Hadronic B Decays in the MSSM with Large $\tan\beta$

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Outline

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- hadronic B decays, etc.

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Consider the MSSM with large $\frac{v_u}{v_d} \equiv \tan\beta$:

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- theoretically appealing
  - Consistent with approximate top and bottom Yukawa couplings unification in some $SO(10)$.
  - Resummation of large $\tan\beta$ enhanced contributions.
- interesting phenomenology
  - Large deviations from Standard Model phenomenology.
  - Specific signatures and correlations.

Effective Lagrangian

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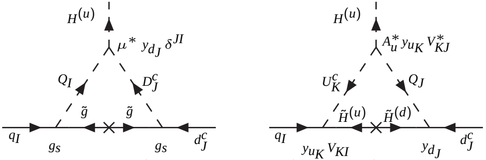
- Integrate out the heavy particles.
- Construction of the effective Lagrangian.
- One obtains a two Higgs doublet model of III type:
- Each Higgs doublet is coupled to both up and down type quarks.

Effective Lagrangian: $SU(3) \times U(1)$ Symmetry Limit

A.J. Buras, P.H. Chankowski, J. Rosiek, Ł. Sławianowska, Nucl.Phys. B 659:3, 2003 (hep-ph/0210145)



$$(\Delta_u \mathbf{Y}_d)^{JI} = -y_{d_J}\left(\epsilon_0\,\delta^{JI} + \epsilon_Y y_t^2 V^{3J*} V^{3I}\right) \equiv -y_{d_J}\left(\tilde{\epsilon}_J\,\delta^{JI} + \epsilon_Y y_t^2 \lambda_0^{JI}\right)$$

- $$\mathcal{L}_{\rm eff} = -\epsilon_{ij} H_i^d \bar{d}_R \cdot (\mathbf{Y}_d + \Delta_d \mathbf{Y}_d) \cdot q_{jL} - H_i^{u*} \bar{d}_R \cdot \Delta_u \mathbf{Y}_d \cdot q_{iL} + \text{h.c.}$$
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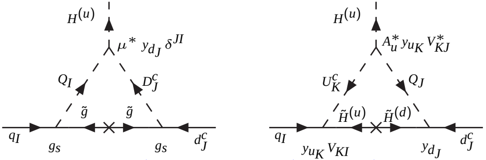

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- Decomposing the Higgs doublet into the mass eigenstates one obtains e.g.

$$\mathcal{L}^{(d)}_{\text{mass}} = \bar{d}_R \cdot \left(\frac{v_d}{\sqrt{2}} y_d + \frac{v_d}{\sqrt{2}} \Delta_d \mathbf{Y}_d - \frac{v_u}{\sqrt{2}} \Delta_u \mathbf{Y}_d\right) \cdot d_L + \text{h.c.},$$

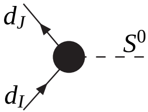
$$\Downarrow$$

$$(\Delta m_d)^{JI} = -\frac{v_d}{\sqrt{2}}(\Delta_d \mathbf{Y}_t - \tan\beta \Delta_u \mathbf{Y}_d)^{JI} \simeq \frac{v_d}{\sqrt{2}} \tan\beta (\Delta_u \mathbf{Y}_d)^{JI}$$

$$\Downarrow$$

$$m_{d_J} = \frac{\bar{m}_{d_J}}{1 + \tilde{\epsilon}_J \tan\beta}, \quad m_{u_J} \simeq \bar{m}_{u_J}, \quad m_{l_J} \simeq \bar{m}_{l_J}.$$

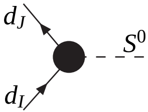
Effective Lagrangian: Neutral Higgs-Fermion Vertices



$$-i\left(\left(X^{S^0}_{dRL}\right)^{JI}P_L+\left(X^{S^0}_{dLR}\right)^{JI}P_R\right)$$

