The Meaning of "Higgs": $\tau\tau$ and $\gamma\gamma$ at Hadron Colliders

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Based on:

A. Belyaev, A.Blum, S.Chivukula, E. Simmons; hep-ph/0506086

Outline

- Introduction
- Supersymmetry (MSSM)
- Dynamical Symmetry Breaking (Technicolor)
- Distinguishing MSSM from Technicolor
- Conclusions

Introduction

- *As you are all well aware...*
  The origin of electroweak symmetry breaking remains unknown.

- *CDF and D0 are searching hard for signs of either*
  a Standard Model (SM) Higgs boson
  or Beyond the Standard Model (BSM) physics such as
  Supersymmetry or Dynamical Symmetry Breaking

- *The production cross-sections and decay branching fractions of the SM Higgs have been predicted in great detail. Search strategies have been optimized and re-optimized.*

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- *What happens if the Tevatron finds evidence for a new scalar state?*
- *How sure will we be that it is really the SM Higgs?*
- *The spectra of many BSM scenarios include (pseudo) scalar states whose masses can lie in the range to which Tevatron Run II is sensitive.*
- *This talk looks at the possibility of extracting information about BSM physics from the searches for a light SM Higgs now underway at Run II and planned for the LHC.*

Context

- *The literature* includes many papers that use LEP's SM Higgs search results to constrain BSM physics. The Tevatron and LHC are sensitive to heavier scalars than LEP, so the strategy bears repeating.*
- *The literature* on hadron collider Higgs searches identifies the $\tau\tau$ channel as potentially valuable for enhancing the visibility of an SM Higgs or rendering an MSSM Higgs visible via $gg \to h_{MSSM} \to \tau\tau$.*
- *We build on this in three ways*
  – additional production mechanism ($b\bar{b} \to h$)
  – additional decay channels ($h \to b\bar{b},\ W^+W^-,\ ZZ,\ \gamma\gamma$)
  – comparing Supersymmetry with Dynamical Symmetry Breaking

* ***See references 1-12 of hep-ph/0506086.***

Comparing Non-standard "Higgs" Sectors with SM Higgs

- In the presence of BSM physics, such as SUSY or Dynamical Symmetry Breaking, the SM Higgs gives way to the multiple Higgs bosons of the MSSM or the technipions of technicolor.
- We will look at the extent to which the signal in certain standard Higgs search channels is enhanced when one is seeing a BSM scalar ($\mathcal{H}$) rather than an SM Higgs.
- We define the enhancement factor for the process $yy \to \mathcal{H} \to xx$ as

$$\kappa^{\mathcal{H}}_{yy/xx} = \frac{\Gamma(\mathcal{H} \to yy) \times BR(\mathcal{H} \to xx)}{\Gamma(h_{SM} \to yy) \times BR(h_{SM} \to xx)}$$

Supersymmetry (MSSM)

- *each ordinary fermion (boson) is paired with a new boson (fermion)*
- *two Higgs doublets exist to provide masses to both up-type and down-type quarks, and to ensure tiangle anomaly cancellation*
  $\Phi_d = (\Phi_d^0, \Phi_d^-)$ *and* $\Phi_u = (\Phi_u^+, \Phi_u^0)$
  $$\langle\Phi_d\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_d \\ 0 \end{pmatrix}, \quad \langle\Phi_u\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_u \end{pmatrix}, \quad \sqrt{v_d^2 + v_u^2} = 246 \text{ GeV.}$$
- *SUSY relates the scalar self-coupling to gauge couplings* $\Rightarrow M_H$ *is predicted!*
- *Of the 8 degrees of freedom in the Higgs sector, 3 serve as "eaten" Goldstone bosons, leaving 5 states in the spectrum:*
  - *two neutral, CP-even states:* h, H *(mixing* α*)*
  - *one neutral, CP-odd state:* A
  - *a charged pair:* $H^\pm$

Yukawa interactions in MSSM

At tree level, the Higgs sector is defined by $\tan\beta = v_u/v_d$ *and* M_A

One derives $h_t = \frac{\sqrt{2}\, m_t}{v_u} = \frac{\sqrt{2}\, m_t}{v \sin\beta}, \quad h_{b,\tau} = \frac{\sqrt{2}\, m_{b,\tau}}{v_d} = \frac{\sqrt{2}\, m_{b,\tau}}{v \cos\beta}$.

$$Y_{ht\bar{t}}/Y^{SM}_{ht\bar{t}} = \cos\alpha/\sin\beta \qquad Y_{hb\bar{b}}/Y^{SM}_{hb\bar{b}} = -\sin\alpha/\cos\beta$$

$$Y_{Ht\bar{t}}/Y^{SM}_{ht\bar{t}} = \sin\alpha/\sin\beta \qquad Y_{Hb\bar{b}}/Y^{SM}_{hb\bar{b}} = \cos\alpha/\cos\beta$$

$$Y_{At\bar{t}}/Y^{SM}_{ht\bar{t}} = \cot\beta \qquad Y_{Ab\bar{b}}/Y^{SM}_{hb\bar{b}} = \tan\beta$$

For large M_A $\quad \Rightarrow Y_{Hb\bar{b}}/Y^{SM}_{hb\bar{b}} = Y_{H\tau\bar{\tau}}/Y^{SM}_{h\tau\bar{\tau}} \simeq \tan\beta,$

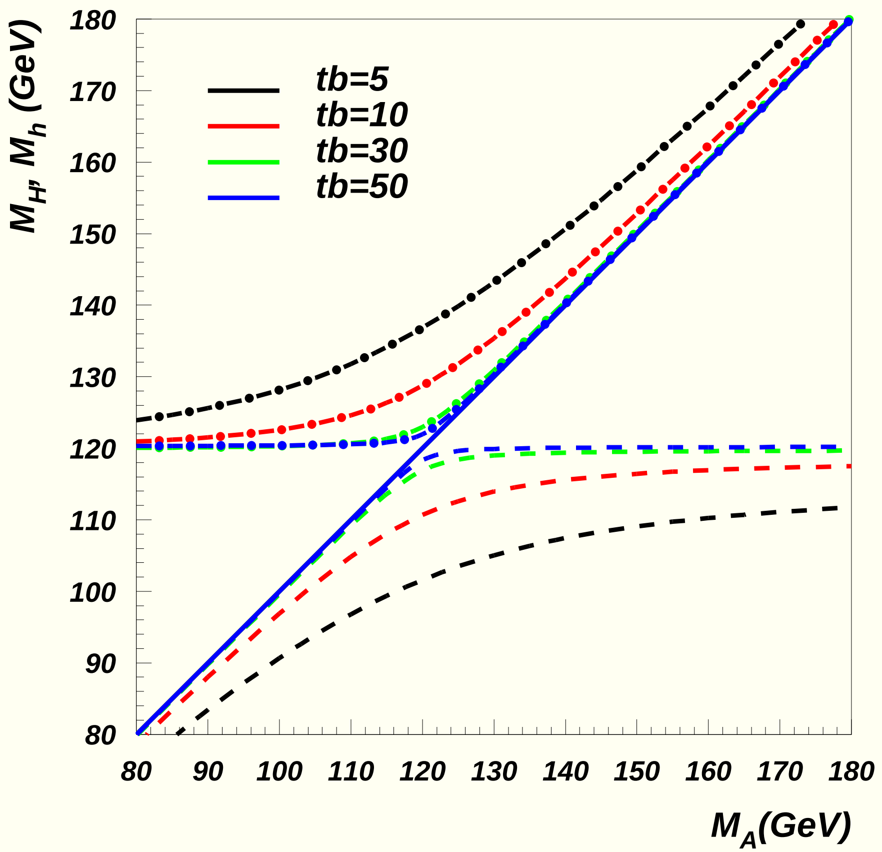
For small $M_A \simeq M_h$ $\quad \Rightarrow Y_{hb\bar{b}}/Y^{SM}_{hb\bar{b}} = Y_{h\tau\bar{\tau}}/Y^{SM}_{h\tau\bar{\tau}} \simeq \tan\beta$

At large $\tan\beta$*, we see enhancements of the Yukawa couplings (*$Y_{Ab\bar{b}}, Y_{A\tau\bar{\tau}}$*)*

and also of either ($Y_{Hb\bar{b}}, Y_{H\tau\bar{\tau}}$*) or (*$Y_{hb\bar{b}}, Y_{h\tau\bar{\tau}}$*) depending on the size of* M_A*.*

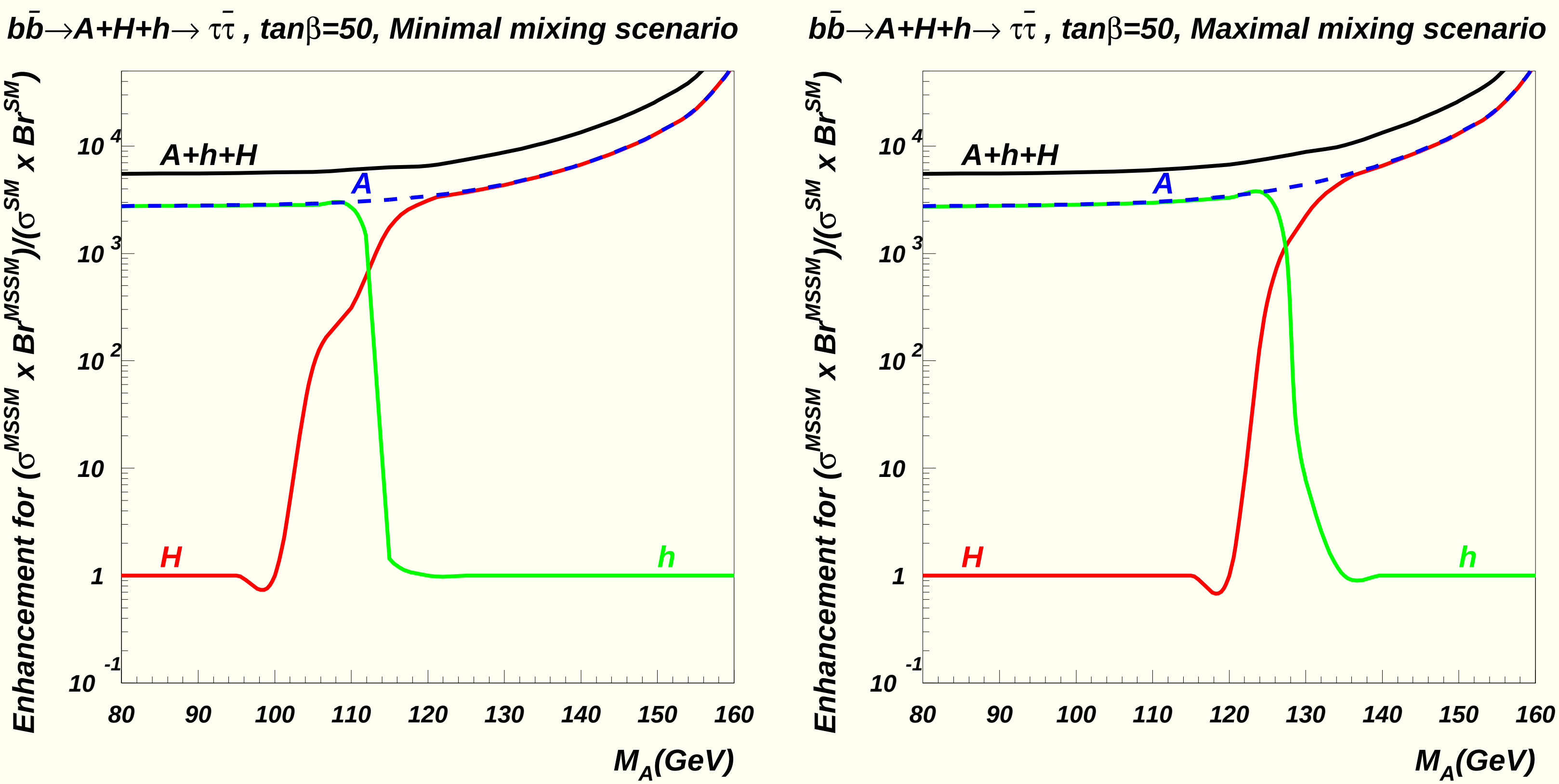
Factors affecting signal strength in comparison with SM - I

- $\mathcal{H} = (h, H, A)$ Neutral Higgs bosons could be degenerate and contribute to the same signal. We assume this happens if $|M_A - M_h|$ and/or $|M_A - M_H|$ is less than 0.3$\sqrt{M_A/GeV}$ GeV for $\tau\tau$ or $b\bar{b}$ channels.



