SUSY Higgs boson flavor-changing neutral currents at the LHC

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S. Béjar, J.G., J. Solà, hep-ph/0508043

S. Béjar, F. Dilmé, J.G., J. Solà, JHEP 0408 (2004) 018, hep-ph/0402188

Outline

- Introduction
  - Flavour Changing Neutral Currents
  - Minimal Supersymmetric Standard Model
- Computation
  - Leading contributions
- Constrains and fine-tuning
- Numerical results $BR(h \to bs)$
- Combined analysis $\sigma(pp \to h \to qq')$
  - $\sigma(pp \to h \to bs)$
  - $\sigma(pp \to h \to tc)$
- Conclusions

Introduction

Flavour Changing Neutral Courrents (FCNC)

- FCNC are processes in which one up-type (or down-type) quark is converted into another one of the same type.
  - $K^0 - \bar{K}^0$ $(d \leftrightarrow s)$, $b \to s\gamma$
- In the Standard Model (SM)
  - absent at the tree-level (One-loop $W^{\pm}$ and CKM)
  - GIM-mechanism

    $\Rightarrow$ FCNC processes have very small rates
- Experimentally they have small rates
  - $BR(b \to s\gamma) = (3.3 \pm 0.4) \times 10^{-4}$

    CLEO+ALEPH+BELLE+BABAR $\to$ Particle Data Group
- SM values:

$$BR(H^{SM} \to b\bar{s}) \lesssim 10^{-7} \quad (m_H < 2M_W), \quad \lesssim 10^{-10} \quad (m_H > m_t)$$

$$BR(H^{SM} \to t\bar{c}) \lesssim 10^{-13}$$

S. Béjar, J.G., J. Solà, **Nucl. Phys. B**675 (2003) 270, hep-ph/0307144

S. Béjar, F. Dilmé, J.G., J. Solà, JHEP 0408 (2004) 018, hep-ph/0402188

New Physics $\Longrightarrow$ New FCNC Sources

– Strong constrains from low energy data

– Possible enhancement of t- and b-quark FCNC

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$\Rightarrow$ Look at the Higgs sector!

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Is there a way to obtain large FCNC in the top sector, while being small in the first and second generation fermion families?

$\Rightarrow$ Look at the Higgs sector!

Computation of

$$\begin{aligned} \sigma(pp \to h \to q q') &\equiv \sigma(pp \to hX) B(h \to \bar{q} q') \\ &\equiv \sigma(pp \to hX) \frac{\Gamma(h \to q \bar{q}' + \bar{q} q')}{\sum_i \Gamma(h \to X_i)} \quad (qq' \equiv bs \text{ or } tc)\,. \end{aligned}$$

in the general Minimal Supersymmetric Standard Model, with Flavour Violating couplings

Minimal Supersymmetric Standard Model (MSSM)

- Minimal Supersymmetric extension of the SM
- A SUSY partner for each SM particle
- Existence of a light Higgs boson, $M_{h^0} \lesssim 130\,\mathrm{GeV}$.

M. Carena *et al.*, *Nucl. Phys.* **B580** (2000) 29 [hep-ph/0001002]; J.R. Espinosa, R. Zhang, *JHEP* **0003** (2000) 026, [hep-ph/9912236]...

$\tan\beta = \frac{v_2}{v_1}$				
m_f	M_{A^0}			
$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix} \cdots \begin{pmatrix}t' \\ b\end{pmatrix}$	$H_1\ H_2$	B	W	g
$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix} \cdots \begin{pmatrix}t \\ b\end{pmatrix}$	$H^\pm, A^0, H^0, h^0$	$\gamma, W^\pm, Z$		g
$\begin{pmatrix}\tilde{\nu}_e \\ \tilde{e}^-\end{pmatrix}_L \tilde{e}_R^+ \cdots \begin{pmatrix}\tilde{t} \\ \tilde{b}\end{pmatrix}_L \tilde{b}_R \tilde{t}_R$	$\tilde{h}_1, \tilde{h}_2$	$\tilde{b}$	$\tilde{w}$	$\tilde{g}$
$\tilde{\nu}_e, \tilde{e}_1^-, \tilde{e}_2^- \cdots \tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2, \tilde{t}_R$	$\chi_{1,2}^\pm, \chi_{1\ldots4}^0$			$\tilde{g}$
$M_{\tilde{q}_L}, M_{\tilde{q}_R}, A_q$ (m_1, m_2, θ_q)		M'	M	$m_{\tilde{g}}$
μ				
$\tan\beta$				

- Constrained Type II 2HDM: $h^0, H^0, A^0, H^\pm$
  - Only two free parameters: $\tan\beta$, M_{A^0}
  - α: CP-even Higgs bosons mixing angle

    $\Rightarrow$ α and m_h receive large radiative corrections

- Squark mixing

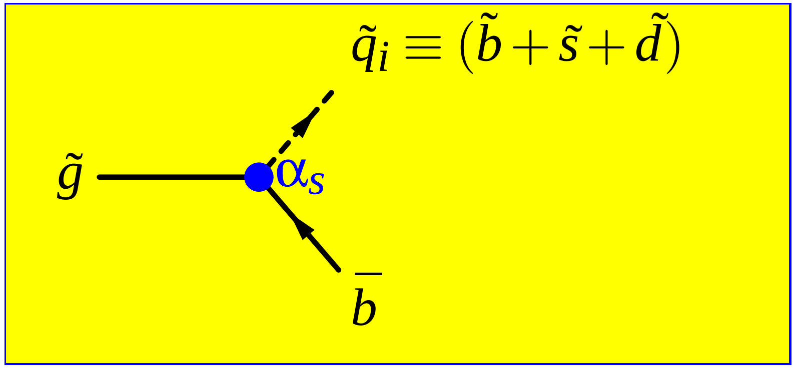
$$\mathcal{M}_{\tilde{q}} = \begin{pmatrix} M^2_{\tilde{q}_L} + m_q^2 + \cos 2\beta (T_3^{q_L} - Q_q s_W^2) M_Z^2 & m_q M_{LR}^q \\ m_q M_{LR}^q & M^2_{\tilde{q}_R} + m_q^2 + \cos 2\beta\, Q_q s_W^2 M_Z^2 \end{pmatrix},$$

$$M_{LR}^u = A_u - \mu \cot\beta\ , \ M_{LR}^d = A_d - \mu \tan\beta\ .$$

$M_{\tilde{u}_L} = M_{\tilde{d}_L}$ by $SU(2)_L$ invariance

- In general, $M^2_{\tilde{q}_L}$, $M^2_{\tilde{q}_R}$, A_q are 3×3 matrices in flavour space ($M^2_{\tilde{u}_L} \sim M^2_{\tilde{d}_L}$)

$\Rightarrow$ induces tree-level FCNC strong interactions!



- Tree-Level FCNC: e.g. $t - \tilde{c} - \tilde{g}$

  $\Rightarrow$ Solution: Degeneracy, Alignment

Good?

- Assuming Alignment at $\mu \sim \Lambda \Rightarrow$ RGE generates unalignment at $\mu \sim 100\,\mathrm{GeV}$ in the LL sector

  M.J. Duncan, **Nucl. Phys. B** 221, 285 (1993)

- Assuming Alignment: $\Gamma(\tilde{t} \to c\chi^0)$ is divergent (!)

  K.Hikasa, M.Kobayashi **Phys. Rev. D** 36, 724 (1987);

  G.Jahn, ITP-Karlsruhe Diplomarbeit (1998)

- One-loop FCNC: $H^{\pm}$, $\chi^{\pm}$

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- One-loop FCNC: $H^\pm$, $\chi^\pm$

- giving up Alignment
  - $\delta_{ij} = m^2_{ij}/(\tilde{m}_i \tilde{m}_j)$ $i \neq j$
  - δ_{ij} constrained (mass insertion approximation)

    $$\begin{aligned} \delta_{12} &\lesssim .1\sqrt{m_{\tilde{u}} m_{\tilde{c}}}/500\,\mathrm{GeV} \\ \delta_{13} &\lesssim .098\sqrt{m_{\tilde{u}} m_{\tilde{t}}}/500\,\mathrm{GeV} \\ \delta_{23} &\lesssim 8.2\, m_{\tilde{c}} m_{\tilde{t}}/(500\,\mathrm{GeV})^2 \end{aligned}$$

