Higgs Physics

SUSY at Colliders

SS 2011

Outline

⋆ Introduction MSSM Higgs sector

⋆ Higgs decays

⋆ Higgs production

⋆ Higher order corrections

⋆ Higgs couplings

⋆ Higgs quantum numbers

⋆ Higgs self-couplings

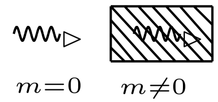
Experimental verification of the Higgs mechanism

Higgs mechanism:

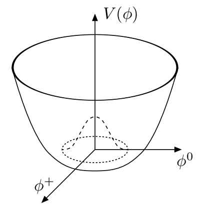
Creation of particle masses without violating gauge principles

Test of the Higgs mechanism

- Discovery – m
- Interaction with a scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



- Spin- and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$



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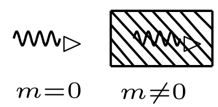

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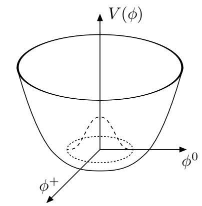

$\mathcal{M}$inimal $\mathcal{S}$upersymmetric $\mathcal{E}$xtension of the $\mathcal{SM}$ ($\mathcal{MSSM}$)

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

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

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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;...

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Decoupling limit:

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

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

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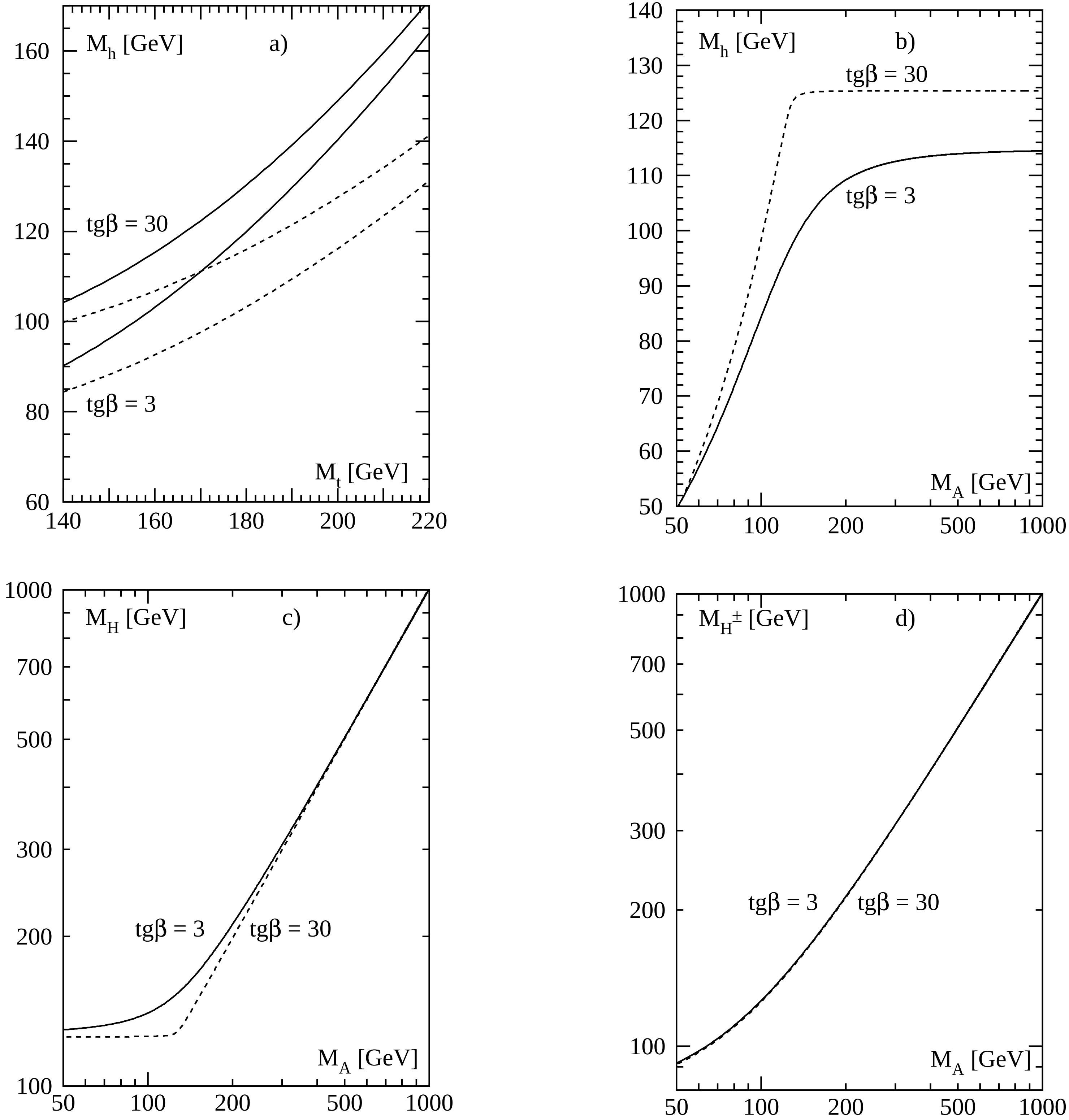
Modified couplings w/ respect to the SM: (decoupling limit Gunion,Haber)

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

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

$g_{\Phi dd} \uparrow$

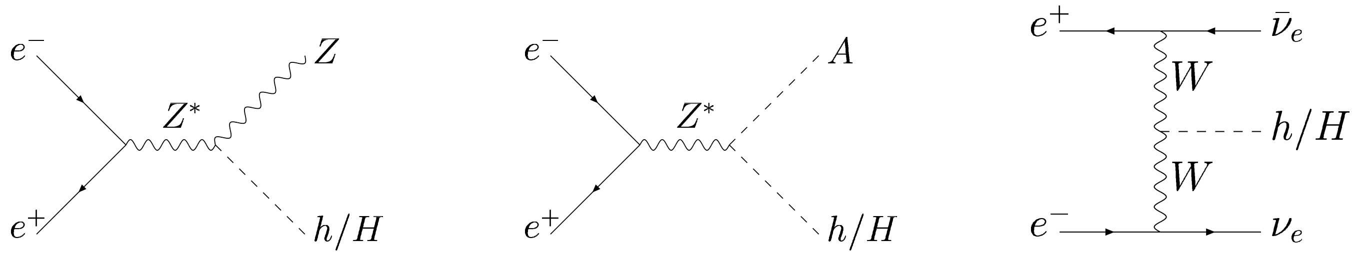
$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$

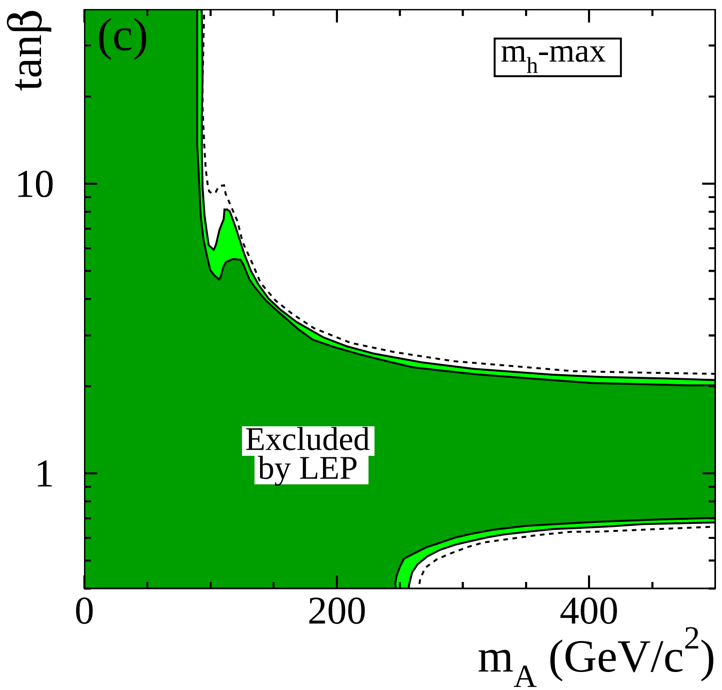


M_h [GeV]
a)
tgβ = 30
tgβ = 3
M_t [GeV]
M_h [GeV]
b)
tgβ = 30
tgβ = 3
M_A [GeV]
M_H [GeV]
c)
tgβ = 3
tgβ = 30
M_A [GeV]
$M_{H^\pm}$ [GeV]
d)
tgβ = 3
tgβ = 30
M_A [GeV]

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass $\mathcal{L}$imits

▷ 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

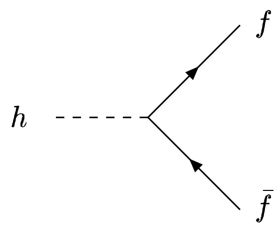
$M_{H^\pm} > 78.6$ GeV

$0.6 < \tan\beta < 2.5$ excluded

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

Higgs decays

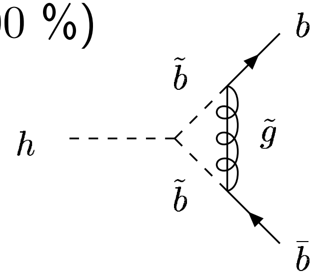
- $h \to b\bar{b}, \tau^+\tau^-, c\bar{c}$



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

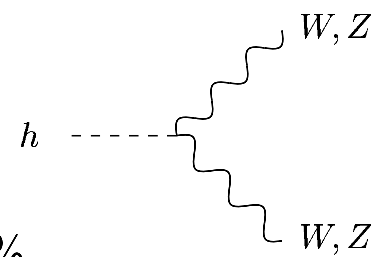
large SUSY-QCD corrections: $\mathcal{O}(10...100$ %)

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



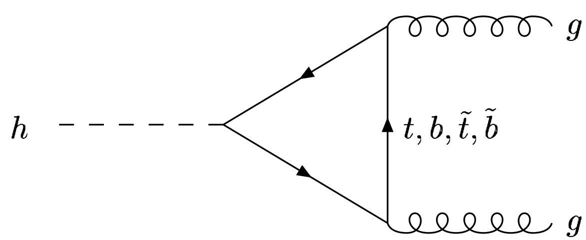
$+ \ldots$

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

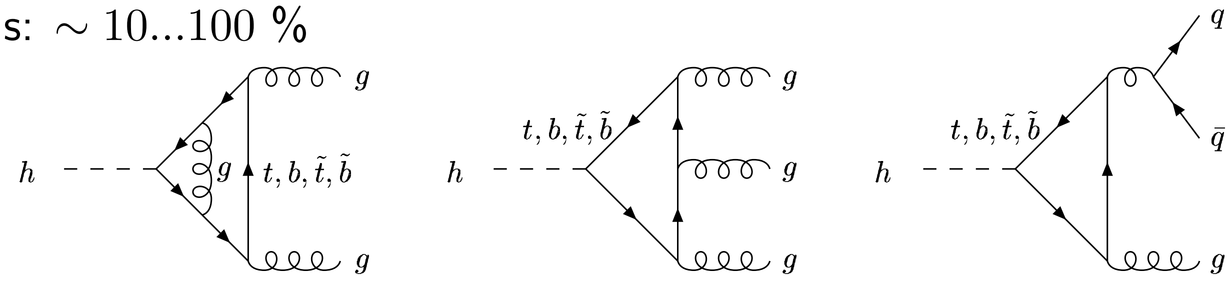


electroweak corrections: $\sim 5...10$ %

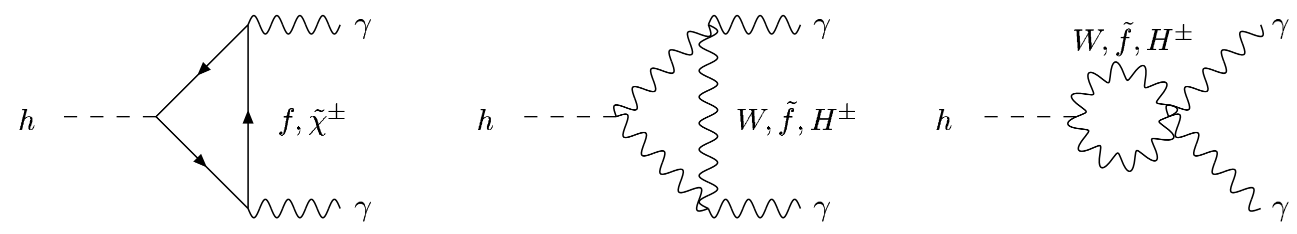
- $h \to gg$



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

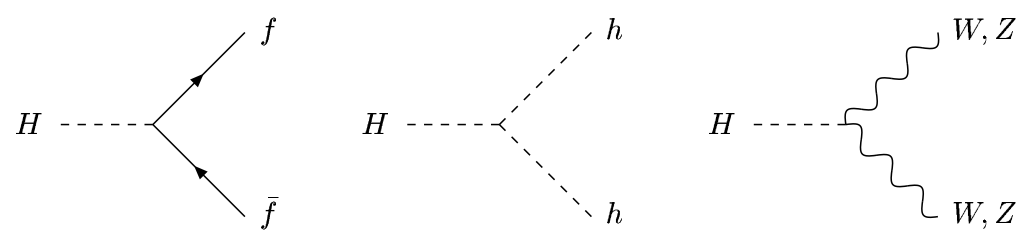


- $h \to \gamma\gamma$

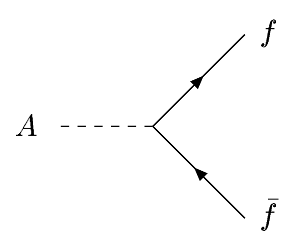


Extremely important decay channel for the LHC

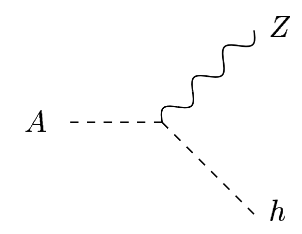
- $H \to b\bar{b}, \tau^+\tau^-$: dominant for large $\tan\beta$
- $H \to hh, WW, ZZ, t\bar{t}$

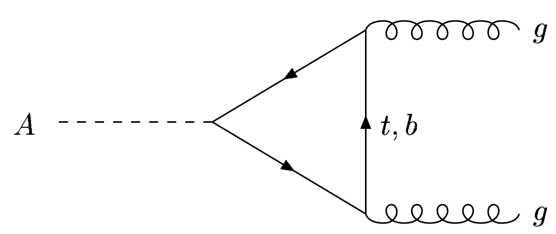


- $A \to b\bar{b}, \tau^+\tau^-$: dominant for large $\tan\beta$
- $A \to t\bar{t}$: dominant above the $t\bar{t}$ threshold for small and moderate $\tan\beta$

