MSSM vs. NMSSM in $\Delta F = 2$ transitions

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After first run of LHC...

- No convincing evidence of New Physics including low-SUSY.
- Non-SM particles pushed to higher scales.
- Higgs-like mass at **125 *GeV*:**

MSSM

- **Low** $\tan\beta$**:** hMSSM realization with close-to-maximal stop mixing and very heavy stops ($\sim 100\ TeV$).
- **Large** $\tan\beta$**:** Large mixing to keep stops relatively light,

$$m_h^2 \approx M_Z^2 + \mathcal{R}^2, \quad \mathcal{R} \simeq 85\ GeV$$

NMSSM

- **Low** $\tan\beta$**:** Larger tree level mass for **large** $\boldsymbol{\lambda}$**.**

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \cancel{\frac{\lambda^2}{\kappa^2} v^2 \left(\lambda - \sin 2\beta (\kappa + \frac{A_\lambda}{\sqrt{2} v_s})\right)^2}$$

- **Large** $\tan\beta$**:** MSSM-like (or even worse), $m_h^2 \approx M_Z^2 + \mathcal{R}^2 - \cancel{\text{Mix}(H_u - S)}$

MSSM and NMSSM have similar “Flavour” structure - ***Identical squark mass-structure.***

For Flavour observables, typically *(but not always!)*:

“common predictions - common squark parameter space.”

How can we distinguish between them?

1. **Different predictions - “common” physical parameter space.**

   What are the underlying mechanisms which reverse the typical *“common-prediction”* behaviour?

   How large is the deviation in their predictions and ***where*** it appears?

2. **Common “predictions” - different allowed parameter space.**

   How LHC limits on Higgs and Heavy Higgs measurements can be translated into ***different bounds*** on the $\tan\beta - m_{H^\pm}$ planes of the two models?

   What these bounds suggest for the (different) ***maximal allowed NP-effects*** in $\Delta F = 2$ observables (MFV) in the two models? [Barbieri, Buttazzo, Sala, Straub JHEP 1405 (2014) 105]

Table of Contents

1. General considerations in meson-antimeson mixing

2. Part - I. Different predictions
   - Deviations in **Box Diagrams** - the singlino effect.
   - Deviations in **Double Penguins** - the singlets effect *(brief)*.

3. Part - II. Common predictions
   - Maximal-NP in MFV - charged Higgs effect *(brief)*

4. Conclusions

General considerations in meson-antimeson mixing

The amplitude for $B_q - \bar{B}_q$ mixing is $M_{12}^q = \langle B_q | H_{eff} | \bar{B}_q \rangle$, where

$$H_{eff} = \sum_i C_i Q_i + h.c\,,$$

There are *eight* **dimension-six** operators Q_i, $(q = d, s)$,

$$Q^{\mathbf{VLL}} = (\bar{b}_L \gamma_\mu q_L)(\bar{b}_L \gamma^\mu q_L)\ , \quad Q_1^{\mathbf{SLL}} = (\bar{b}_R q_L)(\bar{b}_R q_L)\ , \quad Q_2^{\mathbf{SLL}} = (\bar{b}_R \sigma_{\mu\nu} q_L)(\bar{b}_R \sigma^{\mu\nu} q_L)\ ,$$

$$Q^{\mathbf{VLR}} = (\bar{b}_L \gamma_\mu q_L)(\bar{b}_R \gamma^\mu q_R)\ , \quad Q^{\mathbf{SLR}} = (\bar{b}_R q_L)(\bar{b}_L q_R)\ ,$$

$$\left[Q^{\mathbf{VRR}}, Q_1^{\mathbf{SRR}}, Q_2^{\mathbf{SRR}} : (L \leftrightarrow R) \right]$$

with $\sigma_{\mu\nu} = \frac{1}{2}[\gamma_\mu, \gamma_\nu]$.