    F. Gabbiani *et. al.* **Nucl. Phys B** 477, 321 (1996)
  - $B(b \to s\gamma)$: additional constrains

Some works

- $t \longrightarrow cX$ MSSM
  - J. G., QEMMSM Barcelona, Spain, hep-ph/9710267.
  - J. G., J. Solà, Nucl. Phys. B **562** (1999) 3 [hep-ph/9906268].
  - J. G., J. Solà, IWLC, Sitges, Spain, hep-ph/9909503.
  - S. Béjar, J. G., J. Solà, RADCOR00, Carmel, USA, hep-ph/0101294.
- $H \longrightarrow bs$, $H \longrightarrow tc$ MSSM
  - A. M. Curiel, M. J. Herrero, W. Hollik, F. Merz and S. Peñaranda, Phys. Rev. D **69** (2004) 075009 [hep-ph/0312135].
  - A. M. Curiel, M. J. Herrero and D. Temes, Phys. Rev. D **67** (2003) 075008 [hep-ph/0210335].
- $H \longrightarrow bs + b \longrightarrow s\gamma$
  - S. Béjar, F. Dilmé, J. G., J. Solà, JHEP **0408** (2004) 018 [hep-ph/0402188].
  - T. Hahn, W. Hollik, J.I. Illana, S. Peñaranda, talk at SUSY05, Durham, UK.
- $pp \longrightarrow H + H \longrightarrow bs + H \longrightarrow tc + b \longrightarrow s\gamma$
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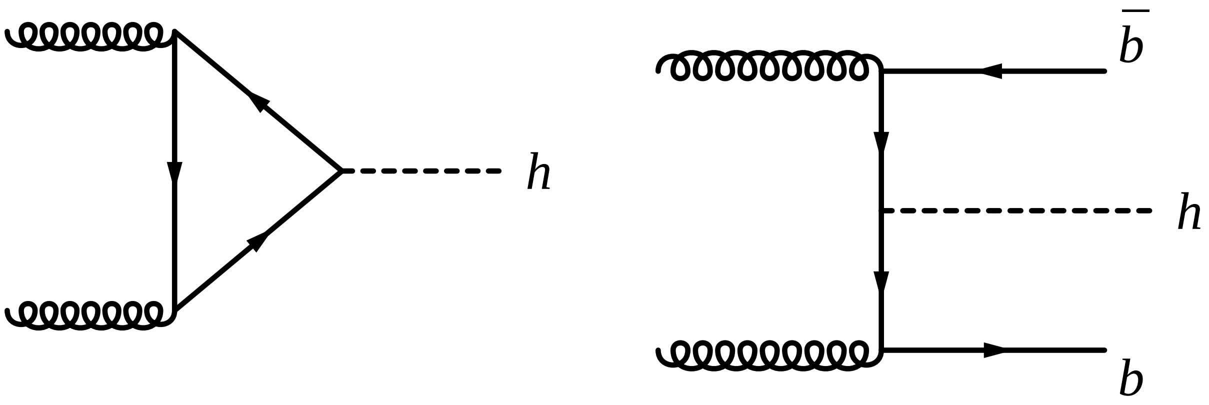
  - S. Béjar, J.G., J. Solà, hep-ph/0508043
- See also J. Solà talk for alternative signatures of MSSM FCNC

Computation

$$\sigma(pp\to h\to q\bar{q}') \equiv \sigma(pp\to hX)\frac{\Gamma(h\to q\bar{q}'+\bar{q}q')}{\sum_i \Gamma(h\to X_i)} \quad (qq'\equiv bs \text{ or } tc)\,.$$

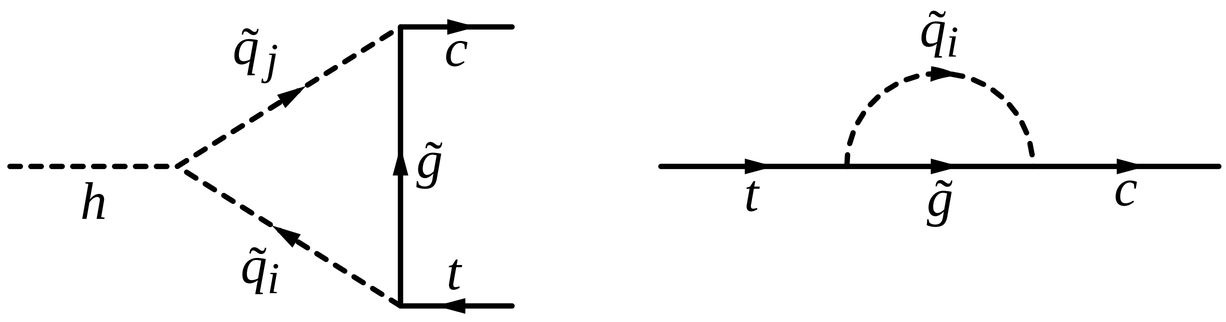
- $\sigma(pp\to hX)$: HIGLU and HQQ packages

M. Spira, hep-ph/9510347; `http://people.web.psi.ch/~spira/higlu/`, and `http://people.web.psi.ch/~spira/hqq/`.



- $\Gamma(h\to X)$
  - Self-computed Leading Order 2- and 3-body decays
    * LO: Same QCD order in numerator and denominator
    * 3-body decays: necessary when $\Gamma(h\to b\bar{b})\to 0$ (small α_{eff} scenario)

- $\Gamma(h->q\bar{q'})$: SUSY-QCD contributions
  - Don't assume alignment
  - Exact diagonalization of 6×6 squark mass matrix
  - Assume mixing only in the LL sector

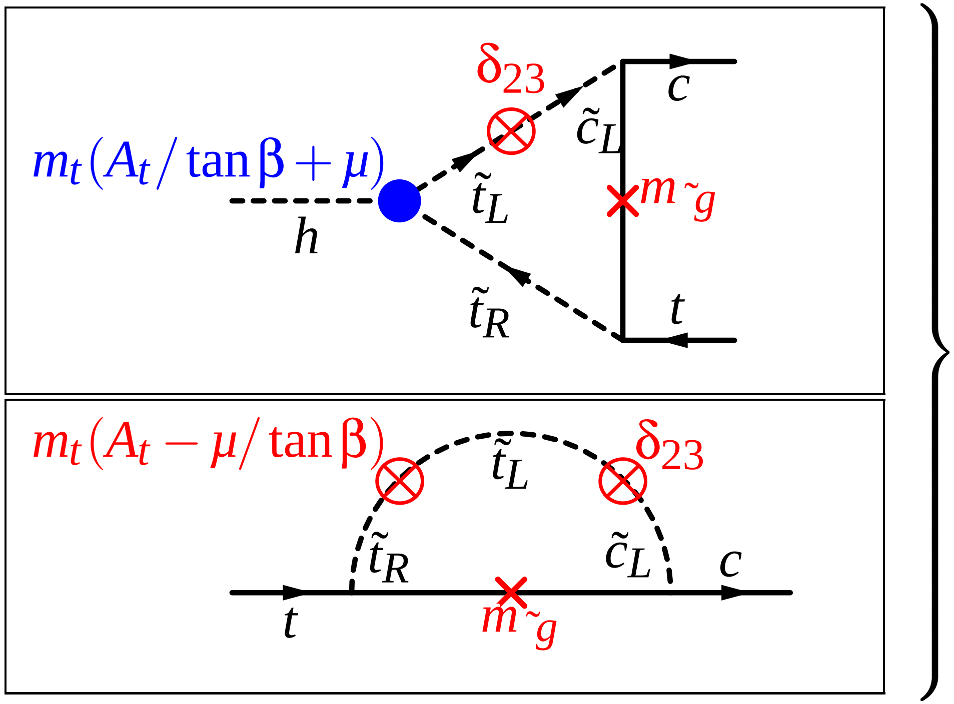


- One-loop predicition for M_{h^0}, M_{H^0}, α

A. Dabelstein, *Z. Phys.* **C67** (1995) 495, `hep-ph/9409375`.

Leading contributions

- Diagrams with a chirality flip are enhanced by $m_{\tilde{g}}$: mass-insertion approximation



- The terms proportional to A_t cancel in the sum.

