Towards understanding the nature of Electroweak Symmetry Breaking at hadron colliders

Alexander Belyaev
Michigan State University
Department of Physics and Astronomy

First Meeting 16 - 18 Sept. '04 Fermilab • Midterm meetings at Brookhaven & CERN • Final meeting at Fermilab, Fall '05

TeV4LHC WORKSHOP

Using the data & experience
from the Tevatron
to prepare for the LHC

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Working Groups
QCD, Top & Electroweak Physics,
Higgs, and Physics Landscape.

Contacts: Cynthia M. Sazama (FNAL)
sazama@fnal.gov • tev4lhc-org@fnal.gov

Information & Registration: http://conferences.fnal.gov/tev4lhc/

Outline

- *Understanding the origin of Electroweak Symmetry Breaking(EWSB): where we are?*
- *Why do we need a New Physics?*
- *Inclusive Higgs production at hadron colliders: New Physics versus SM*
- *Distinguishing SUSY from Technicolor models*
- *Conclusions*

Collaborators:

A.Blum, S.Chivukula, E.Simmons

"The meaning of Higgs: $\tau\bar{\tau}$ and $\gamma\gamma$ at the Tevatron and the LHC",hep-ph/0506086

Electroweak Symmetry Breaking

- status of theory of electro-weak interactions: permil precision measurements confirm its $SU(2)_L \times U(1)_Y$ gauge structure
- Unbroken Yang-Mills theory $\Rightarrow$ vector bosons are massless
- Eventually it is not the case since $W^{\pm}$ and Z bosons are massive
- Explicit introduction of the massive gauge bosons breaks gauge invariance of the theory $\Rightarrow$ must be spontaneously broken
- In general, there are serious problems in any Lorentz-invariant theory of massive vector bosons, unless those particles are Yang-Mills bosons and the gauge symmetry is spontaneously broken

  Nambu,Anderson; Higgs; Englert,Brout; Guralnik, Hagen,Kibble;...
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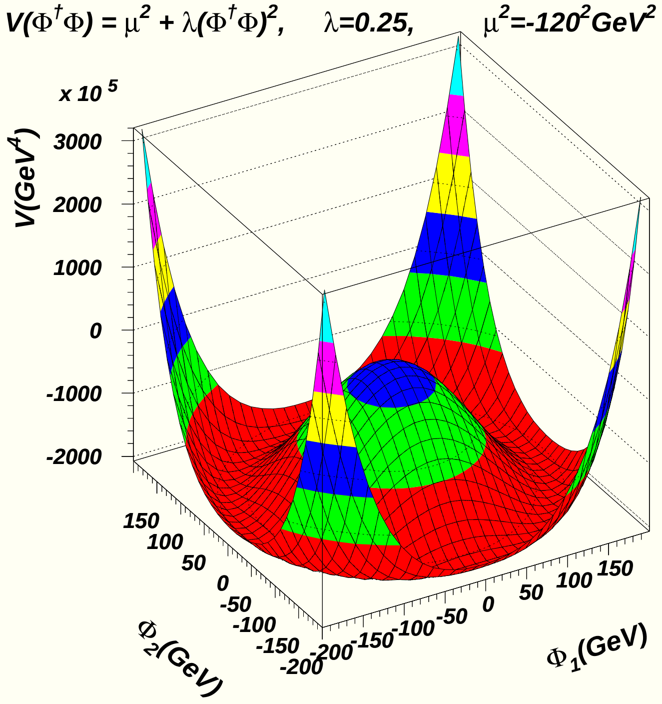
  - *Higgs mechanism?*
  - *Dynamical symmetry breaking (Technicolor)?*
  - *Extra dimensions?*
  - *...?*

Higgs Mechanism: $SU(2)_L \times U(1)_Y \to U(1)_Q$



$$\mathcal{L}_{\text{scalar}} = (D^\mu\Phi)^\dagger D_\mu\Phi - \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

Φ ***acquires non-zero, degenerate minimum if***

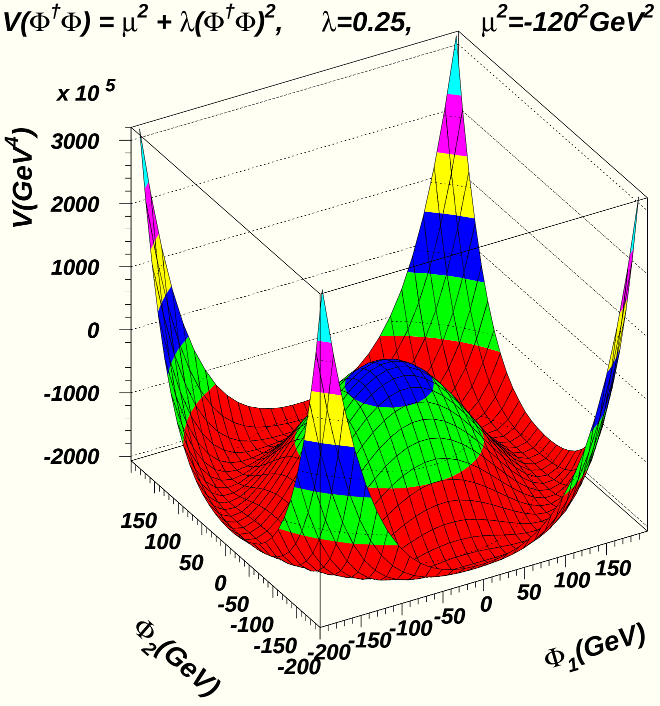
$\mu^2 < 0, \lambda > 0$ ***. The choice of*** $\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$

with $v = \sqrt{\frac{-\mu^2}{\lambda}}$ ***breaks the symmetry.***

$$\mathcal{L}_{\text{scalar}} =$$

$$\frac{g^2v^2}{4} W^+_\mu W^{-\mu} + \frac{1}{2}\frac{g^2v^2}{4\cos^2\theta_W} Z_\mu Z^\mu - \frac{1}{2}\left(-2\mu^2\right) H^2 + \frac{\mu^2}{v}H^3 + \frac{\mu^2}{4v^2}H^4 + \ldots$$

$$v = 2M_W/g \simeq 246\ GeV, \quad M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}v \simeq \sqrt{\lambda}\ 350\text{GeV}$$



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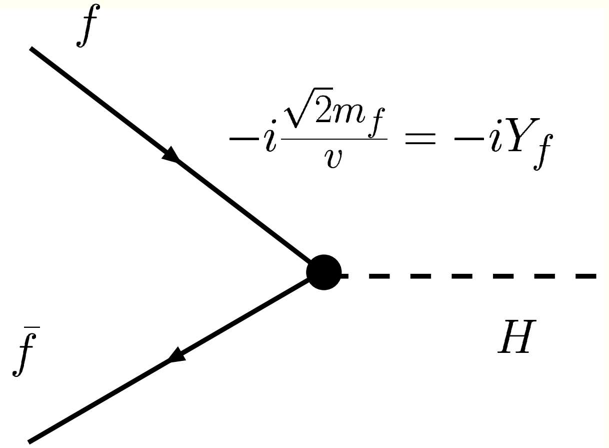
$$\mathcal{L}_{Yukawa} = -Y_u \bar{Q}_L \Phi^c u_R - Y_d \bar{Q}_L \Phi d_R - Y_\ell \bar{L}_L \Phi l_R + h.c.$$

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \Rightarrow m_f = Y_f \frac{v}{\sqrt{2}}$$



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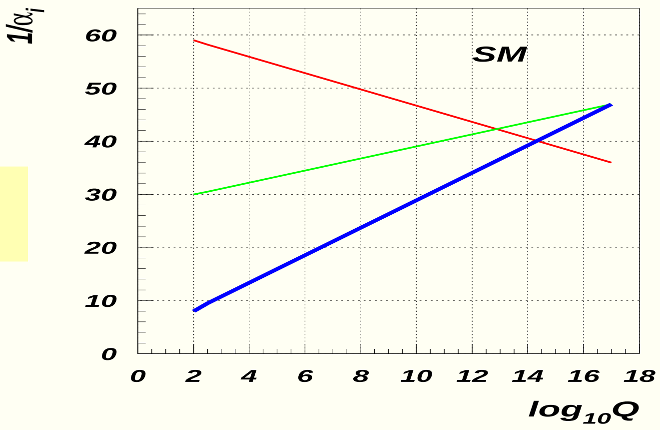

- **Theoretical problems**
  - naturalness and gauge hierarchy problem

    $$M_H^2 = M_{H^0}^2 + \Delta M_H, \quad \text{SM: } \Delta M_H \sim \Lambda_{UV}^2$$

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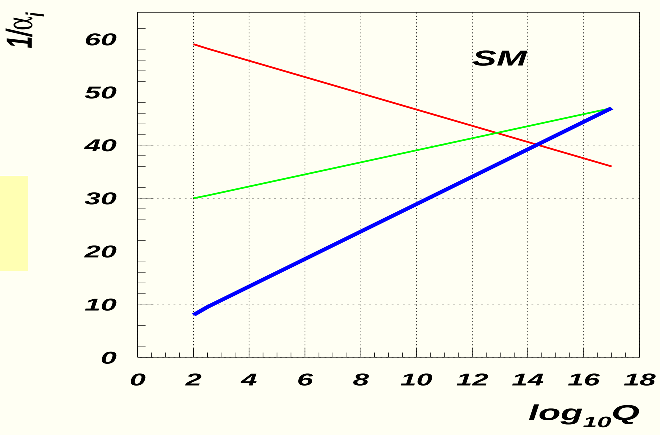

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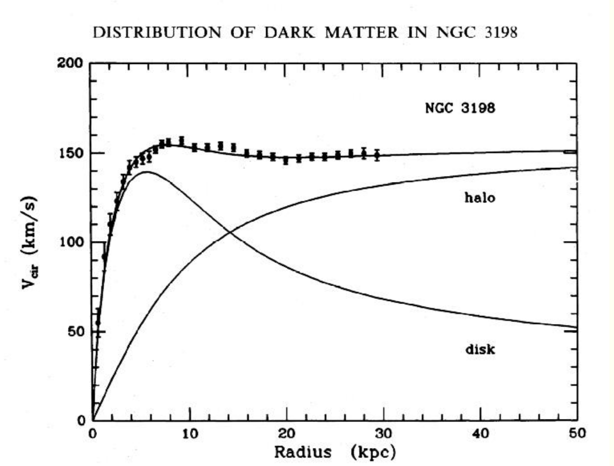
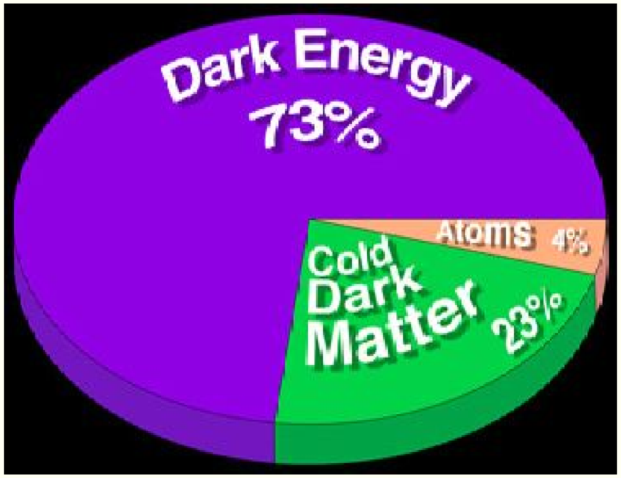
- **Experimental Problems**
  - Does not explain Dark Matter (WMAP results, galactic rotation curves, gravitational lensing)


DISTRIBUTION OF DARK MATTER IN NGC 3198


Gravitational Lens HST · WFPC2
Galaxy Cluster 0024+1654
PRC96-10 · ST ScI OPO · April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA



  - Baryogenesis: the amount of CP violation is not enough because it predicts baryon asymmetry 10 orders of magnitude below the observed one

Supersymmetry is the perfect solution!