Effective Lagrangian: Neutral Higgs-Fermion Vertices

$$\left[X_d^{H^0}\right]^J = \frac{\bar{m}_{d_J}}{1+\tilde{\epsilon}_J \tan\beta} \tan\beta \left(c_\alpha + \tilde{\epsilon}_J s_\alpha\right),$$
$$\left[X_d^{h^0}\right]^J = \frac{\bar{m}_{d_J}}{1+\tilde{\epsilon}_J \tan\beta} \tan\beta \left(-s_\alpha + \tilde{\epsilon}_J c_\alpha\right),$$
$$\left[X_d^{A^0}\right]^J = \frac{\bar{m}_{d_J}}{1+\tilde{\epsilon}_J \tan\beta} i \tan\beta,$$



$$\left[X_{dRL}^{H^0}\right]^{JI} = \frac{\bar{m}_{d_J} V_{\text{eff}}^{3J*} V_{\text{eff}}^{3I}}{(1+\tilde{\epsilon}_3 \tan\beta)(1+\epsilon_0 \tan\beta)} \epsilon_Y y_t^2 \tan\beta^2 s_{\alpha-\beta},$$
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$$\left[X_{dRL}^{A^0}\right]^{JI} = \frac{\bar{m}_{d_J} V_{\text{eff}}^{3J*} V_{\text{eff}}^{3I}}{(1+\tilde{\epsilon}_3 \tan\beta)(1+\epsilon_0 \tan\beta)} \epsilon_Y y_t^2 (-i) \tan\beta^2,$$

$$-i\left(\left(X_{dRL}^{S^0}\right)^{JI} P_L + \left(X_{dLR}^{S^0}\right)^{JI} P_R\right)$$

for $(IJ) = (13), (23), (31), (32)$;

One finds similar expressions for the other RL and the LR couplings.

Example: $B_s^0 - \bar{B}_s^0$ Mixing and $B_s^0 \to \mu^+\mu^-$

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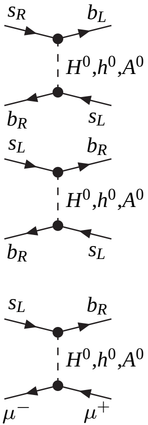


- $B_s^0 - \bar{B}_s^0$ Mass Difference:

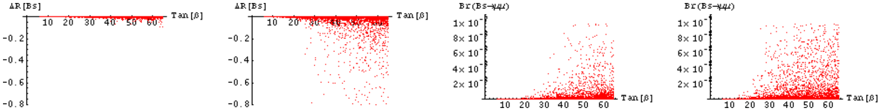
$$(\Delta M_s)^{SM} = (20.9 \pm 2.6)\mathrm{ps}^{-1},$$

$$(\Delta M_s)^{DP} = (-12)\mathrm{ps}^{-1} \cdot \left[\frac{\tan\beta}{50}\right]^4 \left[\frac{P_2^{LR}}{2.5}\right] \left[\frac{F_{B_s}}{230\mathrm{MeV}}\right]^2 \left[\frac{|V_{ts}|}{0.040}\right]^2 \cdot \left[\frac{\bar{m}_b(\mu_S)}{3.0\mathrm{GeV}}\right] \left[\frac{\bar{m}_s(\mu_S)}{0.06\mathrm{GeV}}\right] \left[\frac{\bar{m}_t^4(\mu_S)}{M_W^2 M_A^2}\right] \frac{(16\pi^2)^2 \epsilon_Y^2}{(1+\tilde{\epsilon}_3 \tan\beta)^2 (1+\epsilon_0 \tan\beta)^2}.$$

