SUSY Higgs Physics

Beyond the Standard Model Physics

WS 2014/2015

SUSY2215

SUSY: THE NEW HOPE

- QUANTUM MECHANICS AND QFT STILL HOLD
- THE ORBITAL COLLIDER STILL SEES NOTHING

THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!

The seasonal trends
Extremely-weeny constrained SUSY
NSFWMSSM
FF3C10ACBA9-MSSM
MSSM retrograde
Anthropic landscaping and trimming it down
The problem of condensed matter: They still don't get it
Strings - The Perpetual Revolution
Number of free parameters: P or NP complete?

Invited seminar
How to ensure your model remains predictability-free

Forum
Is choice moral?
"Every time you choose a path of action, a multiverse is killed"

Special topic
If the universe is not supersymmetric is it necessarily existing?

The perpetual conference

5 Jan - 5 Mar: Chamonix
15 Mar - 30 June: Hainan Island
1 July - 15 Sep: Wailea, Maui
15 Sep - 20 Nov: Jumeirah 1
21 Nov - 24 Dec: Hainan Island

Sponsored by:
The Milner-Zuckerberg Institution

Minimal Supersymmetric Extension of the SM (MSSM)

MSSM Higgs sector – supersymmetry & anomaly-free theory $\Rightarrow$ 2 complex Higgs doublets

$\overset{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-

Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;Harlander et al;
Kant,Harlander,Mihaila,Steinhauser;...

Decoupling limit:

$M_A \sim M_H \sim M_{H^\pm} \gg v$

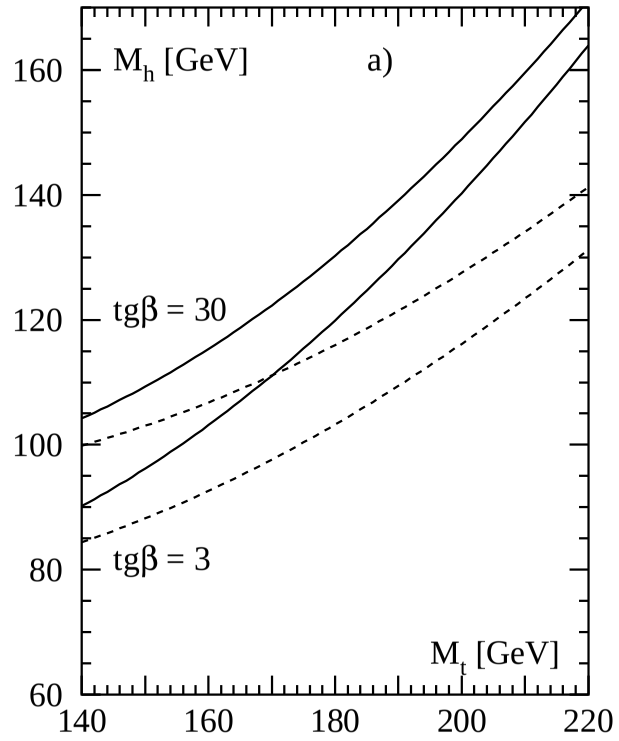
$M_h \rightarrow$ max. value, $\tan\beta$ fixed; h SM-like

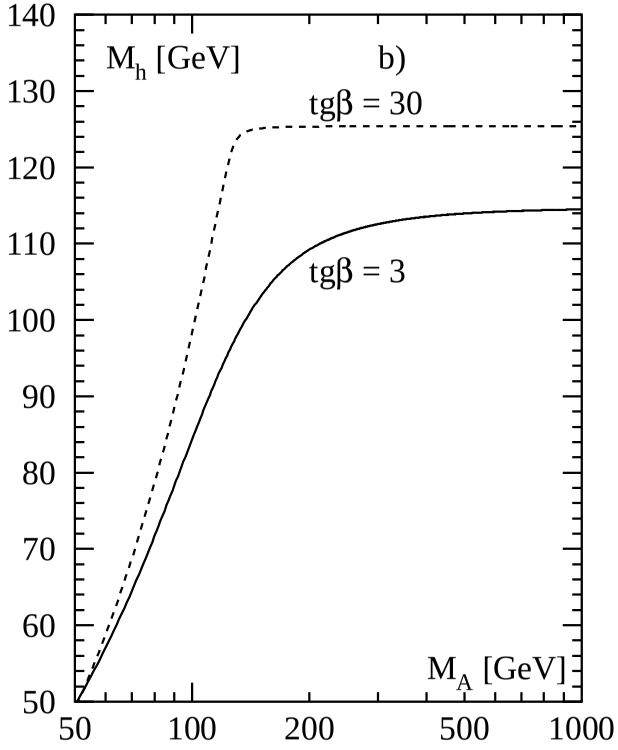
Modified couplings w/ respect to the SM: (decoupling limit Gunion,Haber)

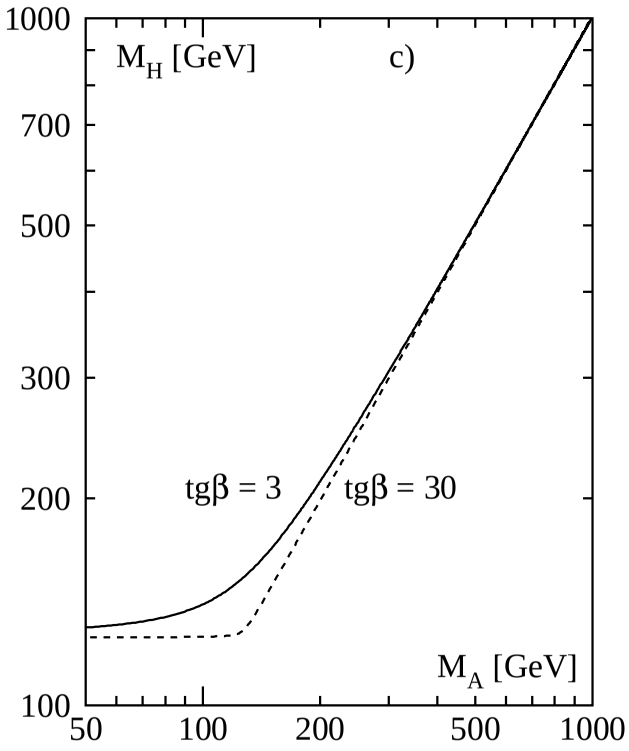
Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \rightarrow 1$	$-s_\alpha/c_\beta \rightarrow 1$	$s_{\beta-\alpha} \rightarrow 1$
H	$s_\alpha/s_\beta \rightarrow 1/\text{tg}\beta$	$c_\alpha/c_\beta \rightarrow \text{tg}\beta$	$c_{\beta-\alpha} \rightarrow 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

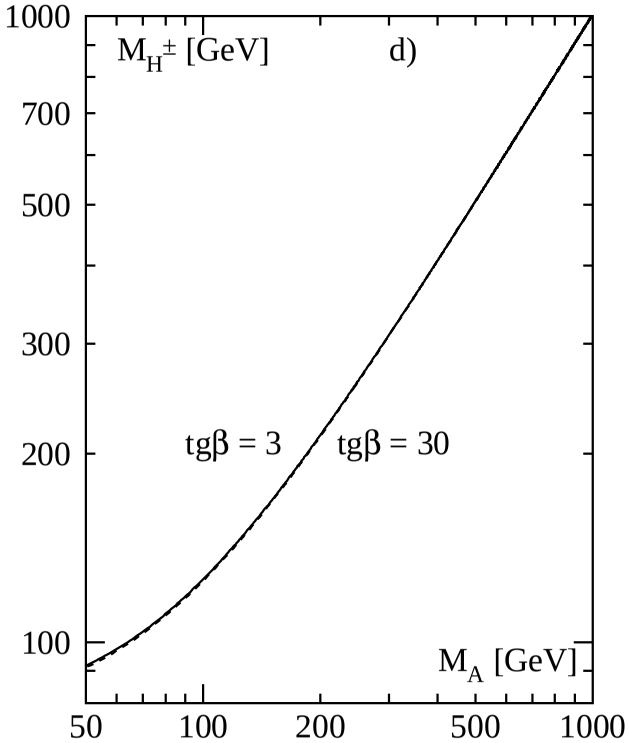
$\tan\beta \uparrow \Rightarrow g_{\Phi uu} \downarrow$, $g_{\Phi dd} \uparrow$

$g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$


M_h [GeV]
a)
tgβ = 30
tgβ = 3
M_t [GeV]
160
140
120
100
80
60
140
160
180
200
220

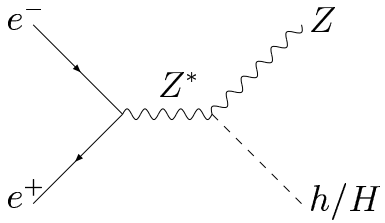

M_h [GeV]
b)
tgβ = 30
tgβ = 3
M_A [GeV]
140
130
120
110
100
90
80
70
60
50
50
100
200
500
1000

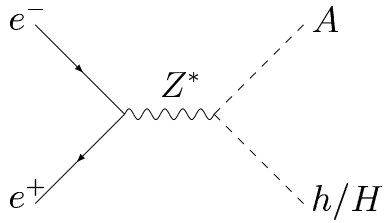

M_H [GeV]
c)
tgβ = 3
tgβ = 30
M_A [GeV]
1000
700
500
300
200
100
50
100
200
500
1000

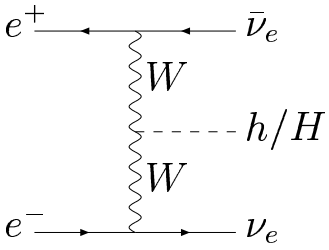

M_H± [GeV]
d)
tgβ = 3
tgβ = 30
M_A [GeV]
1000
700
500
300
200
100
50
100
200
500
1000