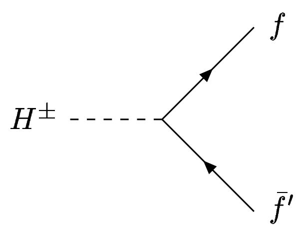


- $A \to Zh, gg$

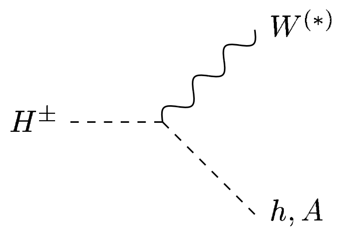


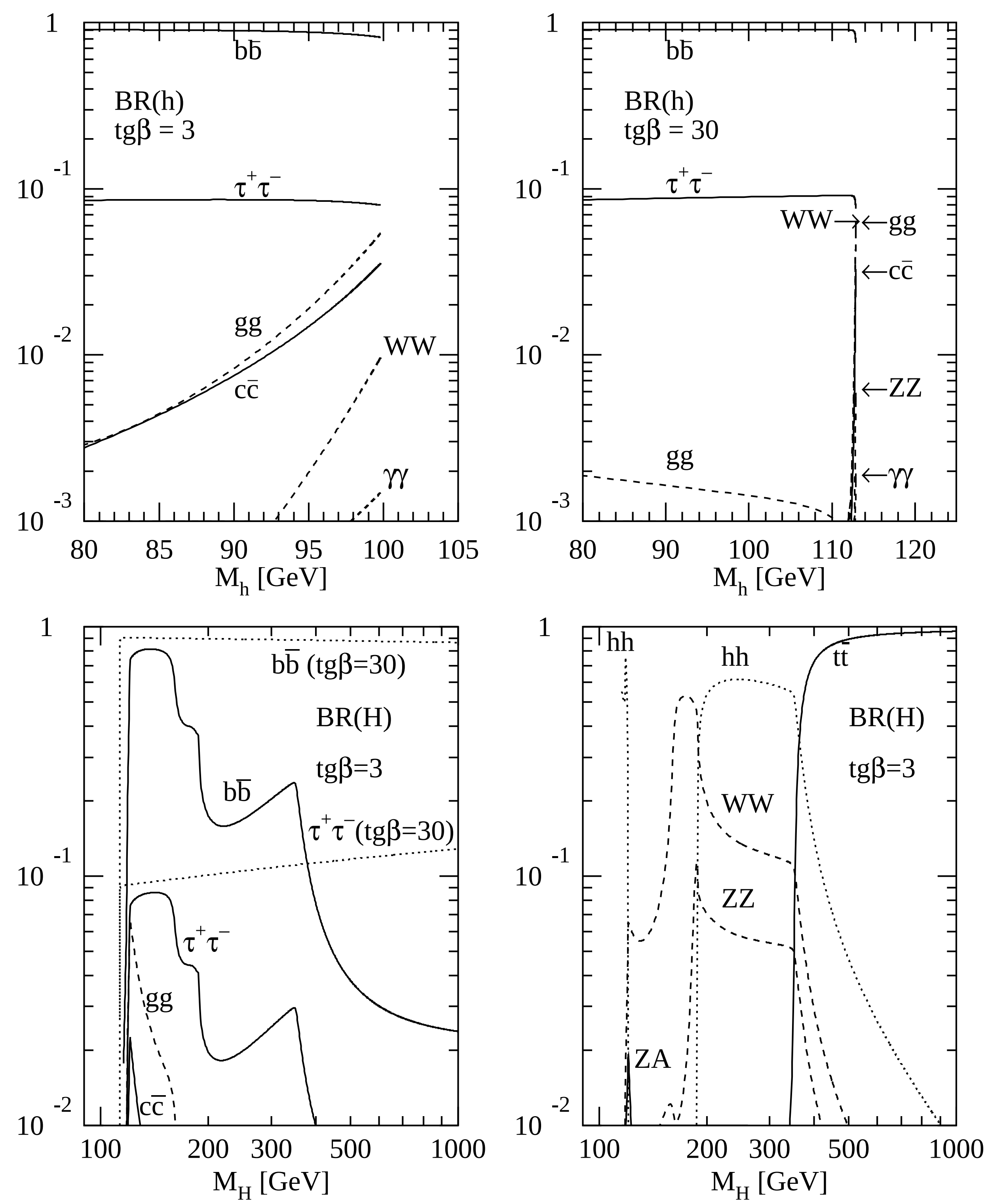


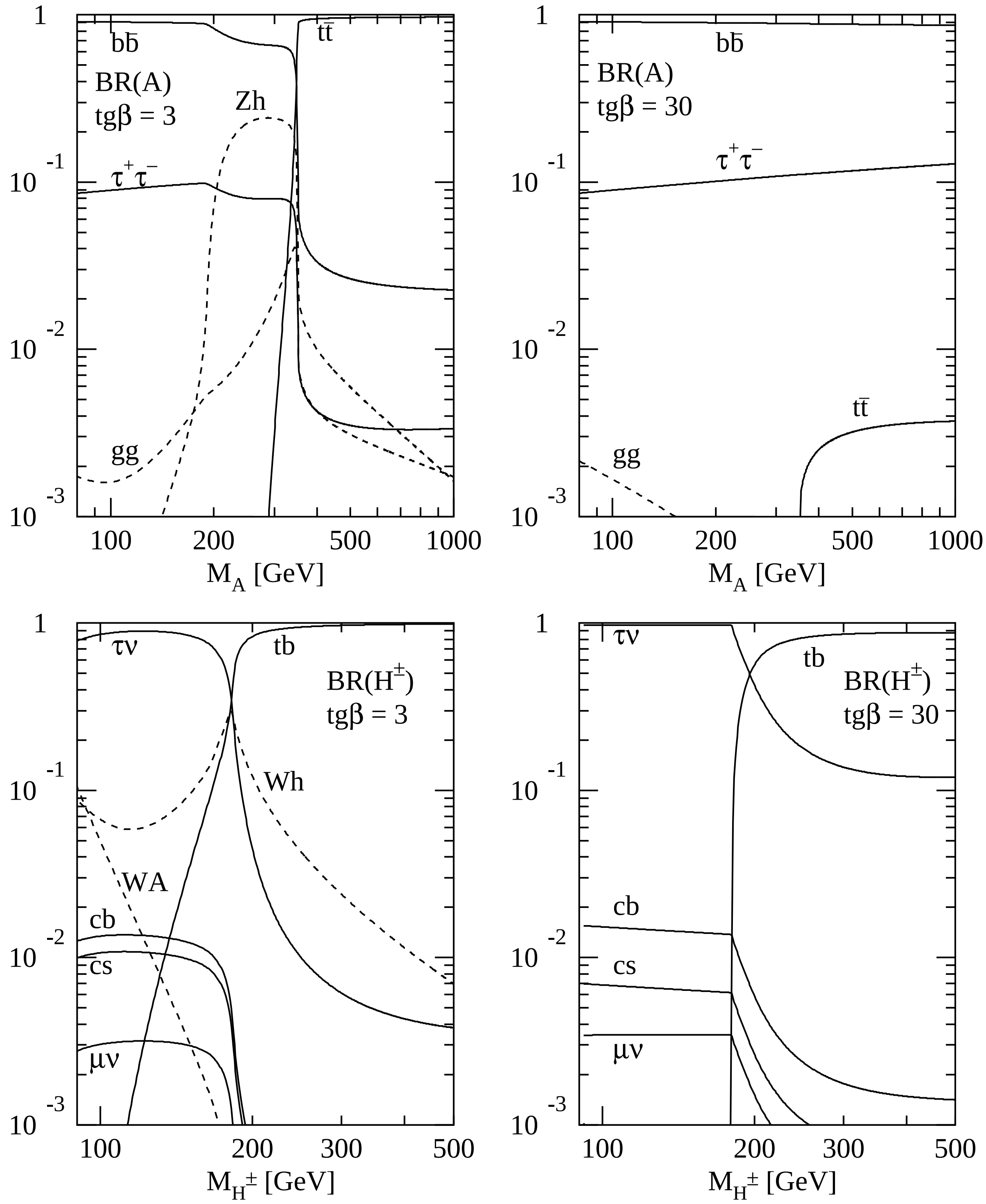
- $H^+ \to \tau^+ \nu_\tau, t\bar{b}$



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

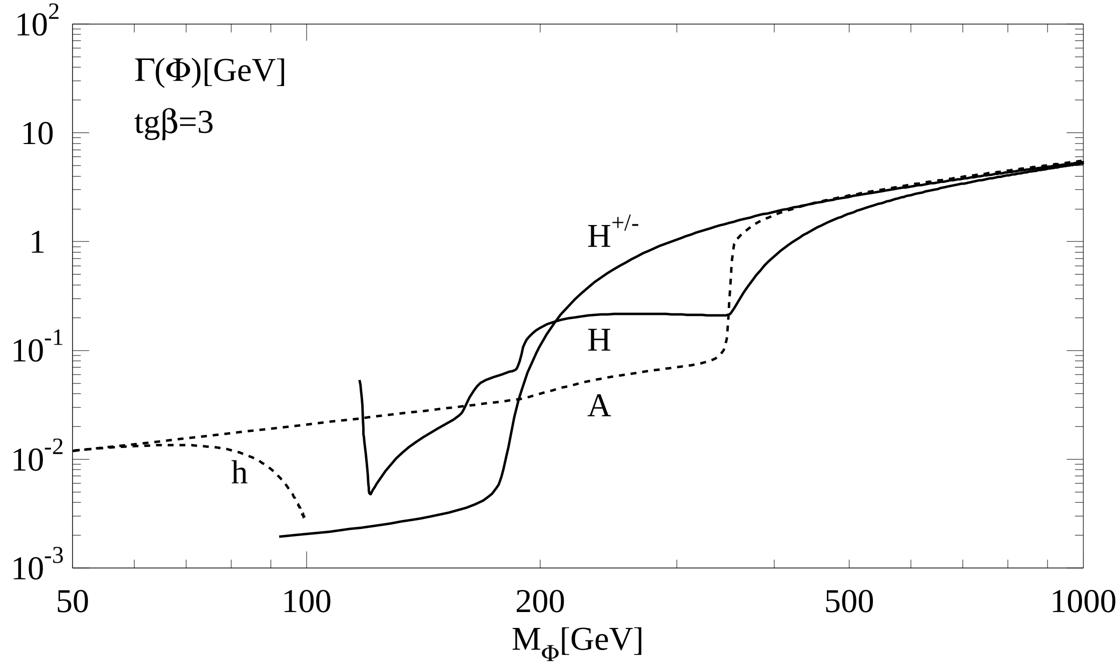


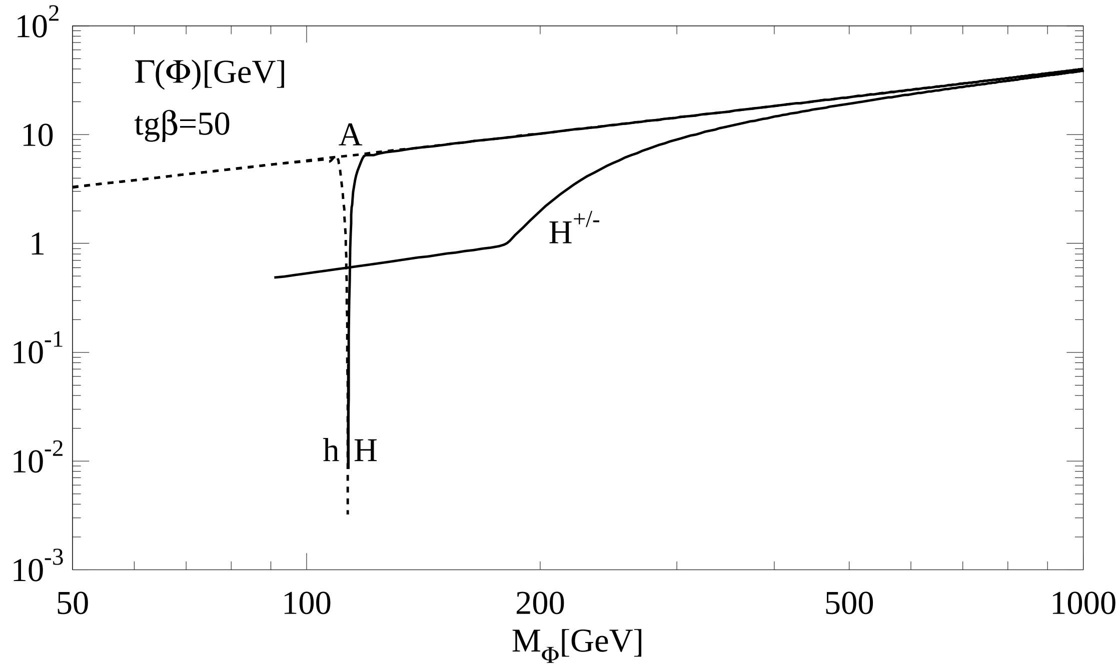

BR(h)
tgβ = 3
bb̄
τ⁺τ⁻
gg
cc̄
WW
γγ
M_h [GeV]
BR(h)
tgβ = 30
WW→ ←gg
←cc̄
←ZZ
←γγ
BR(H)
tgβ=3
bb̄ (tgβ=30)
τ⁺τ⁻(tgβ=30)
M_H [GeV]
hh
ZA
ZZ
tt̄



