Connections between B physics and rare top decays in the MSSM

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also based on work done in collaboration with
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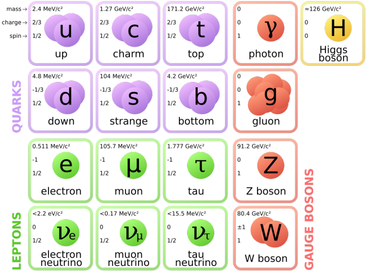
Introduction

Key ideas

- B physics is well studied
- Rare top decays ($t \to cV$, $V \in \{\gamma, g, Z\}$) are heavily suppressed in the SM
- MSSM could enhance $t \to cV$ significantly
- Use data from B physics to constrain the rare top decays

Outline

Short reminder: Flavor in the standard model



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`http://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg`

What is flavor?

- Matter comes in three generations
- Transitions between generations only through charged currents ($W^{\pm}$ bosons)
- No flavor changing neutral currents (FCNC) at tree level

Basics of supersymmetry

Supersymmetry (SUSY)

- Symmetry between bosons and fermions
- Motivation: Stabilises the higgs mass, lightest supersymmetric particle (LSP) $\Rightarrow$ dark matter candidate, ...

Soft SUSY breaking

- No superpartners seen yet $\Rightarrow$ SUSY must be broken
- Use spontaneous, soft symmetry breaking

Minmal supersymmetric standard model (MSSM)

- Minimal extension of the standard model (SM)
- Introduce one SUSY particle for each SM particle

Basics of supersymmetry (cont'd)

Particle content

	Quarks			Leptons		Gauge bosons			Higgs	
"SM"	Q_L	u_R	d_R	L_L	e_R	g	W	B	H_u	H_d
MSSM	$\widetilde{Q}_L$	$\widetilde{u}_R$	$\widetilde{d}_R$	$\widetilde{L}_L$	$\widetilde{e}_R$	$\widetilde{g}$	$\widetilde{W}$	$\widetilde{B}$	$\widetilde{H}_u$	$\widetilde{H}_d$
	Squarks			Sleptons		Gauginos			Higgsinos	

Soft SUSY breaking

- Sparticles would have same mass
  $\Rightarrow$ should have been seen
- Break SUSY with additional terms in the Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{soft}} = & m_{\widetilde{g}}\, \widetilde{g}\widetilde{g} + \dots && \text{gaugino masses}\\ & - \widetilde{Q}_L^\dagger\, m_Q^2\, \widetilde{Q}_L - \widetilde{u}_R^\dagger\, m_u^2\, \widetilde{u}_R - \widetilde{d}_R^\dagger\, m_d^2\, \widetilde{d}_R && \text{squark masses}\\ & + \dots\end{aligned}$$

Basics of supersymmetry (cont'd)

Particle content

	Quarks			Leptons		Gauge bosons			Higgs	
"SM"	Q_L	u_R	d_R	L_L	e_R	g	W	B	H_u	H_d
MSSM	$\widetilde{Q}_L$	$\widetilde{u}_R$	$\widetilde{d}_R$	$\widetilde{L}_L$	$\widetilde{e}_R$	$\widetilde{g}$	$\widetilde{\chi}^\pm$		$\widetilde{\chi}^0$	
	Squarks			Sleptons			Charginos		Neutralinos	

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$$- \widetilde{Q}_L^\dagger\, m_Q^2\, \widetilde{Q}_L - \widetilde{u}_R^\dagger\, m_u^2\, \widetilde{u}_R - \widetilde{d}_R^\dagger\, m_d^2\, \widetilde{d}_R \qquad \text{squark masses}$$
$$+ \dots$$

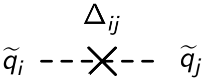
Squark mass matrix

LL | LR

$$\mathcal{M}^2_{\widetilde{u}} = \begin{pmatrix} m^2_{\widetilde{q}} & * & (\Delta^{\widetilde{u}}_{13})_{\mathrm{LL}} & * & * & * \\ & m^2_{\widetilde{q}} & (\Delta^{\widetilde{u}}_{23})_{\mathrm{LL}} & * & * & (\Delta^{\widetilde{u}}_{23})_{\mathrm{LR}} \\ & & m^2_{\widetilde{q}} & * & * & (\Delta^{\widetilde{u}}_{33})_{\mathrm{LR}} \\ & & & m^2_{\widetilde{q}} & * & * \\ & \text{h.c.} & & & m^2_{\widetilde{q}} & * \\ & & & & & m^2_{\widetilde{t}_{\mathrm{R}}} \end{pmatrix}$$