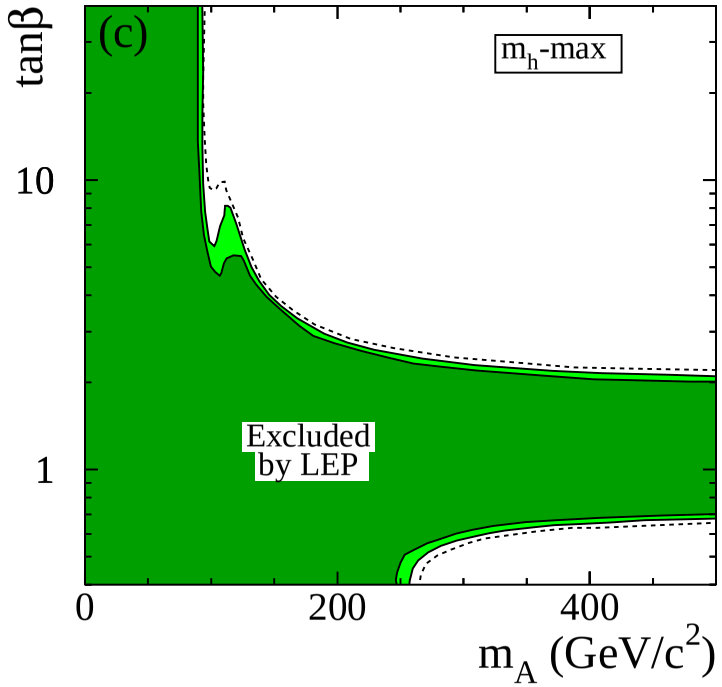
MSSM Higgs Mass Limits

▷ Direct Search at LEP $e^+e^- \to Z + h/H,\ A + h/H,\ \nu_e\bar{\nu}_e + h/H$









$M_{h/H} \gtrsim 92.6$ GeV

$M_A \gtrsim 93.4$ GeV

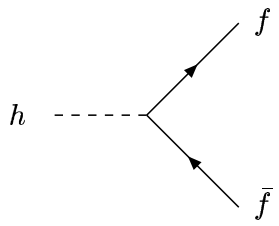
$M_{H^\pm} > 78.6$ GeV

$0.6 < \tan\beta < 2.5$ excluded

(only in this scenario, $m_t = 174.3$ GeV!)

Higgs decays

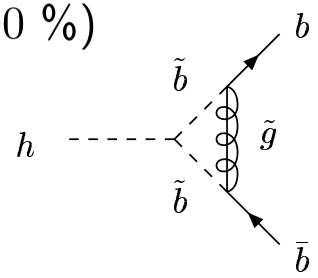
- $h \to b\bar{b}, \tau^+\tau^-, c\bar{c}$



large QCD corrections: $\sim -50... - 80$ %

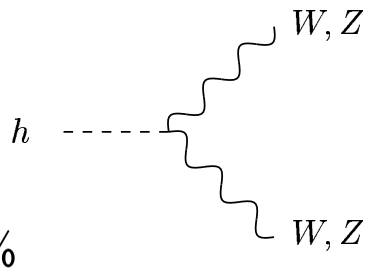
large SUSY-QCD corrections: $\mathcal{O}(10...100$ %$)$

$$\propto \frac{\alpha_s}{\pi} \frac{m_{\tilde{g}} \mu \tan\beta}{m^2_{\tilde{b}}}$$



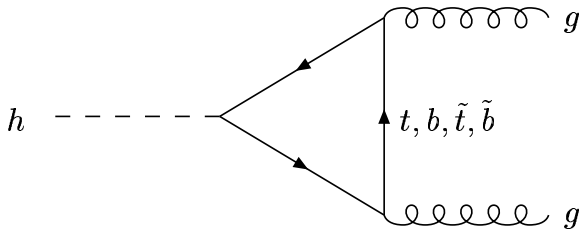
$+ \ldots$

- $h \to WW^*, ZZ^*$

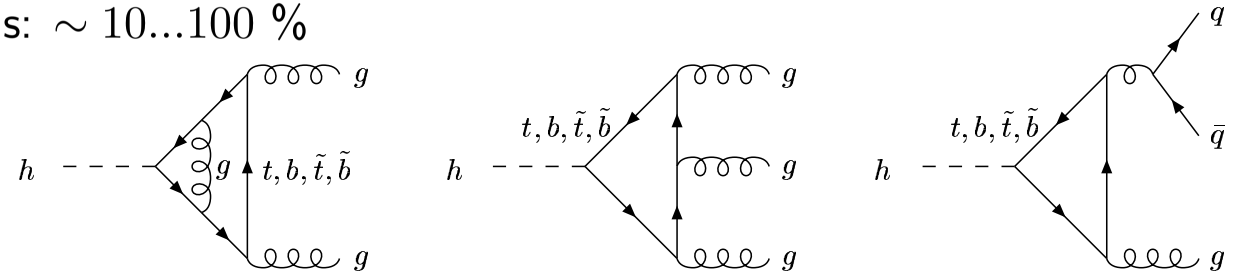


electroweak corrections: $\sim 5...10$ %

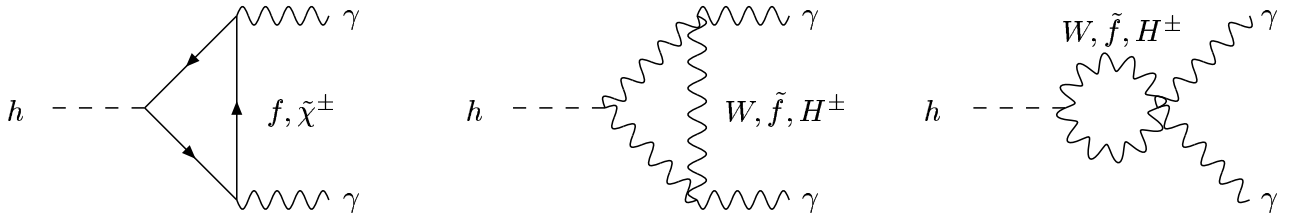
- $h \to gg$



large QCD corrections: $\sim 10...100$ %

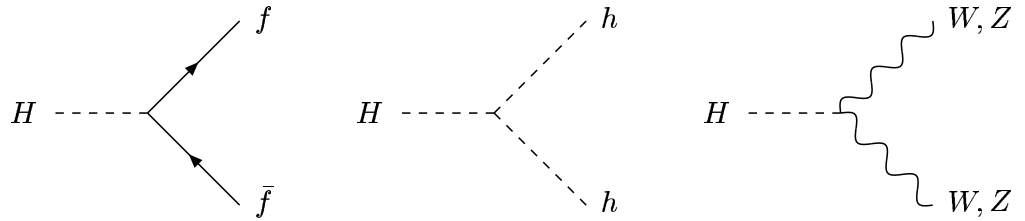


- $h \to \gamma\gamma$

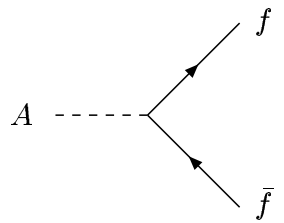


Extremely important decay channel for the LHC

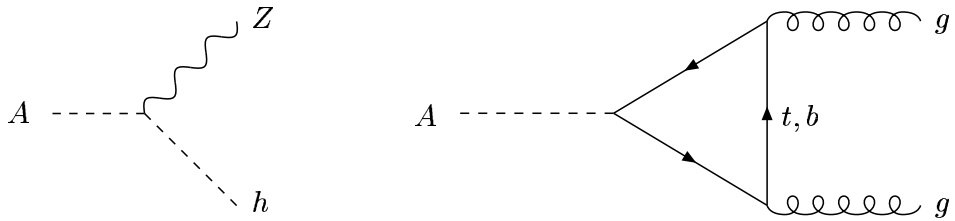
- $H \to b\bar{b}, \tau^+\tau^-$: dominant for large $\tan\beta$
- $H \to hh, WW, ZZ, t\bar{t}$



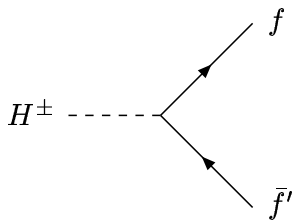
- $A \to b\bar{b}, \tau^+\tau^-$: dominant for large $\tan\beta$
- $A \to t\bar{t}$: dominant above the $t\bar{t}$ threshold for small and moderate $\tan\beta$