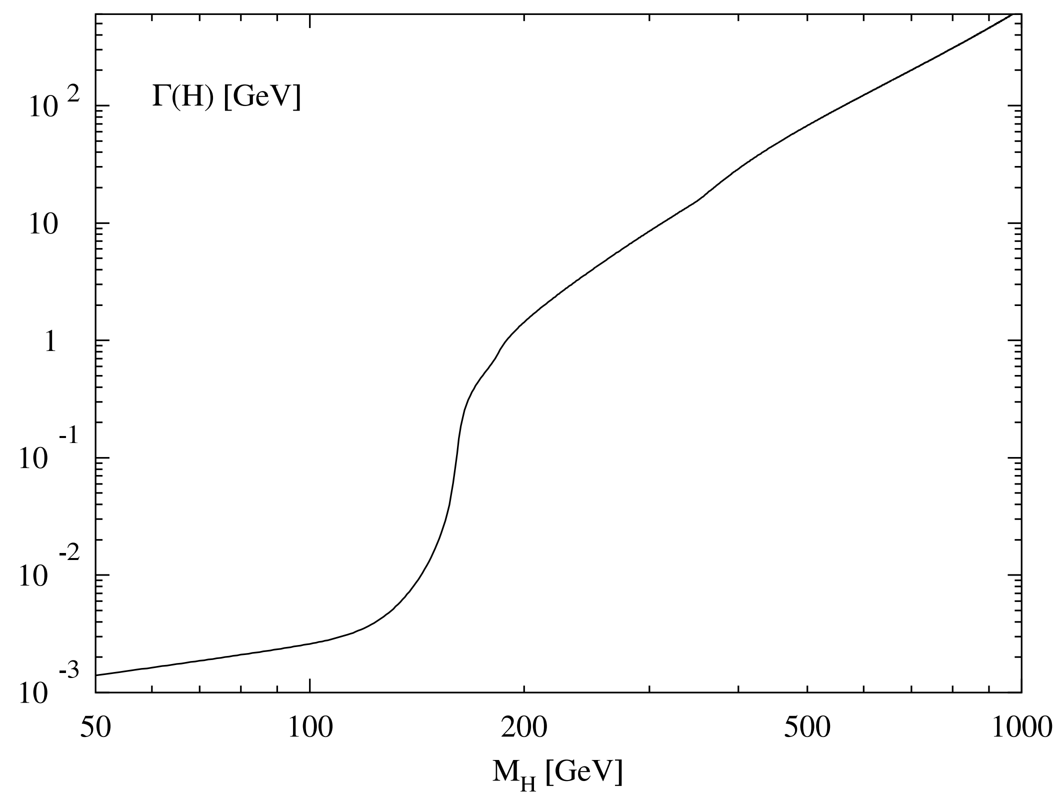
bb̄
BR(A)
tgβ = 3
Zh
tt̄
τ+τ−
gg
M_A [GeV]
BR(A)
tgβ = 30
bb̄
τ+τ−
tt̄
gg
M_A [GeV]
τν
tb
BR(H±)
tgβ = 3
Wh
WA
cb
cs
μν
M_H± [GeV]
τν
tb
BR(H±)
tgβ = 30
cb
cs
μν
M_H± [GeV]

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

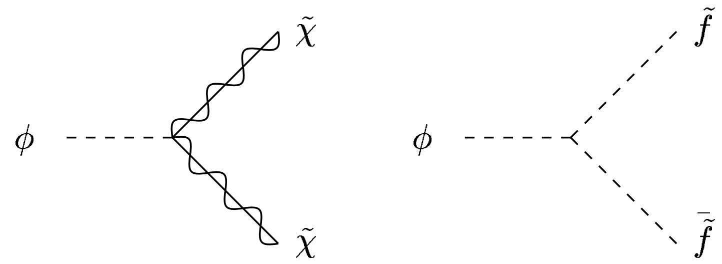


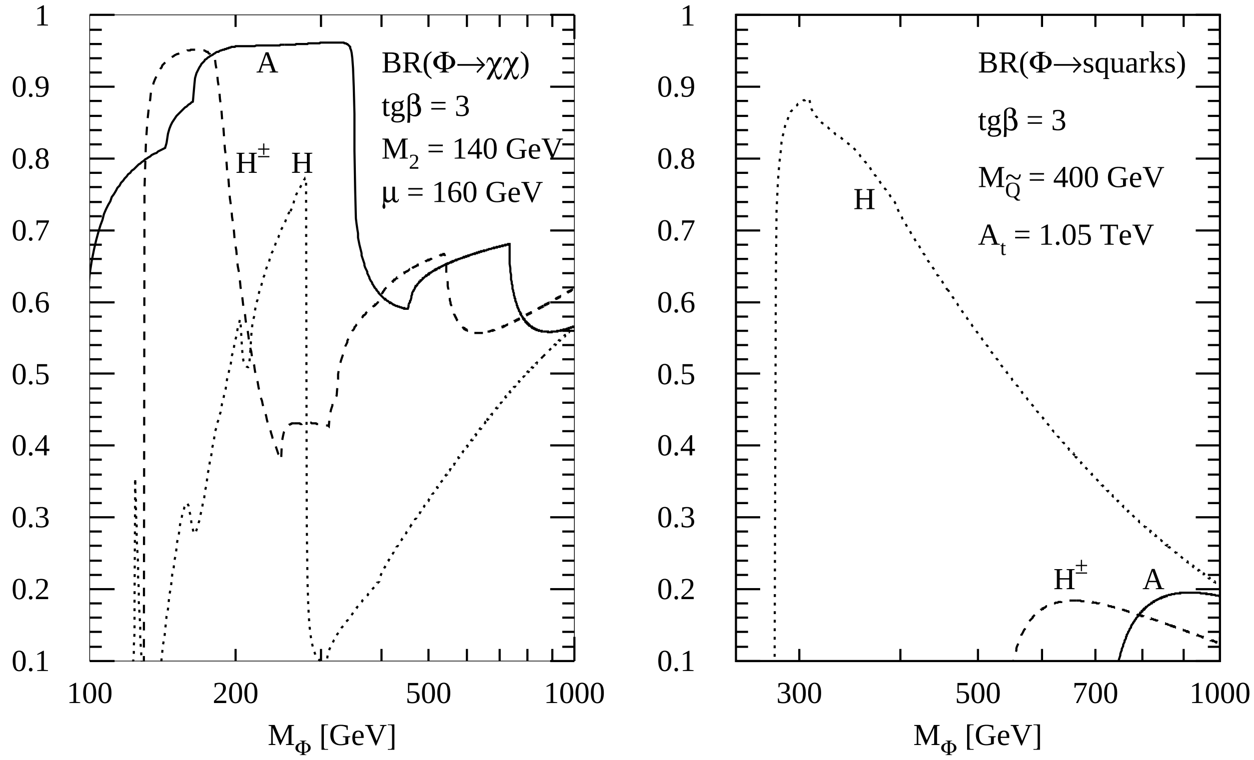


- for comparison: the total width in the SM



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

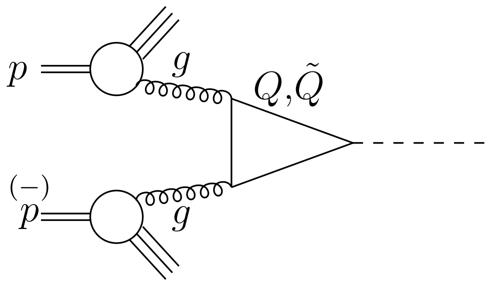




Higgs boson production in SM/MSSM

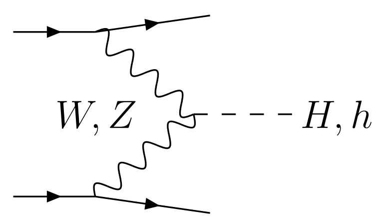
- **Gluon Gluon Fusion**

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



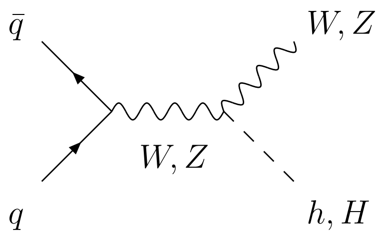
- **W/Z Fusion**

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



- **Higgs-strahlung**

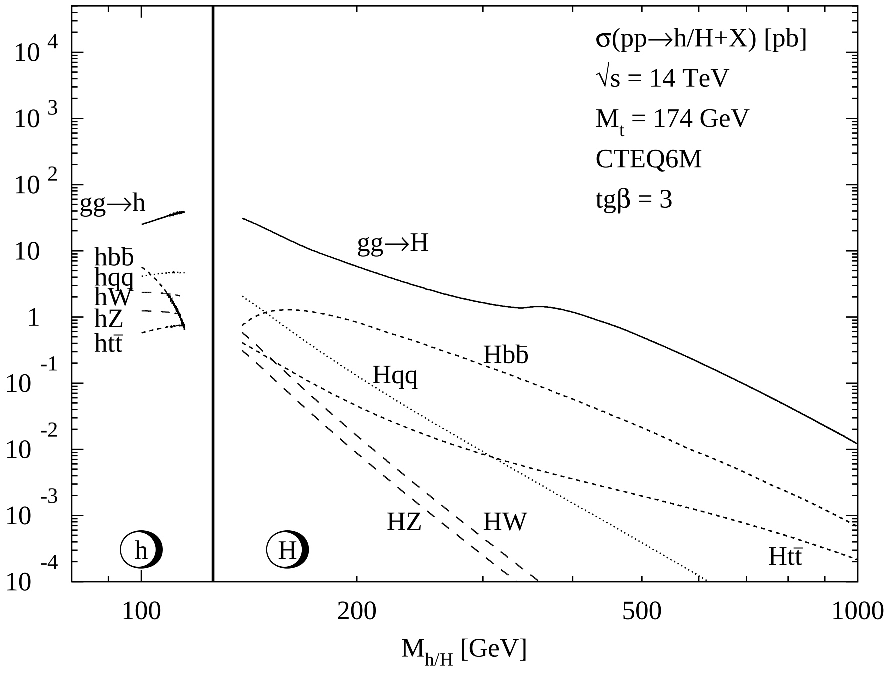
  $pp \to W^*/Z^* \to W/Z + H^{SM} \,/\, h, H$

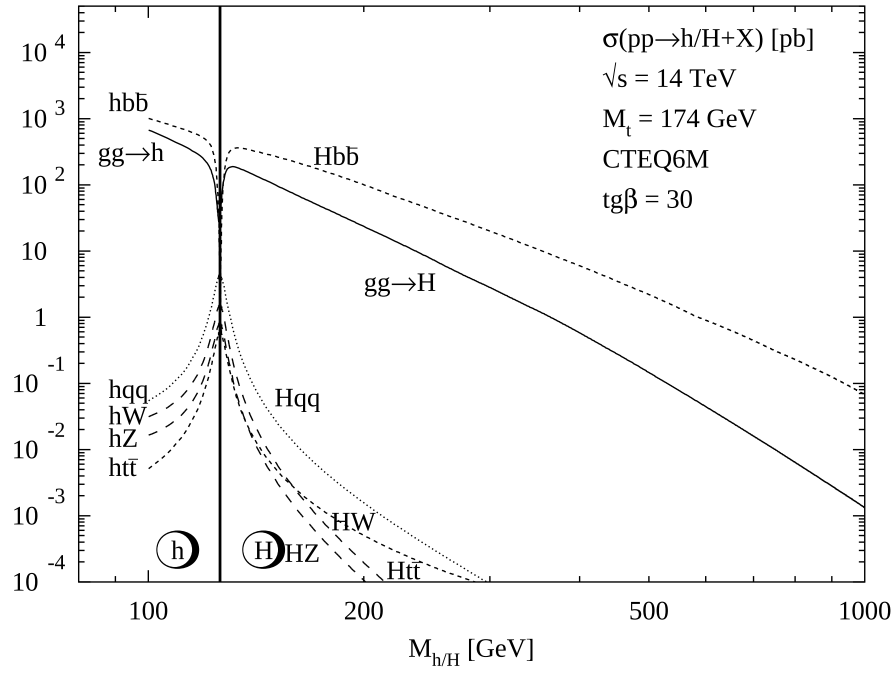


- **Associated Production**

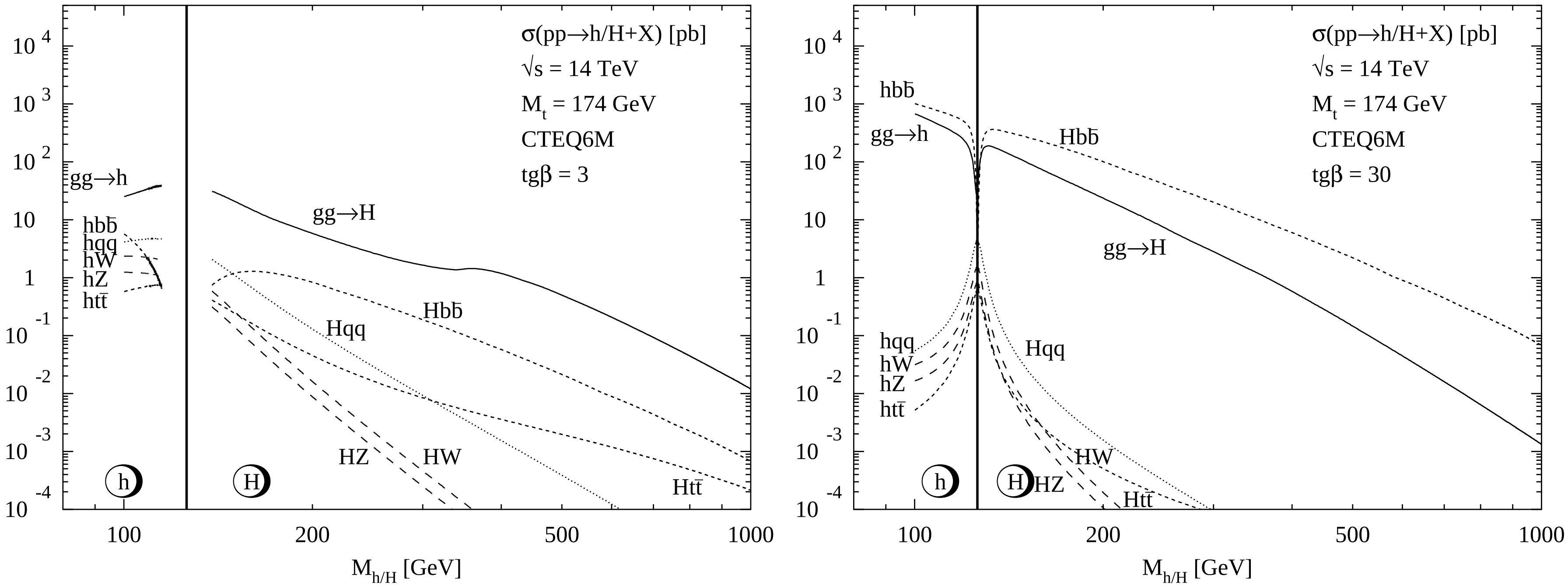
  $pp \to t\bar{t}/b\bar{b} + (H^{SM}) \,/\, h, H, A$

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction at the $\mathcal{LHC}$





