MSSM at large $\tan\beta$ beyond the decoupling limit

Lars Hofer Ulrich Nierste Dominik Scherer

Institut für Theoretische Teilchenphysik
Karlsruhe Institute of Technology

Interplay Flavour and Collider - CERN, december 2009

$\tan\beta$ in the MSSM

- MSSM contains two Higgs doublets: H_u, H_d
  (2-Higgs-Doublet model, Type II)

$\tan\beta$ in the MSSM

- MSSM contains two Higgs doublets: H_u, H_d (2-Higgs-Doublet model, Type II)
- both doublets have a vacuum expectation value: v_u, v_d

$$v_u^2 + v_d^2 = \frac{2m_w^2}{g^2} \equiv v \quad , \quad \frac{v_u}{v_d} = \tan\beta = ?$$

$\tan\beta$ in the MSSM

- MSSM contains two Higgs doublets: H_u, H_d (2-Higgs-Doublet model, Type II)
- both doublets have a vacuum expectation value: v_u, v_d

$$v_u^2 + v_d^2 = \frac{2m_w^2}{g^2} \equiv v \qquad , \qquad \frac{v_u}{v_d} = \tan\beta = ?$$

- interesting case for Yukawa unification: $y_b \approx y_t \approx 1$,

then $$\tan\beta = \frac{v_u}{v_d} \sim \mathcal{O}\left(\frac{m_t}{m_b}\right) \sim \mathcal{O}(50)$$

$\tan\beta$ in the MSSM

- MSSM contains two Higgs doublets: H_u, H_d (2-Higgs-Doublet model, Type II)
- both doublets have a vacuum expectation value: v_u, v_d

$$v_u^2 + v_d^2 = \frac{2m_w^2}{g^2} \equiv v \qquad , \qquad \frac{v_u}{v_d} = \tan\beta = ?$$

- interesting case for Yukawa unification: $y_b \approx y_t \approx 1$,

then $\tan\beta = \frac{v_u}{v_d} \sim \mathcal{O}\left(\frac{m_t}{m_b}\right) \sim \mathcal{O}(50)$

large tan β $\longleftrightarrow$ small $v_d \ll v$

$\tan\beta$-enhancement

- consider tree-level amplitude with *suppression* by v_d

$\tan\beta$-enhancement

- consider tree-level amplitude with *suppression* by v_d
- one-loop correction possibly contains v_u instead

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

$\tan\beta$-enhancement

- consider tree-level amplitude with *suppression* by v_d
- one-loop correction possibly contains v_u instead

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

- well-known example:

$m_b \propto v_d$, $\delta m_b \propto$ *loop* $\cdot\, v_u$

$\tan\beta$-enhancement

- consider tree-level amplitude with *suppression* by v_d
- one-loop correction possibly contains v_u instead

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

- well-known example:

$$m_b \propto v_d \quad , \quad \delta m_b \propto \textit{loop} \cdot v_u$$

-

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

$\tan\beta$-enhancement

- consider tree-level amplitude with *suppression* by v_d
- one-loop correction possibly contains v_u instead

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

- well-known example:

$$m_b \propto v_d \quad , \quad \delta m_b \propto \textit{loop} \cdot v_u$$

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

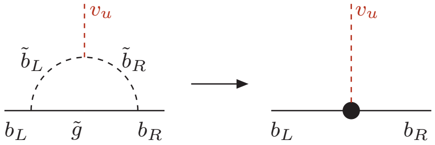
Question:

How should we account for such $\mathcal{O}(1)$ corrections?

Accounting for $\tan\beta$-enhanced corrections

1. Effective Lagrangian in the decoupling limit
[Babu,Kolda; Buras,Chankowski,Rosiek,Slawianowska; Dedes,Pilaftsis;...]

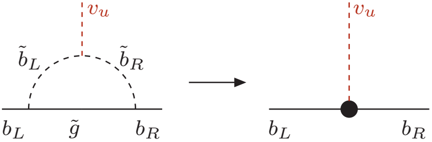
- assume $M_{\text{SUSY}} \gg M_{\text{EW}}$ and integrate out SUSY fields, keep only Higgs and SM fields. E.g. mass correction



Accounting for $\tan\beta$-enhanced corrections

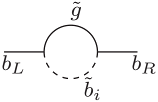
1. Effective Lagrangian in the decoupling limit
   [Babu,Kolda; Buras,Chankowski,Rosiek,Slawianowska; Dedes,Pilaftsis;...]