- *provides cancellation of quadratic divergences, gauge couplings unification, perfect DM candidate, EW baryogenesis (SO(10) SUSY GUTS)*
- *each ordinary fermion (boson) is paired with a new boson (fermion)*
- *two Higgs doublets*
  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* $\Phi_u = (\Phi_u^+, \Phi_u^0)$*:*
- *relates the scalar self-coupling to gauge couplings* $\Rightarrow$ M_H *is predicted!*

$$\langle\Phi_d\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_d \\ 0 \end{pmatrix}, \quad \langle\Phi_u\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_u \end{pmatrix}, \quad \sqrt{v_d^2 + v_u^2} = 2M_W/g = 246 \text{ GeV.}$$

Higgs sector and Yukawa interactions im MSSM

8 degrees of freedom, 3 serve as Goldstone bosons, absorbed into longitudinal components of the $W^\pm$ and Z, 5 degrees of freedom remains:

two neutral, CP-even states: h, H (mixing α)

one neutral, CP-odd state: A

a charged pair: $H^\pm$

$\tan\beta = v_u/v_d$ and M_A define the Higgs sector at tree level

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

$$\begin{aligned} Y_{ht\bar t}/Y^{SM}_{ht\bar t} &= \cos\alpha/\sin\beta & \qquad Y_{hb\bar b}/Y^{SM}_{hb\bar b} &= -\sin\alpha/\cos\beta \\ Y_{Ht\bar t}/Y^{SM}_{ht\bar t} &= \sin\alpha/\sin\beta & \qquad Y_{Hb\bar b}/Y^{SM}_{hb\bar b} &= \cos\alpha/\cos\beta \\ Y_{At\bar t}/Y^{SM}_{ht\bar t} &= \cot\beta & \qquad Y_{Ab\bar b}/Y^{SM}_{hb\bar b} &= \tan\beta \end{aligned}$$

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$$

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

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

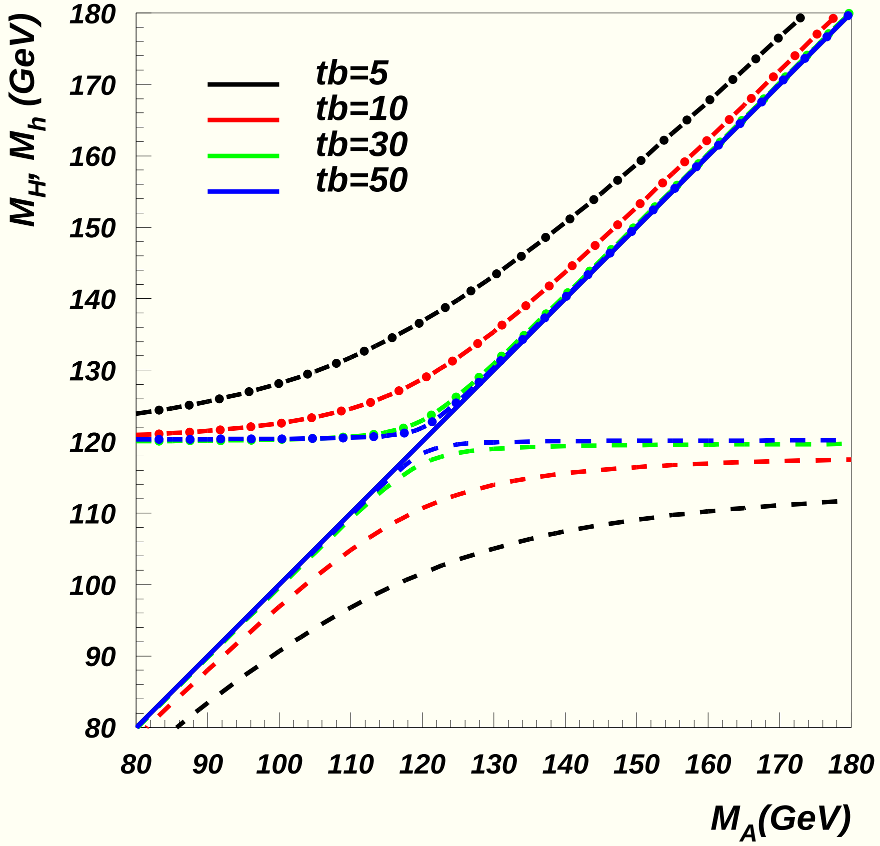
$(Y_{hb\bar b}, Y_{Ab\bar b})$ or $(Y_{hb\bar b}, Y_{Ab\bar b})$ are enhanced at large $\tan\beta$!

New factors affecting signal strength in comparison with SM

Enhancement factor for the process $yy \to \mathcal{H} \to xx$ can be defined as

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

- $\mathcal{H} = (h, H, A)$ Two or three neutral Higgs bosons could be degenerate and contribute to the same signature (we require $|M_A - M_h|$ and/or $|M_A - M_H|$ to be less than 0.3$\sqrt{M_A/GeV}$ GeV)



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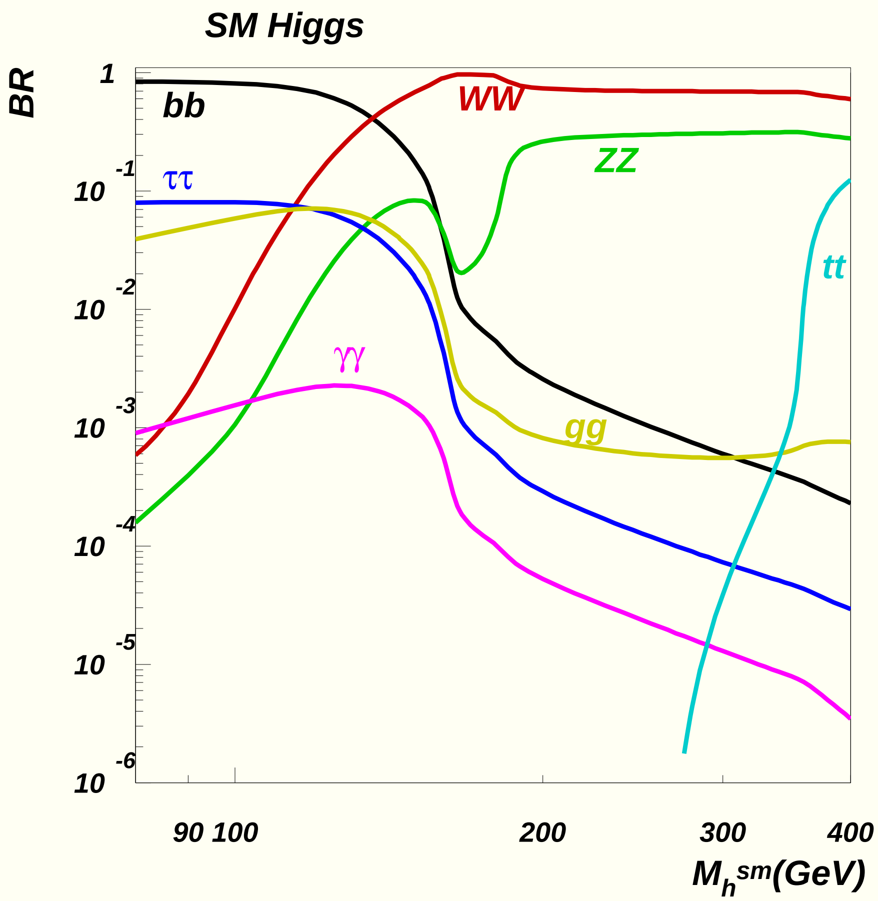

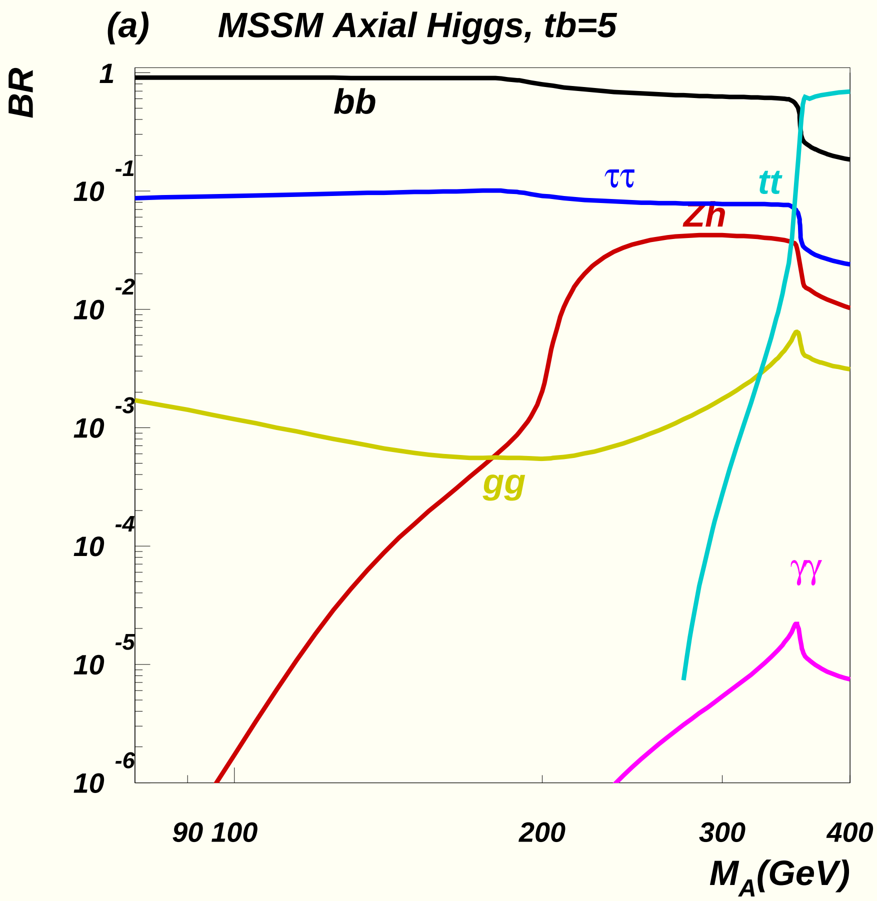

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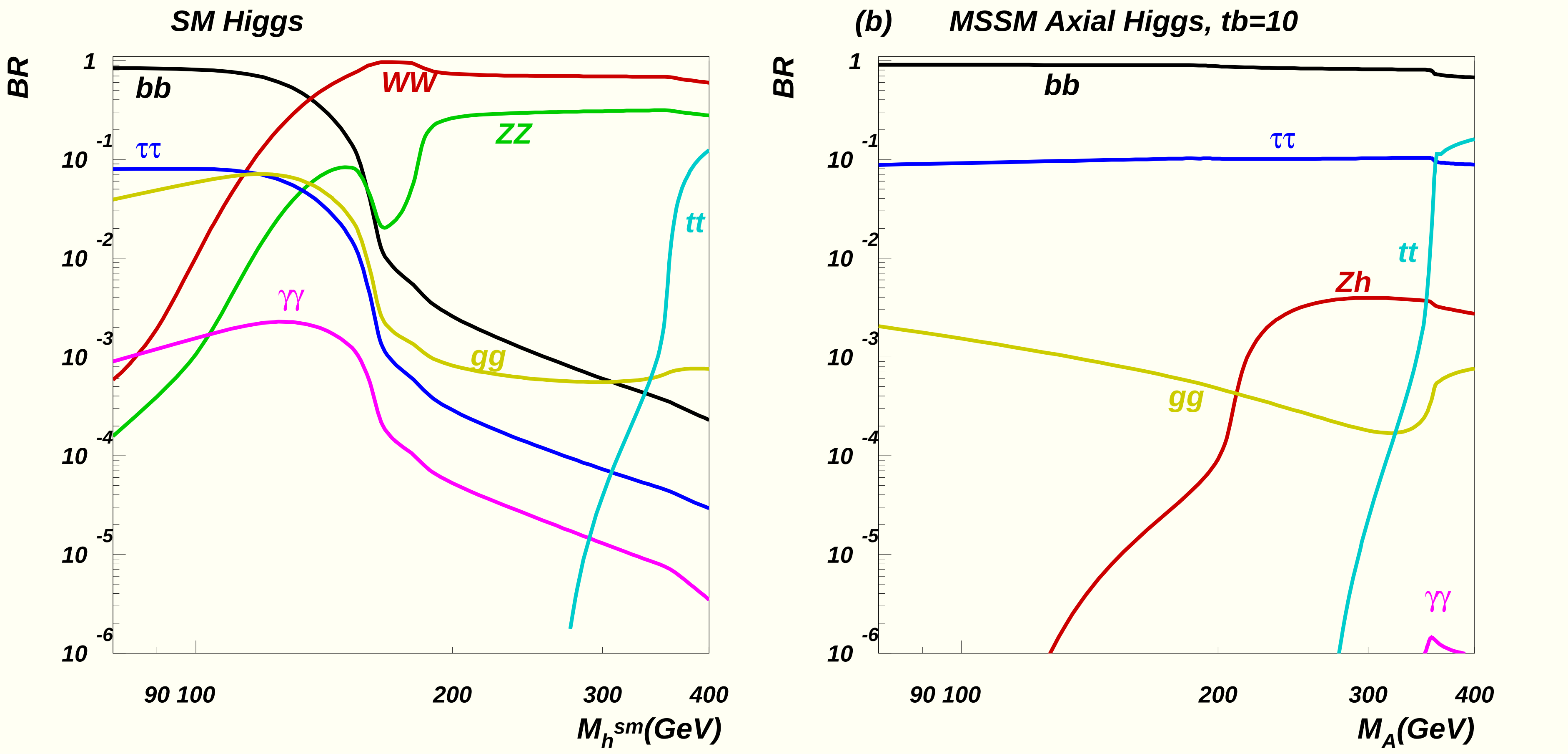

