The MSSM with large tanβ

beyond the decoupling limit

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The Parameter $\tan\beta$

- MSSM contains two Higgs-doublets H_u, H_d:

$$\boxed{\mathcal{L}_{q,y} = -y_u^{ij}\bar{u}_i Q_j H_u - y_d^{ij}\bar{d}_i Q_j H_d + h.c.}$$

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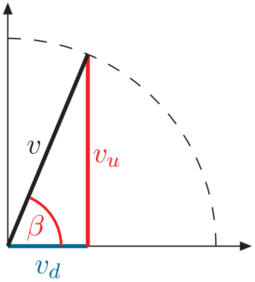
- VEVs: $\langle H_u \rangle = v_u$, $\langle H_d \rangle = v_d$
  with $v_u^2 + v_d^2 = v^2 \approx (174 GeV)^2$
  $\Rightarrow$ free parameter $\tan\beta = v_u/v_d$

- large $\tan\beta$ $\Leftrightarrow$ small v_d



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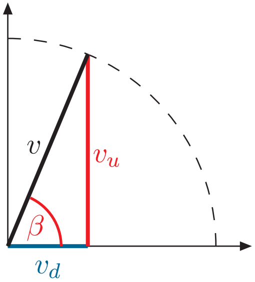
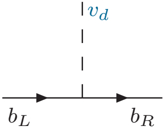


- Motivation for large $\tan\beta \sim 50$: Unification of y_t and y_b possible ($\Rightarrow$ SO(10) GUTs)

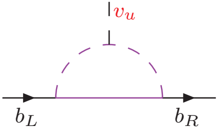
The pattern of tanβ-enhancement

- Consider tree-level amplitude with suppression v_d.
  One-loop corrections may involve v_u instead.
  [Hall,Rattazzi,Sarid; Blazek,Raby,Pokorski]

- Example: b-quark mass



$m_b \sim v_d$



$\delta m_b \sim \epsilon \cdot v_u$

$$\frac{\delta m_b}{m_b} \sim \epsilon \cdot \tan\beta$$
$$\sim \mathcal{O}(1)$$

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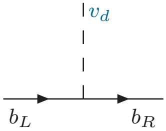

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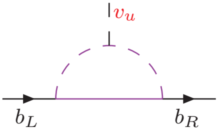

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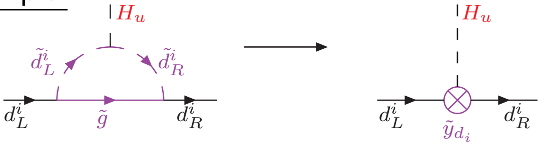
- Two possibilities to deal with such $\mathcal{O}(1)$ corrections
  1. Effective Lagrangian for $M_{\text{SUSY}} \gg v, M_{A^0}, M_{H^0}, M_{H^+}$
  2. Calculation in the full MSSM beyond decoupling

Effective Lagrangian in the decoupling limit

- Integrate out all particles with masses $M_{\text{SUSY}} \gg v$, keep only SM particles and Higgs fields
- Example:



$$\mathcal{L}_{d,y}^{eff} = -y_{d_i} \bar{d}_i Q_i H_d - \tilde{y}_{d_i} \bar{d}_i Q_i H_u$$

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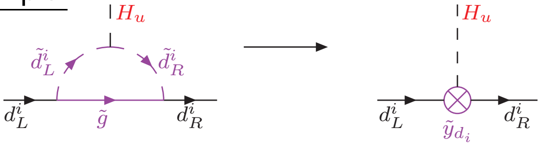


$$\mathcal{L}^{eff}_{d,y} = -y_{d_i}\bar{d}_i Q_i H_d - \tilde{y}_{d_i}\bar{d}_i Q_i H_u$$

- Consequence: Modified relation between y_{d_i} and m_{d_i}

$$m_{d_i} = y_{d_i} v_d + \tilde{y}_{d_i} v_u \qquad \Rightarrow \qquad \boxed{y_{d_i} = \frac{m_{d_i}}{v_d(1+\epsilon_i \tan\beta)}}$$

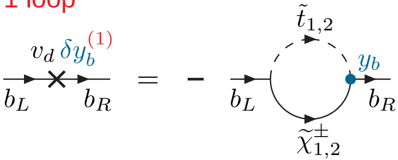
contains contributions of the form $(\epsilon \tan\beta)^n$ to all orders
$\rightarrow$ resummation?