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



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

   - $\tan\beta$-enhanced mass corrections from finite self-energies. Re-enter self-energy, produces higher-order terms



$\propto \tan\beta \qquad \Rightarrow y_b = \frac{m_b(1 - \Delta_b + \Delta_b^2 - \ldots)}{v\cos\beta} = \frac{m_b}{v\cos\beta(1+\Delta_b)}$

   - resummation of $\Sigma_b = m_b\Delta_b = m_b\epsilon_b\tan\beta$ to all orders
     [Carena,Garcia,Nierste,Wagner]

Motivation: Why go beyond the decoupling limit?

- $M_{\text{SUSY}} \sim M_{\text{EW}}$ is natural

Motivation: Why go beyond the decoupling limit?

- $M_{\text{SUSY}} \sim M_{\text{EW}}$ is natural
- validity of decoupling assumption $M_{\text{SUSY}} \gg M_{\text{EW}}$ unclear $\rightarrow$ test accuracy

Motivation: Why go beyond the decoupling limit?

- $M_{\text{SUSY}} \sim M_{\text{EW}}$ is natural
- validity of decoupling assumption $M_{\text{SUSY}} \gg M_{\text{EW}}$ unclear $\rightarrow$ test accuracy
- experimental constraints from $B_s \rightarrow \mu^+\mu^-$ and $B^- \rightarrow \tau\bar{\nu}_\tau$ require heavy Higgs masses if $\tan\beta$ is large $\rightarrow$ why integrate out SUSY particles while keeping Higgs bosons?

Motivation: Why go beyond the decoupling limit?

- $M_{\text{SUSY}} \sim M_{\text{EW}}$ is natural
- validity of decoupling assumption $M_{\text{SUSY}} \gg M_{\text{EW}}$ unclear $\rightarrow$ test accuracy
- experimental constraints from $B_s \rightarrow \mu^+\mu^-$ and $B^- \rightarrow \tau\bar{\nu}_\tau$ require heavy Higgs masses if $\tan\beta$ is large $\rightarrow$ why integrate out SUSY particles while keeping Higgs bosons?
- study $\tan\beta$-enhanced effects in couplings of SUSY particles (inaccessible from eff. Lagrangian)

Motivation: Why go beyond the decoupling limit?

- $M_{\text{SUSY}} \sim M_{\text{EW}}$ is natural
- validity of decoupling assumption $M_{\text{SUSY}} \gg M_{\text{EW}}$ unclear $\rightarrow$ test accuracy
- experimental constraints from $B_s \rightarrow \mu^+\mu^-$ and $B^- \rightarrow \tau\bar{\nu}_\tau$ require heavy Higgs masses if $\tan\beta$ is large $\rightarrow$ why integrate out SUSY particles while keeping Higgs bosons?
- study $\tan\beta$-enhanced effects in couplings of SUSY particles (inaccessible from eff. Lagrangian)
- full control over renormalization scheme (see below...)

Our method beyond the decoupling limit

- no effective Lagrangian $\rightarrow$ Renormalize MSSM Lagrangian to account for $\tan\beta$-enhanced self-energies

Our method beyond the decoupling limit

- no effective Lagrangian $\longrightarrow$ Renormalize MSSM Lagrangian to account for $\tan\beta$-enhanced self-energies
- use on-shell renormalization to insert measured SM parameters

Our method beyond the decoupling limit

- no effective Lagrangian $\rightarrow$ Renormalize MSSM Lagrangian to account for $\tan\beta$-enhanced self-energies
- use on-shell renormalization to insert measured SM parameters
- at one-loop:

Our method beyond the decoupling limit

- no effective Lagrangian $\rightarrow$ Renormalize MSSM Lagrangian to account for $\tan\beta$-enhanced self-energies
- use on-shell renormalization to insert measured SM parameters
- at one-loop:
  - flavour-conserving quark self-energies subtracted by mass or Yukawa counterterms