MSSM Higgs Boson Production at the LHC

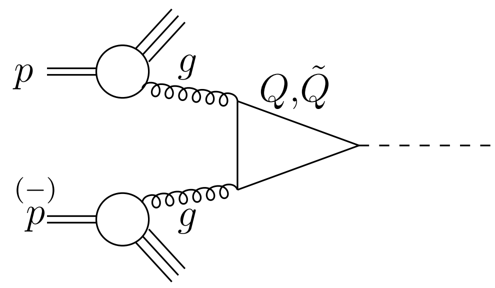


Reminder

$$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$$
$$g_{\Phi dd} \uparrow$$
$$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$$

Gluon gluon fusion: higher order corrections

Gluon Gluon fusion: lowest order - 1 loop



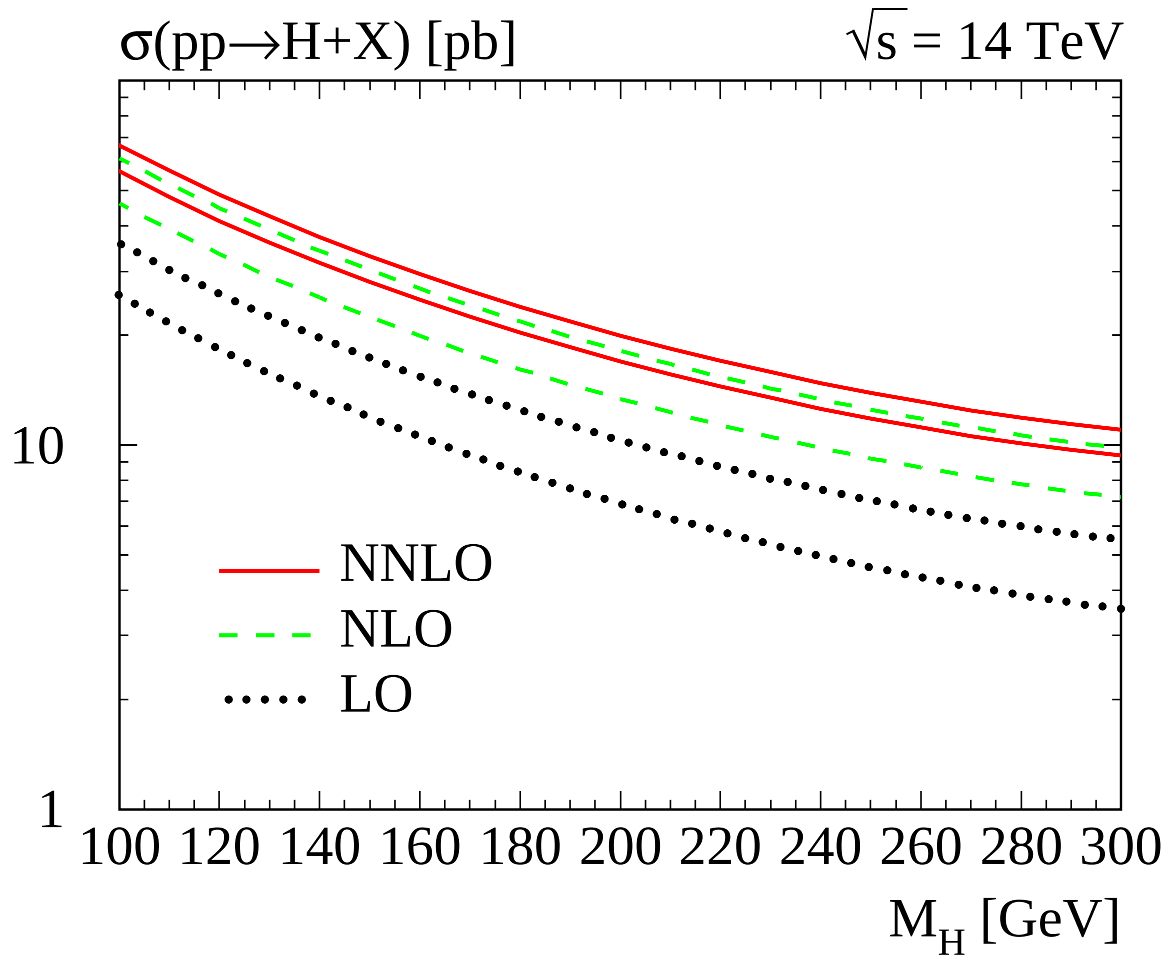
Georgi,...;Gamberini,...

QCD corrections to top & bottom loops

◇ NLO (SM, MSSM)	enhance σ by $\sim$ 10...100%	Spira,Djouadi,Graudenz,Zerwas Dawson;Kauffman,Schaffer
◇ SM; tg$\beta \lesssim 5$: limit $M_\Phi \ll m_t$	approximation $\sim$ 20-30%	Krämer,Laenen,Spira
◇ NNLO @ $M_\Phi \ll m_t \Rightarrow$ scale dependence:	further enhancement by 20-30% $\Delta \lesssim 10-15\%$	Harlander,Kilgore;Anastasiou, Melnikov;Catani,deFlorian,Grazzini; Ravindran,Smith,van Neerven
◇ m_t effect: NNLO K-factor	better than 1% for $M_H \lesssim 300$ GeV	Marzani et al.;Harlander eal; Pak,Rogal,Steinhauser
◇ estimate of the NNNLO effects	$\rightsquigarrow$ improved convergence	Moch,Vogt Ravindran
◇ soft gluon resummation:	$+\sim 10\%$	Catani,de Florian,Grazzini,Nason
◇ EW 2-loop effects	$\sim +5... -2\%$ enhancement	Anastasiou et al;Aglietti et al.; Degrassi,Maltoni;Actis et al.
◇ EW, b contrs to $H+j$	$\sim \mathcal{O}(1\%)$	Keung,Petriello;Brein

$gg \to H$ $\mathcal{NNLO}$

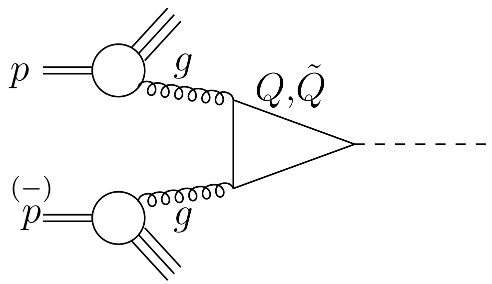
Harlander, Kilgore



Gluon gluon fusion: higher order corrections

Gluon Gluon fusion: lowest order - 1 loop

Georgi,...;Gamberini,...



NLO corrections to squark loops

heavy squark mass limit — Dawson,Djouadi,Spira

full SUSY-QCD corrections in the heavy mass limit — Harlander,Steinhauser;Harlander, Hofmann;Degrassi,Slavich

$\mathbf{m_{\tilde{Q}} \lesssim 400}$ **GeV:**

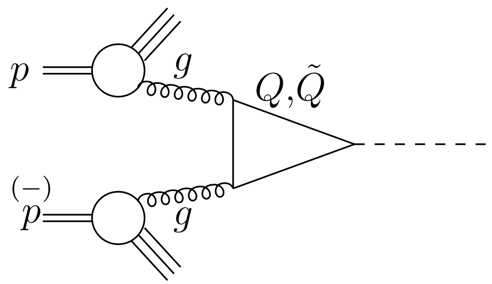
NLO squark mass effects — Anastasiou,Beerli,Bucherer,Daleo,Kunszt; Aglietti,Bonciani,Degrassi,Vicini; MMM,Spira

full NLO SUSY QCD calculation — Anastasiou,Beerli,Daleo; MMM,Rzehak,Spira

$gg \to H, h$ at leading order

Lowest order - 1 loop

Georgi,...;Gamberini,...



$$\boxed{\sigma(pp \to \Phi + X) \quad = \quad \sigma_0^{\Phi} \tau_{\Phi} \frac{d\mathcal{L}^{gg}}{d\tau_{\Phi}}}$$

$$\sigma_0^{h/H} = \frac{G_F \alpha_S^2(\mu_R)}{288\sqrt{2}\pi} \left| \sum_Q g_Q^{h/H} F_Q^{h/H}(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^{h/H} F_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \right|^2 \qquad \sigma_0^A = \frac{G_F \alpha_s^2}{128\sqrt{2}\pi} \left| \sum_Q g_Q^A F_Q^A(\tau_Q) \right|^2$$

$$F_Q^{h/H}(\tau_Q) \quad = \quad \tfrac{3}{2}\tau_Q \Big[1 + (1-\tau_Q) f(\tau_Q)\Big] \qquad F_Q^A(\tau_Q) = \tau_Q f(\tau_Q)$$

$$F_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \quad = \quad -\tfrac{3}{4}\tau_{\tilde{Q}} \Big[1 - \tau_{\tilde{Q}} f(\tau_{\tilde{Q}})\Big]$$

$$f(\tau) \quad = \quad \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \tau < 1 \end{cases} \qquad \tau_\Phi = \frac{M_\Phi^2}{s}, \quad \tau_{Q,\tilde{Q}} = \frac{4m_{Q,\tilde{Q}}^2}{M_\Phi^2}$$

The Scenario

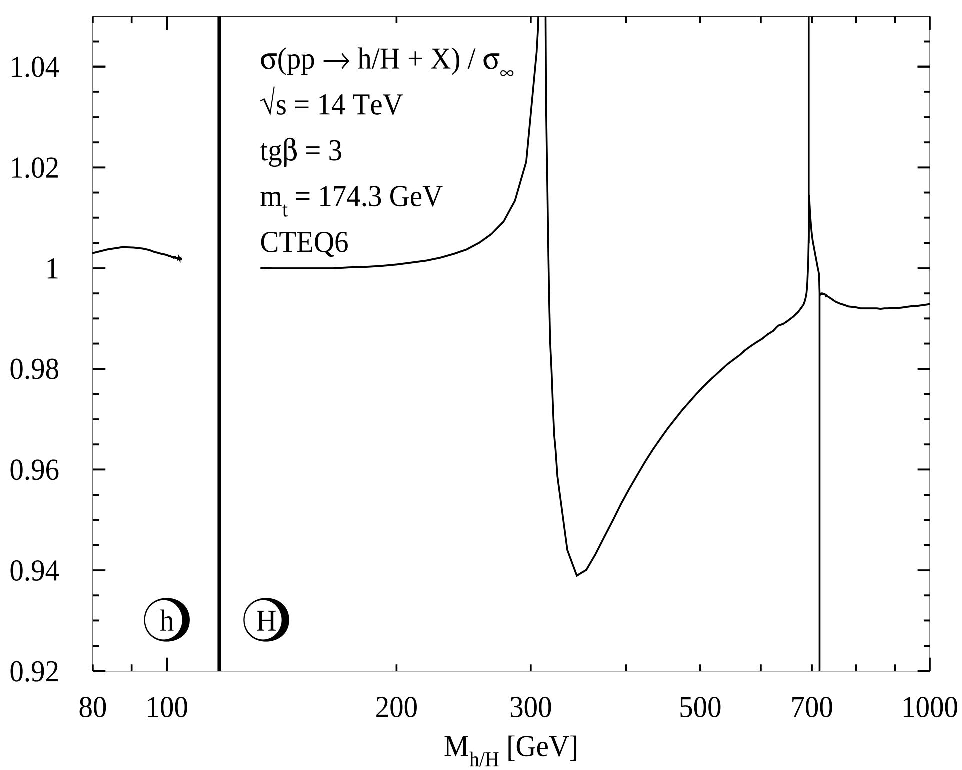
The gluophobic Higgs scenario $[m_t = 174.3$ GeV$]$ Carena,Heinemeyer,Wagner,Weiglein

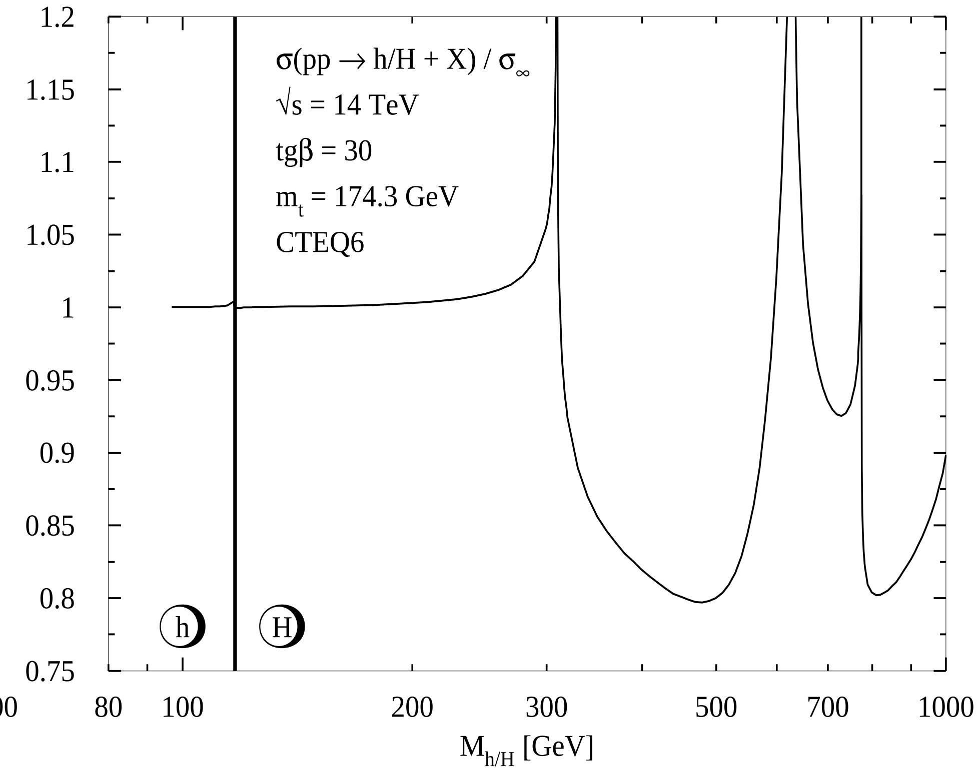
$$M_{SUSY} = 350 \text{ GeV},\ \mu = M_2 = 300 \text{ GeV},\ X_t = -770 \text{ GeV},\ A_b = A_t,\ m_{\tilde{g}} = 500 \text{ GeV}$$

$\tan\beta = 3$		$\tan\beta = 30$	
$m_{\tilde{t}_1} = 156$ GeV	$m_{\tilde{t}_2} = 517$ GeV	$m_{\tilde{t}_1} = 155$ GeV	$m_{\tilde{t}_2} = 516$ GeV
$m_{\tilde{b}_1} = 346$ GeV	$m_{\tilde{b}_2} = 358$ GeV	$m_{\tilde{b}_1} = 314$ GeV	$m_{\tilde{b}_2} = 388$ GeV

NLO cross section $\longrightarrow$

σ_{NLO} w/ full squark mass dependence / σ_{NLO} in the heavy squark limit





$\sigma(pp \to h/H + X)/\sigma_\infty$ up to 20%

Kinks, bumps, spikes: $\tilde{t}_1\bar{\tilde{t}}_1, \tilde{b}_1\bar{\tilde{b}}_1, \tilde{b}_2\bar{\tilde{b}}_2$ thresholds in consecutive order with rising Higgs mass.

