(Non) Decoupling properties of Higgs boson decays

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From work in collaboration with:

H.Haber, H.Logan, S.P. and D.Temes, In preparation, 2009

H.Haber, H.Logan, S.P. and D.Temes, Nucl. Phys. B157 (2006), hep-ph/0601237

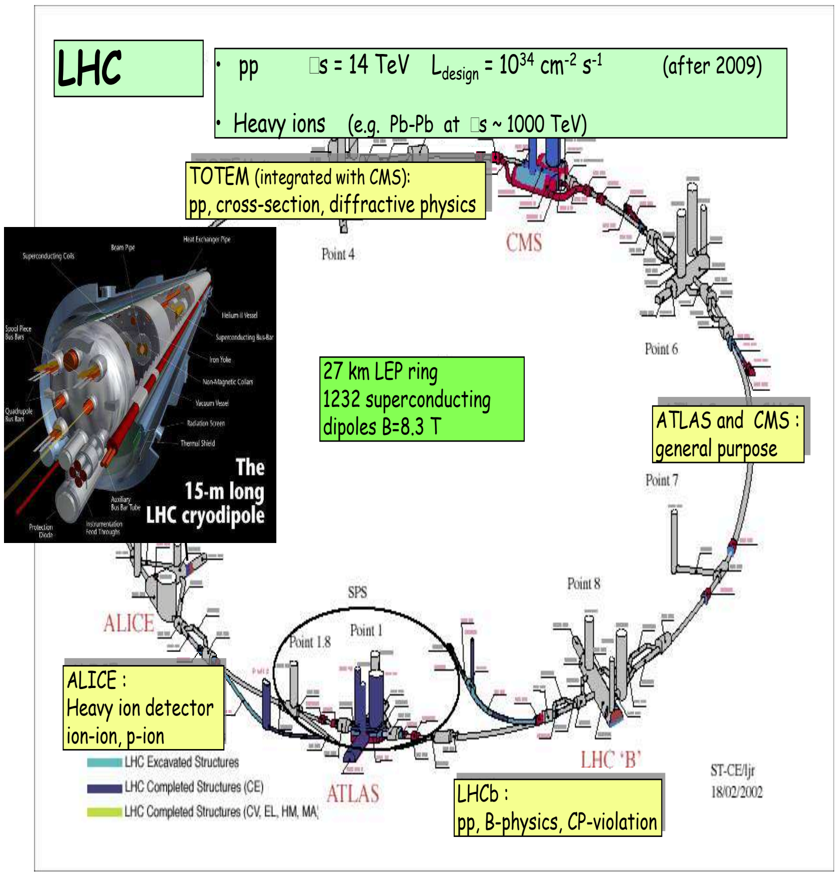
H.Haber, M.J.Herrero, H.Logan, S.P., S.Rigolin and D.Temes, Phys.Rev.D63:055004, 2001, hep-ph/0007006

Plan of the talk

- Introduction
  - Motivations
  - Meaning of Decoupling
  - Minimal Supersymmetric Standard Model
- Decoupling limit in the MSSM
- Neutral Higgs boson decays: $h^0 \to b\bar{b}$
  - SUSY-QCD corrections
  - SUSY-EW corrections
  - Decoupling behaviour
- Conclusions

Introduction

Motivations



LHC is going to be the most complex scientific undertaking ever

It will begin operations this year !!!

Foremost task of the LHC is to find the Higgs boson.

Once the Higgs is found,

- we shall want to study its couplings and quantum numbers

$\Rightarrow$ establish the Higgs mechanism

- a question will still be open: whether it is the SM Higgs particle or whether there is an extended Higgs structure beyond the SM

Motivations

- Use radiative corrections from non-standard particles in observables with external SM particles as indirect signals of new physics from MSSM

  (Same spirit of EW precision fits: indirect top signals before Tevatron direct searches)

- In particular, we concentrate in the neutral Higgs boson decay:

$$h^0 \longrightarrow b\bar{b}$$

  - Higgs boson physics : optimal to look for these indirect signals

  - are significantly affected by radiative corrections from heavy SUSY particles and/or heavy Higgses

  - the associated couplings, λ_{Hqq} , enter in relevant Higgs production processes

- Interested in the decoupling behaviour of heavy SUSY particles

  - SUSY non-decoupling: clear signal at low energy observables, even if $M_{SUSY} \sim \mathcal{O}(TeV)$

The meaning of decoupling

Decoupling Theorem (Appelquist and Carazzone '75)

Theorem

When integrating out the heavy modes from a given underlying theory, if the remaining theory is renormalizable, then
all the effects of the heavy particles appear in the effective theory either as renormalization of the parameters and wave function of the light fields or else they are suppresed by negative powers of the heavy particle mass M

If $M \to \infty$ the influence of the heavy particle disappears at low energies $\equiv$ Decoupling

Examples of (non) decoupling

- Effective action formalism (Illustrative example: QED at low energies)

Decoupling of e^- in low energy QED ($k^2 \ll m_e^2$)

$$e^{i\Gamma_{eff}[A_\mu]} = \int [d\psi][d\tilde{\psi}]\, e^{iS_{\text{QED}}[A_\mu,\psi,\tilde{\psi}]}$$

$$S_{\text{QED}}[A_\mu,\psi,\tilde{\psi}] = \int d^4x \left[-\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \tilde{\psi}(i\not{D} - m_e)\psi \right]$$

$$\Downarrow$$

$$\Gamma_{eff}[A_\mu] = \int \overbrace{d^4x \left[-\frac{1}{4} F_{\mu\nu}F^{\mu\nu} \right]}^{\text{Renorm.LowEn.Th.}} \underbrace{- \frac{e^2}{15(4\pi)^2 m_e^2} \int d^4x\, F_{\mu\nu}\Box F^{\mu\nu} + o\left(\frac{k^2}{m_e^2}\right)^2}_{\hookrightarrow\, 0 \text{ if } m_e \to \infty}$$

All large m_e effects can be absorbed in A_μ wave function renormalization.