Our method beyond the decoupling limit

- no effective Lagrangian $\rightarrow$ Renormalize MSSM Lagrangian to account for $\tan\beta$-enhanced self-energies
- use on-shell renormalization to insert measured SM parameters
- at one-loop:
    - flavour-conserving quark self-energies subtracted by mass or Yukawa counterterms
    - flavour-changing quark self-energies subtracted by (antihermitian) flavour-changing wave-function counterterms

Our method beyond the decoupling limit

- no effective Lagrangian $\rightarrow$ Renormalize MSSM Lagrangian to account for $\tan\beta$-enhanced self-energies
- use on-shell renormalization to insert measured SM parameters
- at one-loop:
  - flavour-conserving quark self-energies subtracted by mass or Yukawa counterterms
  - flavour-changing quark self-energies subtracted by (antihermitian) flavour-changing wave-function counterterms
  - CKM counterterms adjusted accordingly

[Denner,Sack; Gambino,Grassi,Madricardo]

Our method beyond the decoupling limit

- no effective Lagrangian → Renormalize MSSM Lagrangian to account for $\tan\beta$-enhanced self-energies
- use on-shell renormalization to insert measured SM parameters
- at one-loop:
  - flavour-conserving quark self-energies subtracted by mass or Yukawa counterterms
  - flavour-changing quark self-energies subtracted by (antihermitian) flavour-changing wave-function counterterms
  - CKM counterterms adjusted accordingly

    [Denner,Sack; Gambino,Grassi,Madricardo]
  - squark self-energies not $\tan\beta$-enhanced → neglected

Our method beyond the decoupling limit

- no effective Lagrangian $\to$ Renormalize MSSM Lagrangian to account for $\tan\beta$-enhanced self-energies
- use on-shell renormalization to insert measured SM parameters
- at one-loop:
  - flavour-conserving quark self-energies subtracted by mass or Yukawa counterterms
  - flavour-changing quark self-energies subtracted by (antihermitian) flavour-changing wave-function counterterms
  - CKM counterterms adjusted accordingly

    [Denner,Sack; Gambino,Grassi,Madricardo]
  - squark self-energies not $\tan\beta$-enhanced $\to$ neglected
- then: define counterterms for higher orders in $(\text{loop}\cdot\tan\beta)$ and resum!

Issues beyond the decoupling limit

Questions:

Issues beyond the decoupling limit

Questions:

- How does the resummation formula for m_{d_i} depend on the renormalization scheme?

Issues beyond the decoupling limit

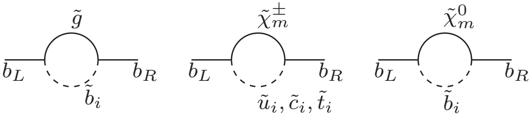
Questions:

- How does the resummation formula for m_{d_i} depend on the renormalization scheme?
- Can we also resum the effects of flavour-changing self-energies? And what are the consequences?

Defining a renormalization scheme for m_{d_i} (1)

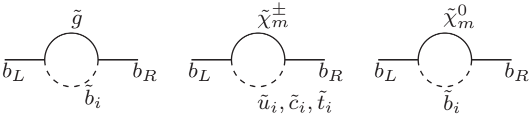
- Subtract SUSY-loops on-shell. Still freedom to choose (SUSY) input parameters!

Defining a renormalization scheme for m_{d_i} (1)

- Subtract SUSY-loops on-shell. Still freedom to choose (SUSY) input parameters!
- E.g. 