- In **SM** only $Q^{\mathbf{VLL}}$ contributes, through $W^\pm$ - up quarks at one-loop.
- But in **(N)MSSM ...**

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Deviations in **Box Diagrams**

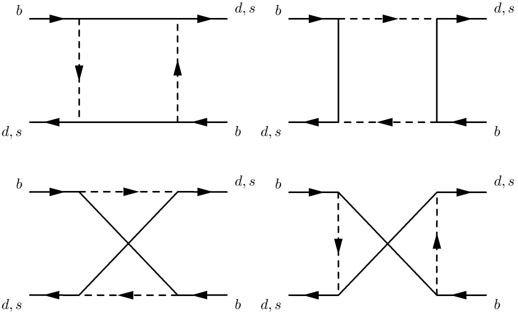


Figure : One-loop box diagrams contributing to $\Delta F = 2$ amplitude. ***Crossed boxes*** apply to *Majorana-fermions* (*i.e.*, ***gluinos, neutralinos***)

(N)MSSM one-loop box contributions

- **Charged Higgs - up quarks :** MSSM $\simeq$ NMSSM ($\sim m_{H^\pm}$, *Part-II*)
- **Charginos - up squarks :** MSSM = NMSSM.
- **Gluinos - down squarks :** MSSM = NMSSM.
- **Neutralinos - down squarks :** MSSM $\neq$ NMSSM, (*negligible*).
- **Neutralino - gluino - down squarks :** MSSM $\neq$ NMSSM, (potentially ***significant***).

- Only *Neutralinos* can cause deviations at one-loop! -

Deviations in **box diagrams** - the Z_3-NMSSM

The scale invariant **superpotential** of ***Z_3*-NMSSM** in the presence of a singlet superfield $\hat{S}$, reads,

$$W_{NMSSM} = W_{MSSM}\Big|_{\mu=0} + \lambda\,\hat{S}\,\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\,\hat{S}^3,$$

$$W_{MSSM}\Big|_{\mu=0} = \cancel{\mu\hat{H}_u\hat{H}_d} \;+\; Y_\ell\;\hat{H}_d\hat{L}\hat{e}^c \;+\; Y_d\;\hat{H}_d\hat{Q}\hat{d}^c \;+\; Y_u\;\hat{H}_u\hat{Q}\hat{u}^c$$

where an ***effective μ-parameter*** is generated when the singlet scalar S acquires a non-vanishing vacuum expectation value (vev), as

$$\boldsymbol{\mu_{eff} \equiv \lambda < S > = \lambda\frac{v_s}{\sqrt{2}}}.$$

The ***soft-breaking*** sector includes besides the standard MSSM terms, also the genuine-NMSSM contributions,

$$-\mathcal{L}^N_{soft} = m_S^2|S|^2 + (\lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3 + h.c.),$$

where m_S^2 can be eliminated through the minimization conditions.
Thus the **genuine-NMSSM** couplings are:

superpotential/soft $\sim \lambda, \kappa$, soft $\sim A_\lambda, A_\kappa$

Soft-terms are ***irrelevant for neutralinos*** we focus now...

Deviations in **box diagrams** - the Neutralino mass-matrix

"Flavour-space $\equiv$ any internal space of eigenstates which produces mixing effects."
i.e., neutralino, Higgs, quark, squark flavour-space but no gluon or gluino!

The **Neutralino mass-matrix** of **NMSSM** is,

$$\mathbf{M_N} = \begin{pmatrix} M_1 & 0 & -\frac{ev_d}{2c_\mathrm{w}} & \frac{ev_u}{2c_\mathrm{w}} & 0 \\ & M_2 & \frac{ev_d}{2s_\mathrm{w}} & -\frac{ev_u}{2s_\mathrm{w}} & 0 \\ & & 0 & -\mu_{eff} & -\frac{\lambda v_u}{\sqrt{2}} \\ & & & 0 & -\frac{\lambda v_d}{\sqrt{2}} \\ & & & & \frac{2\kappa v_s}{\sqrt{2}} \end{pmatrix}$$

in $(\tilde{B}, \tilde{W}, \tilde{H_d^0}, \tilde{H_u^0}, \tilde{S})$-basis, where M_1, M_2 are the Bino, Wino masses.

- **Singlino** ($\tilde{S}$) effects in *5th-dimension*, λ controls its *mixing*.
- In the **MSSM-limit** of **NMSSM**,

$$\lambda \to 0 \ , \quad \lambda/\kappa = \ \text{fixed} \ (\mu_{eff} \neq 0)$$

all ***"genuine-NMSSM"*** effects **decouple**.

Deviations in **box diagrams** - neutralino vertices

"Genuine-NMSSM ≡ all contributions/effects characteristic to NMSSM."

