Higgs Physics

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LHC DAYS IN SPLIT

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Outline

- Standard Higgs bosons
- Two-Higgs Doublet Models
- Higgs bosons in the MSSM
- Distinguishing scenarios?
- Outlook

recent review:
A. Djouadi, hep-ph/0503172 + hep-ph/0503173

Scalars in EW theory needed for

- masses of gauge bosons and fermions
- restoration of unitarity at high energies

  compensate rising cross sections from
  – longitudinal polarizations of vector bosons
  – massive fermions

done via Higgs mechanism

(i) non-vanishing VEV, masses $\sim$ VEV

(ii) exchange of Higgs bosons in high-energy amplitudes

(iii) all couplings proportional to masses of particles

$\longrightarrow$ **central element of electroweak theory**

$\Rightarrow$ Higgs search (& Higgs physics) is one of the main goals of collider physics

$\leq$ 2000:	LEP:
	e^+e^- collider, $E_{\mathrm{CM}} \lesssim 206$ GeV
$\geq$ 2001:	Tevatron, Run II:
	$p\bar{p}$ collider, $E_{\mathrm{CM}} \approx 2$ TeV
$\gtrsim$ 2007:	LHC:
	pp collider, $E_{\mathrm{CM}} \approx 14$ TeV
$\gtrsim$ 2015: ?	ILC:
	e^+e^- collider, $E_{\mathrm{CM}} \approx 500$–$1000$ GeV

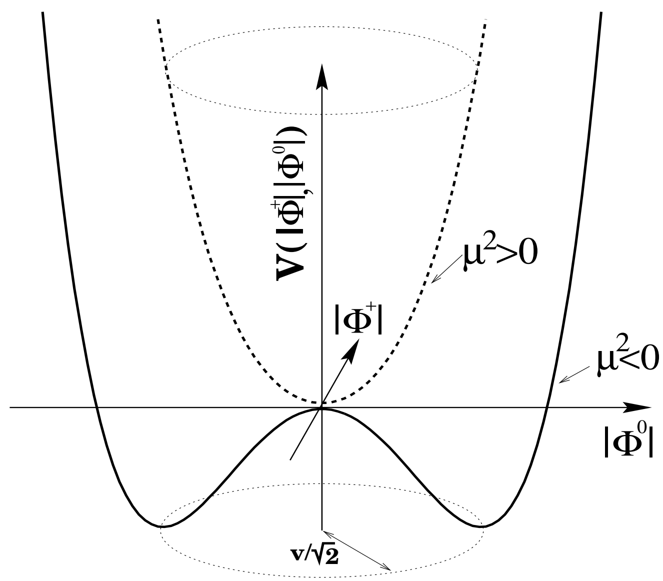
Higgs sector of the Standard Model:

scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: spontaneous symmetry breaking



minimum of the potential at $\langle \Phi \rangle = \frac{1}{\sqrt{2}}\sqrt{\frac{-\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}}$

Gauge-invariant interaction with gauge fields:

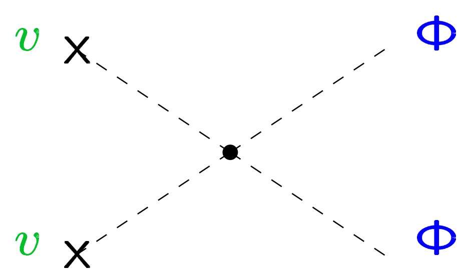
$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

$\Rightarrow$ mass terms

Unitary gauge:

$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

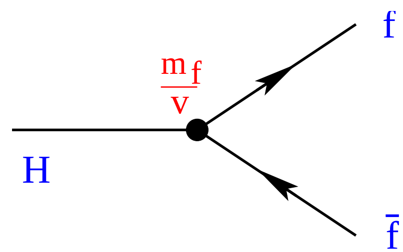
Mass of the Higgs boson: self-interaction



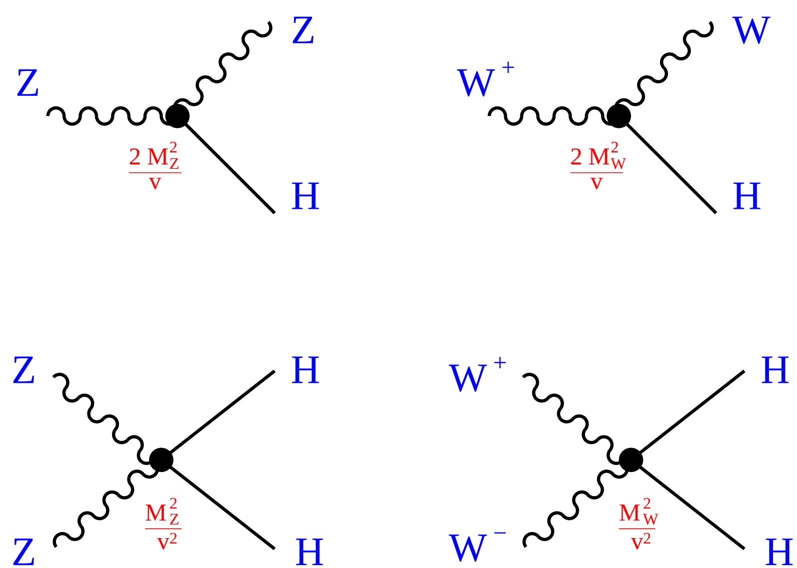
$M_{\text{H}} = v\sqrt{\lambda}$ free parameter

Interactions of the Higgs boson

with fermions:

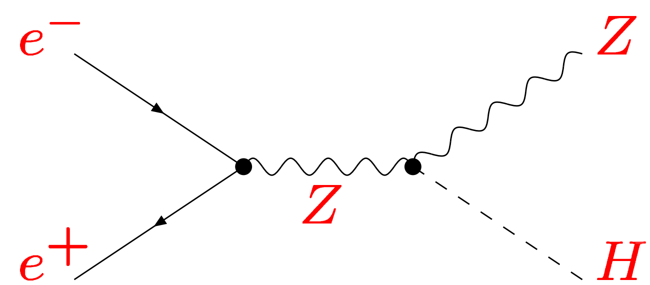


with gauge bosons: $\left(\frac{2M_W}{v} = g\right)$

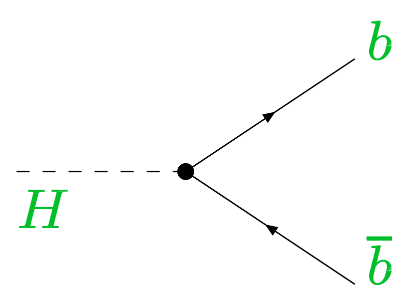


Search for the Standard Model Higgs at LEP

Dominant production process: $e^+e^- \to ZH$



Dominant decay process: $H \to b\bar{b}$

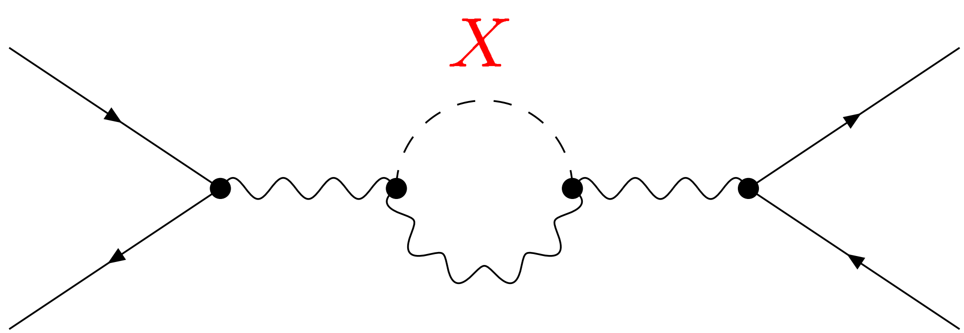


exclusion limit (95% C.L.): $M_{\mathrm{H}} > 114.4\ \mathrm{GeV}$

indirect bounds from EW precision data

Test of theory at quantum level:

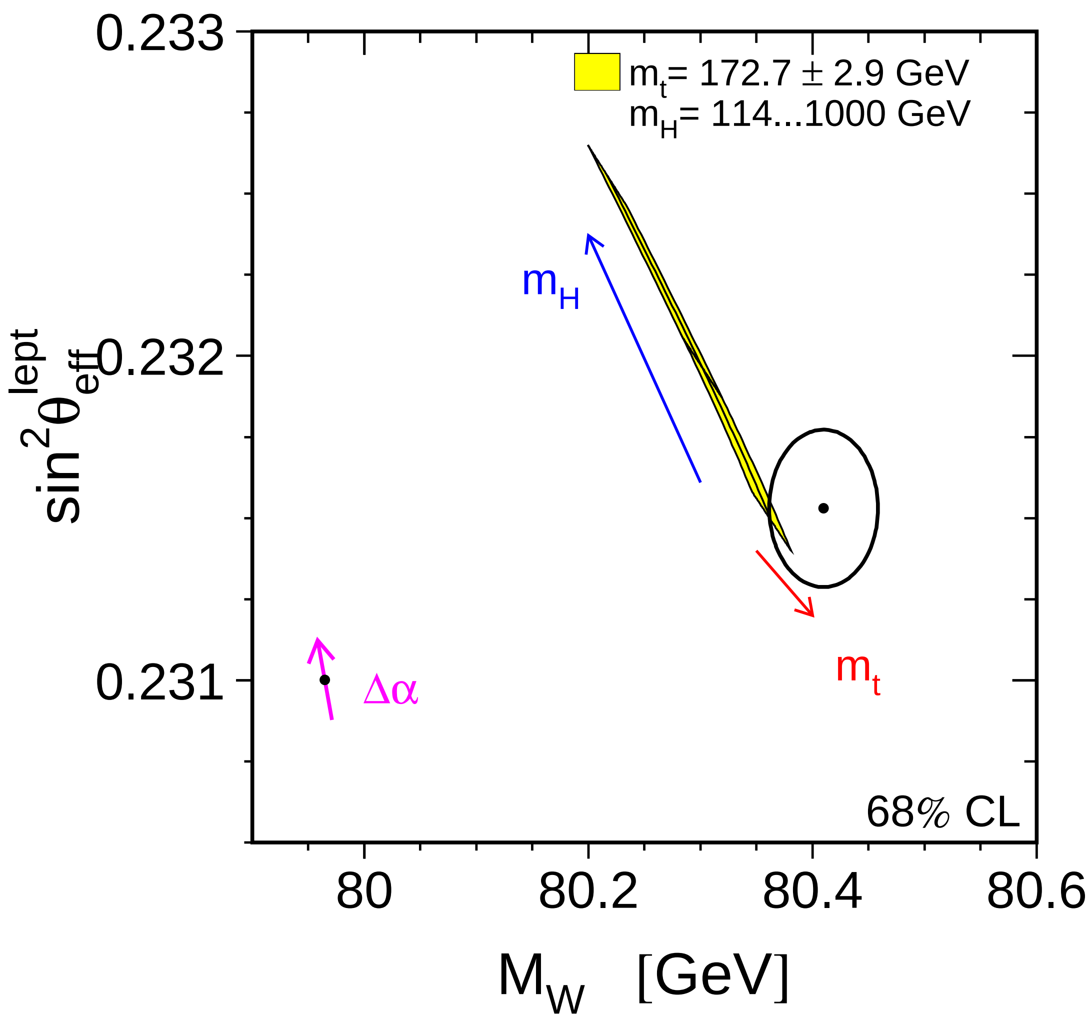
Sensitivity to loop corrections



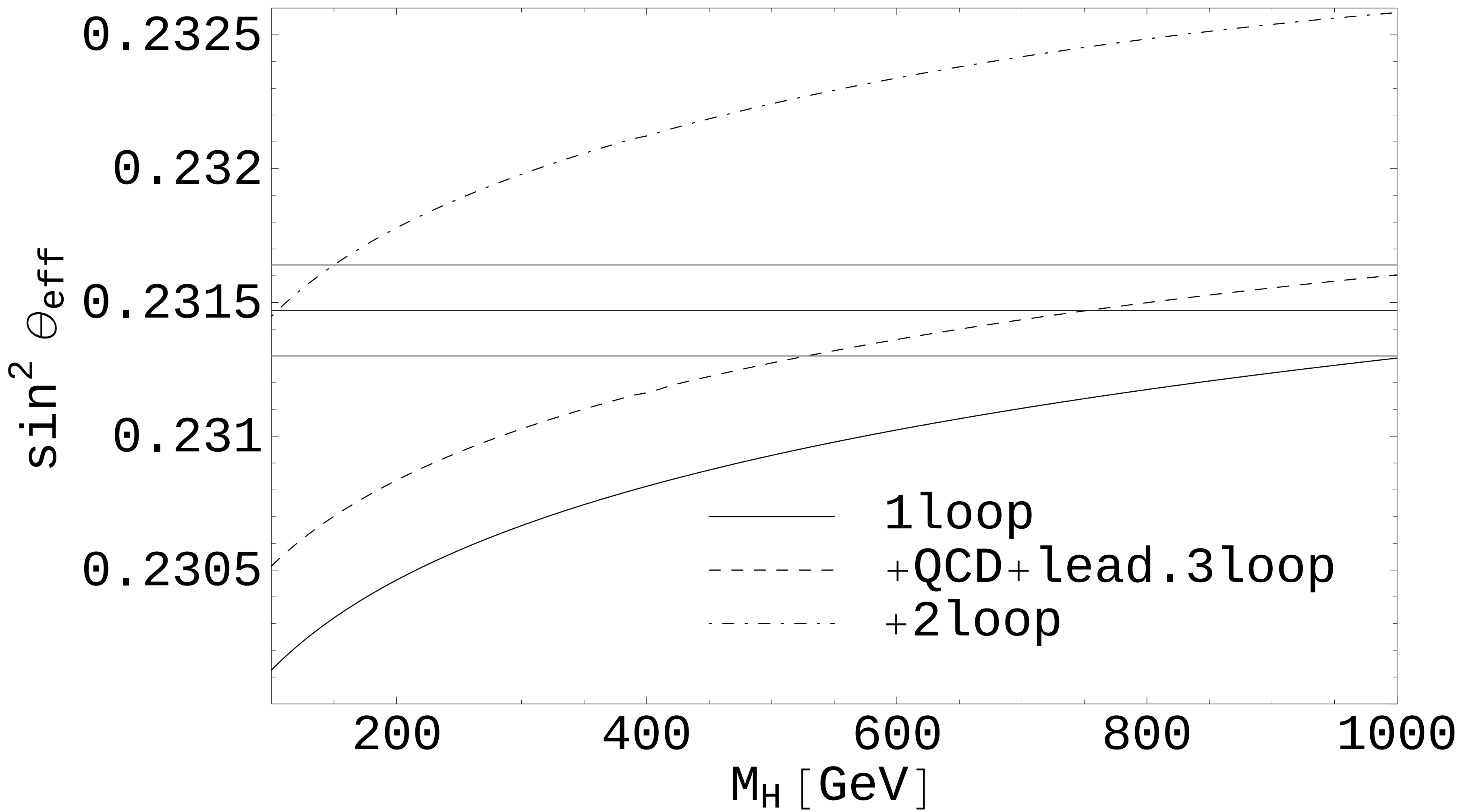
sensitivity to internal particles (X)

