The MSSM with large tan β

beyond the decoupling limit

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

tan β-enhancement

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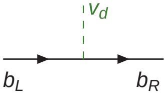

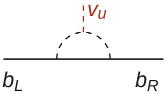

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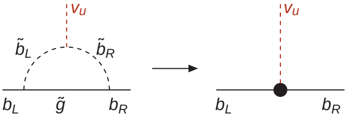
- How can we deal with such $\mathcal{O}(1)$ corrections?

Resummation of tan β-enhanced corrections

1. Effective Lagrangian in the decoupling limit

[Hall,Rattazzi,Sarid; Hamzaoui,Pospelov,Toharia; Babu,Kolda; Buras,Chankowski,Rosiek,Slawianowska; Dedes,Pilaftsis; Beneke,Ruiz-Femenia,Spinrath; Gorbahn,Jäger,UN,Trine]

- assume $M_{\text{SUSY}} \gg M_{\text{EW}}$ and integrate out SUSY fields, keep only Higgs and SM fields, e.g.



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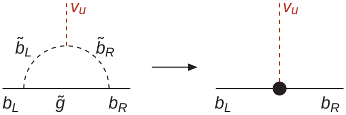
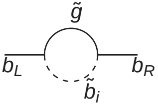


2. Calculation in the full MSSM beyond decoupling (this work)

- renormalization of bottom mass via self-energies like



$$\propto \tan\beta \quad \Rightarrow y_b = \frac{m_b\left[1-\Delta_b+\Delta_b^2-\ldots\right]}{v\cos\beta} = \frac{m_b}{v\cos\beta}\,\frac{1}{1+\Delta_b}$$

- resummation of $\Sigma_b = m_b\Delta_b = m_b\epsilon_b \tan\beta$ to all orders.

[Carena,Garcia,UN,Wagner]

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- $M_{\text{SUSY}} \sim M_{\text{EW}}$ is natural
- validity of the assumption $M_{\text{SUSY}} \gg M_{\text{EW}}$ unclear, test accuracy
- study tan β-enhanced effects in couplings of SUSY particles
  (impossible in decoupling limit)

Three applications

Beyond the decoupling limit:

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c) new effects in decoupling FCNC processes.

a) definition of the sbottom mixing angle

Bottom-squark mass matrix:

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

Diagonalise as

$$\widetilde{R}^b \mathcal{M}^2_{\tilde{b}} \widetilde{R}^{b\dagger} = \mathrm{diag}(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2})$$

with

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

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Note:

- $\tilde{\theta}_b$ vanishes for $v_u/M_{\text{SUSY}} \to 0$.
- $\tilde{\theta}_b$ depends on y_b and is affected by the resummation.

y_b depends on $\tilde{\theta}_b$ and the physical squark masses $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$ through Δ_b .

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Relations like

$$\sin 2\tilde{\theta}_b = \left| \frac{-2 y_b \mu v_u}{m^2_{\tilde{b}_1} - m^2_{\tilde{b}_2}} \right|$$

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[Carena,Garcia,UN,Wagner]

...but in collider physics it is natural to use $\tilde{\theta}_b$.

The resummation depends on the choice of input parameters.

Write $\Delta_b = \Delta_b^{\tilde{g}} + \Delta_b^{\tilde{\chi}^\pm} + \Delta_b^{\tilde{\chi}^0}$:

i) Express Δ_b in terms of μ, $\tan\beta, m_{\tilde{b}_1}, m_{\tilde{b}_2}$ (simplest formula):

$$y_b = \frac{m_b}{v_d(1 + \Delta_b^{\tilde{g}} + \Delta_b^{\tilde{\chi}^\pm} + \Delta_b^{\tilde{\chi}^0})} \equiv \frac{m_b}{v_d(1 + \epsilon_b \tan\beta)}$$

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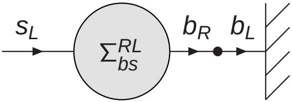
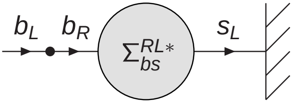
iii) Express Δ_b in terms of $\mu, \tan\beta, m_{\tilde{b}_L}, m_{\tilde{b}_R}$:
analytic resummation impossible, instead use formula i) iteratively

b) Resummation of flavour non-diagonal self-energies

Consider FCNC loops only with charginos (naive MFV).
New feature: Flavour-changing self-energies in external legs:





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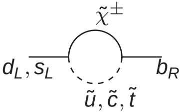
If one chooses to introduce flavour-changing wave-function renormalisation constants $\delta Z_{bs}^{L,R}$, they will contain these $\tan\beta$ -enhanced effects.