RL | RR

Parametrization: Mass insertions



- Treat Δ_{ij} as perturbations to propagator
- Normalize to mean squark mass: $\delta_{ij} = \Delta_{ij}/\overline{m}^2$
- δ_{ij} encode flavor (and CP) violation

Squark bases in the MSSM

Squark mass matrices

- Two 6×6 matrices $\mathcal{M}_u^2$, $\mathcal{M}_d^2$
- Subdivide into 3×3 blocks (LL, RR, LR, RL)
  e.g. $(\mathcal{M}_u^2)_{\mathrm{LL}} = v_u^2\, Y_u^\dagger Y_u + m_Q^2 + m_Z^2\, \cos(2\beta)\, g_{q,\mathrm{L}} \mathbb{1}$

SuperCKM basis

- SM: Rotate quarks by V_u, V_d, etc. to diagonalise mass terms
- Result: Diagonal mass terms, but CKM matrix $V = V_u V_d^\dagger$ at the $W^\pm$ vertex
- SuperCKM basis: Rotate squarks the same way as quarks

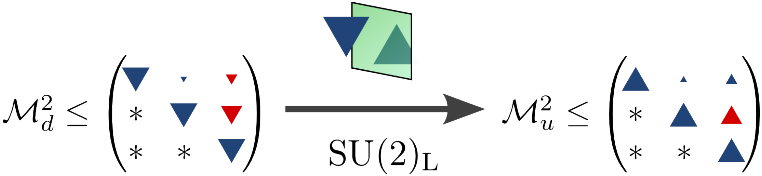
$\mathrm{SU(2)_L}$ relation between up and down squarks

Squark mass matrices

Gauge basis
$$\begin{cases} (\mathcal{M}_u^2)_{\mathrm{LL}} = \dots + m_Q^2 + \dots \\ (\mathcal{M}_d^2)_{\mathrm{LL}} = \dots + m_Q^2 + \dots \end{cases}$$

- Simple algebra reveals: $m_u^2 = V m_d^2 V^\dagger$
  where V is the SM CKM matrix!
- Soft squark mass terms dominant $\Rightarrow$ approximate:

$$(\mathcal{M}_u^2)_{\mathrm{LL}} = V (\mathcal{M}_d^2)_{\mathrm{LL}} V^\dagger$$



$\mathrm{SU(2)_L}$ relation between up and down squarks

Squark mass matrices

$$\text{SuperCKM basis} \begin{cases} (\mathcal{M}_u^2)_{\mathrm{LL}} = \cdots + m_u^2 + \dots \\ (\mathcal{M}_d^2)_{\mathrm{LL}} = \cdots + m_d^2 + \dots \end{cases}$$

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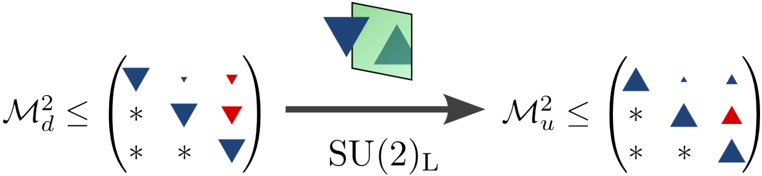


B meson flavor physics

Relevant processes in this talk

B mixing and $\overline{B} \to \overline{K}^{(*)} \ell^+ \ell^-$

Theoretical description

Description using effective Hamiltonians:

$$H_{\text{eff}} \sim \sum_i C_i \, O_i$$

- C_i - Wilson coefficients:
  - short distance physics
  - may contain new physics contributions
- O_i - Wilson operators:
  - long distance physics
  - essentially unchanged by new physics

Approaches to new physics (NP)

Top down approach

- Calculate process in the full theory of a particular NP model
- Match result to the operators at some high scale (e.g. μ_{SUSY})
- Use RGE to evolve coefficients to the low scale (μ_b)
- Compare observables to experimental data

Bottom up approach

- Treat Wilson coefficients C_i as free parameters
- Fit observables to experimental data in terms of the C_i
- Compare results for particular NP models at the level of the C_i

B mixing / CP violation: Overview

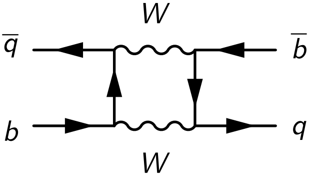
B mixing

- Neutral B mesons can mix with thier anti-partners
- Observables: Δm (and $\Delta\Gamma$)