1. Contributions depending on genuine-NMSSM parameters $\lambda, \kappa, (A_\lambda, A_\kappa)$.
2. They **vanish** in the **MSSM-limit.**

Neutralino-quark-squark Vertices:

$$\left(V^L_{\chi Dd}\right)_{Iia} = -\frac{e}{\sqrt{2}\ s_{\rm w} c_{\rm w}}\ (Z_D)_{Ii}\left(\frac{s_{\rm w}}{3}(Z_N)_{1a} - c_{\rm w}\ (Z_N)_{2a}\right) + \boldsymbol{Y_d^I (Z_D)_{I+3,i}\ (Z_N)_{3a}}$$

$$\left(V^R_{\chi Dd}\right)_{Iia} = -\frac{e\sqrt{2}}{3c_{\rm w}}(Z_D)_{I+3,i}(Z_N)^*_{1,a} + \boldsymbol{Y_d^I (Z_D)_{Ii}(Z_N)^*_{3a}}$$

- Same in both models but a-index runs up to 5 in NMSSM.
- Notice the **fixed-indices!** i.e., $(1,2) \to (\tilde{B}, \tilde{W})$, $3 \to \tilde{H}^0_d$

- Singlino effects can come only through mixing -

- Singlino primarily mixes with $\tilde{H}^0_d$ (mass matrix/FET) -

- Higgsino ($\tilde{H}^0_d$) couples also with Y_b-coupling -

- Y_b becomes comparable to g_3 at large $\tan\beta$ -

Deviations in **box diagrams** - diagrammatic origin of deviations

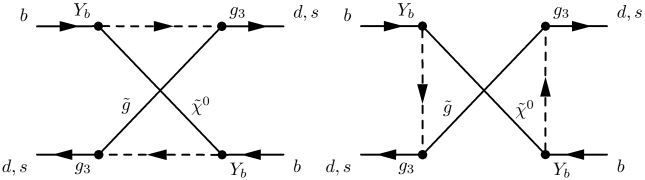


Figure : Neutralino-gluino box contributions in mass basis, mediating genuine-NMSSM contributions proportional to $g_3^2 Y_b^2$, which become enhanced in the large $\tan\beta$ regime. Neutralino-neutralino diagrams have suppressed couplings (i.e. $g_3 \to (g_1, g_2, Y_s)$), thus negligible. Same for Kaon.

We can **isolate the leading, genuine-NMSSM,** contributions in the Wilson Coefficients:

- Keep only the leading higgsino-related term at **large-**$\tan\beta$ in vertex:

$$\left(V^L_{\chi D d}\right)_{3ia} \approx Y_b (Z_D)_{6i} (Z_N)_{3a}$$
$$\left(V^R_{\chi D d}\right)_{3ia} \approx Y_b (Z_D)_{3i} (Z_N)^*_{3a}$$

Wilson coefficients -neutrlaino- gluino contributions

$$C^{VLL} = -\frac{g_3^2}{16\pi^2}\frac{1}{6}\ V^L_{2ka}\ V^{L*}_{3la}\ Z_{2l}\ Z^*_{3k}\ D_2(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) - \frac{g_3^2}{16\pi^2}\frac{1}{6}\left(V^L_{2ka}\ V^L_{2la}\ Z^*_{3k}\ Z^*_{3l} + V^{L*}_{3ka}\ V^{L*}_{3la}\ Z_{2k}\ Z_{2l}\right) m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) \quad (1)$$

$$C^{VRR} = -\frac{g_3^2}{16\pi^2}\frac{1}{6}\ V^R_{2ka}\ V^{R*}_{3la}\ Z_{5l}\ Z^*_{6k}\ D_2(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) - \frac{g_3^2}{16\pi^2}\frac{1}{6}\left(V^R_{2ka}\ V^R_{2la}\ Z^*_{6k}\ Z^*_{6l} + V^{R*}_{3ka}\ V^{R*}_{3la}\ Z_{5k}\ Z_{5l}\right) m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) \quad (2)$$

$$C_1^{SLL} = \frac{g_3^2}{16\pi^2}\frac{7}{6}\ V^L_{2ka}\ V^{R*}_{3la}\ Z^*_{6k}\ Z_{2l}\ m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) + \frac{g_3^2}{16\pi^2}\ \frac{1}{6}\left(V^{R*}_{3ka}\ V^{R*}_{3la}\ Z_{2k}\ Z_{2l} + V^L_{2ka}\ V^L_{2la}\ Z^*_{6k}\ Z^*_{6l}\right) m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) \quad (3)$$

