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

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Outline

SM and SUSY Flavor Puzzle

SM Flavor Puzzle

- SM gauge sector has $U(3)^5$ flavor symmetry
- Breaking by Yukawa coupling of fermions with Higgs field
- Origin of hierarchy? $\lambda_{\text{Top}} \sim 1,\ \lambda_b,\ \ldots,\ \lambda_{e^-} \sim 10^{-2}, \ldots, 10^{-6}$

SUSY Flavor Puzzle

- SUSY says nothing about flavor violation in SUSY breaking
  $\Rightarrow$ SUSY flavor violation (FV) generically arbitrary large
- FCNCs: partly drastic constraints on SUSY FV
  $\Rightarrow$ Hierarchy also necessary here $\Rightarrow$ SUSY flavor puzzle

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.

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

Parametrization of Flavor Violation

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

$$(\delta^q_{IJ})_{XY} = \frac{\left(M^2_{\tilde{q}\,IJ}\right)_{XY}}{\frac{1}{6}\sum_I \left[M^2_{\tilde{q}}\right]_{II}}, \quad I,J = 1,2,3, \quad X,Y = R,L$$

- FCNC bounds on MI parameter: [Artuso et. al. 2008]

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

- $\Rightarrow$ SUSY flavor puzzle
- But: No such bounds for $(\delta^u_{23})_{LR}$.

Effective Field Theory

- Effective Field Theory (EFT) for B physics at $\mu_b \ll \mu_W \approx m_W$.
- "Integrating out" heavy particles:
  $\Rightarrow$ Parameters of couplings of lighter fields
- $\Delta B = 1$-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 $b \to s l^+ l^-$

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

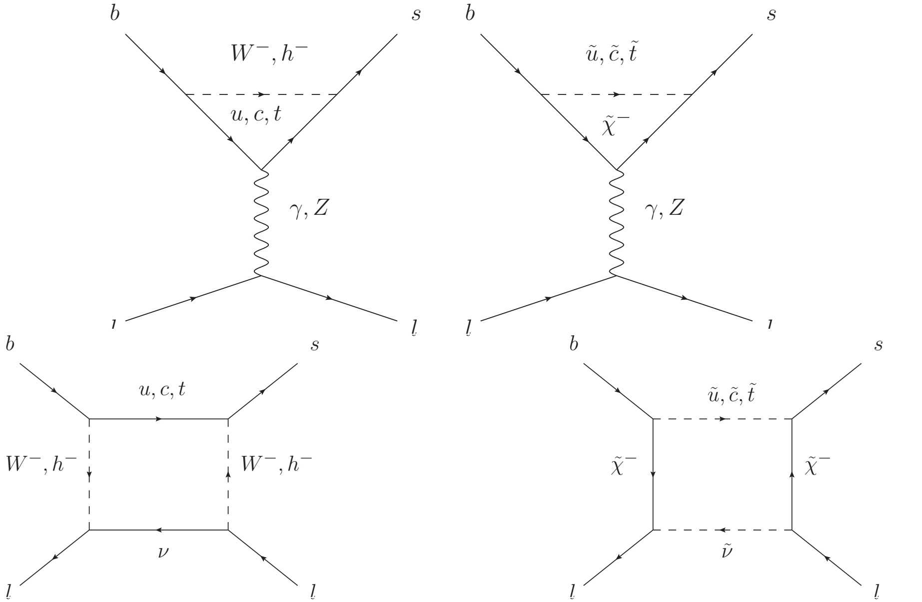
$$O_{10} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma_\mu P_L b\right) \left(\bar{l}\gamma^\mu \gamma_5 l\right)$$

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: $i = 7, 9, 10$

Full Theory: Charged Higgs/Charginos in $b \to sl^+l^-$



Comparison of SUSY Predictions with Data

- C_7 heavily constrained by $\bar{B} \to X_s \gamma$
- New theoretical and experimental results on $\bar{B} \to \bar{K}^* l^+ l^-$ (semileptonic decay) in particular in the kinematic region of low recoil of $\bar{K}^{(*)}$, i.e. large dilepton masses $q^2 \sim \mathcal{O}(m_b^2)$
  $\Rightarrow$ Constraint of allowed C_9 and C_{10} region