$\Rightarrow$ Decoupling a la Appelquist-Carazzone

- Computing observables: two examples

Non-decoupling of Top quark in $Z \to \bar{b}b$: $\Gamma(Z \to \bar{b}b) = \Gamma_0 \left(1 + a\frac{\alpha}{4\pi}\frac{m_t^2}{m_W^2}\right)$

Decoupling of SUSY particles in $t \to W^+b$: $\Gamma(t \to W^+b) = \Gamma_0 \left(1 + b\frac{\alpha_S}{4\pi}\frac{m_t^2}{M_{SUSY}^2}\right)$

Supersymmetry

Supersymmetry $N = 1$ (SUSY) :

fermion	f	1/2	$\Leftrightarrow$	sfermion	$\tilde{f}$	0
gauge boson	G	1	$\Leftrightarrow$	gaugino	$\tilde{g}$	1/2
Higgs boson	H	0	$\Leftrightarrow$	higgsino	$\tilde{h}$	1/2

Minimal Supersymmetric Standard Model (MSSM)

Standard Model (Enlarged Higgs sector)				
	$m_{A^0}, \tan\beta$			
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, e^+_R \dots \begin{pmatrix} t \\ b \end{pmatrix}_L, t^c_R, b^c_R$	$\begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}, \begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix}$	B	$W^\pm, W^3$	g
$\nu_e, e^-, \dots, t, b$	$H^\pm, A^0, H^0, h^0$	$\gamma, Z, W^\pm$		g
SUSY particles				
$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e}^- \end{pmatrix}_L, \tilde{e}^+_R \dots \begin{pmatrix} \tilde{t} \\ \tilde{b} \end{pmatrix}_L, \tilde{t}^*_R, \tilde{b}^*_R$	$\begin{pmatrix} \tilde{H}_1^+ \\ \tilde{H}_1^0 \end{pmatrix}, \begin{pmatrix} \tilde{H}_2^0 \\ \tilde{H}_2^- \end{pmatrix}$	$\tilde{B}$	$\tilde{W}^\pm, \tilde{W}^3$	$\tilde{g}$
$\tilde{\nu}_e, \tilde{e}_1^-, \tilde{e}_2^- \dots \tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$	$\tilde{\chi}^-_{\{1,2\}}, \tilde{\chi}^o_{\{1,\dots,4\}}$			$\tilde{g}$
$M^2_{\tilde{L}}, M^2_{\tilde{E}}, M^2_{\tilde{Q}}, M^2_{\tilde{U}}, M^2_{\tilde{D}}$ $A_e,\ A_b,\ A_t$		M_1	M_2	M_3
μ, $\tan\beta$				

renormalizable quantum field theory, precision calculations possible (predictions $\longleftrightarrow$ experiments)

Decoupling limit in the MSSM

DECOUPLING LIMIT IN THE HIGGS SECTOR : $M_A \gg M_Z$

Haber, Nir, 1990

Two Higgs Doublets Model with 5 physical particles : $h^0, H^0, A^0, H^\pm$

2HDM type II : H_1 couple to b and H_2 to t

New free parameters appear : two are independent (M_A and $\tan\beta$)

$\longrightarrow$ Tree level: $M_{h^o} \simeq M_Z|cos2\beta|$

Higgs couplings in the MSSM normalized to SM couplings

ϕ		$g_{\phi\bar{t}t}$	$g_{\phi\bar{b}b}$	$g_{\phi VV}$
SM	H	1	1	1
MSSM	h^o	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$

$$\frac{\cos\alpha}{\sin\beta} \simeq 1+\mathcal{O}(M_Z^2/M_A^2)\,,\ -\frac{\sin\alpha}{\cos\beta} \simeq 1+\mathcal{O}(M_Z^2/M_A^2)\,,\ \sin(\beta-\alpha) \simeq 1+\mathcal{O}(M_Z^4/M_A^4)$$

$\longrightarrow$ Beyond tree level: $M_{H^o} \simeq M_{H^\pm} \simeq M_A \gg M_Z$

$M_{h^o} \leq 130\, GeV$

DECOUPLING LIMIT IN THE SUSY SECTOR :

STOPS AND SBOTTOMS :

We consider the limit: $M_{SUSY} \sim M_{\tilde{Q}} \sim M_{\tilde{D}} \sim M_{\tilde{U}} \sim \mu \sim A_b \sim A_t \gg M_Z$

$\Longleftrightarrow$ heavy squarks

CHARGINOS :

We consider the limit: $M_{SUSY} \sim \mu \sim M_2 \gg M_Z$ $\Longleftrightarrow$ heavy charginos

GLUINOS :

We consider the limit: $M_{SUSY} \sim M_3 = M_{\tilde{g}} \gg M_Z$ $\Longleftrightarrow$ heavy gluino