$$C_1^{SRR} = \frac{g_3^2}{16\pi^2}\frac{7}{6}\ V^R_{2ka}\ V^{L*}_{3la}\ Z^*_{3k} Z_{5l}\ m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) + \frac{g_3^2}{16\pi^2}\ \frac{1}{6}\left(V^{L*}_{3ka}\ V^{L*}_{3la}\ Z_{5k}\ Z_{5l} + V^R_{2ka}\ V^R_{2la}\ Z^*_{3k}\ Z^*_{3l}\right) m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) \quad (4)$$

$$C_2^{SLL} = -\frac{g_3^2}{16\pi^2}\frac{1}{24}\ V^L_{2ka}\ V^{R*}_{3la}\ Z^*_{6k}\ Z_{2l}\ m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) + \frac{g_3^2}{16\pi^2}\ \frac{1}{24}\left(V^{R*}_{3ka}\ V^{R*}_{3la}\ Z_{2k}\ Z_{2l} + V^L_{2ka}\ V^L_{2la}\ Z^*_{6k}\ Z^*_{6l}\right) m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) \quad (5)$$

$$C_2^{SRR} = -\frac{g_3^2}{16\pi^2}\frac{1}{24}\ V^R_{2ka}\ V^{L*}_{3la}\ Z^*_{3k}\ Z_{5l}\ m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) + \frac{g_3^2}{16\pi^2}\ \frac{1}{24}\left(V^{L*}_{3ka}\ V^{L*}_{3la}\ Z_{5k}\ Z_{5l} + V^R_{2ka}\ V^R_{2la}\ Z^*_{3k}\ Z^*_{3l}\right) m_{\tilde g}\ m_a\ D_0(m^2_{\tilde g}, m^2_a, m^2_k, m^2_l) \quad (6)$$

Deviations in **box diagrams** - isolating algebraically deviations

- Apply vertex approximation on Wilsons and keep only relevant terms. e.g., for B_s,

$$C_1^{SRR} \supset \frac{g_3^2}{16\pi^2}\ \frac{1}{6}\ \left(V^{L*}_{3ka}\ V^{L*}_{3la}\ Z_{5k}\ Z_{5l}\right)\ m_{\tilde{g}}\ m_a\ D_0(m_{\tilde{g}}^2, m_a^2, m_k^2, m_l^2)$$

$$\approx \frac{g_3^2 Y_b^2}{16\pi^2}\ \frac{1}{6}\ \left((Z_D)^*_{6k}\ (Z_D)^*_{6l}\ (Z_D)_{5k}\ (Z_D)_{5l}\ \right) \times$$

$$m_{\tilde{g}}\left[(Z_N)_{3a} m_a\ D_0(m_{\tilde{g}}^2, m_a^2, m_k^2, m_l^2)(Z_N)_{3a}\right]$$

- Suppress irrelevant couplings and squark-flavour. **Only two general neutralino-flavour structures are allowed up to c.c. (FET)!**

$$C_i \supset \quad \sim m_{\tilde{g}}\left[(Z_N)_{3a} m_a\ D_0(m_{\tilde{g}}^2, m_a^2, x)(Z_N)_{3a}\right]$$

$$\sim \left[(Z_N)_{3a} D_2(m_{\tilde{g}}^2, m_a^2, x)(Z_N)^*_{3a}\right]$$

Dedes, Paraskevas, Rosiek, Suxho, JHEP 1506 (2015) 151

- Take also large-$\tan\beta$ limit ($v_u \gg v_d$) on M_N, M_N^2:

$$\mathbf{M_N} \approx \begin{pmatrix} M_1 & 0 & 0 & \frac{ev_u}{2c_W} & 0 \\ & M_2 & 0 & -\frac{ev_u}{2s_W} & 0 \\ & & 0 & -\mu_{eff} & -\boldsymbol{\frac{\lambda v_u}{\sqrt{2}}} \\ & & & 0 & 0 \\ & & & & \frac{2\kappa v_s}{\sqrt{2}} \end{pmatrix}, \quad \mathbf{M_N^2} \approx \begin{pmatrix} M_{11}^2 & M_{12}^2 & M_{13}^2 & M_{14}^2 & 0 \\ & M_{22}^2 & M_{23}^2 & M_{24}^2 & 0 \\ & & M_{33}^2 & 0 & \boldsymbol{M_{35}^2} \\ & & & M_{44}^2 & M_{45}^2 \\ & & & & M_{55}^2 \end{pmatrix}$$