See also J.G., P.Häfliger, M.Spira Phys. Rev. **D68** 115001, 2003, hep-ph/0305101

- Equivalent structure for bs-channel

- We can write and effective Lagrangian:

$$G_{Hqq'} \sim \delta_{23}\,\frac{m_{\tilde{g}}\mu}{M^2_{SUSY}} \left\{ \begin{array}{cc} \cos(\beta-\alpha_{\rm eff}) & (h^0) \\ \sin(\beta-\alpha_{\rm eff}) & (H^0) \\ 1 & (A^0) \end{array} \right. \xRightarrow[\alpha_{\rm eff}\to\beta-\pi/2]{M_{A^0}\gg M_Z} \left. \begin{array}{cc} 0 & (h^0) \\ 1 & (H^0) \\ 1 & (A^0) \end{array} \right\}$$

D. A. Demir, Phys. Lett. **B571**, 193–208 (2003), `hep-ph/0303249`.

Constrains & fi ne-tuning

- The Flavour-Changing terms are communicated from the up- to the down-sector by CKM

  e.g. M.Misiak, S.Pokorski, J. Rosiek, Adv.Ser.Direct.High Energy Phys.15:795-828,1998, hep-ph/9703442

$$(M^d_{LL})^2 \quad = CKM^\dagger \times \quad (M^u_{LL})^2 \quad \times CKM$$

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$$\begin{array}{cccc} (M^d_{LL})^2 & = CKM^\dagger \times & (M^u_{LL})^2 & \times CKM \\ \not\parallel & & \not\parallel & \\ (M^d_{LL})^2_{\mathrm{DIAG}} & & \mathbb{1}\tilde{M}^2 & \end{array}$$

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$\Rightarrow$ top-charm FCNC are constrained by $B(b \rightarrow s\gamma)$

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  $\Rightarrow$ top-charm FCNC are constrained by $B(b \to s\gamma)$

- $BR^{exp}(b \to s\gamma) = (3.3 \pm 0.4) \times 10^{-4}$

  CLEO+ALEPH+BELLE+BABAR $\to$ Particle Data Group

- $BR^{SM}(b \to s\gamma) = (3.29 \pm 0.33) \times 10^{-4}$

  K. Chetyrkin, M. Misiak, M. Münz, Phys. Lett. B **400** (1997) 206 [Erratum-ibid. B **425** (1998) 414], hep-ph/9612313;

  A. J. Buras, A. Kwiatkowski and N. Pott, Phys. Lett. B **414** (1997) 157 [Erratum-ibid. B **434** (1998) 459], hep-ph/9707482;

  A. L. Kagan and M. Neubert, Eur. Phys. J. C **7** (1999) 5, hep-ph/9805303;

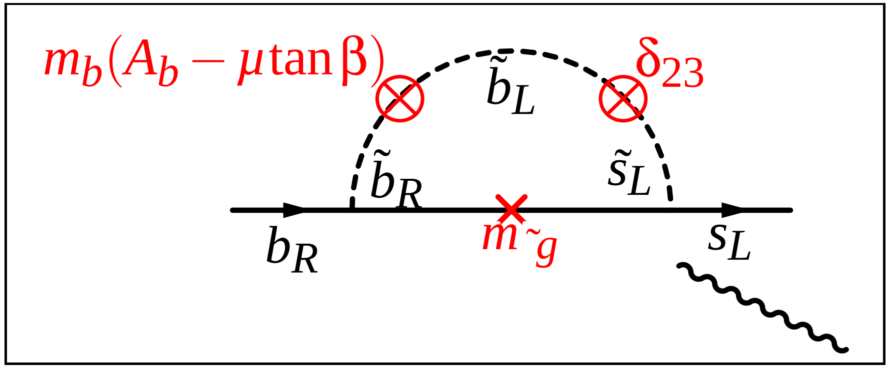
  + $\cdots$

$B(b \longrightarrow s\gamma)$

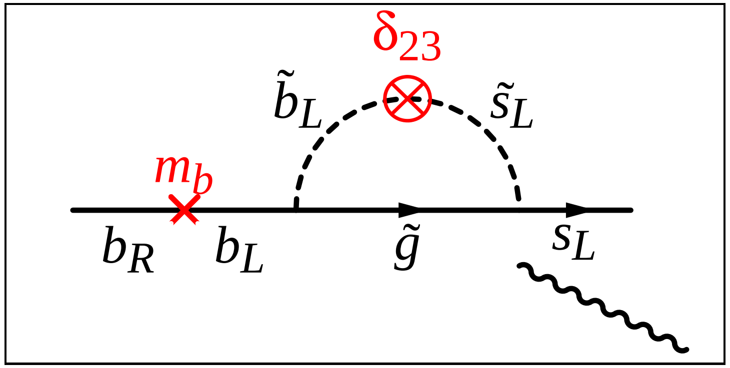
[True for Left-Left mixing only!]

- The relevant Wilson operator in the effective theory involves a chirality flip

$$O_7 = \frac{e}{16\pi^2} m_b \, (\bar{s}_L \, \sigma^{\mu\nu} \, b_R) \, F_{\mu\nu}$$



Leading, Double insertion



Sub-Leading, Single insertion

- The Feynman Amplitude:

$$A^{SUSY-QCD}(b \longrightarrow s\gamma) \sim \delta_{23} \frac{m_b(A_b - \mu \tan\beta)}{M^2_{SUSY}} \times \frac{1}{m_{\tilde{g}}}$$

- Different coupling structure in Hqq' ($\sim \mu$) and $bs\gamma$ ($\sim A_b - \mu \tan\beta$)

$\Rightarrow$ Possibility of small contribution to $A(b \longrightarrow s\gamma)$ and large contribution to $BR(H \longrightarrow qq')$

fi ne-tuning

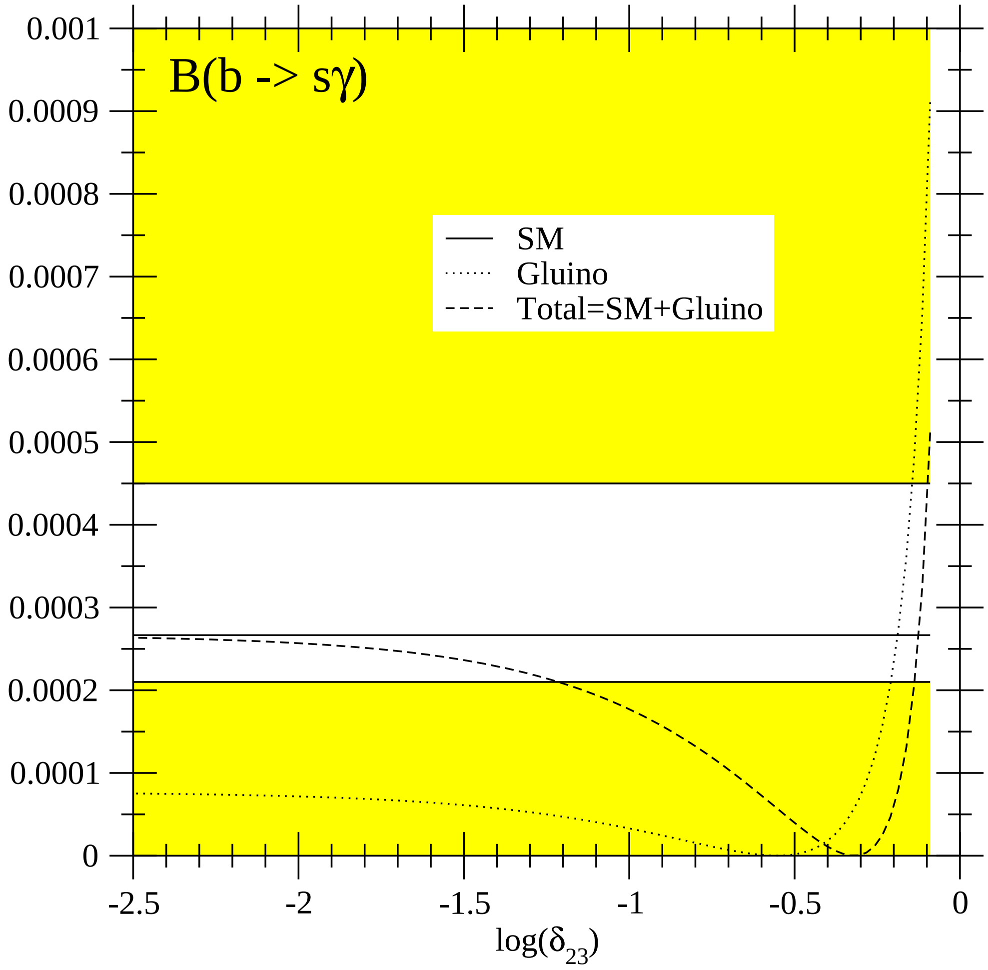
- $A(b \to s\gamma) = A^{SM} + A^{SUSY-QCD} + \cdots$
- $BR^{exp}(b \to s\gamma) \simeq BR^{SM}(b \to s\gamma)$

  $\Rightarrow$ $A^{SUSY-QCD}(b \to s\gamma) \ll A^{SM}$:

  Normal situation

  $\Rightarrow$ $A^{SUSY-QCD}(b \to s\gamma) \simeq -2A^{SM}(b \to s\gamma)$:

  Fine-Tuning!!!!
- At 3σ: $BR^{exp}(b \to s\gamma) = (2.1 - 4.5) \times 10^{-4}$



small $\alpha_{\rm eff}$

- Large value of $BR(h \to qq') = \frac{\Gamma(h \to qq')}{\Gamma(h \to X)}$
  - $\Gamma(h \to qq')$ is large
  - $\Gamma(h \to X)$ is small:
    - Lightest Higgs boson: $\Gamma(h^0 \to b\bar{b}) \sim \left(\frac{\sin\alpha_{\rm eff}}{\cos\beta}\right)^2$
    - in the small $\alpha_{\rm eff}$ scenario:

M. Carena, S. Heinemeyer, C. E. M. Wagner, G. Weiglein, Eur. Phys. J. **C26**, 601–607 (2003), `hep-ph/0202167`.

$\Rightarrow$ $\Gamma(h^0 \to b\bar{b}) \to 0$

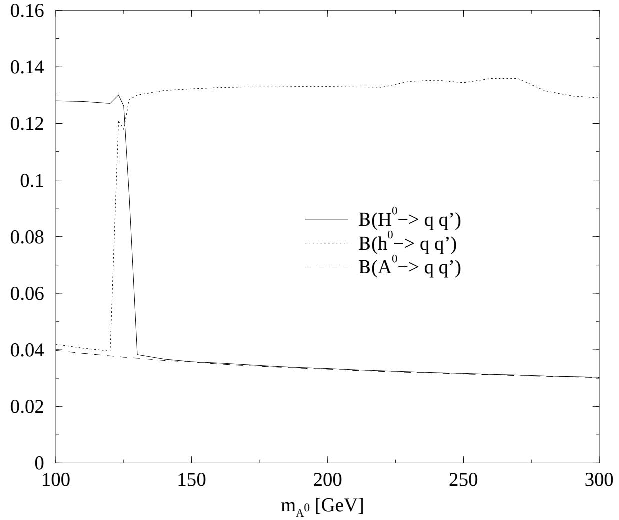
$\Rightarrow$ $\Gamma(h^0 \to X) = \Gamma(h^0 \to c\bar{c} + gg + ZZ^* + W^\pm W^{\pm *})$: strongly suppressed

Numerical results $BR(h \to bs)$

- Find the maximum $BR(h \to bs)$: MSSM parameter space scan

fine-tuning

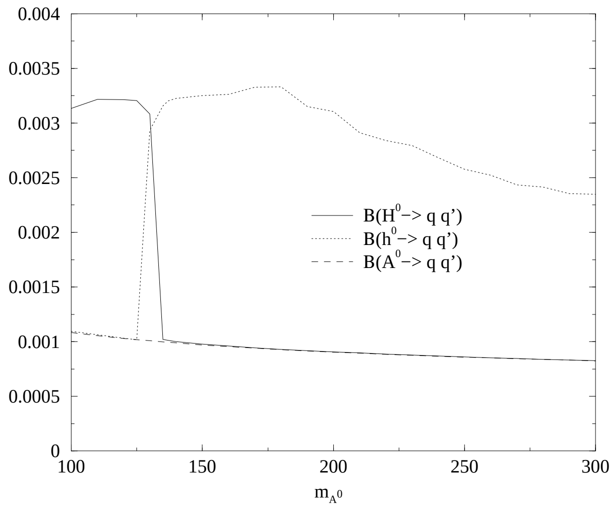
small α_{eff}



$BR^{max}(h^0 \to bs) \sim 13\%$

no fine-tuning

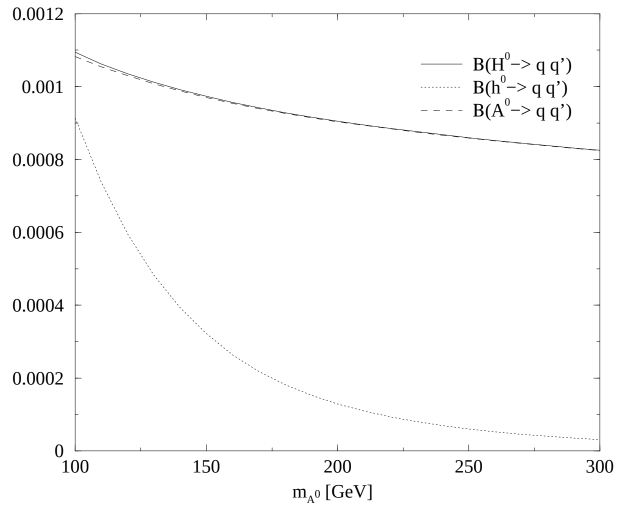
small α_{eff}



$BR^{max}(h^0 \to bs) \sim 3.1 \times 10^{-3}$

no fine-tuning

no small α_{eff}



$BR(h^0 \to bs) \sim 1.3 \times 10^{-4}$

$(M_{A^0} = 200\,\mathrm{GeV})$

- We will avoid the fine-tuning region from now on

- The maximum $BR(h^0 \to bs)$ is obtained in the small α_{eff} scenario

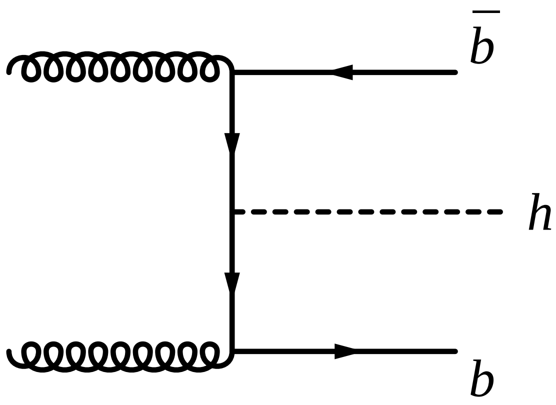
$BR^{max}(h \to bs)$

$M_{A^0} = 200\,\text{GeV}$

Particle	H^0		h^0		A^0	
	$\Gamma(\text{GeV})$	$B(h \to bs)$	$\Gamma(\text{GeV})$	$B(h \to bs)$	$\Gamma(\text{GeV})$	$B(h \to bs)$
small-α_{eff} fine-tuning	11.0	3.3×10^{-2}	1.6×10^{-3}	1.3×10^{-1}	11.3	3.3×10^{-2}
tree-Higgs fine-tuning	11.3	3.3×10^{-2}	5.4×10^{-3}	4.3×10^{-3}	11.3	3.3×10^{-2}
small-α_{eff} no-fine-tuning	11.2	9.1×10^{-4}	1.4×10^{-3}	3.1×10^{-3}	11.3	9.0×10^{-4}
tree-Higgs no-fine-tuning	11.3	9.1×10^{-4}	5.4×10^{-3}	1.3×10^{-4}	11.3	9.0×10^{-4}
$\tan\beta = 5$	0.11	2.0×10^{-3}	6.0×10^{-3}	1.7×10^{-4}	0.11	2.1×10^{-3}
$\tan\beta = 5$ tree Higgs	0.12	1.9×10^{-3}	4.4×10^{-3}	2.6×10^{-4}	0.11	2.1×10^{-3}
$\tan\beta = 5$ no-fine-tuning	0.15	3.8×10^{-4}	9.7×10^{-3}	1.1×10^{-4}	0.11	5.1×10^{-4}

Combination with production

- At large $\tan\beta$ the main production channel for h^0 is associated production: $\sigma(pp->h^0b\bar{b})$



Combination with production

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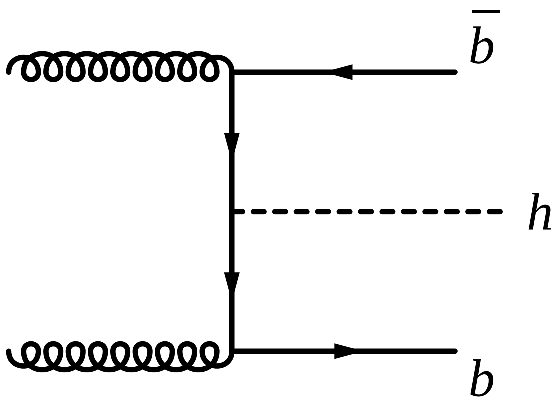
$BR(h^0 \to bs)$ enhanced