Factors affecting signal strength in comparison with SM - I

- *Jumping ahead slightly... combining signals from degenerate $\mathcal{H}$ makes the enhancement factor essentially independent of the degree of top-squark mixing (for fixed M_A and μ and moderate-to-high $\tan\beta$)*



Factors affecting signal strength in comparison with SM - II

- *Alterations of the couplings directly affect widths and branching ratios relative to those in the SM. But: a gain in B($\mathcal{H} \to \tau\tau$) caused by a smaller $b\bar{b}\mathcal{H}$ coupling may be offset by a reduction in Higgs production.*

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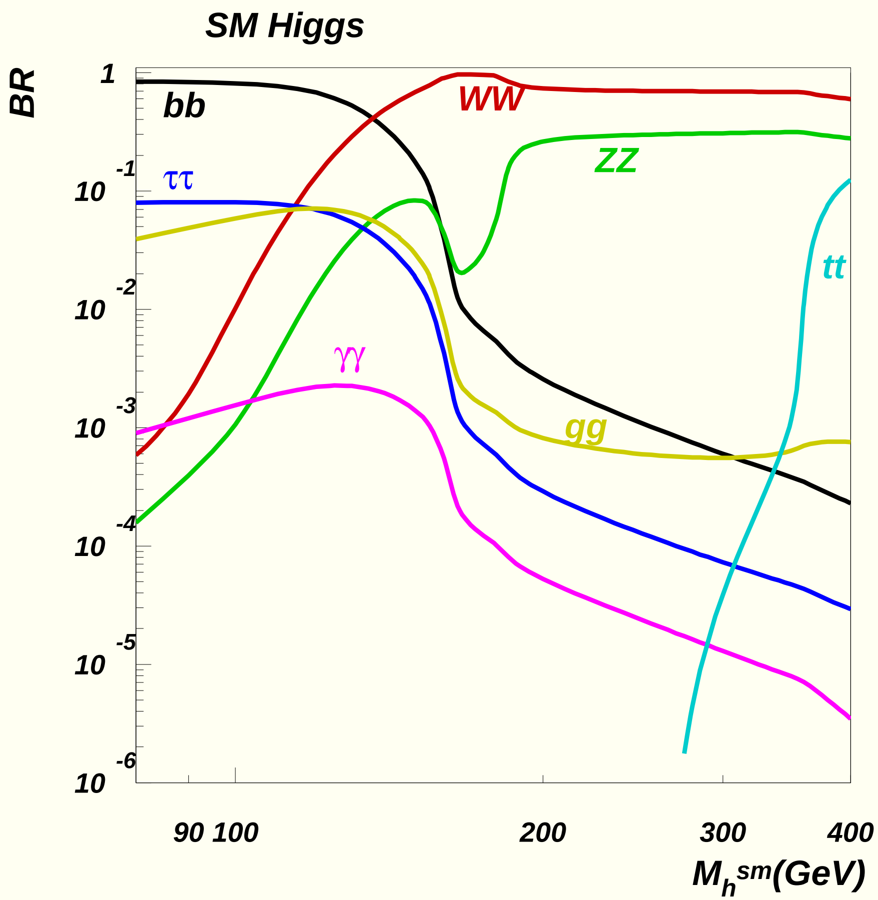

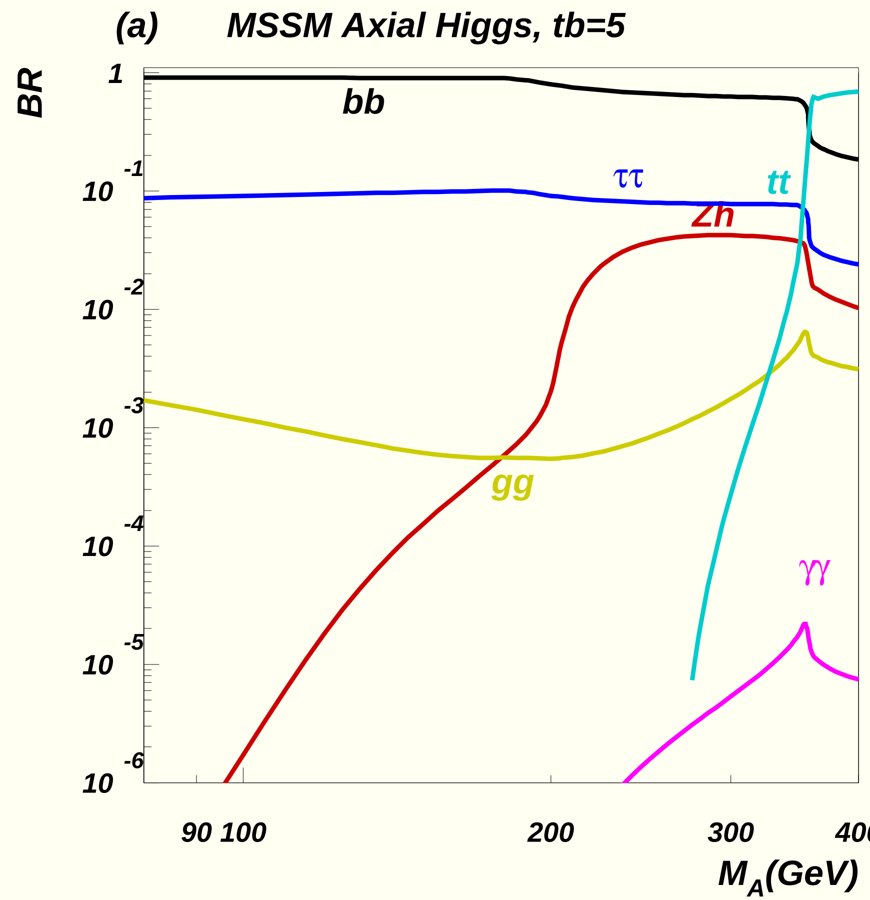

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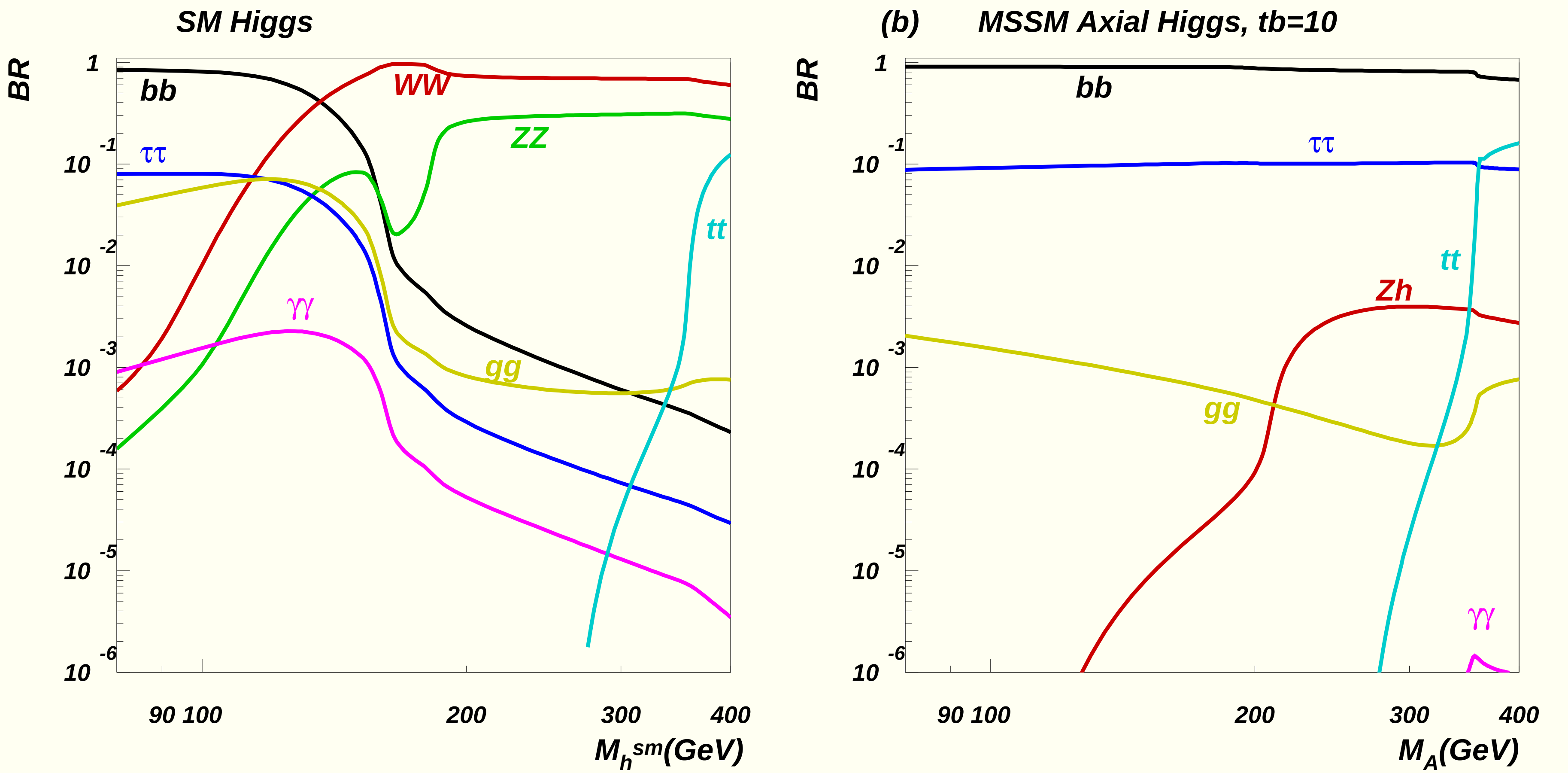

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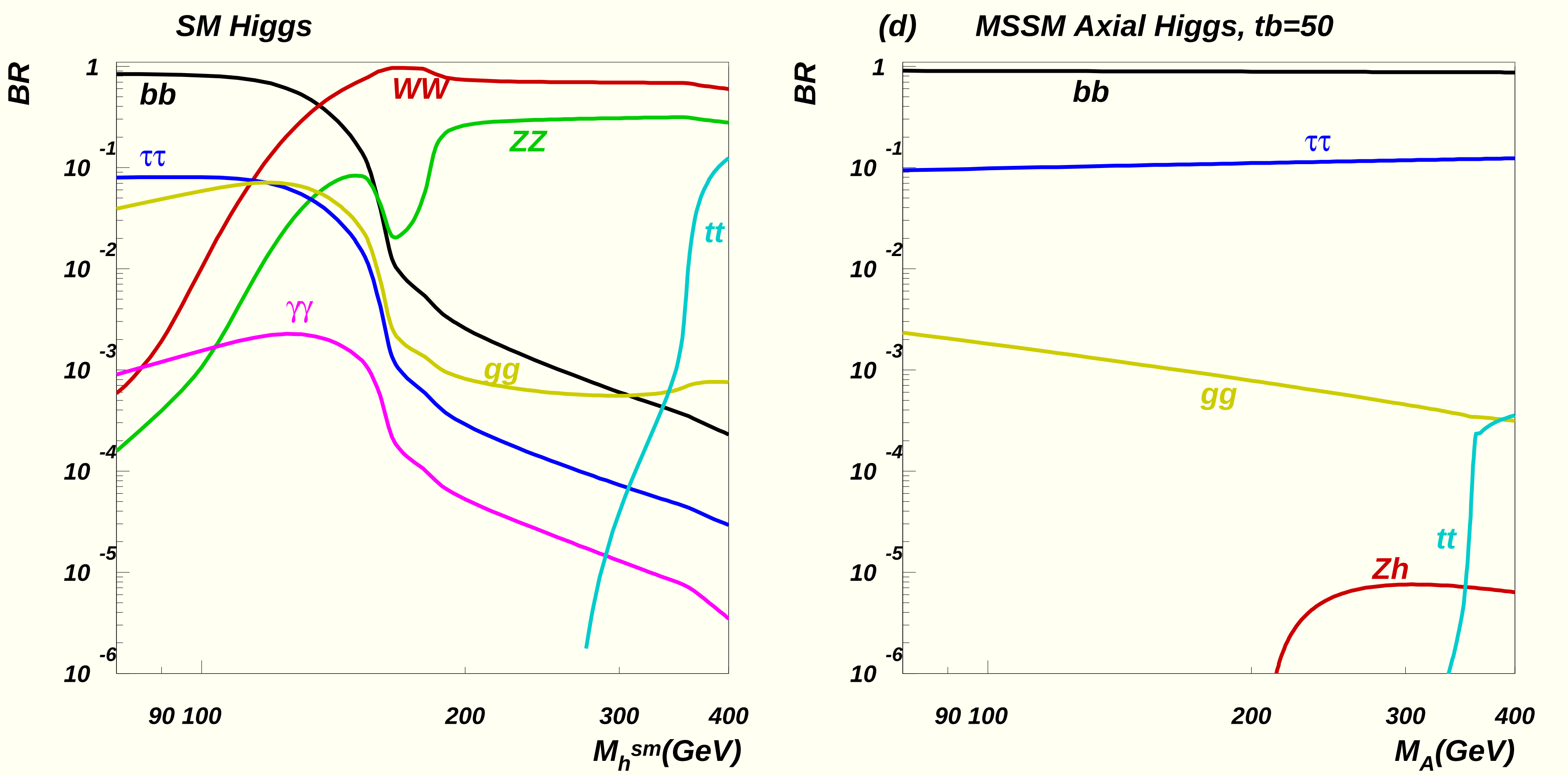