Coulomb singularities

$\tilde{Q}\bar{\tilde{Q}}$ thresholds: Formation of 0^{++} states $\rightsquigarrow$ Coulomb singularities

Singular behaviour can be derived from the Sommerfeld rescattering corrections $\rightsquigarrow$

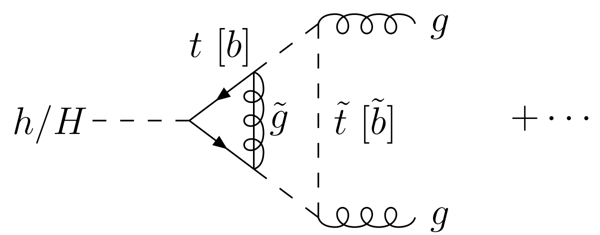
At each specific $\tilde{Q}_0\bar{\tilde{Q}}_0$ threshold:

$$C_1(\tau_Q, \tau_{\tilde{Q}}) \to \mathrm{Re}\left\{ \frac{g^\Phi_{\tilde{Q}_0} \tilde{F}(\tilde{Q}_0) \frac{16\pi^2}{3(\pi^2-4)} \left[-\ln\left(\tau^{-1}_{\tilde{Q}_0} - 1\right) + i\pi + const \right]}{\sum_Q g^\Phi_Q F(\tau_Q) + \sum_{\tilde{Q}} g^\Phi_{\tilde{Q}} \tilde{F}(\tau_{\tilde{Q}})} \right\}$$

Agrees quantitatively with numerical results.

Genuine SUSY-QCD corrections

- **Limit heavy SUSY masses** $\rightarrow \mathcal{O}(10\ \%)$ Harlander, Steinhauser, Hofmann



- **Numerical analysis:** $F_Q^{h/H}(\tau_Q) \rightarrow F_Q^{h/H}(\tau_Q)[1 + C_{SUSY}^{Q} \frac{\alpha_S}{\pi}]$

- $m^2_{Q/\tilde{Q}} \rightarrow m^2_{Q/\tilde{Q}}(1 - i\epsilon)$

- **5-dimensional Feynman integral $\rightarrow$ endpoint subtractions:**

$$\int_0^1 dx\, \frac{f(x)}{x(1-x)} \rightarrow \int_0^1 dx \left\{ \frac{f(x)}{x(1-x)} - \frac{f(0)}{x} - \frac{f(1)}{(1-x)} \right\}$$

$\Rightarrow$ isolation of singularities

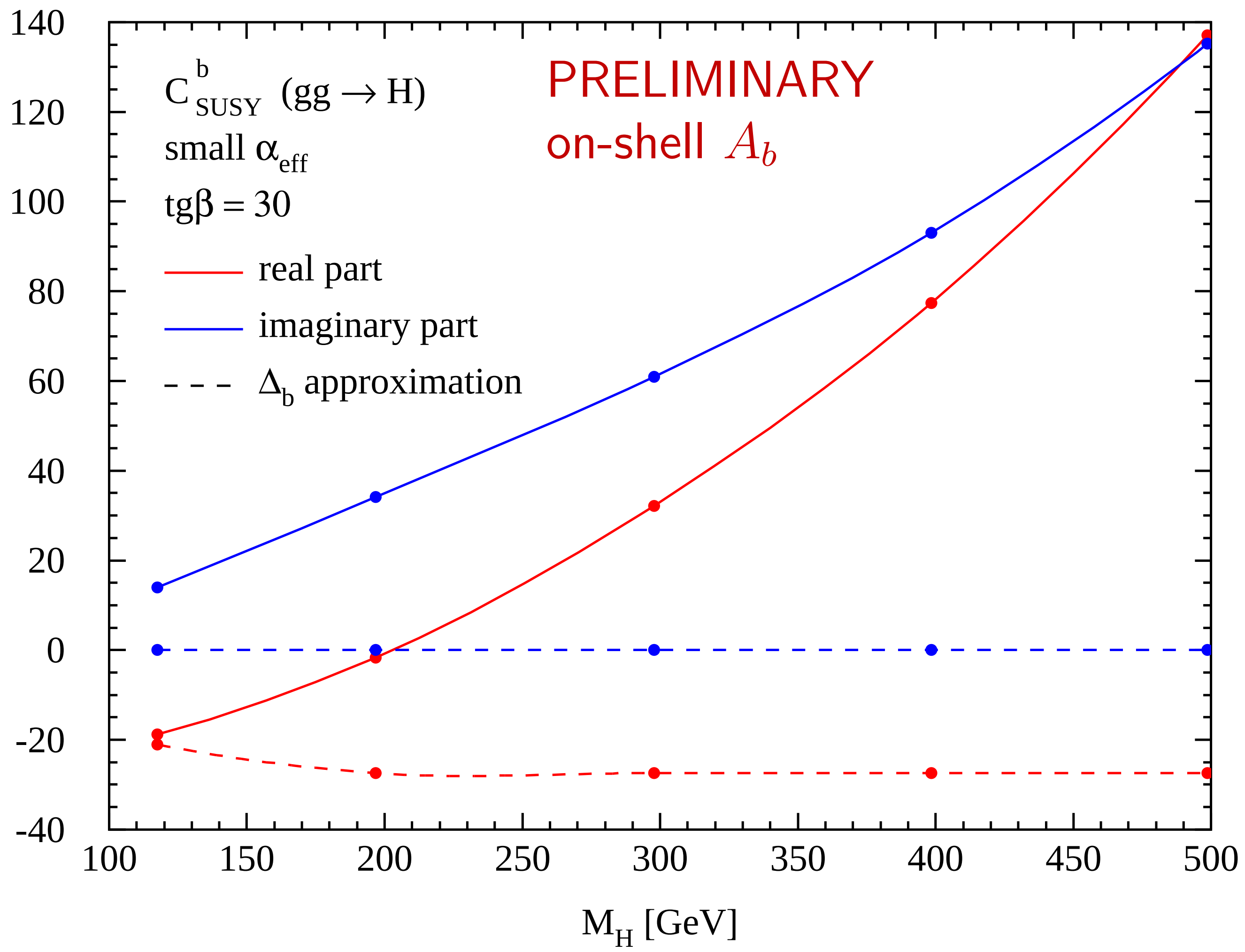
The Scenario

Small α_{eff} scenario [modified]

$$
\begin{aligned}
\tan\beta &= 30 \\
M_{\tilde{Q}} &= 800\ \text{GeV} \\
M_{\tilde{g}} &= 1000\ \text{GeV} \qquad \longleftarrow \\
M_2 &= 500\ \text{GeV} \\
A_b = A_t &= -1.133\ \text{TeV} \\
\mu &= 2\ \text{TeV}
\end{aligned}
$$

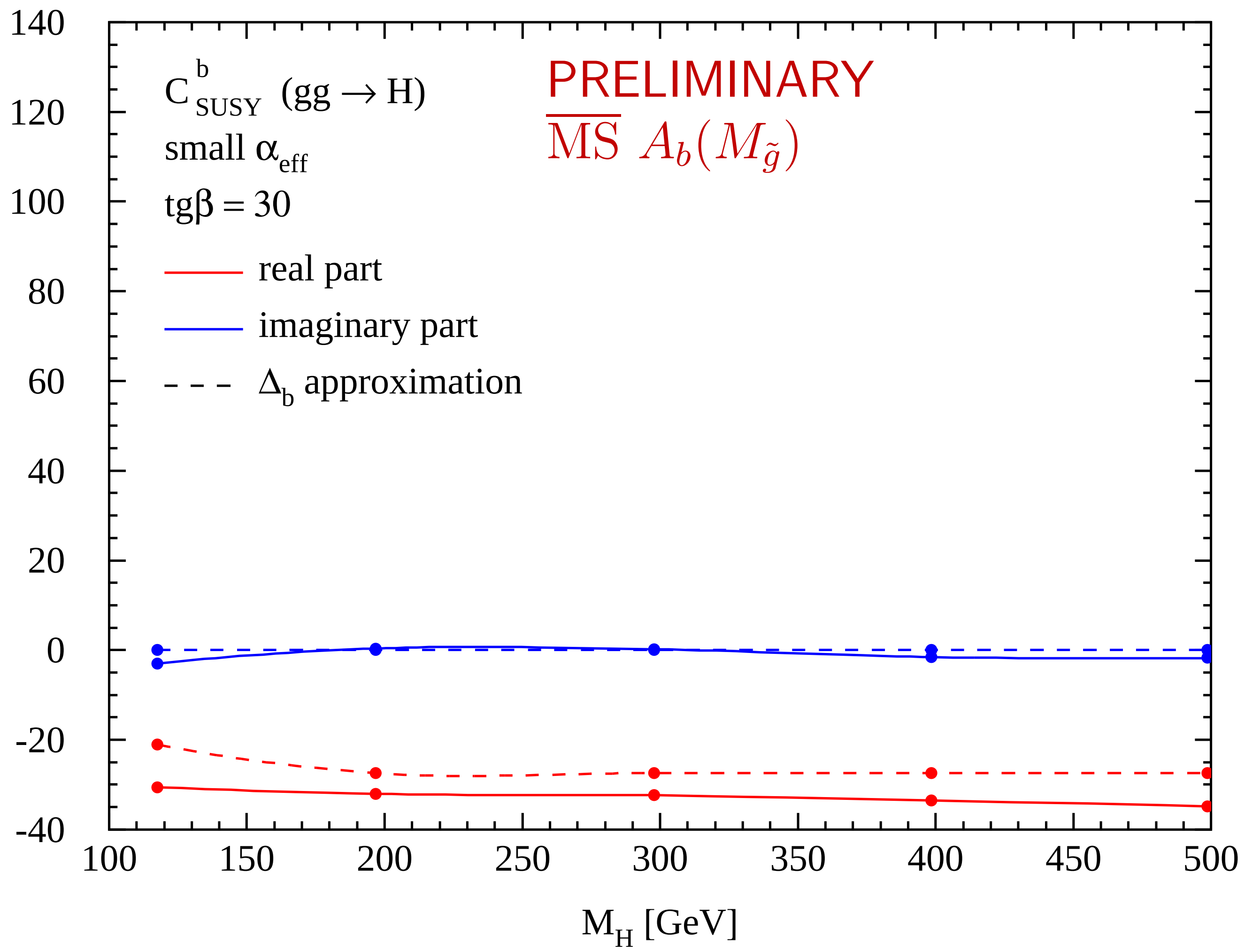
$$
\begin{aligned}
m_{\tilde{t}_1} &= 679\ \text{GeV} & m_{\tilde{t}_2} &= 935\ \text{GeV} \\
m_{\tilde{b}_1} &= 601\ \text{GeV} & m_{\tilde{b}_2} &= 961\ \text{GeV}
\end{aligned}
$$

Preliminary results



MMM, Rzehak, Spira

Preliminary results



MMM, Rzehak, Spira

$\mathcal{H}$igher order corrections to $\mathcal{H}$iggs production at the $\mathcal{LHC}$

- **W/Z Fusion**

NLO QCD σ (SM/MSSM)	$\sim$ 5 bis 10%	Han, Valencia, Willenbrock	EW & QCD	~ 5 %	Ciccolini, Denner Dittmaier
Verteilungen	$\sim$ 10 %	Figy et al; Berger, Campbell	SUSY QCD	klein	Djouadi, Spira
NLO QCD H+3j		Figy, Hankele, Zeppenfeld	SUSY QCD&EW	klein	Hollik, Plehn, Rauch, Rzehak
NNLO QCD		Bolzoni et al			
VBFNLO	MC	Figy eal; Arnold eal	HAWK for $H+2j$	MC NLO	Denner, Dittmaier, Mück
$gg \to H+2j$		DelDuca eal; Campbell eal			

$\mathcal{H}$igher order corrections to $\mathcal{H}$iggs production at the $\mathcal{LHC}$

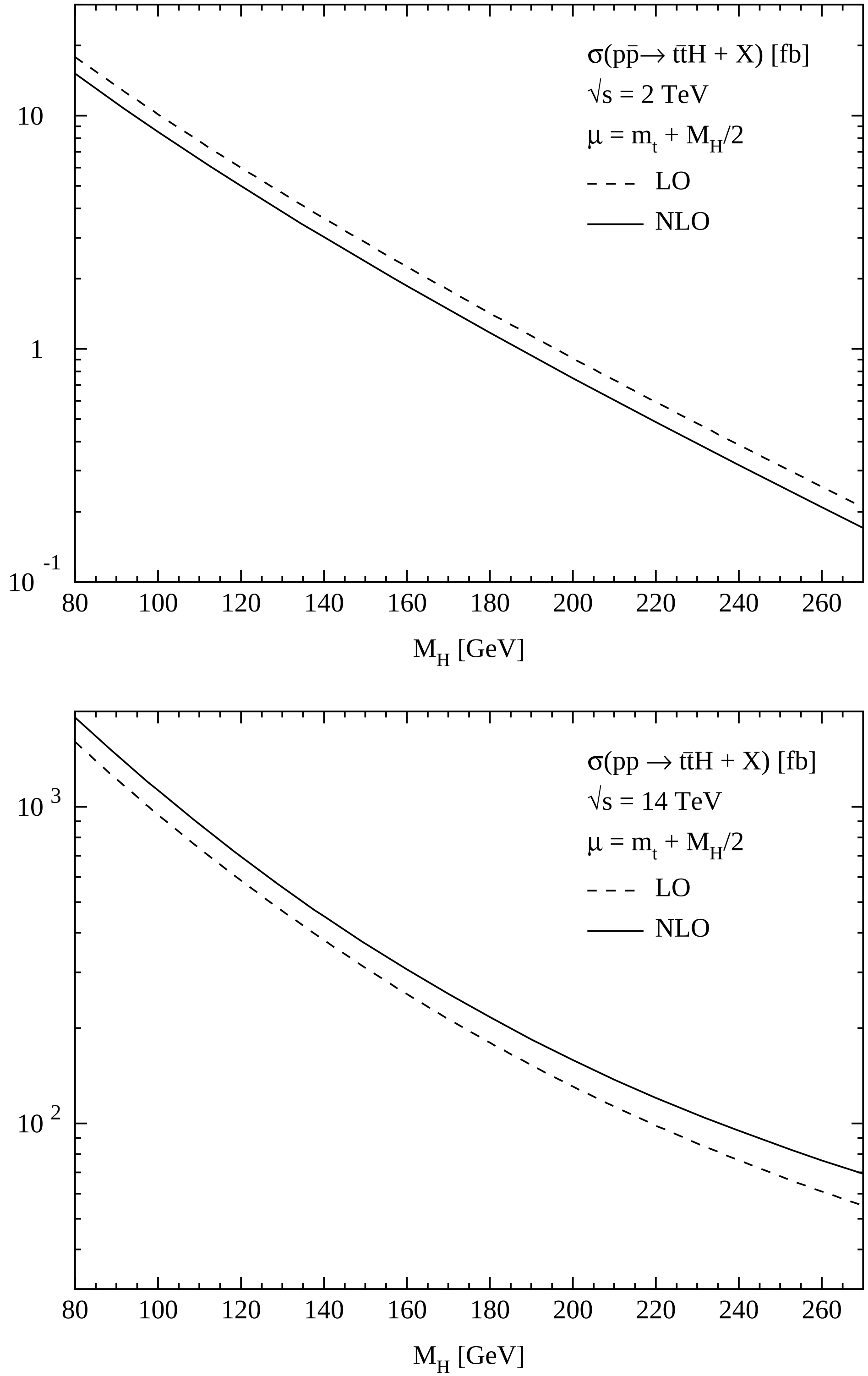
- **Higgs-strahlung**

NLO QCD (SM/MSSM)	$\sim +30$ % (Drell-Yan)	Han,Willenbrock;Baer eal; Ohnemus,Stirling	
NNLO QCD (SM/MSSM)	$\sim +5-10$ %	Hamberg,Van Neerven,Matsuura Brein,Djouadi,Harlander	$\Delta_{\text{theor}} \sim 5$ %
SUSY QCD: klein Djouadi, Spira	full EW(SM):-5-10%	Ciccolini,Dittmaier,Krämer	