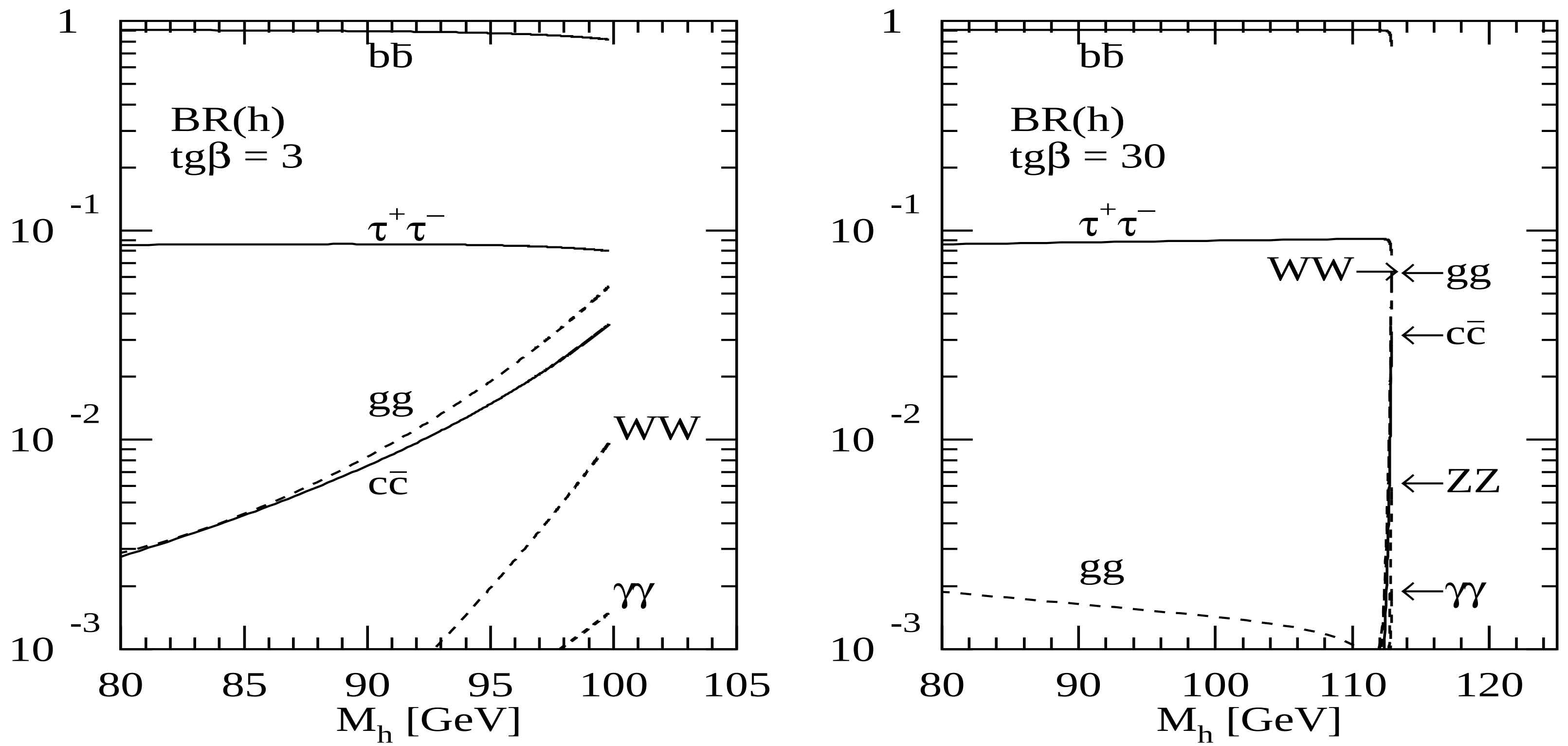
$\Longrightarrow$ Focus on:

- Loops of squarks and gluinos : These $\mathcal{O}(\alpha_S)$ are the dominant SUSY corrections
- Loops of squarks and charginos : $\mathcal{O}(Y_t)$ Yukawa corrections ($Y_t = \frac{g^2 m_t^2}{8\pi m_W^2 \sin^2\beta}$)
- Decoupling/Non-decoupling behaviour of SUSY particles

Neutral Higgs boson decays : $h^0 \longrightarrow b\bar{b}$

- Dominant decay in most of the MSSM parameter space

Branching Ratios of Higgs decays - MSSM



M.Spira, hep-ph/9705337, hep-ph/9810289

- Relevant for production

(production processes $gg \to b\bar{b}h^0$ and $q\bar{q} \to b\bar{b}h^0$ relevant at large tan β)

- LIGHT HIGGS BOSON PHENOMENOLOGY:

MSSM VERSUS SM

HIGGS PRODUCTION

Same dominant Higgs production mechanisms in SM and MSSM :

- $e^+e^- \to Z^* \to ZH_{SM}(h^o)$ at LEP
- $gg \to H_{SM}(h^o)$ at TeVatron and LHC.

  Main differences are for large $\tan\beta$

  For $\tan\beta \gg 1$:

  $gg/q\bar{q} \to b\bar{b} \to h^o b\bar{b}$ dominates over relevant hW and hZ channels due to extra factor in $g_{h^o b\bar{b}}$ coupling

$$g_{h^o b\bar{b}} \propto -\frac{\sin\alpha}{\cos\beta}$$

HIGGS DECAYS

$H_{SM}/h^o \to b\bar{b}$ dominant if $M_{H_{SM}} \leq 130$ GeV

Differences in SM and MSSM Branching Ratios if $\tan\beta$ is large due to enhacement in $g_{h^o b\bar{b}}$ couplings

Neutral Higgs boson decay $h^0 \to b\bar{b}$:

- Tree-level $h^0 \to b\bar{b}$ coupling: $g_{hbb} = \frac{g\, m_b \sin\alpha}{2\, m_W \cos\beta}$

  $\longrightarrow$ At tree level, the mixing angle α is determined by fixing $\tan\beta$ and m_A

- $\Gamma(h^o \to b\bar{b})$ decay rate to one loop:

$$\Gamma_1(h^o \to b\bar{b}) \equiv \Gamma_0(h^o \to b\bar{b})\,(1 + 2\,\Delta_{\text{Rad.Corr.}})$$

$$\Delta_{\text{Rad.Corr.}} = \Delta^{\text{Loops}} + \Delta^{\text{CT}}$$

- Counterterms:

$$\Delta^{\text{CT}} = \left(\frac{\delta m_b}{m_b} + \frac{\delta v}{v} + \delta Z_V^b\right) + \frac{\cos\alpha}{\sin\alpha}\,\underbrace{\frac{\hat{\Sigma}_{h^0 H^0}}{m_{h^0}^2 - m_{H^0}^2}}_{\hookrightarrow\ \tan\Delta\alpha}$$