Standard Model: $X = H$

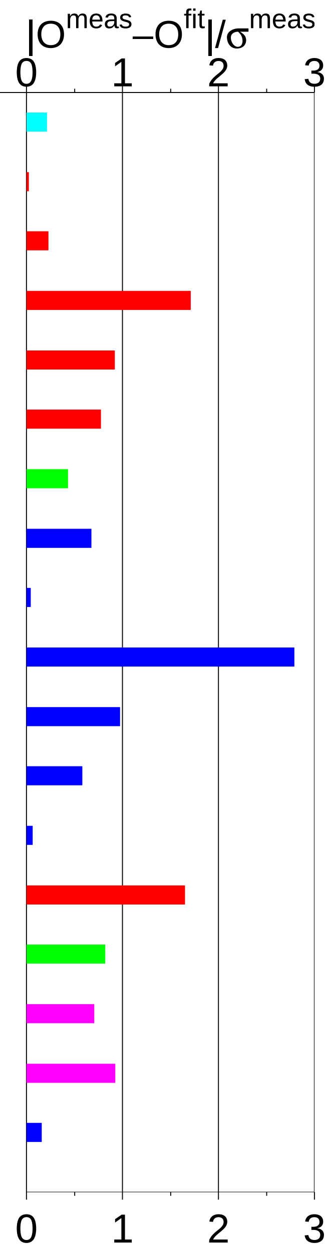
LEP Electroweak Working Group

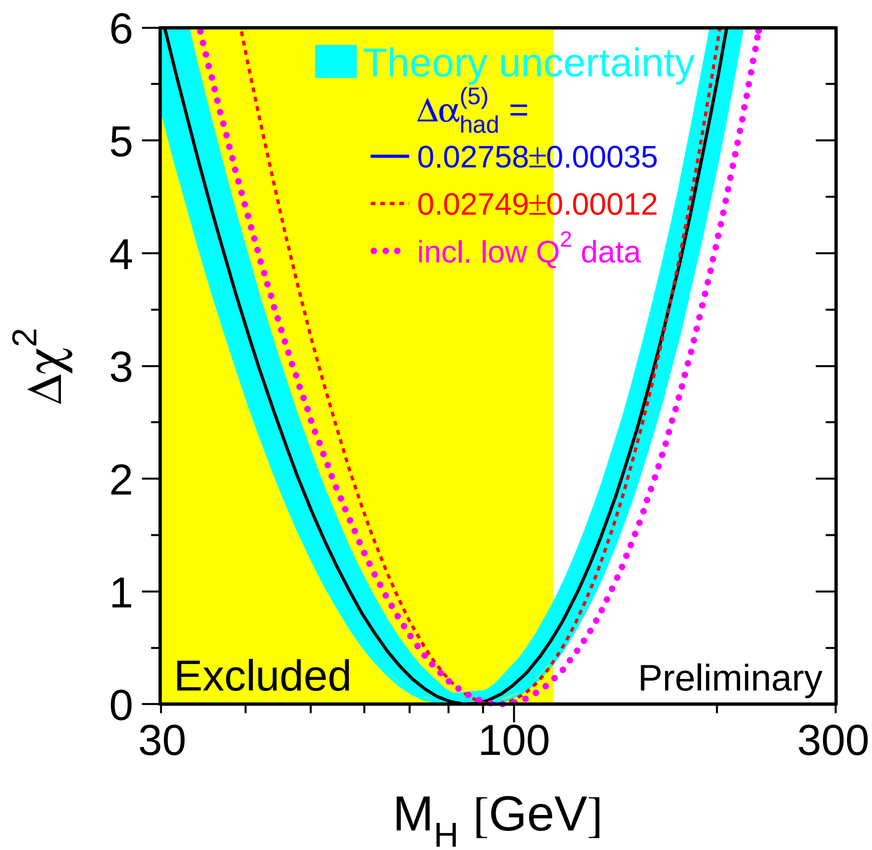


importance of two-loop calculations



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7





$M_{\mathrm{H}} < 166\ \mathrm{GeV} \quad (95\%\mathrm{C.L.})$

with renormalized probability for $M_{\mathrm{H}} > 114$ GeV:

$M_{\mathrm{H}} < 199\ \mathrm{GeV} \quad (95\%\mathrm{C.L.})$

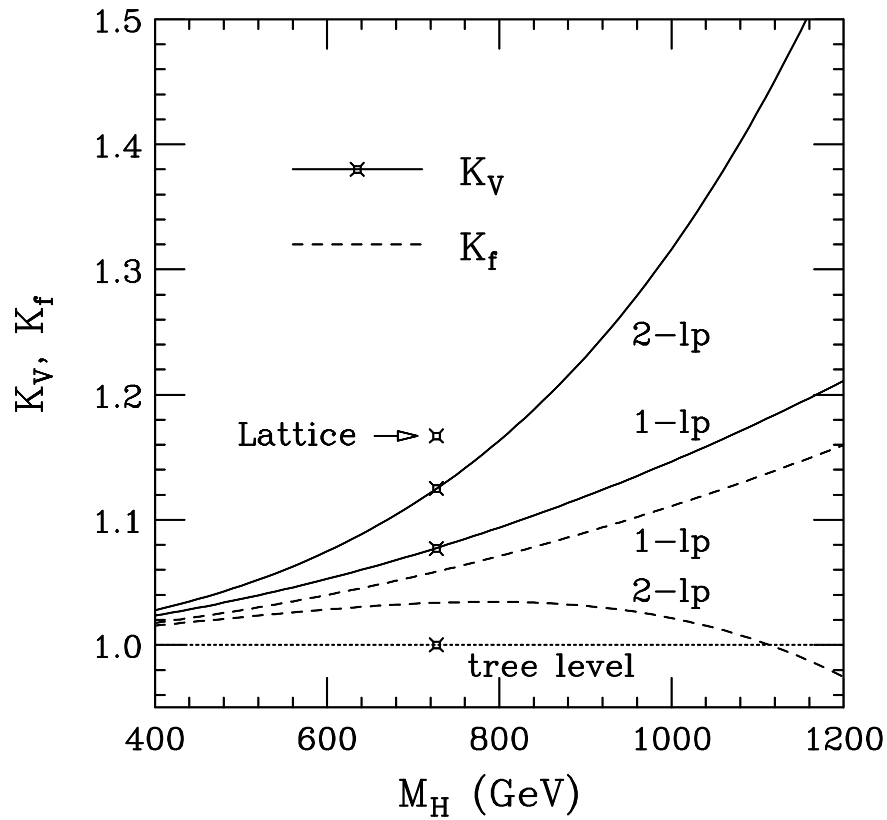
Theoretical bounds on Higgs boson mass from

- perturbativity $\longrightarrow$ upper bound
- unitarity $\longrightarrow$ upper bound
- triviality (Landau pole) $\longrightarrow$ upper bound
- vacuum stability $\longrightarrow$ lower bound

perturbativity

decay widths into fermions: $\Gamma(H \to f\bar{f}) = \Gamma_{\mathrm{tree}} \cdot K_f$

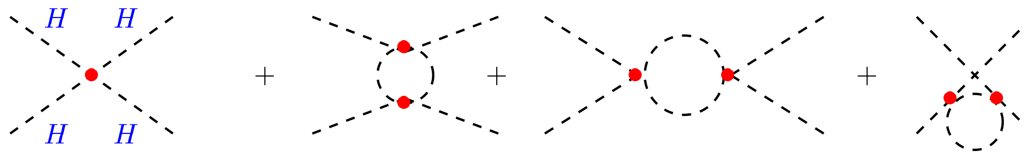
decay widths into vector bosons: $\Gamma(H \to V\bar{V}) = \Gamma_{\mathrm{tree}} \cdot K_V$



[Ghinculov; Frinck, Kniehl, Riesselmann]

triviality (Landau pole)

Higgs self coupling is scale dependent, $\lambda(Q)$



variation with scale Q described by RGE

$$\frac{d\lambda}{dt} = \frac{3}{4\pi^2}\,\lambda^2, \qquad t = \log\frac{Q^2}{v^2}$$

solution:

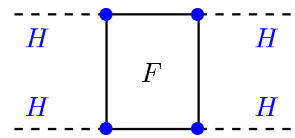
$$\lambda(Q) = \frac{\lambda(v)}{1 - \frac{3}{4\pi^2}\lambda(v)\log\frac{Q^2}{v^2}} \quad \text{with} \quad \lambda(v) = \frac{M_H^2}{2v^2}$$

diverges at scale $Q = \Lambda_C$ (Landau pole)

$$\Lambda_C = v\,\exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

vacuum stability

top-quark Yukawa coupling $g_t \sim m_t$ contributes to the running Higgs self coupling $\lambda(Q)$ through top loop $\sim g_t^4$



variation with scale Q described by RGE

$$\frac{d\lambda}{dt} = \frac{3}{4\pi^2}\left(\lambda^2 - \frac{m_t^4}{v^4}\right)$$

$\lambda(Q) < 0$ for $Q > \Lambda_C$ $\rightarrow$ vacuum not stable

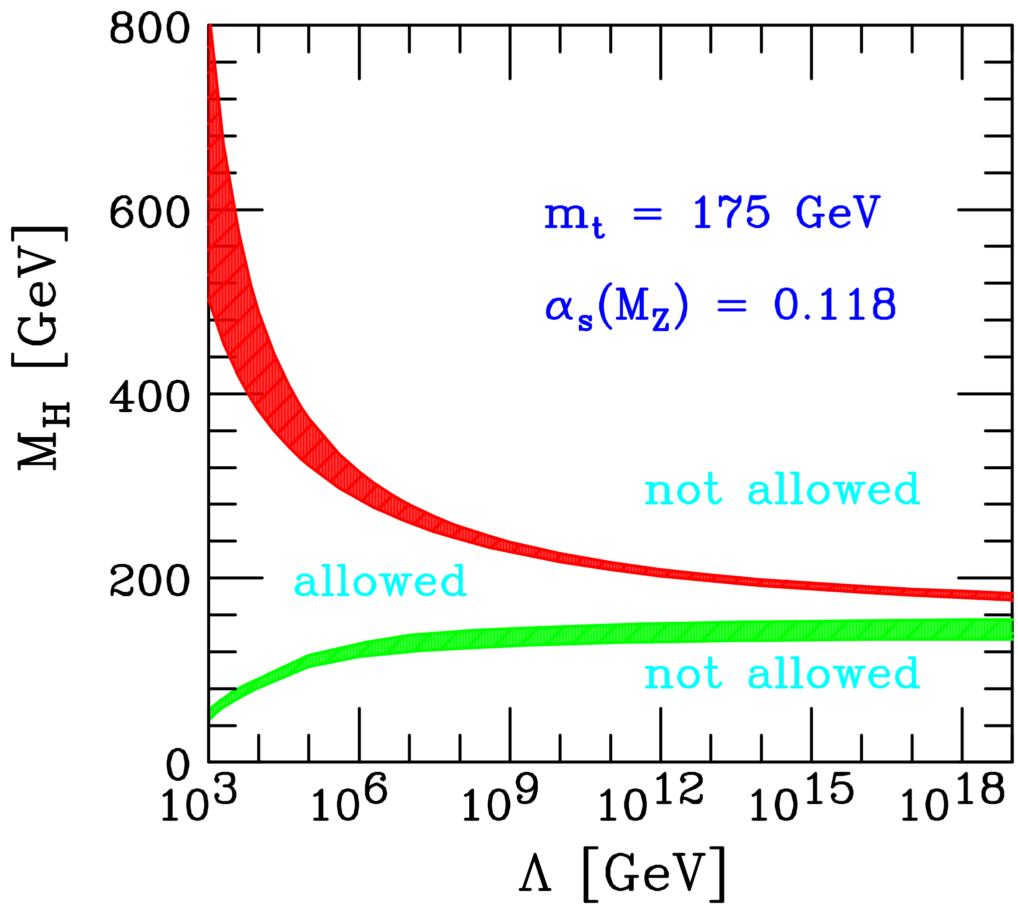
high value of Λ_C needs M_H large enough

$$\Lambda_C \sim 10^{16}: \quad M_H > 130\,\mathrm{GeV}$$

$$\Lambda_C \sim 10^{3}: \quad M_H > 70\,\mathrm{GeV}$$

combined effects, RGE in two-loop order:

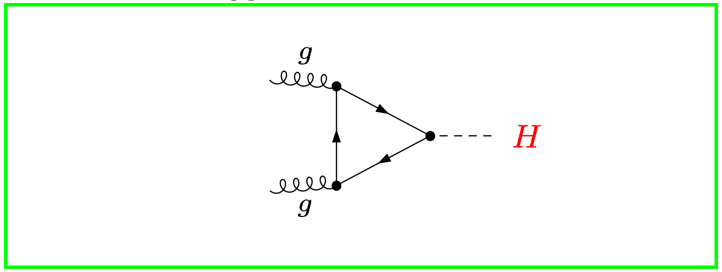
$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\left(12\lambda^2 - 3\,g_t^2 + 6\,\lambda\,g_t^2\; + \cdots\right)$$



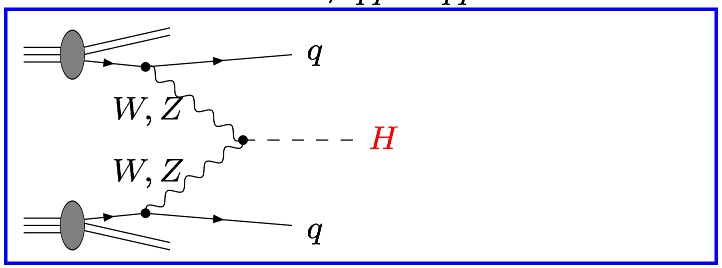
[Hambye, Riesselmann]