Factors affecting signal strength in comparison with SM - III

- *a larger $b\bar{b}\mathcal{H}$ coupling increases both*
  - $gg \to \mathcal{H}$ *through a* b*-quark loop*
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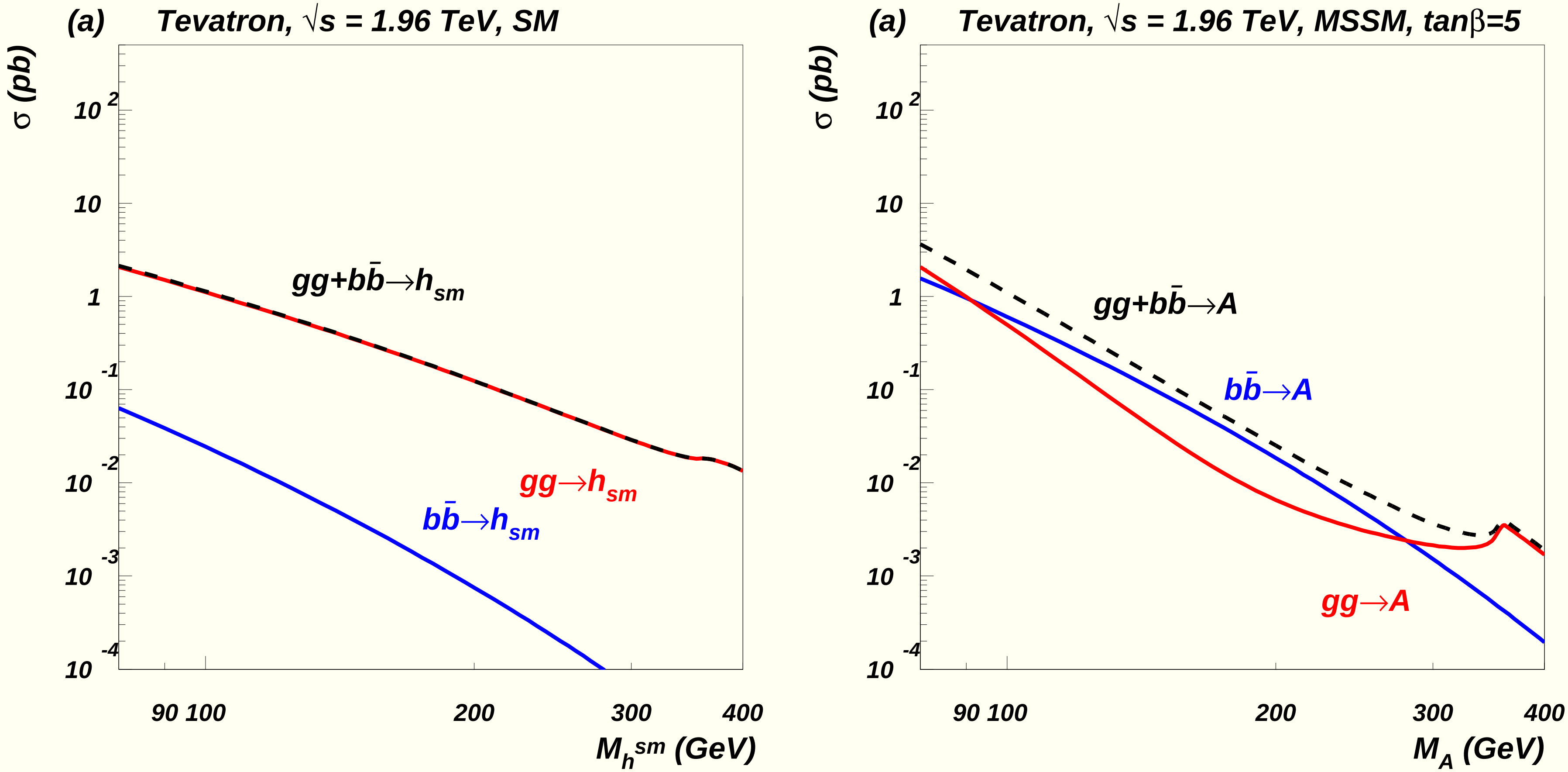

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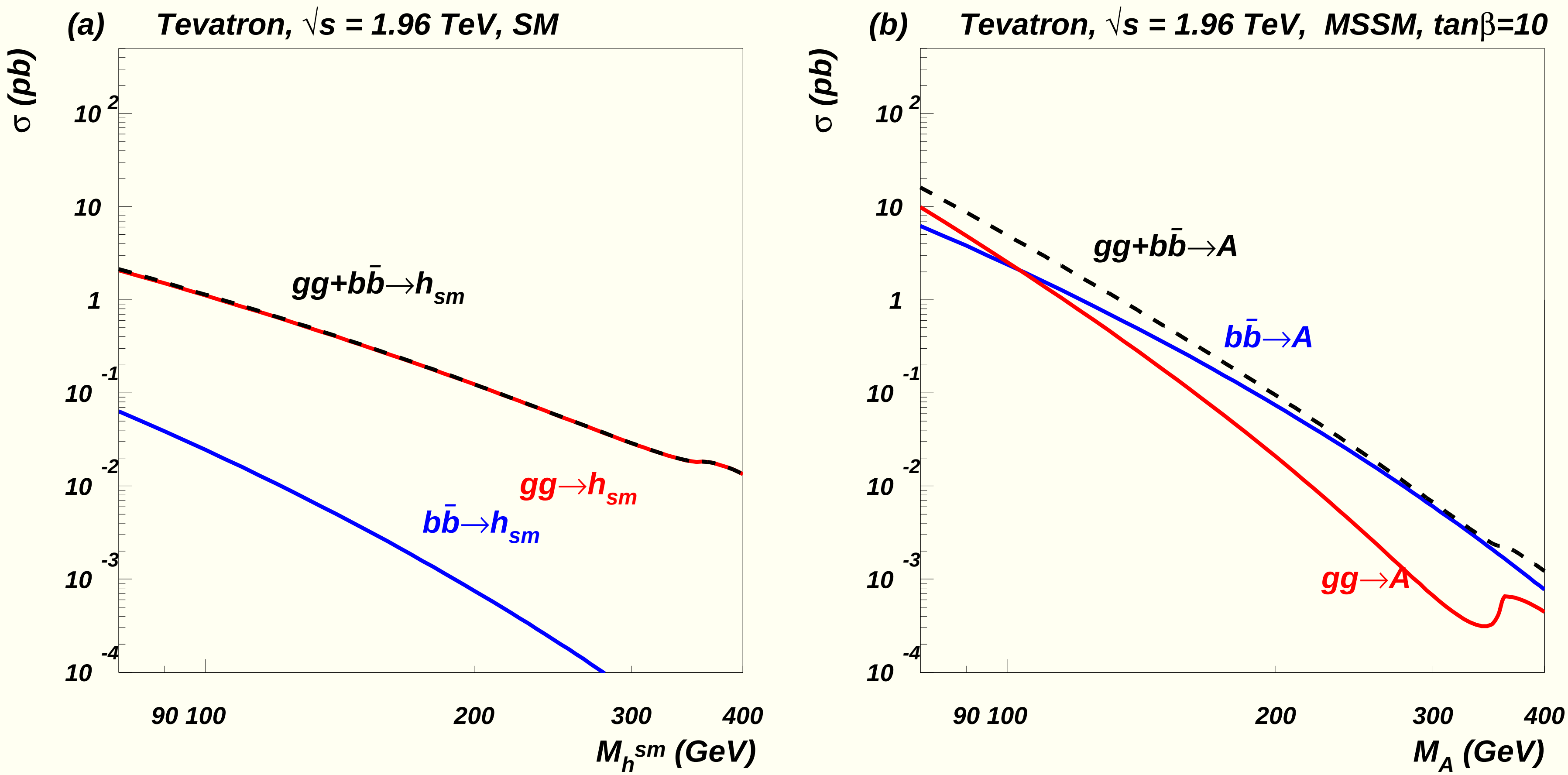

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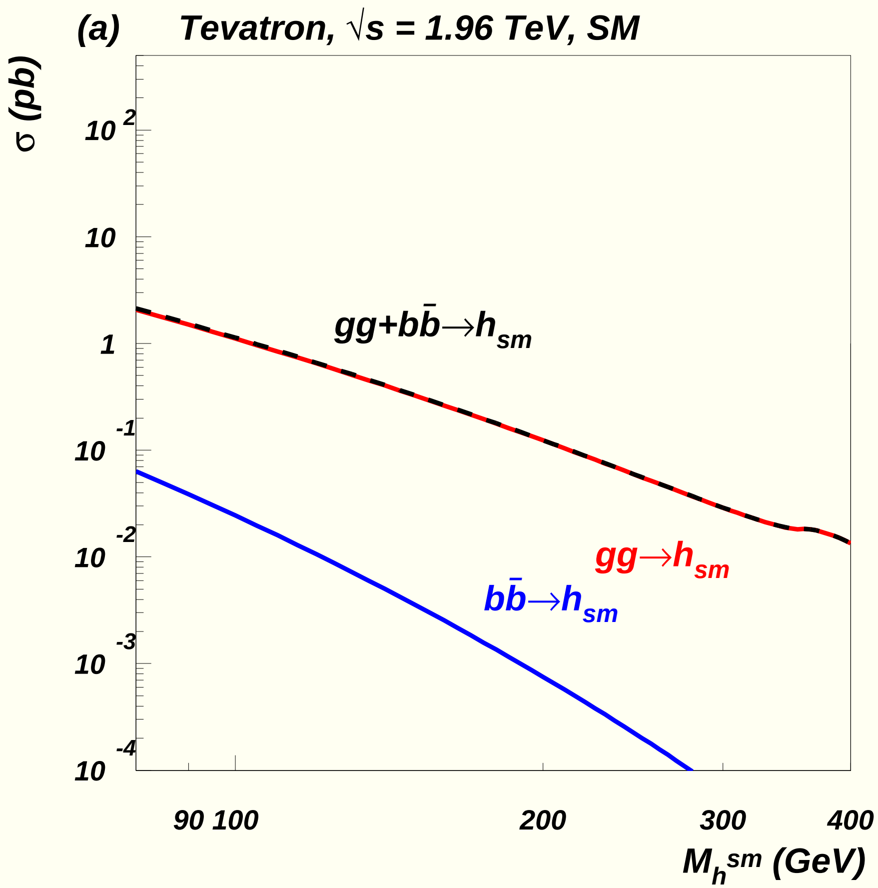