$$M_{11}^2 = M_1^2 + \frac{e^2 v_u^2}{4c_W^2}, \; M_{22}^2 = M_2^2 + \frac{e^2 v_u^2}{4s_W^2},$$

$$M_{33}^2 = \mu_{eff}^2 + \frac{\lambda^2 v_u^2}{2}, \; M_{44}^2 = \mu_{eff}^2 + \frac{e^2 v_u^2}{4c_W^2 s_W^2}, \; M_{55}^2 = 2\kappa^2 v_s^2 + \frac{\lambda^2 v_u^2}{2}.$$

The off-diagonal entries of M_N^2, associated with genuine NMSSM effects, are

$$\boldsymbol{M_{35}^2 = -(\kappa v_s)(\lambda v_u)}, \; M_{45}^2 = \mu_{eff}\left(\frac{\lambda v_u}{\sqrt{2}}\right), \tag{17}$$

Deviations in **box diagrams** - isolating algebraically deviations

- **Apply FET:**

$$m_{\tilde{g}}\Big[(Z_N)_{3a}m_a\ D_0(m_{\tilde{g}}^2, m_a^2, x)(Z_N)_{3a}\Big] = m_{\tilde{g}}\ \Big[\mathbf{M_N} D_0(m_{\tilde{g}}^2, \mathbf{M_N^2}, x)\Big]_{33}$$
$$= m_{\tilde{g}}\ (M_N)_{35}\ (M_N^2)_{53}\ E_0\Big(m_{\tilde{g}}^2, (M_N^2)_{55}, (M_N^2)_{33}, x\Big) + \ldots$$
$$= m_{\tilde{g}}\ (\lambda v_u)(\kappa v_u \mu_{eff})\ E_0\Big(m_{\tilde{g}}^2, (M_N^2)_{55}, (M_N^2)_{33}, x\Big) + \ldots$$

Genuine-NMSSM, vanishes in MSSM-limit!

$$\Big[(Z_N)_{3a} D_2(m_{\tilde{g}}^2, m_a^2, x)(Z_N)^*_{3a}\Big] = \Big[D_2(m_{\tilde{g}}^2, \mathbf{M_N^2}, x)\Big]_{33}$$
$$= D_2\Big(m_{\tilde{g}}^2, (M_N^2)_{33}, x\Big) + \ldots$$

Mixed-NMSSM, does not vanish!

- Mixed is expected larger (no neutralino mass-insertion, same coupling $\propto g_3^2 Y_b^2$).

Is the **genuine-NMSSM** effect **"screened"**?

Deviations in **box diagrams** - squark flavour dependence

- Apply FET-MIA for **squarks:**

Q^{VLL}	Q^{VRR}	Q_1^{SLL}	Q_1^{SRR}	Q_2^{SLL}	Q_2^{SRR}	Q^{VLR}	Q^{SLR}
$\delta^{q3}_{LR}\delta^{q3}_{LR}$	$\delta^{q3}_{RL}\delta^{q3}_{RL}$	$\delta^{q3}_{LL}\delta^{q3}_{LL}$	$\delta^{q3}_{RR}\delta^{q3}_{RR}$	$\delta^{q3}_{LL}\delta^{q3}_{LL}$	$\delta^{q3}_{RR}\delta^{q3}_{RR}$	$\delta^{q3}_{LL}\delta^{q3}_{RR}$	$\delta^{q3}_{LL}\delta^{q3}_{RR}$
						$\delta^{q3}_{RL}\delta^{q3}_{LR}$	$\delta^{q3}_{RL}\delta^{q3}_{LR}$
genuine	*genuine*	*genuine*	*genuine*	*genuine*	*genuine*	*mixed*	*mixed*

Table : Down-squark flavour dependence of *genuine* and *mixed* NMSSM contributions, related to higgsino-singlino crossed boxes. It is obtained by isolating all terms displaying the two neutralino flavour structures in the Wilsons and subsequently applying the MIA for down-squarks. Here $q = 1, 2$ refers to B_d, B_s -mixing respectively.

Different squark-dependence - Typically **genuine** and **mixed** do not appear together in the same scenario.

Deviations in **box diagrams** - MSSM screening

What about other sources of **"screening"**?
MSSM-screening ≡ the general property that some pure-MSSM contribution may be sizeable in the same region of the parameter space, where we study our effects.