Resummation beyond the decoupling limit

- Subtract $\tan\beta$-enhanced corrections to all orders by appropriate finite counterterms. [Carena,Garcia,Nierste,Wagner]

- <u>Example:</u> $\Sigma^{RL}_{b,\widetilde{\chi}^\pm}(y_b) = y_b v_d \Delta_b^{\widetilde{\chi}^\pm}, \qquad \Delta_b^{\widetilde{\chi}^\pm} = \epsilon_b^{\widetilde{\chi}^\pm} \tan\beta$

1 loop



$$\delta y_b{}^{(1)} = -\Delta_b^{\widetilde{\chi}^\pm} y_b = -\Delta_b^{\widetilde{\chi}^\pm} \frac{m_b}{v_d}$$

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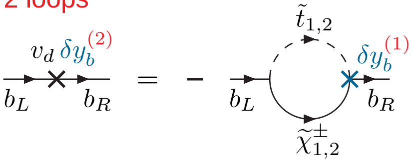

$$\delta y_b{}^{(2)} = -\Delta_b^{\widetilde{\chi}^\pm}\,\delta y_b{}^{(1)} = (-\Delta_b^{\widetilde{\chi}^\pm})^2 \frac{m_b}{v_d}$$

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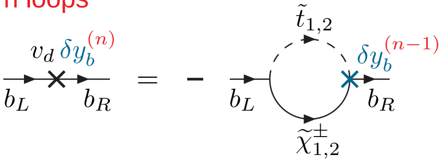
n loops



$$\delta y_b{}^{(n)} = -\Delta_b^{\widetilde{\chi}^\pm}\,\delta y_b{}^{(n-1)}$$
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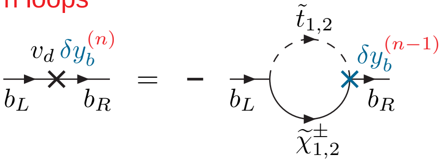

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$$y_b^0 = \frac{m_b}{v_d}\left(1 - \Delta_b^{\widetilde{\chi}^{\pm}} + \Delta_b^{\widetilde{\chi}^{\pm}\,2} - \ldots\right) = \frac{m_b}{v_d(1+\Delta_b^{\widetilde{\chi}^{\pm}})}$$

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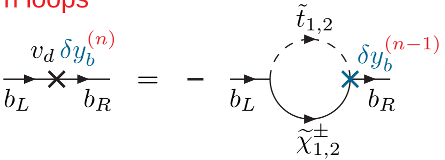

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- Explicit resummation of contributions of the form $\Delta_b = \epsilon_b \tan\beta$

Why go beyond decoupling limit?

- $M_{\text{SUSY}} \sim v$ is natural.
  - $M_{\text{SUSY}} \gg v$ introduces hierarchy problem.
  - Scenarios with neutralino LSP involve several SUSY-particles with masses $\sim v$.
- Test accuracy of calculations done with the effective Lagrangian approach.
- Study $\tan\beta$-enhanced effects in couplings of SUSY-particles like $\tilde{g}$, $\widetilde{\chi}^0$.

  Impossible in the decoupling limit where these particles are integrated out!

Summary of large-tanβ effects

effect	decoupling limit	beyond
modified relation $y_{d_i} \leftrightarrow m_{d_i}$	[Hall,Rattazzi,Sarid; Carena,Olechowski, Pokorski,Wagner]	[Carena,Garcia, Nierste,Wagner], $\boxed{1}$
corrections to CKM matrix	[Blazek,Raby,Pokorski]	[Buras,Chankowski, Rosiek,Slawianowska], $\boxed{2}$
enhanced FCNCs $d_i\, d_j\, H^0/A^0$	[Hamzaoui,Pospelov,Toharia; Babu,Kolda; Buras,Chankowski,Rosiek, Slawianowska]	[Buras,Chankowski, Rosiek,Slawianowska], $\boxed{3}$
enhanced FCNCs $d_i\, \tilde{d}_j\, \tilde{g}/\widetilde{\chi}^0$	not accessible	$\boxed{3}$
vertex corrections $\bar{u}_{i,R}\, d_{j,L}\, H^+$	[Degrassi,Gambino,Giudice; Carena,Garcia, Nierste,Wagner]	process-dependent (non-universal)