[Bobeth, Hiller, Wacker, van Dyk, 2010, 2011]

Vary SUSY parameters at the electroweak scale

$$300\,\text{GeV} \le m_{H^\pm} \le 1000\,\text{GeV} \qquad 100\,\text{GeV} \le M_2 \le 1000\,\text{GeV}$$
$$80\,\text{GeV} \le |\mu| \le 1000\,\text{GeV} \qquad 2 \le \tan\beta \le 15$$
$$m_{\tilde{q}} = 1000\,\text{GeV} \qquad 200\,\text{GeV} \le m_{\tilde{t}_R} \le 600\,\text{GeV}$$
$$-1000\,\text{GeV} \le A_t \le 1000\,\text{GeV} \qquad m_{\tilde{\nu}} = 100\,\text{GeV}$$

- Implementation by MSSM extension of the EOS-code
  Tool for the calculation of flavor observables
  http://project.het.physik.tu-dortmund.de/eos/

Flavor-diagonal SUSY

- Mass Insertion Parameter $\left(\delta^q_{IJ}\right)_{XY} = 0 \quad \forall \quad I \neq J$
- Measure New Physics effect with:

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

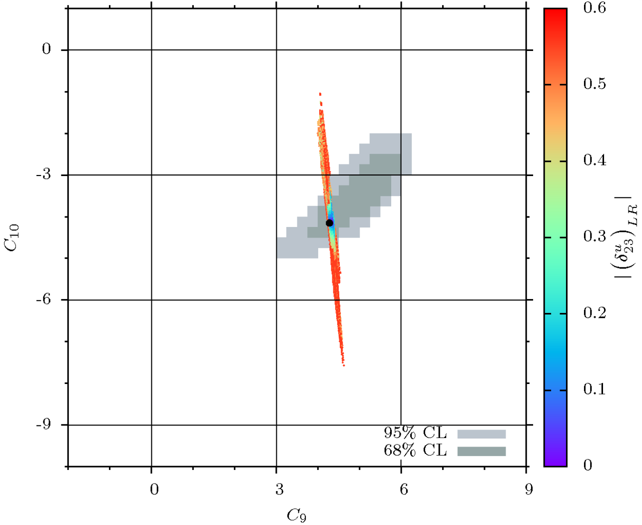
$R_9^{\max}(\mu_b)$	$R_{10}^{\max}(\mu_b)$
2 %	8 %

- Relative flavor-diagonal effect rather small.

. . . turn on flavor violation. . .

SUSY with Flavor Violation

- $C_7 < 0$ (SM-like)
- Large effect in C_{10} possible
- $\frac{C_{10}^{\rm MI}}{C_9^{\rm MI}} \simeq \frac{1}{4s_w^2 - 1}$
- $R_9^{\max}(\mu_b) = 8\%$
- $R_{10}^{\max}(\mu_b) = 82\%$

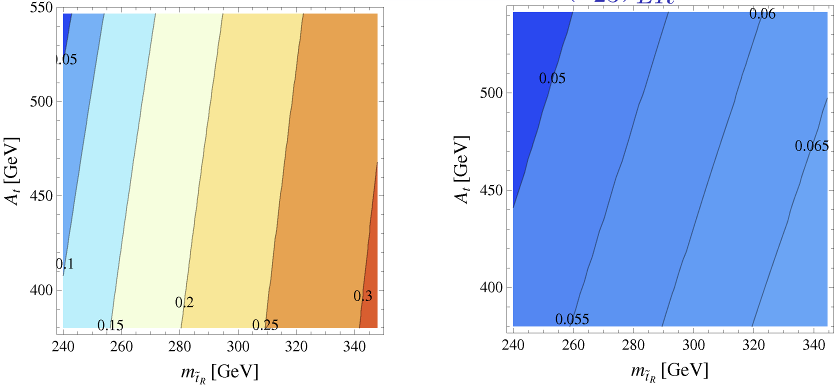


preliminary result

- Colored: SUSY points [Gross,Hiller,StS], Gray: Data [Bobeth,Hiller,van Dyk,Wacker 2011]