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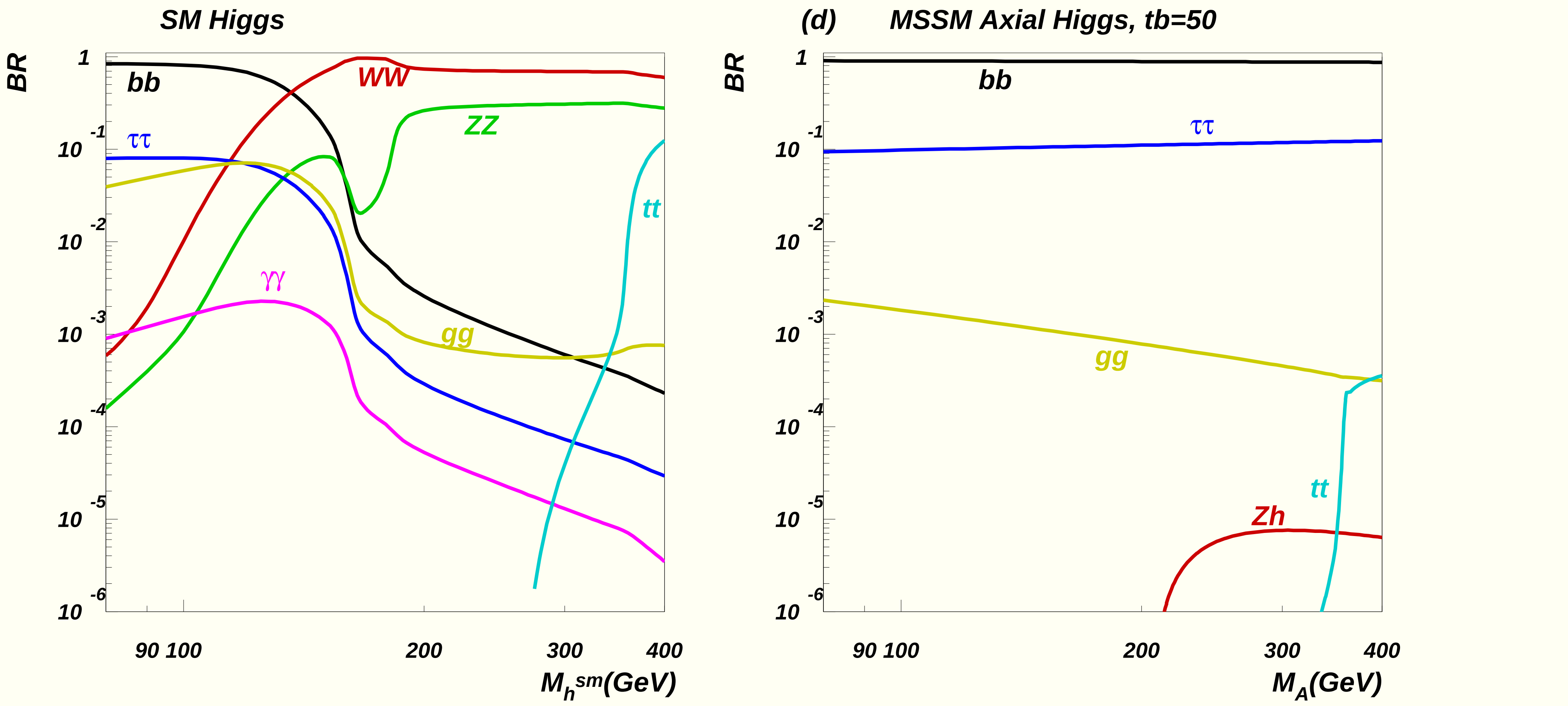

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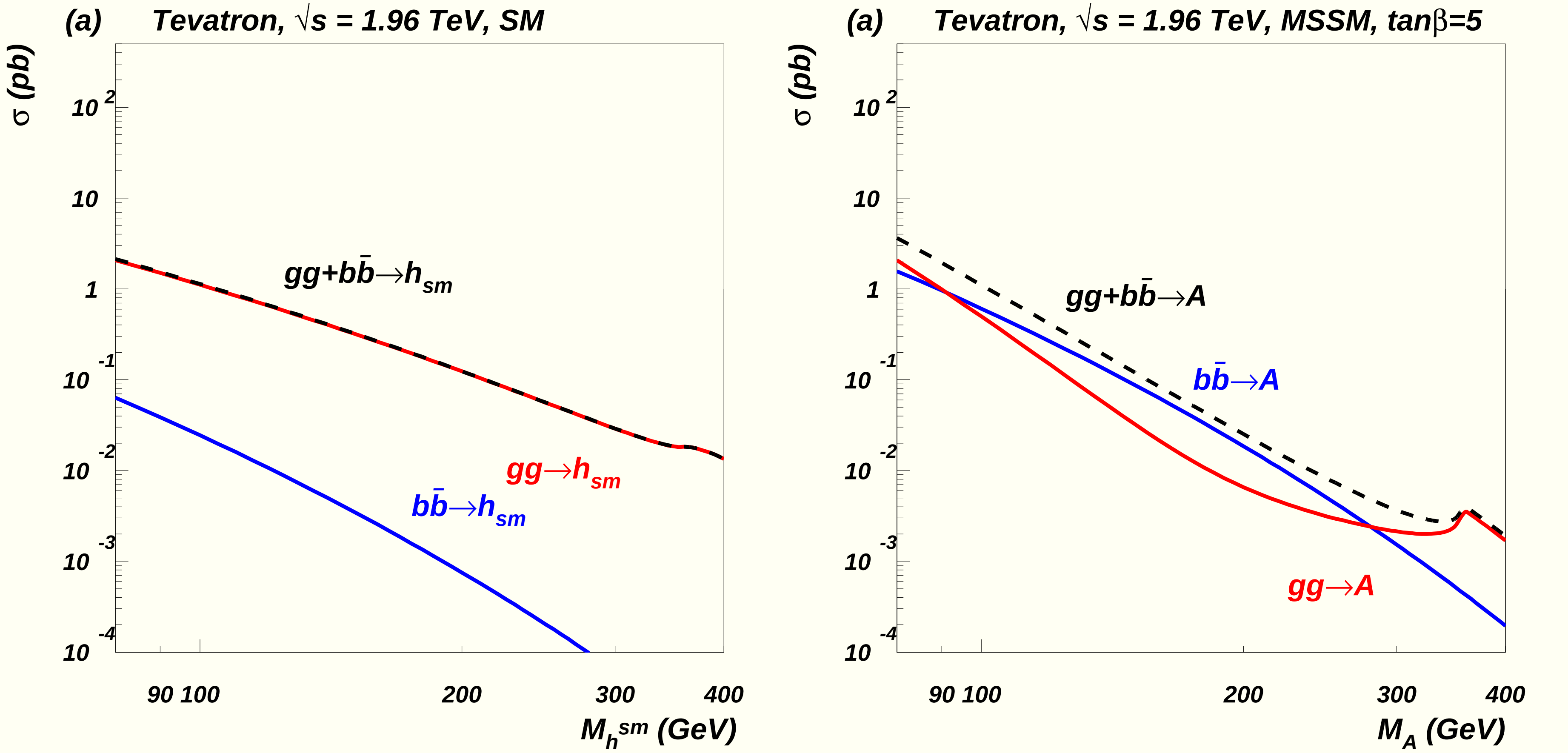

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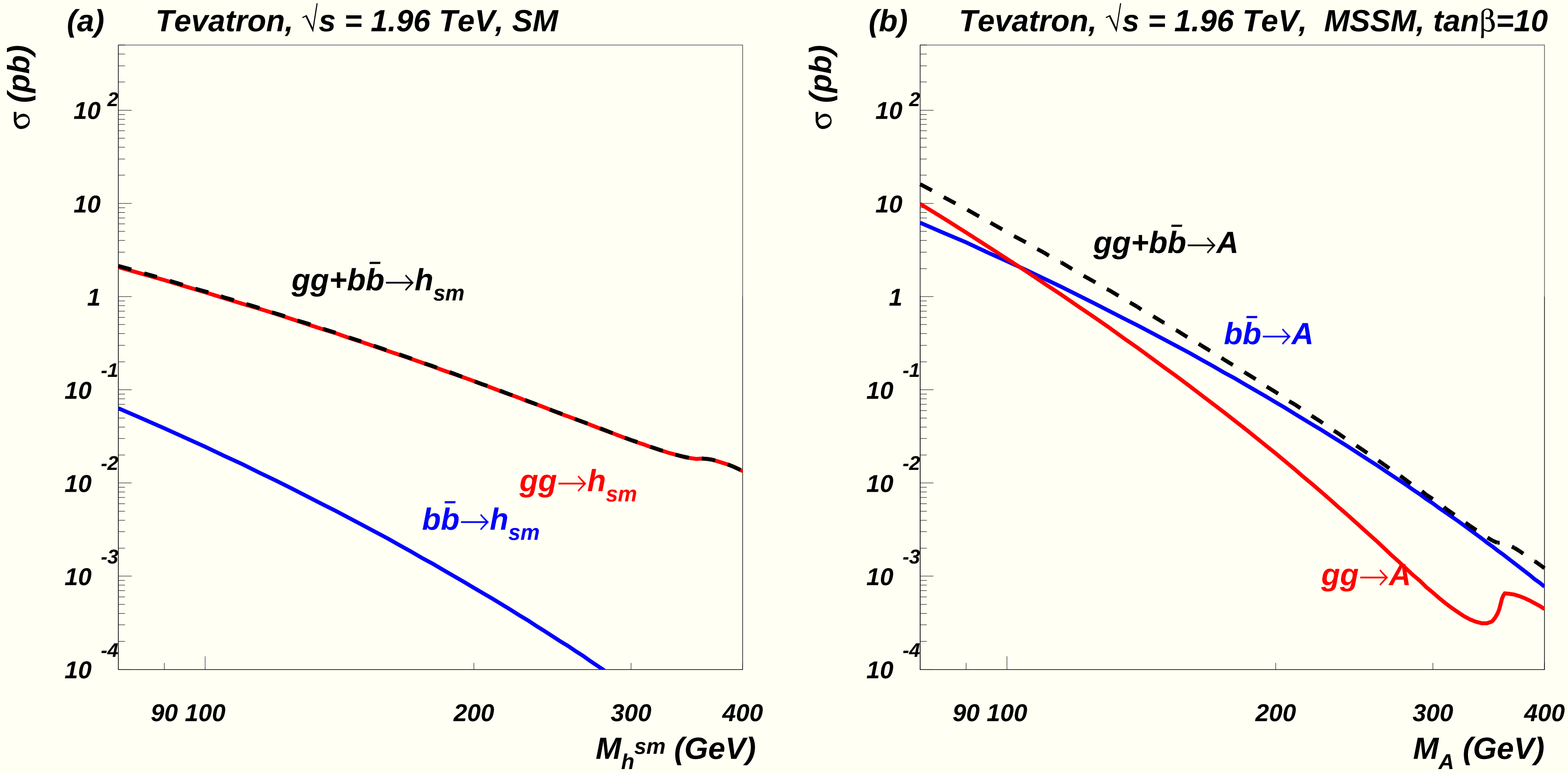