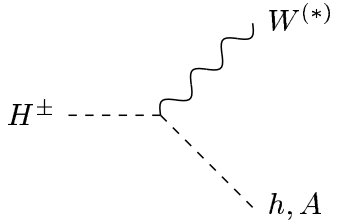
- $A \to Zh, gg$

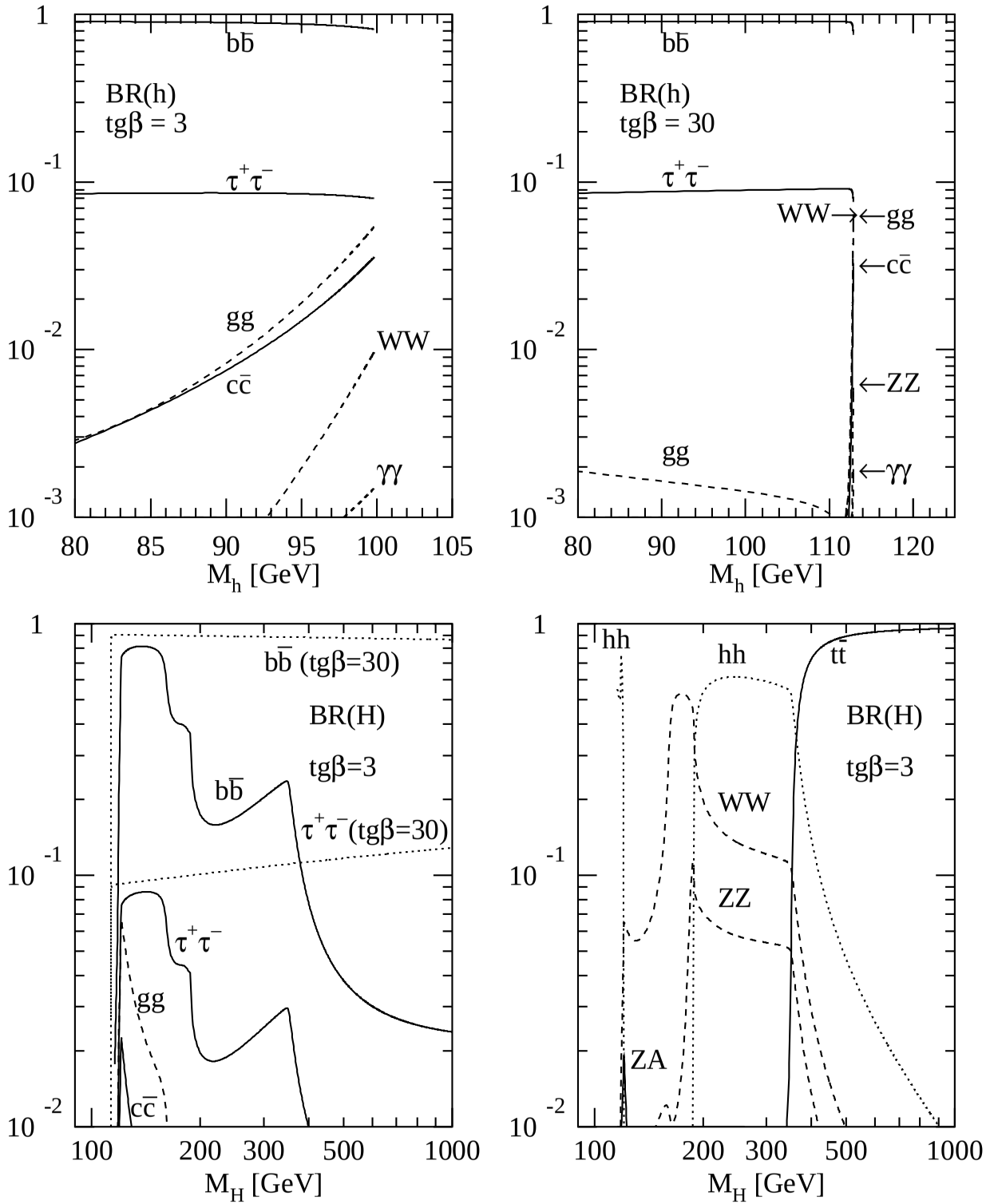


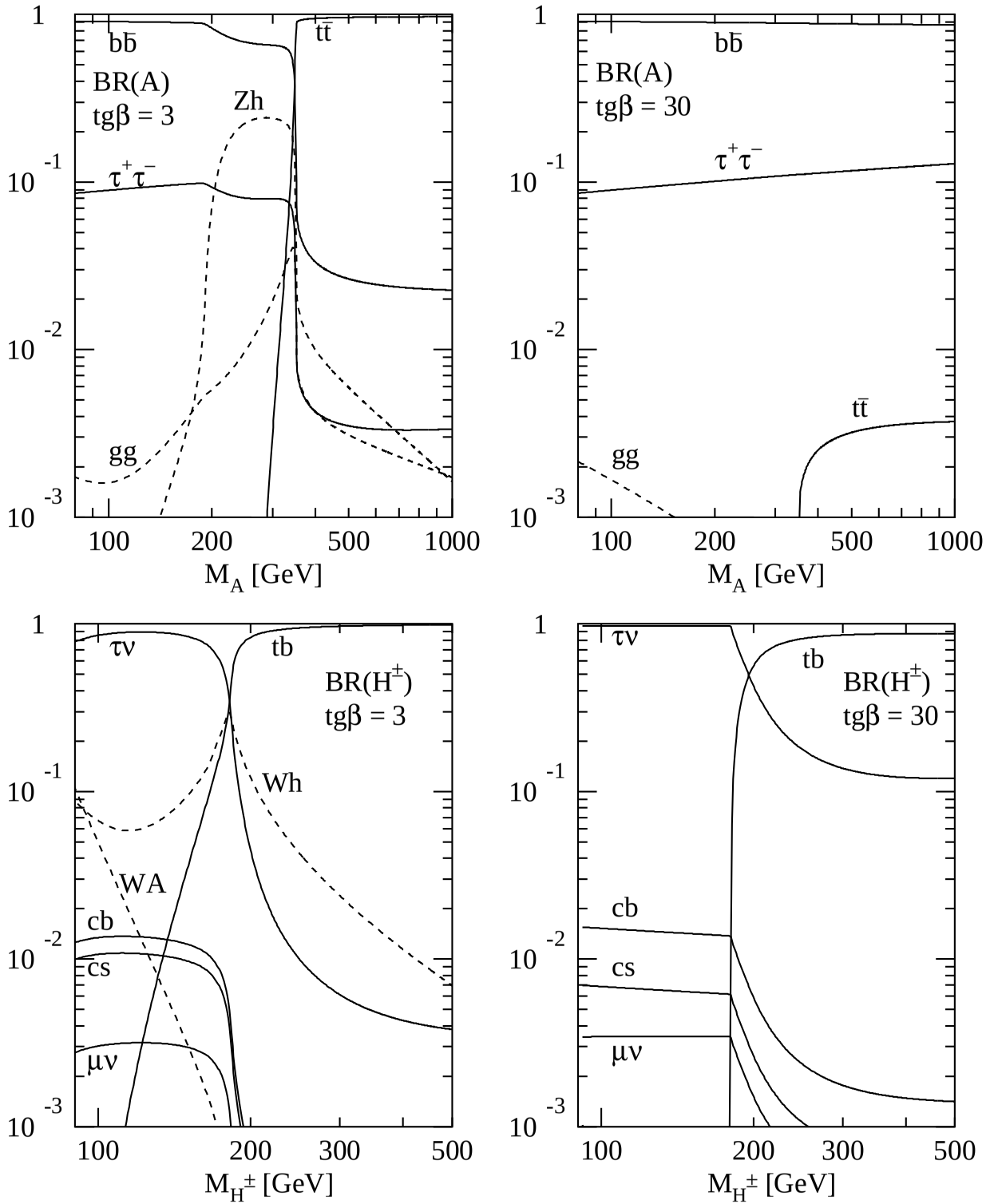
- $H^+ \to \tau^+\nu_\tau, t\bar{b}$



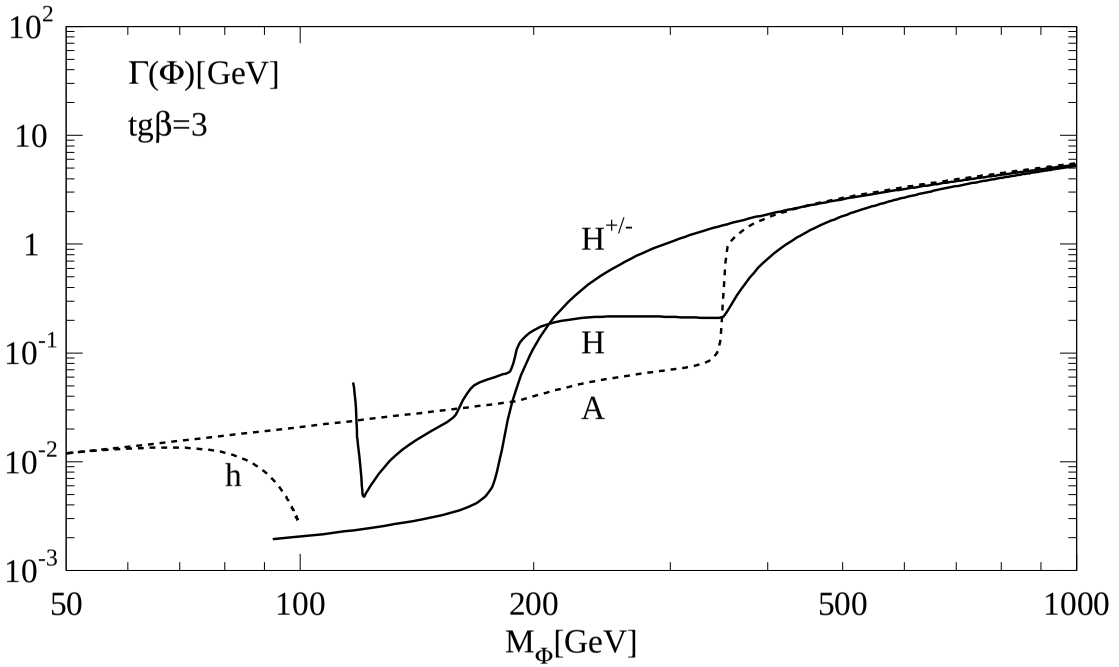
- $H^+ \to W^* A, Wh$

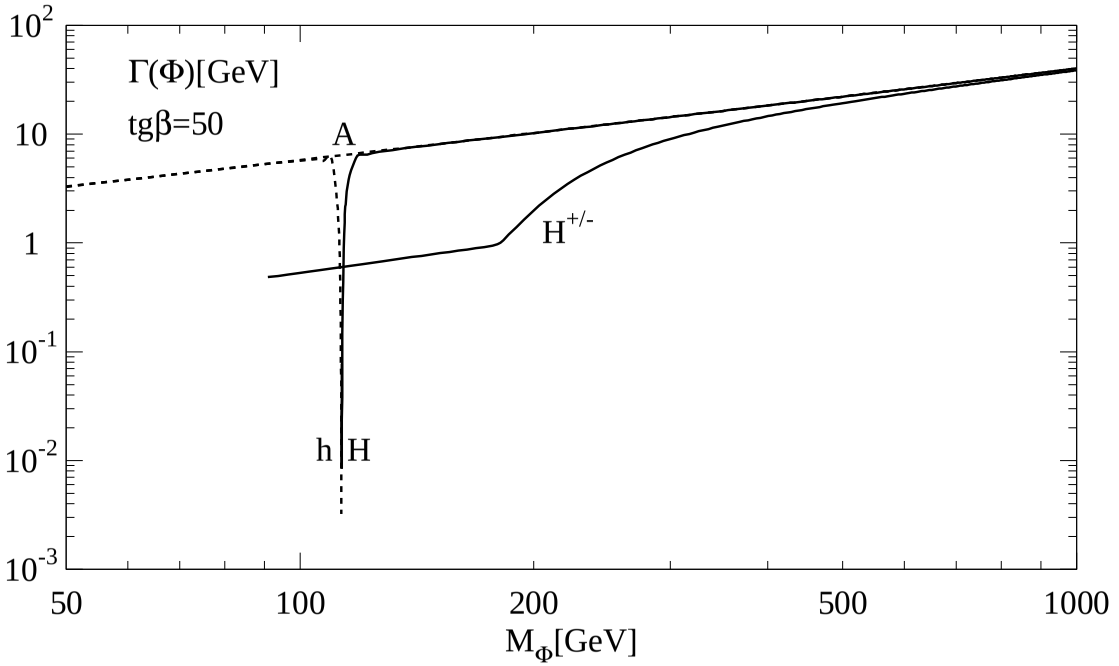



BR(h)
tgβ = 3
bb̄
τ+τ−
gg
cc̄
WW
γγ
M_h [GeV]
BR(h)
tgβ = 30
WW→
←gg
←cc̄
←ZZ
←γγ
bb̄ (tgβ=30)
BR(H)
tgβ=3
τ+τ−(tgβ=30)
M_H [GeV]
hh
tt
ZA

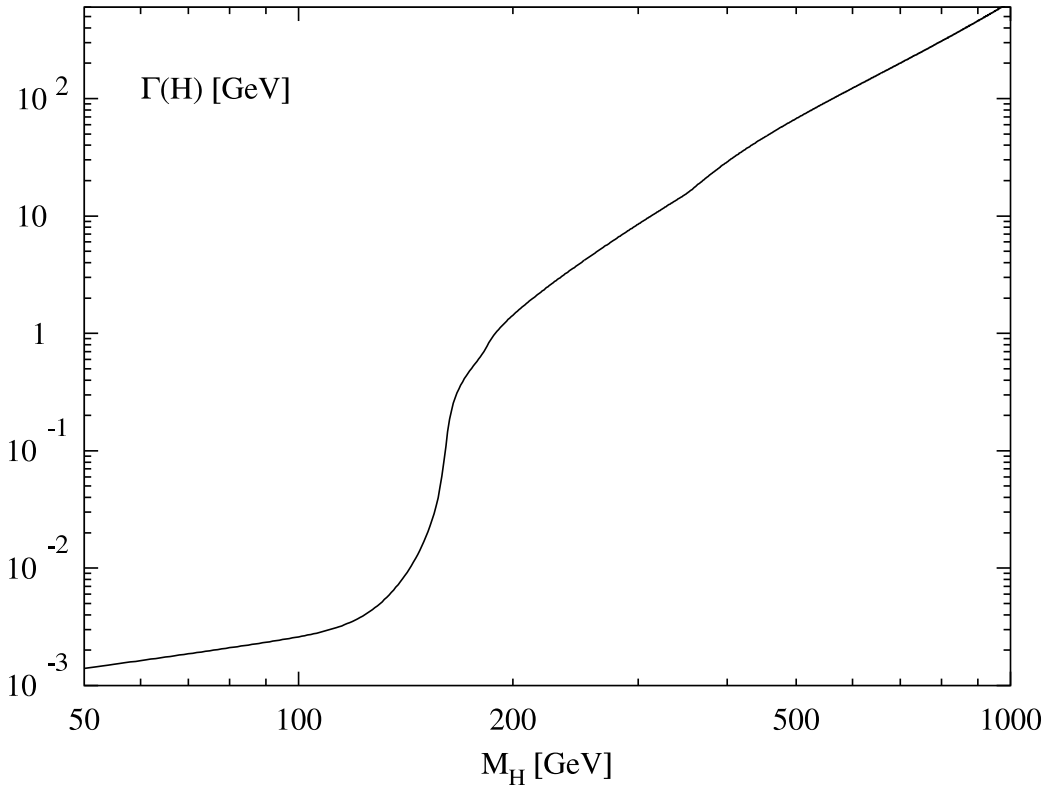

1
10^-1
10^-2
10^-3
bb̄
tt̄
BR(A)