- The radiatively corrected $h^0 b\bar{b}$ coupling depends on the CP-even Higgs mixing angle α

  $\longrightarrow$ SUSY-QCD corrections: There are no $\mathcal{O}(\alpha_s)$ corrections to α

  $\longrightarrow$ SUSY-Electroweak corrections: Radiative corrections to α must be included

Radiative corrections to $h^0 \to \bar{b}b$

- $\Gamma(h^0 \to b\bar{b})$ decay rate to one loop:

$$\Gamma_1(h^o \to b\bar{b}) \equiv \Gamma_0(h^o \to b\bar{b})(1 + 2\Delta_{QCD} + 2\Delta_{SQCD} + 2\Delta_{SEW})$$

- Both $\mathcal{O}(\alpha_s)$ contributions are large:

  Δ_{QCD}: gives $\sim$ 50% reduction in $\Gamma(h^o \to b\bar{b})$ for M_{h^0} in its MSSM range.

  QCD correction has the same form in MSSM as in SM .

  Braaten & Leveille 1980, Sakai 1980, Inami & Kubota 1981

  Δ_{SQCD} : SUSY-QCD correction is comparable to QCD correction for a wide window of the parameter space.

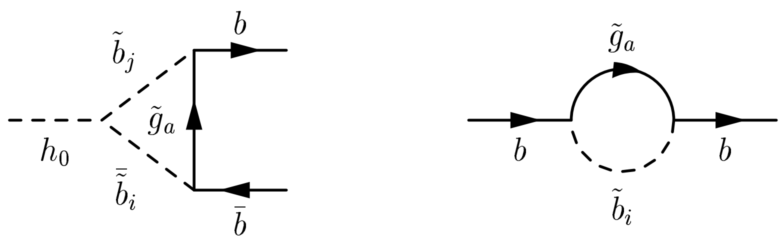
  Dabeltein 1995, Corasa, Jimenez & Sola 1995

- Δ_{SEW}: SUSY-Electroweak corrections are smaller, being $\mathcal{O}(m_t^2)$ contributions the dominant ones.

We explored decoupling behaviour both numerically and analytically

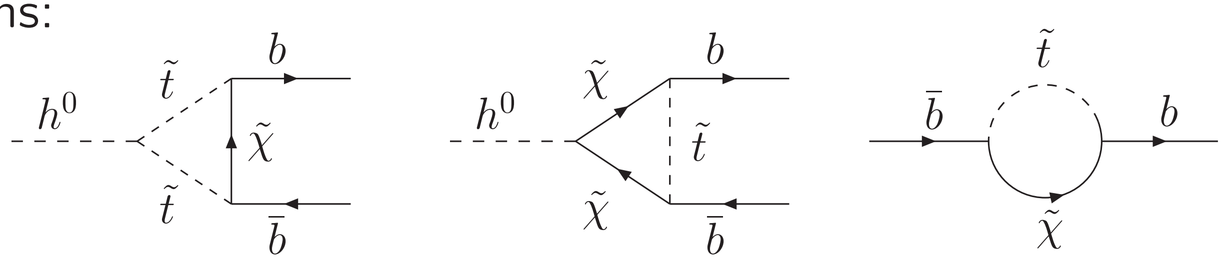
SUSY-QCD Corrections

One-loop diagrams:



SUSY-Electroweak Corrections

One-loop diagrams:



- On-shell renormalization scheme assumed
- We perform expansions of integrals and mixing angles for $M_{SUSY} \gg m_{EW}$ and get terms $\mathcal{O}(\frac{m_{EW}^2}{M_{SUSY}^2})^n$, $n = 0, 1$

Analytical results

- Leading terms, $n = 0$:

SUSY-QCD Corrections ($\theta_{\tilde{b}} \sim 45^\circ$):

$$\Delta_{SQCD} = \frac{\alpha_s}{3\pi}\left\{\frac{-\mu M_{\tilde{g}}}{\tilde{M}_S^2}(\tan\beta + \cot\alpha)\, f_1(R) + \mathcal{O}\left(\frac{m_{EW}^2}{M_{SUSY}^2}\right)\right\}$$

$$\tilde{M}_S^2 \equiv \frac{1}{2}(M_{\tilde{b}_1}^2 + M_{\tilde{b}_2}^2)\,,\ \ R \equiv M_{\tilde{g}}/\tilde{M}_S\,,\ \ f_1(1) = 1$$

SUSY-EW Corrections ($\theta_{\tilde{t}} \sim 45^\circ$):

$$\Delta_{SEW} = \frac{g^2}{64\pi^2 m_W^2}\frac{1}{\sin^2\beta} m_t^2 \left\{\frac{-\mu\, A_t}{\tilde{M}_S^2}(\tan\beta + \cot\alpha)\, f_1(R) + \mathcal{O}\left(\frac{m_{EW}^2}{M_{SUSY}^2}\right)\right\}$$

$$\tilde{M}_S^2 \equiv \frac{1}{2}(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2)\,,\ \ R \equiv M_{\tilde{\chi}_2^\pm}/\tilde{M}_S\,,\ \ f_1(1) = 1\,,\ \ \mu = M_{\tilde{\chi}_2^\pm}$$

$\Rightarrow$ Non-decoupling with M_{SUSY}

$\Rightarrow$ Enhanced at large $\tan\beta$

How can we interpret these results?

$\Rightarrow$ In terms of effective Higgs-quark-quark interactions

Tree-level Potential:

$$V = \epsilon_{ij} \left[h_b \, H_1^i \, Q^j \, b_R + h_t \, H_2^j \, Q^i \, t_R \right] + h.c. \quad , \quad Q = \begin{pmatrix} t_L \\ b_L \end{pmatrix}.$$

By taking M_{SUSY} large, the low-energy effective theory is a generic 2HDM type II.

