Distinguishing the MSSM and THDM Higgs Sectors through $H^{\pm}W^{\mp}$ Production at Hadron Colliders

Oliver Brein

(Institut für Theoretische Physik E, RWTH Aachen, Germany)

in collaboration with

Eri Asakawa and Shinya Kanemura

[see also hep-ph/0506249]

outline :

- Introduction
  - Spontaneous symmetry breaking
  - Standard Model extensions
- THDM type II parameter constraints
  - THDM type II
  - theoretical constraints
  - experimental constraints
- $H^{\pm}W^{\mp}$ production @ LHC
  - Charged Higgs search at LHC/Tevatron
  - MSSM/THDM $H^{\pm}W^{\mp}$ production
  - Numerical results

• Introduction

– Spontaneous symmetry breaking

Theory: non-Abelian gauge symmetry forbids $M^2 A_\mu A^\mu$-terms $\longrightarrow$ problem $\longleftarrow$ Experiment: massive gauge bosons exist

solution: **spontaneous symmetry breaking (SSB)**,

i.e. introduce gauge invariant dynamics, which breaks gauge symmetry in the ground state.

SSB can be realized by

- weakly interacting scalar gauge multiplets that acquire a VEV
  $\longrightarrow$ Higgs mechanism

- strongly interacting dynamics, e.g. particles that form scalar condensates with a VEV

– Standard Model extensions

Experimental situation so far:

– no Higgs signal.

– no significant deviation from SM.

Theory:

– many distinct possibilities to realize the Higgs mechanism

which meet major constraints, like

- the electroweak rho-parameter
  $\rho_{\mathrm{exp.}} = \frac{m_W}{\cos\theta_W m_Z} \approx 1$ up to a few per mille
- absence of flavour changing neutral currents (FCNC).

$\longrightarrow$ take extensions of the SM (Higgs sector) seriously

SM:

matter, gauge bosons + 1 Higgs doublet Φ

$\rightarrow$ 1 physical Higgs boson

$\swarrow$ $\searrow$

THDM:

(two Higgs doublet model)

SM matter, SM gauge bosons
+ 2 Higgs doublets Φ_1, Φ_2

MSSM:

(minimal supersym. standard model)

SM matter, SM gauge bosons
+ 2 Higgs doublets Φ_1, Φ_2
+ Superpartners

$\rightarrow$ 5 physical Higgs bosons: h^0, H^0, A^0, H^+, H^-

note! : charged Higgs bosons cannot appear with *one* Higgs doublet

$\rightarrow$ $\boxed{\text{discovery of } H^\pm \text{ : unambiguous sign of an extended Higgs sector}}$

• THHDM type II parameter constraints

– THDM type II

- Higgs sector: 2 SU(2)-doublets (Φ_1, Φ_2) with hypercharge $Y(\Phi_i) = 1$
- Higgs potential (CP conserving case):

$$\begin{aligned} V(\Phi_1,\Phi_2) = {} & \lambda_1({\Phi_1}^\dagger\Phi_1 - {v_1}^2)^2 + \lambda_2({\Phi_2}^\dagger\Phi_2 - {v_2}^2)^2 \\ & + \lambda_3\Big\{({\Phi_1}^\dagger\Phi_1 - {v_1}^2) + ({\Phi_2}^\dagger\Phi_2 - {v_2}^2)\Big\}^2 \\ & + \lambda_4\Big\{({\Phi_1}^\dagger\Phi_1)({\Phi_2}^\dagger\Phi_2) - ({\Phi_1}^\dagger\Phi_2)({\Phi_2}^\dagger\Phi_1)\Big\} \\ & + \lambda_5\Big\{\mathrm{Re}({\Phi_1}^\dagger\Phi_2) - v_1 v_2\Big\}^2 + \lambda_6\Big\{\mathrm{Im}({\Phi_1}^\dagger\Phi_2)\Big\}^2 \end{aligned}$$

- potential minimum at: $\Phi_i = (0, v_i)^T$
- 8 parameters (v_1, v_2) ($\propto$ mass) and $\lambda_1, \ldots, \lambda_6$ (dimensionless) can be re-expressed in terms of $v = \sqrt{{v_1}^2 + {v_2}^2} \approx 174\,\mathrm{GeV}$, $m_{h^0}, m_{H^0}, m_{A^0}$, $m_{H^\pm}$, mix. angles α,β, and λ_5
- discrete symmetry of the Higgs potential, e.g. $\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$, broken by mass^2-term $\propto M^2 = v^2\lambda_5$.
- fermions couple: all to Φ_1 (type I), down(up)-type to $\Phi_1(\Phi_2)$ (type II)

– theoretical constraints

• vacuum stability (at tree-level) :
all Φ^4-interactions have to have positive coefficients

$$\Rightarrow \quad \begin{aligned} &\lambda_1 + \lambda_3 > 0, \\ &\lambda_2 + \lambda_3 > 0, \\ &2\sqrt{(\lambda_1 + \lambda_3)(\lambda_2 + \lambda_3)} + 2\lambda_3 + \lambda_4 + \min\,[0, \lambda_5 - \lambda_4, \lambda_6 - \lambda_4] > 0 \end{aligned}$$

• perturbative unitarity (at tree-level) :
all S-wave amp. for scattering of long. gauge and Higgs bosons, e.g.

$$\{W_L^+, H^+\} \otimes \{W_L^-, H^-\} \to \{W_L^+, H^+\} \otimes \{W_L^-, H^-\},$$
$$\{Z_L, A, h, H\} \otimes \{Z_L, A, h, H\} \to \{Z_L, A, h, H\} \otimes \{Z_L, A, h, H\},$$

should stay within the limit set by unitarity

$\Rightarrow$ eigenvalues of the S-matrix $a_i(\lambda_1, \ldots, \lambda_6)$ are constrained by

$$|a_i(\lambda_1, \ldots, \lambda_6)| < \frac{1}{2}$$

– experimental constraints

• rho-parameter:

– definition:

$$\rho = \rho_0 \rho_{\text{SM}} = m_W^2/(m_Z^2 c_w^2) \qquad (\overline{MS} \text{ scheme})$$

– ρ_0 parameterizes effects of physics beyond the SM

– global fit to data gives

$$\rho_0 = 0.9998^{+0.0025}_{-0.0010} \ (2\sigma \text{ level})$$ [PDG'04]

– radiative corrections in the THDM: [Toussaint'78; Bertolini'86; Hollik'86]

$$\delta\rho_0 = \rho_{\text{THDM,Higgs}} - \rho_{\text{SM,Higgs}}$$

→ we restrict THDM parameters to yield $-0.0012 \leq \delta\rho_0^{\text{one-loop}} \leq 0.0023$.