tgβ = 3
Zh
τ+τ−
gg
100
200
500
1000
M_A [GeV]
bb̄
BR(A)
tgβ = 30
τ+τ−
tt̄
gg
100
200
500
1000
M_A [GeV]
τν
tb
BR(H±)
tgβ = 3
Wh
WA
cb
cs
μν
100
200
300
500
M_H± [GeV]
τν
tb
BR(H±)
tgβ = 30
cb
cs
μν
100
200
300
500
M_H± [GeV]

- total widths: $\Gamma_\phi \lesssim 10...30$ GeV narrow

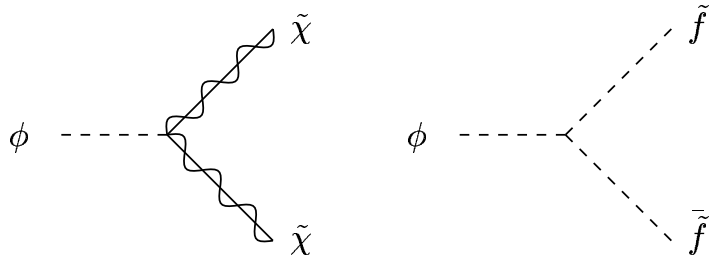


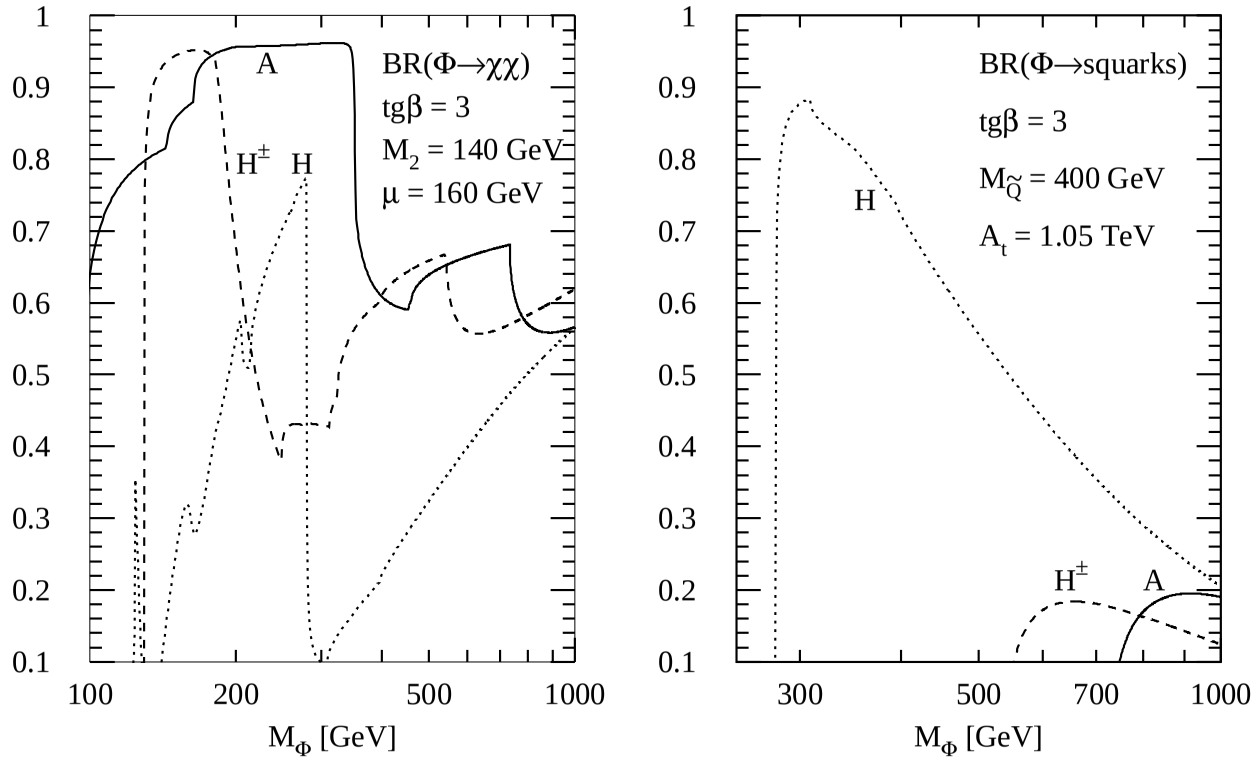


- for comparison: the total width in the SM



- Decays in gauginos and sfermions (3rd generation) important, if kinematically allowed