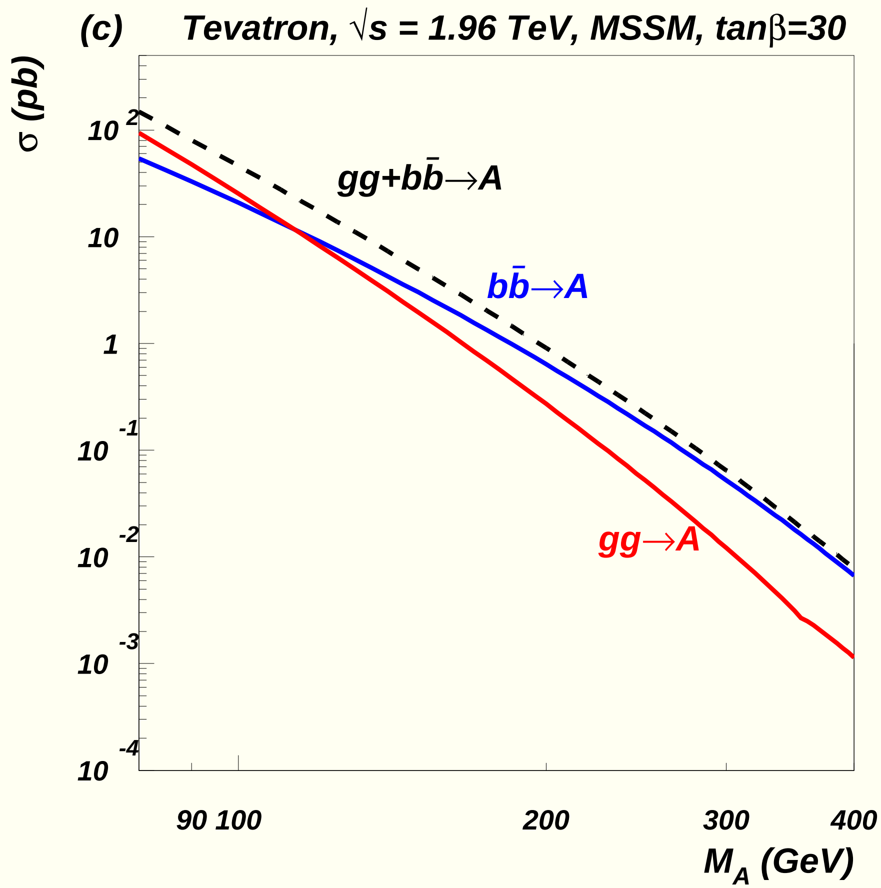

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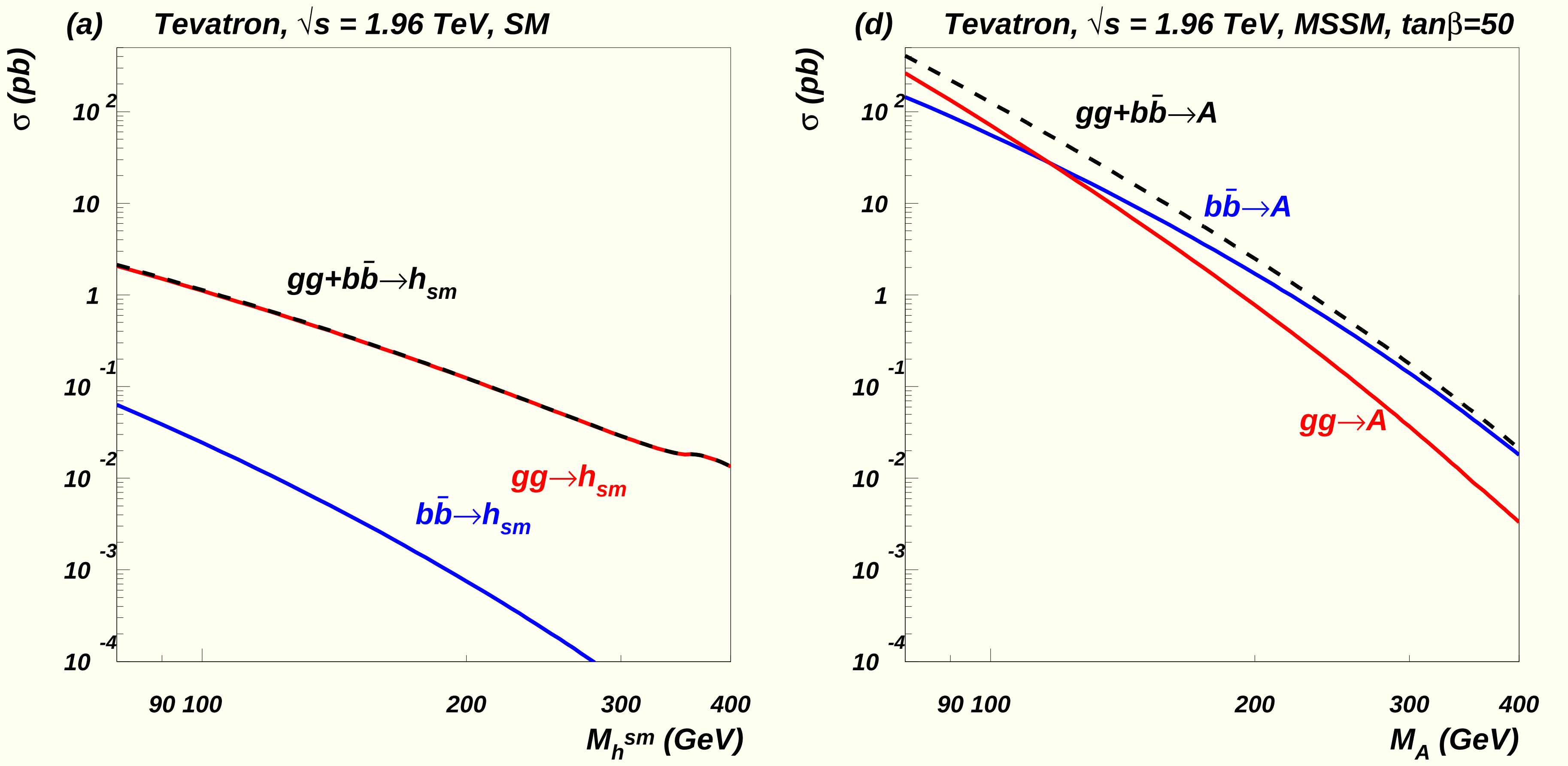

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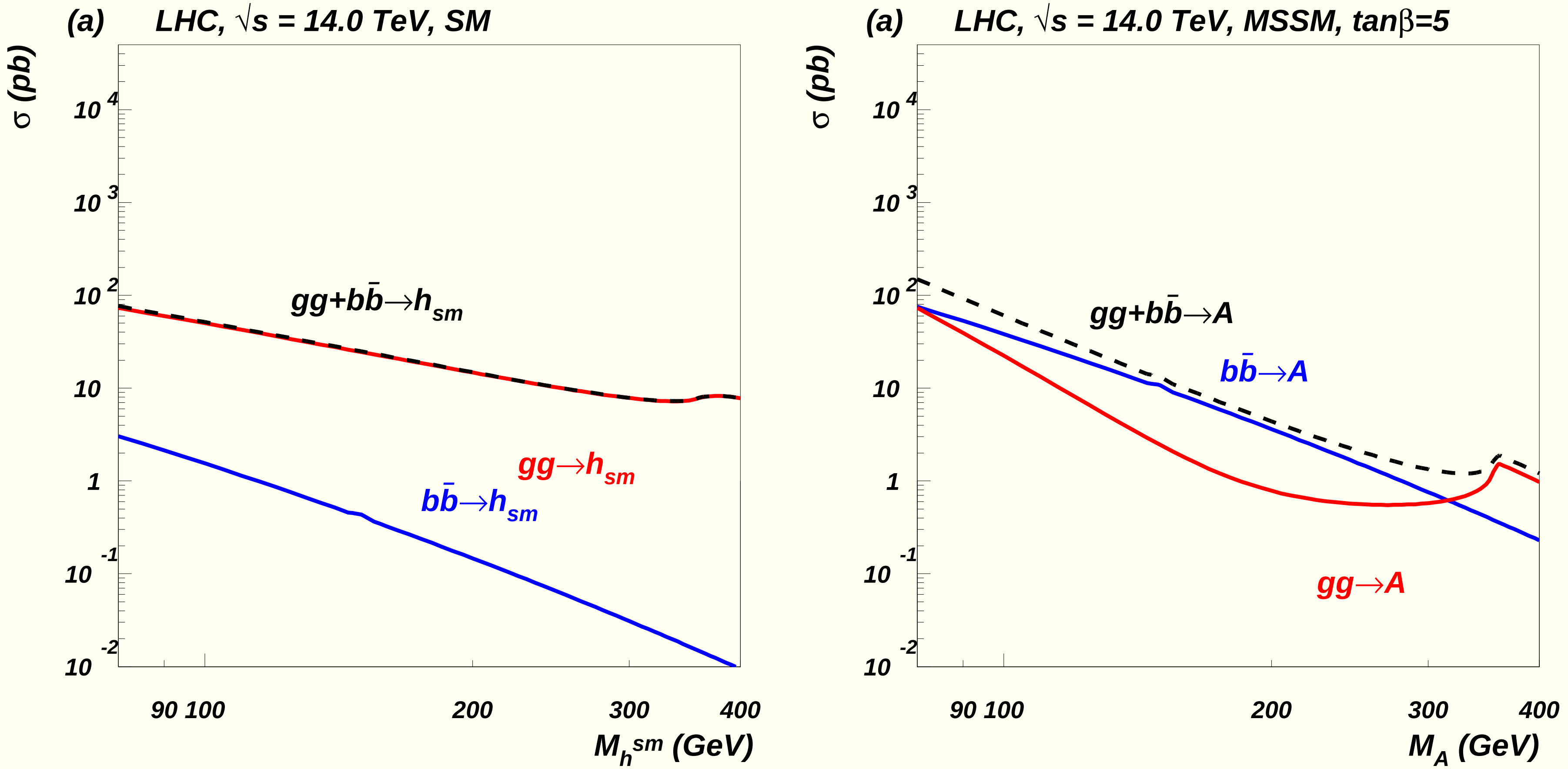

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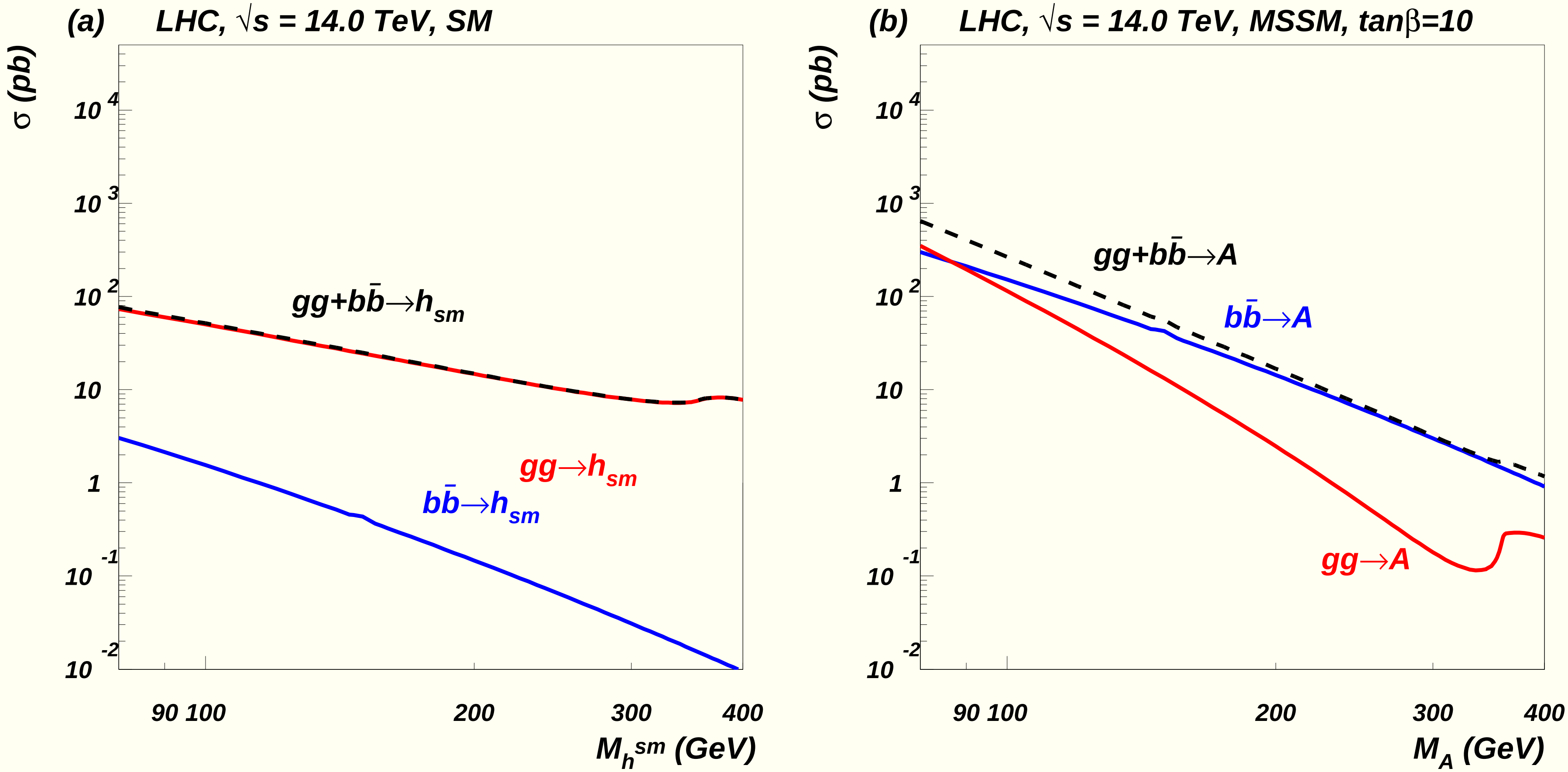