- $B_s^0 \to \mu^+\mu^-$ Branching ratio:

$$\mathrm{Br}(B_s \to \mu^+\mu^-)^{SM} = (3.8 \pm 0.1) \times 10^{-9},$$

$$\mathrm{Br}(B_s \to \mu^+\mu^-)^{P} = 3.5 \times 10^{-5} \left[\frac{\tan\beta}{50}\right]^6 \left[\frac{\tau_{B_s}}{1.5\mathrm{ps}}\right] \left[\frac{F_{B_s}}{230\mathrm{MeV}}\right] \cdot \left[\frac{|V_{ts}|}{0.040}\right]^2 \left[\frac{m_t}{M_A}\right]^4 \frac{(16\pi^2)^2 \epsilon_Y^2}{(1+\tilde{\epsilon}_3 \tan\beta)^2 (1+\epsilon_0 \tan\beta)^2}.$$



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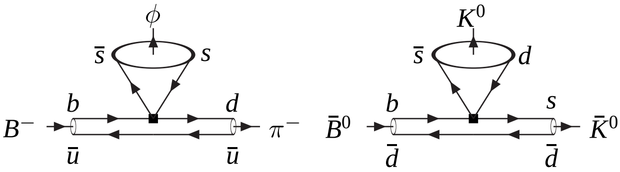

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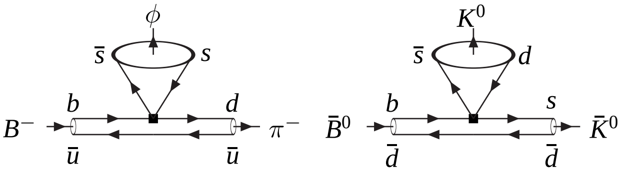

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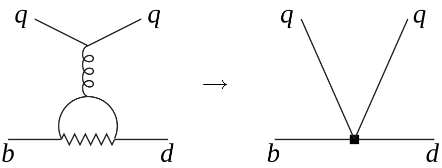

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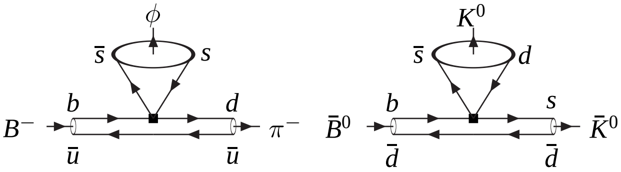

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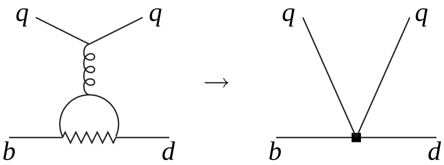

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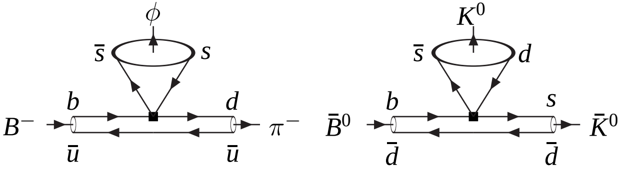

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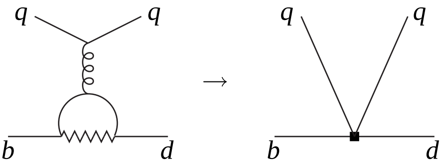

- EW scale vs hadronic scales: M_W vs m_B, Λ_{QCD}:
- Realistic picture: point-like vertex $\longrightarrow$ four-quark operator.

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- Construct the effective Hamiltonian: $\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\mu) Q_i(\mu).$

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- In the case considered here the relevant operators are

$$Q_3 = (\bar{d}b)_{V-A} \sum_q (\bar{q}q)_{V-A}, \qquad Q_4 = (\bar{d}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A},$$
$$Q_5 = (\bar{d}b)_{V-A} \sum_q (\bar{q}q)_{V+A}, \qquad Q_6 = (\bar{d}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A},$$

This includes QCD effects.

