The MSSM with large tanβ

beyond the decoupling limit

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The pattern of tanβ-enhancement

- The MSSM contains two Higgs doublets H_u, H_d.

  Both acquire vevs: v_u, v_d $\quad\longrightarrow\quad$ $\tan\beta \equiv \dfrac{v_u}{v_d}$

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

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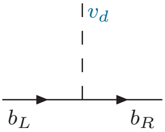
- large $\tan\beta$ $\quad\Leftrightarrow\quad$ small v_d

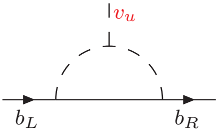
- Consider tree-level amplitude with suppression v_d.
  One-loop corrections may involve v_u instead.

  [Hall,Rattazzi,Sarid; Blazek,Raby,Pokorski]

- Example: b-quark mass



$m_b \sim v_d$



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

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

Effective Lagrangian vs. full MSSM

- 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

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- Why go beyond decoupling limit?
  - $M_{\text{SUSY}} \sim v$ is natural.
  - 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
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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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  - 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 $\mathcal{M}_{\tilde{b}}^2$: $m_{\tilde{b}_1}, m_{\tilde{b}_2}, \mu, \tan\beta$

- 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

- Write $\Sigma_b^{RL} = m_b \Delta_b = m_b \epsilon_b \tan\beta$
- Modified relation $y_b \leftrightarrow m_b$ in the decoupling limit:

$$y_b = \frac{m_b}{v_d(1 + \Delta_b)}$$

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- Beyond decoupling: Formula depends on renormalization scheme (choice of input)!!!
- Example: Gluino-contribution $\Sigma_{b,\tilde{g}}^{RL} = m_b \Delta_b^{\tilde{g}}$

  (i) Input: $m_{\tilde{b}_1}, m_{\tilde{b}_2}, \mu, \tan\beta \quad \rightarrow \quad y_b = \dfrac{m_b}{v_d(1 + \Delta_b^{\tilde{g}})}$

  (ii) Input: $m_{\tilde{b}_1}, m_{\tilde{b}_2}, \tilde{\theta}_b, \tilde{\phi}_b \quad \rightarrow \quad y_b = \dfrac{m_b}{v_d}\left(1 - \Delta_b^{\tilde{g}}\right)$

  (iii) Input: $m_{\tilde{b}_L}, m_{\tilde{b}_R}, \mu, \tan\beta$
  $\rightarrow$ analytic resummation impossible, use (i) iteratively.

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3. New effects in FCNC processes

Flavour-changing self-energies in external legs

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

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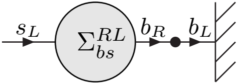

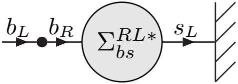

- New source of $\tan\beta$-enhancement:

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

- 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!

Resummed results

- $(\epsilon_{FC} \tan\beta)^n$-effects can be analytically resummed to all orders:

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

$$\frac{\delta Z^R_{bi}}{2} = -V^*_{tb} V_{ti} \frac{m_{d_i}}{m_b} \left[\frac{\epsilon_{FC} \tan\beta}{1 + \epsilon_b \tan\beta} + \frac{\epsilon^*_{FC} \tan\beta}{(1 + \epsilon^*_i \tan\beta)} \right] \frac{1 + \epsilon_b \tan\beta}{1 + (\epsilon_b - \epsilon_{FC}) \tan\beta}$$

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- results in corrections to the CKM matrix:

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

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

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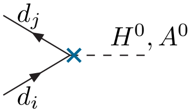
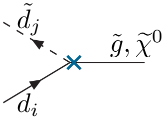
FCNC-couplings at large $\tan\beta$

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



known in the decoupling limit

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



new! (not accessible in the decoupling limit)

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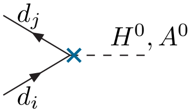

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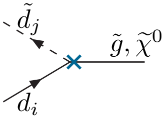


new! (not accessible in the decoupling limit)

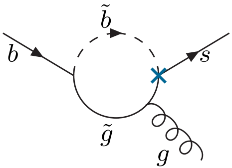
- $\delta Z^L_{bi} \propto \kappa V^*_{tb} V_{ti}$ $\Rightarrow$ CKM structure of MFV preserved