One-loop screening

- **Charged Higgs - up quarks :** MSSM ≃ NMSSM (irrelevant)
- **Charginos - up squarks :** MSSM = NMSSM. (irrelevant)
- **Gluinos - down squarks :** MSSM = NMSSM. (significant)
- **Neutralinos - down squarks :** MSSM ≠ NMSSM, (*negligible*).
- **Neutralino - gluino - down squarks :** MSSM ≠ NMSSM, ***subleading pure-MSSM*** .

Double-penguin screening

Decouple for large M_A which is favoured by minimization conditions (i.e., at large $\lambda, \tan\beta$).

- Gluino-gluino boxes are the most important screening effects. -

Deviations in **box diagrams** - Numerical Analysis

The genuine-NMSSM effects at one loop have the rough behaviour:

$$g_3^2 Y_b^2 \times (\text{squark flavour violation } \sim \delta_D \delta_D) \times (\tilde{H}_d^0 - \tilde{S} \text{ mixing} \sim \lambda, \kappa, \mu_{eff})$$

The effects become significant for:

- Large $\tan\beta \gtrsim 40$. ($\propto Y_b^2$)
- Large down-squark insertions. ($\propto (\delta_D)^2$)
- Large $\lambda \sim \kappa \gtrsim 0.5$ and small $\mu_{eff} \lesssim 300\ GeV$. (maximize $\tilde{H}_d^0 - \tilde{S}$ mixing)

But due to perturbativity $\lambda \sim \kappa \lesssim 1$ (0.6) and experiment $\mu_{eff} \gtrsim 100\ GeV$ the effect is bounded.

Deviations in **box diagrams** - ΔM_s

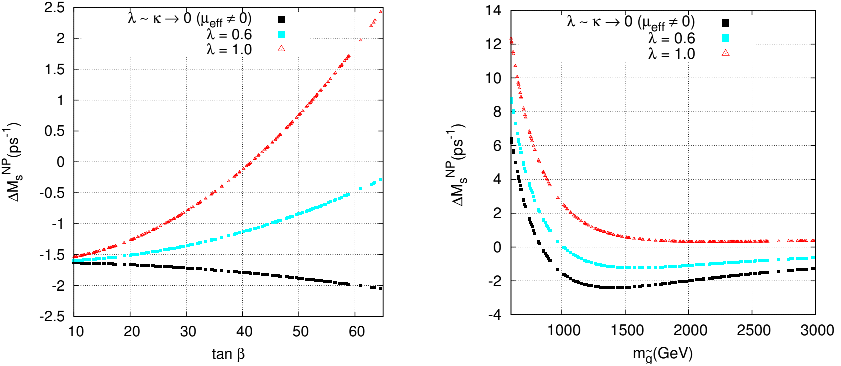
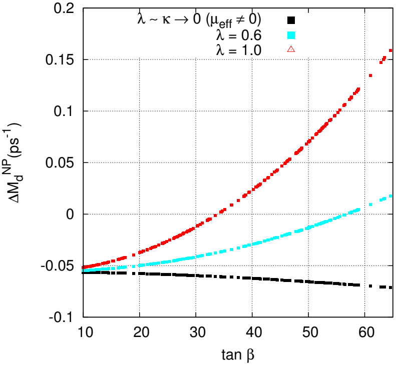


Figure : Genuine-NMSSM effects in ΔM_s, understood as deviations with respect to the MSSM predictions under $\tan\beta$ (left) and gluino mass (right), scaling. Input parameters primarily controlling the effect read $(m_D^2)_{ii} = 650\ GeV$, $M_S = 3\ TeV$, $\boldsymbol{\delta^{23}_{RR} = 0.6}$, while $m_{\tilde{g}} = 1.1\ TeV$ and $\tan\beta = 60$ were used for left and right plot, respectively. **Cyan line ($\kappa = 0.4$)** corresponds to **perturbative NMSSM** up to GUT-scale. **Red line ($\kappa = 1$)** requires **UV-completion before GUT-scale**, as in λ-susy models. The **black line** is the **MSSM-limit** of the NMSSM model.