The radiative corrections generate new terms:

Effective Lagrangian approach:

Carena *et al.* hep-ph/9402253, hep-ph/9808312, hep-ph/9907422; Pierce *et al.* hep-ph/9606211

$$V^{1-loop} = V + \epsilon_{ij} \left[h_b \, \Delta_b \, H_2^j \, Q^i \, b_R + h_t \, \Delta_t \, H_1^i \, Q^j \, t_R \right] + h.c.$$

$\longrightarrow$ New $Hq\bar{q}$ couplings emerge of 2HDMIII type

1-loop $h^0 b\bar{b}$ Effective couplings:

$$C_{hbb} = \frac{m_b}{v} \frac{\sin\alpha}{\cos\beta} \frac{1}{1 + \Delta_b \tan\beta} \left(1 - \frac{\Delta_b}{\tan\alpha} \right)$$

- SUSY indirect effects at low energies

Recovering decoupling if all MSSM spectra heavy

If, in addition to heavy sbottoms and gluino, and heavy stops and charginos, we have also heavy extra Higgses, $M_A \gg M_Z$, then:

$$\cot\alpha = -\tan\beta - 2\frac{M_Z^2}{M_A^2}\tan\beta\cos 2\beta + \mathcal{O}\left(\frac{M_Z^4}{M_A^4}\right)$$

$$\Longrightarrow \; \Delta_{SQCD} = \frac{\alpha_s}{3\pi}\left\{\frac{-2\mu M_{\tilde{g}}}{\tilde{M}_S^2} f_1(R)\tan\beta\cos 2\beta\,\frac{m_Z^2}{m_A^2} + \mathcal{O}\left(\frac{m_{EW}^2}{M_{SUSY}^2}\right)\right\}$$

$$\Longrightarrow \; \Delta_{SEW} = \frac{g^2}{32\pi^2 m_W^2 s_\beta^2} m_t^2 \left\{\frac{-\mu\, A_t}{\tilde{M}_S^2} f_1(R)\tan\beta\cos 2\beta\,\frac{m_Z^2}{m_A^2} + \mathcal{O}\left(\frac{m_{EW}^2}{M_{SUSY}^2}\right)\right\}$$

Decoupling if and only if M_{SUSY} and $M_A \to \infty$

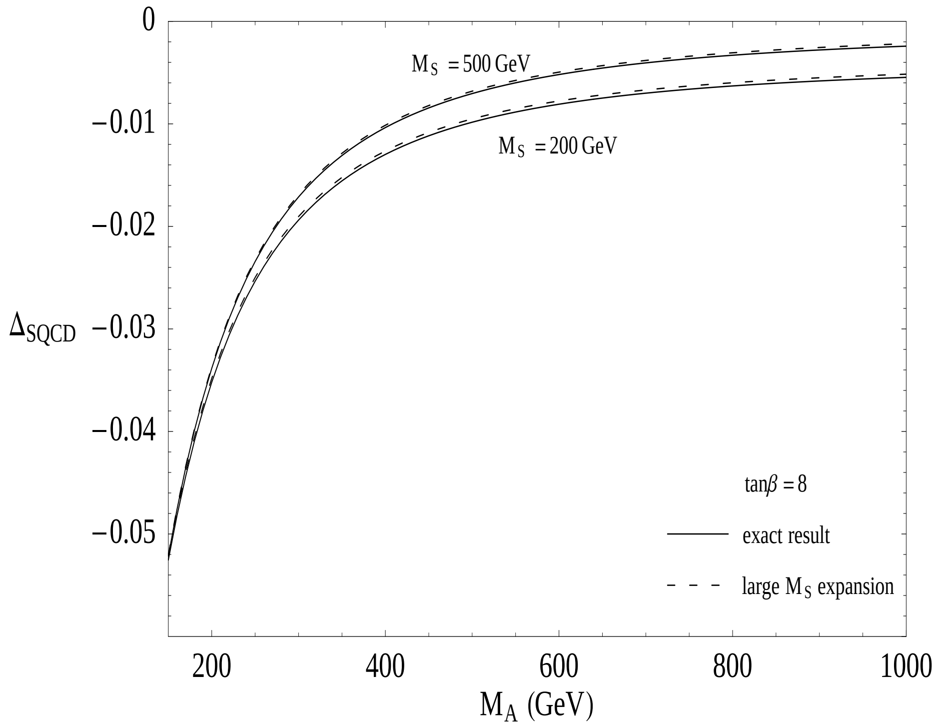
Comments:

- corrections grows linearly with $\tan\beta$
- Δ_{SQCD} (Δ_{SEW}) is proportional to $\mu\, M_{\tilde{g}}$ ($\mu\, A_t$)
  the sign of corrections is governed by sign of μ and $M_{\tilde{g}}$, A_t
- Similar results for $\theta_{\tilde{b}} \sim 0^\circ$