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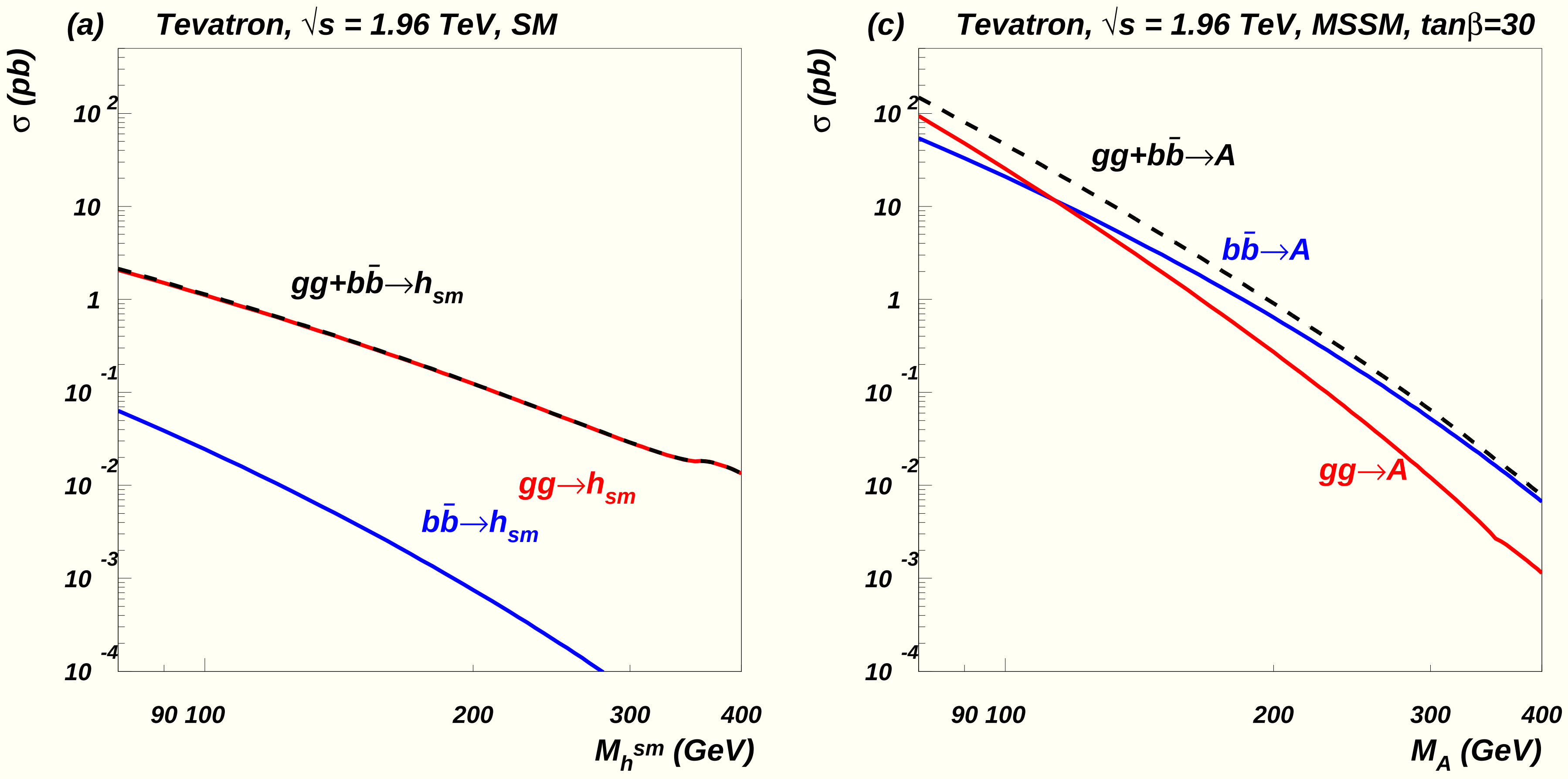

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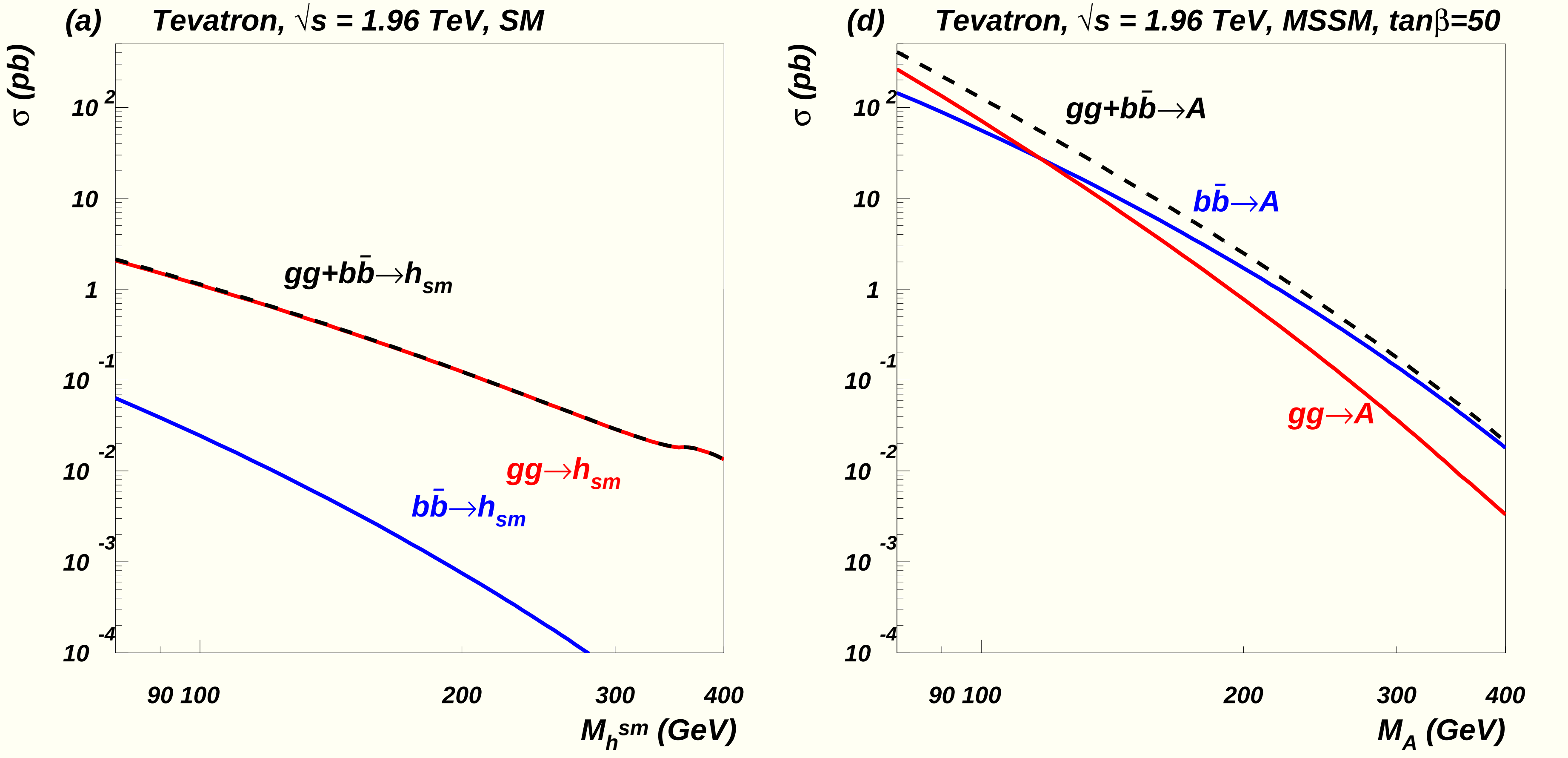

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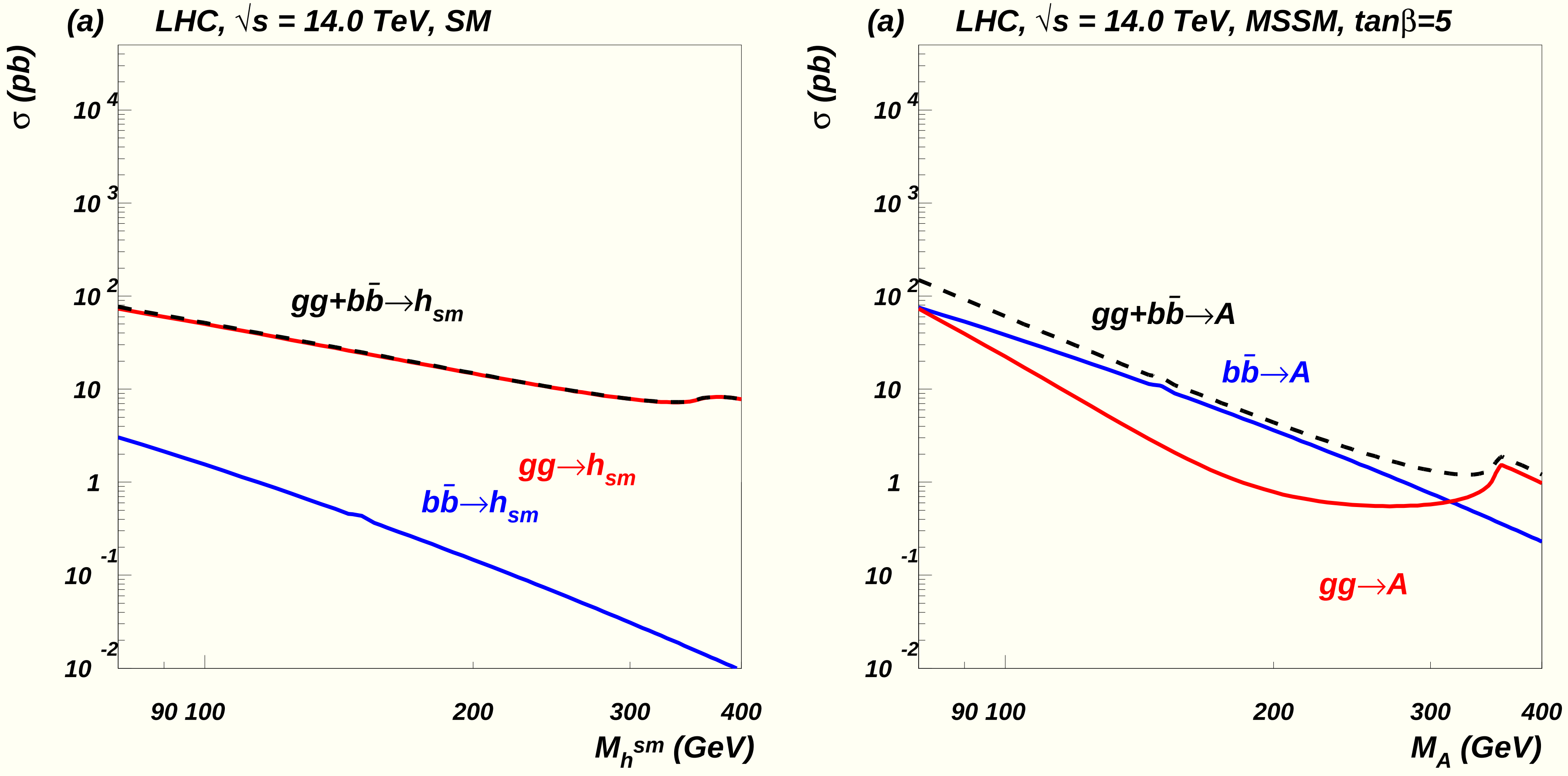

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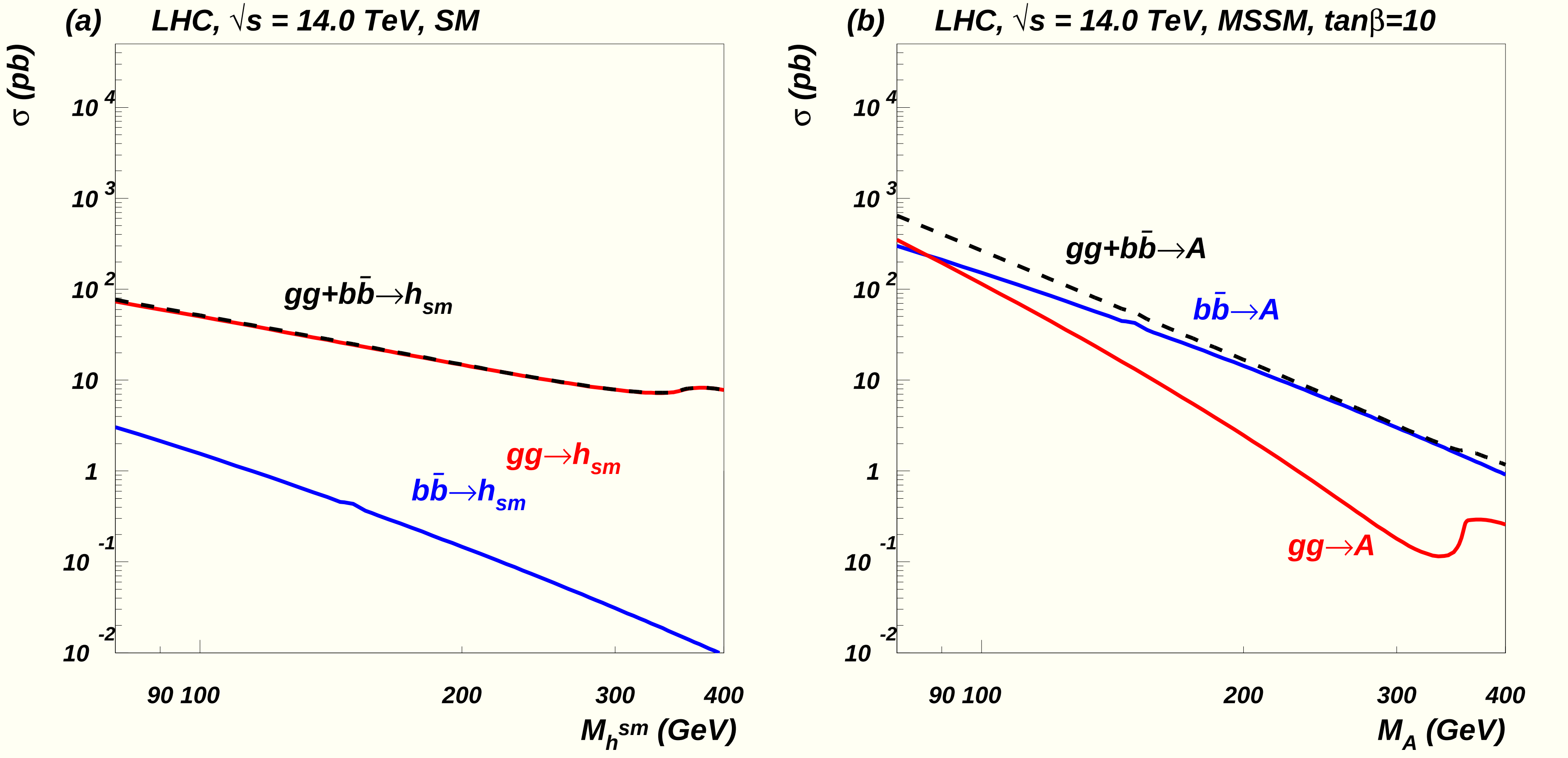