$\boxed{1} - \boxed{3} =$ this talk

Three new results

Beyond the decoupling limit:

1. Scheme dependence of the resummation formula for the Yukawa coupling
2. Resummation of flavour-changing self-energies
3. New effects in FCNC processes

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Input schemes for bottom-squark mixing

- Bottom-squark mass matrix: $$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} m^2_{\tilde{b}_L} & -y_b^* v_u \mu \\ -y_b v_u \mu^* & m^2_{\tilde{b}_R} \end{pmatrix}$$

- Mixing matrix: $$\widetilde{R}_b \mathcal{M}^2_{\tilde{b}} \widetilde{R}_b^\dagger = \text{diag}(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}),$$

$$\widetilde{R}_b = \begin{pmatrix} \cos\tilde{\theta}_b & \sin\tilde{\theta}_b e^{i\tilde{\phi}_b} \\ -\sin\tilde{\theta}_b e^{-i\tilde{\phi}_b} & \cos\tilde{\theta}_b \end{pmatrix}$$

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- What to choose as input? $\rightarrow$ different possibilities, e.g.
  - elements of $\mathcal{M}^2_{\tilde{b}}$: $m_{\tilde{b}_L}$, $m_{\tilde{b}_R}$, μ, $\tan\beta$
  - mass eigenvalues and mixing angle: $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$, $\tilde{\theta}_b$, $\tilde{\phi}_b$
  - eigenvalues and off-diag. entries of $\mathcal{M}^2_{\tilde{b}}$: $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$, μ, $\tan\beta$

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  - eigenvalues and off-diag. entries of $\mathcal{M}^2_{\tilde{b}}$: $m_{\tilde{b}_1}, m_{\tilde{b}_2}, \mu, \tan\beta$
- Note: $\tilde{\theta}_b$vanishes for $v/M_{\text{SUSY}} \rightarrow 0$
  $\rightarrow$ No different input schemes in the decoupling limit.

Scheme Dependence of the Resummation Formula

- $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$ and $\tilde{\theta}_b$ depend on y_b through $\mathcal{M}^2_{\tilde{b},12} = -y_b^* v_u \mu$.
- Change between different input schemes using relations like

$$m^2_{\tilde{b}_{1,2}} = \frac{1}{2}\left(m^2_{\tilde{b}_L} + m^2_{\tilde{b}_R} \pm \sqrt{\left(m^2_{\tilde{b}_L} - m^2_{\tilde{b}_R}\right)^2 + 4|y_b v_u \mu|^2}\right),$$

$$\sin 2\tilde{\theta}_b \, e^{-i\tilde{\phi}_b} = \frac{-2 y_b v_u \mu}{m^2_{\tilde{b}_1} - m^2_{\tilde{b}_2}}$$

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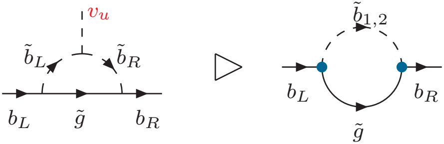
- y_b-dependence of $\Sigma_b^{RL}(y_b)$ $\longleftrightarrow$ choice of input parameters
- y_b-dependence of $\Sigma_b^{RL}(y_b)$ determines possible counterterm insertions

  $\Rightarrow$ Resummation formula depends on renormalization scheme!!!

Example: $\Sigma_{b,\tilde{g}}^{RL} = m_b \Delta_b^{\tilde{g}} = m_b \epsilon_b^{\tilde{g}} \tan\beta$



$$\propto \sin 2\tilde{\theta}_b \, e^{-i\tilde{\phi}_b} = \frac{-2\mu^* m_b \tan\beta}{m_{\tilde{b}_1}^2 - m_{\tilde{b}_2}^2}$$