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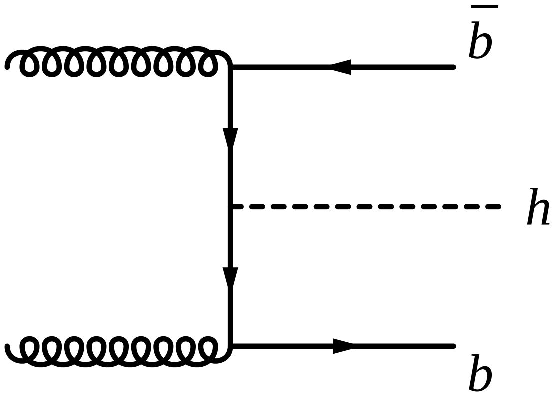

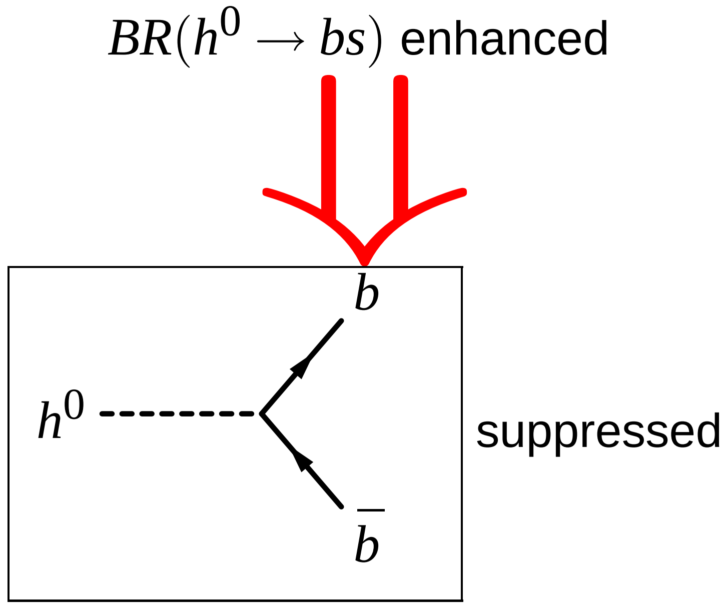

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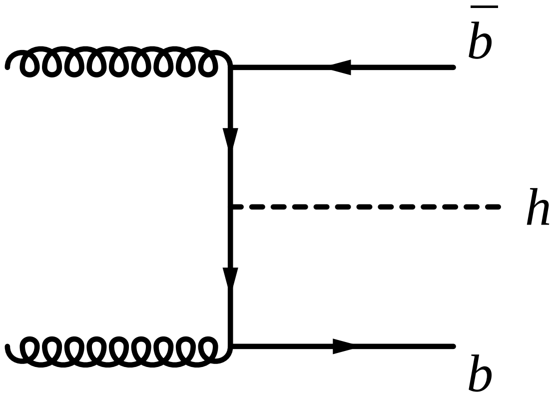
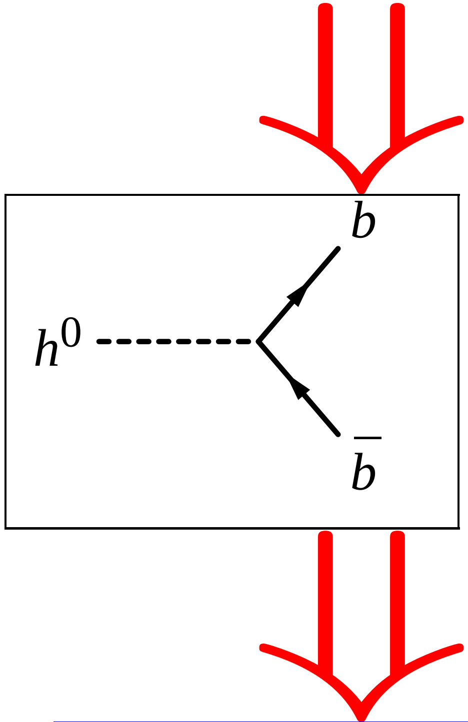


$BR(h^0 \to bs)$ enhanced



suppressed

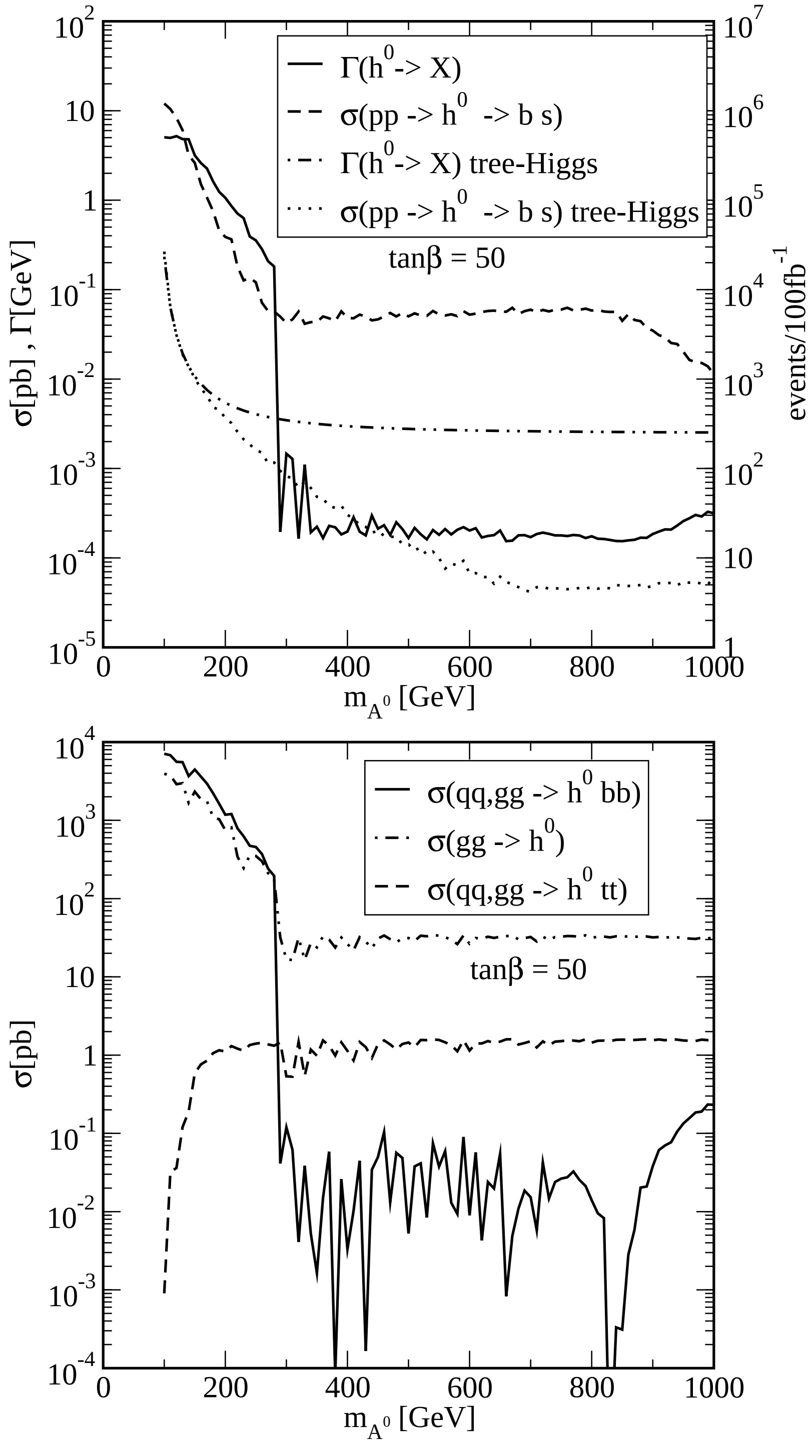
$\sigma(pp \to h^0)$ suppressed !!!