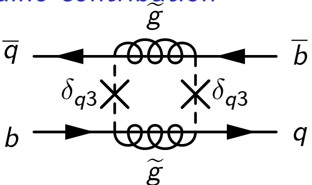
CP violation

- SM: Only one CP violating phase (CKM mechanism)
- MSSM: Many possible CP phases $\Rightarrow$ good probe
- Observables: $S_{J/\psi K_S}$ for B_d, ϕ_s for B_s

SM contribution



Gluino contribution



B mixing / CP violation

The effective Hamiltonian

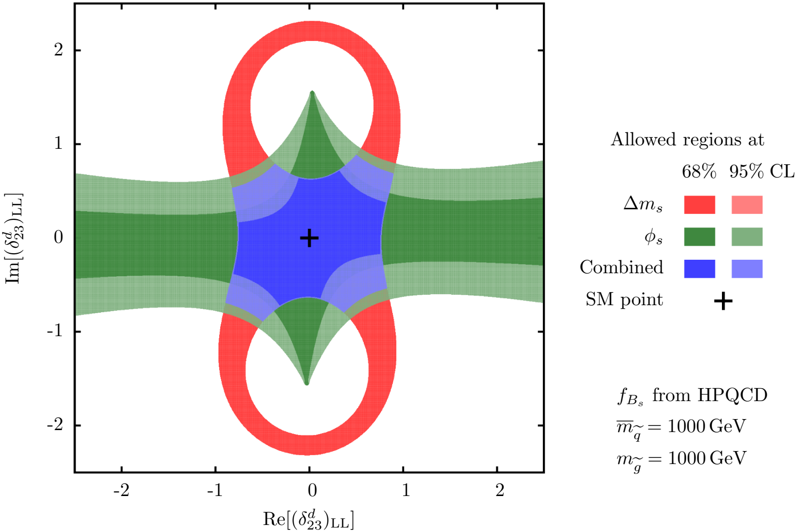
- MSSM: Focus on gluino contributions
- Relevant operator: $O_1 = (\overline{q}_L \gamma_\mu b_L)(\overline{q}_L \gamma^\mu b_L)$
- Relevant mass insertions: $(\delta^d_{23})_{LL}$ for B_s and $(\delta^d_{13})_{LL}$ for B_d

$$C_1 = -\frac{\alpha_s^2}{216\, m_{\tilde{q}}^2} F(x_{\tilde{g}})\,(\delta^d_{q3})^2_{LL} \qquad \text{where } x_{\tilde{g}} = m^2_{\tilde{g}}/m^2_{\tilde{q}}$$

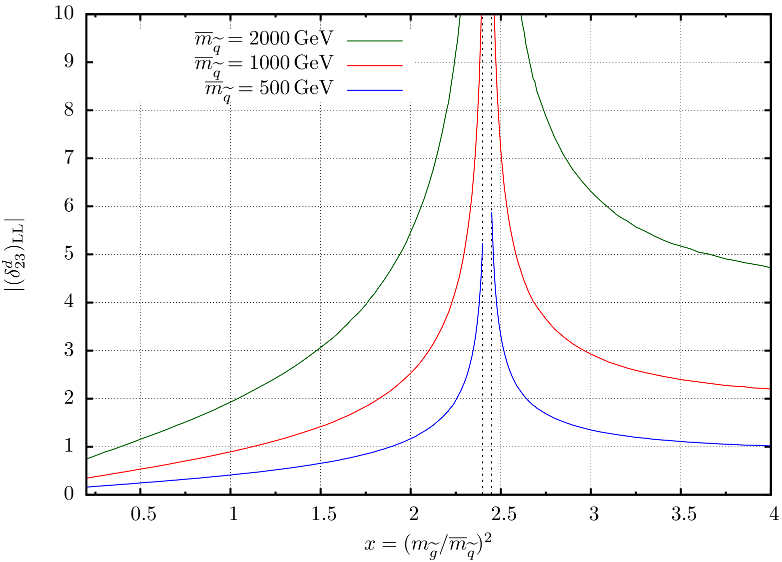
How to constrain $(\delta^d_{ij})_{LL}$

- Top down approach
- Calculate values for observables (Δm, ϕ_s and $S_{J/\psi K_S}$)
- Compare to experimental measurements
- See what values are allowed for $(\delta^d_{ij})_{LL}$

B_s mixing: Bounds on $(\delta^d_{23})_{LL}$



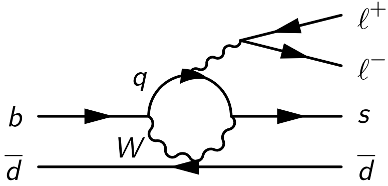
B_s mixing: Bounds on $(\delta^d_{23})_{\text{LL}}$