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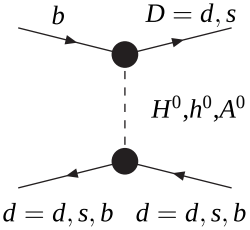
- $C_3(M_W) = C_5(M_W) = -\frac{\alpha_s(M_W)}{24\pi} \tilde{E}_0(x_t)$, $C_4(M_W) = C_6(M_W) = \frac{\alpha_s(M_W)}{8\pi} \tilde{E}_0(x_t)$;

$C_3(m_B)$	$C_4(m_B)$	$C_5(m_B)$	$C_6(m_B)$
0.014	-0.036	0.009	-0.042

Hadronic B Decays: MSSM New Contributions

- Relevant new operators:

$$Q_{15}^{d} = (\bar{D}b)_{S+P}(\bar{d}d)_{S-P}, \quad Q_{16}^{d} = (\bar{D}_i b_j)_{S+P}(\bar{d}_j d_i)_{S-P}.$$



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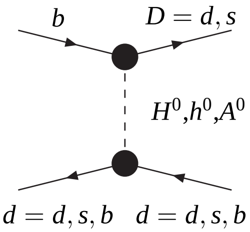
- Wilson Coefficients (at leading order in QCD):

$$C_{15}^d(M_{S^0}) = -\frac{\bar{m}_b \bar{m}_d \epsilon_Y y_t^2 \tan\beta^3}{(1+\tilde{\epsilon}_3 \tan\beta)(1+\epsilon_0 \tan\beta)(1+\tilde{\epsilon}_d \tan\beta)} \mathcal{F}_{2,d}^-,$$
$$C_{16}^d(M_{S^0}) = 0,$$

with

$$\mathcal{F}_{2,d}^{\pm} = \frac{s_{\alpha-\beta}(c_\alpha + \tilde{\epsilon}_d s_\alpha)}{M_{H_0}^2} + \frac{c_{\alpha-\beta}(-s_\alpha + \tilde{\epsilon}_d c_\alpha)}{M_{h_0}^2} \pm \frac{1}{M_{A_0}^2},$$



Numerical Estimate of Wilson Coefficients

- The Wilson coefficients depend on Supersymmetric parameters through the loop functions ϵ_i:

$$\epsilon_0 = -\frac{2\alpha_s}{3\pi}\frac{\mu}{m_{\tilde{g}}}H_2(x^{Q/g}, x^{D/g}), \qquad \epsilon_Y = \frac{1}{16\pi^2}\frac{A_t}{\mu}H_2(x^{Q/\mu}, x^{U/\mu}),$$

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- In Minimal Supergravity one finds $|\epsilon_i| \sim 0.005$

Numerical Estimate of Wilson Coefficients

- $C^d_{15}(M_{S^0}) \simeq -0.0008 \left[\frac{\bar{m}_b}{3.0\text{GeV}}\right] \left[\frac{\bar{m}_d}{0.002\text{GeV}}\right] \left[\frac{\bar{m}_t}{160\text{GeV}}\right]^2 \left[\frac{\epsilon_Y}{0.005}\right] \left[\frac{\tan\beta}{60}\right]^3 \cdot \left[\frac{0.7}{(1+\tilde{\epsilon}_3\tan\beta)}\right] \left[\frac{0.7}{(1+\epsilon_0\tan\beta)}\right] \left[\frac{0.7}{(1+\tilde{\epsilon}_2\tan\beta)}\right],$
- $C^s_{15}(M_{S^0}) \simeq -0.03 \left[\frac{\bar{m}_b}{3.0\text{GeV}}\right] \left[\frac{\bar{m}_s}{0.07\text{GeV}}\right] \left[\frac{\bar{m}_t}{160\text{GeV}}\right]^2 \left[\frac{\epsilon_Y}{0.005}\right] \left[\frac{\tan\beta}{60}\right]^3 \cdot \left[\frac{0.7}{(1+\tilde{\epsilon}_3\tan\beta)}\right] \left[\frac{0.7}{(1+\epsilon_0\tan\beta)}\right] \left[\frac{0.7}{(1+\tilde{\epsilon}_2\tan\beta)}\right],$
- $C^b_{15}(M_{S^0}) \simeq$
  $-1.2 \left[\frac{\bar{m}_b}{3.0\text{GeV}}\right]^2 \left[\frac{\bar{m}_t}{160\text{GeV}}\right]^2 \left[\frac{\epsilon_Y}{0.005}\right] \left[\frac{\tan\beta}{60}\right]^3 \left[\frac{0.7}{(1+\tilde{\epsilon}_3\tan\beta)}\right]^2 \left[\frac{0.7}{(1+\epsilon_0\tan\beta)}\right],$
- to compare with