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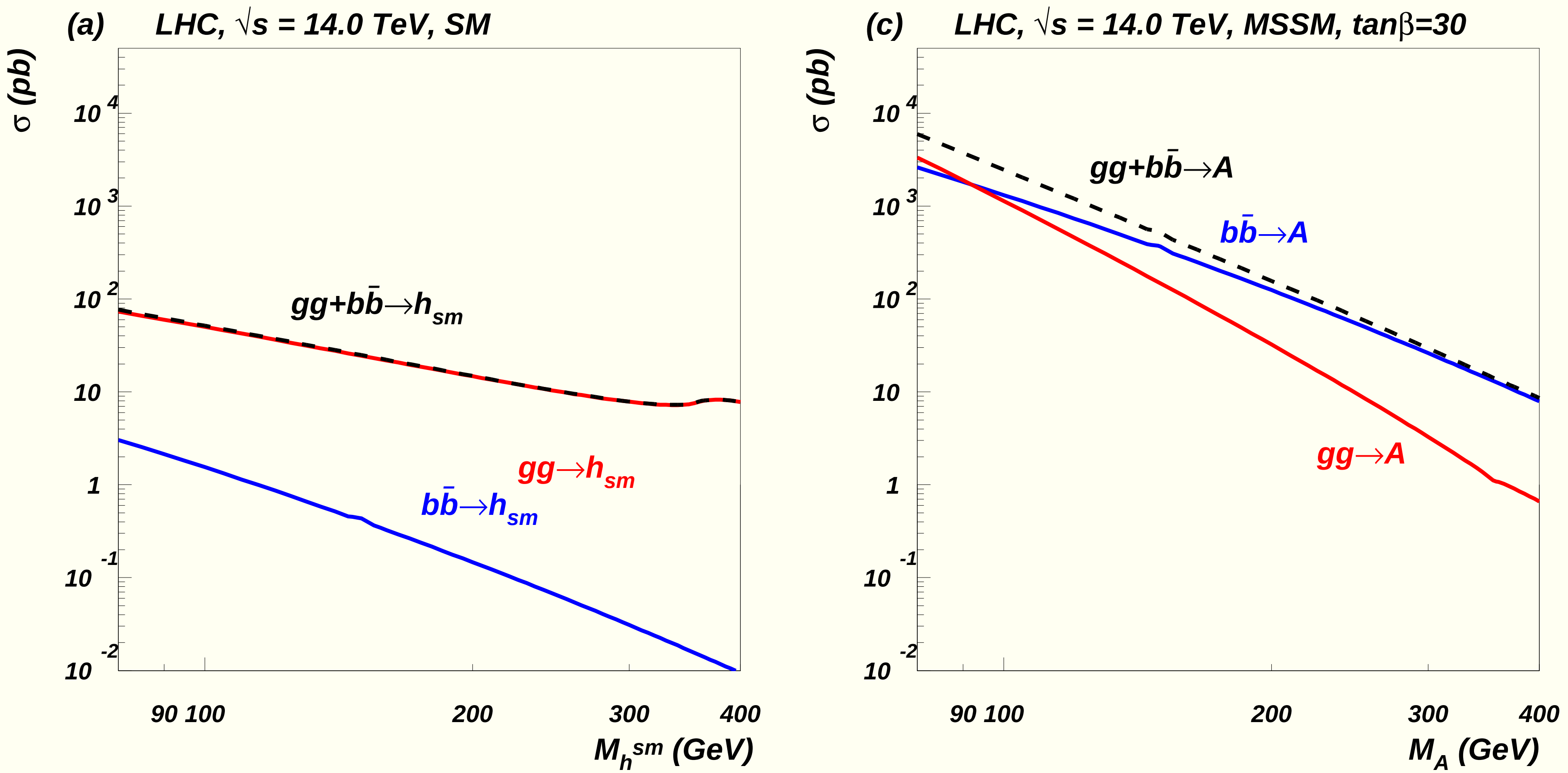

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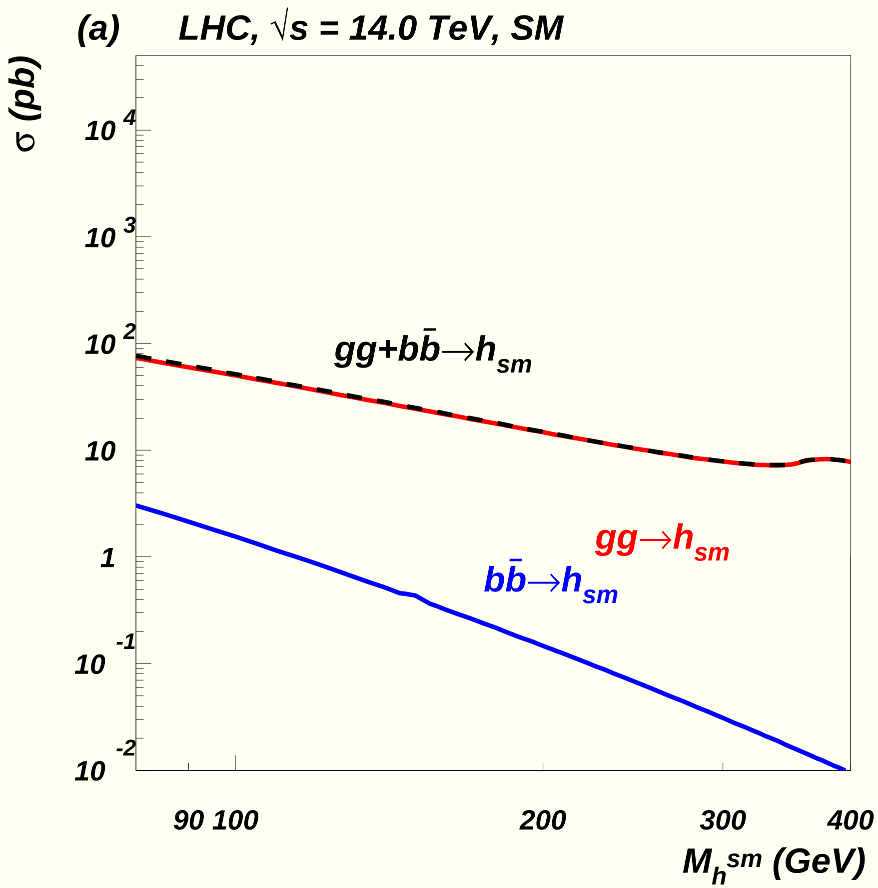

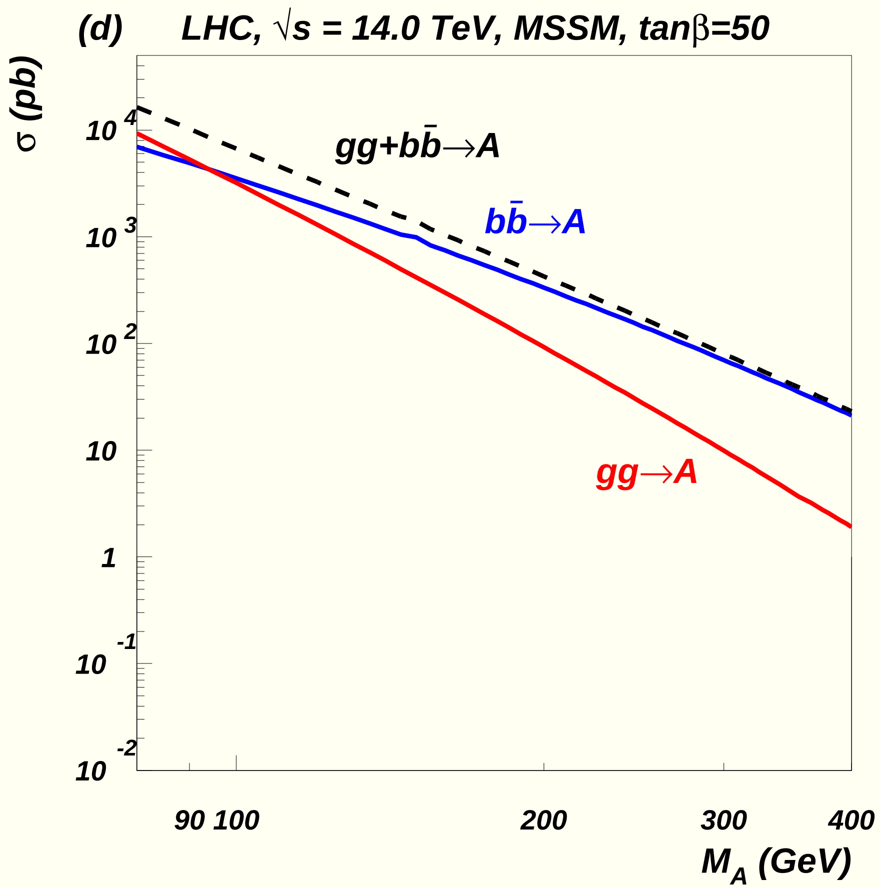

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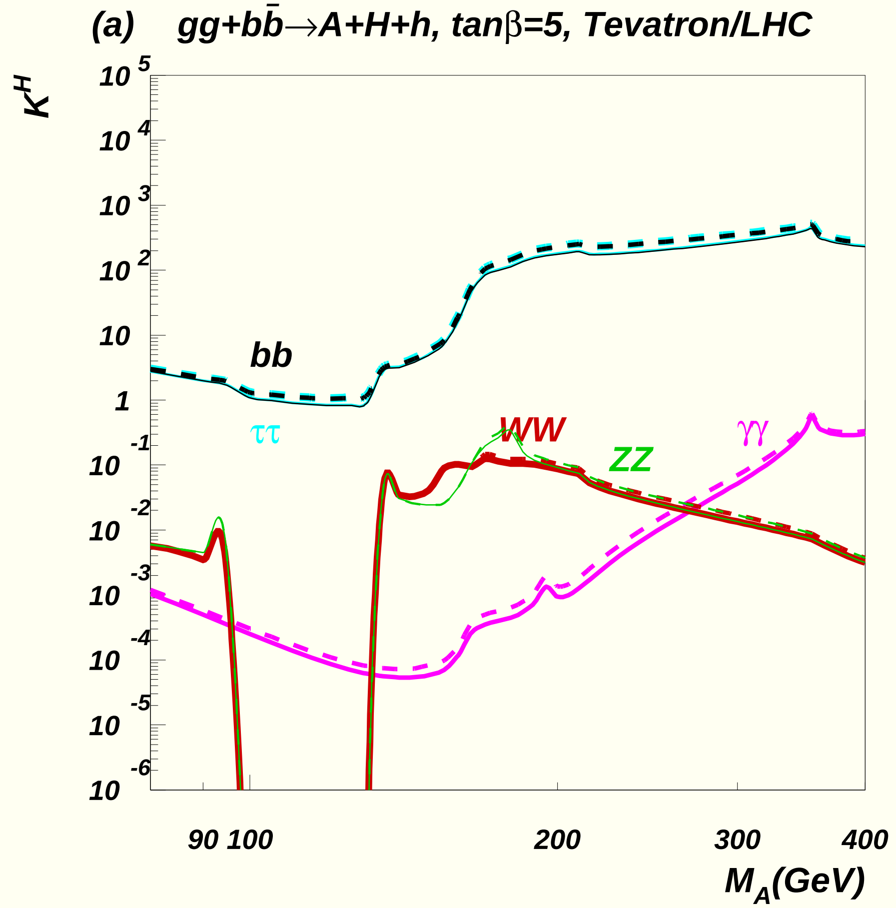