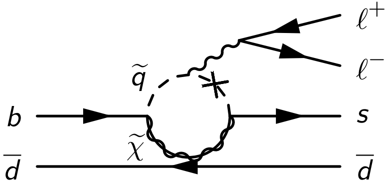
$\overline{B} \to \overline{K}^{(*)} \ell^+ \ell^-$: Overview

- Rare process in the SM: Br $\sim \mathcal{O}(10^{-7})$
- Contributions in the MSSM especially from charginos

SM contriubtion



Chargino contribution



$\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$: The effective Hamiltonian

Use OPE to describe B decays:

$$H_{\text{eff}} \sim \sum_i C_i O_i + \text{h.c.}$$

Relevant operators here:

$b \to s\gamma$

$O_7 \sim m_b(\bar{s}_\text{L}\sigma_{\mu\nu}b_\text{R})F^{\mu\nu}$

$\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$

$O_9 \sim (\bar{s}_\text{L}\gamma_\mu b_\text{L})(\bar{\ell}\gamma^\mu\ell)$

$O_{10} \sim (\bar{s}_\text{L}\gamma_\mu b_\text{L})(\bar{\ell}\gamma^\mu\gamma_5\ell)$

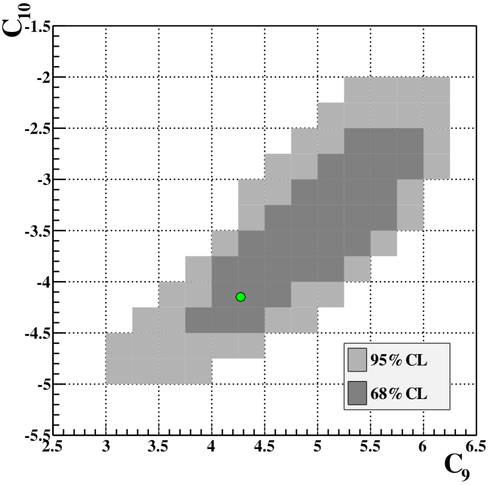
Decompose Wilson coefficients:

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

MSSM contribution is sensitive to $(\delta^u_{23})_{\text{LR}}$:

$$C_i^{\text{NP}} \sim (\delta^u_{23})_{\text{LR}}$$

$\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$: Allowed region for $C_{9,10}$



We build upon previous work by [Bobeth, Hiller, van Dyk, Wacker '12]

- Bottom up approach: Treat Wilson coefficients C_i as parameters
- Constrain $C_{9,10}$ using available data (Br, A_{FB}, F_{L}, ...)

- SM prediction ($C_7 = -0.33$, $C_9^{\text{SM}} = 4.27$, $C_{10}^{\text{SM}} = -4.15$)

$\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$: The scan

Scan MSSM parameter space

Vary parameters:

$\tan\beta, m_{H^\pm}, M_2, \mu$	higgs sector
$m_{\tilde{t}_R}, A_t, (\delta^u_{23})_{LR}$	squark sector

Check constraints

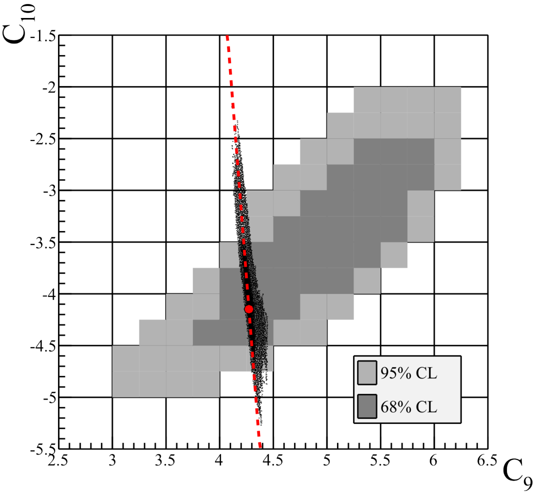
Calculate for each parameter point

C_7, C_9, C_{10}	extending & using EOS[1]
$m_{h^0}, \Delta\rho$	using FeynHiggs[2]
$m_{\tilde{t}_1}, m_{\chi^\pm_1}$	

[1] http://project.het.physik.tu-dortmund.de/eos/

[2] [S. Heinemeyer et al. '99, '00, '03, '07],

$\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$: Bounds on $(\delta^d_{23})_{LR}$



- Black: Allowed parameter points in the $C_{9,10}$ plane
- Observe correlation between C_9 and C_{10} (red dashes):