$C_3(m_B)$	$C_4(m_B)$	$C_5(m_B)$	$C_6(m_B)$
0.014	-0.036	0.009	-0.042

Hadronic B Decays: SM Amplitudes (LO)

- The decay amplitude is given by:

$$\mathcal{A} = \langle M_1 M_2 | \mathcal{H}_{\text{eff}} | \bar{B} \rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle M_1 M_2 | Q_i(\mu) | \bar{B} \rangle.$$

MSSM

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- Introduce the transition operator $\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V^p_{CKM} \mathcal{T}^p$,

$$\begin{aligned} \mathcal{T} = & \, a_3^p \sum_q (\bar{d}b)_{V-A} \otimes (\bar{q}q)_{V-A} \\ & + a_4^p \sum_q (\bar{q}b)_{V-A} \otimes (\bar{d}q)_{V-A} \\ & + a_5^p \sum_q (\bar{d}b)_{V-A} \otimes (\bar{q}q)_{V+A} \\ & + a_6^p \sum_q (-2)(\bar{q}b)_{S-P} \otimes (\bar{d}q)_{S+P} ; \end{aligned}$$

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- $a_3^p = C_3 + \frac{C_4}{N_c}, \quad a_4^p = C_4 + \frac{C_3}{N_c}, \quad a_5^p = C_5 + \frac{C_6}{N_c}, \quad a_6^p = C_6 + \frac{C_5}{N_c}.$

MSSM

Hadronic B Decays: SM Amplitudes (LO)

- Rewrite the transition operator according to the flavour structure:

$$\mathcal{T}^p = \alpha_3^p(M_1, M_2) \sum_q A([\bar{q}_s d][\bar{q}q]) + \alpha_4^p(M_1, M_2) \sum_q A([\bar{q}_s q][\bar{q}d]),$$

with $\alpha_3^p = a_3^p + a_5^p, \quad \alpha_4^p = a_4^p + a_6^p.$

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- One obtains

$$\mathcal{A}_{B^- \to \pi^- \phi} = A_{\pi\phi}[\alpha_3^p] \to \text{color suppressed} \to \text{Br}^{SM} \sim (0.009) \times 10^{-6},$$

$$\mathcal{A}_{\bar{B}^0 \to \bar{K}^0 K^0} = A_{\bar{K}K}[\alpha_4^p] \to \text{color allowed} \to \text{Br}^{SM} = (1.58\,^{+1.25}_{-0.75}) \times 10^{-6}.$$

MSSM

Hadronic B Decays: New Contributions (LO)

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- rearranged as

$$\mathcal{T}_H^{d,p} = \alpha_{3,H}^{d,p}(M_1, M_2)A([\bar{q}_s D][\bar{d}d]) + \alpha_{4,H}^{d,p}(M_1, M_2)A([\bar{q}_s d][\bar{d}D]).$$

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- Features:
  - New Dirac structures, but no tensor operators;
  - No summation over d and no u contribution: isospin violation.