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

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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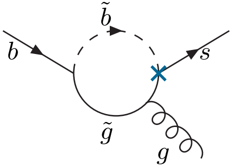
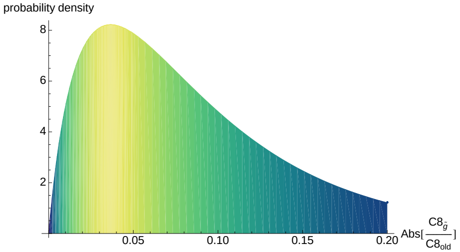
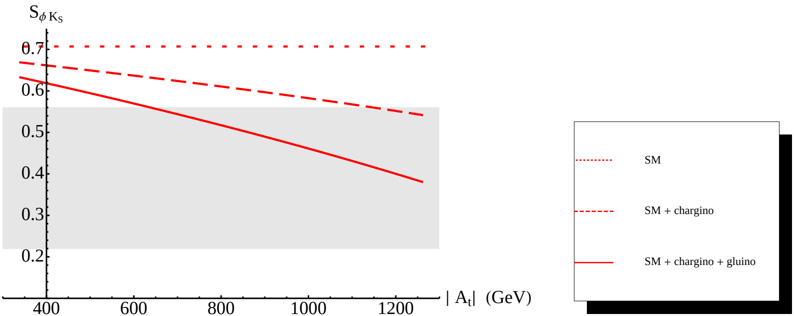
  - small effects in Wilson coefficients of four-quark operators and C_7.
  - large effect in C_8 possible
- Estimate for equal SUSY-masses:
  $|C_8^{\tilde{g}}/C_8^{\widetilde{\chi}^{\pm}}| \sim 0.42$, for $\mu > 0$; $|C_8^{\tilde{g}}/C_8^{\widetilde{\chi}^{\pm}}| \sim 1.3$, for $\mu < 0$





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 $\mathcal{B}(\bar{B} \to X_s\gamma)$.

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},

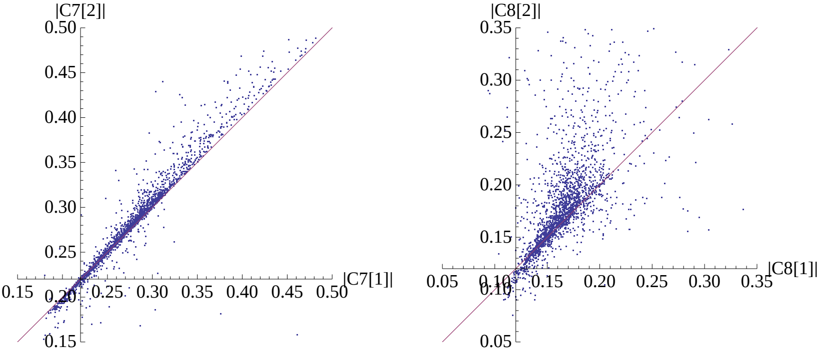
	min (GeV)	max (GeV)
$\tilde{m}_{Q_L}, \tilde{m}_{u_R}, \tilde{m}_{d_R}$	200	1000
$\vert A_t \vert$	100	1000
μ, M_1, M_2	200	1000
M_3	300	1000
m_{H^+}	200	1000

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}	$3\pi/2$

The Wilson coefficients C_7 and C_8

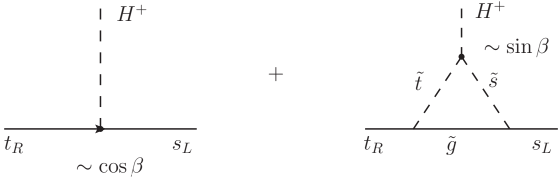
- $C_{7,8}[1] = C_{7,8}^{\tilde{\chi}^{\pm}} + C_{7,8}^{H^+}$, $\quad C_{7,8}[2] = C_{7,8}^{\tilde{\chi}^{\pm}} + C_{7,8}^{H^+} + C_{7,8}^{\tilde{g}}$
- Scan over relevant SUSY parameter space with
  $(\mu, M_1, M_2, m_{\tilde{g}}, M_{H^+}, m_{\tilde{t},LL}, m_{\tilde{t},RR}, m_{\tilde{b},LL}, m_{\tilde{b},RR}) \leq 1TeV$,
  $|A_t| \leq 3TeV$, $\quad 0 \leq \phi_{A_t} \leq 2\pi$, $\quad \tan\beta = 50$



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

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

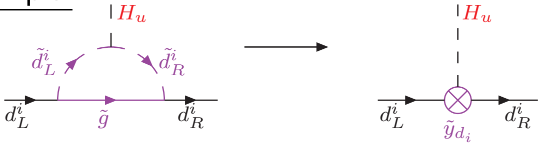
- They obtain enhanced vertex corrections $\sim \sin\beta$, e.g.