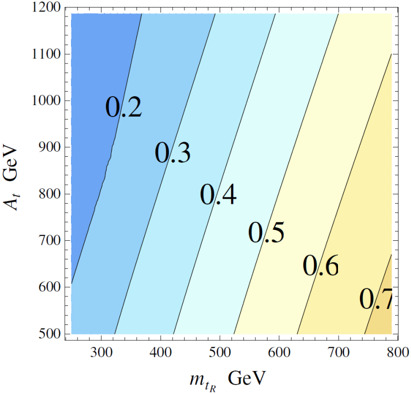
$$\frac{C_9^{\tilde{\chi}}}{C_{10}^{\tilde{\chi}}} \sim 4\sin^2\theta_W - 1 \ll 1$$

(results from Z-penguin dominance)

$\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$: Bounds on $(\delta^d_{23})_{\mathrm{LR}}$

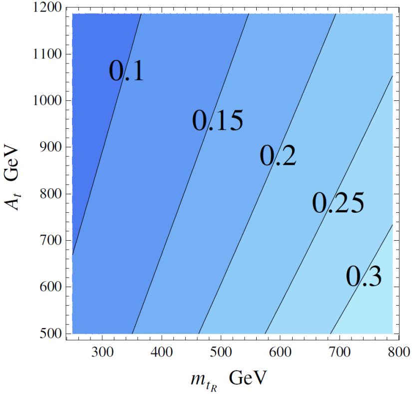
Bounds on $|(\delta^u_{23})_{\mathrm{LR}}|$ at an example parameter point

BEFORE



Without $\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$ bounds

AFTER



With $\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$ bounds

Review: What do we have so far?

B mixing

- We have: Bounds on $(\delta^d_{23})_{\mathrm{LL}}$
- $\mathrm{SU}(2)_{\mathrm{L}}$ relation $\Rightarrow$ bounds on $(\delta^u_{23})_{\mathrm{LL}}$
- Next step: Use $(\delta^u_{23})_{\mathrm{LL}}$ in $t \to cV$

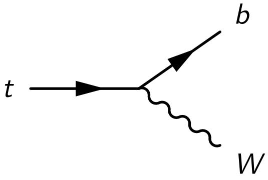
$\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$

- We have: Bounds on $(\delta^u_{23})_{\mathrm{LR}}$
- Next step: Use $(\delta^u_{23})_{\mathrm{LR}}$ in $t \to cV$

SM decays of top quarks

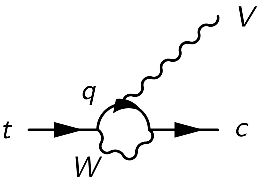
Dominant top decay channel in the SM

- Tops decay dominantly into W^+ and b
- Decay width $\Gamma(t \to W^+ b) \approx 1.47\ \mathrm{GeV}$
- Tree level decay $\Rightarrow$ No significant BSM contributions expected



FCNC decays in the SM

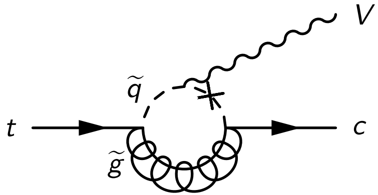
- Decays to c and vector boson $V = \gamma/g/Z^0$
- Heavily suppressed by GIM mechanism
- E.g., $\mathrm{Br}(t \to c\,\gamma) \approx 4.6 \times 10^{-14}$



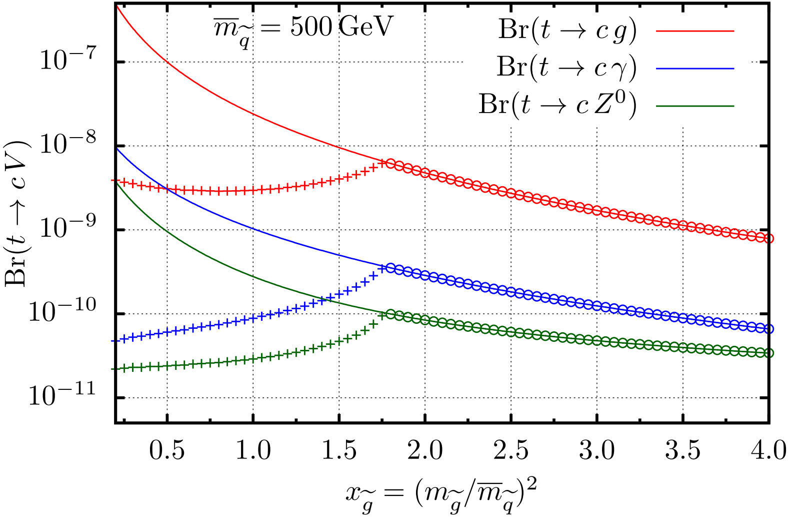
$t \to cV$ in the MSSM

- $t \to c\,V$ receives contributions from gluinos, charginos, neutralinos
- Focus on gluino contributions
- Inside the loop: Gluinos and up squarks
- Depends on off-diagonal elements of $\mathcal{M}_u^2$
- Use bounds
    - on $(\delta^u_{23})_{\mathrm{LL}}$ from B mixing
    - on $(\delta^u_{23})_{\mathrm{LR}}$ from $\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$