Higgs production at the LHC

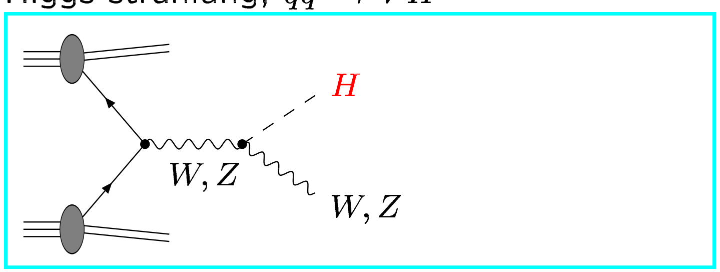
- gluon fusion, $gg \to H$



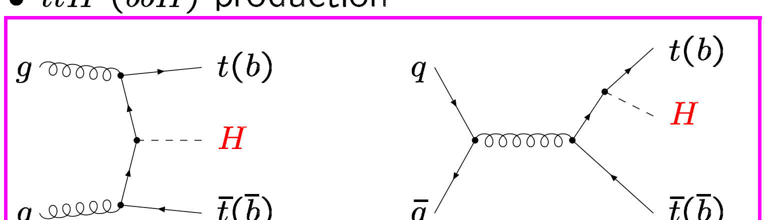
- vector boson fusion, $qq \to qqH$



- Higgs strahlung, $q\bar{q}' \to VH$



- $t\bar{t}H$ $(b\bar{b}H)$ production



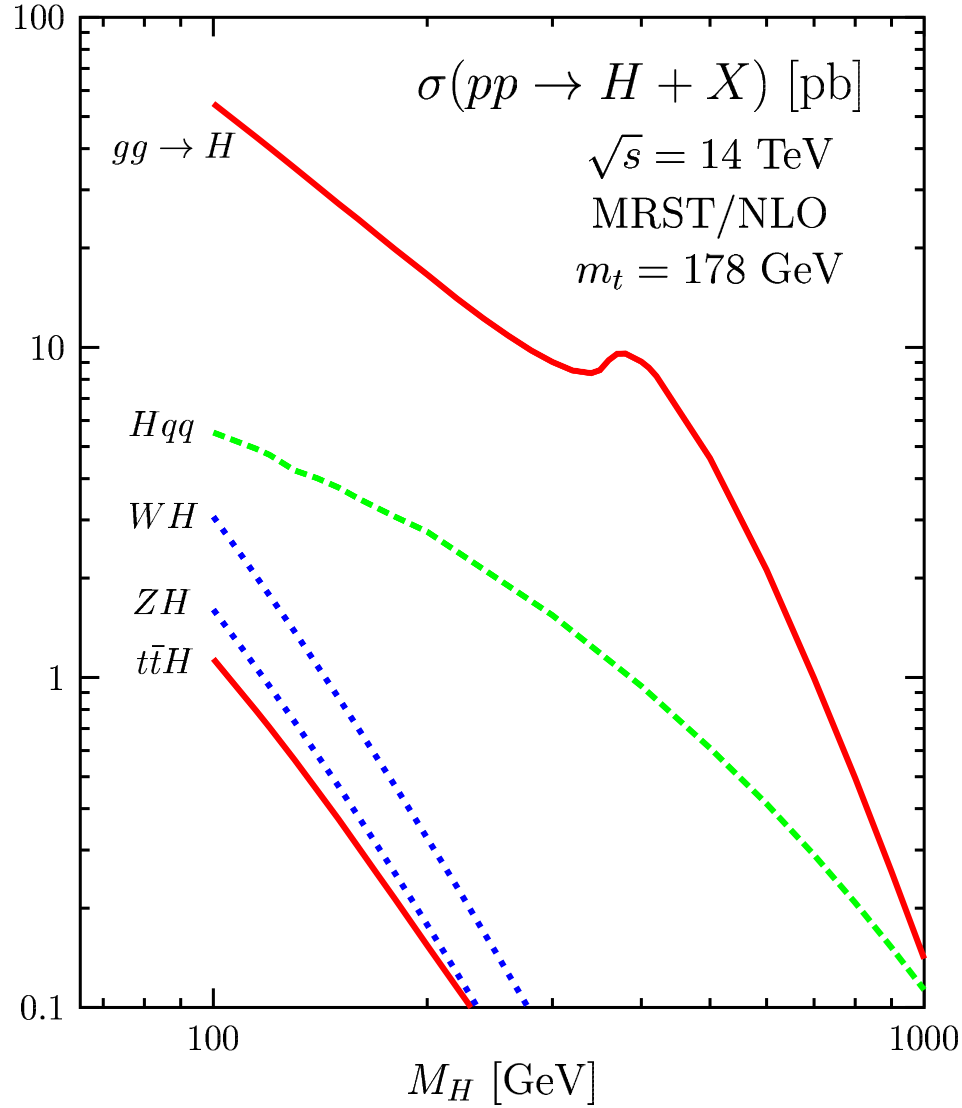
- gluon-gluon fusion:
  NNLO QCD *[Harlander, Kilgore]*
  NL EW *[Degrassi, Maltoni]*

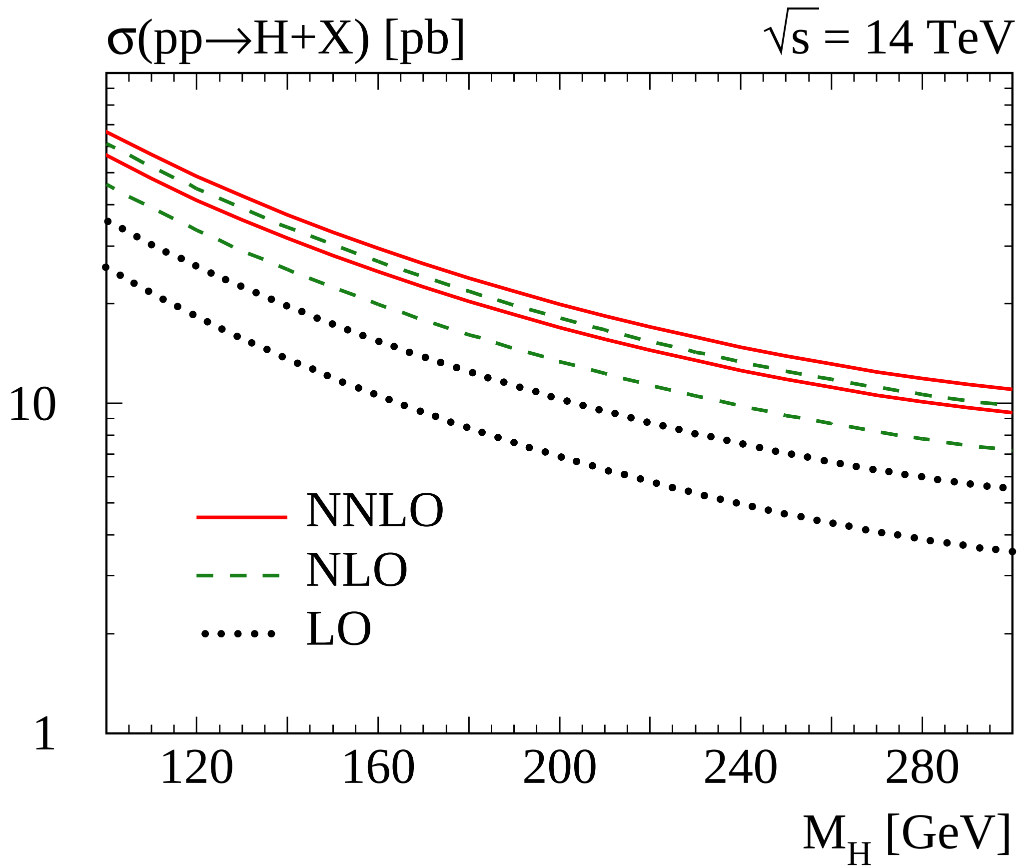
- WW (ZZ) fusion:
  NLO QCD
  [Figy, Oleari, Zeppenfeld]

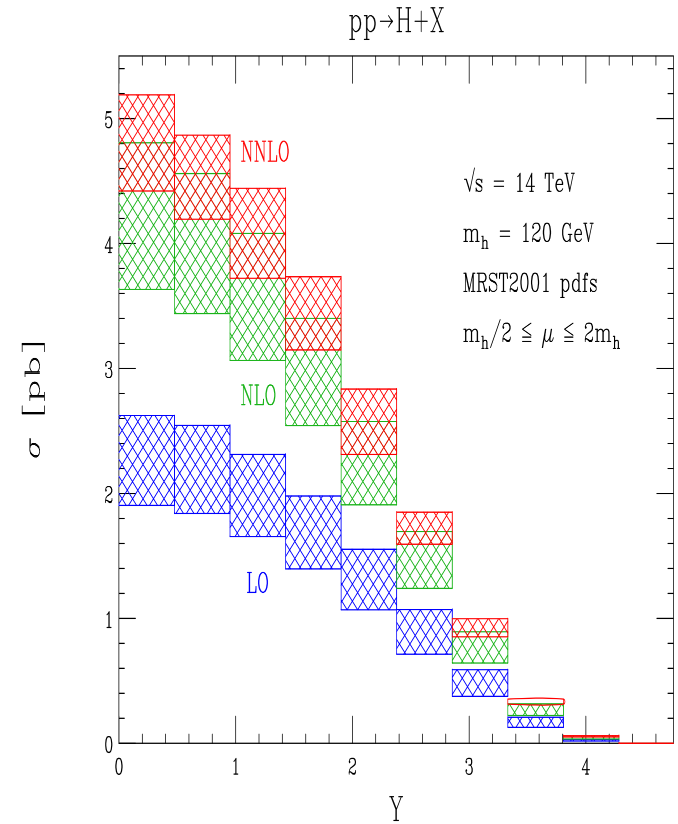
- Higgs-strahlung processes:
  NNLO QCD + NLO EW
  [Brein et al.]

- radiation from heavy quarks:
  NLO QCD *[Beenakker et al., Dawson et al.]*
  NLO EW *[Denner et al.]*

Higgs production at the LHC





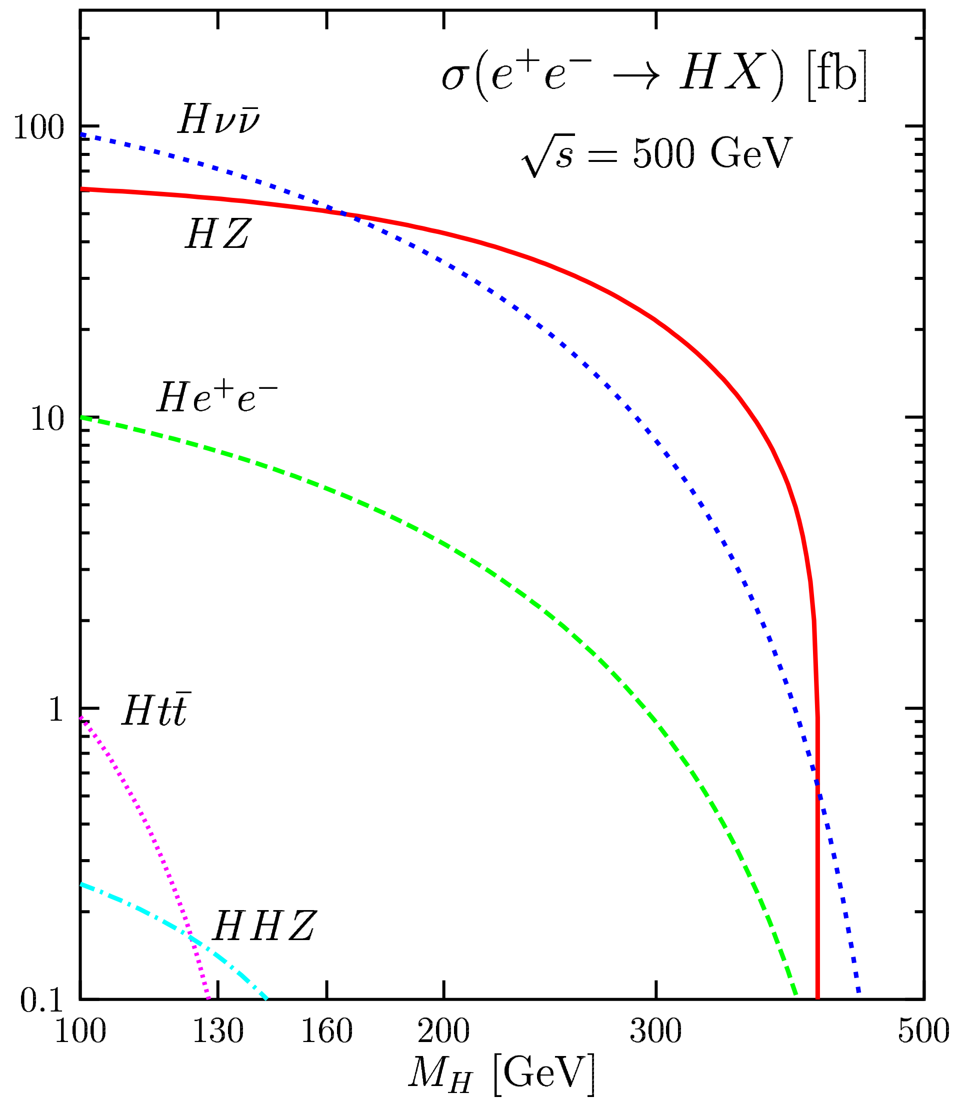


Total cross section: [*R. Harlander, W. Kilgore '02*]

Fully differential: [*C. Anastasiou, K. Melnikov, F. Petriello '04*]