Combined analysis

$\sigma(pp \to h \to qq')$

$\sigma(pp \to h \to bs)$

- Maximized production rates for h^0
- $M_{A^0} < 300\,\mathrm{GeV}$: enhancement of $\sigma(pp \to h^0)$ dominates
- $M_{A^0} > 300\,\mathrm{GeV}$: supression of $\Gamma(h^0 \to X)$ dominates

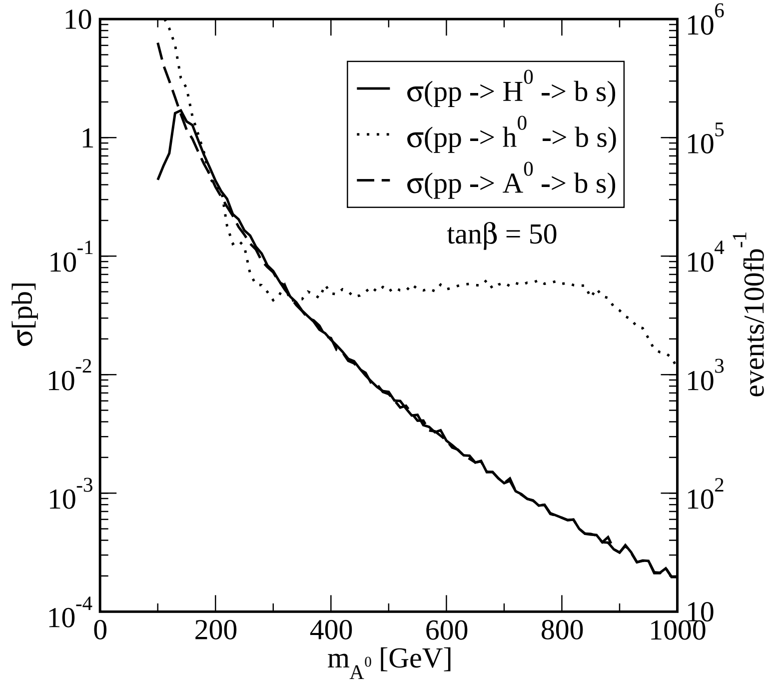


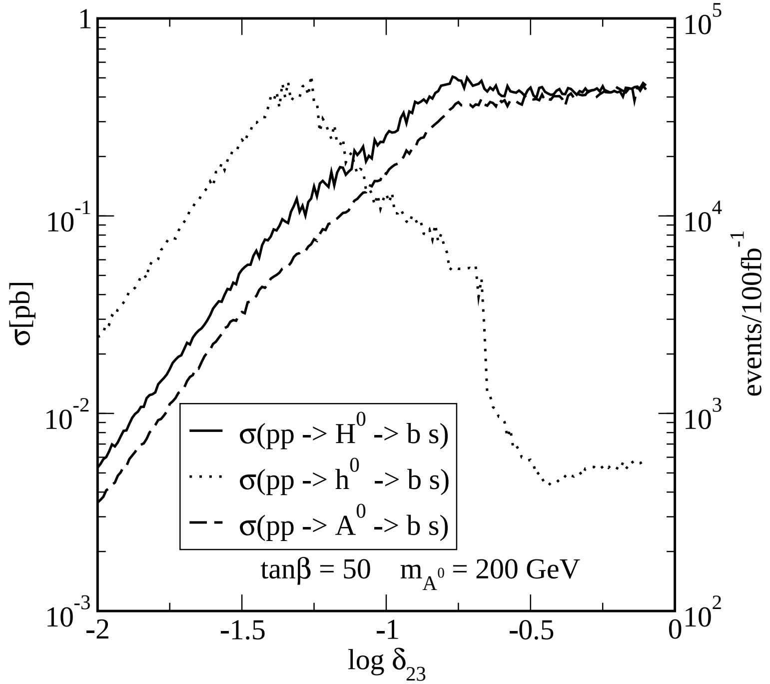
- h^0:
  - $M_{A^0} > 300\,\mathrm{GeV}$: small α_{eff}
  - Dominant contributions are not the leading ones ($\cos(\beta - \alpha_{\mathrm{eff}}) \to 0$)
  - Maximum attained for small δ_{23}, $M_{SUSY} \sim 700\,\mathrm{GeV}$

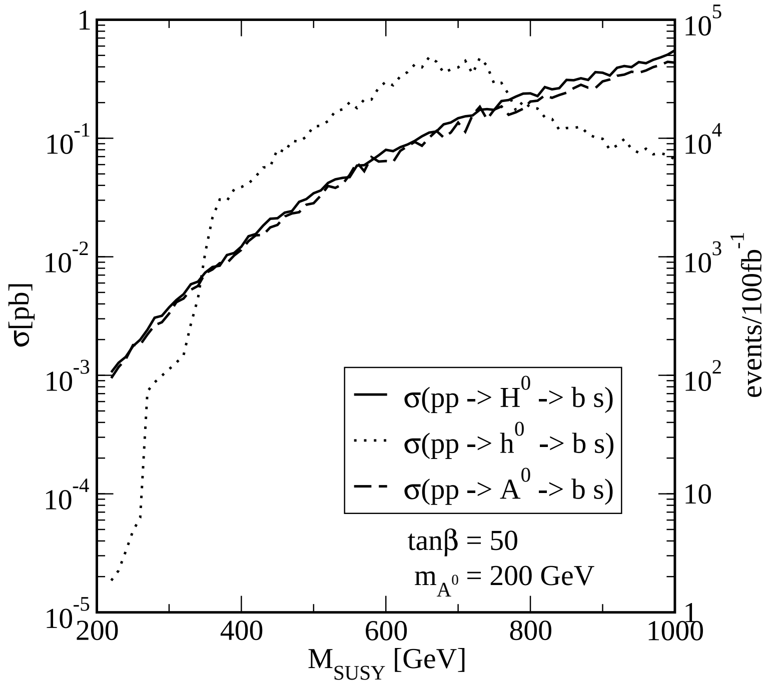
$\Rightarrow$ parameters for which small α_{eff} is possible

$\Rightarrow$ Larger $\delta_{23} \Rightarrow$ smaller μ ($B(b \to s\gamma)$)

$\Rightarrow$ Smaller $M_{SUSY} \Rightarrow$ smaller δ_{23} ($B(b \to s\gamma)$)