input	$\Sigma_{b,\tilde{g}}^{RL}(y_b) \propto$	resummation formula
$m_{\tilde{b}_1}, m_{\tilde{b}_2}, \tilde{\theta}_b, \tilde{\phi}_b$	$\sin 2\tilde{\theta}_b \, e^{-i\tilde{\phi}_b}$	$y_b = \frac{m_b}{v_d}\left(1 - \Delta_b^{\tilde{g}}\right)$
$m_{\tilde{b}_1}, m_{\tilde{b}_2}, \mu, \tan\beta$	$\frac{-2 y_b v_u \mu}{m_{\tilde{b}_1}^2 - m_{\tilde{b}_2}^2}$	$y_b = \frac{m_b}{v_d(1 + \Delta_b^{\tilde{g}})}$
$m_{\tilde{b}_L}, m_{\tilde{b}_R}, \mu, \tan\beta$	$\frac{-2 y_b v_u \mu}{\sqrt{(m_{\tilde{b}_L}^2 - m_{\tilde{b}_R}^2)^2 + 4\|y_b v_u \mu\|^2}}$	analytic resummation impossible, use formula (i) iteratively.

Three new results

Beyond the decoupling limit:

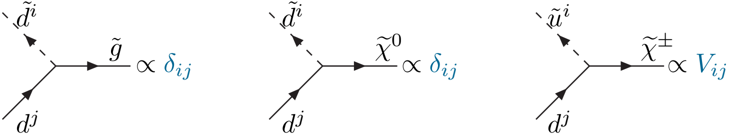
1. Scheme dependence of the resummation formula for the Yukawa coupling

2. Resummation of flavour-changing self-energies

3. New effects in FCNC processes

Naive MFV

- Soft SUSY-breaking terms flavour-diagonal in Super-CKM basis



$\longrightarrow$ Only chargino-loops are flavour-changing

- Usually this condition is imposed at the GUT-scale
  - RG evolution induces flavour-violating $\tilde{g}$- and $\widetilde{\chi}^0$-couplings at the electro-weak scale .
  - Impact of RG-effects on FCNC transitions is small .

[Baer,Brhlik,Castano,Tata; Dudley,Kolda]

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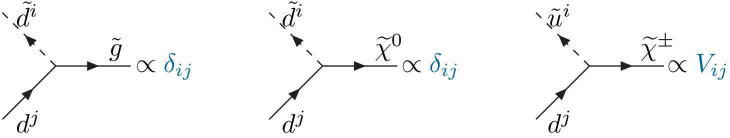

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  - Impact of RG-effects on FCNC transitions is small .

    [Baer,Brhlik,Castano,Tata; Dudley,Kolda]
- We allow for
  - SUSY-breaking terms of third generation to be different from those of the first two.
  - flavour-diagonal CP-violating phases (e.g. complex A_t)

Flavour-changing self-energies in external legs

- Consider flavour-changing self-energies in external quark-legs:

- New source of $\tan\beta$-enhancement:

$\Sigma_{bs}^{RL} \propto \epsilon_{FC} m_b \tan\beta$ and $\mathcal{M} \propto \frac{\Sigma_{bs}^{RL}}{m_b} \propto \epsilon_{FC} \tan\beta$

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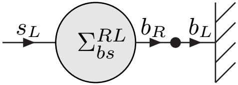

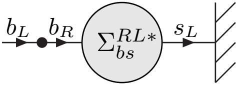

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$$\Sigma_{bs}^{RL} \propto \epsilon_{FC} m_b \tan\beta \qquad \text{and} \qquad \mathcal{M} \propto \frac{\Sigma_{bs}^{RL}}{m_b} \propto \epsilon_{FC} \tan\beta$$

- Subtract self-energies by non-diagonal wave-function CTs:

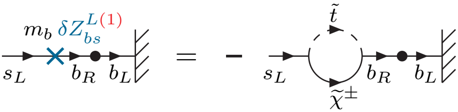
$$\delta Z_{bi}^{L} \propto \epsilon_{FC} \tan\beta, \qquad \delta Z_{bi}^{R} \propto \frac{m_i}{m_b} \epsilon_{FC} \tan\beta \qquad (i = d, s)$$

$\rightarrow$ $\delta Z^{L/R}$ contain the $\tan\beta$ -enhanced effects!