⇒ Next-to-next-to-leading order needed

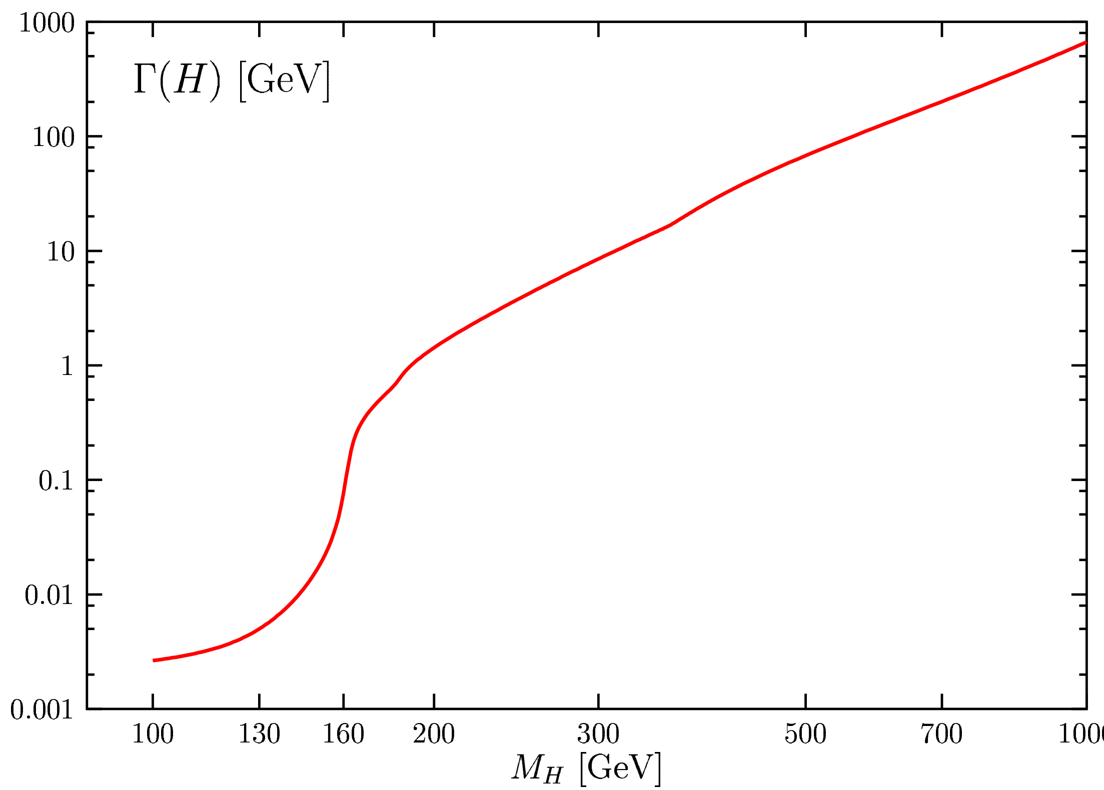
Higgs production at a Linear Collider



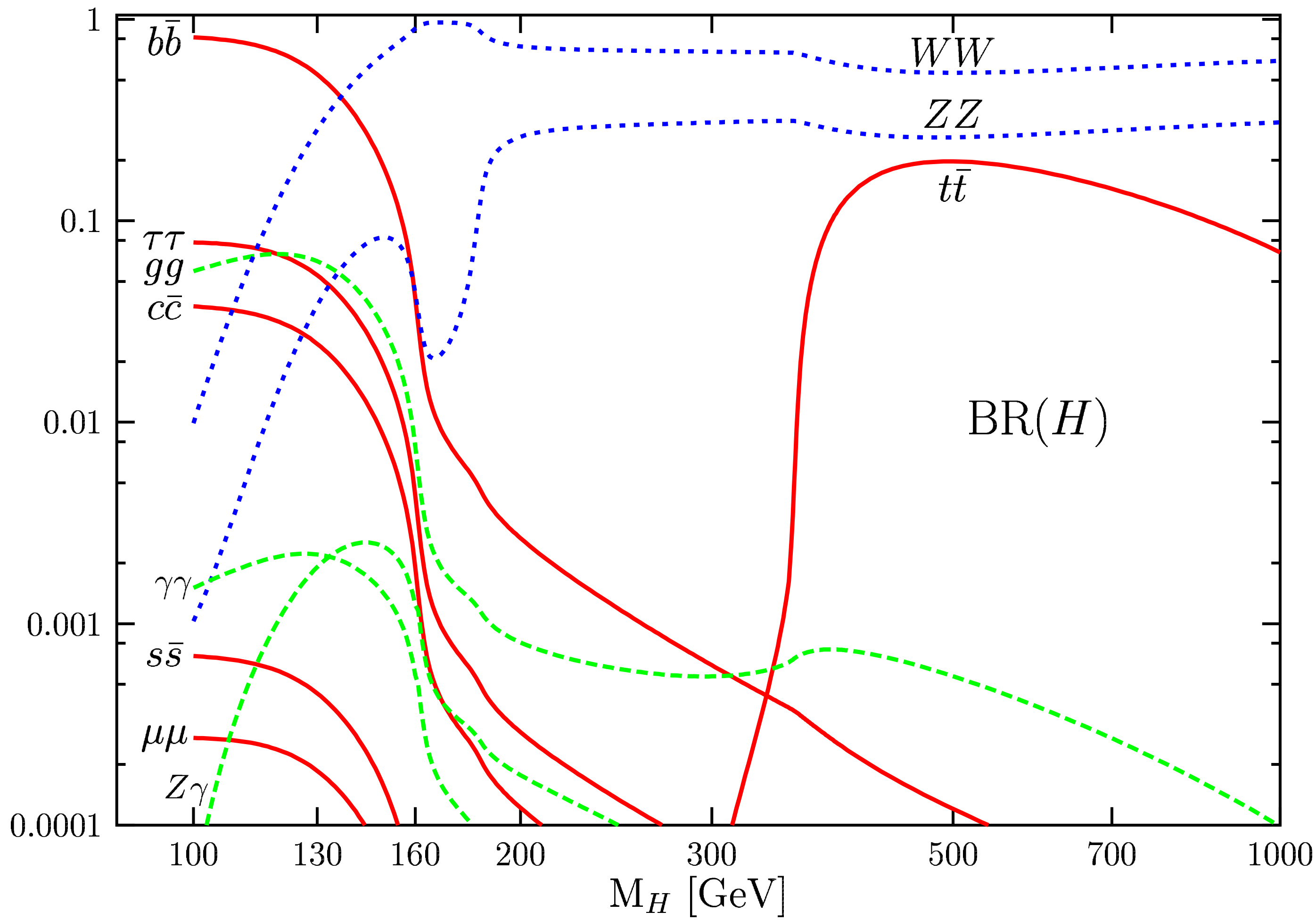
Higgs decays

- $H \to f\bar{f}$: $\Gamma \sim M_H\, m_f^2$
- $H \to WW,\, ZZ$: $\Gamma \sim M_H^3$