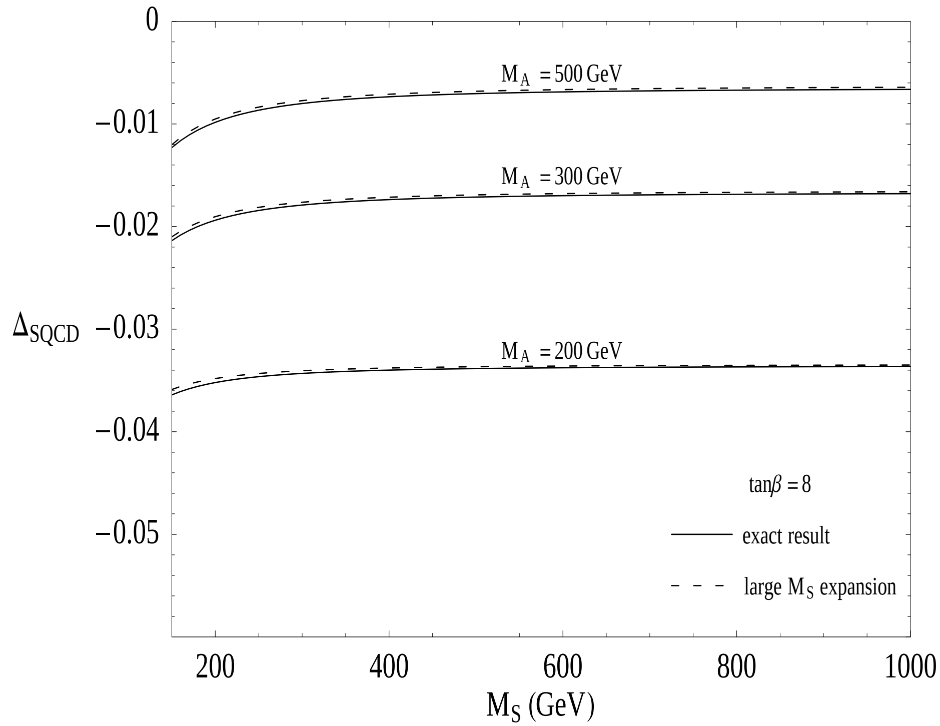
Numerical results

An example with two different scales $M_A \neq M_S$

For fixed M_S and large M_A



For fixed M_A and large M_S



No independent decoupling with M_A

No independent decoupling with M_S

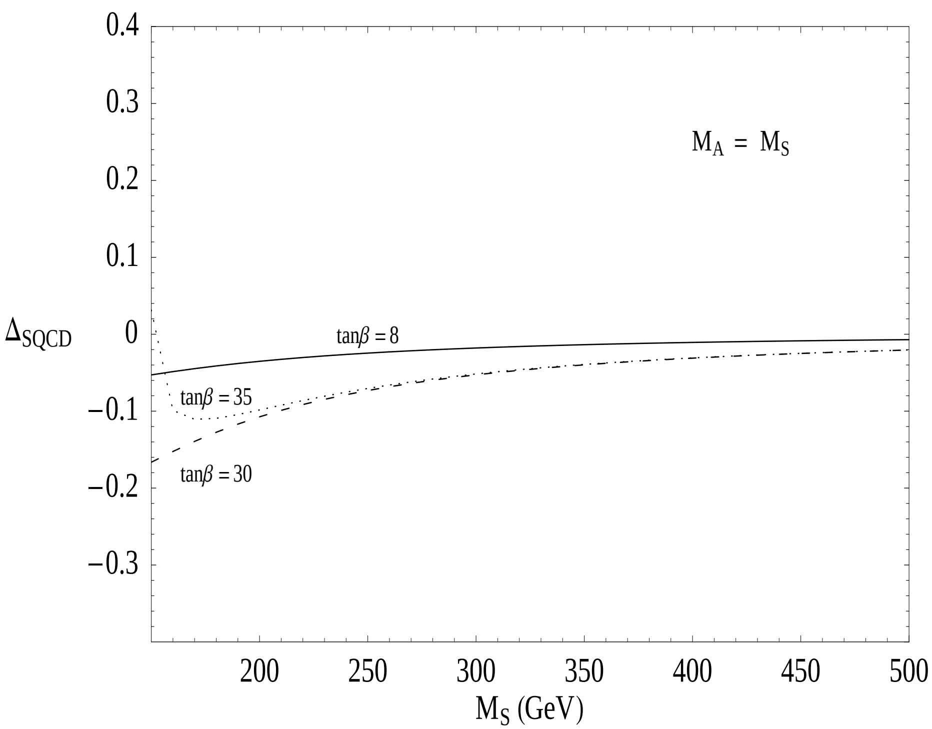
- Δ_{SQCD} tends to a non vanishing constant: SUSY non-decoupling
- Δ_{SEW} have a similar behaviour, but corrections are smaller

Numerical results

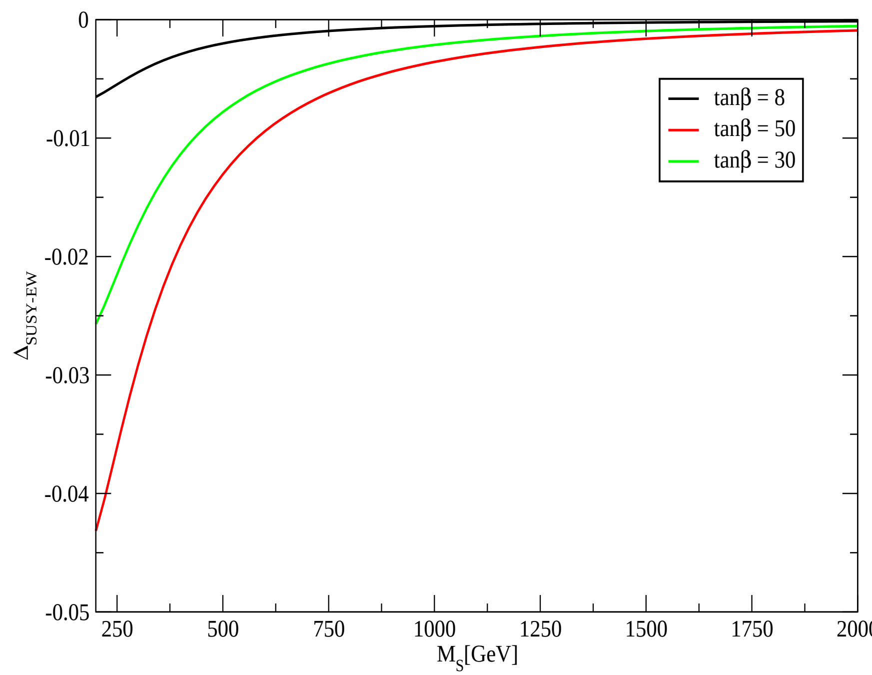
Take just one scale M_S :