SM

Hadronic B Decays: New Contributions (LO)

- with

$$\alpha_{3,H}^{d,p}(M_1,M_2) = \frac{r_\chi^{M_2}}{2}\begin{cases} a_{15}^{d,p}(M_1,M_2), & \text{if } M_1,M_2 = PP,PV, \\ -a_{15}^{d,p}(M_1,M_2), & \text{if } M_1,M_2 = VP,VV, \end{cases}$$

$$\alpha_{4,H}^{d,p}(M_1,M_2) = \frac{1}{2}\begin{cases} -a_{16}^{d,p}(M_1,M_2), & \text{if } M_1,M_2 = PP,VP, \\ a_{16}^{d,p}(M_1,M_2), & \text{if } M_1,M_2 = PV,VV, \end{cases}$$

and

$$a_{15}^{d,p} = \begin{cases} C_{15}^d + \frac{C_{16}^d}{N_c} = C_{15}^d, & \text{if } M_2 = P, \\ 0, & \text{if } M_2 = V; \end{cases} \qquad a_{16}^{d,p} = C_{16}^d + \frac{C_{15}^d}{N_c} = \frac{C_{15}^d}{N_c}.$$

M_2	$a_{15}^{d,p}$	$a_{16}^{d,p}$	$a_{15}^{s,p}$	$a_{16}^{s,p}$
π^0	-0.00085	-0.00020	-0.021	-0.005
π^-	-0.00091	”	-0.022	”
$K^0(\bar{K}^0)$	-0.00091	”	-0.022	”
K^-	-0.00090	”	-0.022	”
η_q^1	-0.00043	”	-0.010	”
η_q^2	-0.00052	”	-0.013	”
η_s^1	-0.00096	”	-0.023	”
η_s^2	-0.00096	”	-0.023	”
V	0	”	0	”

Amplitudes

- $$\sqrt{2}\mathcal{A}_{B^-\to K^-\eta} = A_{\bar{K}\eta_q}[\delta_{pu}\underbrace{\alpha_2}_{\sim 0.17} + 2\underbrace{\alpha_3^p}_{\sim 0.007} + \delta_{pc}\frac{1}{2}\underbrace{\alpha_{3,EW}^c}_{\sim -0.009} + \underbrace{\alpha_{3,H}^{d,p}}_{\sim -0.001}]$$
$$+\sqrt{2}A_{\bar{K}\eta_s}[\underbrace{\alpha_3^p}_{\sim 0.007} + \underbrace{\alpha_4^p}_{\sim -0.07} - \delta_{pc}\frac{1}{2}\underbrace{\alpha_{3,EW}^c}_{\sim -0.009} + \underbrace{\alpha_{3,H}^{s,p}}_{\sim -0.026} + \underbrace{\alpha_{4,H}^{s,p}}_{\sim 0.005}]$$
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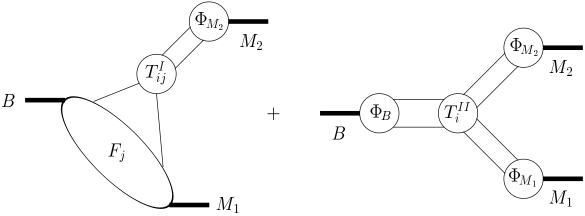
Hadronic B Decays: SM Amplitudes (NLO)

- Improved QCD factorization includes QCD effects up to a scale Λ_{QCD}.

M. Beneke, G. Buchalla, M. Neubert, C.T Sachrajda, Phys.Rev.Lett. 83:1914-1917, 1999 (hep-ph/9905312)
M. Beneke, G. Buchalla, M. Neubert, C.T Sachrajda, Nucl.Phys. B 591:313-418, 2000 (hep-ph/0006124)
M. Beneke, G. Buchalla, M. Neubert, C.T Sachrajda, Nucl.Phys. B 606:245-321, 2001 (hep-ph/0104110)
M. Beneke, M. Neubert, Nucl.Phys. B 675:333-415, 2003 (hep-ph/0308039)



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- At NLO we have

$$a_i(M_1, M_2) = \left(C_i + \frac{C_{i\pm1}}{N_c}\right) N_i(M_2) \\ + \frac{C_{i\pm1}}{N_c} \frac{C_F \alpha_s}{4\pi} \left(V_i(M_2) + \frac{4\pi^2}{N_c} H_i(M_1, M_2)\right) + P_i^p(M_2);$$