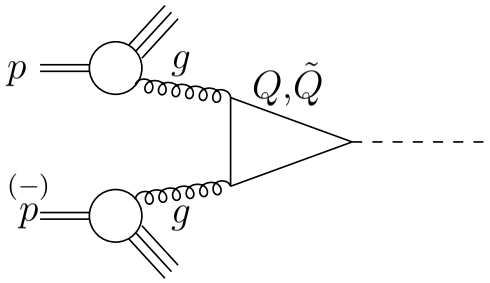




Higgs boson production in SM/MSSM

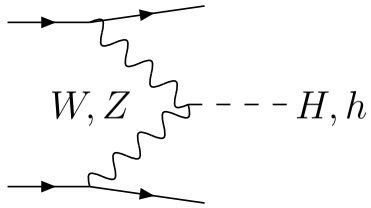
- **Gluon Gluon Fusion**

  $pp \to gg \to H^{SM} \,/\, h, H, A$



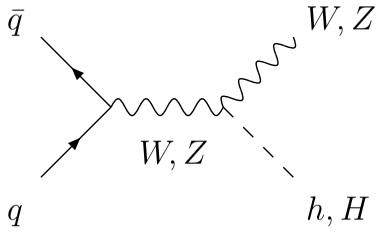
- **W/Z Fusion**

  $pp \to qq \to qq + WW/ZZ \to qq + H^{SM} \,/\, h, H$



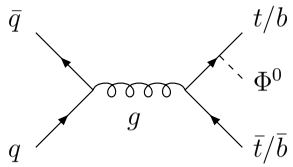
- **Higgs-strahlung**

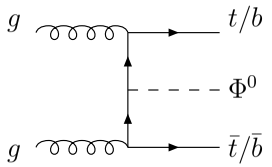
  $pp \to W^*/Z^* \to W/Z + H^{SM} \,/\, h, H$



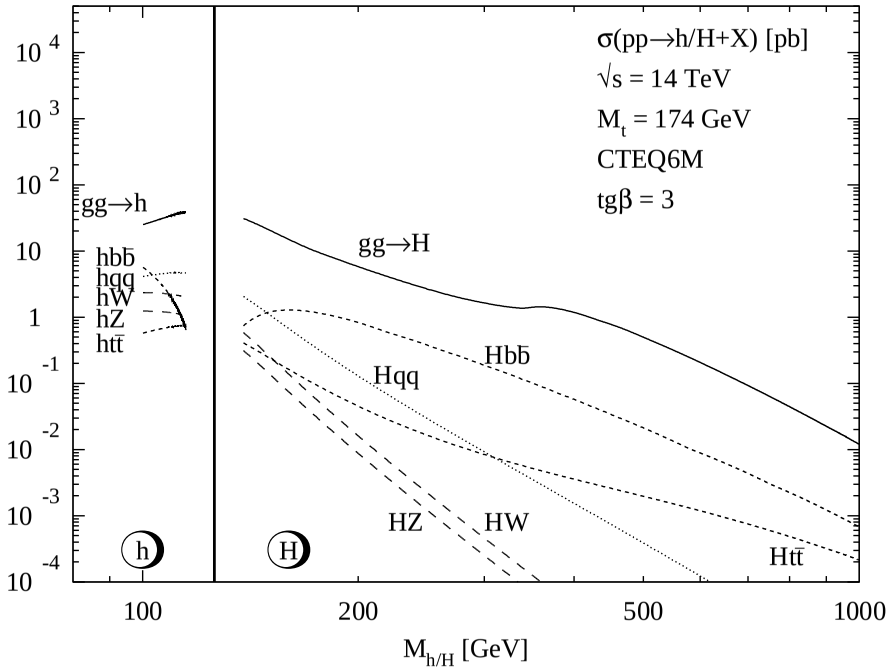
- **Associated Production**

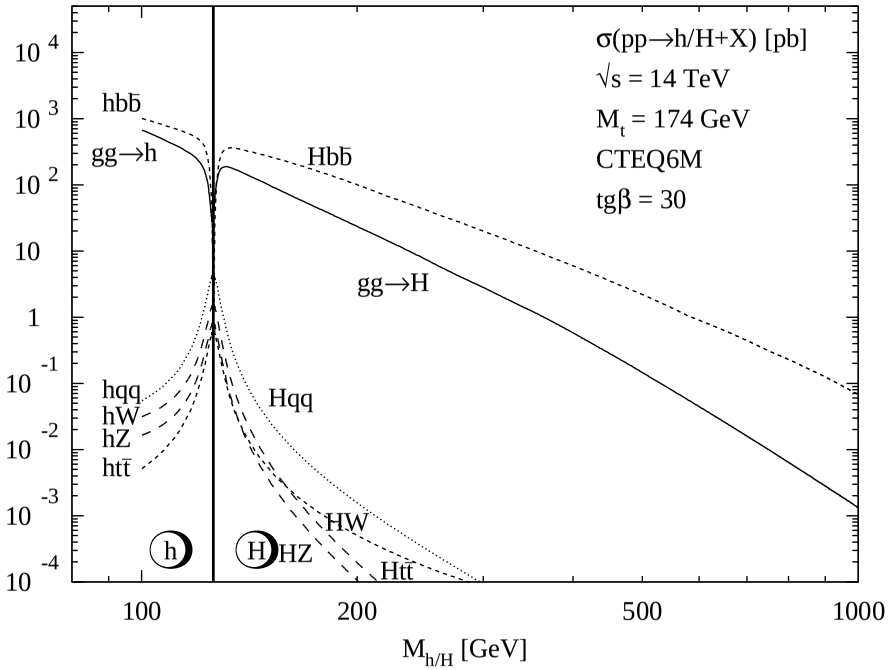
  $pp \to t\bar{t}/b\bar{b} + (H^{SM}) \,/\, h, H, A$