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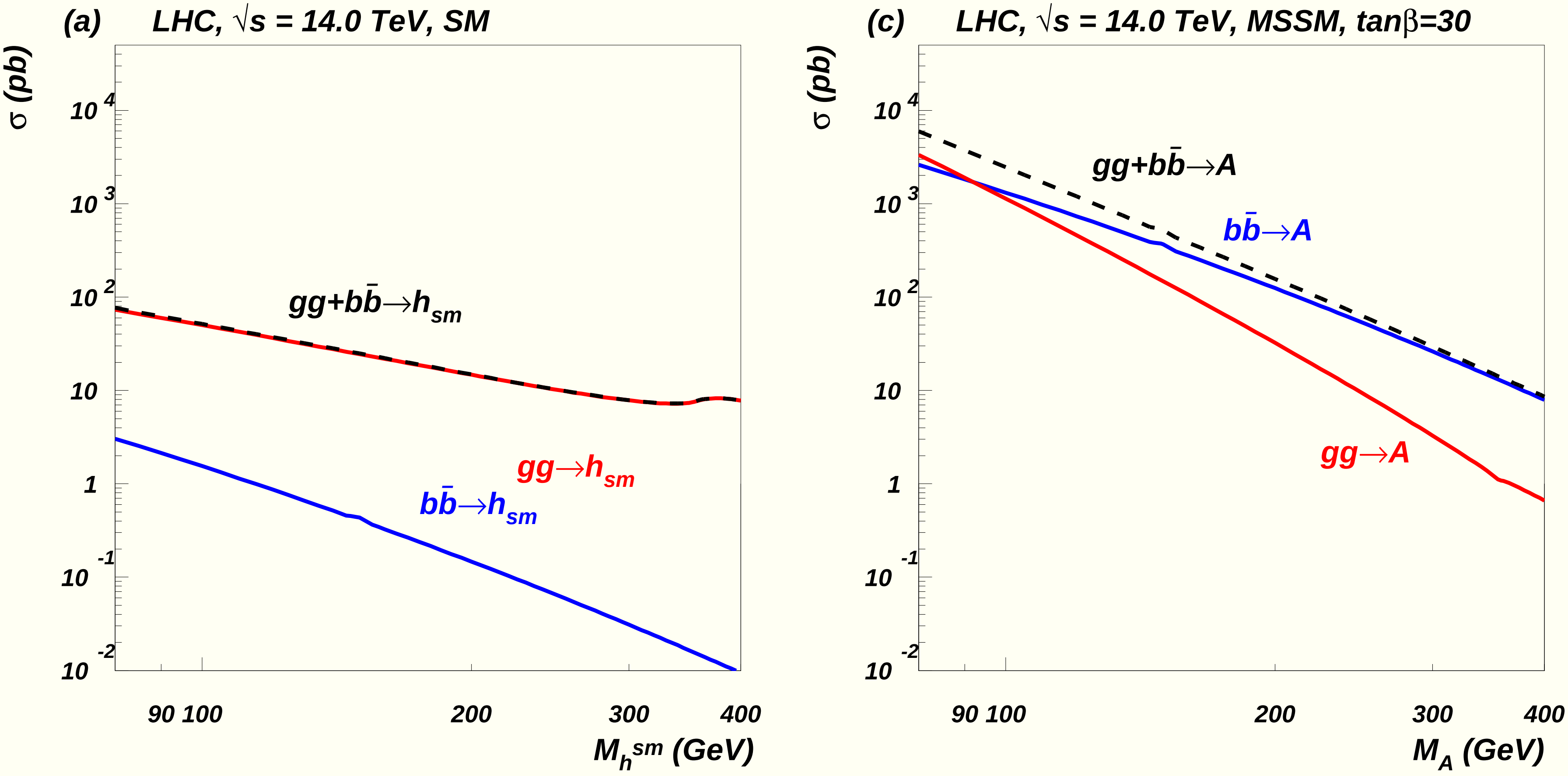

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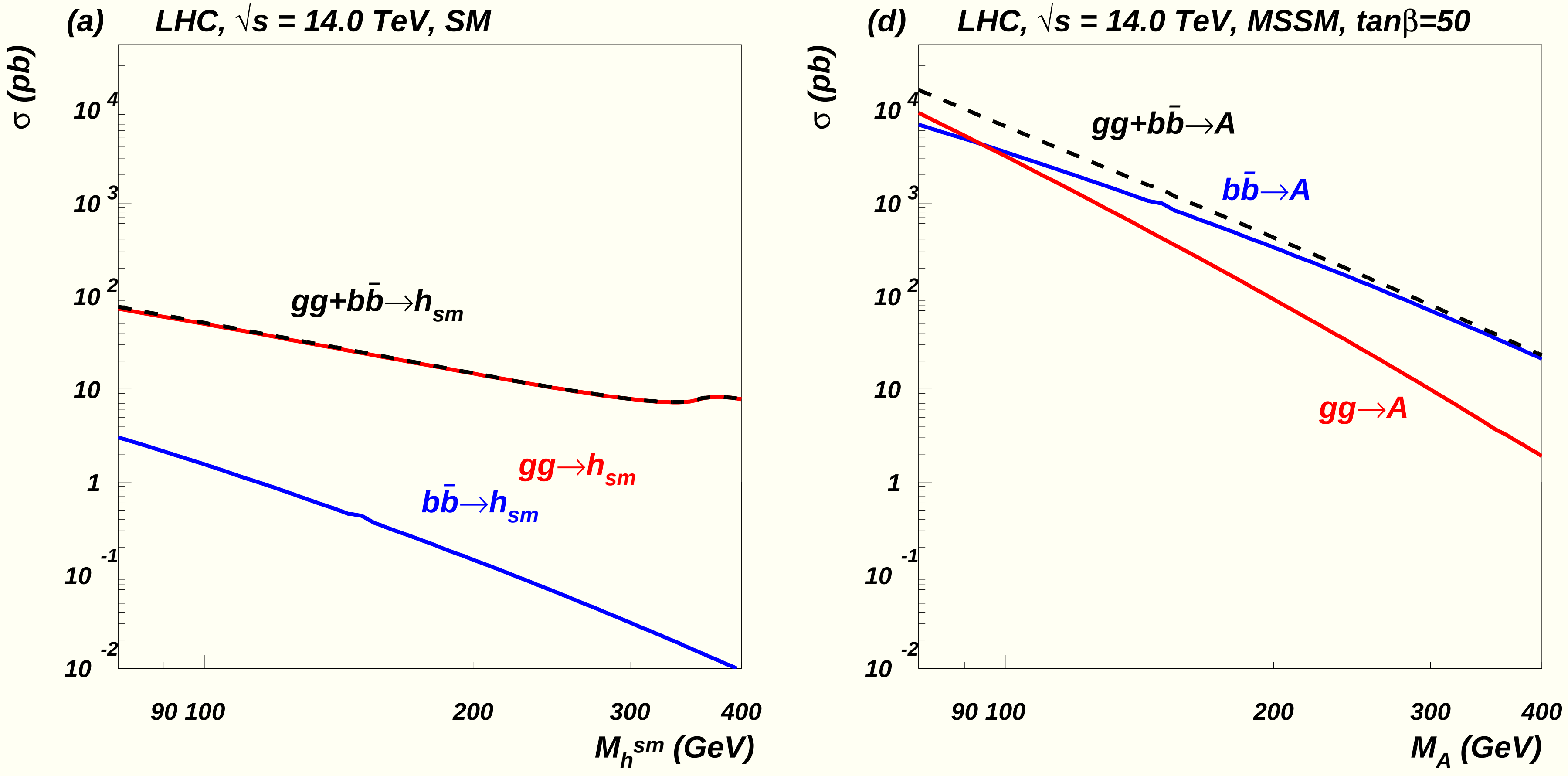

Total enhancement of $xx \to \mathcal{H} \to yy$ channel

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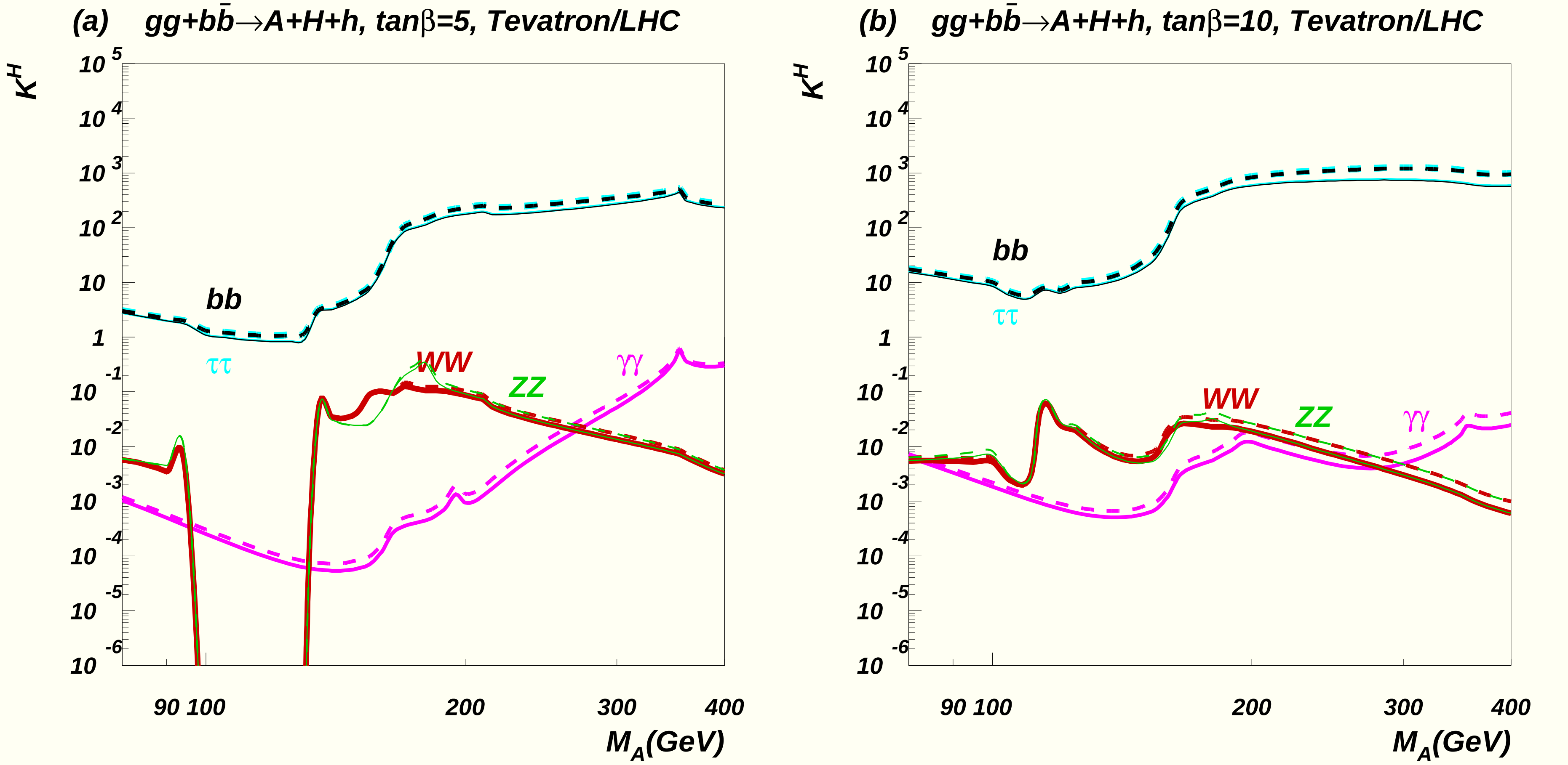