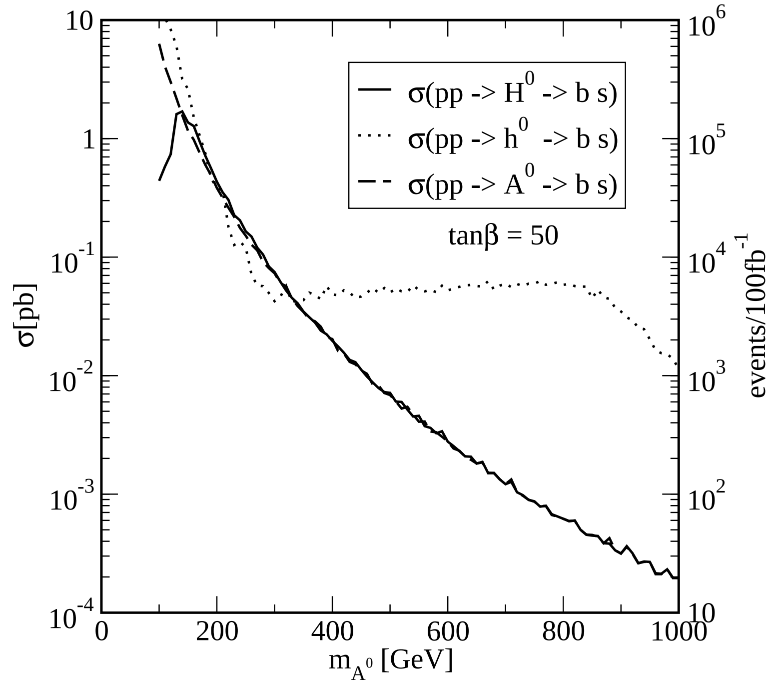


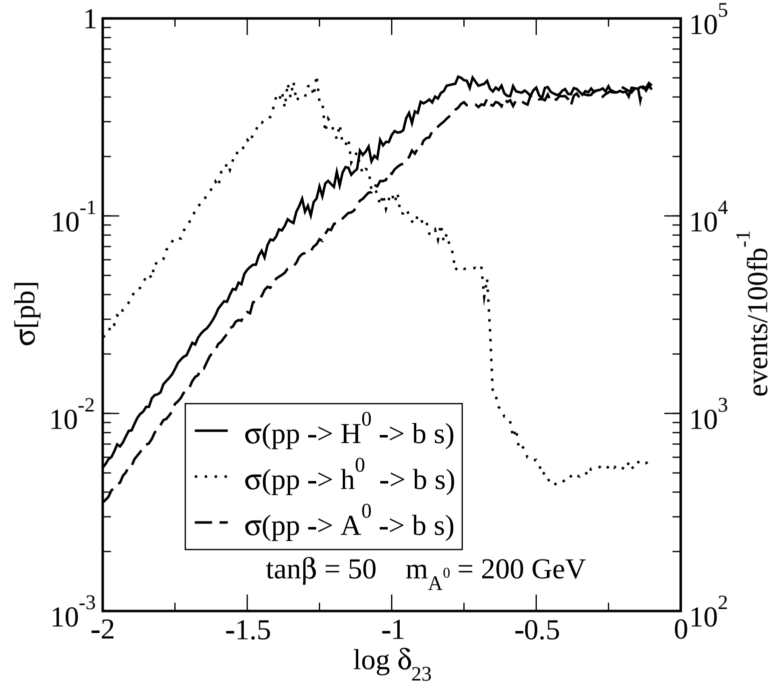


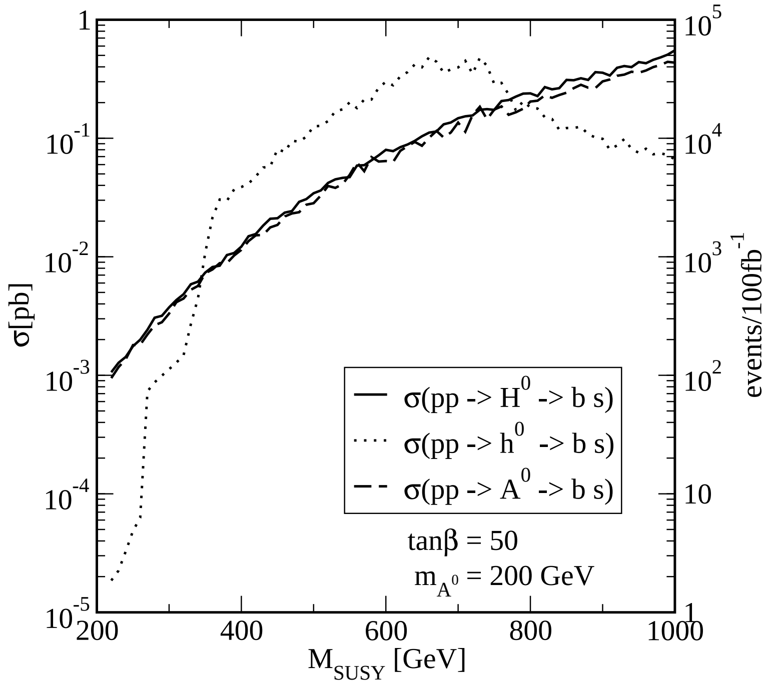


- H^0/A^0
  - Decrease with M_{A^0} due to x-section
  - Dominant contributions are the leading ones
  - Maximum at large M_{SUSY}

    $\Rightarrow$ Large $M_{SUSY} \Longrightarrow$ small $B(b \to s\gamma) \Longrightarrow$ larger δ_{23} allowed
  - At very large $\delta_{23} \Longrightarrow \mu$ has to decrease to obtain acceptable $B(b \to s\gamma) \Longrightarrow BR(H^0/A^0 \to bs)$ can not grow.





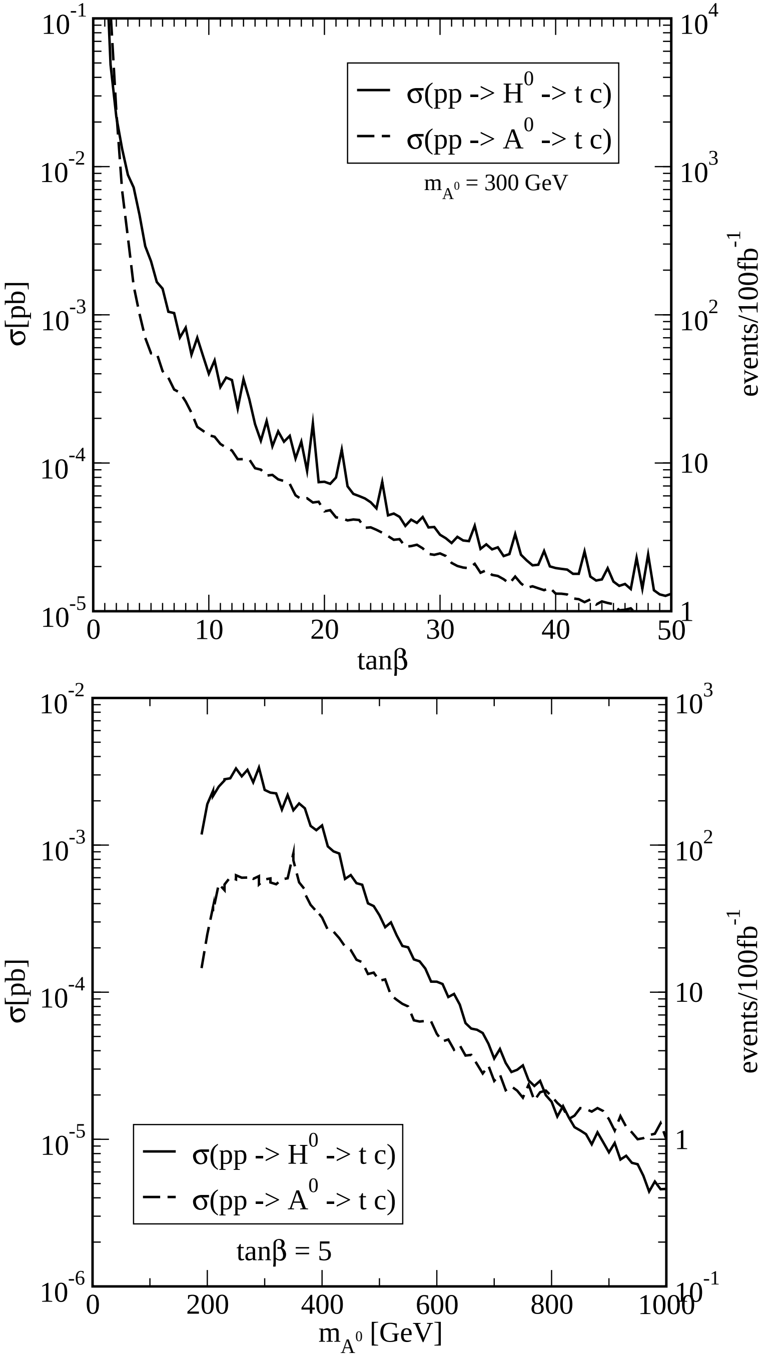


Maximum rates $M_{A^0} = 200\,\mathrm{GeV}, \tan\beta = 50$

h	H^0	h^0	A^0
$\sigma(pp \to h \to bs)$	0.45 pb	0.34 pb	0.37 pb
events/100 fb^{-1}	4.5×10^4	3.4×10^4	3.7×10^4
$B(h \to bs)$	9.3×10^{-4}	2.1×10^{-4}	8.9×10^{-4}
$\Gamma(h \to X)$	$10.9\,\mathrm{GeV}$	$1.00\,\mathrm{GeV}$	$11.3\,\mathrm{GeV}$
δ_{23}	$10^{-0.62}$	$10^{-1.32}$	$10^{-0.44}$
$m_{\tilde{q}}$	$990\,\mathrm{GeV}$	$670\,\mathrm{GeV}$	$990\,\mathrm{GeV}$
A_b	$-2750\,\mathrm{GeV}$	$-1960\,\mathrm{GeV}$	$-2860\,\mathrm{GeV}$
μ	$-720\,\mathrm{GeV}$	$-990\,\mathrm{GeV}$	$-460\,\mathrm{GeV}$
$B(b \to s\gamma)$	4.50×10^{-4}	4.47×10^{-4}	4.39×10^{-4}