– experimental constraints

- muon anomalous magnetic moment a_μ:

– difference between measurement and SM prediction [PDG'04]

$$\Delta a_\mu := a_\mu^{\text{exp.}} - a_\mu^{\text{SM}} = (\, 25.7 \pm 8.54[\text{exp.}] \pm 4.90[\text{th.}] \,) \cdot 10^{-10}$$

– radiative corrections in the THDM:

$$\delta a_\mu = a_\mu^{\text{THDM,Higgs}} - a_\mu^{\text{SM,Higgs}}$$

1-loop is suppressed. we include leading 2-loop contributions

[Chang et al.'01; Cheung et al.'01; Arhrib, Baek'02]

$\rightarrow$ we restrict THDM parameters such that δa_μ stays close to Δa_μ at the 2σ level, i.e $-1.2 \cdot 10^{-10} \leq \delta a_\mu \leq 52.6 \cdot 10^{-10}$

- $b \rightarrow s\gamma$: in our example we take $m_{H^\pm} = 400\,\text{GeV}$

$\rightarrow$ limits for new physics contributions are respected

• $H^{\pm}W^{\mp}$ production @ LHC

– Charged Higgs search at LHC/Tevatron

- $m_{H^{\pm}} < m_t$:

  mainly via $t \to H^+ b$ and c.c. in $t\bar{t}$ events. [Bawa et al.'90]

- $m_{H^{\pm}} > m_t$:

  mainly via $gb \to tH^+$, $gg \to tbH^+$

  [LO: Gunion et el. '87; NLO QCD: Zhu '03; Plehn '03; Berger et al. '03]

  other processes with (much) smaller c.s. :
  $gg/b\bar{b} \to H^{\pm}W^{\mp}$ [. . .] and $gg/q\bar{q} \to H^+H^-$
  [Krause et al. '98; OBr, Hollik '99; Barrientos, Kniehl '99]

most viable signal:

excess of tau events
from the decays $H^+ \to \tau^+\nu_\tau$ and c.c.

– MSSM/THDM $H^\pm W^\mp$ production

Why study $H^\pm W^\mp$ production?

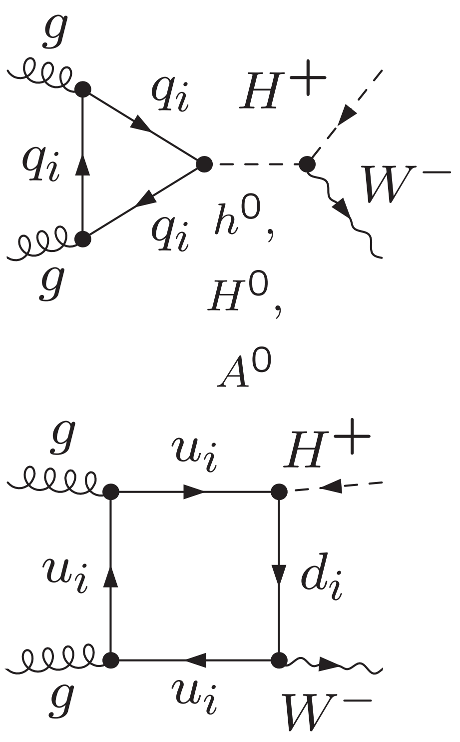
- main production processes:
  - virtual particles: only ordinary SM matter
  - only information on $H^\pm$ mass and Yukawa couplings
- $gg/b\bar{b} \longrightarrow H^\pm W^\mp$:
  - contributions from virtual neutral Higgs bosons
- $gg \longrightarrow H^\pm W^\mp$ loop induced:
  - MSSM: virtual quarks and squarks appear at same order
  - amplitude shows interesting interference pattern

$\longrightarrow$ $W^\pm H^\mp$ production cross section is strongly model dependent

$\longrightarrow$ with a measurement: information on the underlying model

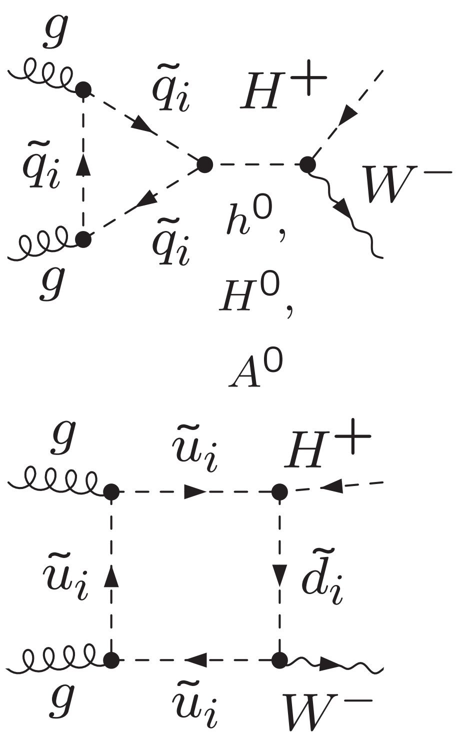
gluon fusion

THDM amplitude



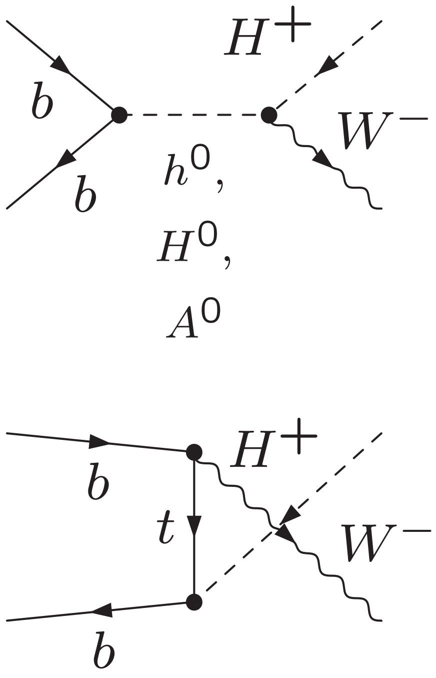
+ more

squark amplitude



+ more

$b\bar{b}$ annihilation



[gg: Dicus et al. '89; Barrientos, Kniehl '99-'00;

OBr, Hollik, Kanemura '00; $b\bar{b}$: MSSM, NLO QCD: Hollik, Zhu '01]

MSSM versus general THDM

MSSM:

interesting feature of $gg \to H^\pm W^\mp$:

strong negative interference between Δ– and $\Box$–amplitudes,

$$\text{i.e. } |\Delta|^2 \approx |\Box|^2 \approx (10 - 100) \cdot |\Delta + \Box|^2$$

reason: Higgs mass relations in the MSSM

$$m_{h^0} = \mathcal{O}(100\text{GeV}),\ m_{H^0} \approx m_{A^0} \approx m_{H^\pm}$$

$\to$ Δ–amplitudes cannot decouple from the process

$\to$ no resonant s-channel Higgs exchange possible

$\to$ negative interference unavoidable

general THDM:

all this need not be true !