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

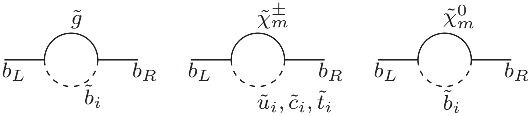
Defining a renormalization scheme for m_{d_i} (1)

- Subtract SUSY-loops on-shell. Still freedom to choose (SUSY) input parameters!
- E.g. 

  to clarify things, write $\delta m_b = \delta m_b^{\tilde{g}} + \delta m_b^{\tilde{\chi}^{\pm}} + \delta m_b^{\tilde{\chi}^0}$
- from Feynman diagrams:

Defining a renormalization scheme for m_{d_i} (1)

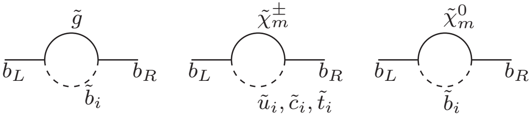
- Subtract SUSY-loops on-shell. Still freedom to choose (SUSY) input parameters!
- E.g.



  to clarify things, write $\delta m_b = \delta m_b^{\tilde{g}} + \delta m_b^{\tilde{\chi}^{\pm}} + \delta m_b^{\tilde{\chi}^0}$
- from Feynman diagrams:
  - gluino contribution depends on $\theta_{\tilde{b}}, \varphi_{\tilde{b}}$ (sbottom mixing angle and phase), $m_{\tilde{b}_1}, m_{\tilde{b}_2}$

Defining a renormalization scheme for m_{d_i} (1)

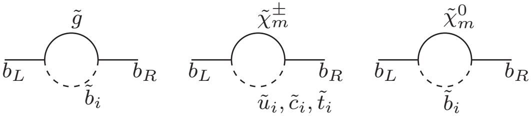
- Subtract SUSY-loops on-shell. Still freedom to choose (SUSY) input parameters!
- E.g.



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

Defining a renormalization scheme for m_{d_i} (1)

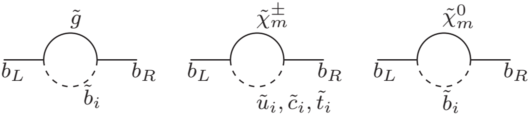
- Subtract SUSY-loops on-shell. Still freedom to choose (SUSY) input parameters!
- E.g.



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

Defining a renormalization scheme for m_{d_i} (1)

- Subtract SUSY-loops on-shell. Still freedom to choose (SUSY) input parameters!
- E.g.



  to clarify things, write $\delta m_b = \delta m_b^{\tilde{g}} + \delta m_b^{\tilde{\chi}^{\pm}} + \delta m_b^{\tilde{\chi}^0}$
- from Feynman diagrams:
  - gluino contribution depends on $\theta_{\tilde{b}}, \varphi_{\tilde{b}}$ (sbottom mixing angle and phase), $m_{\tilde{b}_1}, m_{\tilde{b}_2}$
  - chargino contribution depends on m_b from Yukawa coupling
  - neutralino contribution depends on m_b and $\theta_{\tilde{b}}, \varphi_{\tilde{b}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$
- various relations between sbottom masses, mixing angles, m_b and SUSY-Lagrangian parameters... $\rightarrow$ clear up the picture!

Defining a renormalization scheme for m_{d_i} (2)

Renormalization depends on choice of input parameters:

i) expressing Δ_b by $\mu, \tan\beta, m_{\tilde{b}_1}, m_{\tilde{b}_2}$: (simplest formula)

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

Defining a renormalization scheme for m_{d_i} (2)

Renormalization depends on choice of input parameters:

i) expressing Δ_b by $\mu, \tan\beta, m_{\tilde{b}_1}, m_{\tilde{b}_2}$: (simplest formula)

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

ii) expressing Δ_b by $\theta_{\tilde{b}}, \varphi_{\tilde{b}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$: (collider observables)

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

$\delta m_b^{\tilde{g}}$ independent of m_b $\rightarrow$ no resummation

Defining a renormalization scheme for m_{d_i} (2)

Renormalization depends on choice of input parameters:

i) expressing Δ_b by $\mu, \tan\beta, m_{\tilde{b}_1}, m_{\tilde{b}_2}$: (simplest formula)

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

ii) expressing Δ_b by $\theta_{\tilde{b}}, \varphi_{\tilde{b}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$: (collider observables)

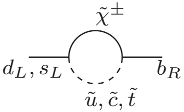
$$y_b = \frac{m_b(1 - \Delta_b^{\tilde{g}})}{v_d(1 + \Delta_b^{\tilde{\chi}^\pm} + \Delta_b^{\tilde{\chi}^0})}$$