$$(\Delta M_s)_{exp} = (17.757 \pm 0.021)\ \text{ps}^{-1}\ ,\ (\Delta M_s)_{SM} = 19.6\ \text{ps}^{-1}$$

$$\text{Set:}\quad \Delta_{NP}^{\mathbf{MSSM}} \approx -10\%$$

Deviations in **box diagrams** - ΔM_d



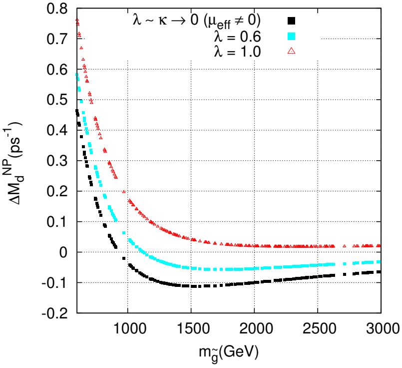


Figure : Genuine NMSSM-effects in ΔM_d with all input parameters as before besides down-squark flavour violation which is now induced through $\boldsymbol{\delta^{13}_{RR} = 0.2}$.

$$(\Delta M_d)_{exp} = (0.5055 \pm 0.020)\ \text{ps}^{-1}\ ,\ (\Delta M_d)_{SM} = 0.63\ \text{ps}^{-1}$$

$$\text{Set:}\quad \Delta^{\mathbf{MSSM}}_{NP} \approx -20\%$$

Deviations in **box diagrams** - A deviation measure.

Introduce a *deviation* measure, defined for B_q mixing as

$$\delta(\Delta M_q)_{N-M} \equiv \frac{(\Delta M_q^{NP})_{\text{NMSSM}} - (\Delta M_q^{NP})_{\text{MSSM}}}{\Delta M_q^{SM}} \propto \frac{(\delta_{RR}^{q3})^2}{\Delta M_q^{SM}}$$

Deviation measure depends on squark flavour violation and thus on MSSM background.

At $m_g \approx 1.1\ TeV, \tan\beta = 60$,

$$B_s: \qquad \Delta_{NP}^{\mathbf{MSSM}} \approx -10\% \quad \rightarrow \quad \delta(\Delta M_s)_{\boldsymbol{N-M}} \approx +20\%$$

$$B_d: \qquad \Delta_{NP}^{\mathbf{MSSM}} \approx -20\% \quad \rightarrow \quad \delta(\Delta M_d)_{\boldsymbol{N-M}} \approx +35\%$$

For the same MSSM background (e.g. $\delta_{RR}^{13} = 0.2/\sqrt{2}$) the effects would be same.

Other scenaria (i.e. LL,LR,RL, smaller M_S) are possible but other flavour constraints are usually stronger and MSSM-screening is typically larger.

The table can be used as a guide.

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Deviations in **double penguins** - the (two) singlets effect

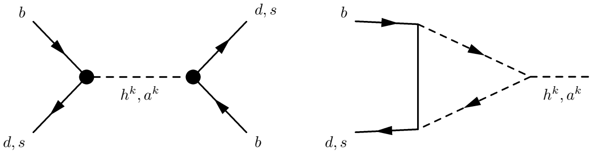

Figure : Double penguin diagrams (formally two-loop) on the left, induced by one-loop effective Yukawa couplings as the one shown on the right, scaling as $\sim (\tan\beta)^4$ and thus potentially significant for $\Delta F = 2$ observables in both MSSM and NMSSM models.

- Two extra singlets (cp-even/odd) induce genuine-NMSSM contributions, either by mixing with A_d, H_d or by themselves.
- MSSM.vs.Genuine-NMSSM effects

$$\frac{1}{M_A v_d} \text{ .vs. } \frac{1}{m^3_{h(a)} v_s}$$

- But $v_s = \sqrt{2}\frac{\mu_{eff}}{\lambda} \gtrsim 150\ GeV$
- Deviations appear roughly for $M_A/m^3_{h(a)} \gtrsim v_s/v_d$, thus **light singlet masses required!**

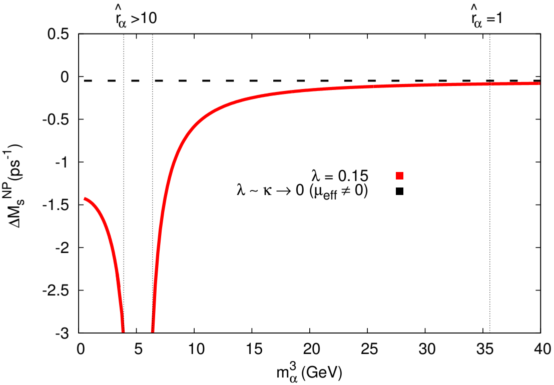

Figure : MSSM (dashed) and NMSSM (red) contributions in ΔM_s^{NP}, under CP-odd mass scaling of the singlet-like eigenstate and driven by $|C_1^{SLL}| \gg |C^{SLR}|$ in the enhancement region. As the singlet CP-odd mass m_a^3 closes to the resonance (M_{B_s}) the size of the effect increases rapidly, sending ΔM_s^{NP} far beyond experimental bounds. The CP-even singlet mass, taken here as an output, remains always heavy.