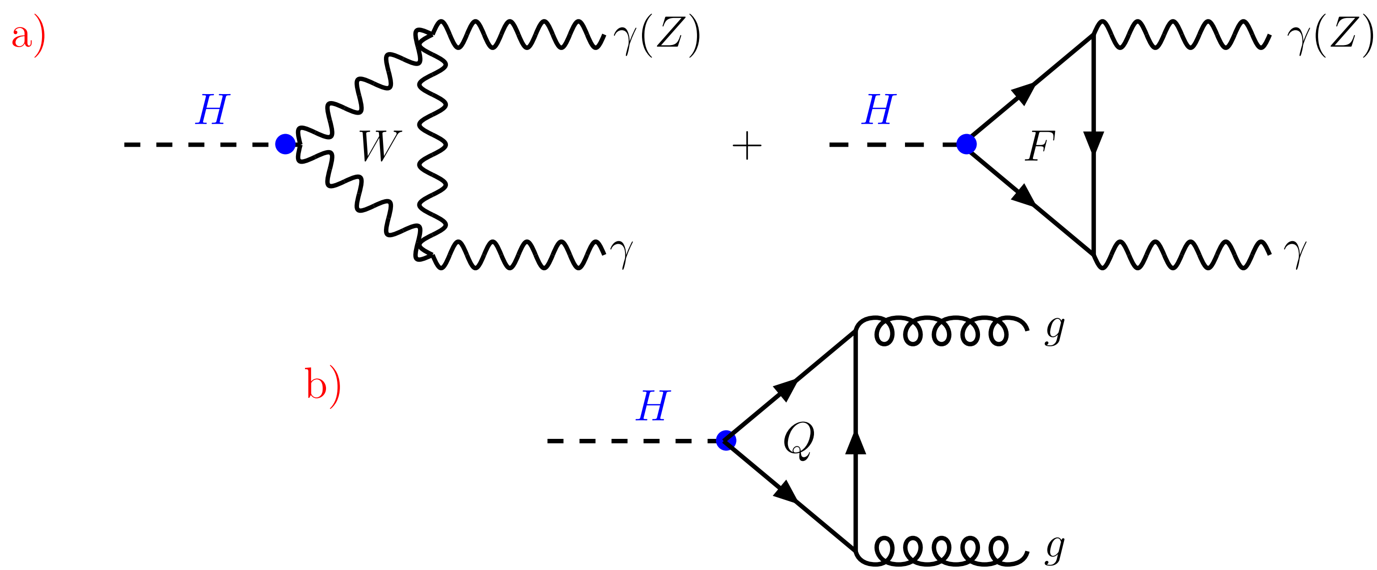
total width



branching ratios

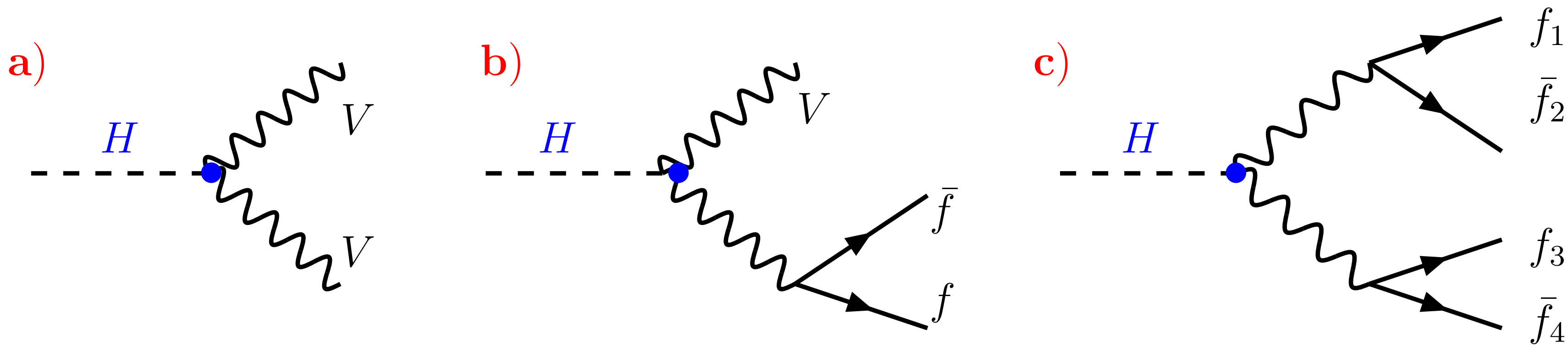


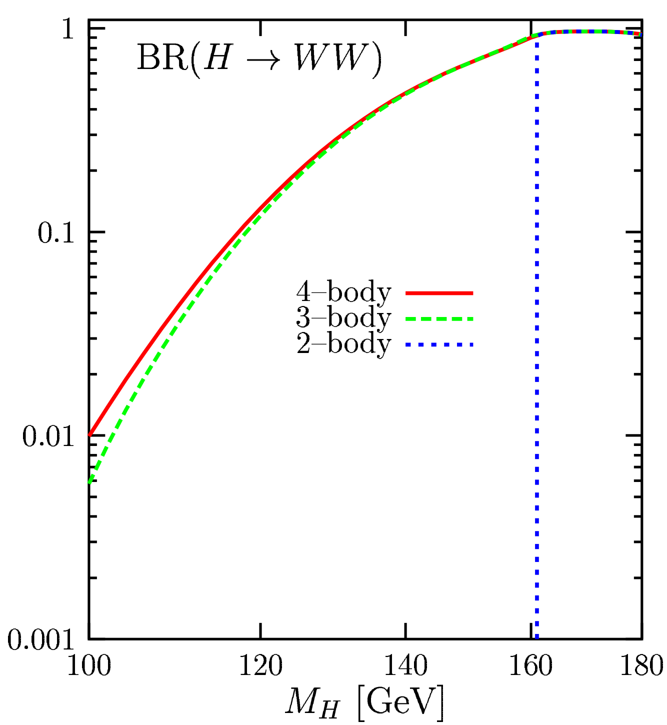
loop-induced decays

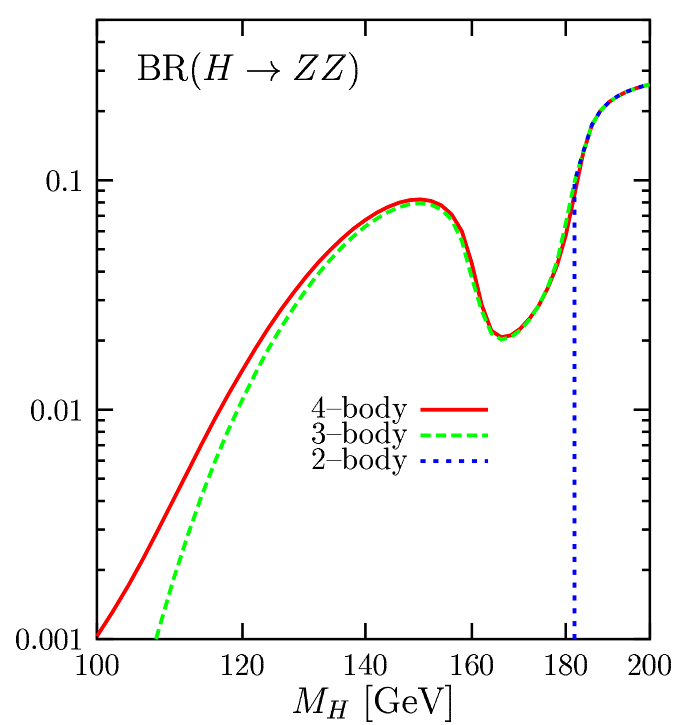


Higgs decays into 4 fermions

also below VV threshold with one or two V off-shell

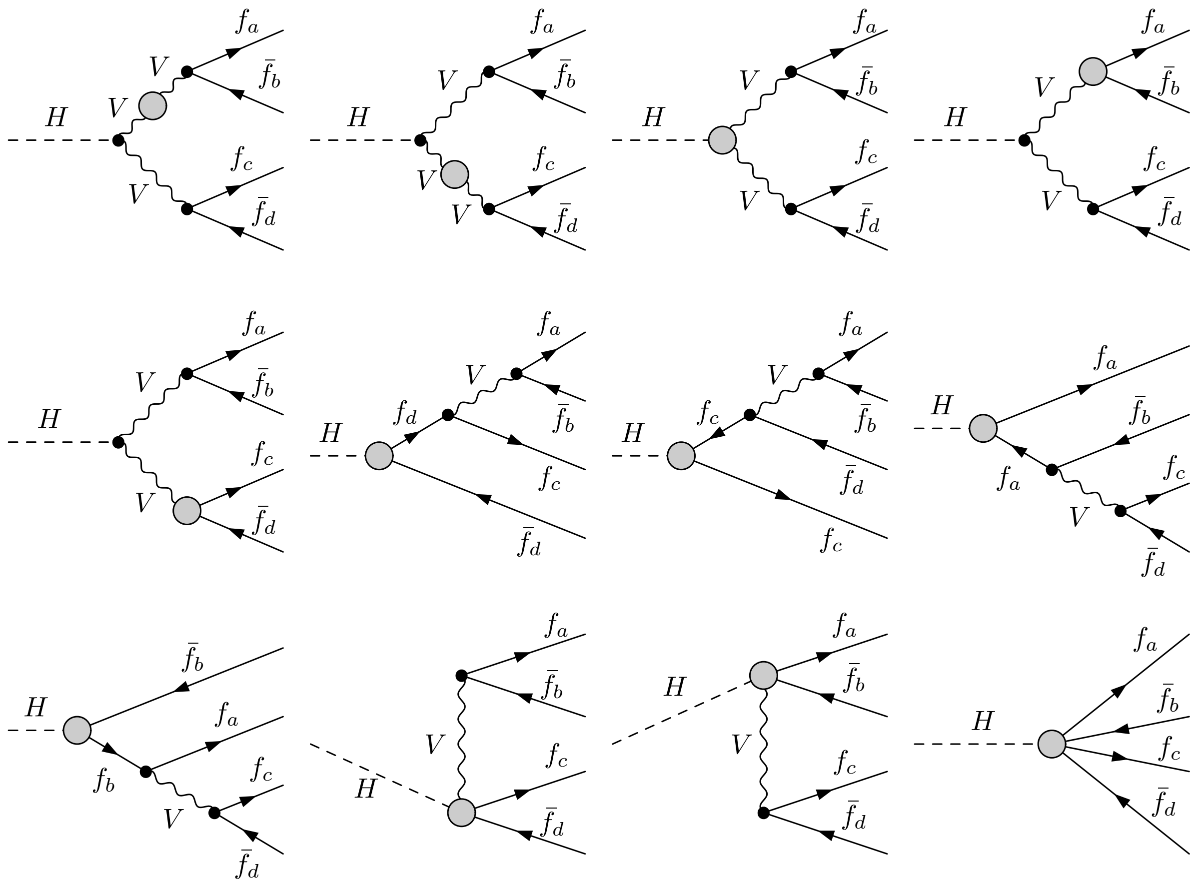




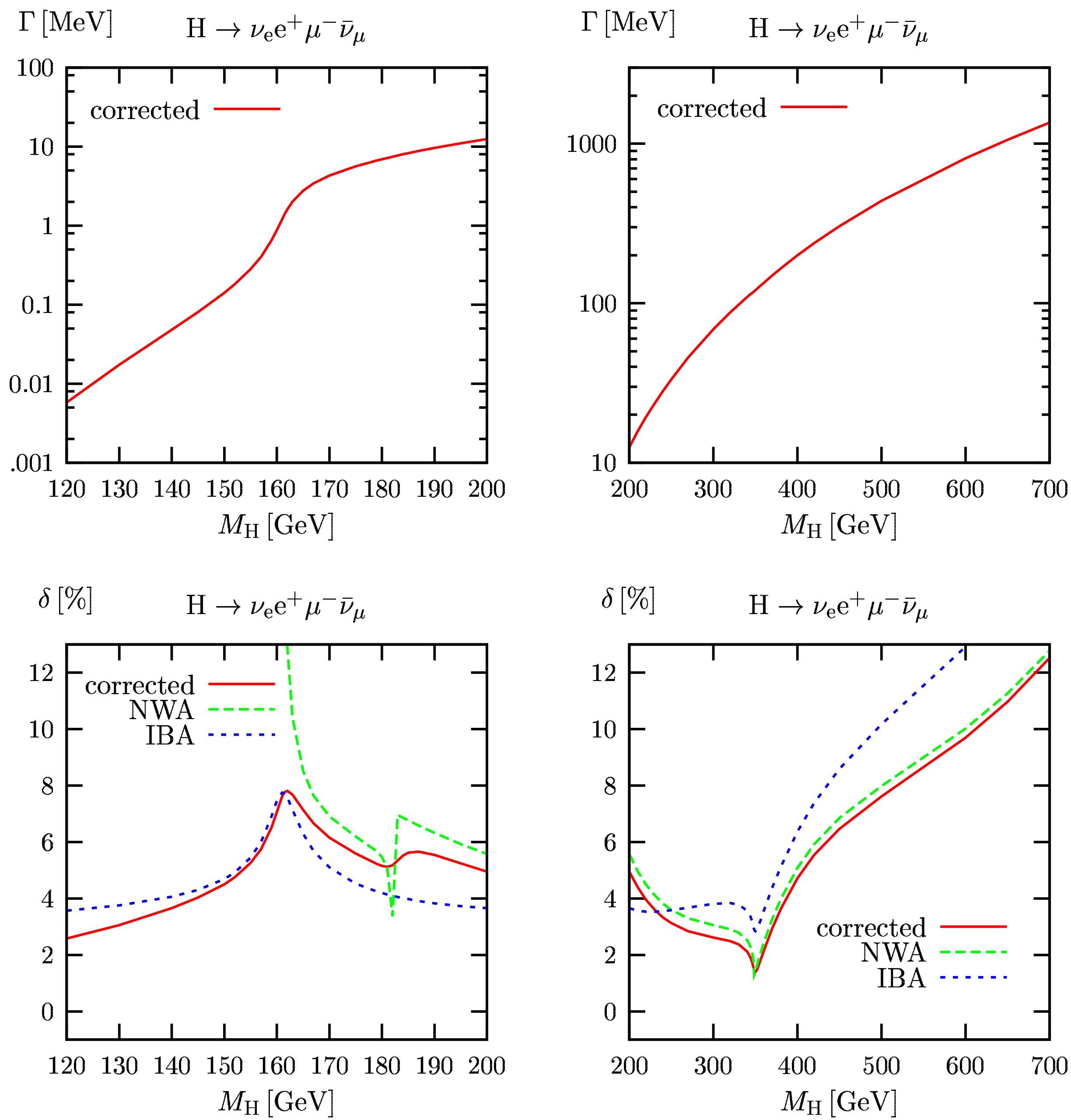


$H \to VV \to 4f$

needs also background pocesses + h.o.



[Bredenstein, Denner, Dittmaier, M.Weber]



Two-Doublet-Model Higgs Bosons

$$V(\Phi_1,\Phi_2) = \lambda_1(\Phi_1^+\Phi_1 - {v_1}^2)^2 + \lambda_2(\Phi_2^+\Phi_2 - {v_2}^2)^2 + \lambda_3[(\Phi_1^+\Phi_1 - {v_1}^2) + (\Phi_2^+\Phi_2 - {v_2}^2)]^2$$

$$+\lambda_4[(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_2) - (\Phi_1^+\Phi_2)(\Phi_2^+\Phi_1)] + \lambda_5[Re(\Phi_1^+\Phi_2) - v_1 v_2]^2 + \lambda_6[Im(\Phi_1^+\Phi_2)]^2$$

mass eigenstates: $h^0, H^0, A^0, H^\pm$

free parameters: $m_h, m_H, m_A, m_{H^\pm}, \quad \tan\beta = \frac{v_2}{v_1}, \ \alpha \quad \lambda_5$

$$\lambda_1 = \frac{g^2}{16\cos^2\beta m_W^2}[m_H^2 + m_h^2 + (m_H^2 - m_h^2)\frac{\cos(2\alpha+\beta)}{\cos\beta}] + \lambda_3(-1+\tan^2\beta)$$

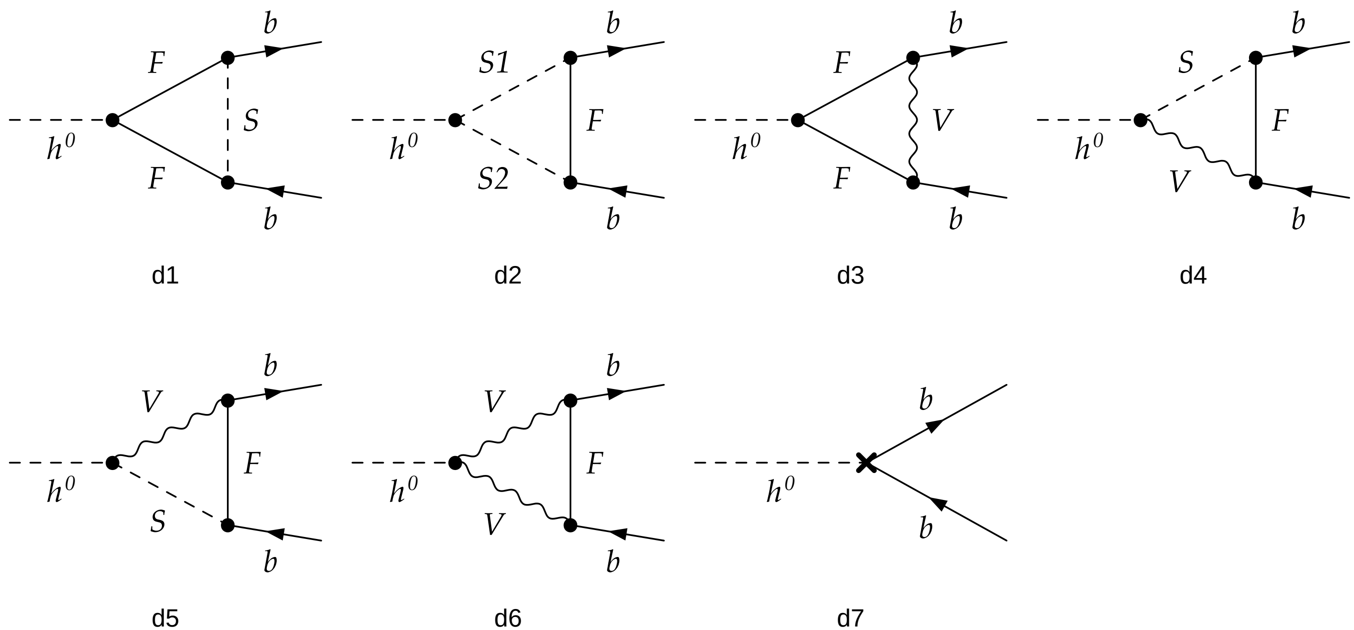
$$\lambda_2 = \frac{g^2}{16\sin^2\beta m_W^2}[m_H^2 + m_h^2 + (m_h^2 - m_H^2)\frac{\sin(2\alpha+\beta)}{\sin\beta}] + \lambda_3(-1+\cot^2\beta)$$

$$\lambda_4 = \frac{g^2 m_{H^\pm}^2}{2m_W^2} \quad , \quad \lambda_5 = \frac{g^2}{2m_W^2}\frac{\sin 2\alpha}{\sin 2\beta}(m_H^2 - m_h^2) \ - \ 4\lambda_3 \quad , \quad \lambda_6 = \frac{g^2 m_A^2}{2m_W^2}$$

$m_H \sim m_A \sim m_{H^\pm} \gg m_Z, \ \alpha \to \beta - \frac{\pi}{2}$: ‘decoupling regime’

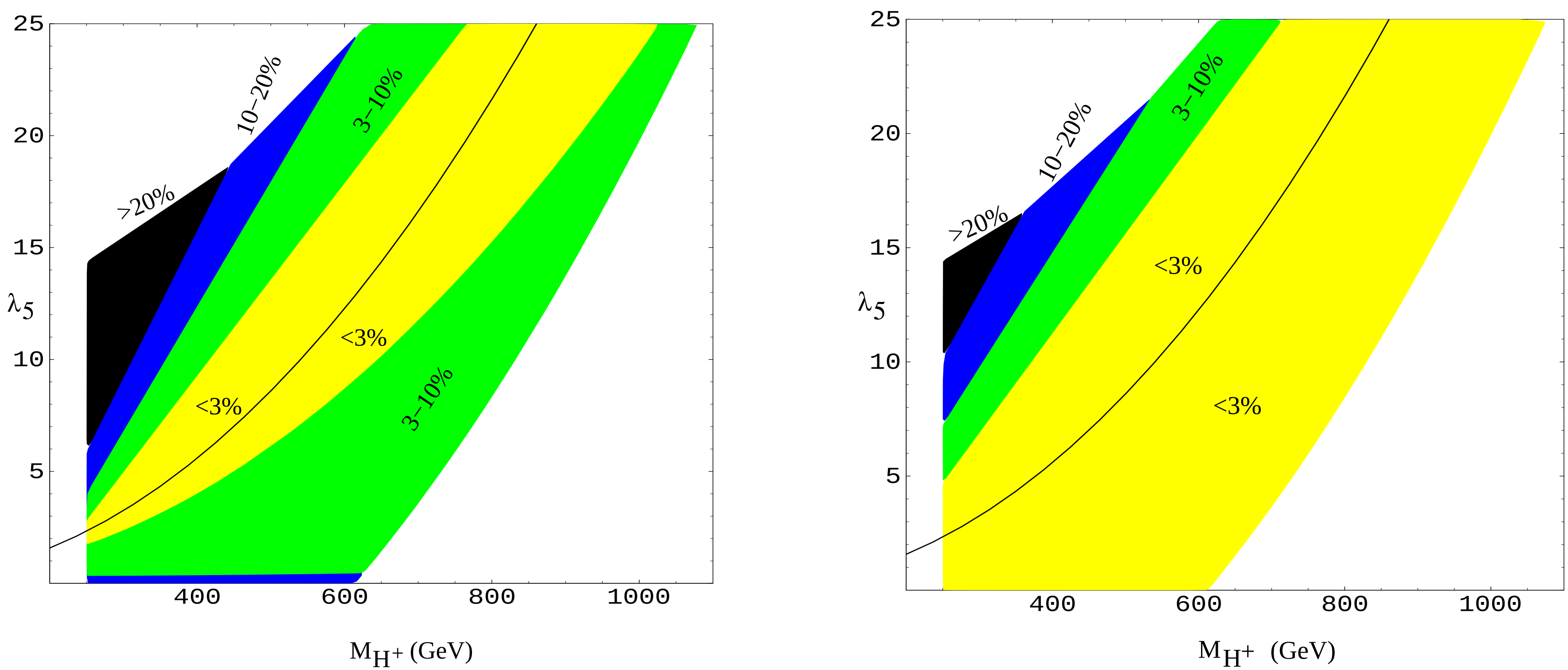
decoupling regime

- $H^0, A^0, H^\pm$ decouple in EW precison observables,
  h^0 with SM-like couplings to gauge bosons and fermions
- non-decoupling effects in h^0 through self-couplings
  e.g. in $\quad h^0 \to \gamma\gamma, \quad h^0 \to b\bar{b}$