$\delta m_b^{\tilde{g}}$ independent of m_b $\rightarrow$ no resummation

iii) expressing Δ_b by $\mu, \tan\beta, m_{\tilde{b}_L}, m_{\tilde{b}_R}$: (parameters in Lagrangian)
$\rightarrow$ direct resummation impossible, only iterative use of formula i) works

Resummation of flavour non-diagonal self-energies (1)

- Assumption: flavour-changing self-energies only from $W^{\pm}, H^{\pm}, \tilde{\chi}^{\pm}$-exchange

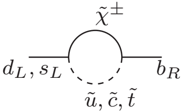


$$= m_b \frac{\epsilon_{\mathrm{FC}} \tan\beta}{1 + \epsilon_b \tan\beta} V_{tb}^{*} V_{ti}$$

(i=d,s)

Resummation of flavour non-diagonal self-energies (1)

- Assumption: flavour-changing self-energies only from $W^\pm, H^\pm, \tilde{\chi}^\pm$-exchange



$$= m_b \frac{\epsilon_{\text{FC}} \tan\beta}{1 + \epsilon_b \tan\beta} V_{tb}^* V_{ti}$$ (i=d,s)

- absorb self-energies in matrix-valued field renormalization

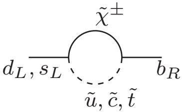
$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}^{\text{bare}} = \left(1 + \frac{\delta Z^L}{2}\right) \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

and likewise for right-handed fields

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

Resummation of flavour non-diagonal self-energies (1)

- Assumption: flavour-changing self-energies only from $W^\pm, H^\pm, \tilde{\chi}^\pm$-exchange



$$= m_b \frac{\epsilon_{\text{FC}} \tan\beta}{1+\epsilon_b \tan\beta} V_{tb}^* V_{ti} \qquad \text{(i=d,s)}$$

- 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]

- counterterms re-enter self-energies $\to \tan^2\beta, \tan^3\beta, \ldots$

Resummation of flavour non-diagonal self-energies (2)

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

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

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

Resummation of flavour non-diagonal self-energies (2)

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

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

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

- this results in corrections to the CKM matrix

[Denner,Sack; Gambino,Grassi,Madricardo]

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

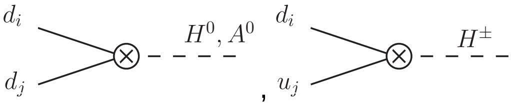
Resummed Feynman rules

With δm_{d_i} , δZ^L_{ij} and δZ^R_{ij} at hand: obtain Feynman rules including $\tan\beta$-enhanced corrections to all orders

Resummed Feynman rules

With δm_{d_i} , δZ^L_{ij} and δZ^R_{ij} at hand: obtain Feynman rules including $\tan\beta$-enhanced corrections to all orders

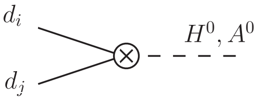
- generalizes well-known vertices from decoupling limit, e.g.

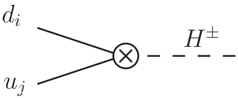


Resummed Feynman rules

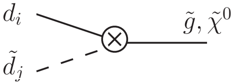
With δm_{d_i} , δZ^L_{ij} and δZ^R_{ij} at hand: obtain Feynman rules including $\tan\beta$-enhanced corrections to all orders

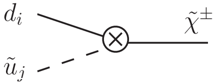
- generalizes well-known vertices from decoupling limit, e.g.



,


- adds new corrected vertices involving superpartners

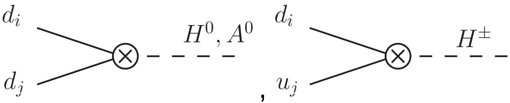


,


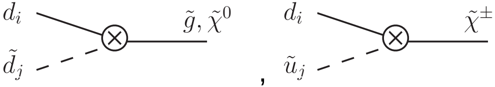
Resummed Feynman rules

With δm_{d_i} , δZ^L_{ij} and δZ^R_{ij} at hand: obtain Feynman rules including $\tan\beta$-enhanced corrections to all orders

- generalizes well-known vertices from decoupling limit, e.g.