$\to$ cross section may be much larger than in the MSSM

note! an MSSM S/B analysis showed: cross section (probably) too low to be seen @ LHC [Moretti, Odagiri'98]

– Numerical results

calculation: inclusive hadronic cross section @ LHC ($S = 14$ TeV)

$$\sigma_{pp\to W^-H^+} = \sum_{n,m}\int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{pp}_{nm}}{d\tau}\,\hat{\sigma}_{nm\to W^-H^+}(\tau S) = \sum_{n,m}\int_{\sqrt{\hat{s}_0}}^{\sqrt{S}} d\sqrt{\hat{s}}\frac{d\sigma_{nm}}{d\sqrt{\hat{s}}}$$

with parton luminosity

$$\frac{d\mathcal{L}^{pp}_{nm}}{d\tau} = \int_{\tau}^{1}\frac{dx}{x}\frac{1}{1+\delta_{nm}}\left[f_{n/p}(x,\mu_F)f_{m/p}(\frac{\tau}{x},\mu_F) + f_{m/p}(x,\mu_F)f_{n/p}(\frac{\tau}{x},\mu_F)\right]$$

and differential hadronic cross section

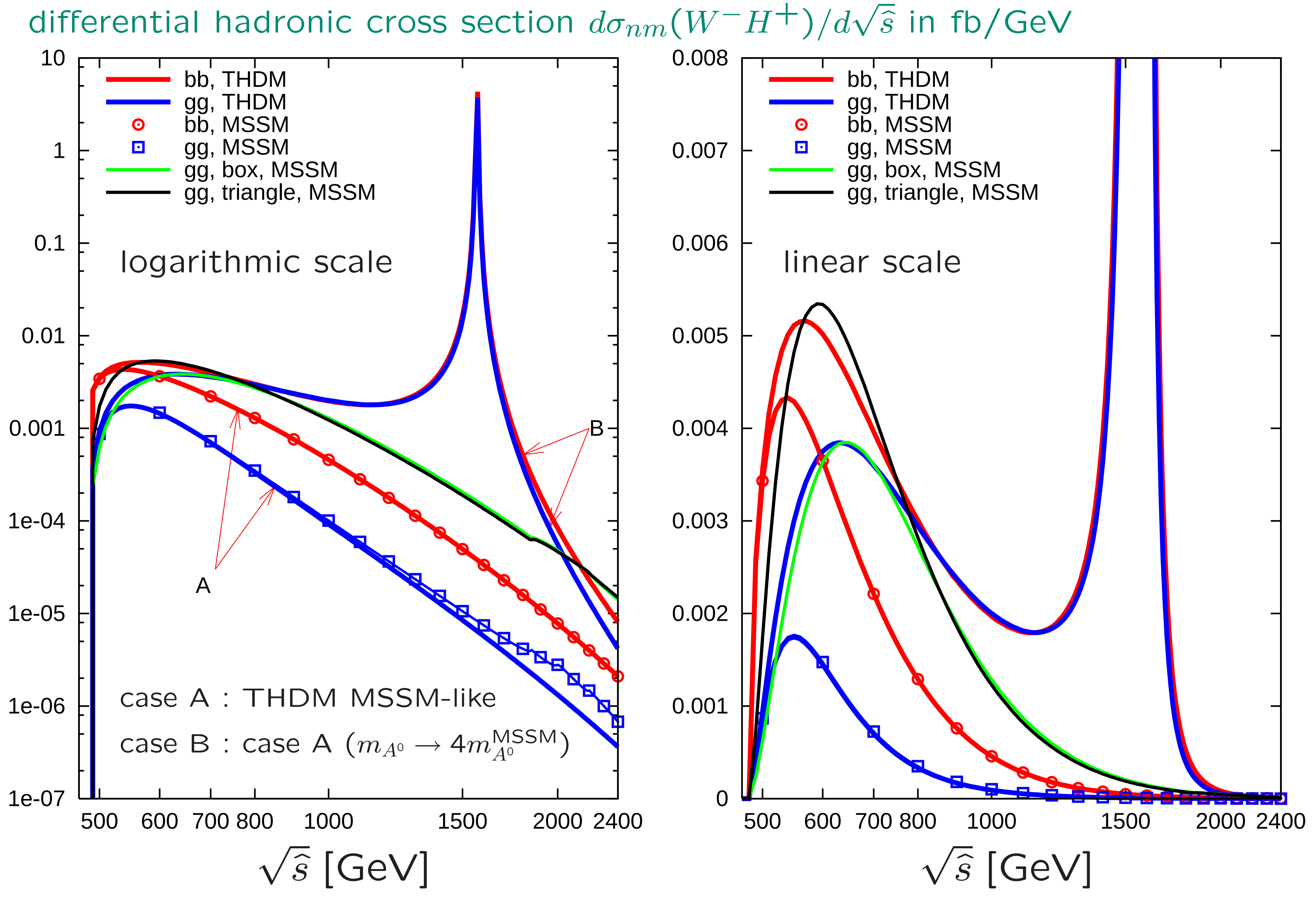
$$\frac{d\sigma_{nm}}{d\sqrt{\hat{s}}} = \frac{2\sqrt{\hat{s}}}{S}\left.\frac{d\mathcal{L}^{pp}_{nm}}{d\tau}\right|_{\tau=\frac{\sqrt{\hat{s}}}{S}}\hat{\sigma}_{nm\to W^-H^+}(\sqrt{\hat{s}},\alpha_S(\mu_R))$$

parameters: one reference MSSM scenario with

$m_{H^\pm} = 400$ GeV, $\mu = 300$ GeV, all $A_q = 0$,
squark mass scale $M_{\text{SUSY}} = 1$ TeV,
stop-mixing parameter $X_t = -1$ TeV