Resummation of $\delta Z_{ij}^{L,R}$

- Subtract self-energies by non-diagonal wave-function CTs:

1 loop



$$\delta Z_{bs}^{L(1)} \propto loop \cdot \tan\beta$$

Resummation of $\delta Z_{ij}^{L,R}$

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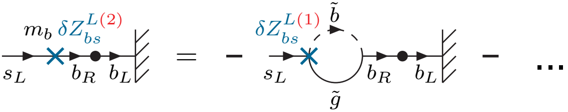
2 loops

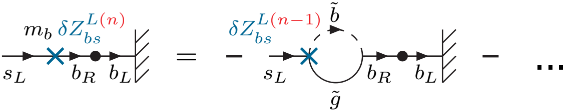


$$\delta Z_{bs}^{L(2)} \propto (loop \cdot \tan\beta)^2$$

Resummation of $\delta Z_{ij}^{L,R}$

- Subtract self-energies by non-diagonal wave-function CTs:

n loops



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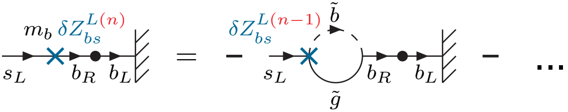


$$\delta Z_{bs}^{L(n)} \propto (loop \cdot \tan\beta)^n$$

- $(loop \cdot \tan\beta)^n$-effects can be analytically resummed.

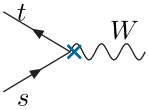
- Results:

$$\frac{\delta Z_{bi}^{L}}{2} = -V_{tb}^{*} V_{ti} \frac{\epsilon_{FC} \tan\beta}{1 + (\epsilon_b - \epsilon_{FC}) \tan\beta},$$

$$\frac{\delta Z_{bi}^{R}}{2} = -V_{tb}^{*} V_{ti} \frac{m_{d_i}}{m_b} \left[\frac{\epsilon_{FC} \tan\beta}{1 + \epsilon_b \tan\beta} + \frac{\epsilon_{FC}^{*} \tan\beta}{(1 + \epsilon_i^{*} \tan\beta)} \right] \frac{1 + \epsilon_b \tan\beta}{1 + (\epsilon_b - \epsilon_{FC}) \tan\beta}$$

Corrections to the CKM matrix

- δZ_{ij}^{L} induces corrections of order $\epsilon_{FC} \tan\beta$ to the W-vertex:



$$\propto V_{tb} \frac{\delta Z_{bs}^{L}}{2} \qquad \propto V_{ts} \left(\epsilon_{FC} \tan\beta\right)$$

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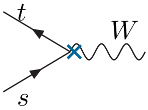


$$\propto V_{tb} \frac{\delta Z^L_{bs}}{2} \qquad \propto V_{ts} \left(\epsilon_{FC} \tan\beta \right)$$

- results in corrections to the CKM matrix:

$$V^0 = \begin{pmatrix} V_{ud} & V_{us} & K^* V_{ub} \\ V_{cd} & V_{cs} & K^* V_{cb} \\ K V_{td} & K V_{ts} & V_{tb} \end{pmatrix}, \qquad K = \frac{1 + \epsilon_b \tan\beta}{1 + (\epsilon_b - \epsilon_{FC}) \tan\beta}$$

- This result
  - is of the same form as in the decoupling limit but with different ϵ_b, ϵ_{FC}.
  - is the analytic expressions for the limit to which the iterative calculation of BCRS converges.

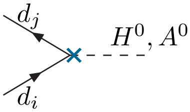
Three new results

Beyond the decoupling limit:

1. Scheme dependence of the resummation formula for the Yukawa coupling
2. Resummation of flavour-changing self-energies
3. New effects in FCNC processes

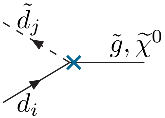
FCNC-couplings at large tanβ

- δZ^L_{ij} induce FCNC-couplings of order $\epsilon_{FC} \tan\beta$:



known in the decoupling limit

new: generalized to $M_{\text{SUSY}} \sim v$



new! (not accessible in the decoupling limit)

FCNC-couplings at large tanβ

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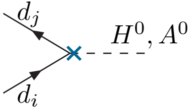

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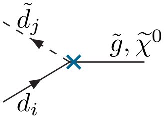


new! (not accessible in the decoupling limit)

- $\delta Z^L_{bi} \propto \kappa V^*_{tb} V_{ti}$ $\quad\Rightarrow\quad$ CKM structure of MFV preserved

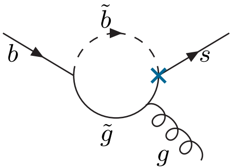
- Coupling strength $\quad \kappa \propto \dfrac{\epsilon_{FC} \tan\beta}{1 + (\epsilon_b - \epsilon_{FC}) \tan\beta}$