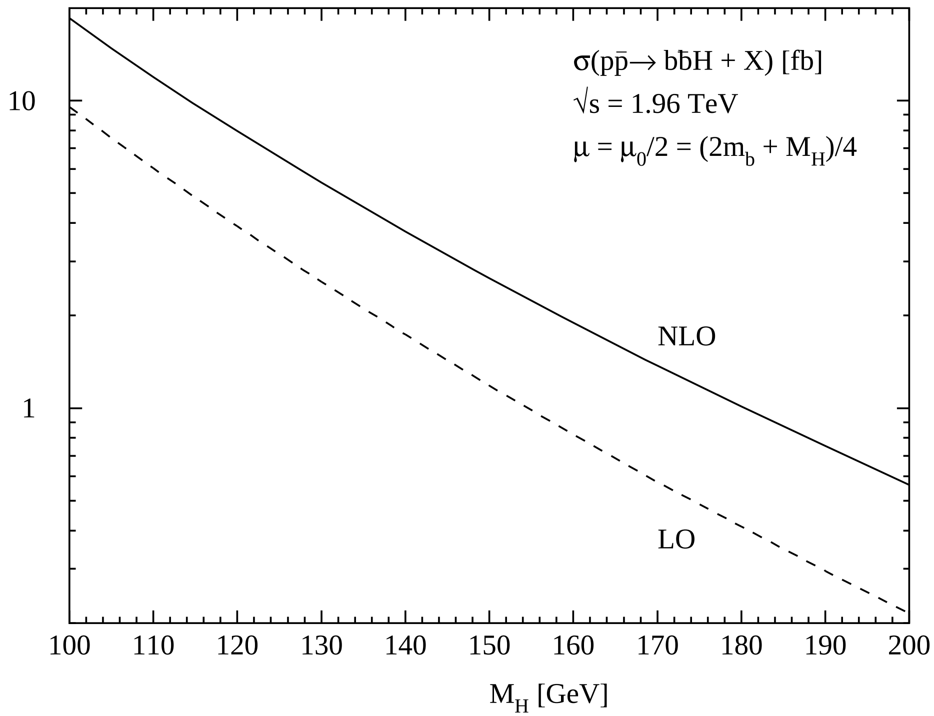
- **Associated production**

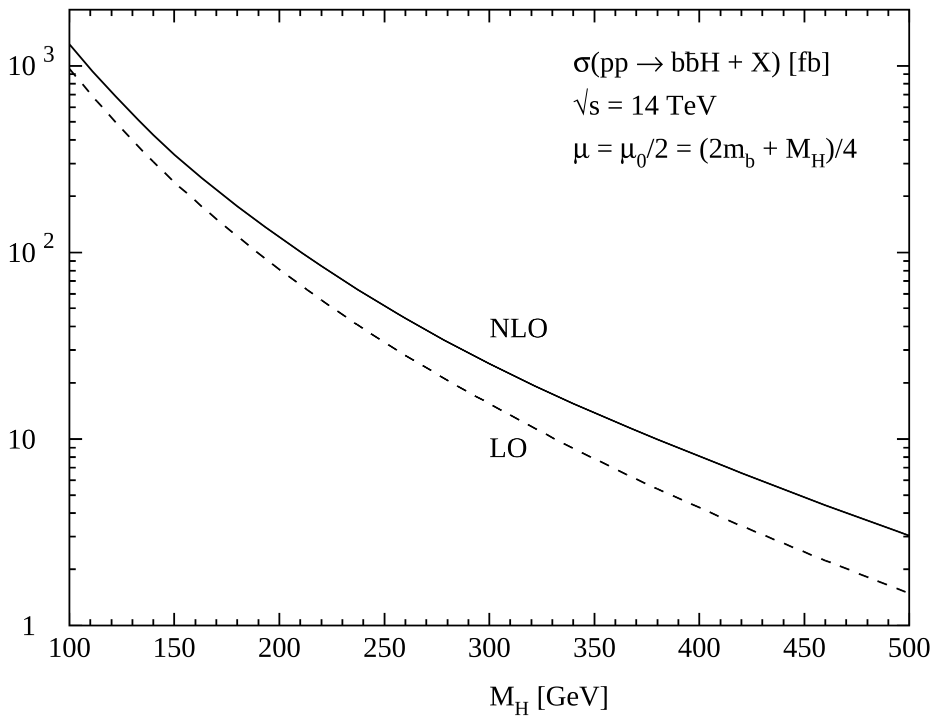
$b\bar{b}\Phi^0$	NLO	Dittmaier,Krämer,Spira, Walser;Dawson,Jackson, Reina,Wackeroth	$b\bar{b} \to \Phi^0$	NLO,NNLO	Dicus,Willenbrock;Stelzer et al.; Balazs et al.;Campbell et al.; Harlander,Kilgore;Kidonakis
t Beitr.	NNLO	Boudjema,Ninh		EW	Dittmaier,Krämer, Mück,Schlüter
	SUSY QCD	Gao et al.; Hollik,Rauch	$b\bar{b} \to \Phi^0$ $bg \to b\Phi^0$	SUSY QCD	Dittmaier eal;Dawson,Jackson
$t\bar{t}\Phi^0$	NLO QCD+20%	Beenakker et al.; Dawson et al.	SUSY QCD 20-30%		Peng et al.

- **Background** NLO QCD to $t\bar{t}b\bar{b}$ Bredenstein et al.; Bevilaqua eal et al.

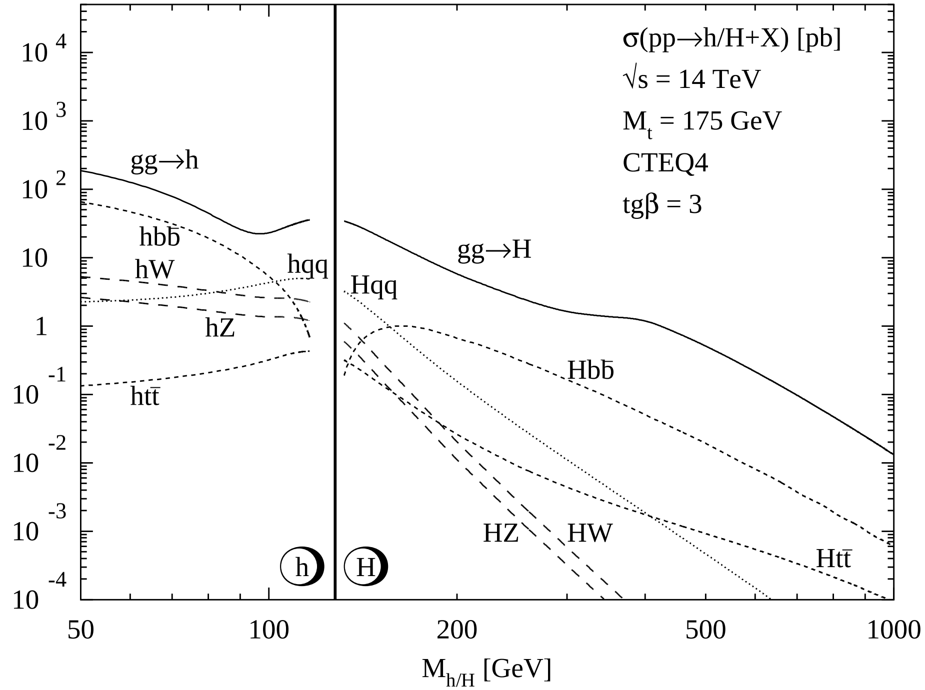


Beenakker,Dittmaier,Krämer,Plümper,Spira,Zerwas

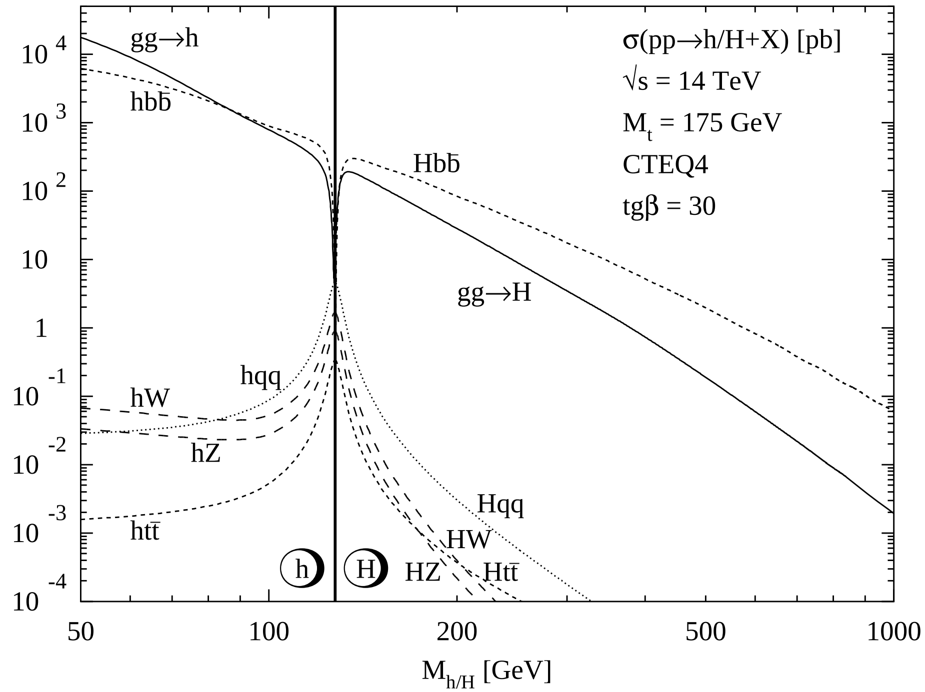




Dittmaier,Krämer,Spira



σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 3
gg→h
hbb̄
hW
hqq
hZ
htt̄
gg→H
Hqq
Hbb̄
HZ
HW
Htt̄
h
H
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
50
100
200
500
1000
M_h/H [GeV]