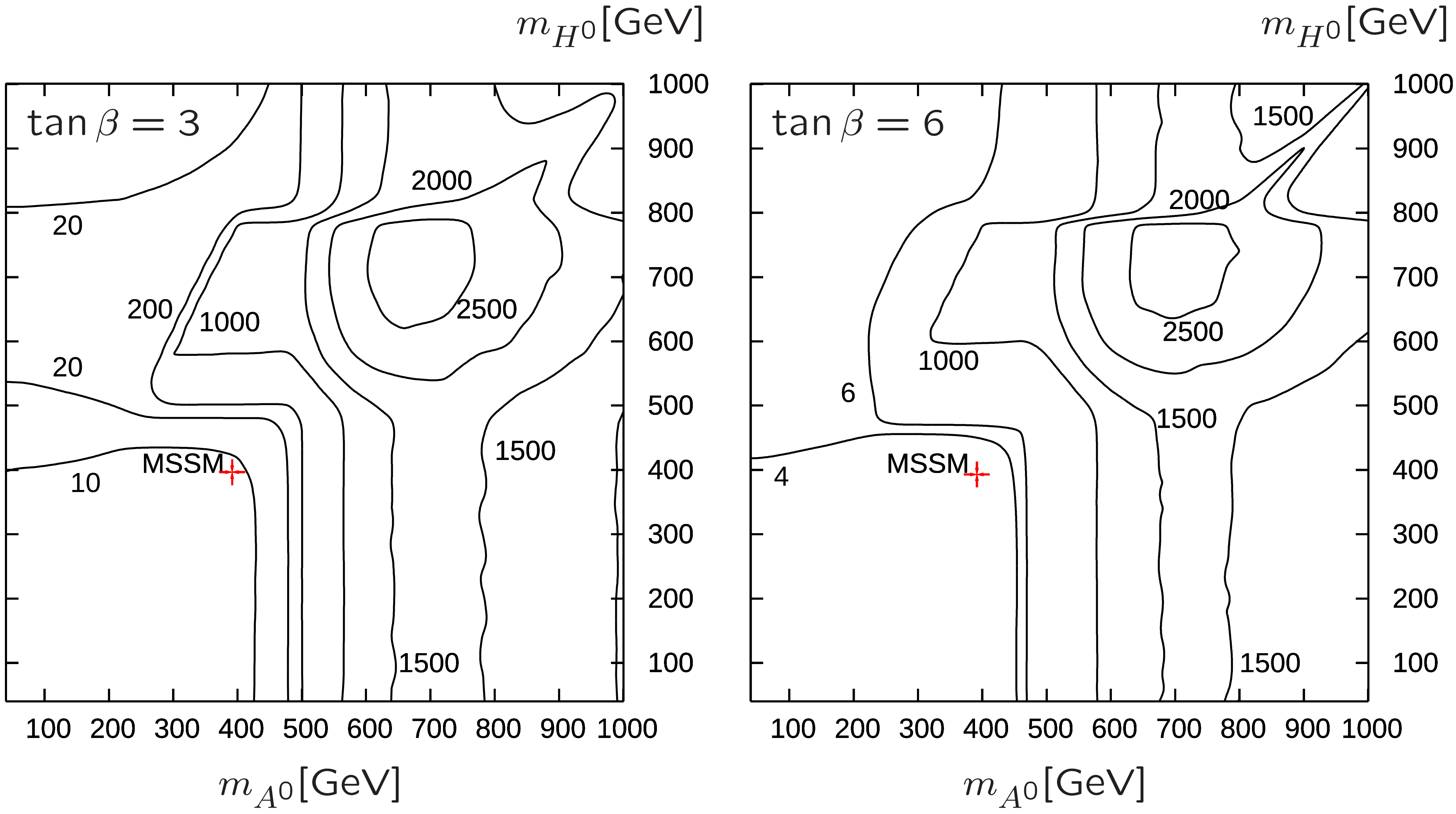
this leads to:

$\tan\beta = 3$: $m_{h^0} = 106$ GeV, $m_{H^0,A^0} \approx 400$ GeV, $\sigma^{\text{MSSM}}_{W^\pm H^\mp} = 9.5$fb
$\tan\beta = 6$: $m_{h^0} = 115$ GeV, $m_{H^0,A^0} \approx 400$ GeV, $\sigma^{\text{MSSM}}_{W^\pm H^\mp} = 3$fb



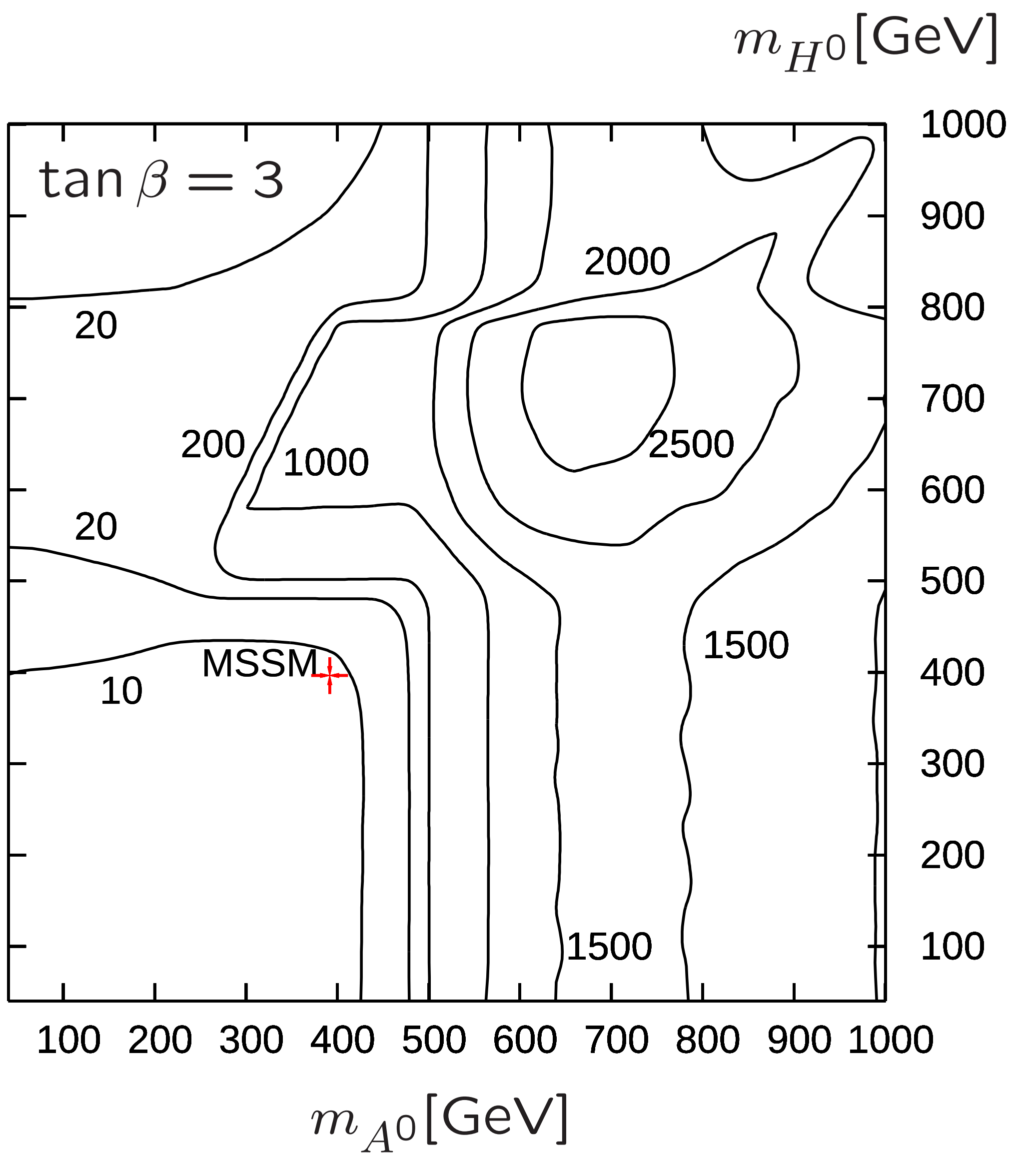
differential hadronic cross section $d\sigma_{nm}(W^-H^+)/d\sqrt{\hat{s}}$ in fb/GeV
bb, THDM
gg, THDM
bb, MSSM
gg, MSSM
gg, box, MSSM
gg, triangle, MSSM
logarithmic scale
linear scale
A
B
case A : THDM MSSM-like
case B : case A ($m_{A^0} \to 4m_{A^0}^{\text{MSSM}}$)
10
1
0.1
0.01
0.001
1e-04
1e-05
1e-06
1e-07
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
500
600
700
800
1000
1500
2000
2400
$\sqrt{\hat{s}}$ [GeV]