$A_b = \mu = M_{\tilde{Q}} = M_{\tilde{D}} = M_{\tilde{g}} = M_S$ and $M_A = M_S$, with $M_S \gg M_Z$

SUSY-QCD



SUSY-EW

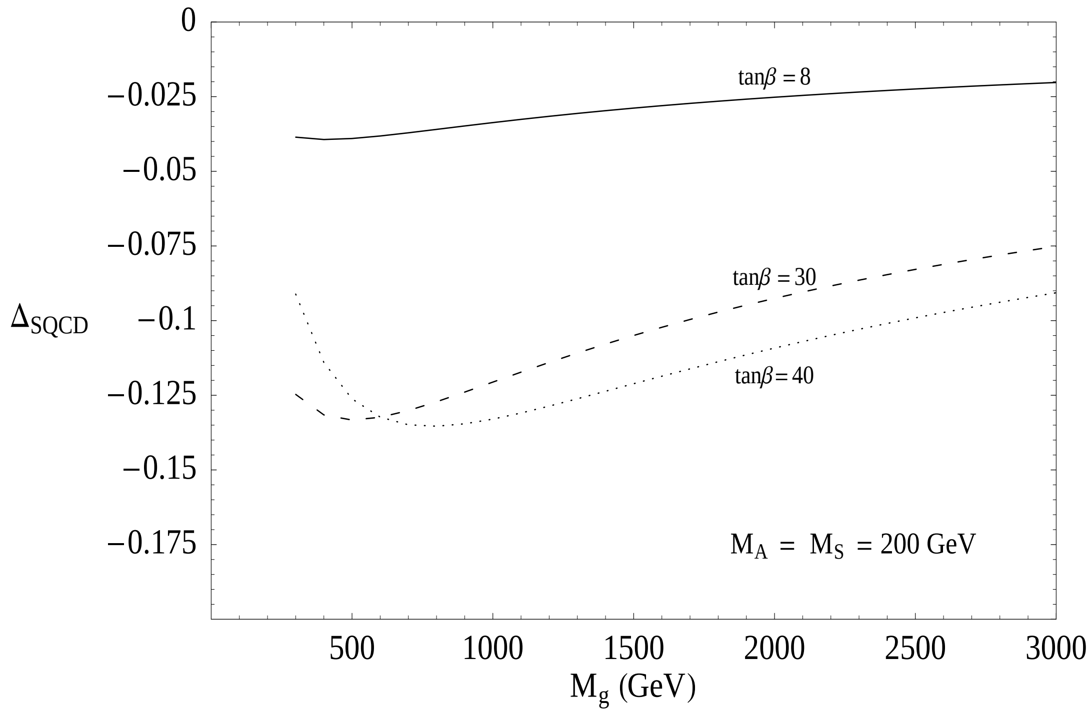


- Decoupling with M_S : recovering SM result
- Typical size for $M_S \geq 250\,GeV$: $\Delta_{SQCD} \leq -10\%$
- For $M_S \sim 250\,TeV$ and $\tan\beta = 30$: $\Delta_{SEW} \simeq -2\%$

Independent decoupling of SUSY particles

- Independent decoupling of gluino

We expand the correction in the heavy gluino limit: $M_{\tilde{g}} \gg \tilde{M}_S \sim \mu \sim A_b \gg M_Z$



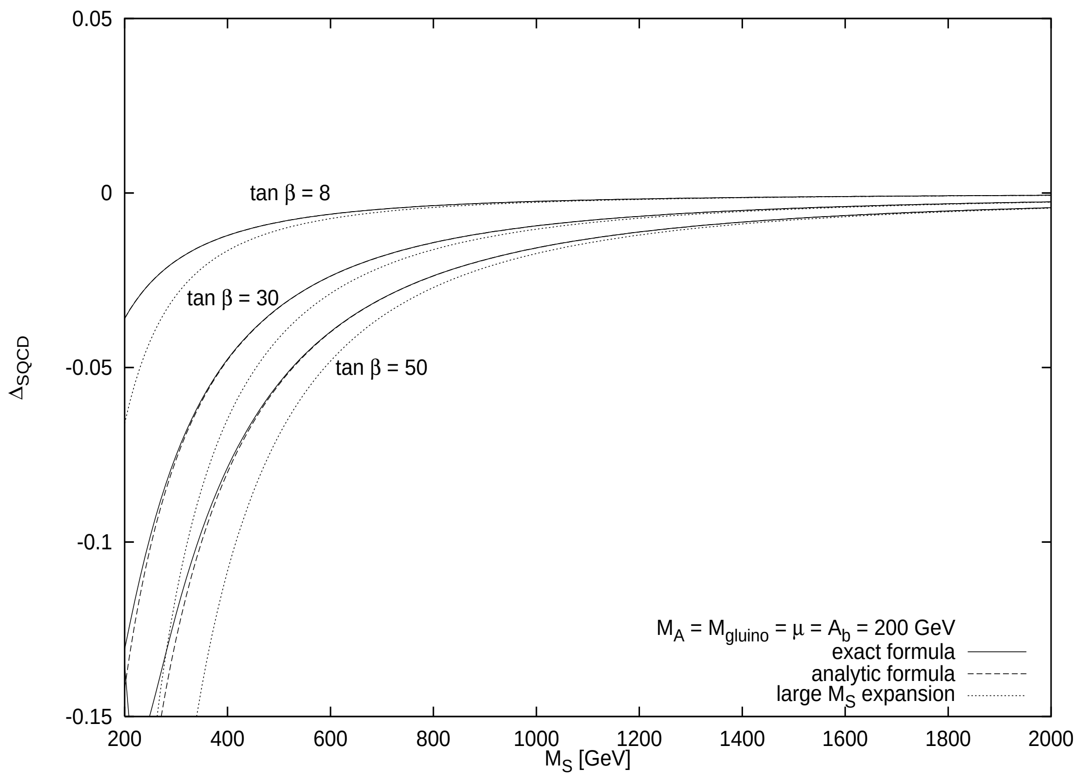
- Very slow decoupling with $M_{\tilde{g}}$