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h
H
10^4
10^3
10^2
10
1
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10^-3
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50
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200
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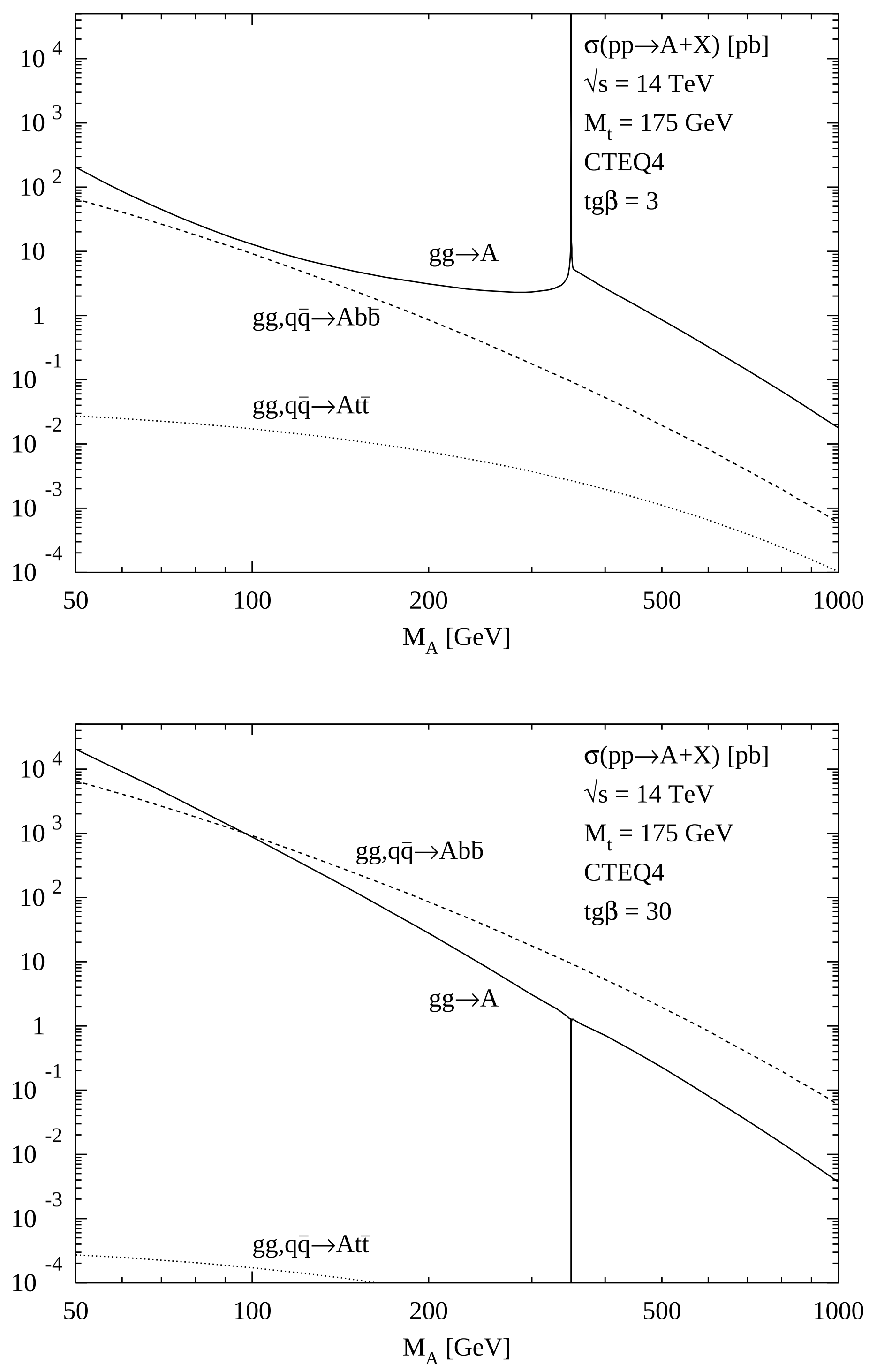
1000
M_h/H [GeV]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gg,qq̄→Abb̄
gg,qq̄→Att̄
M_A [GeV]
σ(pp→A+X) [pb]
√s = 14 TeV
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CTEQ4
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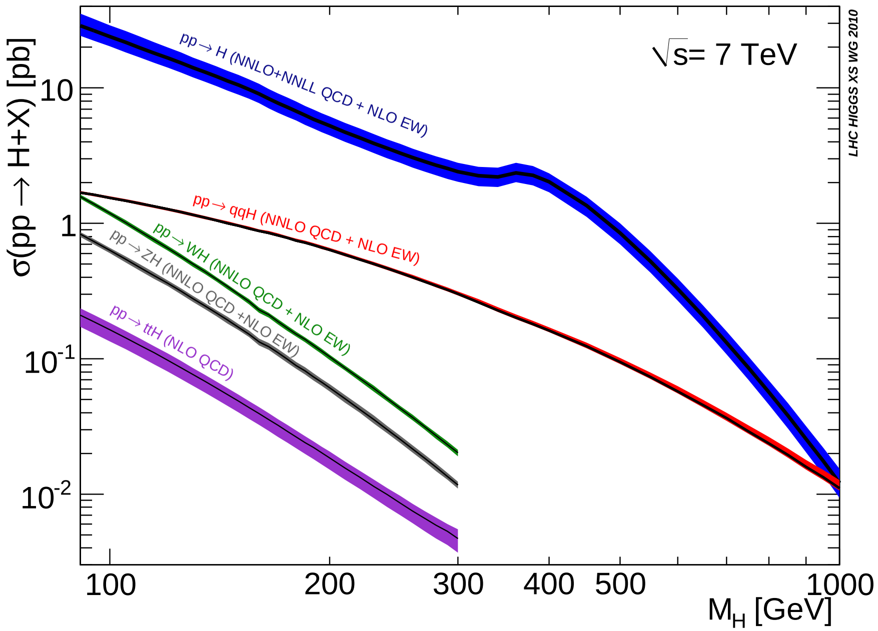
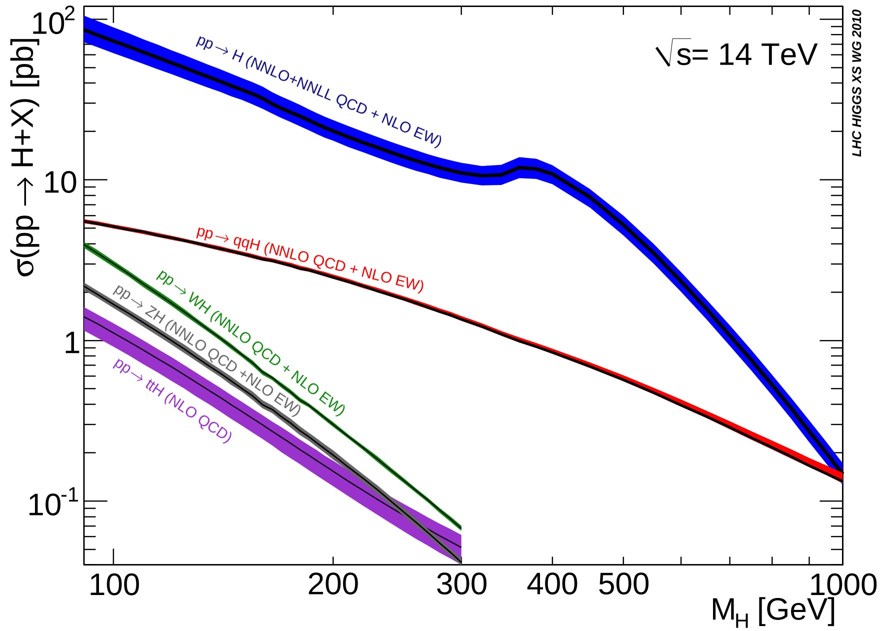
gg,qq̄→Abb̄
gg→A
gg,qq̄→Att̄
M_A [GeV]

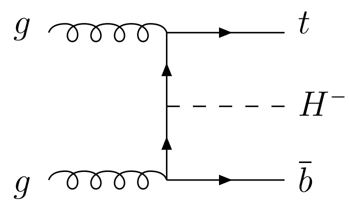
LHC Higgs cxn WG





Charged Higgs Production

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



Bawa eal; Borzumati eal; Belyaev eal

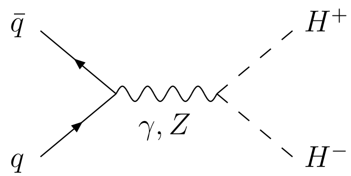
NLO QCD & SUSY QCD corrs.: $50 \ldots 100$ % Peng et al. Dittmaier et al.

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

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

NLO SUSY QCD & EW corrs. Zhu; Plehn; Berger eal; Gao et al.;Kidonakis;Beccaria eal

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



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

genuine SUSY QCD corrs.: small Djouadi,Spira

- **$pp \longrightarrow gg \longrightarrow H^+H^-$ (LO)** Willenbrock;Krause eal; Jiang eal;Brein,Hollik; Barrientos eal

$pp \longrightarrow b\bar{b} \longrightarrow H^+H^-$ Barrientos eal; Hong-Sheng eal

SUSY-QCD significant

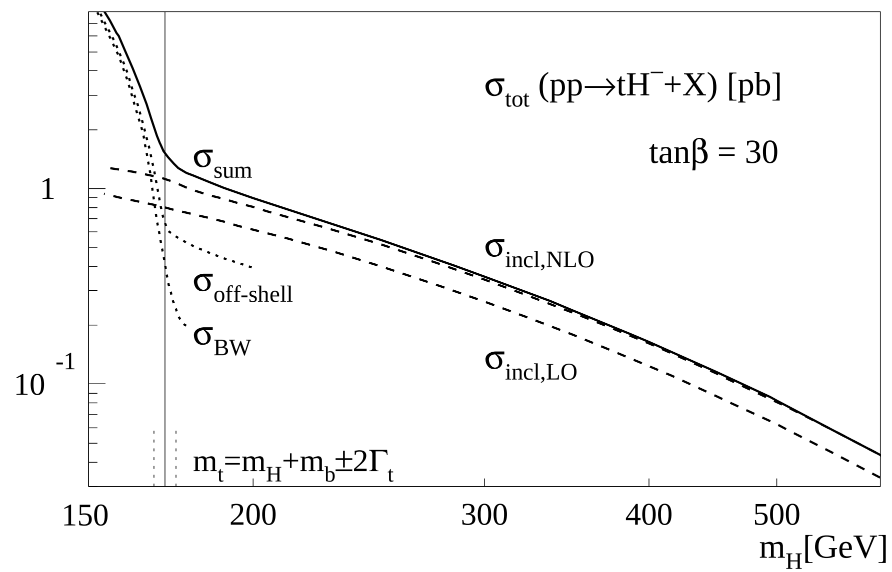
$pp \longrightarrow gg \longrightarrow H^+W^-$ + c.c. (LO) Barrientos et al.; Brein et al.

$pp \longrightarrow b\bar{b} \longrightarrow H^+W^-$+c.c. Dicus eal; Barrientos eal; Brein eal; Hollik eal; Zhao eal

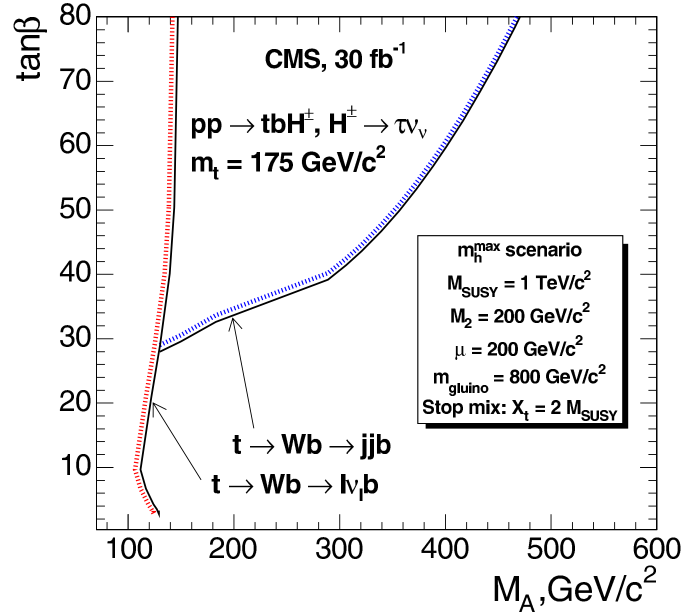
QCD corrs. moderate

Charged Higgs Boson discovery reach

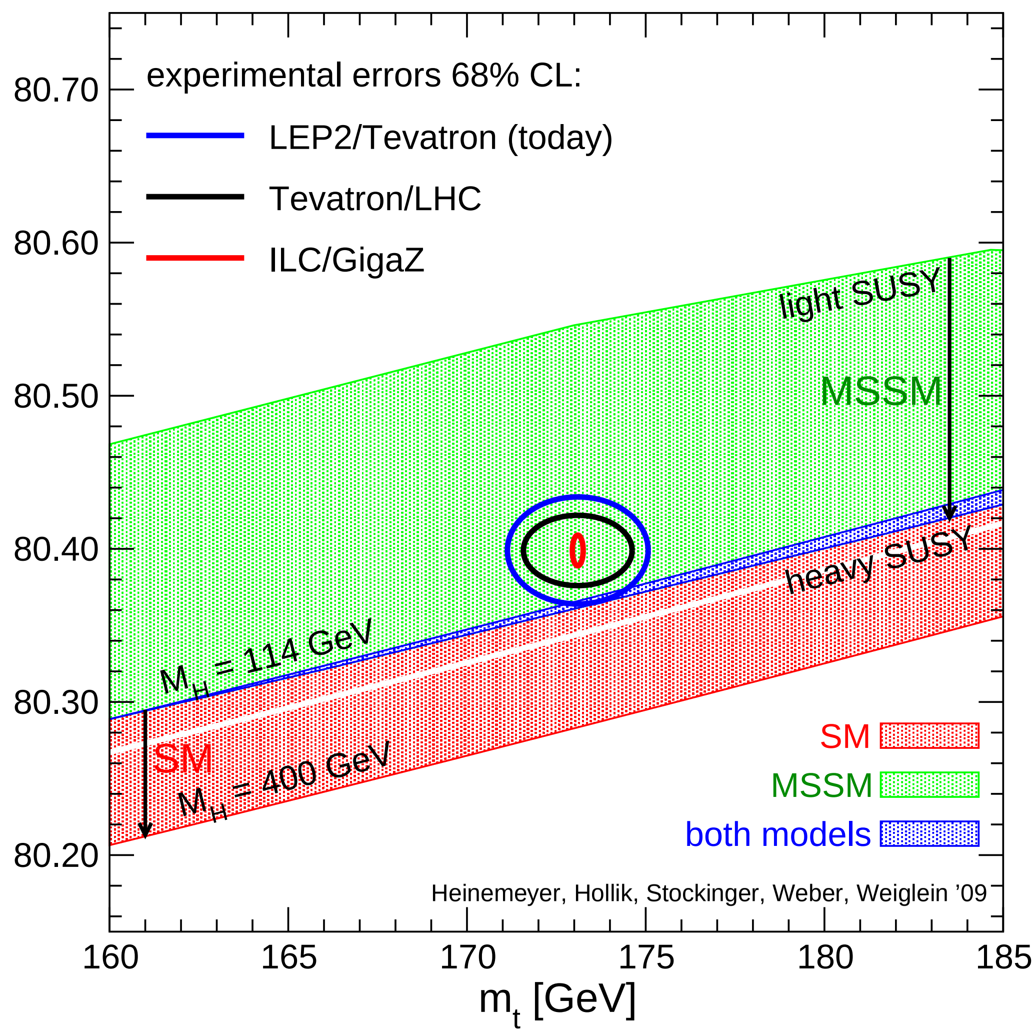
Berger et al.