$\longrightarrow$ deviations from SM branching ratios

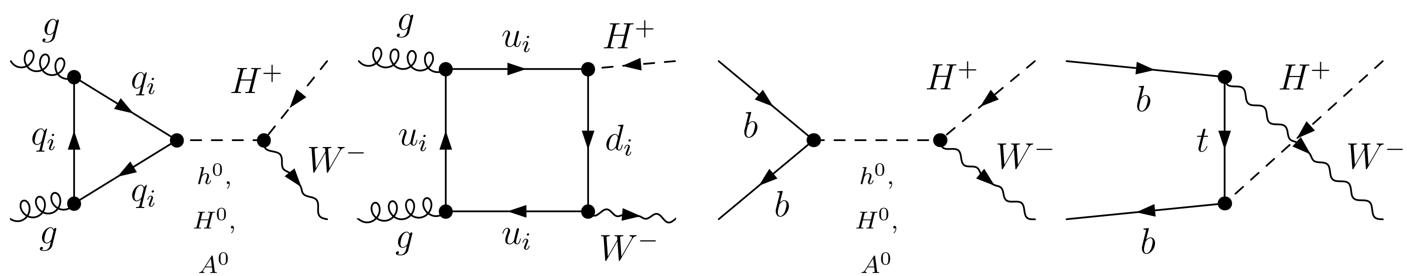
relative deviation from SM branching ratios ($m_h = 120 \text{ GeV}$)



[Arhrib, WH, Peñaranda]

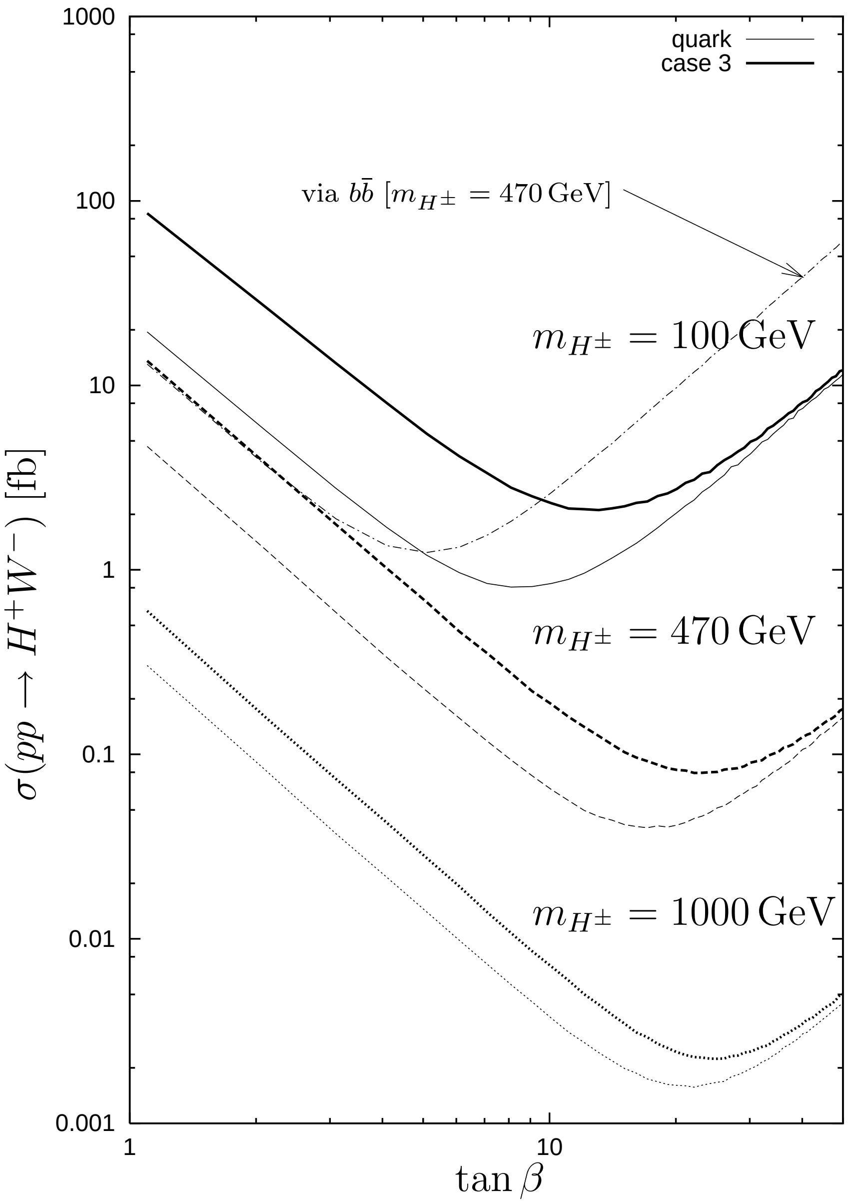
Two-Doublet Higgs production at LHC

- for H^0, H^0, A^0 similar mechanisms as for SM Higgs
- large contributions from $b\bar{b}$ annihilation (enhanced Yukawa couplings)
- charged Higgs $H^{\pm}$ through
  - $b\bar{b} \to H^+H^-,\ H^+W^-$
  - $gg \to H^+H^-,\ H^+W^-$ loop-induced



$H^{\pm}W$ production with quark loops and squark loops (MSSM)

[Brein,WH,Kanemura]



Higgs bosons in the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

Five physical states: $h^0, H^0, A^0, H^\pm$

Input parameters: $\tan\beta = \frac{v_2}{v_1}$, M_A

$\Rightarrow m_\mathrm{h}$, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters

SM Higgs:

- $\lambda\Phi^4$ term ad hoc
- Higgs boson mass: free parameter
- no a-priori reason for a light Higgs boson
- SM (perturbatively) unstable at some high energy

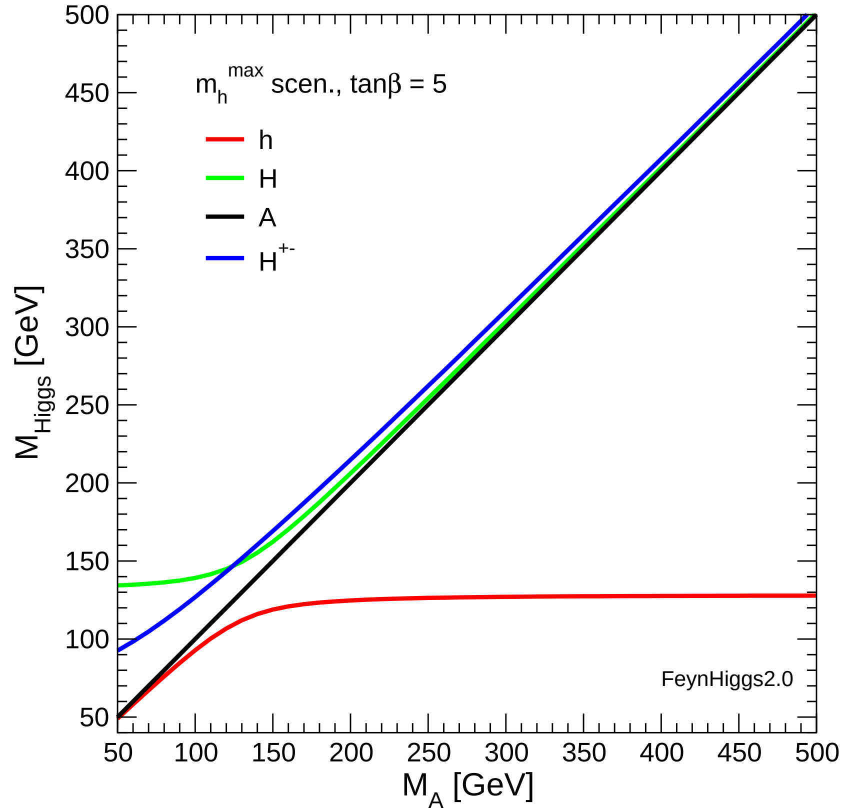
SUSY Standard Model avoids these questions

$$H_2 = \begin{pmatrix} H_2^+ \\ v_2 + H_2^0 \end{pmatrix}, \qquad H_1 = \begin{pmatrix} v_1 + H_1^0 \\ H_1^- \end{pmatrix}$$

$$\text{couples to } u \qquad\qquad \text{couples to } d$$

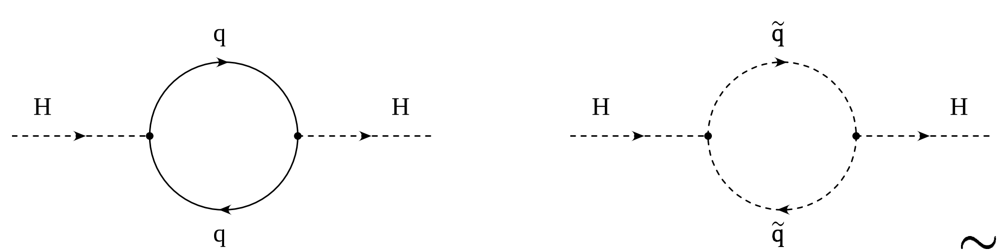
• SUSY gauge interaction $\rightarrow$ H^4 terms
• self coupling remains weak

Spectrum of Higgs bosons in the MSSM (example)



large M_A: h^0 like SM Higgs boson $\sim$ decoupling regime of THDM

m_h^0 strongly influenced by quantum effects, *e.g.*



$\sim \alpha_t$

$\Rightarrow$ Prediction for $m_{\rm h}$, $m_{\rm H}$, ...

Tree-level result for $m_{\rm h}$, $m_{\rm H}$:

$$m^2_{\rm H,h} = \frac{1}{2}\left[M_{\rm A}^2 + M_{\rm Z}^2 \pm \sqrt{(M_{\rm A}^2 + M_{\rm Z}^2)^2 - 4M_{\rm Z}^2 M_{\rm A}^2 \cos^2 2\beta}\right]$$

$\Rightarrow$ $m_{\rm h} \leq M_{\rm Z}$ at tree level

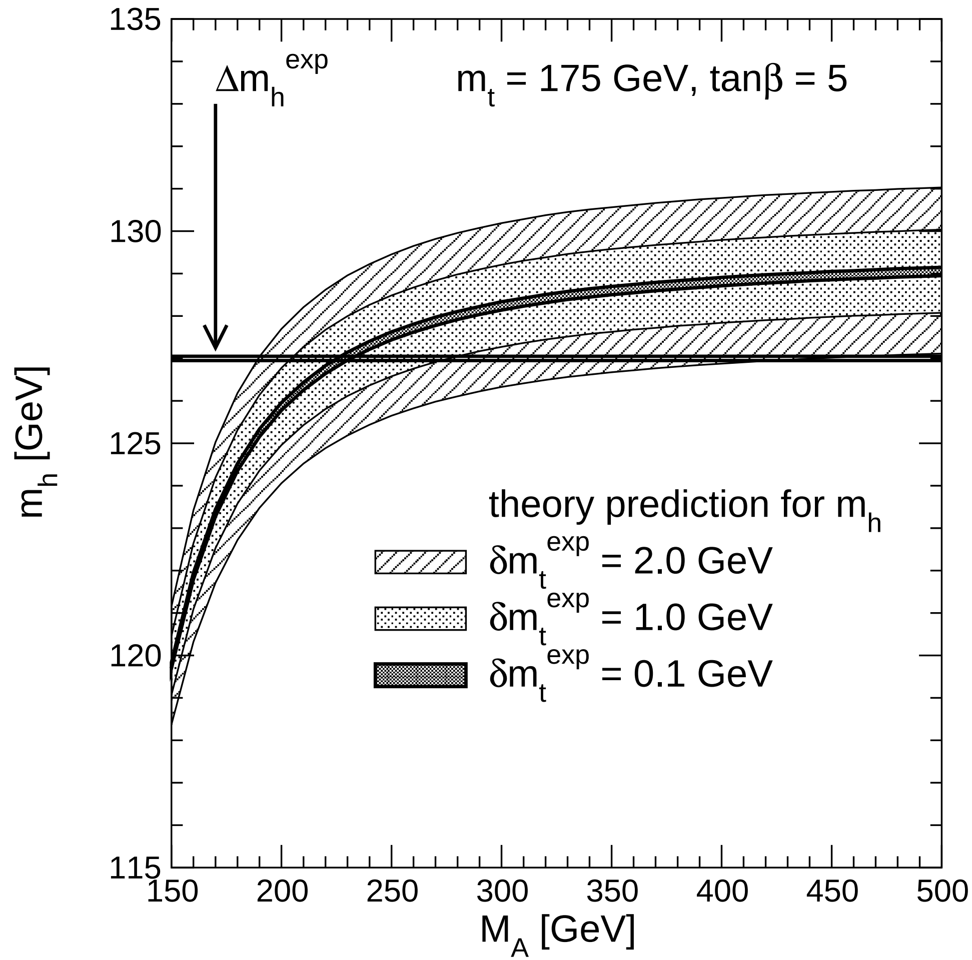
MSSM tree-level bound (gauge sector): excluded by LEP!

Large radiative corrections (Yukawa sector, ...):

Yukawa couplings: $\frac{{\rm e}\, m_{\rm t}}{2 M_{\rm W} s_{\rm W}}$, $\frac{{\rm e}\, m_{\rm t}^2}{M_{\rm W} s_{\rm W}}$, ...