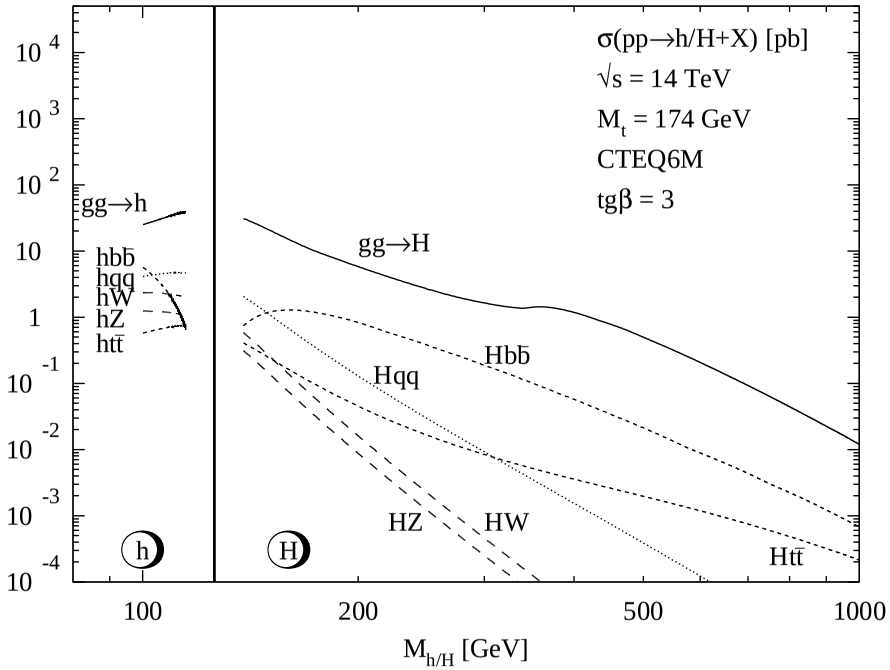


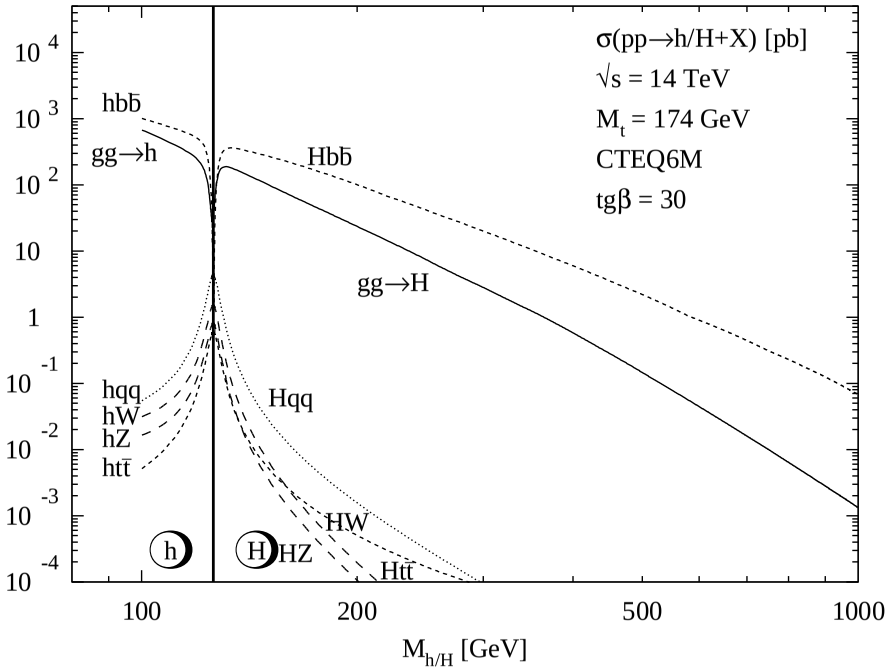
MSSM Higgs Boson Production at the LHC





MSSM Higgs Boson Production at the LHC





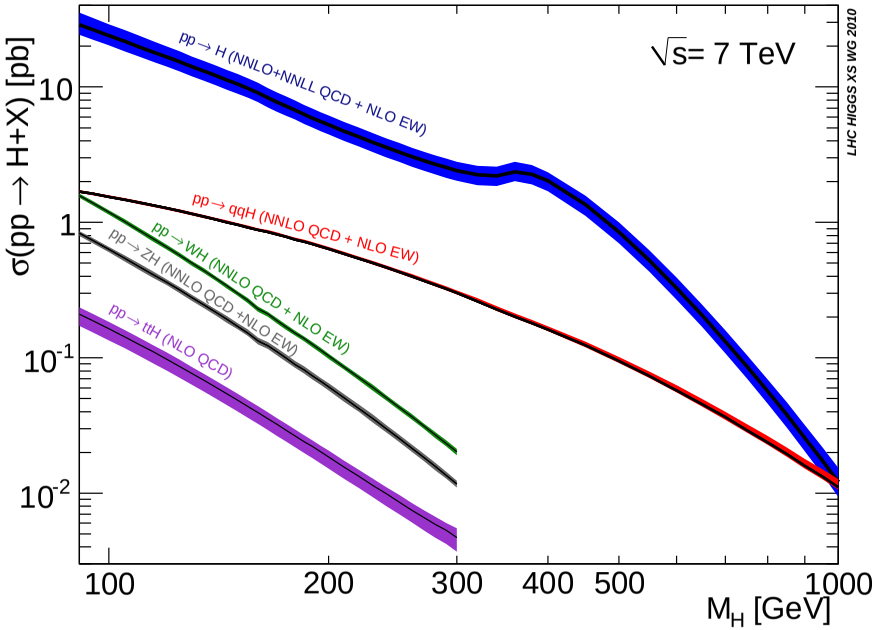
Reminder

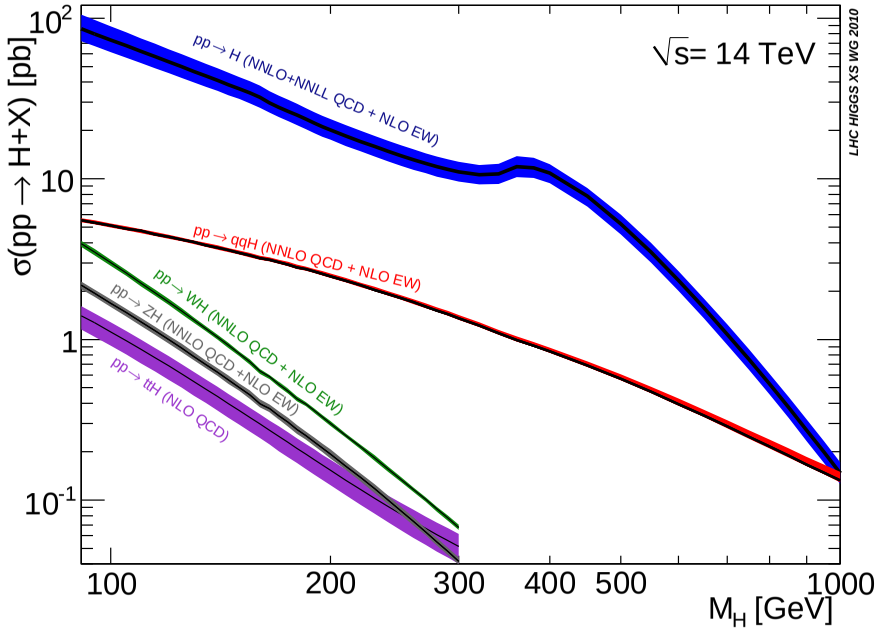
$$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$$

$$g_{\Phi dd} \uparrow$$

$$g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$$

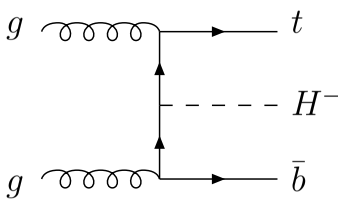
LHC Higgs cxn WG





Charged Higgs Production

- **Dominant: t decay or $pp \to q\bar{q}, gg \to H^- + t\bar{b}$ + c.c.**



Bawa eal;
Borzumati eal;
Belyaev eal

NLO QCD & SUSY QCD corrs.: $50...100$ %

Peng et al.
Dittmaier et al.

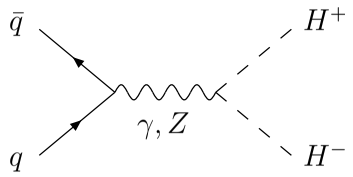
scale dependence reduced: $\Delta \lesssim 15$ %

LO cxn: $gb \to H^- t$ + c.c.

NLO SUSY QCD & EW corrs.

Zhu; Plehn; Berger eal;
Gao et al.;Kidonakis;Beccaria eal

- **$H^\pm$ pair production $pp \to q\bar{q} \to H^+H^-$**



NLO QCD corrs.: ~ 30 % ($\leftarrow$ Drell-Yan)

genuine SUSY QCD corrs.: small Djouadi,Spira

- **$pp \to gg \to H^+H^-$ (LO)**

Willenbrock;Krause eal;
Jiang eal;Brein,Hollik;
Barrientos eal

$pp \to b\bar{b} \to H^+H^-$

SUSY-QCD significant

Barrientos eal;
Hong-Sheng eal

$pp \to gg \to H^+W^-$ + c.c. (LO)

Barrientos et al.;
Brein et al.

$pp \to b\bar{b} \to H^+W^-$+c.c.

QCD corrs. moderate

Dicus eal;
Barrientos eal;
Brein eal;
Hollik eal;
Zhao eal

Charged Higgs Exclusion

MSSM Higgs Mass in View of the LHC Results

- **Vast literature on MSSM Higgs of $\sim$ 125-126 GeV**

  Arbey eal; Li eal; Feng eal; Baer eal; Akula eal; Hall eal; Albornoz Vasquez eal; Heinemeyer eal; Desai et al.; Draper eal; Carena eal; Cao eal; Christensen eal; Kadastik eal; Buchmuller eal; Arvanitaki eal; Ellis eal; Curtin eal; Brummer eal; Barger eal; Hagiwara eal; Arbey eal; Blum eal; Beskidt eal; Baer eal; Giudice eal; Carena eal; Benbrik eal; Akula eal; Cahill-Rowley eal; Hirsch eal; ...

- **Compatibility of MSSM Higgs mass with LHC Search**

  $\star$ Upper mass bound on SM-like Higgs with higher-order correction Δm_h

  $$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

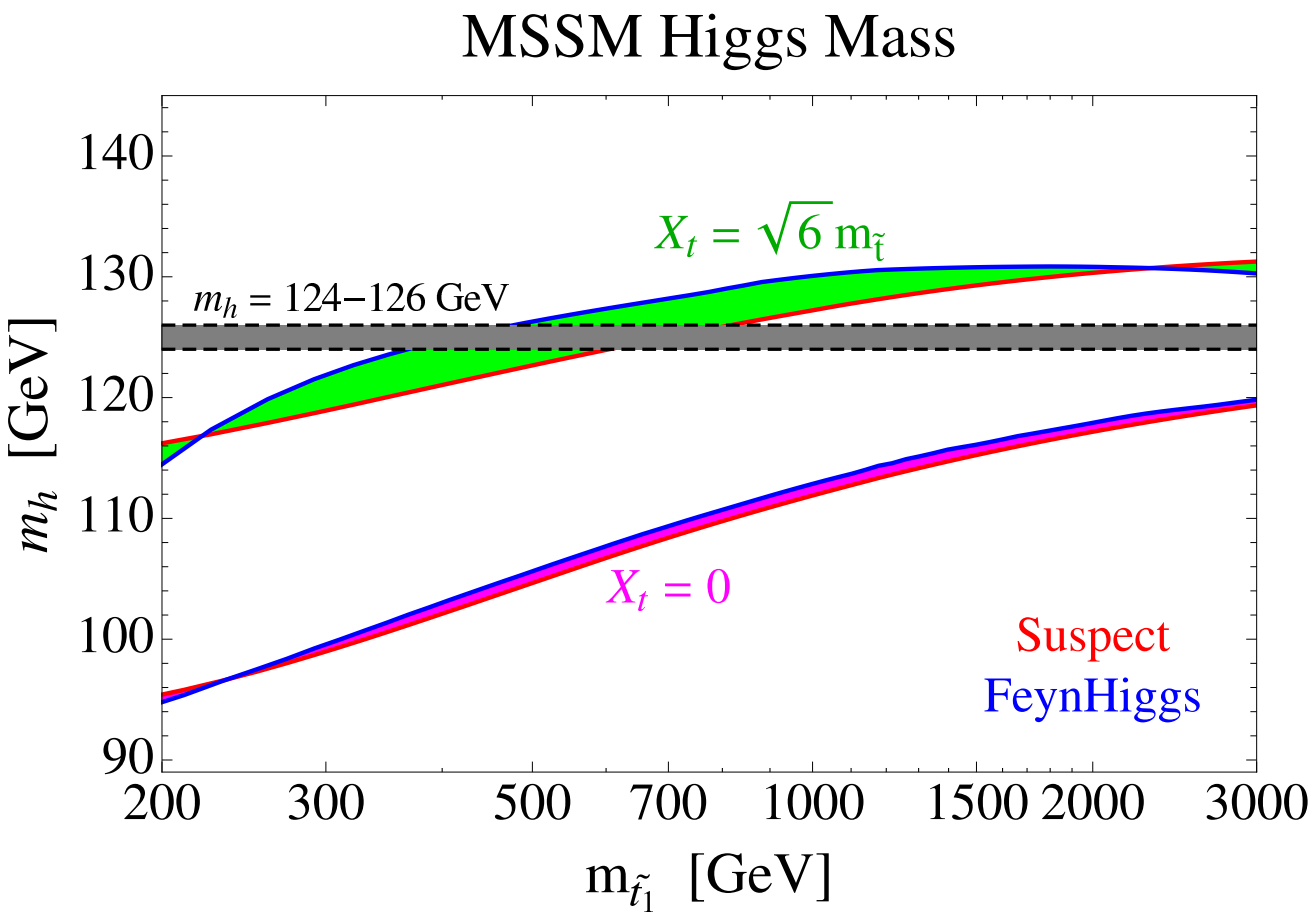
  $\star \Rightarrow M_H \approx 126$ GeV requires

  $$\Delta m_h \approx 85 \text{ GeV } (\tan\beta \text{ large}) \Rightarrow \text{large corrections}$$