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

Backup: 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:



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

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

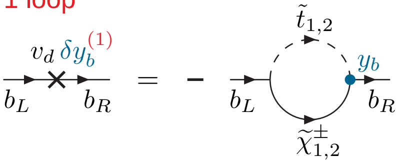
$$m_{d_i} = y_{d_i} v_d + \tilde{y}_{d_i} v_u \qquad \Rightarrow \qquad \boxed{y_{d_i} = \frac{m_{d_i}}{v_d(1+\epsilon_i \tan\beta)}}$$

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

Backup: Resummation beyond decoupling

- Subtract $\tan\beta$-enhanced corrections to all orders by appropriate finite counterterms
- Example: $\quad \Sigma^{RL}_{b,\widetilde{\chi}^\pm}(y_b) = y_b v_d \Delta_b^{\widetilde{\chi}^\pm}, \qquad \Delta_b^{\widetilde{\chi}^\pm} = \epsilon_b^{\widetilde{\chi}^\pm}\tan\beta$

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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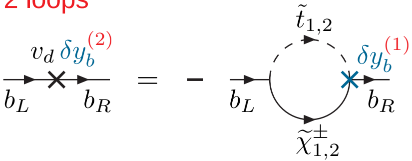
2 loops



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

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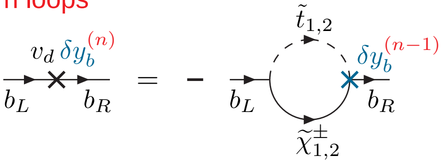
n loops



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

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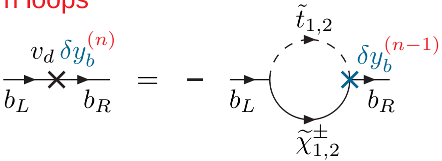

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$$y_b^0 = \frac{m_b}{v_d}\left(1 - \Delta_b^{\widetilde{\chi}^\pm} + \Delta_b^{\widetilde{\chi}^\pm\,2} - \ldots\right) = \frac{m_b}{v_d\left(1+\Delta_b^{\widetilde{\chi}^\pm}\right)}$$

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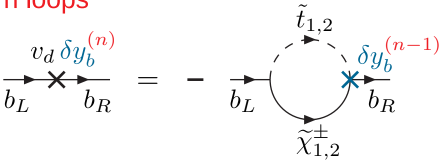
- Example: $\Sigma^{RL}_{b,\tilde{\chi}^\pm}(y_b) = y_b v_d \Delta_b^{\tilde{\chi}^\pm}$, $\quad \Delta_b^{\tilde{\chi}^\pm} = \epsilon_b^{\tilde{\chi}^\pm} \tan\beta$

n loops



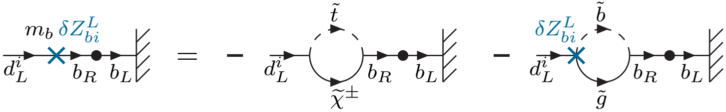
$$\delta y_b{}^{(n)} = -\Delta_b^{\tilde{\chi}^\pm}\, \delta y_b{}^{(n-1)} = (-\Delta_b^{\tilde{\chi}^\pm})^n \frac{m_b}{v_d}$$

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

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

Backup: Resummation of δZ^L_{ij}

- Subtract external leg contributions by matrix-valued wave function renormalization:



$$\frac{\delta Z^L_{bi}}{2} = -\frac{\Sigma^{RL}_{bi}(\delta Z)}{m_b}, \qquad \delta Z^L_{bi} = \mathcal{O}(\epsilon_{FC}\tan\beta)$$

- Resum δZ^L_{ij}-insertions: $$\boxed{\frac{\delta Z^L_{bi}}{2} = -\frac{\Sigma^{RL}_{bi}(\delta Z)}{m_b}}$$

- Result: $$\frac{\delta Z^L_{bi}}{2} = -V_{ti}V^*_{tb}\frac{\epsilon_{FC}\tan\beta}{1+(\epsilon_b-\epsilon_{FC})\tan\beta}$$