  to derive bounds on $\mathrm{Br}(t \to cV)$



Bounds on $Br(t \to cV)$: LL block



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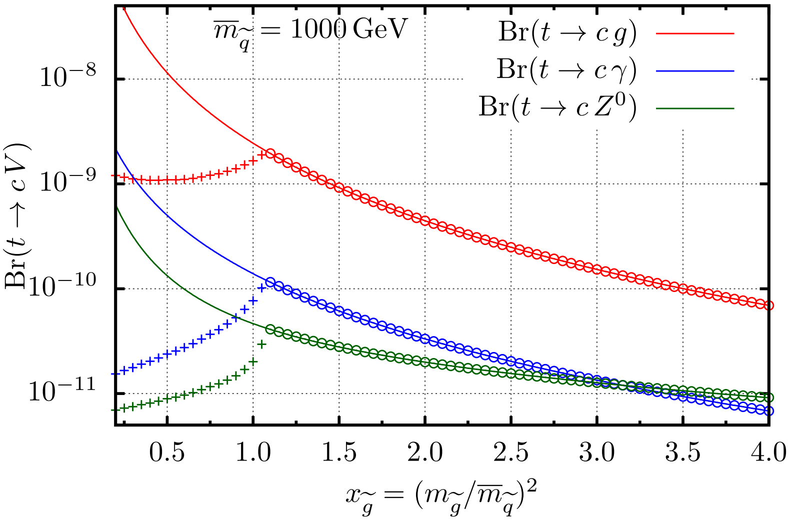

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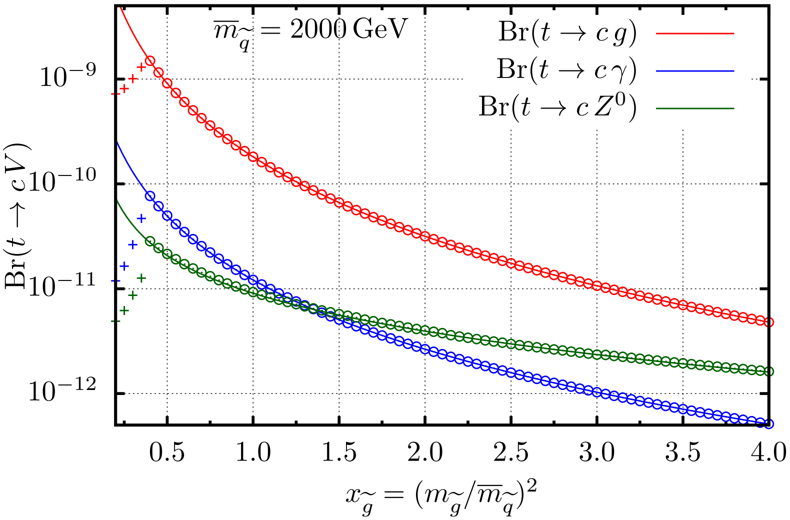
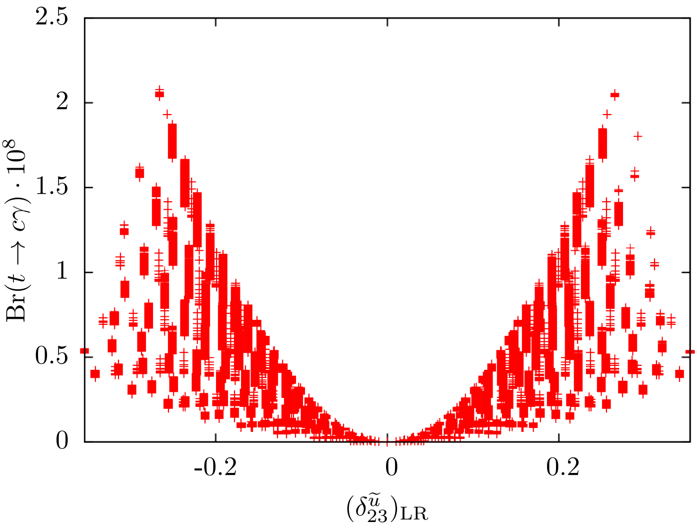