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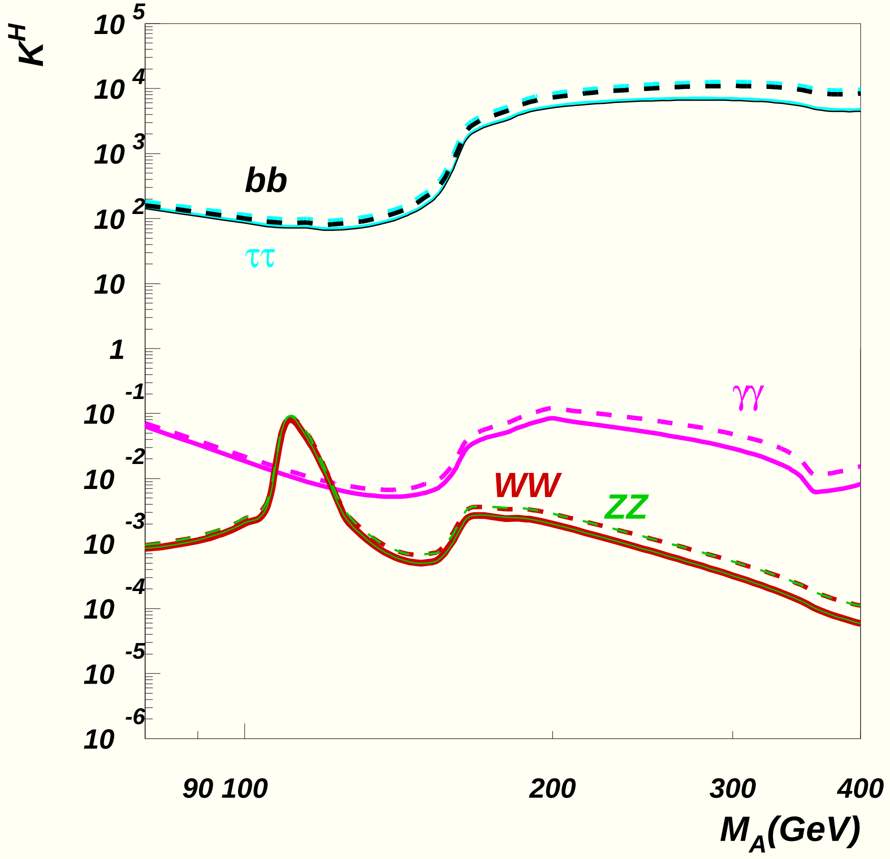
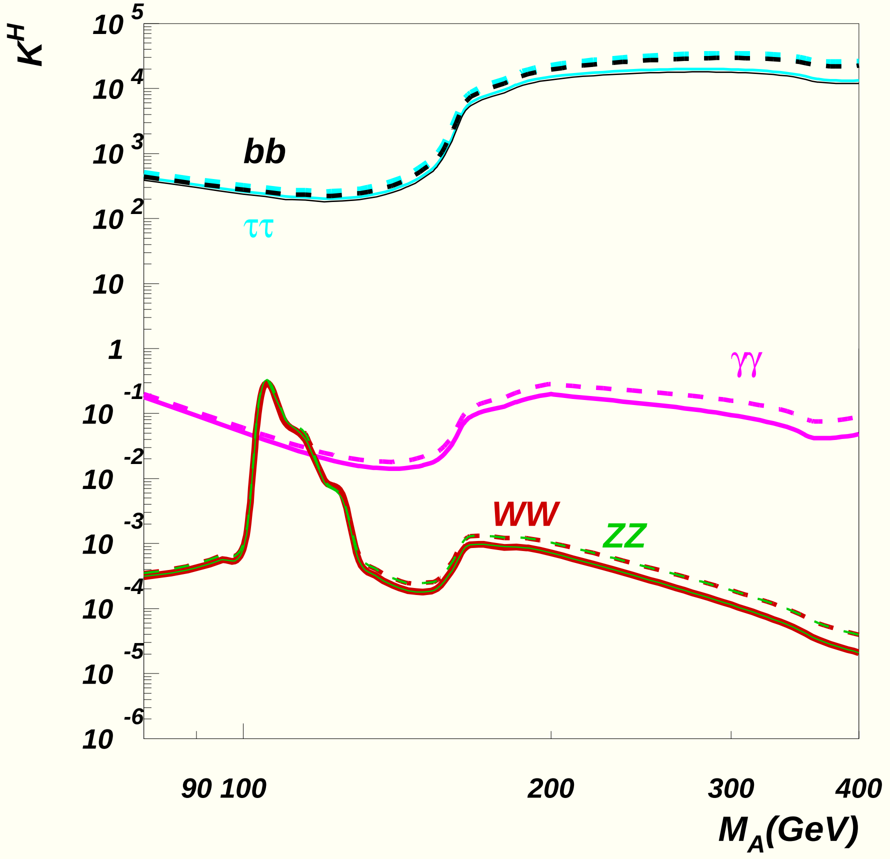
(c) $gg+b\bar{b}\rightarrow A+H+h$, $\tan\beta=30$, Tevatron/LHC



(d) $gg+b\bar{b}\rightarrow A+H+h$, $\tan\beta=50$, Tevatron/LHC



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

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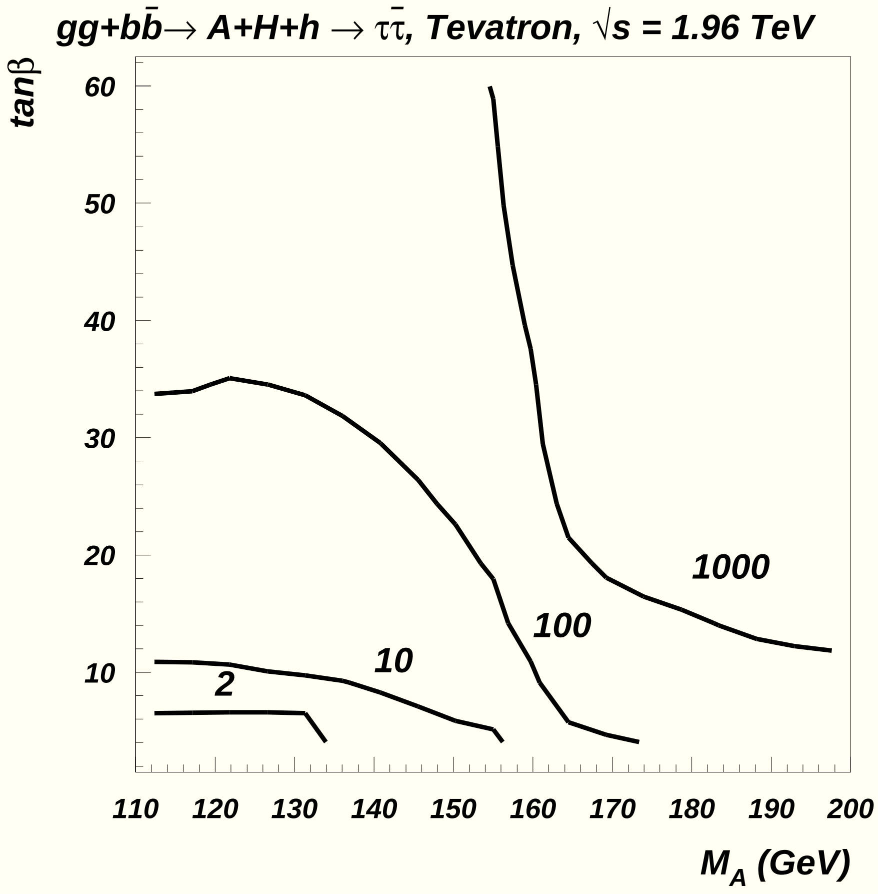
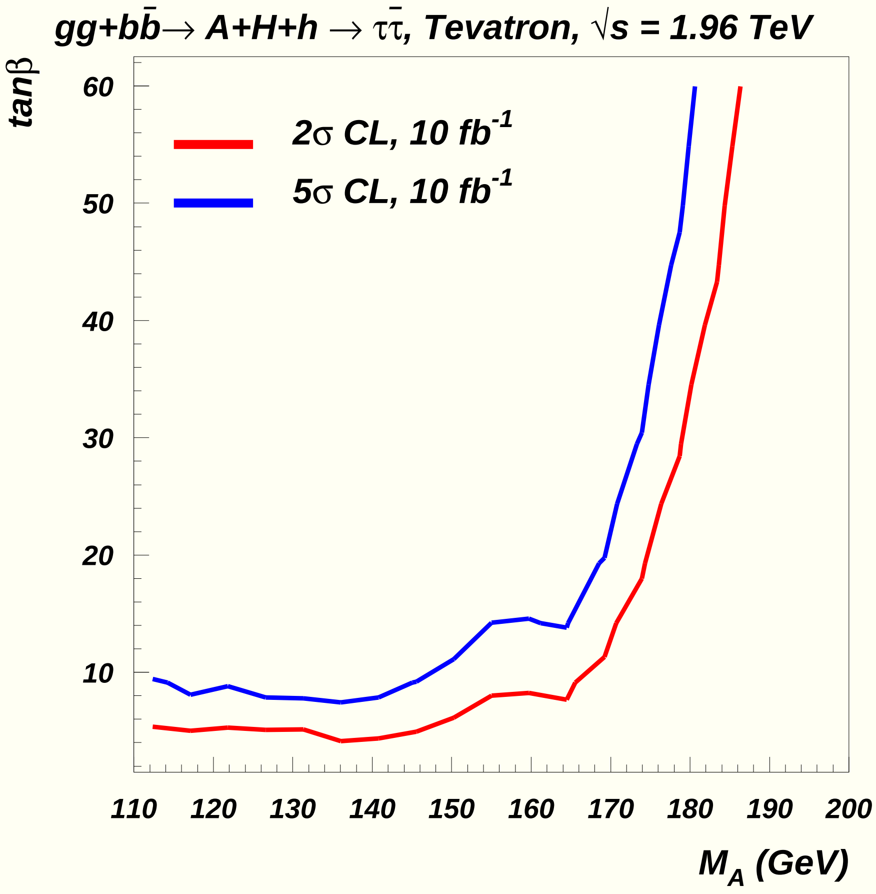
Predicted Tevatron reach, based on the $h_{SM} \to \tau^+\tau^-$ studies

