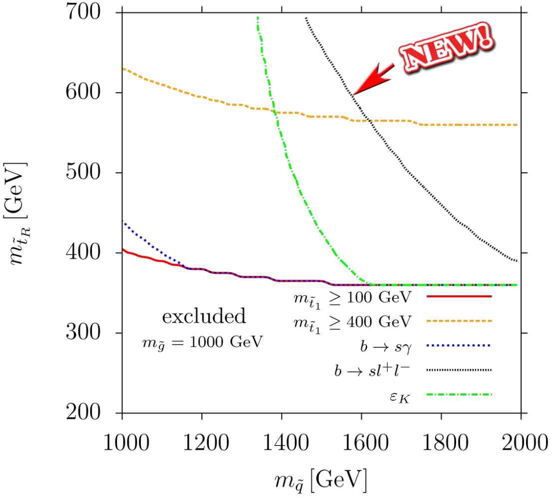
$$V_{cb} = -\frac{2\alpha_s}{3\pi}\frac{\overline{M^2}}{m_t m_{\tilde{g}}}(\delta^u_{23})_{LR}\,\tilde{C}_0\left(m^2_{\tilde{q}}/m^2_{\tilde{g}}, m^2_{\tilde{t}_R}/m^2_{\tilde{g}}\right)$$

- V_{cb} generated by quantum corrections $\propto (\delta^u_{23})_{LR}$
- $\Rightarrow$ relatively large values of $(\delta^u_{23})_{LR}$ needed
- $\Rightarrow$ translate into bound on RFV parameter space...



Improved Bounds on RFV

- Interplay of constraints on allowed RFV parameter space
- **Black:** Bound from $b \to s l^+ l^-$
- Green: Bound from ε_K through $(\delta^u_{23})^*_{LR}\,(\delta^u_{13})_{LR}$
- ➥ Spectrum of RFV with up-sector CKM generation must be $\gtrsim 1$ TeV



SUSY example point: $A_t = 1000$ GeV, $m_{H^\pm} = 300$ GeV, $\tan\beta = 4$, $M_2 = 800$ GeV, $\mu = -300$ GeV, $m_{\tilde{\nu}} = 100$ GeV

Summary

- New theoretical and experimental results on $\bar{B} \to \bar{K}^* l^+ l^-$ in particular in the kinematic region of low recoil give new constraints on squark flavor violation from large chargino contributions to C_9, C_{10}.
- Bounds as low as $(\delta^u_{23})_{LR} \lesssim 0.1$, depending on parameter space.
- Lower limit $\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) \gtrsim 1 \times 10^{-9}$ (assumed no scalar operators).
- $t \to cV$,$V = \gamma, g, Z$ too rare to be observed in foreseeable future.
- Bounds on RFV models partly even sharper than from ε_K.
- Bounds stronger for lighter stops.
- Even more precise measurements to come in the future: LHCb roadmap channel $B \to K^{*0} l^+ l^-$.
  - Future prospects: More statistics and additional observables.

BACK-UP

Sensitivity on MI parameters

- $\left(\delta^d_{23}\right)_{LR}$: Already tightly constrained by bounds on C_7 from $\bar{B} \to X_s\gamma$ Contribution to C_9, C_{10} only in double MI diagrams
- $\left(\delta^d_{23}\right)_{LL}$: effect in Z penguin suppressed by m_b^2/m_Z^2 compared to γ-penguin. No contribution to C_{10}, contribution to C_9 numerically small.
- $(\delta^u_{23})_{LL}$ and $(\delta^u_{23})_{LR}$: Contributions to B_s–$\bar{B}_s$ mixing very small. Contribution from $(\delta^u_{23})_{LL}$ to C_7 much larger than from $(\delta^u_{23})_{LR}$. C_{10} order of magnitude more sensitive to $(\delta^u_{23})_{LR}$.

Constraints on SUSY CPV in complex-valued $(\delta^u_{23})_{LR}$

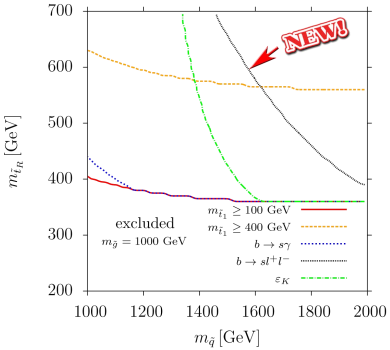
- Complex-valued $(\delta^u_{23})_{LR}$ induces phase in C_{10}
- Relative phase $|\arg C_9 C_{10}^*| \sim \pi$ from $A_{\rm FB}\left(\bar{B} \to \bar{K}^* l^+ l^-\right)$ at large q^2
- Little known about CPV phases of $C_{9,10}$

Observables sensitive to CPV in C_{10}:

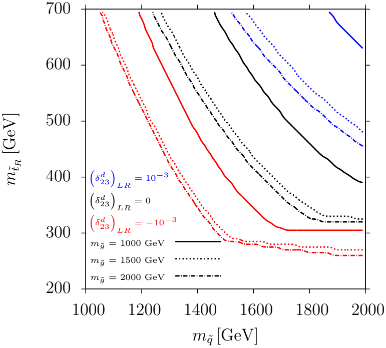
- (Naive) T-odd CP asymmetry $\langle A_7^D \rangle$ at small q^2 (CP-even)
- CP asymmetry $\langle a_{CP}^{(3)} \rangle$ at low recoil (CP-odd)

Up and down sector CKM generation

$$V_{cb} = \frac{2\alpha_s}{3\pi m_{\tilde{g}}} \left(\frac{(\Delta^d_{23})_{LR}}{m_b} \tilde{C}_0 \left(\frac{m^2_{\tilde{q}}}{m^2_{\tilde{g}}}, \frac{m^2_{\tilde{q}}}{m^2_{\tilde{g}}} \right) - \frac{(\Delta^u_{23})_{LR}}{m_t} \tilde{C}_0 \left(\frac{m^2_{\tilde{q}}}{m^2_{\tilde{g}}}, \frac{m^2_{\tilde{t}_R}}{m^2_{\tilde{g}}} \right) \right)$$



interplay of constraints



with $(\delta^d_{23})_{LR} \neq 0$

SUSY example point: $A_t = 1000$ GeV, $m_{H^\pm} = 300$ GeV, $\tan\beta = 4$, $M_2 = 800$ GeV, $\mu = -300$ GeV, $m_{\tilde{\nu}} = 100$ GeV