Resonance effect: appears at M_{B_q} by substituting the Breit-Wigner form of the propagators.(i.e., $\frac{1}{p^2 - m^2} \simeq -\frac{1}{m^2}$ is not effective for light singlets.)

Table of Contents

1. General considerations in meson-antimeson mixing
2. Part - I. Different predictions
    - Deviations in **Box Diagrams** - the singlino effect.
    - Deviations in **Double Penguins** - the singlets effect *(brief)*.
3. Part - II. Common predictions
    - Maximal-NP in MFV - charged Higgs effect *(brief)*
4. Conclusions

Maximal-NP in MFV - charged Higgs effect

- At low $\tan\beta$ MFV charged Higgs contributions dominate and they depend primarily on two parameters $(\tan\beta, M_{H^\pm})$

  Charginos give a subleading contribution of $2-3\%$ only in NMSSM since in hMSSM chargino diagrams decouple (stops are heavy).

- One can take the Heavy Higgs non-observation limits $(H \to ZZ, A \to hZ, H^+ \to \tau^+\nu)$ and Higgs observables and translate them into different bounds on the $\tan\beta - M_A(M_{H^\pm})$ planes of the two models.

- Then one can apply the common predictions of the two models and distinguish between them through their different maximal allowed NP-effect in B-meson observables.

Flavour physics and flavour symmetries after the first LHC phase [Barbieri, Buttazzo, Sala, Straub JHEP 1405 (2014) 105]

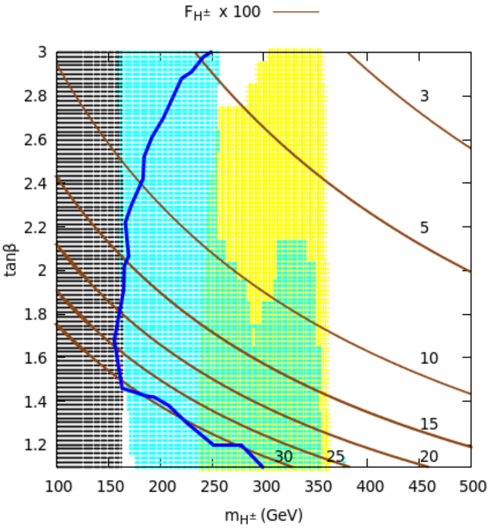

Figure : Brown contours show percentage modification $F_{H^\pm}$ to $\Delta F = 2$ observables originating from charged Higgs diagrams. Gray $(H^+ \to \tau^+\nu)$, **cyan** $(H \to ZZ)$ and yellow $(A \to hZ)$ regions are hMSSM exclusions at $95\% CL$. NMSSM exclusion is on the left-side of the blue contour.

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Conclusions

Two ways to distinguish between MSSM and NMSSM through $B - \bar{B}$ observables:

1. Different predictions - common parameter space:
Squarks, charginos, gluinos and effectively charged Higgs diagrams are identical in the two-models. Thus there are only two sources, both effective for **large** $\tan\beta$:

- Neutralinos: Neutralino-gluino diagrams can be important at large $\tan\beta, \lambda(\sim \kappa)$ and small μ_{eff} in models with significant gluino-gluino MSSM-background.
- Double Penguins: Neutral Higgs diagrams can be significant obviously at large $\tan\beta$ and light singlet masses (CP-even/odd).

Both effects decouple for $\lambda \to 0$ and/or large μ_{eff} since this is effectively the MSSM-limit.

2. Common predictions - different allowed parameter space:
Translate Higgs and Heavy Higgs measurements into different bounds on the $\tan\beta - M_A(M_{H^\pm})$ planes of the two models. Using these planes for low $\tan\beta$ MFV one can distinguish between the two models through their maximal NP-contribution in ΔM_q.