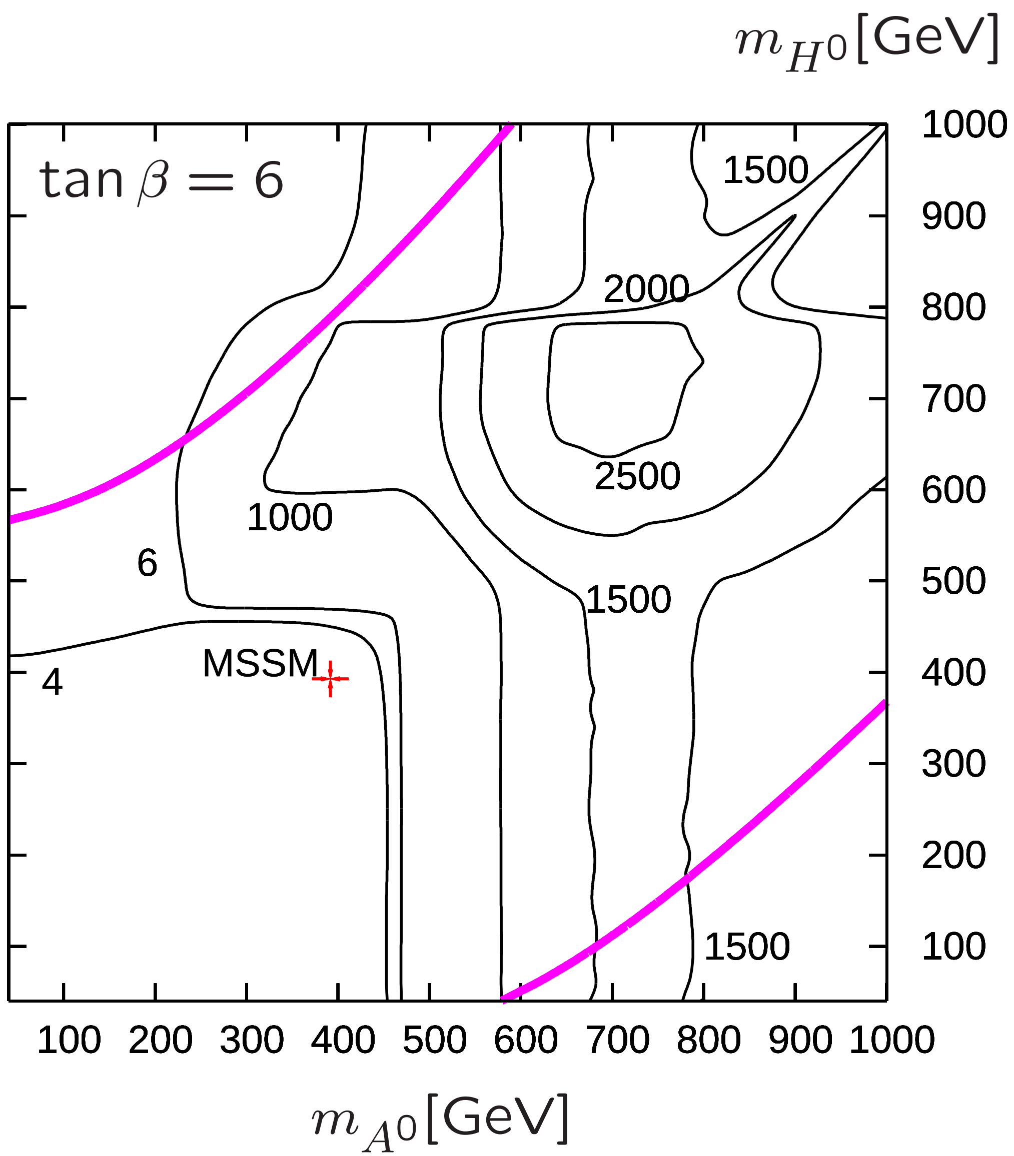
inclusive hadronic cross section $\sigma(W^{\pm}H^{\mp})$ for $M^2 = m_{A^0}^2$