- adds new corrected vertices involving superpartners



- Since $\delta Z^{L,R}_{bi} \sim V^*_{tb} V_{ti} \epsilon_{\mathsf{FC}} \tan\beta$
  $\longrightarrow$ CKM structure of MFV preserved

Applications

Easy inclusion of $\tan\beta$-enhanced corrections in various calculations, e.g.:

Applications

Easy inclusion of $\tan\beta$-enhanced corrections in various calculations, e.g.:

- Higgs masses

Applications

Easy inclusion of $\tan\beta$-enhanced corrections in various calculations, e.g.:

- Higgs masses
- SUSY decays e.g.

$$\frac{\Gamma(\tilde{g} \to \tilde{b}_i\, s)}{\Gamma(\tilde{g} \to \tilde{b}_i\, b)} = \left| \frac{\delta Z^L_{bs}}{2} \tilde{R}^b_{i1} \right|^2 + \left| \frac{\delta Z^R_{bs}}{2} \tilde{R}^b_{i2} \right|^2 \sim \mathcal{O}(10^{-4})$$

Applications

Easy inclusion of $\tan\beta$-enhanced corrections in various calculations, e.g.:

- Higgs masses
- SUSY decays e.g.

$$\frac{\Gamma(\tilde{g} \to \tilde{b}_i\, s)}{\Gamma(\tilde{g} \to \tilde{b}_i\, b)} = \left| \frac{\delta Z^L_{bs}}{2} \tilde{R}^b_{i1} \right|^2 + \left| \frac{\delta Z^R_{bs}}{2} \tilde{R}^b_{i2} \right|^2 \sim \mathcal{O}(10^{-4})$$

- B decays, CP asymmetries $\to$ see talk by Lars Hofer

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM
- resummation to all orders is possible without assuming decoupling of SUSY particles

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM
- resummation to all orders is possible without assuming decoupling of SUSY particles
- the formula for the mass resummation depends on the renormalization (input) scheme

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM
- resummation to all orders is possible without assuming decoupling of SUSY particles
- the formula for the mass resummation depends on the renormalization (input) scheme
- the resummed effects can be incorporated into corrected Feynman rules

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM
- resummation to all orders is possible without assuming decoupling of SUSY particles
- the formula for the mass resummation depends on the renormalization (input) scheme
- the resummed effects can be incorporated into corrected Feynman rules
- these Feynman rules allow for easy and consistent inclusion of large-$\tan\beta$ effects to all orders in calculations of flavour physics and collider physics

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM
- resummation to all orders is possible without assuming decoupling of SUSY particles
- the formula for the mass resummation depends on the renormalization (input) scheme
- the resummed effects can be incorporated into corrected Feynman rules
- these Feynman rules allow for easy and consistent inclusion of large-$\tan\beta$ effects to all orders in calculations of flavour physics and collider physics

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM
- resummation to all orders is possible without assuming decoupling of SUSY particles
- the formula for the mass resummation depends on the renormalization (input) scheme
- the resummed effects can be incorporated into corrected Feynman rules
- these Feynman rules allow for easy and consistent inclusion of large-$\tan\beta$ effects to all orders in calculations of flavour physics and collider physics

Thanks for your attention!

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM
- resummation to all orders is possible without assuming decoupling of SUSY particles
- the formula for the mass resummation depends on the renormalization (input) scheme
- the resummed effects can be incorporated into corrected Feynman rules
- these Feynman rules allow for easy and consistent inclusion of large-$\tan\beta$ effects to all orders in calculations of flavour physics and collider physics

Thanks for your attention!

Conclusion

- effects of $\tan\beta$-enhanced self-energies (flavour diagonal and non-diagonal) can be consistently treated in the full MSSM
- resummation to all orders is possible without assuming decoupling of SUSY particles
- the formula for the mass resummation depends on the renormalization (input) scheme
- the resummed effects can be incorporated into corrected Feynman rules
- these Feynman rules allow for easy and consistent inclusion of large-$\tan\beta$ effects to all orders in calculations of flavour physics and collider physics

Thanks for your attention!