Bounds on $Br(t \to cV)$: LR block



Results for top decays

Maximal branching ratios

SM: [Aguilar-Saavedra et al. '03/'04]
MSSM: [Cao et al. '07]

	$\mathrm{Br}(t \to c\gamma)$	$\mathrm{Br}(t \to cg)$	$\mathrm{Br}(t \to cZ)$
SM	4.6×10^{-14}	4.6×10^{-12}	1×10^{-14}
Prev. MSSM bound	5.2×10^{-7}	3.2×10^{-5}	1.8×10^{-6}
Our bound	2.1×10^{-8}	7.2×10^{-7}	1.0×10^{-7}

Compare to sensitivity of the LHC

[Veloso '08]

L_{int}	$\mathrm{Br}(t \to c\gamma)$	$\mathrm{Br}(t \to cg)$	$\mathrm{Br}(t \to cZ)$
$100\ \mathrm{fb}^{-1}$	3.0×10^{-5}	1.4×10^{-3}	1.4×10^{-4}

$\Rightarrow$ far out of reach

Summary

- B physics yields bounds on
  - $(\delta^u_{23})_{\mathrm{LL}}$ (from B mixing - after $\mathrm{SU(2)_L}$ relation)
  - $(\delta^u_{23})_{\mathrm{LR}}$ (from $\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-$ - directly)
- Translate into constraints on $\mathrm{Br}(t \to cV)$
- $t \to cV$ significantly can be enhanced in MSSM
  Our bounds are $Br \sim \mathcal{O}\left(10^{-8} - 10^{-7}\right)$
  - ⇒ Improvement by $\sim$ one order of magnitude
  - ⇒ Out of reach for the LHC

Backup

Input values

Standard model

$$m_t^{\text{pole}} = 173.3 \text{ GeV}$$
$$m_b(m_b) = 4.19 \text{ GeV}$$
$$m_W = 80.399 \text{ GeV}$$
$$m_Z = 91.1876 \text{ GeV}$$
$$\alpha_s(m_Z) = 0.1184$$
$$s_W^2 = 0.23116$$

MSSM (at $\mu_0 = 120$ GeV)

Fixed parameters:

$$m_{\tilde{q}} = 1000 \text{ GeV}$$
$$m_{\tilde{\nu}} = 100 \text{ GeV}$$
$$m_{\tilde{g}} = 700 \text{ GeV}$$

Parameters in scan:

$$\tan\beta \in [3, 15]$$
$$m_{H^\pm} \in [300, 1000] \text{ GeV}$$
$$M_2 \in [100, 1000] \text{ GeV}$$
$$|\mu| \in [80, 1000] \text{ GeV}$$
$$m_{\tilde{t}_R} \in [170, 800] \text{ GeV}$$
$$A_t \in [-3000, 3000] \text{ GeV}$$
$$(\delta_{23}^u)_{\text{LR}} \in [-0.85, 0.85]$$

The SUSY example point

Our SUSY example parameter point

Input values:

$$m_{H^\pm} = 300\ \mathrm{GeV}$$
$$\tan\beta = 4$$
$$M_2 = 150\ \mathrm{GeV}$$
$$\mu = -300\ \mathrm{GeV}$$
$$m_{\tilde{t}_R} = 300\ \mathrm{GeV}$$
$$m_{\tilde{q}} = 1000\ \mathrm{GeV}$$
$$A_t = 1000\ \mathrm{GeV}$$
$$m_{\tilde{\nu}} = 100\ \mathrm{GeV}$$
$$m_{\tilde{g}} = 700\ \mathrm{GeV}$$

Resulting mass spectrum:

$$m_{\tilde{t}_1} = 236\ \mathrm{GeV}$$
$$m_{\tilde{t}_2} = 1017\ \mathrm{GeV}$$
$$m_{\tilde{\chi}_1} = 150\ \mathrm{GeV}$$
$$m_{\tilde{\chi}_2} = 321\ \mathrm{GeV}$$
$$m_{h^0} = 117\ \mathrm{GeV}$$