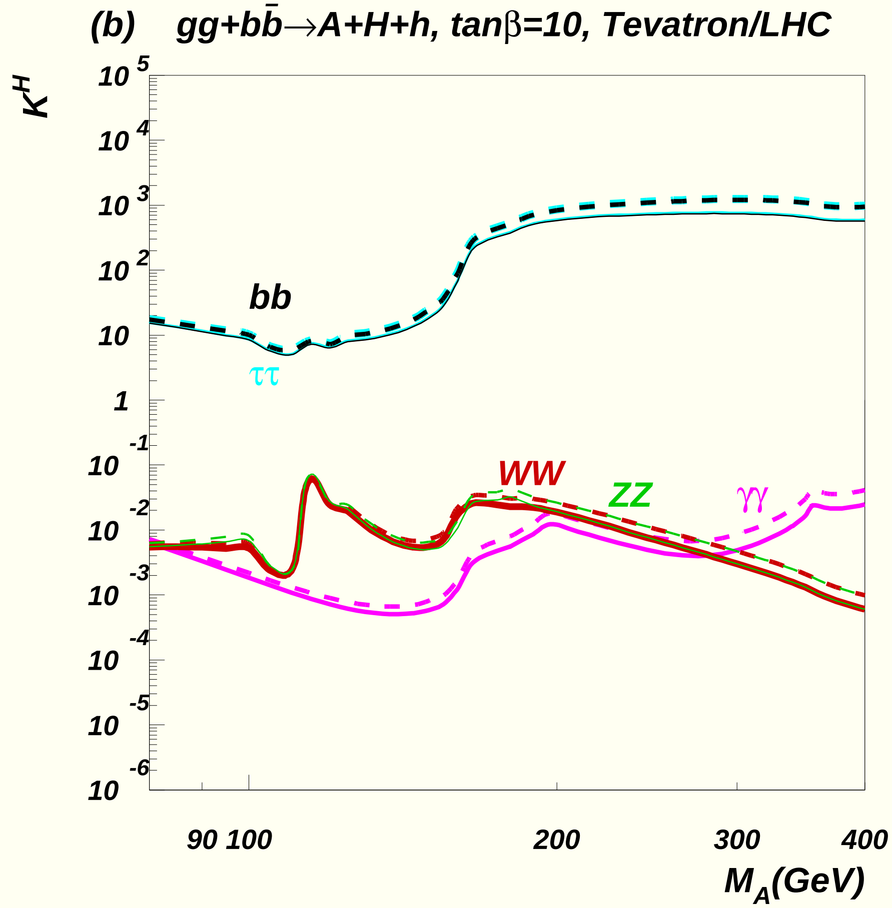

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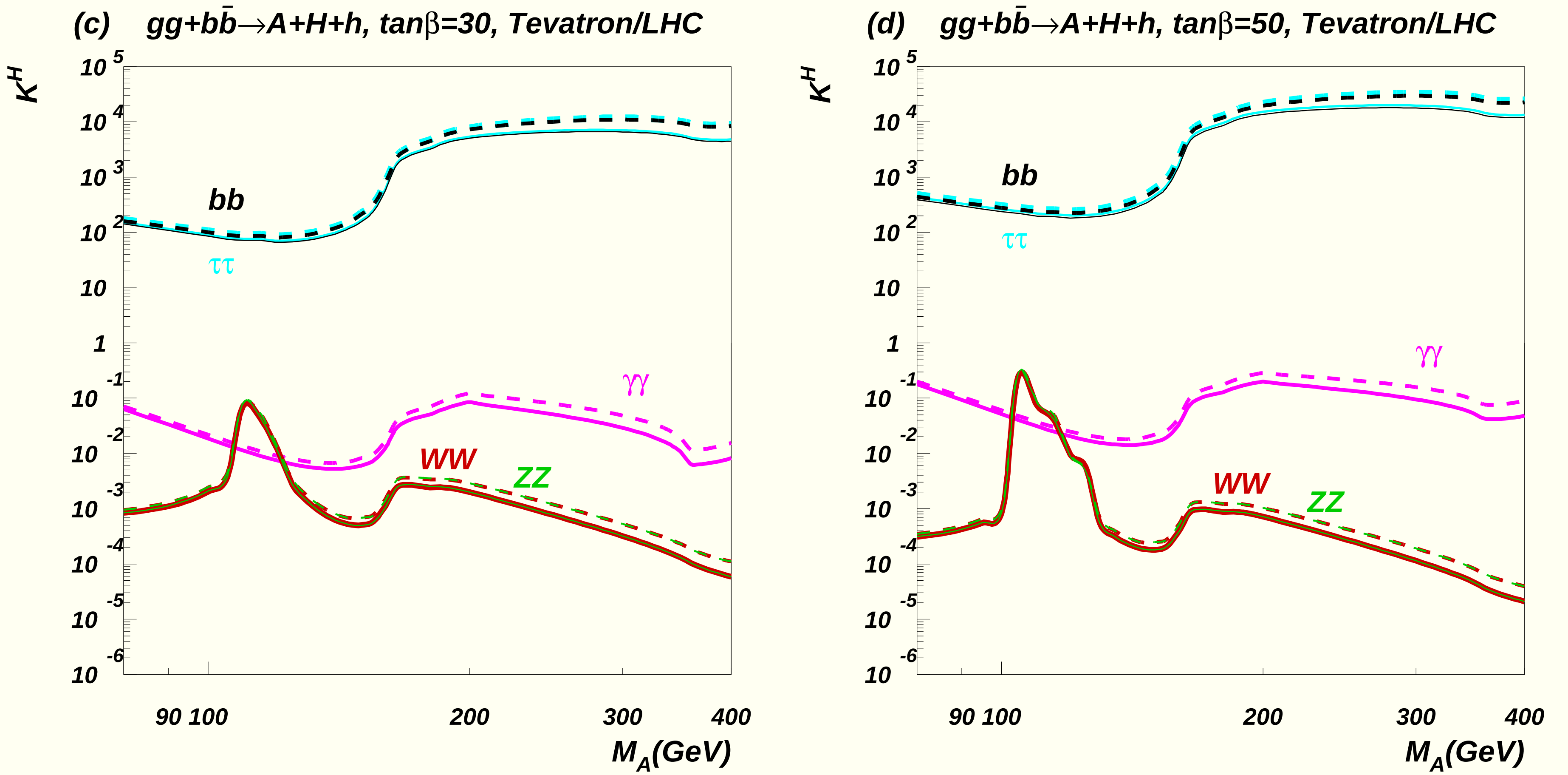

Visibility of MSSM Higgs bosons: $\tau\tau$ channel

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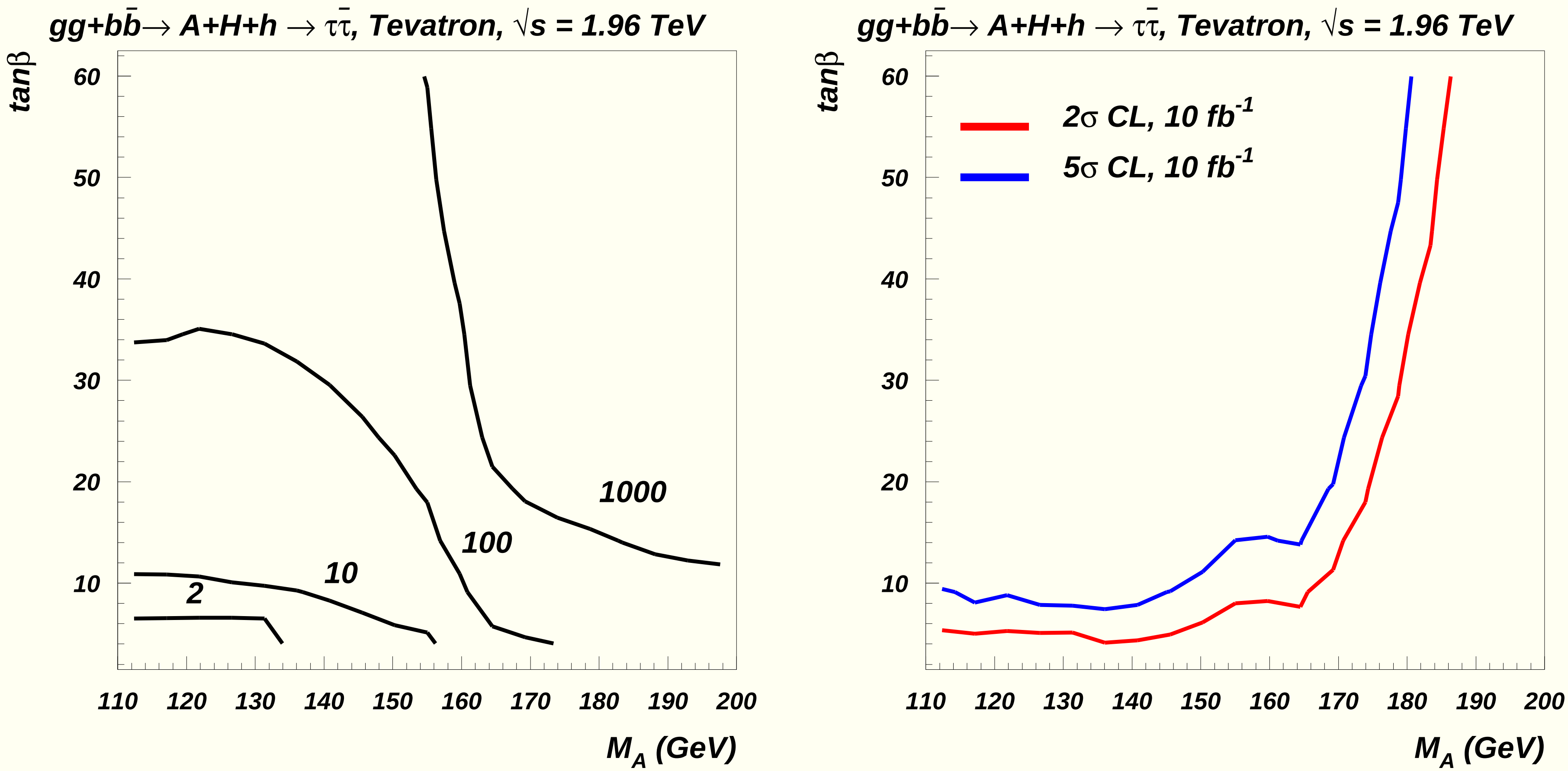
Predicted Tevatron reach, based on the $h_{SM} \rightarrow \tau^+\tau^-$ studies

by A.B., T.Han, R.Rosenfeld, hep-ph/0204210



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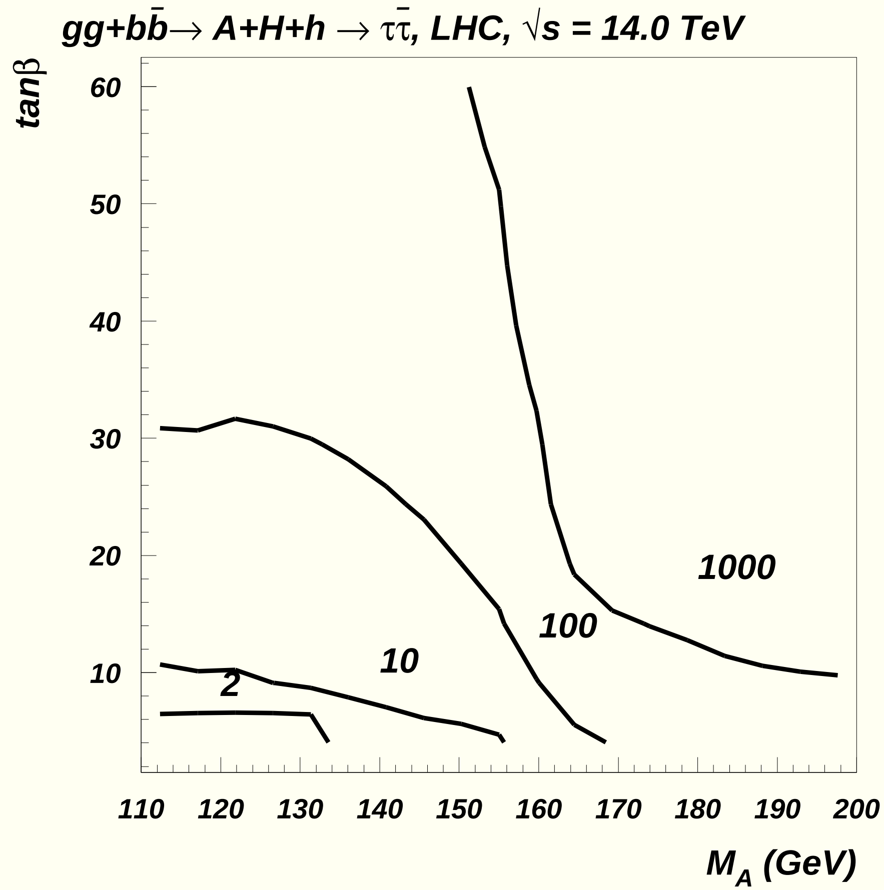
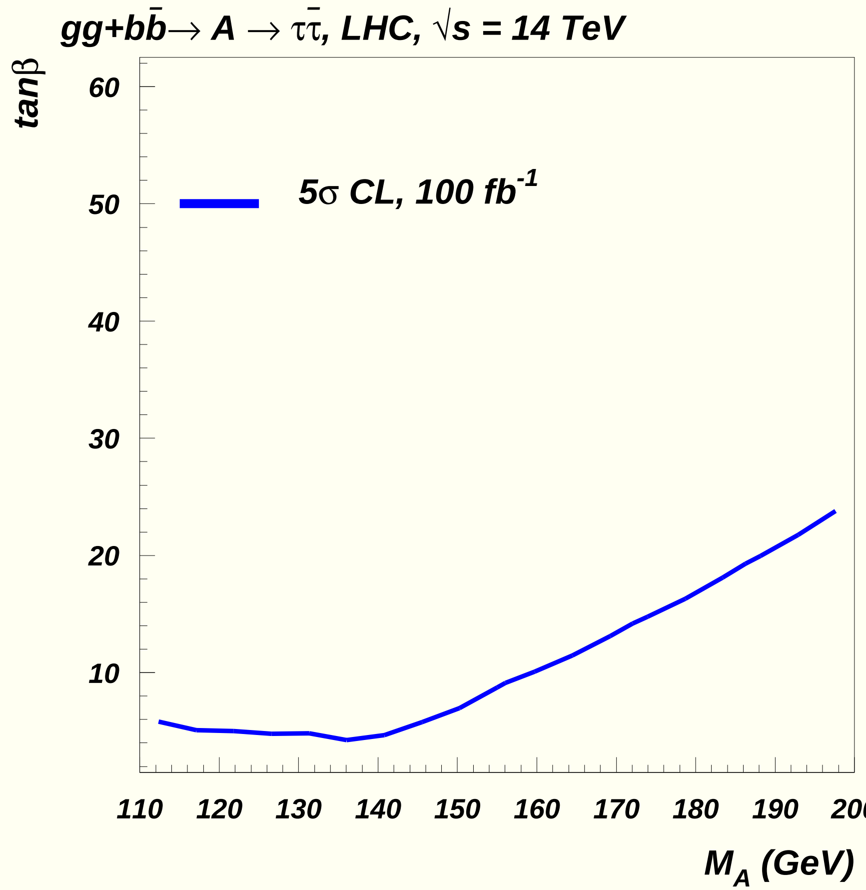