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

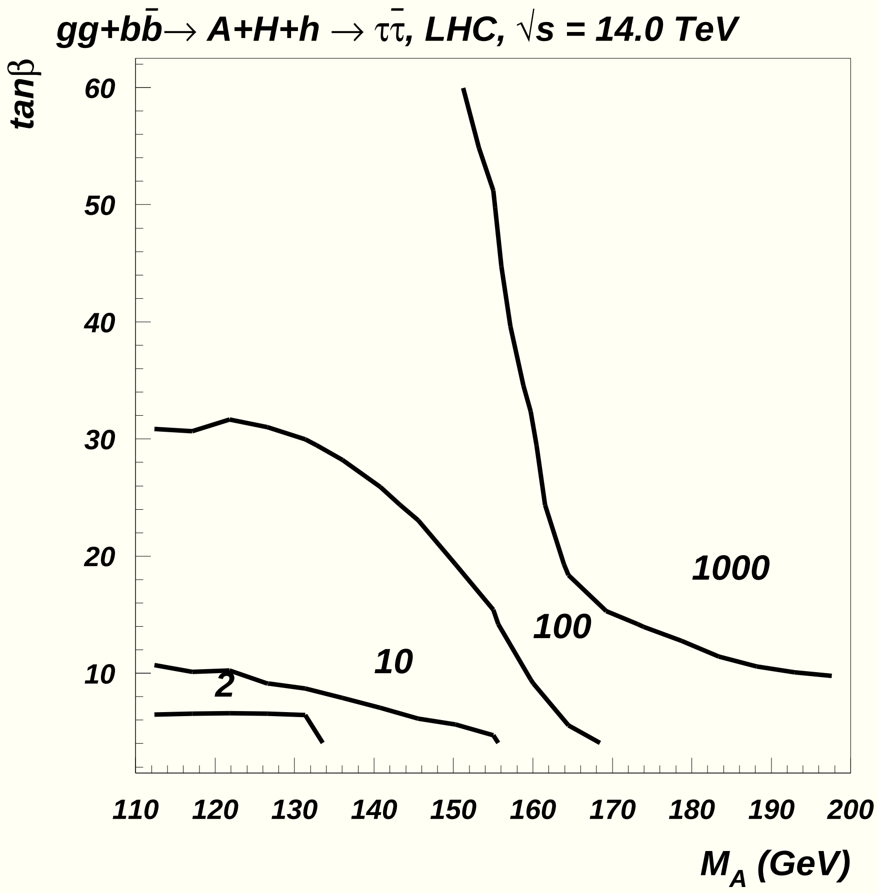


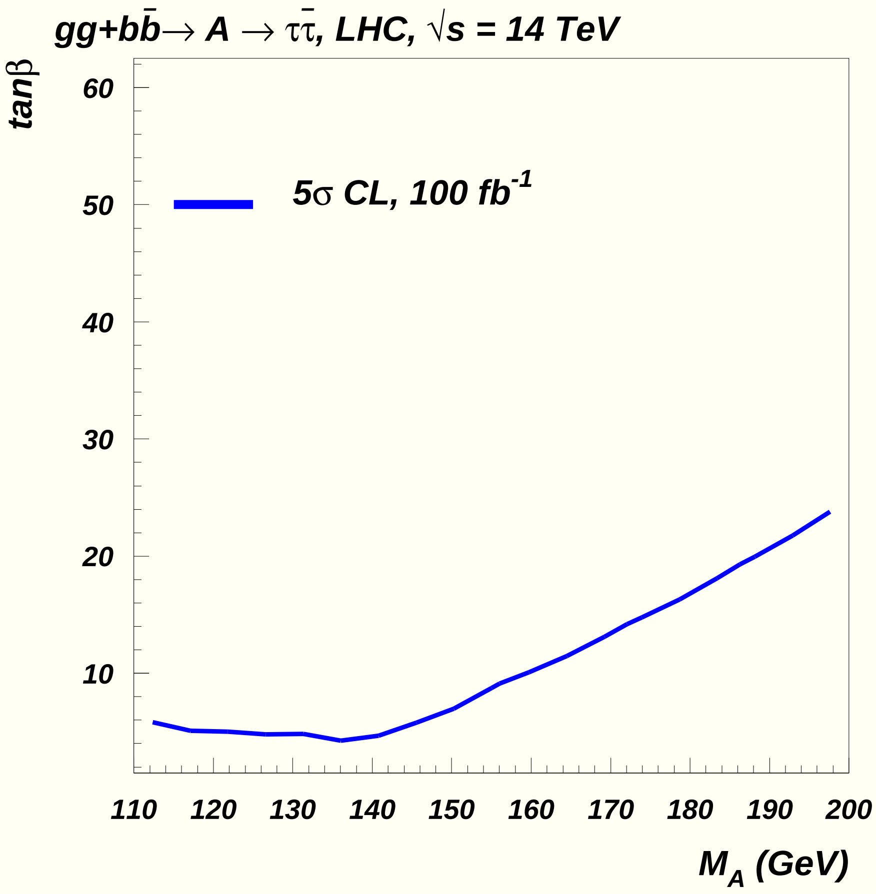


Visibility of MSSM Higgs bosons: $\tau\tau$ channel

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

by D.Cavalli et al, hep-ph/0203056


$gg+b\bar{b} \to A+H+h \to \tau\bar{\tau}$, LHC, $\sqrt{s}$ = 14.0 TeV


$gg+b\bar{b} \to A \to \tau\bar{\tau}$, LHC, $\sqrt{s}$ = 14 TeV

What happens in alternative models of EWSB?

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, (Susskind,Weinberg) breaks the chiral symmetries of massless fermions
- the resulting condensate $\langle \bar{f}_L f_R \rangle \neq 0$ breaks the EW symmetry as desired
- Three of the Nambu-Goldstone Bosons (technipions) of the chiral symmetry breaking become the longitudinal modes of the W and Z
- Dynamical nature of EWSB
- Solves Naturalness, Hierarchy and Triviality problems of SM
- additional light neutral pseudo Nambu-Goldstone bosons: “technipions” in Technicolor models

Technicolor models under study

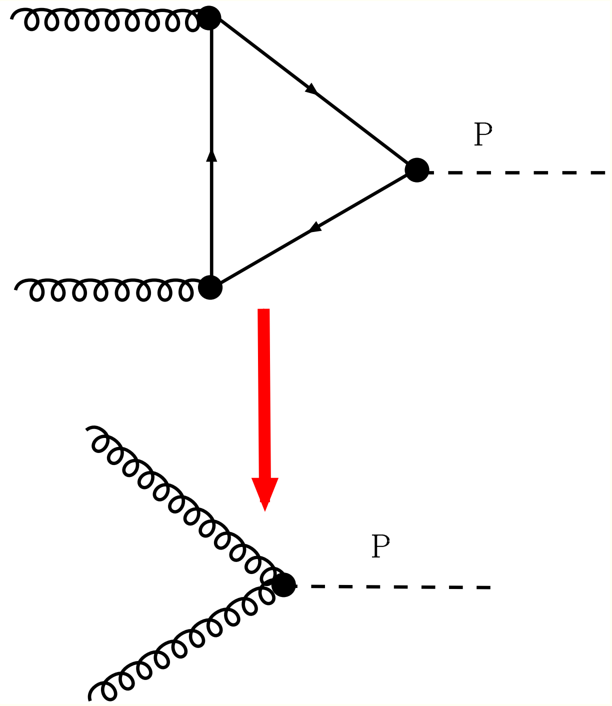
1) the traditional one-family model with a full family of techniquarks and technileptons**(Farhi)**

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)**

3) a multiscale walking Technicolor model designed to reduce flavor-changing neutral currents, **(Lane)**

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)**

$$N_{TC}\mathcal{A}_{V_1V_2} \times \frac{g_1g_2}{8\pi^2F_P} \times \epsilon_{\mu\nu\lambda\sigma}k_1^{\mu}k_2^{\nu}\epsilon_1^{\lambda}\epsilon_2^{\sigma}$$



Technipion decay constant F_P (related to N_D of weak doublets of technifermions 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 and decay

$\Gamma(P \to gg) = \frac{m_P^3}{8\pi}\left(\frac{\alpha_s N_{TC}\mathcal{A}_{gg}}{2\pi F_P}\right)^2$, $m_P = 130$ GeV case

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

	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	

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

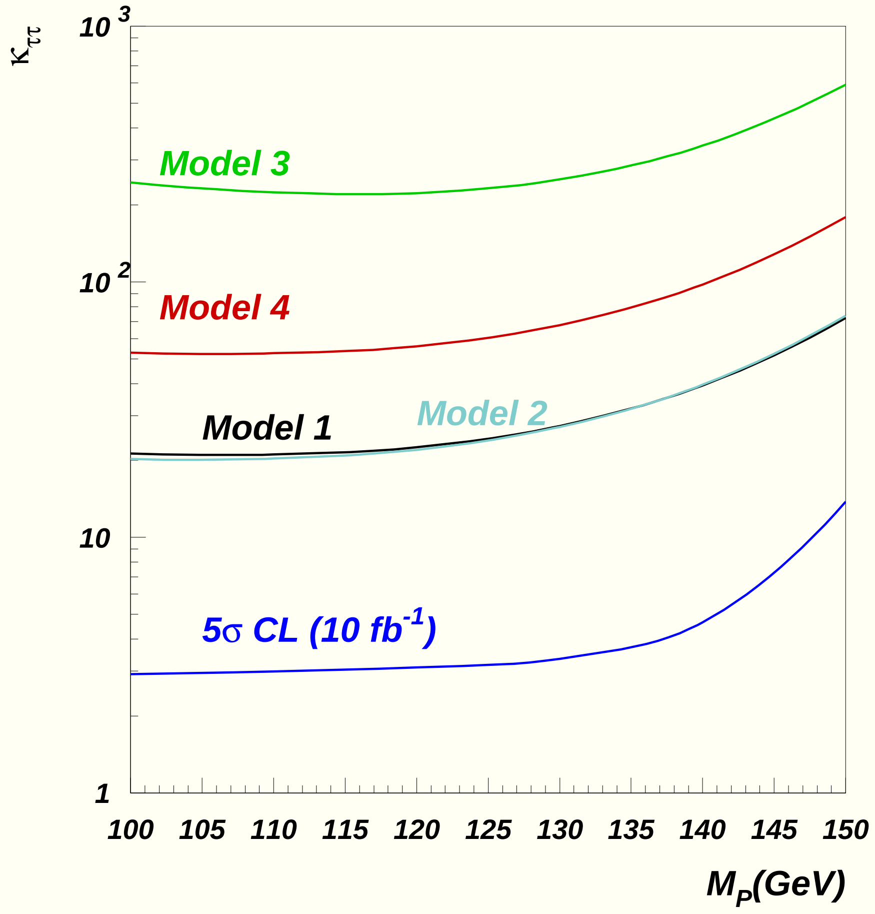
Visibility of Technipions: $\tau\tau$ and $\gamma\gamma$ channels

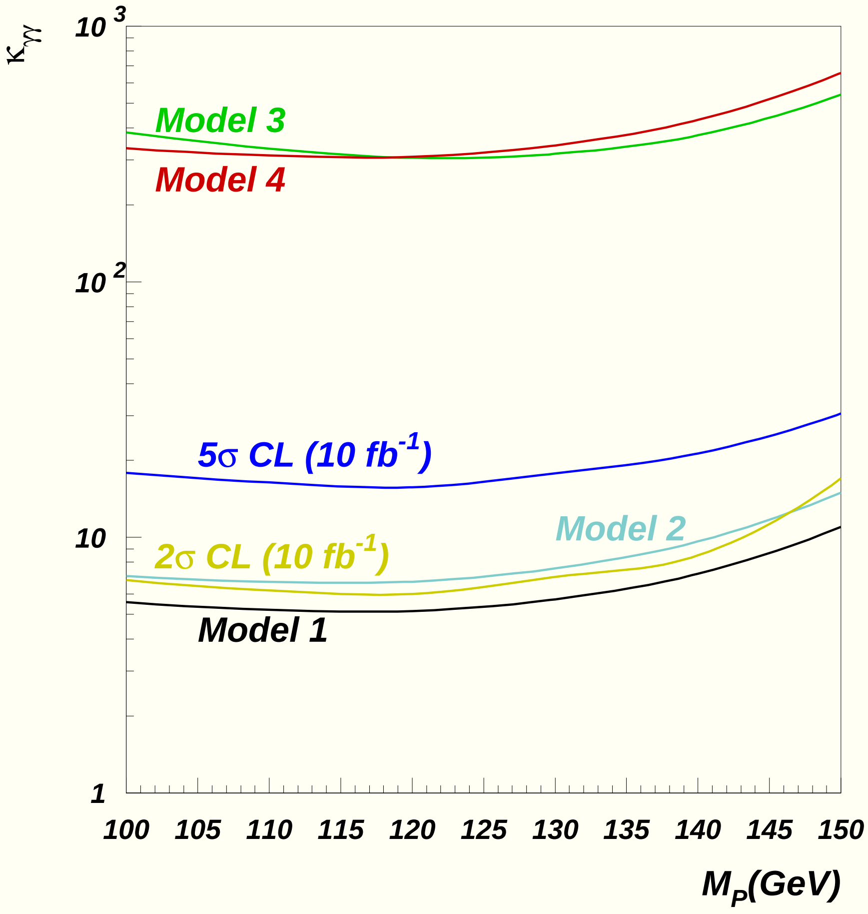
Visibility of Technipions: $\tau\tau$ and $\gamma\gamma$ channels