no constraints

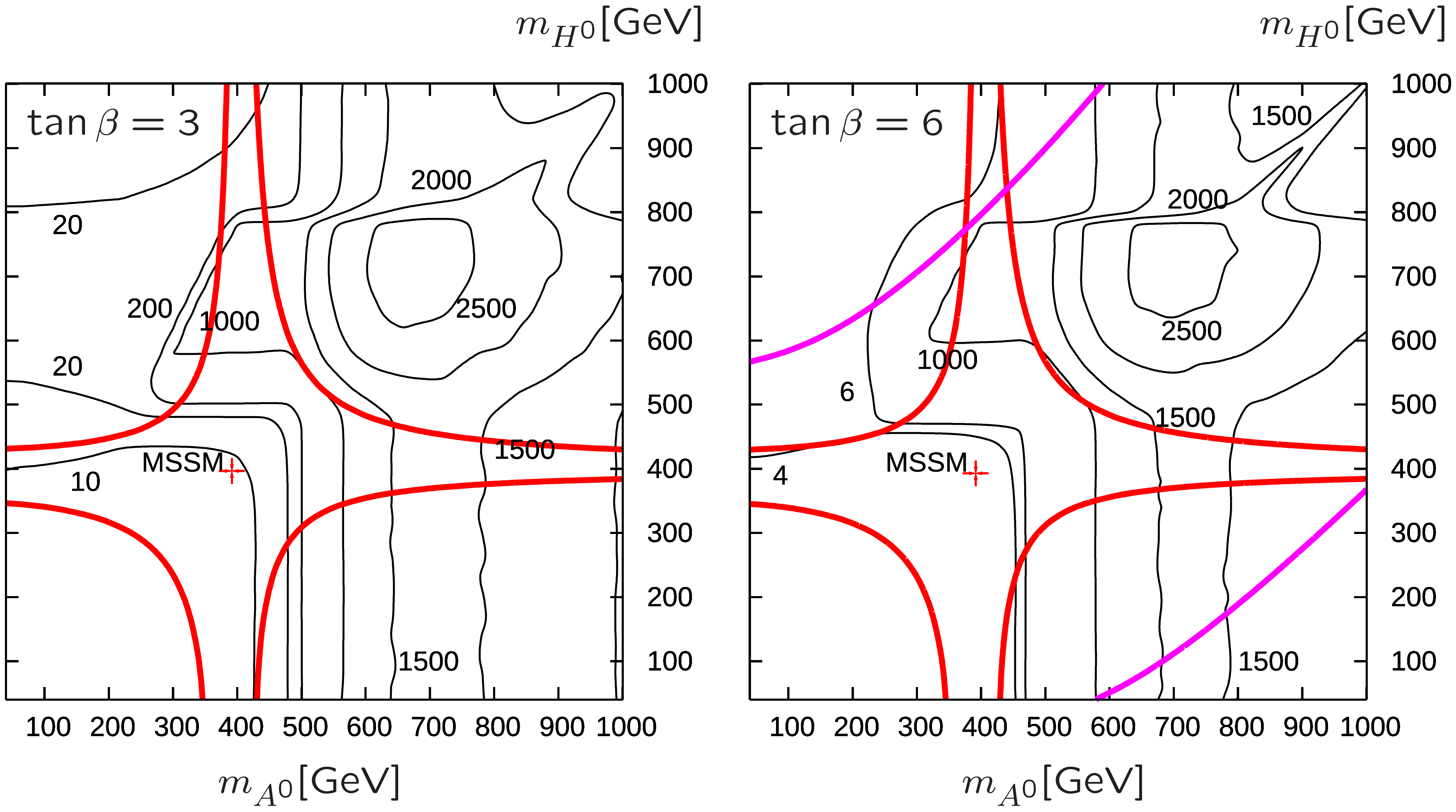
inclusive hadronic cross section $\sigma(W^{\pm}H^{\mp})$ for $M^2 = m^2_{A^0}$