- how can we account for the *flavour non-diagonal* analogon:



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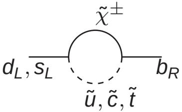

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- solution: absorb self-energies in matrix-valued field renormalization

$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}^{\text{bare}} = \left(1 + \frac{\delta Z^L}{2}\right) \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

and likewise for right-handed fields

[similar approach by Buras,Chankowski,Rosiek,Slawianowska]

Results: b) Resummation of flavour non-diagonal self-energies

- $(\epsilon_{\rm FC} \tan\beta)^n$ effects can be *resummed to all orders*. Yields

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

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

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- this results in corrections to the CKM matrix

[Denner,Sack; Gambino,Grassi,Madricardo]

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

(same form as for $M_{\rm SUSY}=\infty$, but different $\epsilon_b, \epsilon_{\rm FC}$)

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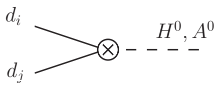

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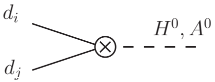

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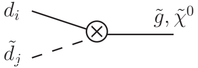

A "flavour problem" in a flavour-blind MSSM?

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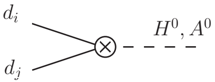

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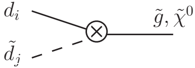

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- No, because: $\delta Z^L_{bi} \propto V^*_{tb} V_{ti}\, \epsilon_{\text{FC}} \tan\beta$
  $\Rightarrow$ CKM structure of MFV preserved
  Estimate: $\epsilon_{\text{FC}} \tan\beta \to -\frac{y_t^2}{32\pi^2} \tan\beta$ for equal SUSY masses

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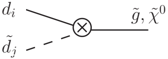

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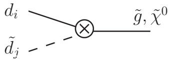

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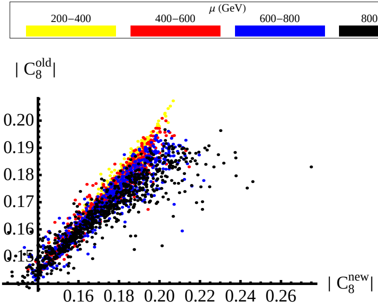

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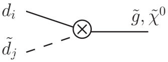

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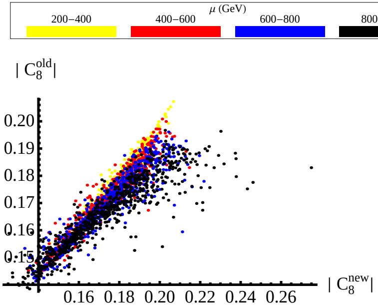

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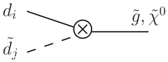

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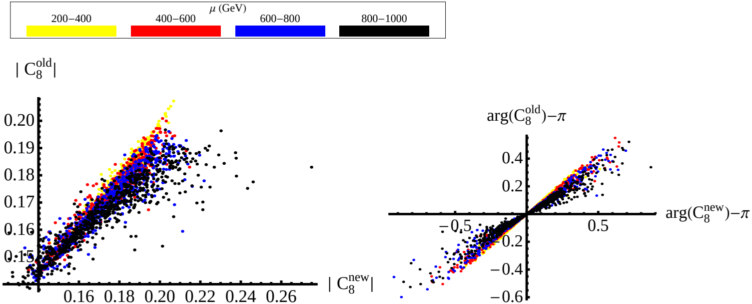
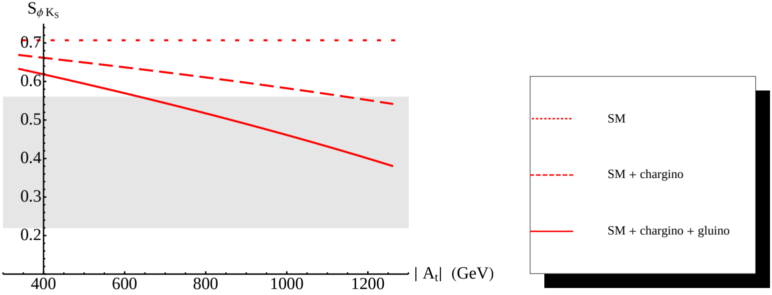


Results: c) New effects in FCNC processes

- Mixing-induced CP asymmetry in $B^0 \to \phi K_S$ in naive factorization, including $\tan\beta$ -enhanced corrections to C_8 :



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

Conclusions

- Effects of tan β-enhanced (flavour-diagonal and flavour-non-diagonal) self-energies can be resummed in the full MSSM for $M_{\text{SUSY}} \sim M_{\text{EW}}$.

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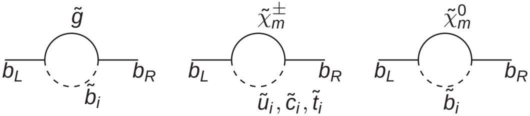
- The resummation formula for the Yukawa coupling depends on the renormalization (input) scheme.
- At large tan β not only the neutral Higgs bosons but also gluino and neutralino have flavour-changing couplings.
- These couplings enter $\mathcal{H}_{\text{eff}}^{\Delta B=1}$ and lead to a sizeable modification of $C_8(m_b)$.