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



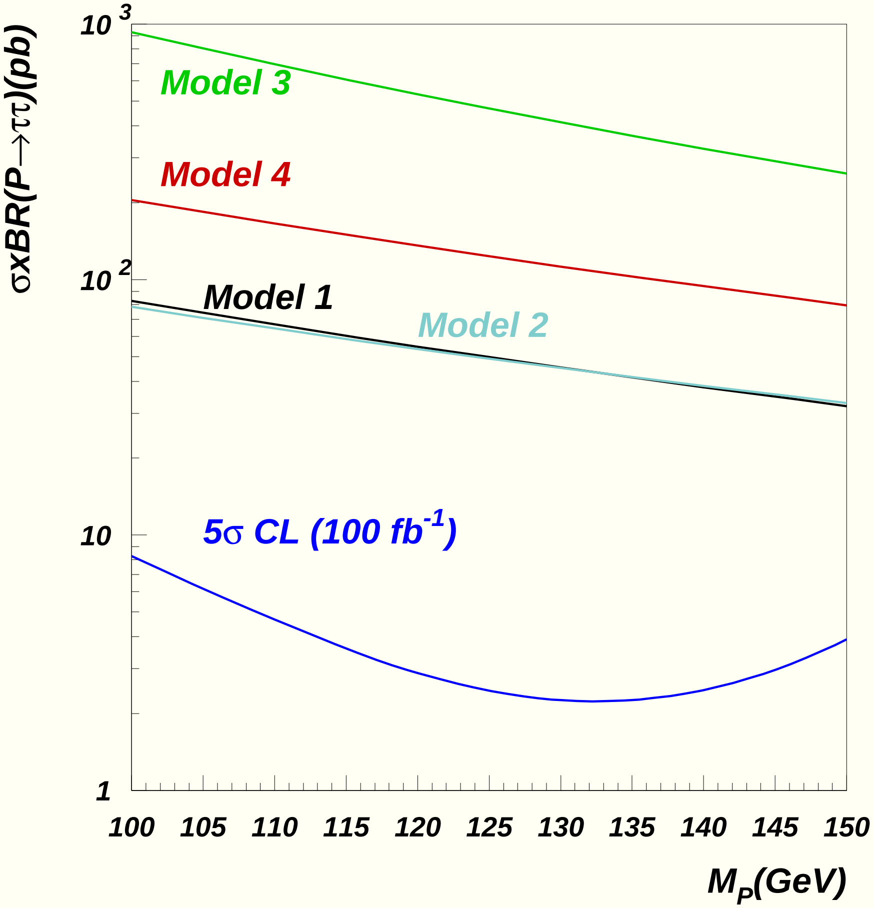


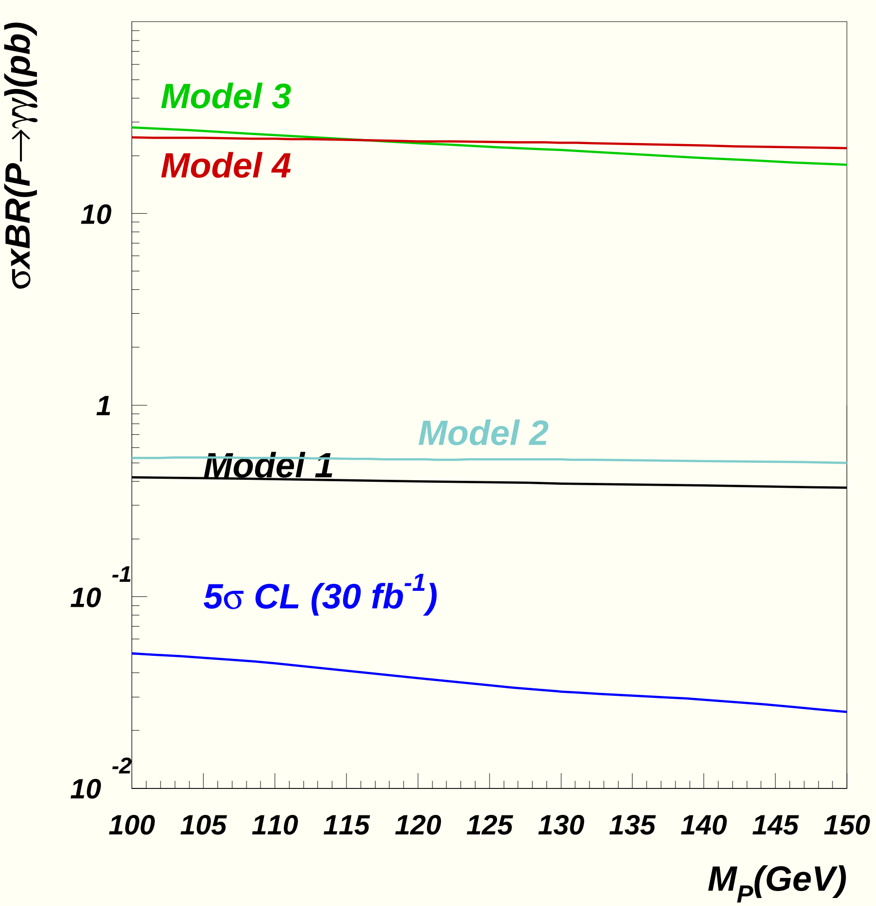
Visibility of Technipions: $\tau\tau$ and $\gamma\gamma$ channels

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

by D.Cavalli et al, hep-ph/0203056 and on the $h_{SM} \to \gamma\gamma$ studies by

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





Distinguishing SUSY from Technicolor models

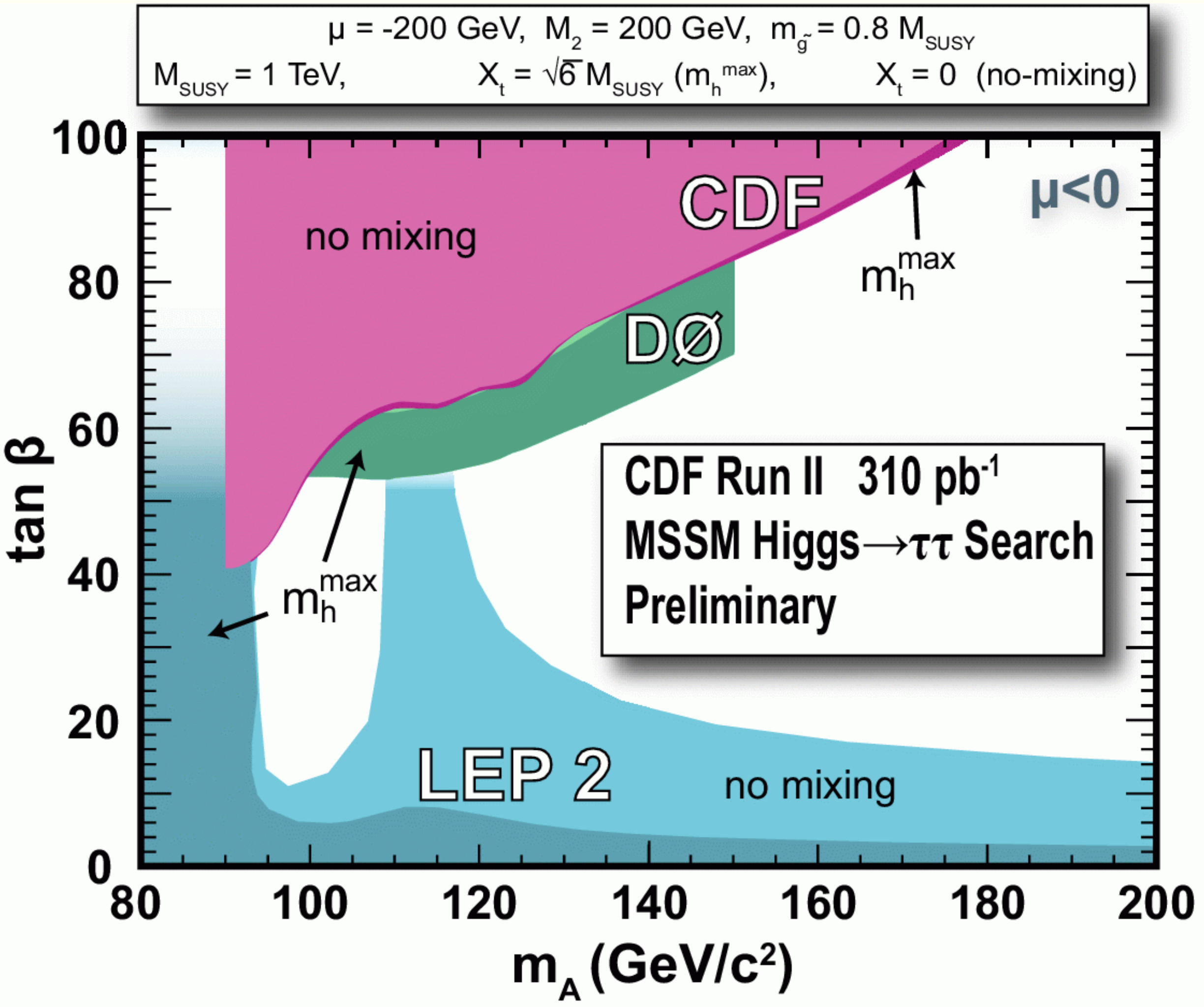
- *Tevatron and LHC have the potential to observe the light (pseudo) scalar states characteristic of both supersymmetry and models of dynamical symmetry breaking $\tau^+\tau^-$ channel!*

- *SUSY case: $\tau^+\tau^-$ channel is enhanced while the $\gamma\gamma$ channel is suppressed, and this suppression is strong enough that even the LHC would not observe the $\gamma\gamma$ signature.*

- *In contrast, for the dynamical symmetry breaking models studied we expect simultaneous enhancement of both the $\tau^+\tau^-$ and $\gamma\gamma$ channels. The enhancement of the $\gamma\gamma$ channel is so significant, that even at the Tevatron we may observe technipions via this 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 observe all four models of DESB*

Results from CDF and D0



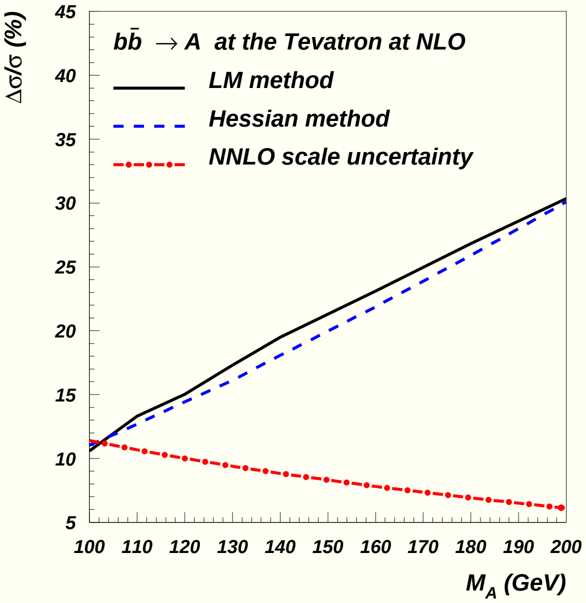
from Anton Anastassov

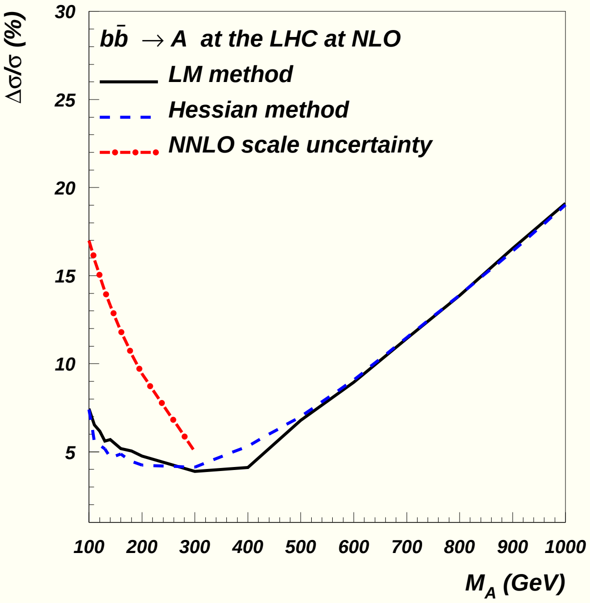
Related issues

- *The role of Scale and PDF uncertainties*

  (also in Chris Jackson’s talk)

  AB, Jon Pumplin, Wu-Ki Tung, C.-P. Yuan

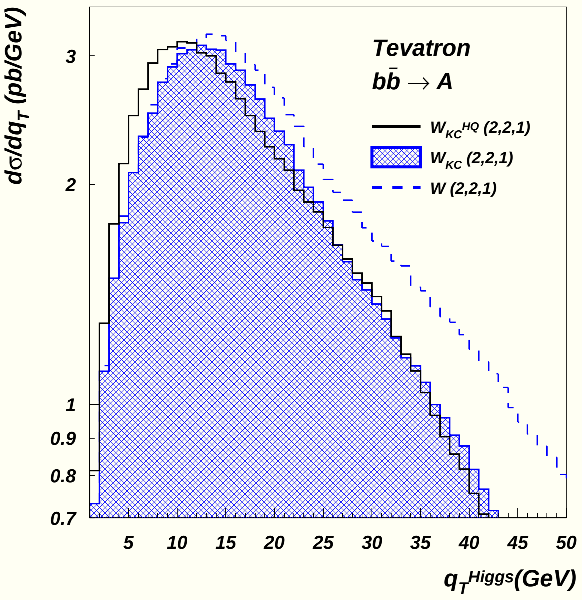




- *The role of resummation effects including heavy quark corrections*

  (see Pavel Nadolsky’s talk)

  AB, Pavel Nadolsky, C.-P. Yuan



Conclusions

- *Searches for a light Standard Model Higgs boson at Tevatron Run II and CERN LHC have the power to provide significant information about important classes of physics beyond the Standard Model*
- *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 the Tevatron Run II and the CERN 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.*