Backup slides

Backup: parameter points

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

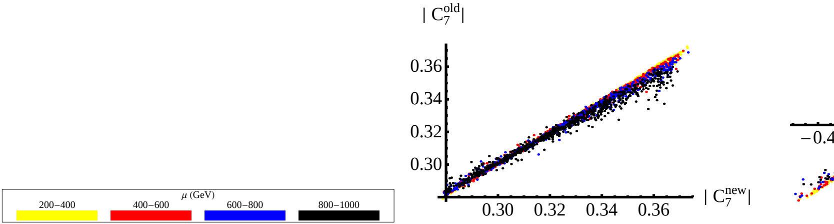
	min (GeV)	max (GeV)
$\tilde{m}_{Q_L}$, $\tilde{m}_{u_R}$, $\tilde{m}_{d_R}$	250	1000
$\lvert A_t \rvert$	100	1000
μ, M_1, M_2	200	1000
M_3	300	1000
m_{A^0}	200	1000

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}	$3\pi/2$

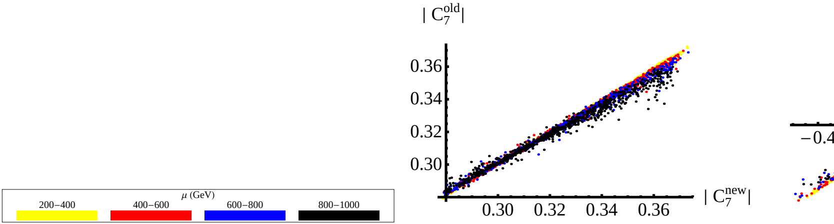
Backup: C_7 and other operators

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



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)



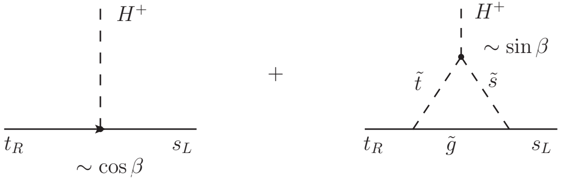
- effective four-quark operators in $\mathcal{H}^{\Delta B=1}$ and $\mathcal{H}^{\Delta B=2}$: gluino-squark loops suppressed by GIM-like cancellation between $\tilde{b}$- and $\tilde{s}$-loops $\rightarrow$ negligible compared to chargino-squark loops

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

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

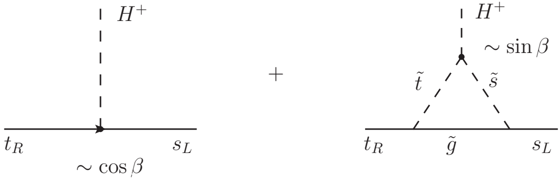
Backup: Non-local $\tan\beta$-enhanced effects

- 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.



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: relation to effective CKM matrix from BCRS

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

$$V_{ji}^{\text{eff}} = (V + \Delta U_L^\dagger V + V\,\Delta D_L)_{ji}$$

Backup: relation to effective CKM matrix from BCRS

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

$$V_{ji}^{\text{eff}} = (V + \Delta U_L^\dagger V + V\,\Delta D_L)_{ji}$$

- They start with $V = V^{\text{eff}}$ to calculate ΔD_L, set $\Delta U_L = 0$ and proceed iteratively

Backup: relation to effective CKM matrix from BCRS

- Buras, Chankowski, Rosiek, Slawianowska find for the effective CKM matrix:
$$V_{ji}^{\text{eff}} = (V + \Delta U_L^\dagger V + V\,\Delta D_L)_{ji}$$
- They start with $V = V^{\text{eff}}$ to calculate ΔD_L, set $\Delta U_L = 0$ and proceed iteratively
- They find that the result agrees numerically with the formula from eff. Lagrangian if ϵ-factors are replaced by full self-energies

Backup: relation to effective CKM matrix from BCRS

- Buras, Chankowski, Rosiek, Slawianowska find for the effective CKM matrix:
$$V_{ji}^{\text{eff}} = (V + \Delta U_L^{\dagger} V + V\, \Delta D_L)_{ji}$$
- They start with $V = V^{\text{eff}}$ to calculate ΔD_L, set $\Delta U_L = 0$ and proceed iteratively
- 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!)