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$$+(C_4+C_6)\left[\frac{4n_f}{3}\log\frac{m_b}{\mu} - (n_f-2)G_{M_2}(0) - G_{M_2}(s_c) - G_{M_2}(1)\right] - 2C_{8g}^{eff}\int_0^1\frac{dx}{1-x}\Phi_{M_2}(x)$$
$$+C_{15}^s\left[\frac{2}{3}\log\frac{m_b}{\mu} - G_{M_2}(0)\right] + C_{15}^b\left[\frac{2}{3}\log\frac{m_b}{\mu} - G_{M_2}(1)\right]\Big\}.$$

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- The loop factor for the b quark turns out to be small.

CP asymmetries

- Additional informations come from direct CP asymmetries:

$$A_{CP}(\bar{f}) \equiv \frac{\mathrm{Br}(\bar{B} \to \bar{f}) - \mathrm{Br}(B \to f)}{\mathrm{Br}(\bar{B} \to \bar{f}) + \mathrm{Br}(B \to f)} = \frac{2\mathrm{Im}(d_f)\sin\gamma}{1 + 2\mathrm{Re}(d_f) + |d_f|^2},$$

where the last definition comes from

$$\mathcal{A}(\bar{B} \to \bar{f}) = V_{cb} V^*_{c(d,s)} a_f^c + V_{ub} V^*_{u(d,s)} a_f^u \propto 1 + e^{-i\gamma} d_f,$$

$$d_f = \epsilon_{KM,d} \frac{a_f^u}{a_f^c}, \quad \epsilon_{KM,d} = \left| \frac{V_{ub} V^*_{ud}}{V_{cb} V^*_{cd}} \right| \sim 0.37, \quad \epsilon_{KM,s} = \left| \frac{V_{ub} V^*_{ud}}{V_{cb} V^*_{cd}} \right| \sim 0.020.$$

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- $d_{f,B^- \to K^- \eta} \sim \epsilon_{KM,s} \frac{g(\alpha_1, \alpha_2, \alpha^u_3, \alpha^u_4, \alpha^{u,s}_{3,H}, \alpha^{u,s}_{4,H})}{g'(\alpha^c_3, \alpha^c_4, \alpha^c_{3,EW}, \alpha^{c,s}_{3,H}, \alpha^{c,s}_{4,H})}.$

Penguin Dominated Decays: Br and A_{CP} (B decays)

- $\bar{B} \to \bar{\pi}\eta$
- $\bar{B} \to \bar{\rho}\eta$
- $\bar{B} \to \bar{K}\eta$
- $\bar{B} \to \bar{K}^*\eta$
- $\bar{B} \to \bar{K}\phi$
- $\bar{B} \to \bar{K}K$
- $\bar{B} \to \bar{K}^*K$
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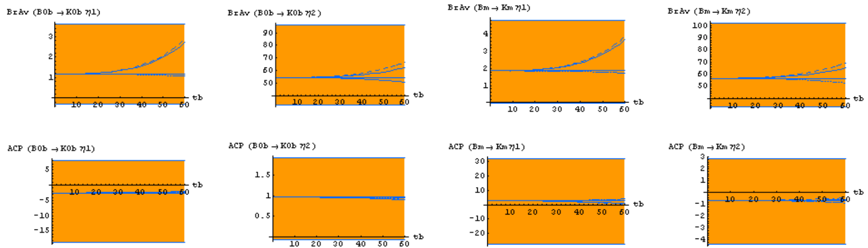

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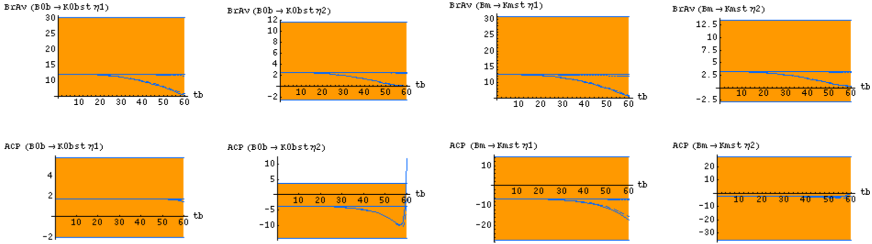