Estimate for equal SUSY-Masses: $|\kappa| \sim 0.08$, for $\mu > 0$

(larger values for large A_t) $|\kappa| \sim 0.24$, for $\mu < 0$

Sizable effect in C_8

- Flavour-changing gluino-coupling enters $\mathcal{H}_{\text{eff}}^{\Delta B=1}$:
  - small effects in Wilson coefficients of four-quark operators and C_7.
  - large effect in C_8 possible



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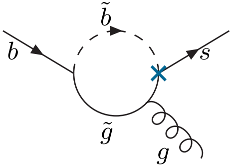
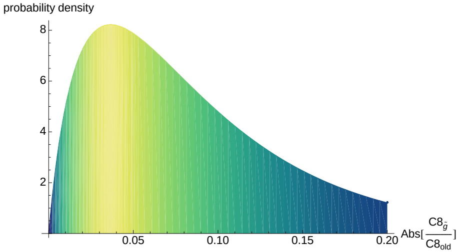
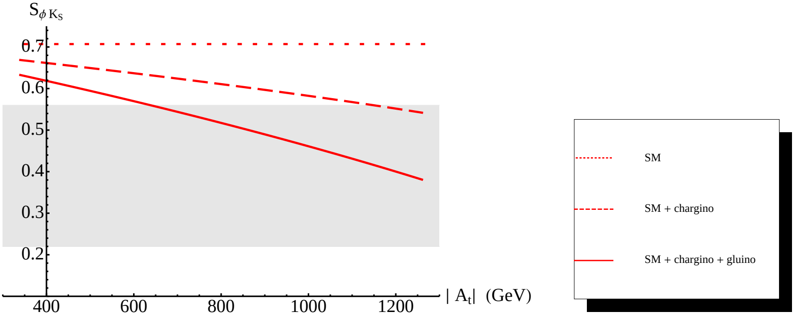
  - large effect in C_8 possible
- Estimate for equal SUSY-masses:
  $|C_8^{\tilde{g}}/C_8^{\widetilde{\chi}^{\pm}}| \sim 0.42$, for $\mu > 0$; $|C_8^{\tilde{g}}/C_8^{\widetilde{\chi}^{\pm}}| \sim 1.3$, for $\mu < 0$





Mixing-induced CP asymmetry in $B^0 \to \phi K_S$

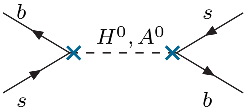
$S_{\phi K_S}$ in naive factorization,
including $\tan\beta$-enhanced corrections to C_8:



Here a rather large value $\mu = 800$ GeV is used,
parameter point is compatible with $\mathcal{B}(\bar{B} \to X_s\gamma)$.

Contributions to $\mathcal{H}_{\text{eff}}^{\Delta B=2}$

- Neutral Higgs exchange:
  - Superficially leading C_1^{SLL} vanishes because H^0- and A^0 cancel each other. [Hamzaoui,Pospelov,Toharia]
  - C_2^{LR} important despite m_s/m_b suppression. [Buras,Chankowski,Rosiek,Slawianowska]



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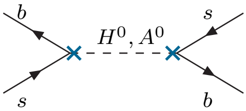
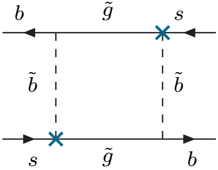
- Gluino-box contributions small (GIM suppression)





CP-violating phase in C_2^{LR}

- Higgs contribution in [Gorbahn,Jäger,Nierste,Trine]: $\widetilde{C}_2^{LR} = \text{real}$
- We find for the Higgs contribution to C_2^{LR} in our scenario:

$$C_2^{LR} = \widetilde{C}_2^{LR}(1 + r), \qquad \text{with} \qquad r = (1 - e^{2i\phi})\frac{(\epsilon_b^* - \epsilon_{FC}^* - \epsilon_s^*)\tan\beta}{1 + \epsilon_s^* \tan\beta},$$

$$\phi = \arg\left\{\epsilon_{FC}\tan\beta\left(1 + (\epsilon_b^* - \epsilon_{FC}^*)\tan\beta\right)\right\}$$

- The correction term r disappears if
  - all parameters are real or
  - all squark masses are equal.