$\Rightarrow$ Dominant one-loop corrections: $G_\mu m_{\rm t}^4 \ln\left(\frac{m_{\tilde{\rm t}_1} m_{\tilde{\rm t}_2}}{m_{\rm t}^2}\right)$, $\quad \mathcal{O}(100\%)$!

[Heinemeyer et al.]



dependent on all SUSY particles and masses/mixings through Higgs self-energies

determination of masses and couplings at higher order

- physical states $h,\ H,\ A,\ H^{\pm}$
- conventional input: M_A, $\tan\beta = v_2/v_1$

dressed $h,\ H$ propagators, renormalized self-energies $\hat{\Sigma}$

$$\left(\Delta_{\rm Higgs}\right)^{-1} = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_H(q^2) & \hat{\Sigma}_{hH}(q^2) \\ \hat{\Sigma}_{Hh}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_h(q^2) \end{pmatrix}$$

- det = 0 $\rightarrow$ $m_{h,H}^{\rm pole}$
- diagonalization $\rightarrow$ effective couplings ($\alpha_{\rm eff}$)

1-loop: complete

2-loop:

– QCD corrections $\sim \alpha_s \alpha_t,\ \alpha_s \alpha_b$

– Yukawa corrections $\sim \alpha_t^2$

present theoretical uncertainty:

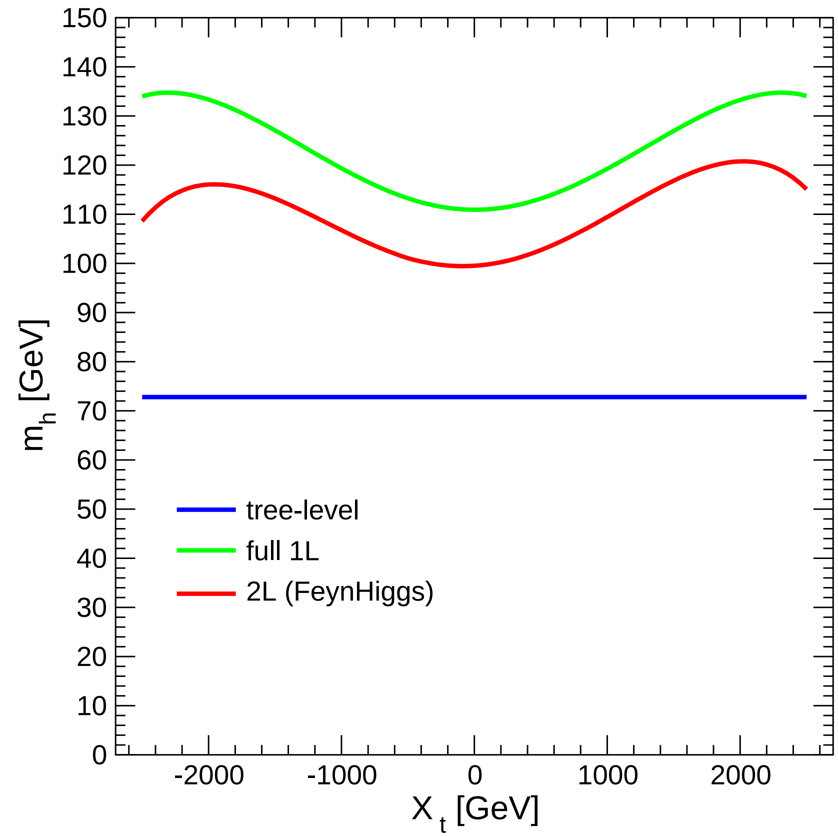
$\delta m_h \simeq 4$ GeV

[Degrassi, Heinemeyer, WH, Slavich, Weiglein]

new version

`FeynHiggs2.4.1`

m_{h^0} prediction at different levels of accuracy:

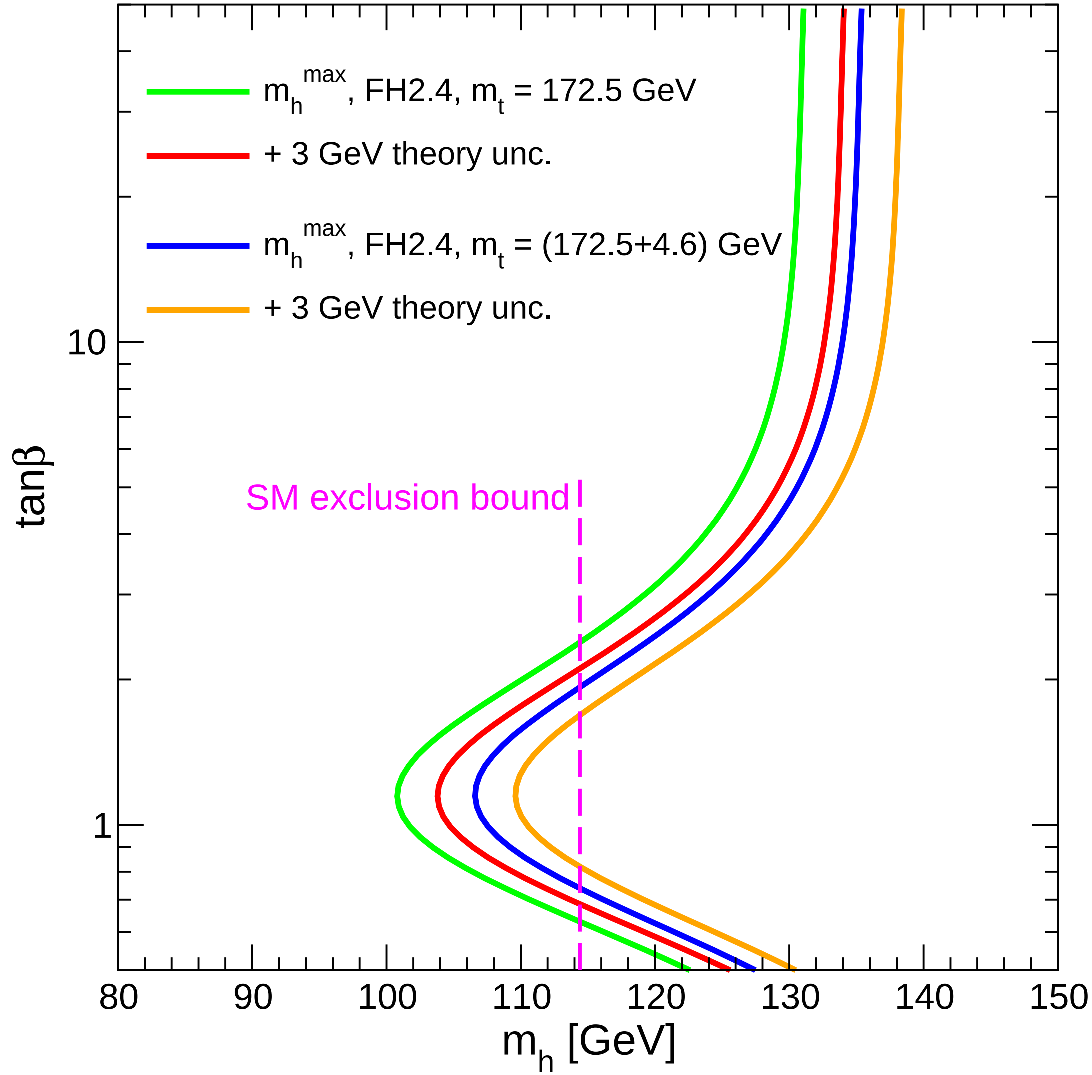


$\tan\beta = 3, \quad M_{\tilde{Q}} = M_A = 1$ TeV, $\quad m_{\tilde{g}} = 800$ GeV

X_t : top-squark mixing parameter

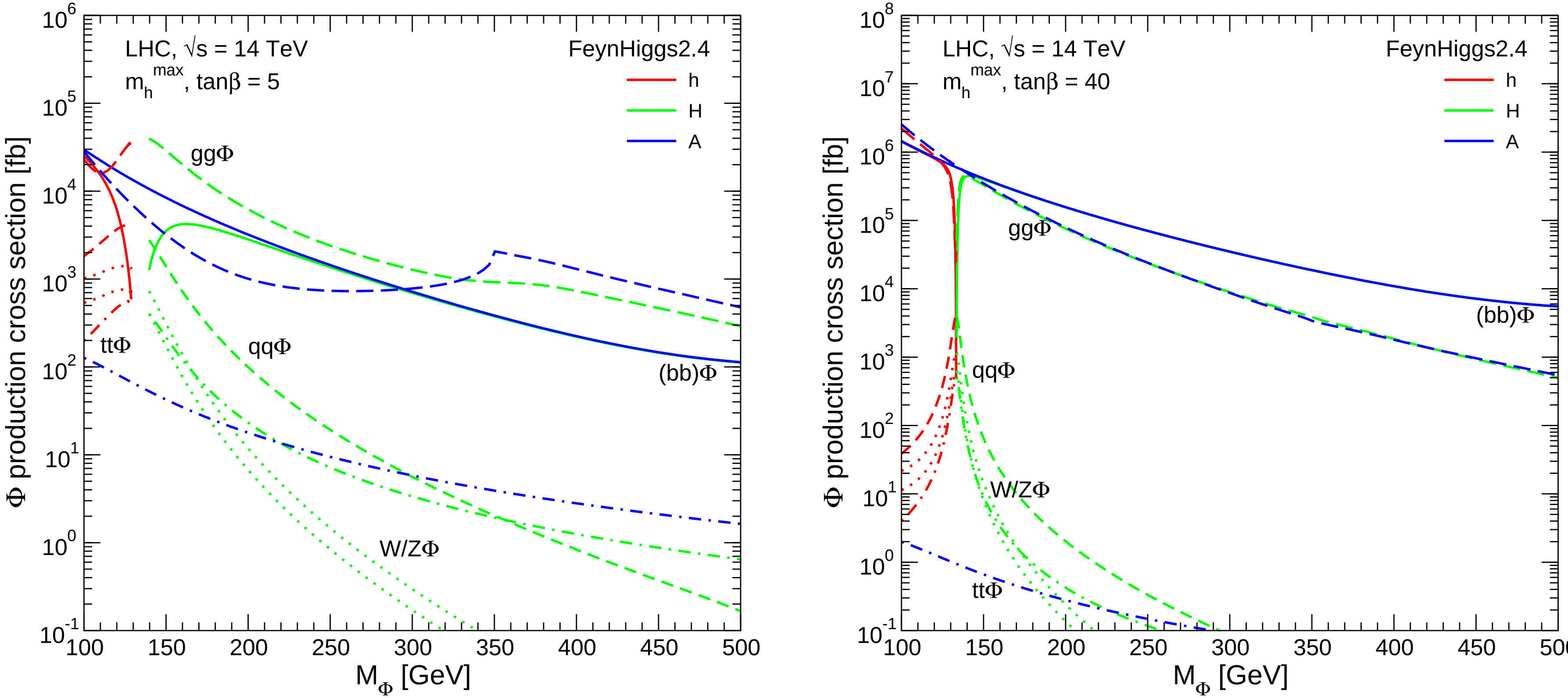
$$\mathrm{X_t} = \mathrm{A_t} - \mu \cot\beta$$

exclusion limits for m_h



[Heinemeyer,WH,Weiglein]

MSSM Higgs production at the LHC



[Hahn,Heinemeyer,Maltoni,WeigleinWillenbrock]

Recent theoretical developments:

1. Counterterms at two-loop order

   ST identities valid in dimensional reduction (DR)

   DR scheme consistent with symmetric counterterms

   [WH, Stöckinger]

2. $\mathcal{O}(\alpha_s \alpha_b)$ beyond $m_b^{\rm eff}$ approximation

   $m_b^{\rm eff} = \frac{m_b}{1+\Delta m_b}$ in α_b Yukawa coupling

   $\Delta m_b =$ non-decoupling SUSY contribution $\sim \alpha_s \tan\beta$

   [Heinemeyer, WH, Rzehak, Weiglein]

   small shifts $\sim$ few GeV, but stabilizes prediction

3. MSSM with complex parameters

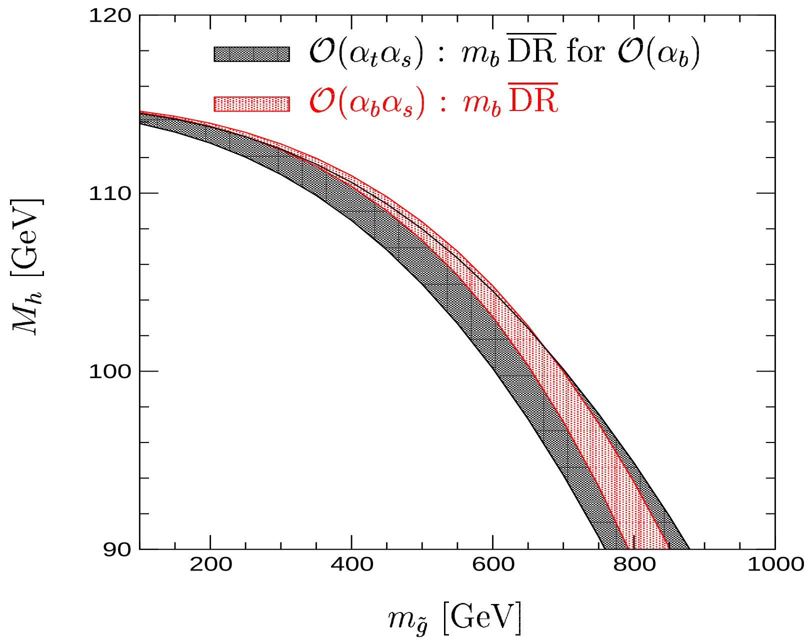
   tree level: CP conserving Higgs sector