Technicolor

- Scalar states involved in EWSB are manifestly composite at scales not much above the electroweak scale $v \sim 250$ GeV
- A new asymptotically free strong gauge interaction, Technicolor, breaks the chiral symmetries of massless fermions
- the resulting condensate $\langle \bar{f}_L f_R \rangle \neq 0$ breaks the EW symmetry
- Three of the Nambu-Goldstone Bosons (technipions) of the chiral symmetry breaking become the longitudinal modes of the W and Z
- additional light neutral pseudo Nambu-Goldstone bosons, "technipions," remain in the spectrum
- we will compare the lightest technipion in each of several technicolor models with SM Higgs

Technicolor models under study

1) the traditional one-family model with a full family of techniquarks and technileptons(Farhi and Susskind, Nucl. Phys. B 155 (1979) 237.)

2) on the one-family model in which the lightest technipion contains only down-type technifermions and is significantly lighter than the other pseudo Nambu-Goldstone bosons, (Casalbuoni et al., hep-ph/9809523)

3) a multiscale walking Technicolor model designed to reduce flavor-changing neutral currents, (Lane and Ramana, Phys. Rev. D 44 (1991) 2678.)

4) low-scale Technicolor model (the Technicolor Straw Man model) with many weak doublets of technifermions, in which the second-lightest technipion P' is the state relevant for our study (the lightest, lacks the anomalous coupling to gluons) (Lane, hep-ph/9903369)

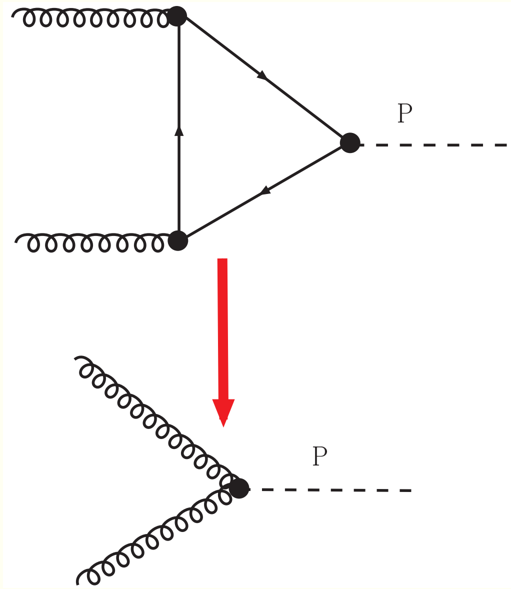
The models have different values of the technipion decay constant F_P, related to N_D of weak technifermion doublets contributing to EWSB:

$$F_P^{(1)} = \frac{v}{2}, \quad F_P^{(2)} = v, \quad F_P^{(4)} = \frac{v}{\sqrt{10}}, \quad F_P^{(3)} = \frac{v}{4}$$

Technicolor enhancement factor for production via gg

Technipions couple anomalously to pairs of gauge bosons

$$N_{TC}\mathcal{A}_{V_1V_2} \times \frac{g_1 g_2}{8\pi^2 F_P} \times \epsilon_{\mu\nu\lambda\sigma} k_1^\mu k_2^\nu \epsilon_1^\lambda \epsilon_2^\sigma$$



Thus, the technipion decay width to gluons depends on the anomaly factor $\mathcal{A}_{gg}$ and F_P

$$\Gamma(P \to gg) = \frac{m_P^3}{8\pi}\left(\frac{\alpha_s N_{TC}\mathcal{A}_{gg}}{2\pi F_P}\right)^2$$

	1) one-family	2) variant one-family	3) multiscale	4) low-scale
$\mathcal{A}_{gg}$	$\frac{1}{\sqrt{3}}$	$\frac{1}{\sqrt{6}}$	$\sqrt{2}$	$\frac{1}{\sqrt{3}}$
$\mathcal{A}_{\gamma\gamma}$	$-\frac{4}{3\sqrt{3}}$	$\frac{16}{3\sqrt{6}}$	$\frac{4\sqrt{2}}{3}$	$\frac{34}{9}$

Enhancement of the gg production rate relative to the SM Higgs is

$$\kappa_{gg\ prod} = \frac{\Gamma(P \to gg)}{\Gamma(h \to gg)} = \frac{9}{4} N_{TC}^2 \mathcal{A}_{gg}^2 \frac{v^2}{F_P^2}$$

Technicolor enhancement factor for production via $b\bar{b}$

Technipions couple to b quarks through extended technicolor (ETC) interactions.

$$\Gamma(P \to b\bar{b}) \approx \frac{3m_f^2\, m_P}{8\pi\, F_P^2}$$

In these technicolor models, the enhancement in P production via $b\bar{b}$ (over SM Higgs production via $b\bar{b}$) is smaller than the enhancement in the gg channel.

$$\frac{\kappa_{gg\ prod}}{\kappa_{bb\ prod}} \approx \frac{9}{4} N_{TC}^2 \mathcal{A}_{gg}^2$$

The overall production enhancement is therefore (for M_P = 130 GeV):

	1) one family	2) variant one-family	3) multiscale	4) low scale
$\kappa^P_{gg\ prod}$	48	6	1200	120
$\kappa^P_{bb\ prod}$	4	0.67	16	10
κ^P_{prod}	47	5.9	1100	120

Technipion branching fractions compared with SM Higgs

The main difference is the lack of a technipion decay to W bosons, which is generally made up for by an increased branching fraction into gg.
Below, we take M_P = 130 GeV.

Decay Channel	1) one family	2) variant one family	3) multiscale	4) low scale	SM Higgs
$b\bar{b}$	0.60	0.53	0.23	0.60	0.53
$c\bar{c}$	0.05	0	0.03	0.05	0.02
$\tau^+\tau^-$	0.03	0.25	0.01	0.03	0.05
gg	0.32	0.21	0.73	0.32	0.07
$\gamma\gamma$	2.7×10^{-4}	2.9×10^{-3}	6.1×10^{-4}	6.4×10^{-3}	2.2×10^{-3}
W^+W^-	0	0	0	0	0.29

Technipion enhancement factors and $\sigma(pp/p\bar{p} \to P \to xx)$

Comparison of the production and decay columns below shows that most of the total enhancement of the cross-section relative to the SM comes from the production rate. Below, we take M_P = 130 GeV.

Model	Decay mode	κ^P_{prod}	κ^P_{dec}	$\kappa^P_{tot/xx}$	σ at Tevatron	σ at LHC
1) one family	$b\bar{b}$	47	1.1	52	14 pb	890 pb
	$\tau^+\tau^-$	47	0.6	28	0.77 pb	48 pb
	$\gamma\gamma$	47	0.12	5.6	.0064 pb	0.4 pb
2) variant one family	$b\bar{b}$	5.9	1	5.9	1.8 pb	100 pb
	$\tau^+\tau^-$	5.9	5	30	0.84 pb	52 pb
	$\gamma\gamma$	5.9	1.3	7.7	.0087 pb	0.55 pb
3) multiscale	$b\bar{b}$	1100	0.43	470	130 pb	8000 pb
	$\tau^+\tau^-$	1100	0.2	220	6.1 pb	380 pb
	$\gamma\gamma$	1100	0.27	300	0.34 pb	22 pb
4) low scale	$b\bar{b}$	120	1.1	130	36 pb	2200 pb
	$\tau^+\tau^-$	120	0.6	72	2 pb	120 pb
	$\gamma\gamma$	120	2.9	350	0.4 pb	25 pb

Visibility of Technipions: $\tau\tau$ *and* $\gamma\gamma$ *channels*

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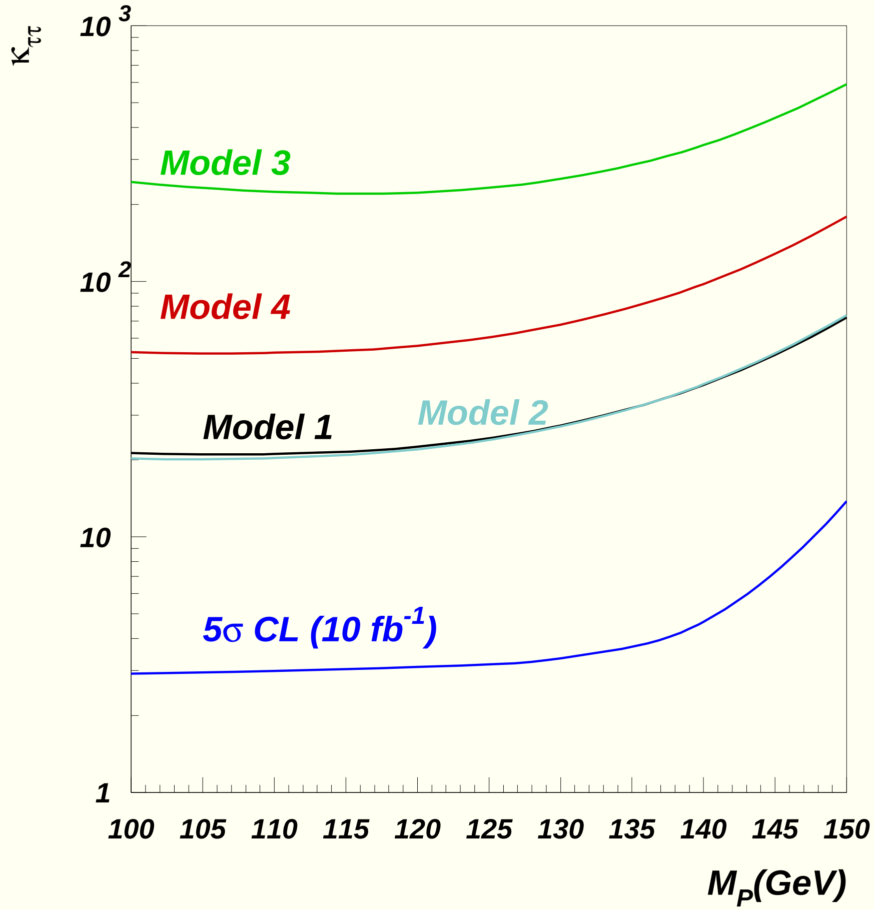
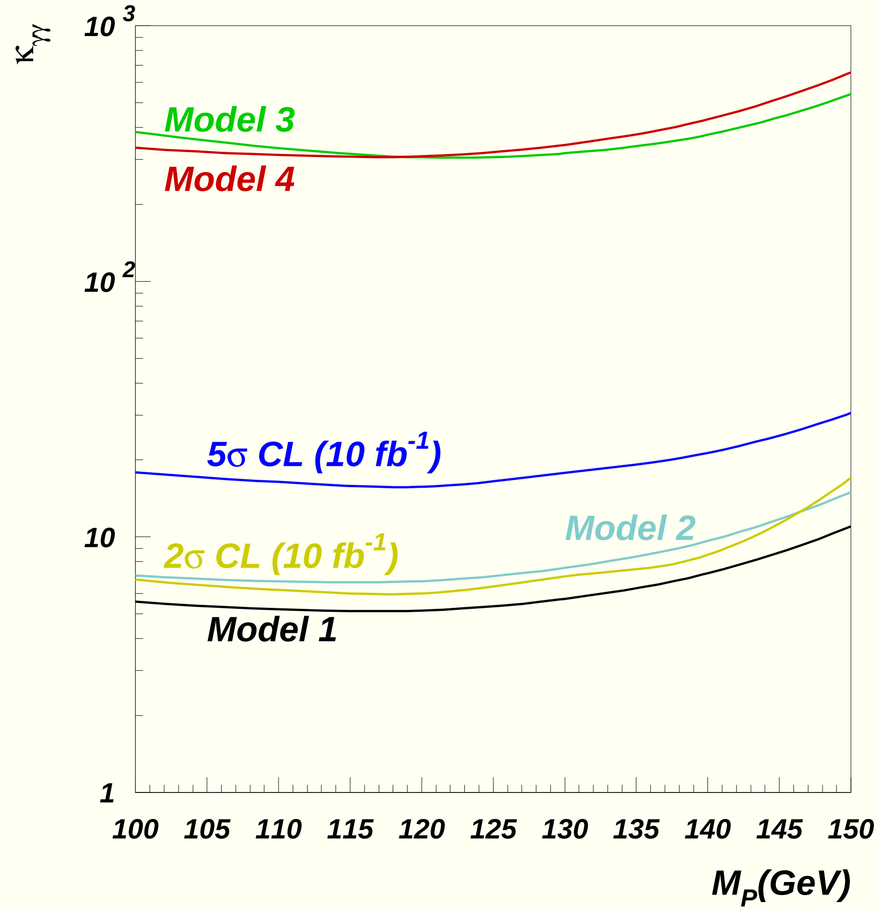
Predicted Tevatron reach, based on the $h_{SM} \to \tau^+\tau^-$ studies by A.B., T.Han, R.Rosenfeld, hep-ph/0204210 and on the $h_{SM} \to \gamma\gamma$ studies by S. Mrenna and J. D. Wells,hep-ph/0001226