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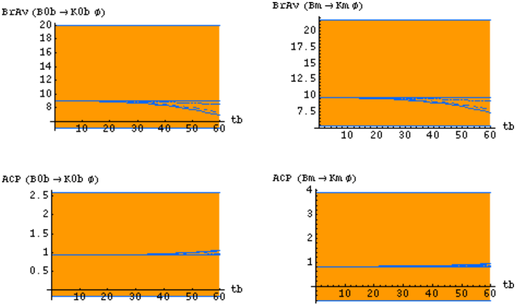

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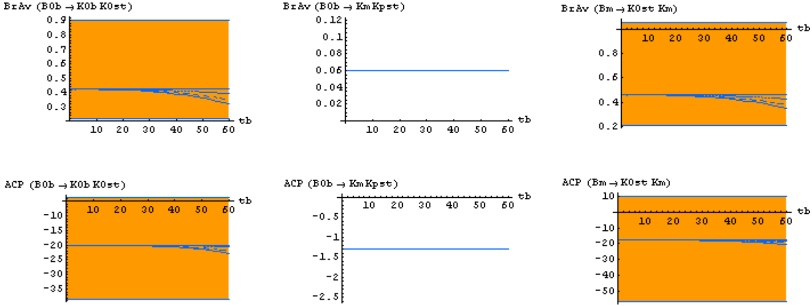

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Penguin Dominated Decays: Br and A_{CP} (B_s decays)

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- $\bar{B}_s \to K^*\eta$
- $\bar{B}_s \to \eta\eta$
- $\bar{B}_s \to \eta\phi$
- $\bar{B}_s \to \phi\phi$

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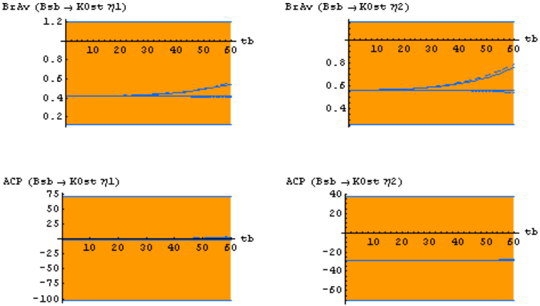

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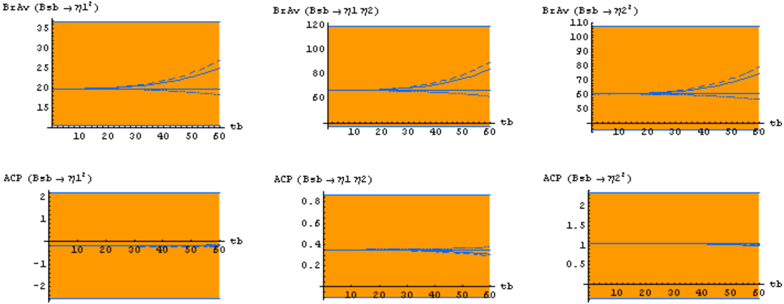

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Summary

- Results
  - A preliminar analysis of hadronic B decays in the MSSM with large $\tan\beta$ has been done.
  - The new contributions are relevant mainly in penguin dominated B decays.
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  - A preliminar analysis of hadronic B decays in the MSSM with large $\tan\beta$ has been done.
  - The new contributions are relevant mainly in penguin dominated B decays.
  - It will be difficult to observe their effect unless $\tan\beta \geq 50$.
- Outlook
  - Improve the estimation of the Wilson coefficients with a complete QCD RGE treatment.
  - Estimate the effects of the weak annihilation contribution.
  - Analysis of helicities amplitudes in $B \to VV$ and of isospin breaking decays.
  - Global fit of hadronic B decays observables.