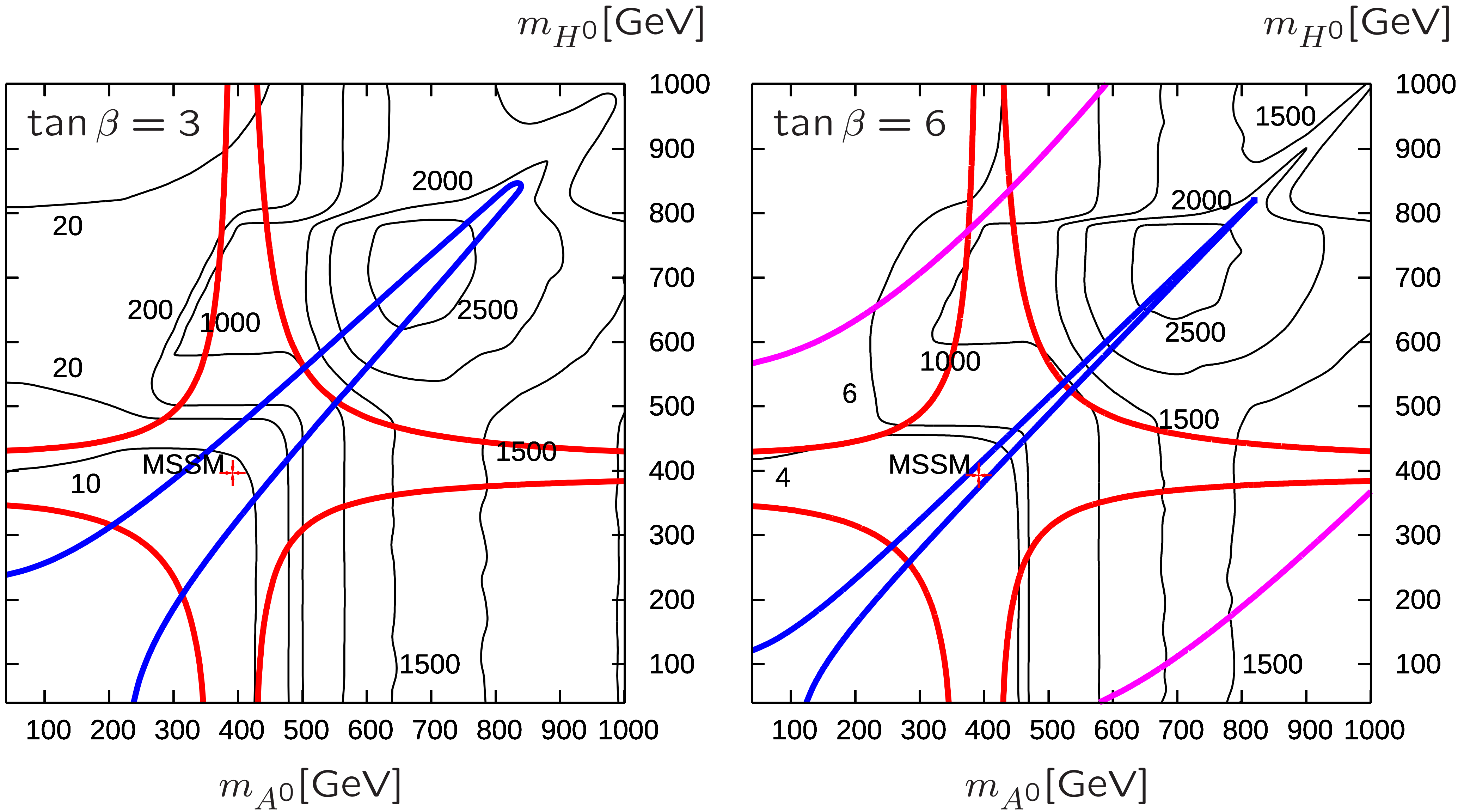


constraints: magn. moment a_μ

inclusive hadronic cross section $\sigma(W^{\pm}H^{\mp})$ for $M^2 = m^2_{A^0}$

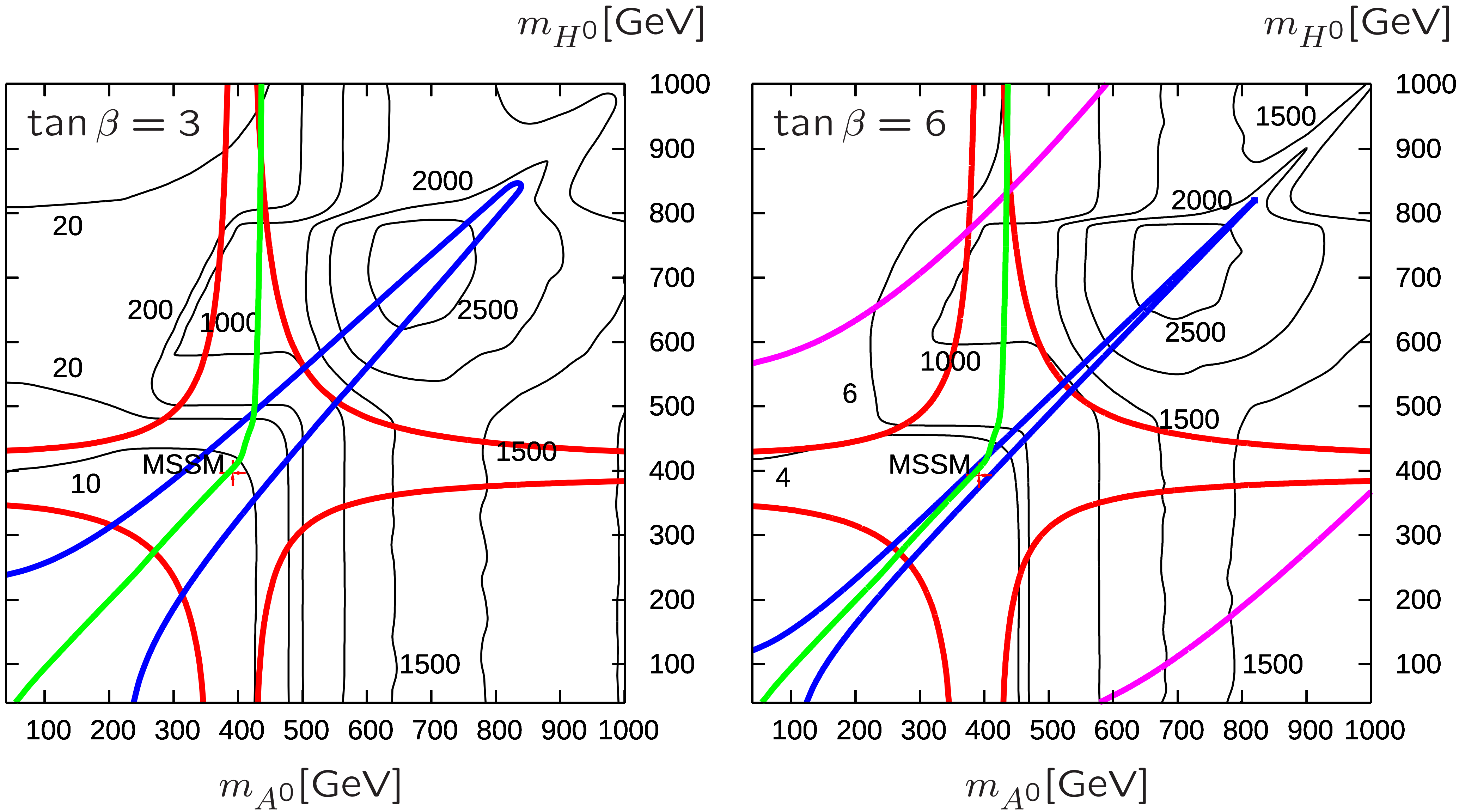


constraints: magn. moment a_μ $+\rho$-parameter inclusive hadronic cross section $\sigma(W^{\pm}H^{\mp})$ for $M^2 = m_{A^0}^2$



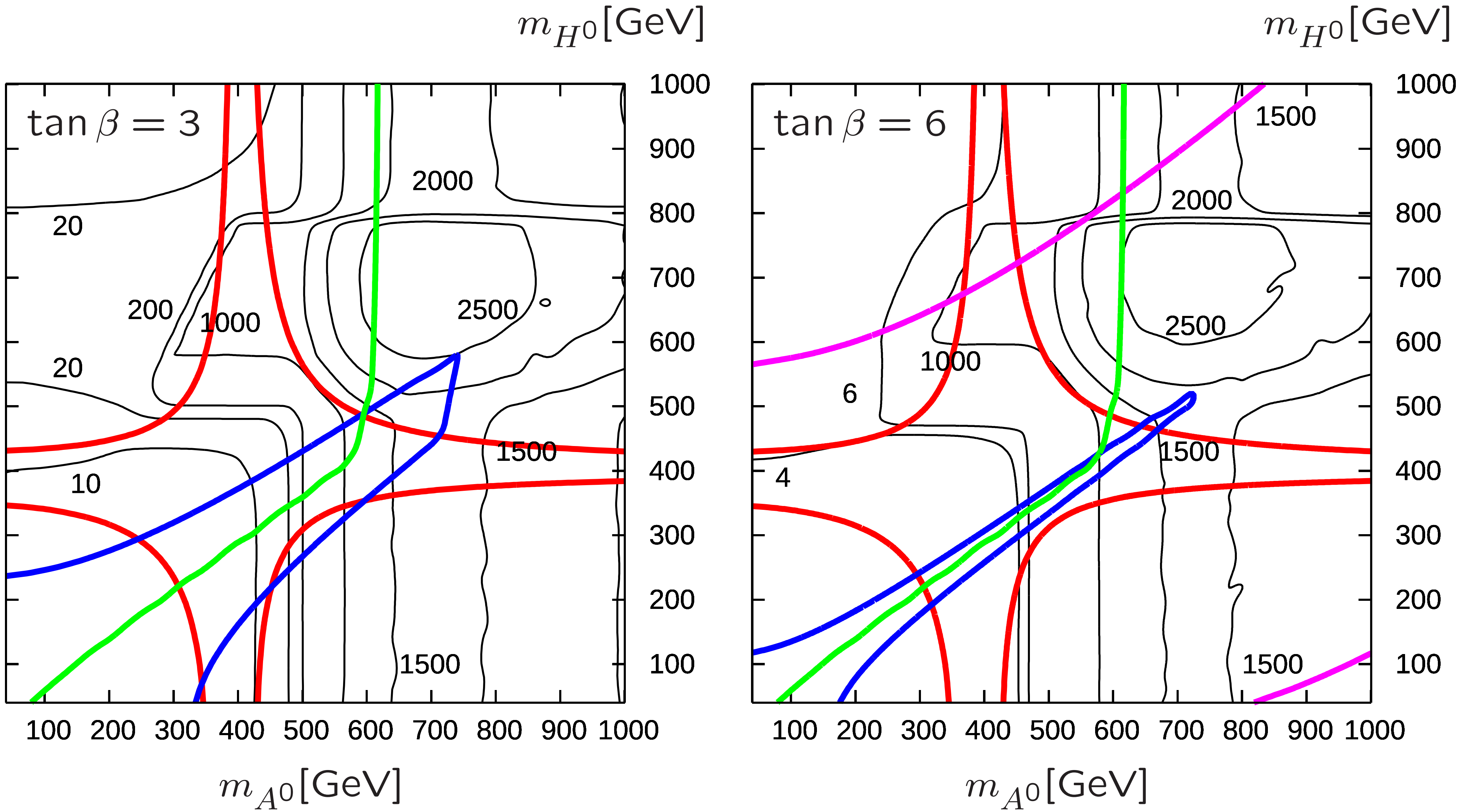
constraints: magn. moment a_μ + ρ-parameter + pert. unitarity