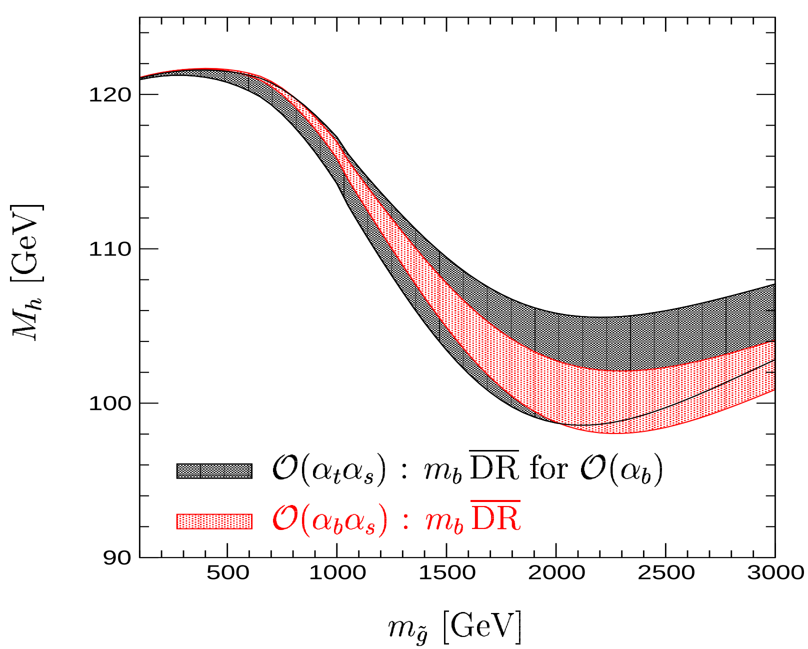
   loop level: CP violation $\leftarrow$ other sectors

$$(h, H, A) \rightarrow (h_3, h_2, h_1)$$

$$m_3 > m_2 > m_1$$

   [Frank, Hahn, Heinemeyer, WH, Rzehak, Weiglein]

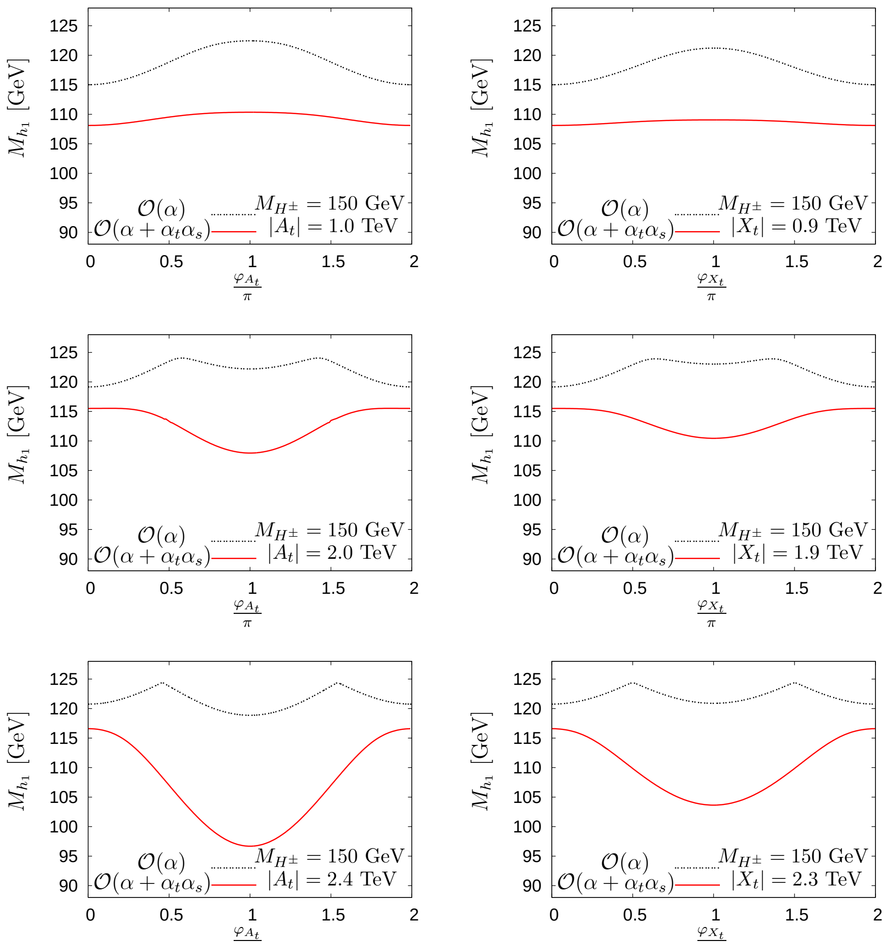


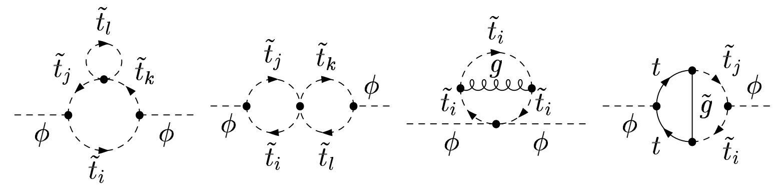


$$m_t/2 < \mu^{\overline{\rm DR}} < 2\,m_t$$

$$M_A = \begin{cases} 120\,\mathrm{GeV} \\ 700\,\mathrm{GeV} \end{cases}$$

phase dependence of m_{h_1}





[H. Rzehak, Thesis]

Distinguishing scenarios?

- direct measured mass(es) of Higgs boson(s) *versus* indirect effects in precison observables
- more than one Higgs boson $\rightarrow$ beyond the SM

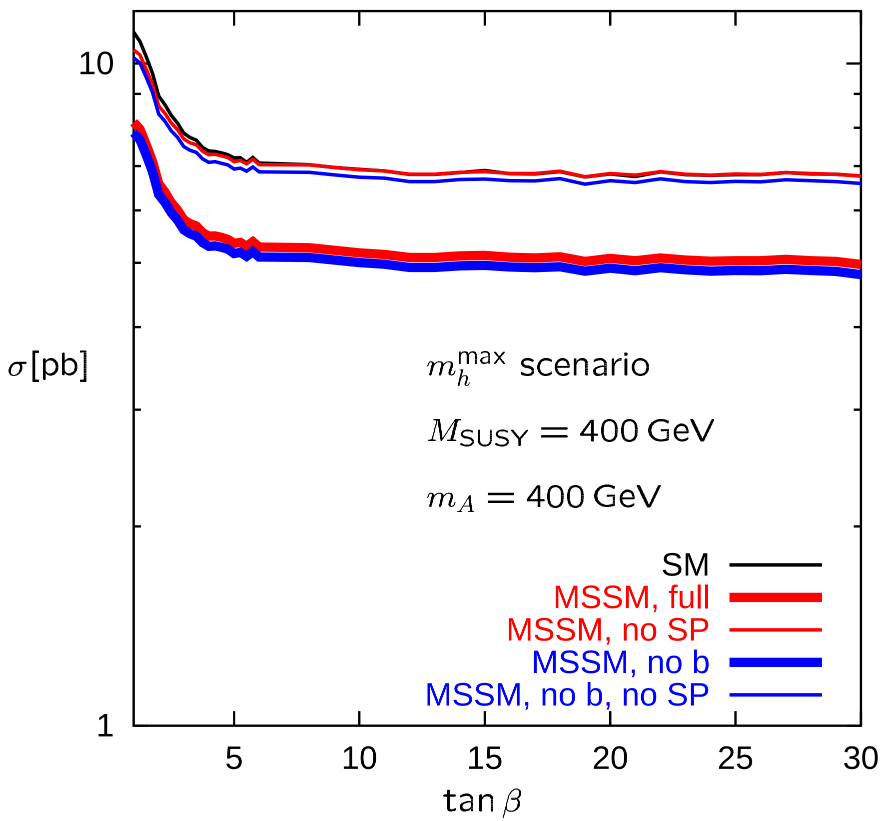
  precise determination of coupling constants
  $\rightarrow$ separate SUSY from general THDM

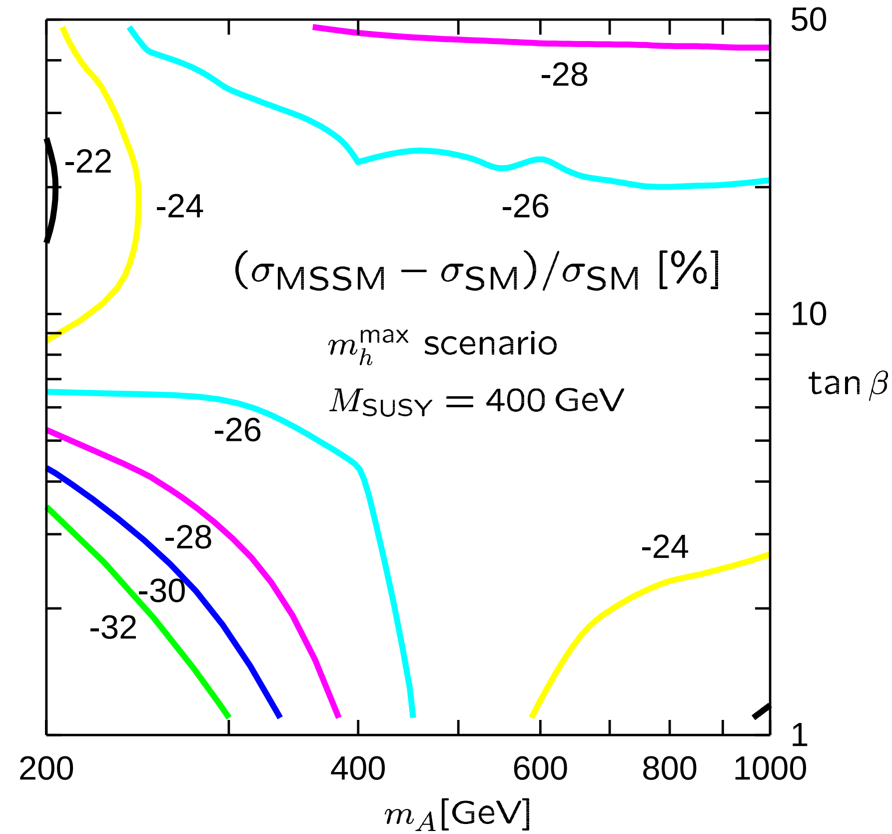
  loop effects are important
- decoupling regime (only single Higgs observed) : difficult

  distinguishable only through quantum effects
  heavy virtual particles + non-decoupling effects

Example 1: $pp \to h^0 + jet$

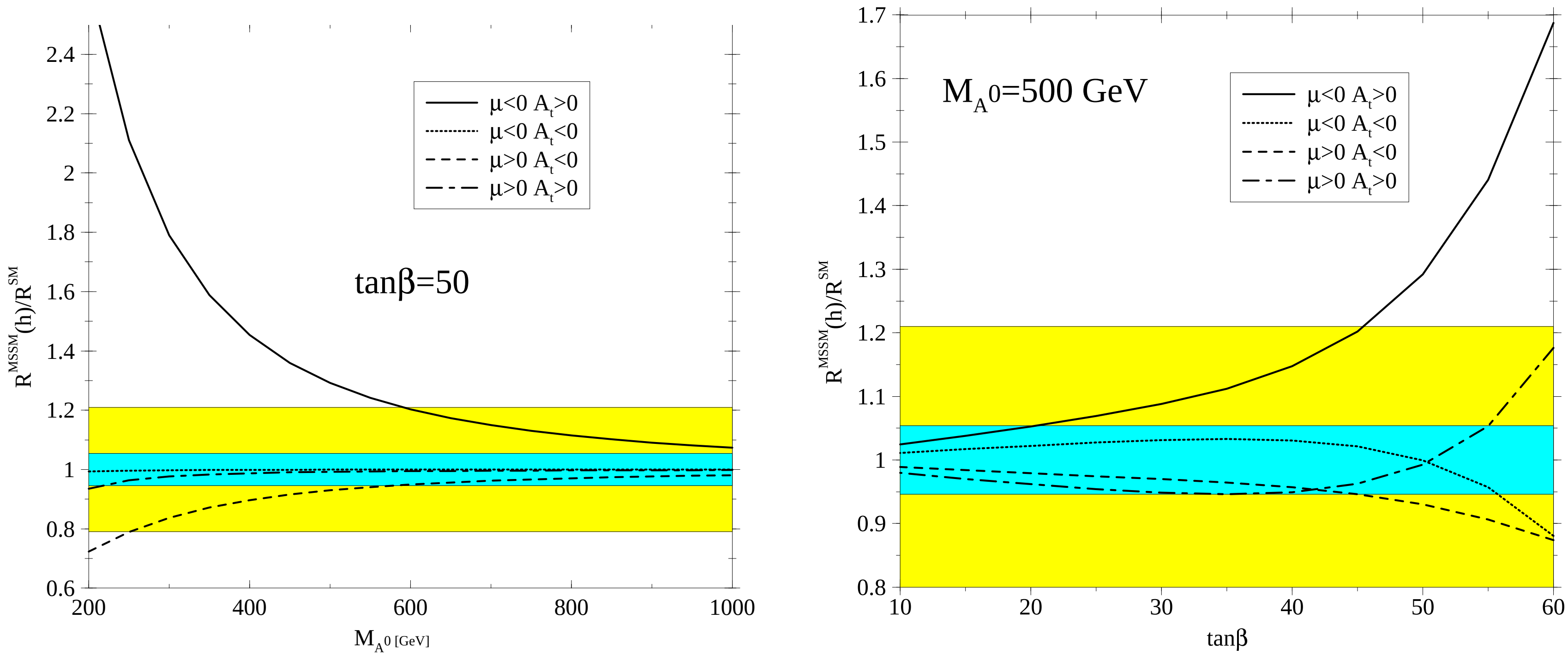
contour lines for deviations from SM [Brein,WH]





Example 2: branching ratio $h \to b\bar{b}/\tau^+\tau^-$

deviations from SM *[Guasch,WH,Peñaranda]*



$$R = \frac{BR(h \to b\bar{b})}{BR(h \to \tau^+\tau^-)}$$ for SM and MSSM

only differences from gluino and bino survive

Outlook –Possible scenarios

- a single light Higgs boson
  – SM Higgs boson?
  – SUSY light Higgs boson?
  $H,\ A,\ H^{\pm}$ heavy (decoupling scenario) $h \sim H_{\rm SM}$
- a light Higgs boson + more ($H, A, H^{\pm}$)
  – SUSY Higgs?
  – non-SUSY 2-Higgs-Doublet model?
- a single heavy Higgs boson ($\gg 200$ GeV)
  – SUSY ruled out
  – SM + (?) strong interaction?
- no Higgs boson
  – strongly interacting weak interaction
  new strong force $\sim$ TeV scale