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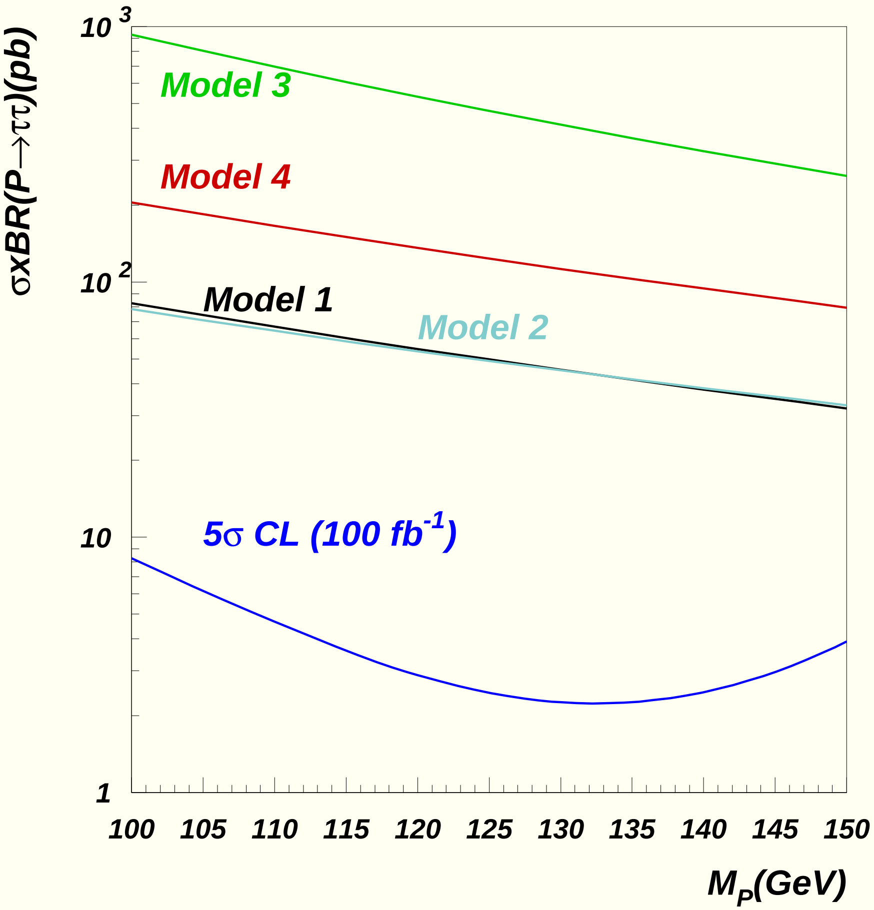
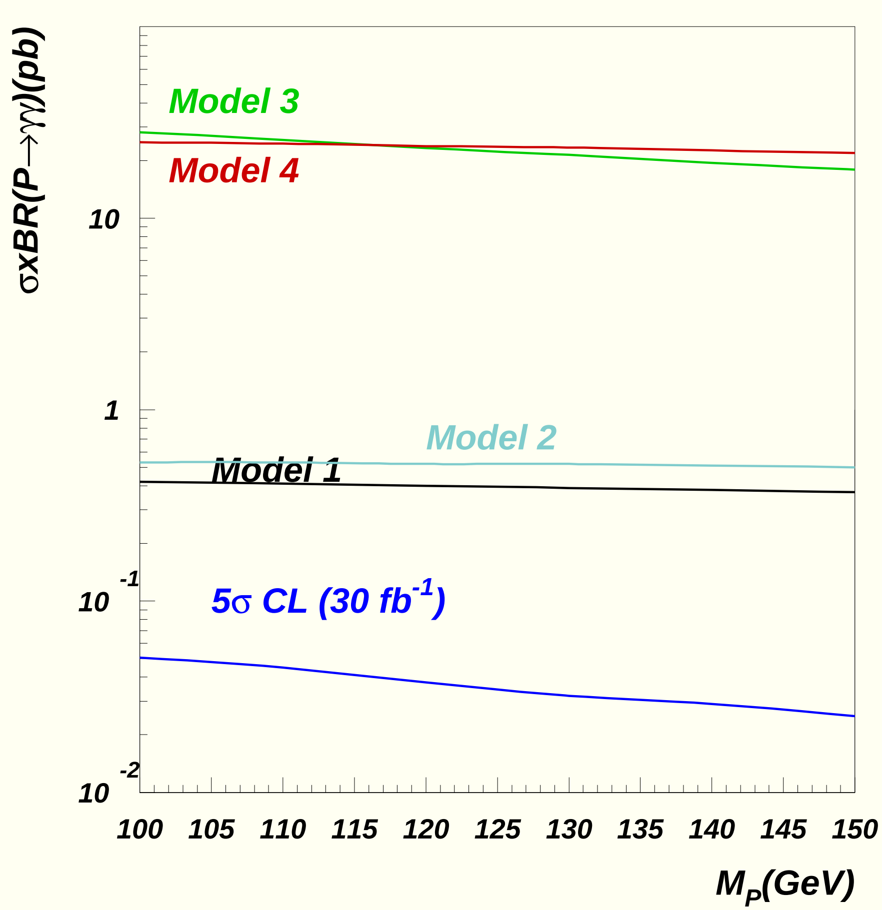
R. Kinnunen, S. Lehti, A. Nikitenko and P. Salmi,hep-ph/0503067

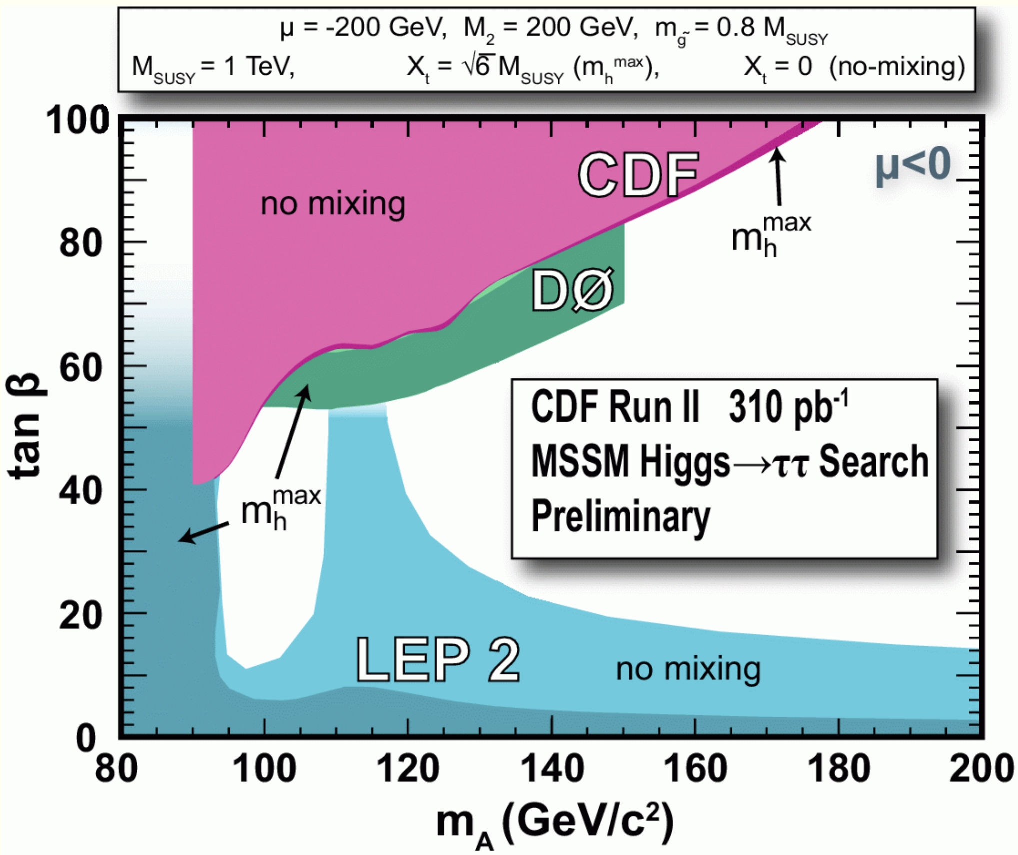


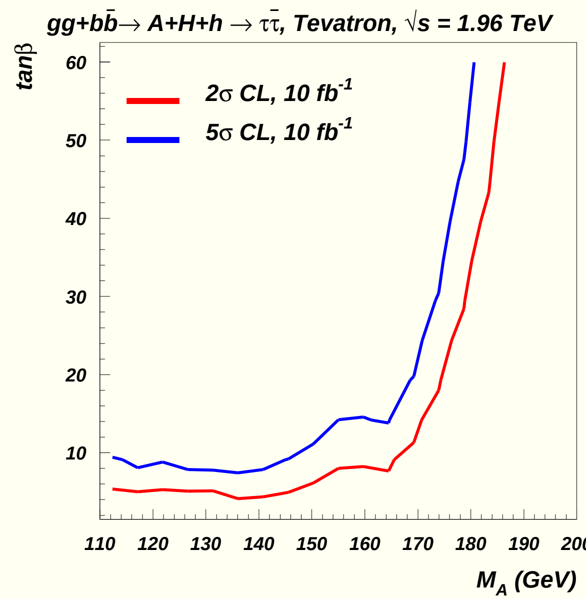


The Meaning of "Higgs": SUSY vs. Technicolor

- The Tevatron and LHC have the potential to observe the light (pseudo) scalar states of both supersymmetric and dynamical symmetry breaking (DSB) models in the $\tau^+\tau^-$ channel.
- In the MSSM, the $\tau^+\tau^-$ channel is enhanced but the $\gamma\gamma$ channel is suppressed: even the LHC would not observe the $\gamma\gamma$ signature.
- In the dynamical symmetry breaking models studied, we expect simultaneous enhancement of both the $\tau^+\tau^-$ and $\gamma\gamma$ channels. Even at the Tevatron we may observe technipions via the $\gamma\gamma$ signature at the 5σ level for Models 3 and 4
- The LHC collider, which will have better sensitivity to the signatures under study, will be able to find the technipions of all four DSB models.
- In the MSSM, scalar production via $b\bar{b}$ fusion can rival gg fusion; in DSB models, $b\bar{b}$ fusion should be negligible. Exploiting this difference (e.g. study H production in association with b-quarks) may prove useful.

Results from CDF and D0 (from Anton Anastassov)





Conclusions

- *Searches for a light Standard Model Higgs boson at Tevatron Run II and CERN LHC can also shed light on physics beyond the SM.*
- *New scalar and pseudo-scalar states predicted in both supersymmetric and dynamical models can have enhanced visibility in standard $\tau^+\tau^-$ and $\gamma\gamma$ search channels making them potentially discoverable at both Run II and the LHC.*
- *The enhancement arises largely from increases in the production rate*
- *The model parameters exerting the largest influence on the enhancement size are $\tan\beta$ in the case of the MSSM and N_{TC} and F_P in the case of dynamical symmetry breaking.*
- *Observation of $pp/p\bar{p} \to \mathcal{H} \to \tau^+\tau^-$ covers a large parameter space*
- *$pp/p\bar{p} \to \mathcal{H} \to \gamma\gamma$ may cleanly distinguish the scalars of supersymmetric models from those of dynamical models.*