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

[Gross, Hiller, StS]



without semileptonic bounds

with all bounds

preliminary results

- By improved measurement of semileptonic B decays at LHCb the bounds will more and more improve

Further parameters: $m_{\tilde{\nu}} = 100\,\mathrm{GeV}$, $m_{H^\pm} = 300\,\mathrm{GeV}$, $m_{\tilde{g}} = 1\,\mathrm{TeV}$, $\tan\beta = 2$,

$$M_2 = 100\,\mathrm{GeV},\ \mu = -750\,\mathrm{GeV},\ m_{\tilde{q}} = 1\,\mathrm{TeV}$$

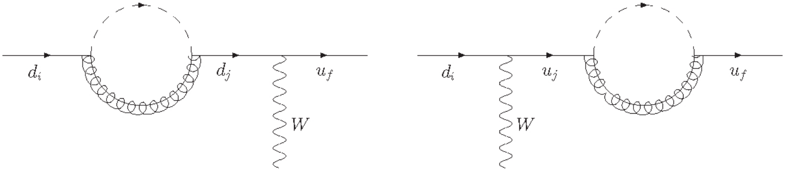
Radiative Flavor Violation (RFV)

[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

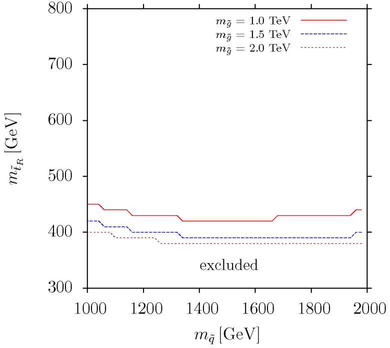


[Feynman diagrams from Crivellin, Hofer, Nierste, Scherer, 2011, arXiv:1105.2818]

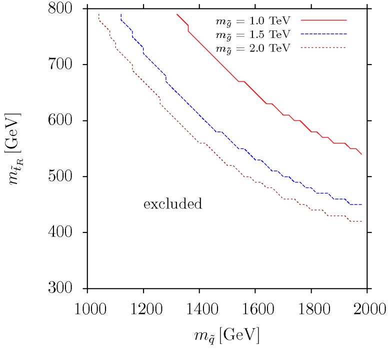
Comparison of Prediction and Bound on $\left(\delta_{23}^{u,d}\right)_{LR}$

Challenge of RFV by data

$$V_{cb} = \frac{2\alpha_s m_{\tilde{g}}}{3\pi}\left(\frac{\left(\Delta_{23}^{d}\right)_{LR} C_0(m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{q}})}{m_b} - \frac{\left(\Delta_{23}^{u}\right)_{LR} C_0(m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{t}_R})}{m_t}\right)$$



without semileptonic bounds



with all bounds

preliminary results

For bounds: $A_t = 800$ GeV, $m_{H^\pm} = 400$ GeV, $\tan\beta = 2$, $M_2 = 100$ GeV, $\mu = -1$ TeV, $m_{\tilde{\nu}} = 100$ GeV

Conclusion

- New theoretical and experimental results on $\bar{B} \to \bar{K}^* l^+ l^-$ in particular in the kinematic region of low recoil give constraints on squark flavor violation.
- Bounds on $(\delta^u_{23})_{LR}$ from large chargino contributions to C_9, C_{10}
- Improvement of the bounds in the future by improved measurement of semileptonic B decays at LHCb.
- The model independent bounds can be related to flavor models with non-MFV contribution.

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