  $\star$ Corrections require large stop masses $m_{\tilde{t}_1}, m_{\tilde{t}_2}$ and/or large mixing $X_t \rightsquigarrow$ 'fine'-tuning

MSSM Higgs Mass in View of the LHC Results

Hall,Pinner,Ruderman 1112.2703



- **Even for maximal stop mixing:** $m_{\tilde{t}_1} \overset{!}{\gtrsim} 500$ GeV

Interpretation within SUSY: The NMSSM Higgs Sector

- **Supersymmetric Higgs Sector:** SUSY & anomaly-free theory $\Rightarrow$ 2 complex Higgs doublets

- **Most economic version:** Minimal Supersymmetric Extension of the SM (MSSM):

  2 complex Higgs doublets

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**

  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

  2 complex Higgs doublets plus one complex singlet field $\rightsquigarrow$

- **Solution of the μ-problem:** μ must be of $\mathcal{O}$(EWSB scale) Kim,Nilles

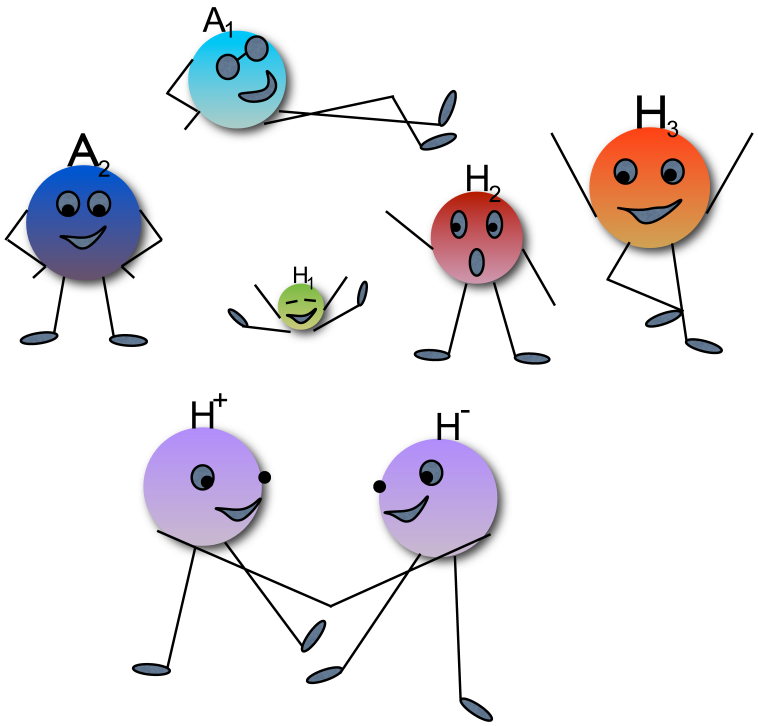
  μ generated dynamically through the VEV of scalar component of an
  additional chiral superfield field $\hat{S}$: $\mu = \lambda \langle S \rangle$ from: $\lambda \hat{S} \hat{H}_u \hat{H}_d$

The $\mathcal{NMSSM}$ Higgs Sector

- **Enlarged Higgs and neutralino sector:** 2 complex Higgs doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

7 Higgs bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 5)$

- **Higgs mass eigenstates:**
  superpositions of doublet and singlet components $\rightsquigarrow$
  the more singlet-like
  the smaller couplings to SM particles



- **Significant changes of Higgs boson phenomenology**
  - light Higgses not excluded, Higgs-to-Higgs decays
  - degenerate Higgs bosons around 125 GeV possible
  - very light singlino-like lightest SUSY particle (LSP)
  - $\rightsquigarrow$ invisible Higgs decays
  - tree-level CP violation ...

$\mathcal{NMSSM}$ Higgs Mass and $\mathcal{LHC}$ Results

- **Vast literature on NMSSM Higgs of $\sim$ 125-126 GeV**

  Hall eal; Ellwanger; Gunion eal; King,MMM,Nevzorov; Albornoz Vasquez eal; Cao eal; Gabrielli eal; Ellwanger, Hugonie; Kang eal; Cheung eal; Jeong eal; Hardy eal; Kim eal; Arvanitaki eal; Cheng eal; Bélanger eal; Kowalska eal; Badziak eal; Moretti eal: Choi eal; Munir eal; Barbieri eal; Beskidt eal; Berg eal; Gherghetta eal; Cerdeno eal; Das eal; Christensen eal; Bhattacherjee eal; Guo eal; ...

- **Compatibility of NMSSM Higgs mass with LHC Searches:**

  $\star$ Upper mass bounds + corrections to the MSSM, NMSSM Higgs boson mass:

  MSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$

  NMSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$

  $\Rightarrow M_H \approx 126$ requires:

  MSSM: $\Delta m_h \approx 85$ GeV ($\tan\beta$ large) $\Rightarrow$ large corrections $\rightsquigarrow$ fine-tuning

  NMSSM: $\Delta m_h \approx 55$ GeV ($\lambda = 0.7, \tan\beta = 2$)

  $\Rightarrow$ NMSSM requires less fine-tuning

  Hall,Pinner,Ruderman; Ellwanger; Arvanitaki,Villadoro; King,MMM,Nevzorov; Kang,Li,Li; Cao,Heng,Yang,Zhang,Zhu

NMSSM Scalar Boson Mass in View of the LHC Results

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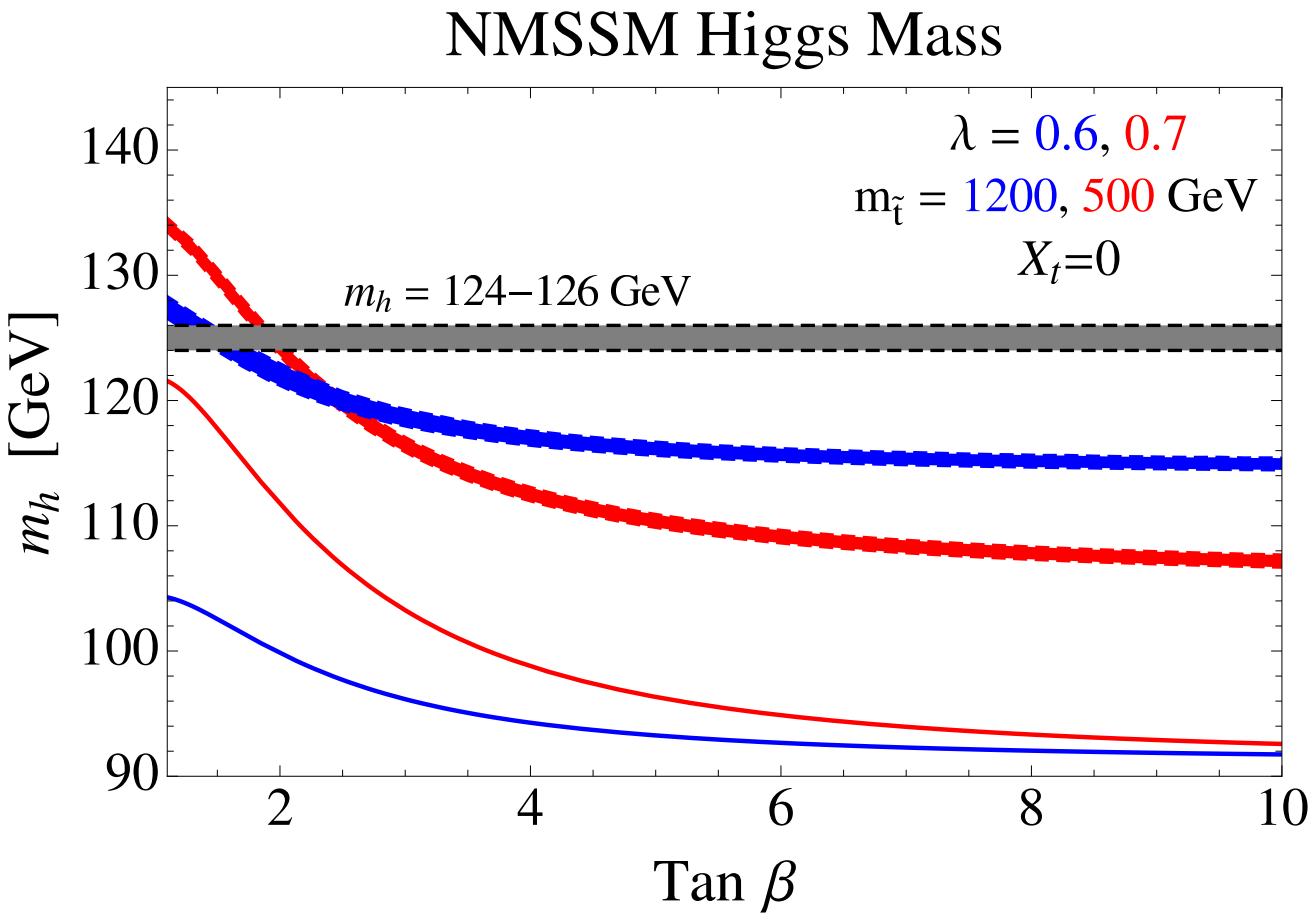


◇ m_h maximized for small values of $\tan\beta$

◇ $m_h \approx 124 - 126$ GeV can be achieved also for zero mixing $X_t = 0$ and $m_{\tilde{t}_1} \geq 500$ GeV

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ignal

- **SM-like scalar boson of $\sim$ 125 GeV**

  Can be either H_1 or H_2 (H_1 singlet like, suppressed SM couplings)

- **Could it be that we already discovered NMSSM Higgs bosons?**

  Higgs signal at $\sim$ 125 GeV is built up by two degenerate Higgs bosons.