- Sizeable correction even for large $M_{\tilde{g}}$:

For $\tan\beta = 30$ and $M_{\tilde{g}} = 1TeV$, $\Delta_{SQCD} = -12\%$

- Independent decoupling of sbottoms

We expand the correction in the heavy sbottoms limit: $\tilde{M}_S \gg M_{\tilde{g}} \sim \mu \sim A_b \gg M_Z$

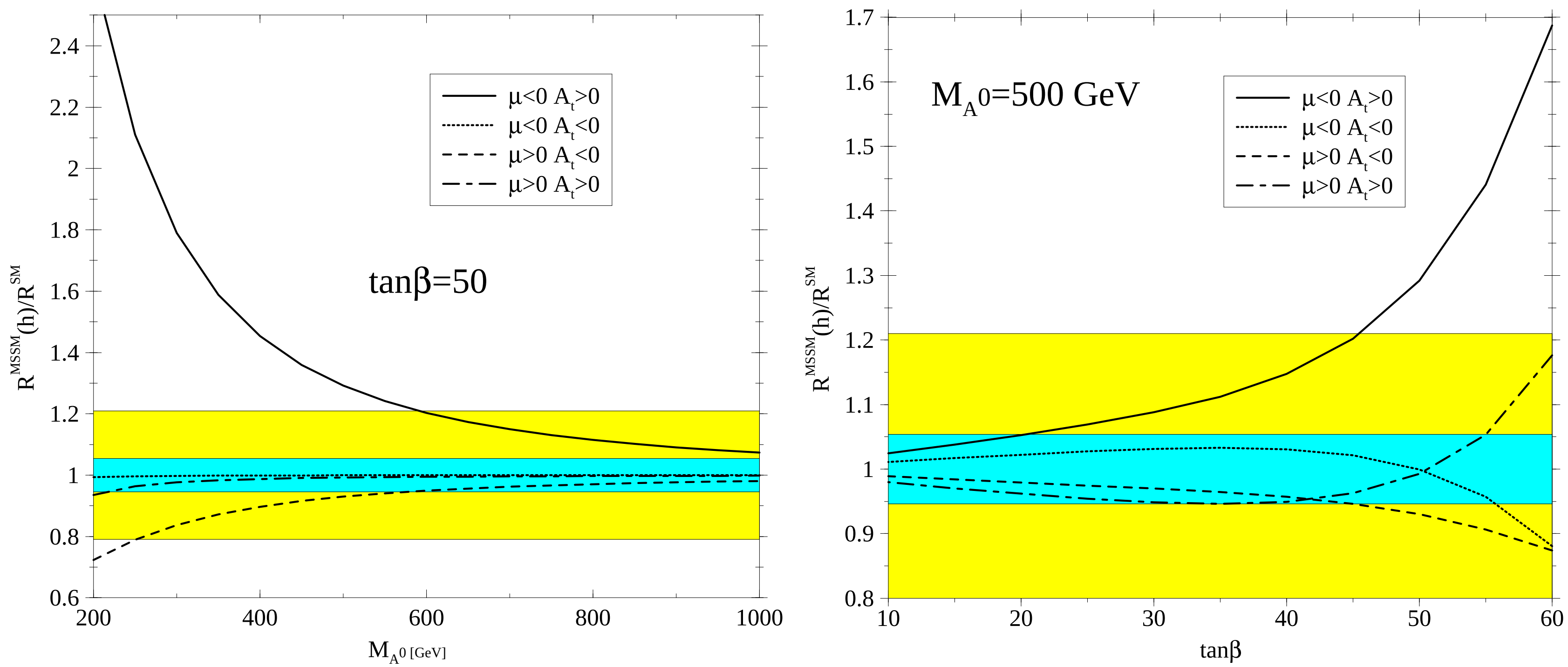


- Fast decoupling with $\tilde{M}_S$

- Similar results for stops (by considering stops-chargino loops)

$h^0 \to b\bar{b}/h^0 \to \tau^+\tau^-$: Deviation of MSSM with respect to the SM value

J.Guasch, W. Hollik, S. P., PLB515 (2001) 367, hep-ph/0106027



LHC: ±21%   ILC: ±5.4%

- The decoupling behaviour with M_{A^0} becomes apparent.
- MSSM deviates significantly from the reference value SM:
  i.e. small m_A, large $\tan\beta$, $\mu < 0$ and $A_t > 0$, the ratio can be as large as two.

CONCLUSIONS

The one-loop corrections to $\Gamma(h^o \to \bar{b}b)$:

- We consider $\mathcal{O}(\alpha_S)$ and $\mathcal{O}(m_t^2)$ SUSY corrections to $\Gamma(h^o \to \bar{b}b)$ in the decoupling limit

- The corrections grow with $\tan\beta$ $\Rightarrow$ Sizeable for large $\tan\beta$

- Corrections can be negative $\Longrightarrow$ Reduction in the partial decay width $\Gamma(h^0 \to \bar{b}b)$

- Decouple if and only if all SUSY masses and M_A are very large

- Do not decouple if internal gluino/squarks and chargino/squarks are very heavy and fixed M_A!!

  $\Rightarrow$ Indirect SUSY breaking signals at low energy Higgs physics?

Within the next years the LHC will bring a decisive test of the ideas about SUSY and the Higgs