Backup slides

Backup: Scheme dependence in m_b-resummation

- observation: sbottom-mixing can (but need not) be expressed by m_b and SUSY-breaking parameters
  $\longrightarrow$ some freedom to choose input parameters...



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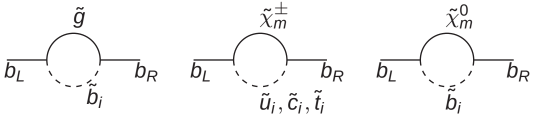

- to clarify things, write $\Delta_b = \Delta_b^{\tilde{g}} + \Delta_b^{\tilde{\chi}^{\pm}} + \Delta_b^{\tilde{\chi}^0}$

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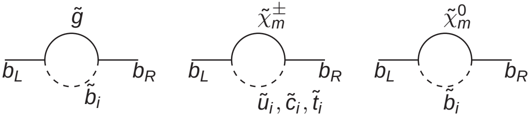


- to clarify things, write $\Delta_b = \Delta_b^{\tilde{g}} + \Delta_b^{\tilde{\chi}^\pm} + \Delta_b^{\tilde{\chi}^0}$
- from Feynman diagrams:
  - gluino contribution depends on $\theta_{\tilde{b}}, \varphi_{\tilde{b}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$
  - chargino contribution depends on m_b from Yukawa coupling
  - neutralino contribution depends on m_b and $\theta_{\tilde{b}}, \varphi_{\tilde{b}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$

Backup: parameter points

Scan ranges for C_7 and C_8: $\tan\beta = 40 - 60$, any value for φ_{A_t},

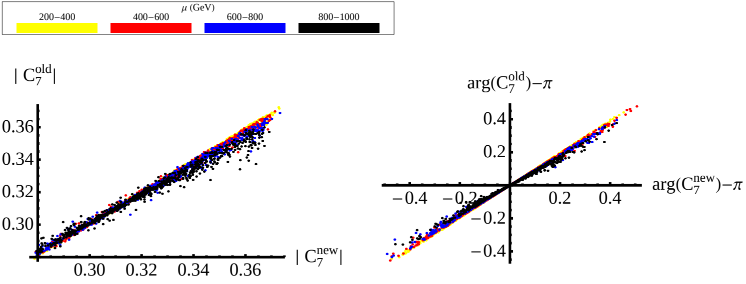
	min (GeV)	max (GeV)
$\tilde{m}_{Q_L}, \tilde{m}_{u_R}, \tilde{m}_{d_R}$	250	1000
$\lvert A_t \rvert$	100	1000
μ, M_1, M_2	200	1000
M_3	300	1000
m_{A^0}	200	1000

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: C_7 and other operators

- effect of gluino-squark contribution in $C_7(m_b)$ accidentally small (suppressed by a numerical factor from loop function)



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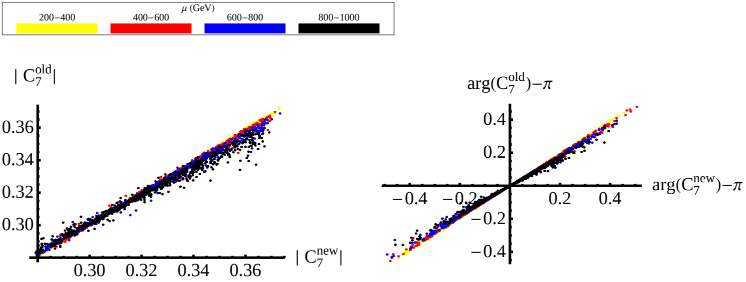

- effective four-quark operators in $\mathcal{H}^{\Delta B=1}$ and $\mathcal{H}^{\Delta B=2}$: gluino-squark loops suppressed by GIM-like cancellation between $\tilde{b}$- and $\tilde{s}$-loops $\rightarrow$ negligible compared to chargino-squark loops

Backup: Non-local tan β-enhanced effects

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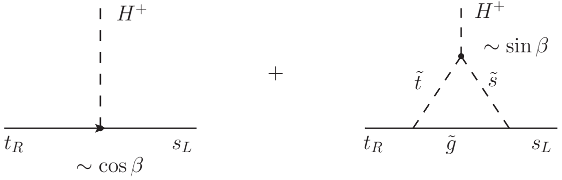

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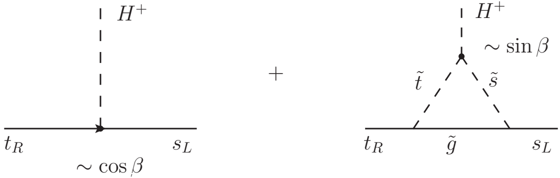

- this effect is local only in the decoupling limit, but cannot be cast into a Feynman rule in the full calculation

Backup: relation to effective CKM matrix from BCRS

- Buras, Chankowski, Rosiek, Slawianowska find for the effective CKM matrix:

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- They find that the result agrees numerically with the formula from eff. Lagrangian if ϵ-factors are replaced by full self-energies
- We prove this analytically via the resummation (iteration not needed!)