inclusive hadronic cross section $\sigma(W^{\pm}H^{\mp})$ for $M^2 = m^2_{A^0}$



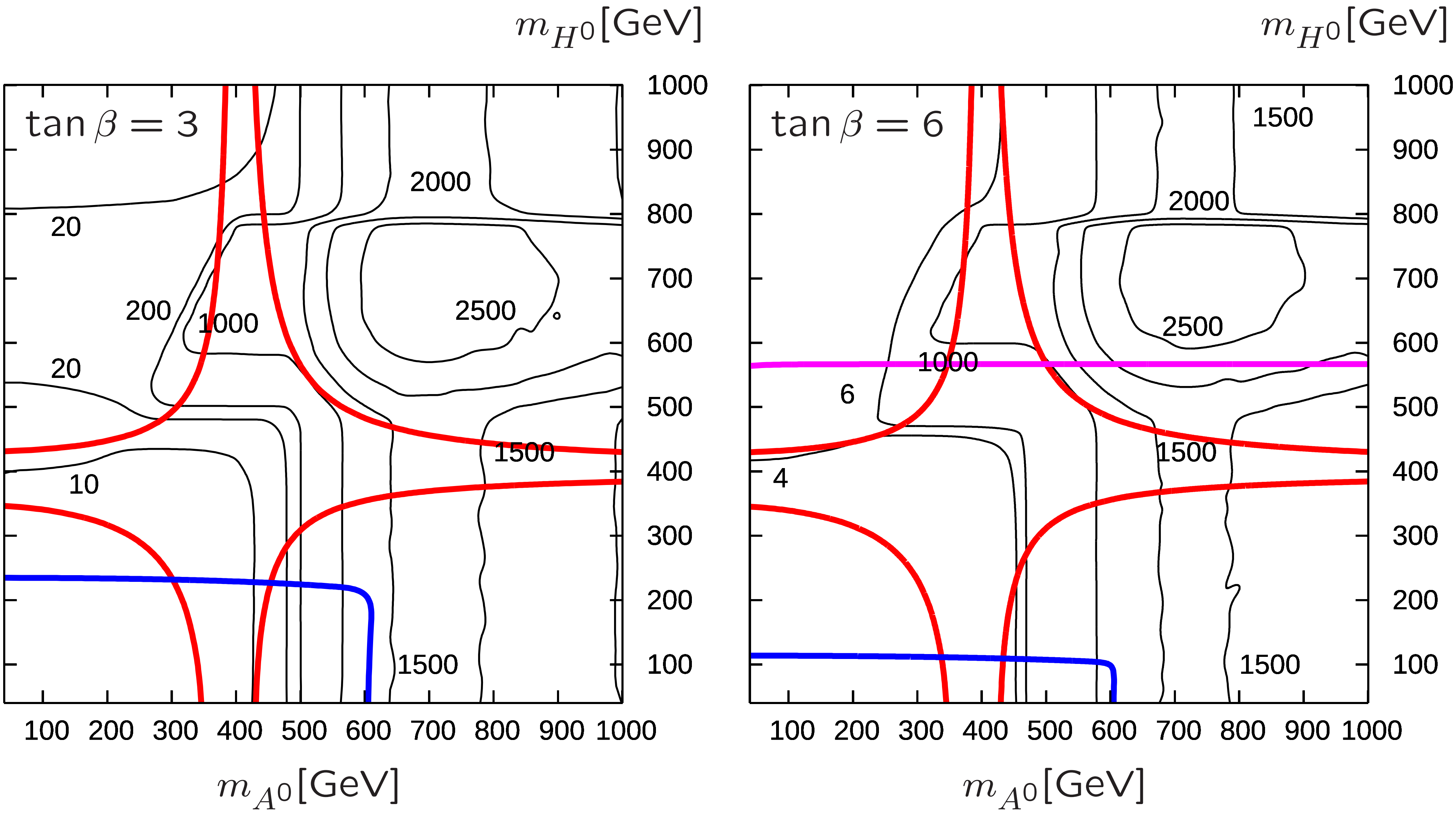
constraints: magn. moment a_μ+ρ-parameter +pert. unitarity+vac. stability

inclusive hadronic cross section $\sigma(W^{\pm}H^{\mp})$ for $M^2 = m_{A^0}^2/2$



constraints: magn. moment a_μ+ρ-parameter +pert. unitarity+vac. stability

inclusive hadronic cross section $\sigma(W^{\pm}H^{\mp})$ for $M^2 = 0$



constraints: magn. moment a_μ+ρ-parameter +pert. unitarity+vac. stability

summary

- $W^\pm H^\mp$ process: not a discovery channel for $H^\pm$ at hadron colliders. However, once the $H^\pm$ has been discovered: observation will help to gain information on the underlying model of the Higgs sector.

- $\sigma_{W^\pm H^\mp}$(THDM) and $\sigma_{W^\pm H^\mp}$(MSSM) can be completely different Especially, the THDM cross section can be up to 100 times larger.

- Parts of the regions of large cross section in the THDM agree with stability and perturbativity constraints of the model and are not excluded by experimental constraints.