$\sigma(pp \to h \to tc)$

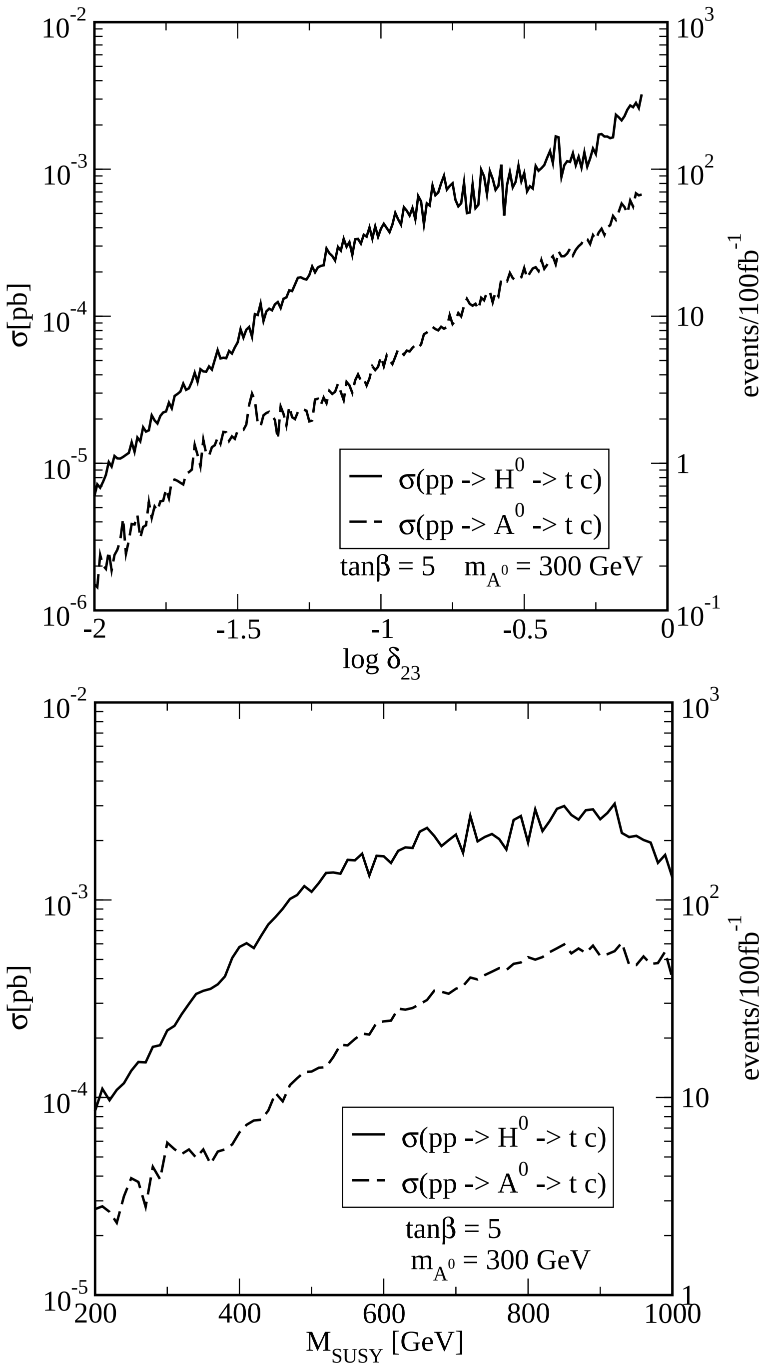
- Only H^0/A^0 possible
- Large at small $\tan\beta$:
  - $\Rightarrow$ no equivalent of small α_{eff}
- differences at small M_{A^0}:
  - Near threshold for $H^0 \to \tilde{q}_1 \tilde{q}_1$
  - not possible for A^0



- Maximum at maximal δ_{23}
- Maximum at maximal M_{SUSY}
- One physical squark is always light

$M_{A^0} = 300\,\text{GeV}, \tan\beta = 5$

h	H^0	A^0
$\sigma(pp \to h \to t\,c)$	2.4×10^{-3} pb	5.8×10^{-4} pb
events/100 fb^{-1}	240	58
$B(h \to tc)$	1.9×10^{-3}	5.7×10^{-4}
$\Gamma(h \to X)$	$0.41\,\text{GeV}$	$0.39\,\text{GeV}$
δ_{23}	$10^{-0.10}$	$10^{-0.13}$
$m_{\tilde{q}}$	$880\,\text{GeV}$	$850\,\text{GeV}$
A_t	$-2590\,\text{GeV}$	$2410\,\text{GeV}$
μ	$-700\,\text{GeV}$	$-930\,\text{GeV}$
$B(b \to s\gamma)$	4.13×10^{-4}	4.47×10^{-4}



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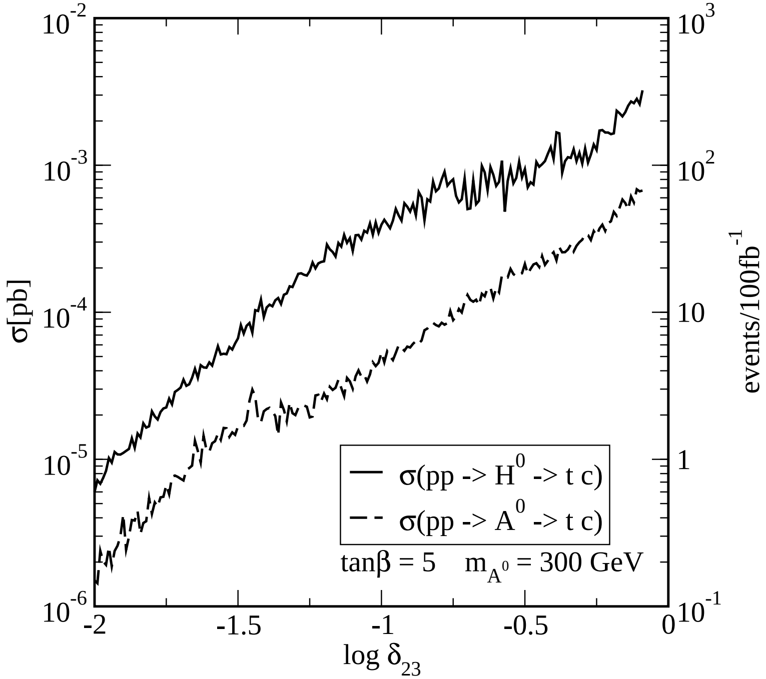
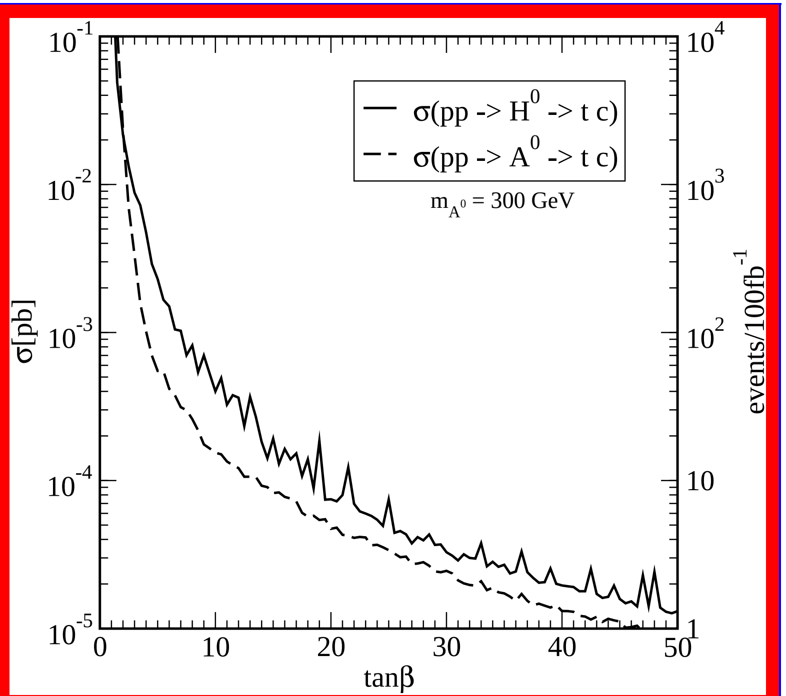
- $\tan\beta = 4 \Longrightarrow \sim$ 500 events/100 fb^{-1}
- $\tan\beta = 3 \Longrightarrow \sim$ 900 events/100 fb^{-1}
- $\tan\beta = 2 \Longrightarrow \sim$ 2000 events/100 fb^{-1}





Conclusions

- $h-b-s$ and $h-t-c$ FCNC couplings are enhanced in the general MSSM
- restrictions from $b \to s\gamma$:
  - Allow extremelly large couplings in fine-tuned regions
  - in non-fine-tuned regions: still 4–10 orders of magnitude larger than SM
- $h-q-q'$ are large at large M_{SUSY}:
  - Leading contributions to $h-q-q'$ do not depend on the average SUSY mass scale
  - at low M_{SUSY} the FCNC couplings are restricted by $b \to s\gamma$

- $h \to bs$:
  - Maximum of $BR(h^0 \to bs)$ obtained in small α_{eff}

	SM	small α_{eff}	tree-Higgs
$BR(h^0 \to bs)$	$\lesssim 10^{-7}$	3×10^{-3}	10^{-4}

  - Production at LHC: negative correlations between production and decay
    - $\sigma(pp \to h \to bs) \lesssim 0.5$ pb $\Longrightarrow 5 \times 10^4$ events/100 fb^{-1}
    - light quarks: difficult to see at LHC

- $H^0/A^0 \to tc$:

	SM	MSSM
$BR(H^0/A^0 \to tc)$	$\lesssim 10^{-13}$	$\lesssim 3 \times 10^{-3}$

  - production at LHC: decreases fast with mass
  - increases fast at low $\tan\beta$:

$\tan\beta$	5	4	3	2
$\sigma(pp \to H^0 \to tc)$	3 fb	5 fb	9 fb	20 fb
events/100 fb^{-1}	300	500	900	2000

  - Several thousand events could be produced
  - Possibility of tagging on single top

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