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- The correction term r disappears if
  - all parameters are real or
  - all squark masses are equal.
- Beyond the decoupling limit squark masses are split due to electro-weak symmetry breaking $\rightarrow$ small effect:

$$|r| \lesssim 0.01, \text{ for } \mu > 0, \qquad |r| \lesssim 0.1, \text{ for } \mu < 0.$$

- Larger effects possible for non-universal squark mass terms

Conclusions

- Effects of $\tan\beta$-enhanced self-energies can be resummed analytically beyond the decoupling limit, also in the flavour-non- diagonal case.
- The resummation formula for the Yukawa coupling depends on the renormalization scheme.
- Not only H^0, A^0 but also $\tilde{g}$, $\widetilde{\chi}^0$ develop flavour-changing couplings at large $\tan\beta$.
- These couplings lead to a sizable modification of C_8.

Backup slides

Backup: Parameter points

Scan ranges for C_8: $\tan\beta = 40 - 60$, any value for φ_{A_t},

	min (GeV)	max (GeV)
$\tilde{m}_{Q_L}$, $\tilde{m}_{u_R}$, $\tilde{m}_{d_R}$	200	1000
$\lvert A_t \rvert$	100	1000
μ, M_1, M_2	200	1000
M_3	300	1000
m_{H^+}	200	1000

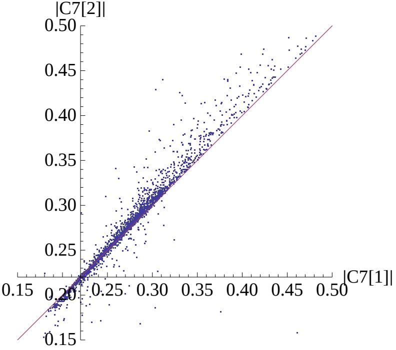
Parameter point used for $S_{\phi K_S}$:

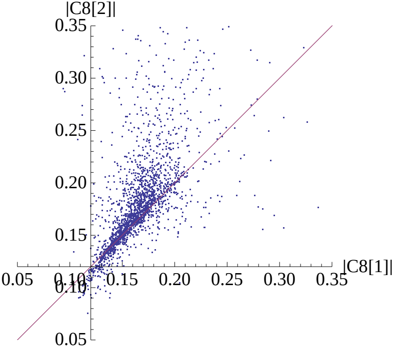
$\tilde{m}_{Q_L}$, $\tilde{m}_{u_R}$, $\tilde{m}_{d_R}$	600 GeV	$\tan\beta$	50
μ	800 GeV	m_{A^0}	350 GeV
M_1	300 GeV	M_2	400 GeV
M_3	500 GeV	φ_{A_t}	$3\pi/2$

Backup: The Wilson coefficients C_7 and C_8

- $C_{7,8}[1] = C_{7,8}^{\widetilde{\chi}^{\pm}} + C_{7,8}^{H^+}, \qquad C_{7,8}[2] = C_{7,8}^{\widetilde{\chi}^{\pm}} + C_{7,8}^{H^+} + C_{7,8}^{\tilde{g}}$

- Scan over relevant SUSY parameter space with
  $(\mu, M_1, M_2, m_{\tilde{g}}, M_{H^+}, m_{\tilde{t},LL}, m_{\tilde{t},RR}, m_{\tilde{b},LL}, m_{\tilde{b},RR}) \leq 1TeV,$
  $|A_t| \leq 3TeV, \qquad 0 \leq \phi_{A_t} \leq 2\pi, \qquad \tan\beta = 50$

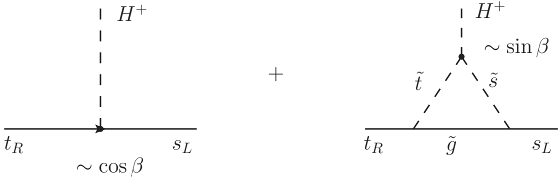




Backup: Non-local $\tan\beta$-enhanced effects

- Some couplings of H^+ and h^0 are suppressed by $\cos\beta$ at tree-level.

- They obtain enhanced vertex corrections $\sim \sin\beta$, e.g.



- This effect is local only in the decoupling limit, but cannot be cast into a Feynman rule in the full calculation.