Wilson coefficients in MIA

Dependence of the Wilson coefficients C_7, C_9 and C_{10} on $(\delta^u_{23})_{\rm LR}$

$$C_7^{\rm MI,\widetilde{\chi}}(\mu_0) = \frac{V^*_{cs}}{V^*_{ts}}\frac{\lambda_t}{g_2}\frac{m_W^2}{m_{\widetilde{q}}^2} F \times (\delta^u_{23})_{\rm LR}$$

$$C_9^{\rm MI,\widetilde{\chi}}(\mu_0) = \frac{V^*_{cs}}{V^*_{ts}}\frac{\lambda_t}{g_2}\frac{1}{4s_W^2}\times \left((4s_W^2-1)F^{Z-p} + 4s_W^2\frac{m_W^2}{m_{\widetilde{q}}^2}F^{\gamma-p} - \frac{m_W^2}{m_{\widetilde{q}}^2}F^{\rm box}\right)\times (\delta^u_{23})_{LR}$$

$$C_{10}^{\rm MI,\widetilde{\chi}}(\mu_0) = \frac{V^*_{cs}}{V^*_{ts}}\frac{\lambda_t}{g_2}\frac{1}{4s_W^2}\left(F^{Z-p} + \frac{m_W^2}{m_{\widetilde{q}}^2}F^{\rm box}\right)\times (\delta^u_{23})_{\rm LR}$$

Relative importance $\widetilde{\chi}/\widetilde{g}$ contriubtions

Dependence of $C_{7,9,10}$ on $(\delta^{u,d}_{23})_{AB}$

Chargino contributions:

$$C_7^{\mathrm{MI},\widetilde{\chi}} = 0.01(\delta^u_{23})_{\mathrm{LR}} - 0.38(\delta^u_{23})_{\mathrm{LL}}$$

$$C_9^{\mathrm{MI},\widetilde{\chi}} = 0.17(\delta^u_{23})_{\mathrm{LR}} - 0.11(\delta^u_{23})_{\mathrm{LL}}$$

$$C_{10}^{\mathrm{MI},\widetilde{\chi}} = -2.24(\delta^u_{23})_{\mathrm{LR}} + 0.19(\delta^u_{23})_{\mathrm{LL}}$$

Gluino contributions:

$$C_7^{\mathrm{MI},\widetilde{g}} = 16.35(\delta^u_{23})_{\mathrm{LR}} - 0.02(\delta^u_{23})_{\mathrm{LL}}$$

$$C_9^{\mathrm{MI},\widetilde{g}} = 0.04(\delta^u_{23})_{\mathrm{LL}}$$

$$C_{10}^{\mathrm{MI},\widetilde{g}} = -$$

Meson mixing formalism

- Describe mesons using a non-hermitian Hamiltonian

$$H = M - {}^{i}/_{2}\,\Gamma \qquad M = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^{*} & M_{11} \end{pmatrix}, \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^{*} & \Gamma_{11} \end{pmatrix}$$

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}\,t}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{11} \end{pmatrix}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

- Diagonalise Hamiltonian: Find mass eigenstates $|B_{\mathrm{L}}\rangle$, $|B_{\mathrm{H}}\rangle$
- Define observables

$$\Delta m \approx 2|M_{12}|$$

$$\phi = \arg(-{}^{M_{12}}/_{\Gamma_{12}})$$

$$\Delta\Gamma \approx 2|\Gamma_{12}|\cos\phi$$

CP violation

A *CP* asymmetry

- *CP* is violated by weak interactions in the SM
  $\Rightarrow$ complex phase in CKM matrix
- New physics can have new phases
- For decays of B mesons into CP eigenstates f_{CP} define

$$a_{f_{CP}} = \frac{\Gamma(\overline{B^0}(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B^0}(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

CP violation continued

B_d mesons

- For B_d choose for example $f_{CP} = J/\psi\, K_S$

$$a_{J/\psi K_S} \approx S_{J/\psi K_S} \sin(\Delta m\, t)$$
$$S_{J/\psi K_S} \approx \sin(\arg(M_{12}))$$

B_s mesons

- For B_s choose for example $f_{CP} = J/\psi\, \phi$
- ϕ is a vector meson $\Rightarrow$ angular analysis needed
- Extract ϕ_s and $\Delta\Gamma$ by a combined fit

$$\phi_s \approx \arg(M_{12})$$

Effective Hamiltonians

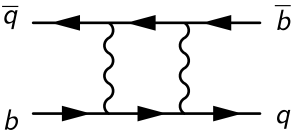
How to calculate M_{12}

- Use an effective Hamiltonian

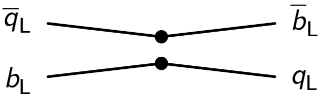
$$H_{\text{eff}} = \sum_i C_i \, O_i$$

- Operators O_i: Contributions from low scales (bound quarks)
- Coefficients C_i: Contributions from large scales (W, top, ...)

$$M_{12} = \frac{\langle B^0 | \, H_{\text{eff}} \, | \overline{B^0} \rangle}{2 \, m_B}$$



$\Rightarrow$



$$O_1 = (\overline{q}_{\text{L}} \gamma_\mu b_{\text{L}})(\overline{q}_{\text{L}} \gamma^\mu b_{\text{L}})$$