- **What about the MSSM?**

  Two light MSSM CP-even Higgs bosons $\Longleftrightarrow$ light CP-odd A, relatively light $H^{\pm}$

  light $M_{H^{\pm}}$ excluded ATLAS-CONF-2012-011 and 2013-090, CMS-HIG-12-052

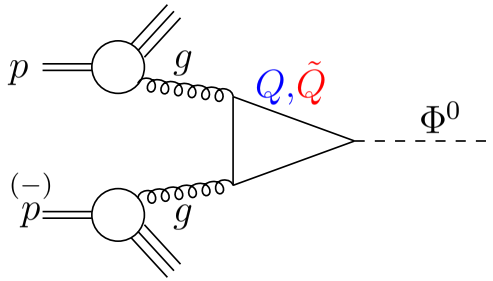
Compatibility with $\mathcal{SM}$-Like $\mathcal{H}$iggs $\mathcal{S}$ignal

- **SM-like NMSSM Higgs rate:** $h = H_1$ or H_2, $M_h = M_{H^{\rm SM}} \approx 125$ GeV

$$\mu_{XX}(h) = \frac{\sigma_{\rm prod}(h)\, BR(h \to XX)}{\sigma_{\rm prod}(H^{\rm SM})\, BR(H^{\rm SM} \to XX)}$$

- **NMSSM h Production:** small $\tan\beta$ favoured $\rightsquigarrow$ gluon fusion dominant $\sigma_{\rm prod}$
  for SM-like production cxn: h must be up-type doublet-like $\rightsquigarrow$ $g_{htt} \approx g_{H^{\rm SM}tt}$

- **Enhancement/supression on the production side**



- **Enhanced/suppressed gluon fusion production** See e.g. King,MMM,Nevzorov,Walz

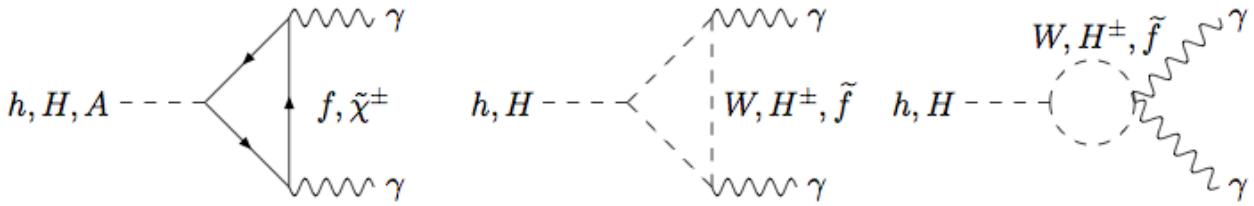
  * Stop, sbottom loop contributions in $gg \to H_i$ can enhance/suppress the production cxn for small/large mixing

Compatibility with $\mathcal{SM}$-Like $\mathcal{H}$iggs $\mathcal{S}$ignal

- **Branching ratios - e.g. into $XX = \gamma\gamma$**

$$BR(h \to \gamma\gamma) = \frac{\Gamma(h \to \gamma\gamma)}{(\Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + ... + \Gamma_{\phi_i\phi_j} + \Gamma_{\chi_1^0\chi_1^0} + ...)[h]}$$

  * $\Gamma_{b\bar{b}}$ dominant decay rate for 125 GeV SM-Higgs boson $\rightsquigarrow$ $BR(h \to XX)$ very sensitive to $\Gamma_{b\bar{b}}$
  * Suppression of $\Gamma(h^{125\,\text{GeV}} \to b\bar{b})$ due to Hall,Pinner,Ruderman; Ellwanger; King,MMM,Nevzorov; Cao,Heng,Yang,Zhang,Zhu; Albornoz-Vasquez,Belanger,Boehm,DaSilva,Richardson,Wymant
    - strong singlet-doublet mixing $\rightsquigarrow$ reduced coupling to $b\bar{b}$
    - Δ_b corrections to $hb\bar{b}$ coupling Carena eal; Guasch eal; Noth,Spira; Mihaila,Reisser
  * Enhanced $\Gamma(h^{125\,\text{GeV}} \to \gamma\gamma)$ due to charged boson, chargino, stop loop contributions



  * BR modifications due to Higgs-to-Higgs and/or Higgs-to-SUSY deays

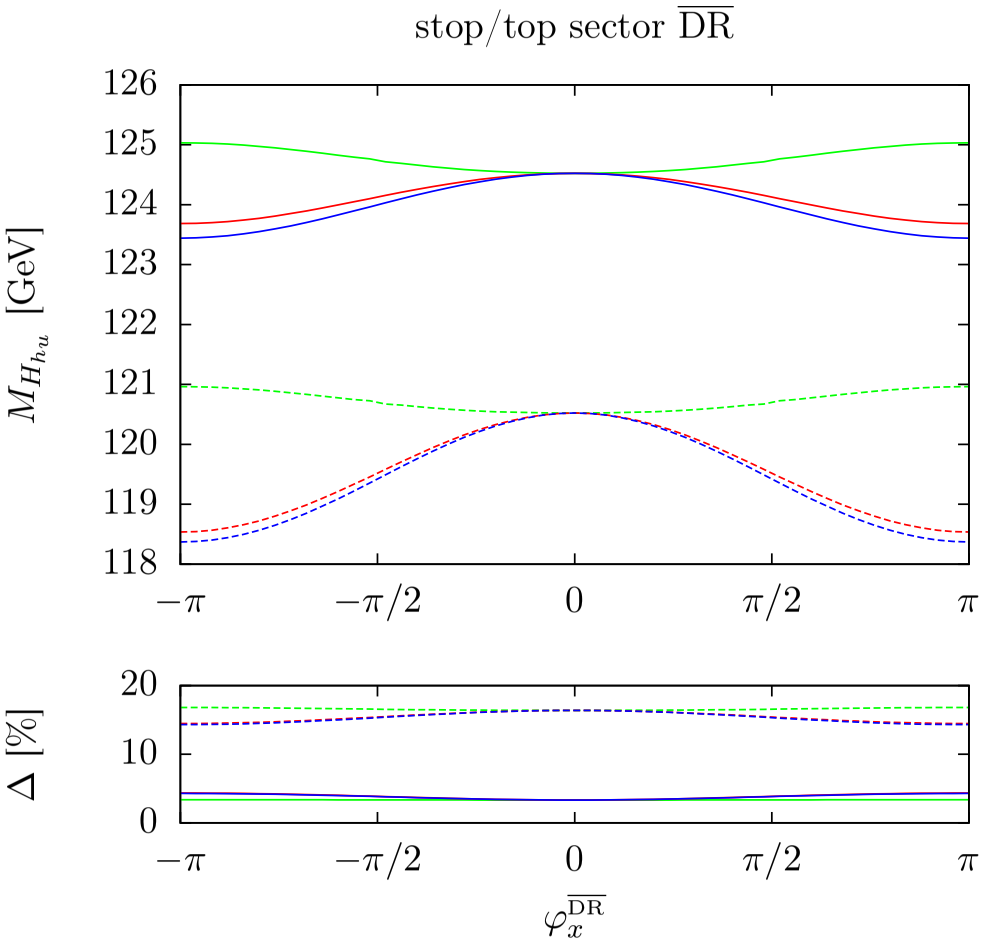
$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{M}$ass

- **NMSSM Higgs boson masses given in terms of Higgs potential parameters**
- **Higher order corrections:**
  - ∗ important to shift SM-like NMSSM Higgs boson mass to $\sim$ 125 GeV;
  - ∗ Higgs masses enter production cxn's and BR's $\rightsquigarrow$
  - ∗ need to be known at highest possible accuracy for proper interpretation of exp results, for distinction of Higgs sectors of different BSM models

$\mathcal{NMSSM}$ Higgs Boson Mass

- **Status of higher order corrections:**
  - Real NMSSM:
    - leading one-loop [Ellwanger;Elliott eal; Pandita;Ellwanger,Huggonie]
    - full one-loop in $\overline{\text{DR}}$ scheme [Degrassi,Slavich;Staub eal]
    - full one-loop in mixed $\overline{\text{DR}}$-OS scheme [Ender(→Walz),Graf,MMM,Rzehak]
    - $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s)$ $\overline{\text{DR}}$ w/ zero external momentum [Degrassi,Slavich]
    - first results beyond this [Goodsell eal]
  - Complex NMSSM:
    - various one-loop contributions in effective potential approach [Ham,Kim,Oh,Son;Ham,Oh,Son;Ham,Jeong,Oh;Funakubo,Tao;Ham,Kim,Oh,Son]
    - full one-loop & leading two-loop in effective potential approach [Cheung,Hou,Lee,Senaha]
    - full one-loop in diagrammatic approach [Graf,Grober,MMM,Rzehak,Walz]
    - $\mathcal{O}(\alpha_t\alpha_s)$ mixed $\overline{\text{DR}}$-OS scheme w/ zero external momentum [MMM,Nhung,Rzehak,Walz]

$\mathcal{NMSSM}$ Higgs Boson Mass 2-Loop Corrections



$m_t^{pole} = 173.5$ GeV

$m_t^{\overline{\rm DR}} = 143.14$ GeV at $Q = 1.25$ TeV

MMM,Nhung,Rzehak,Dao '14

dashed: one-loop, full: two-loop

variation of φ_{A_t}

variation of φ_{M_3}

variation of φ_μ

$$\Delta = |M_{H_{hu}}^{(n)} - M_{H_{hu}}^{(n-1)}|/M_{H_{hu}}^{(n-1)}$$

dashed: $n = 1$, solid: $n = 2$

difference in $\overline{\rm DR}$ and OS masses:
one-loop: $\mathcal{O}(15 - 25\%)$
two-loop: $\mathcal{O}(\lesssim 1.5\%)$