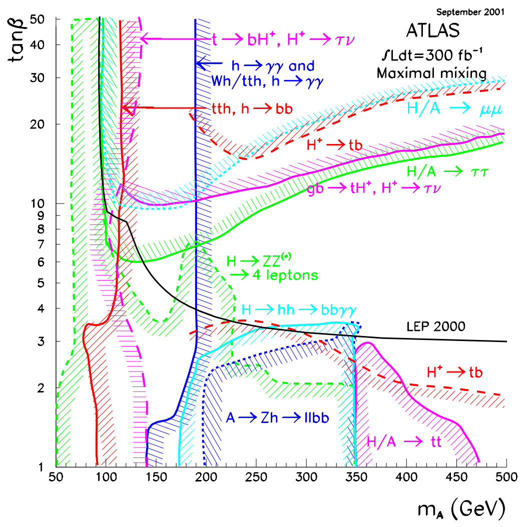
CMS



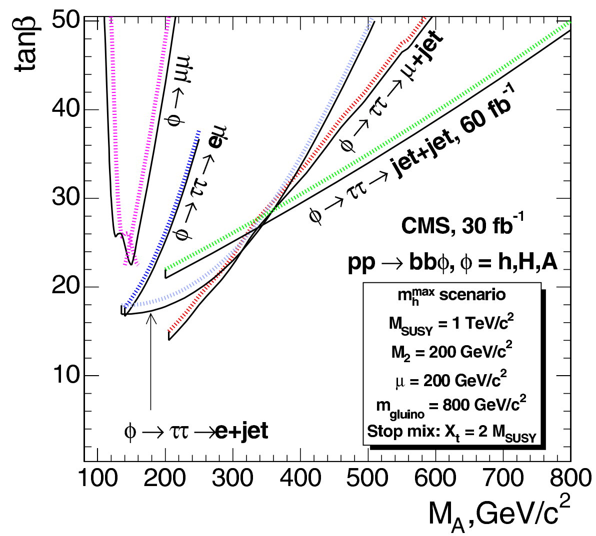
Higgs boson search: MSSM Higgs mass limits



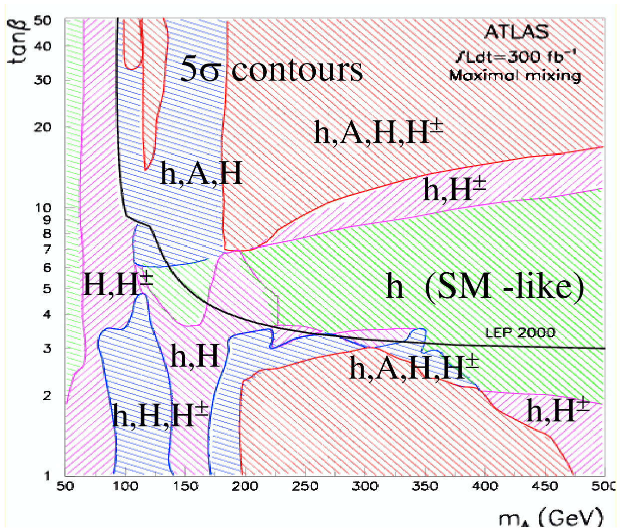
ATLAS



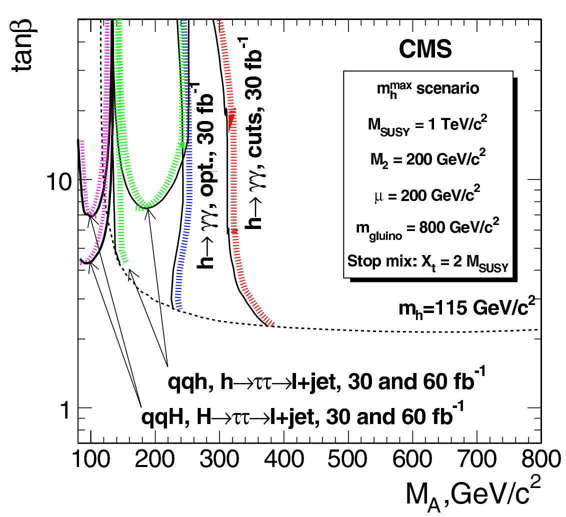
CMS



ATLAS

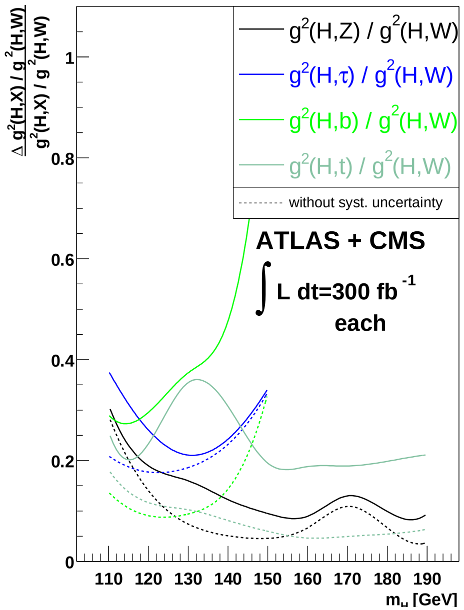


CMS

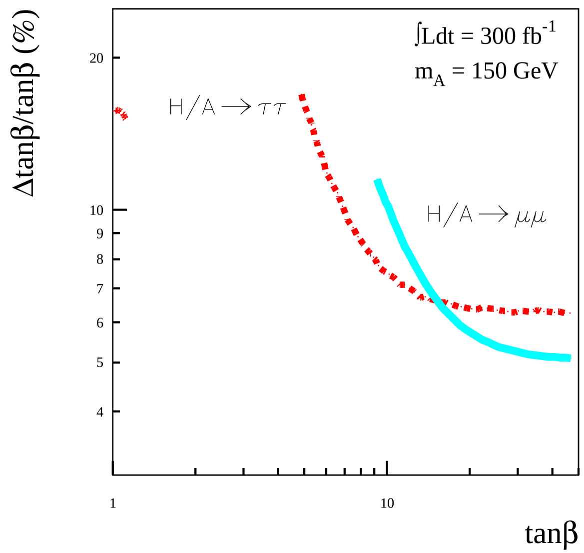


$\mathcal{E}$xpected $\mathcal{A}$ccuracies

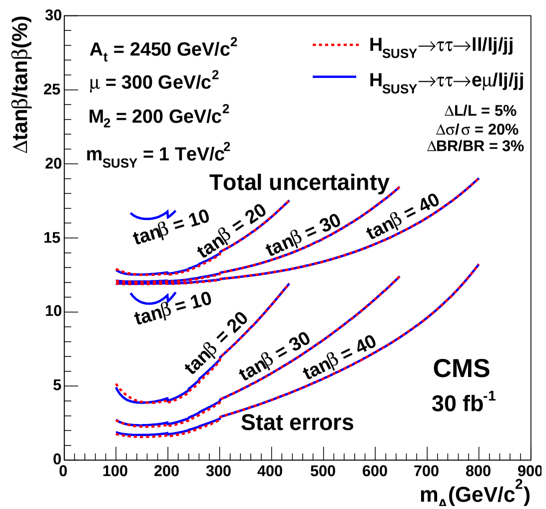
Dührssen et al.



ATLAS



Kinnunen eal

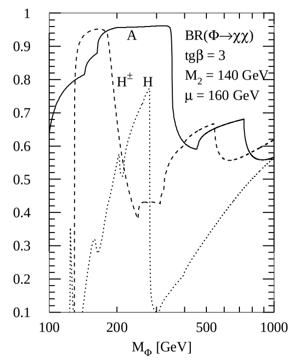


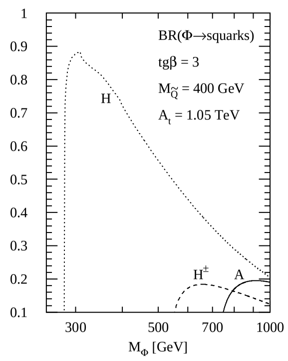
- $\frac{\delta M_H}{M_H} \sim 10^{-3}$
- $\frac{\delta \tan\beta}{\tan\beta} \sim 10 - 15\ \%$

$\mathcal{H}$iggs $\mathcal{S}$earch in SUSY Particle Final States

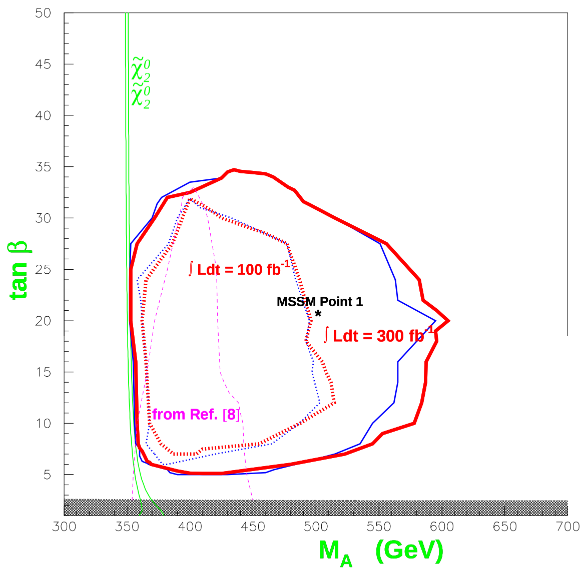
▷ Decays in gauginos and sfermions (3rd generation) important, if kinematically allowed.

HDECAY





▷ Four-lepton LHC events from MSSM Higgs boson decays into neutralino and chargino pairs
Event-generator level simulations w/ realistic detector effects and analyses of all significant bkgs



Bisset,Li,Kersting,Moortgat,Moretti

$(\mu, M_2, M_2, m_{\tilde{l}_{soft}}, m_{\tilde{\tau}_{soft}}) =$
$(-500, 180, 90, 250, 250)$ GeV

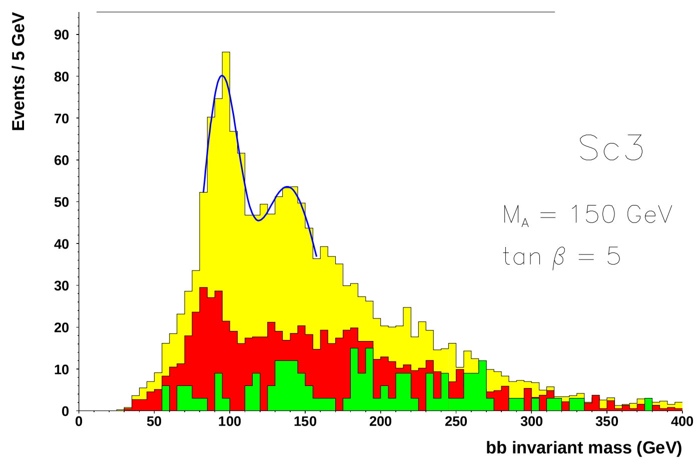
$\Phi^0 \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$ totally dominates

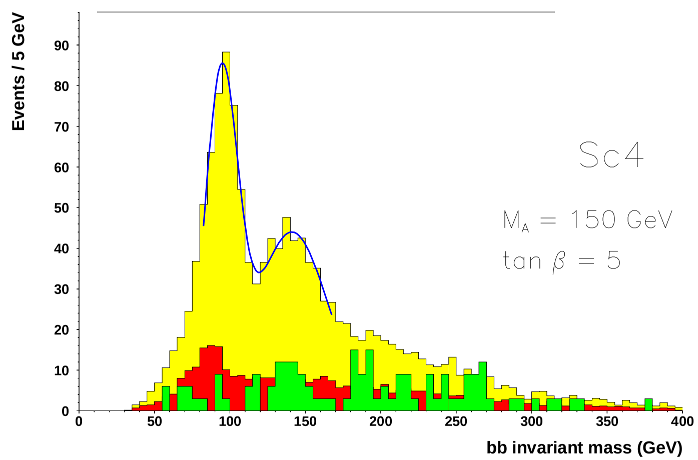
Part of difficult wedge region (only h discovery) can be covered

$\mathcal{H}$iggs $\mathcal{S}$earch in SUSY cascade decays

▷ Few scenarios considered Datta, Djouadi, Guchait, Moortgat

$$\begin{array}{llllll} \text{Sc3} & pp & \rightarrow & \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g} & \rightarrow & \chi_2^\pm, \chi_3^0, \chi_4^0 + X \\ & & & & \rightarrow & \chi_1^\pm, \chi_2^0, \chi_1^0 + h, H, A, H^\pm + X \\ \text{Sc4} & pp & \rightarrow & \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g} & \rightarrow & \chi_1^\pm, \chi_2^0 + X \\ & & & & \rightarrow & \chi_1^0 + H^\pm, h, H, A + X \end{array}$$



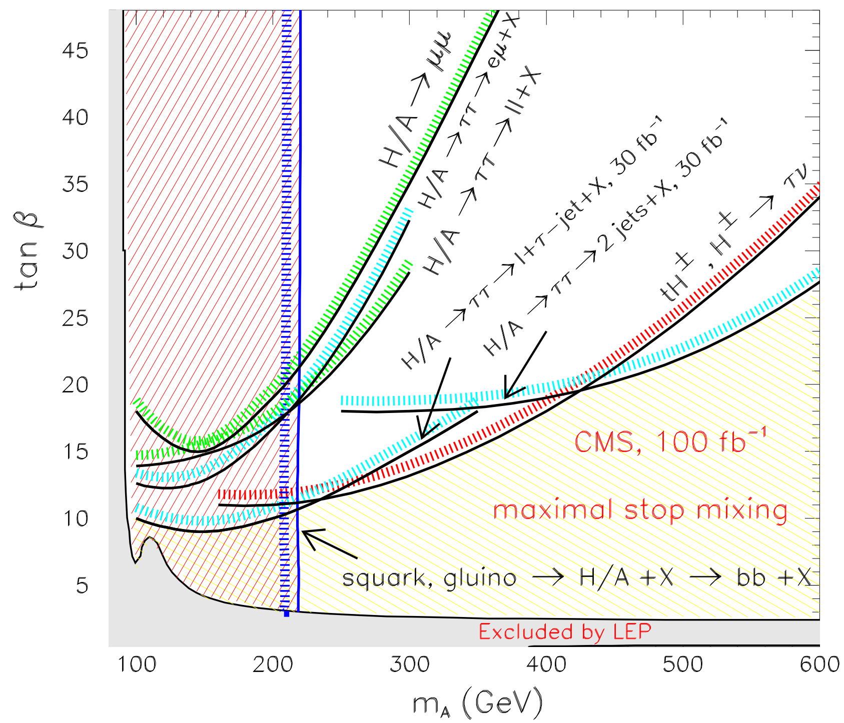


green - SM $t\bar{t}$ red - SUSY bkg

$\mathcal{H}$iggs $\mathcal{S}$earch in SUSY cascade decays

▷ Few scenarios considered Datta,Djouadi,Guchait,Moortgat

$$\begin{array}{llllll}
\text{Sc3} & pp & \to & \tilde g\tilde g, \tilde q\tilde q, \tilde q\tilde q^*, \tilde q\tilde g & \to & \chi_2^\pm, \chi_3^0, \chi_4^0 + X \\
 & & & & \to & \chi_1^\pm, \chi_2^0, \chi_1^0 + h, H, A, H^\pm + X \\
\text{Sc4} & pp & \to & \tilde g\tilde g, \tilde q\tilde q, \tilde q\tilde q^*, \tilde q\tilde g & \to & \chi_1^\pm, \chi_2^0 + X \\
 & & & & \to & \chi_1^0 + H^\pm, h, H, A + X
\end{array}$$



Difficult region of low M_A and low $\tan\beta$ can be explored

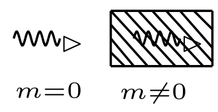
Experimental verification of the Higgs mechanism

Higgs mechanism:

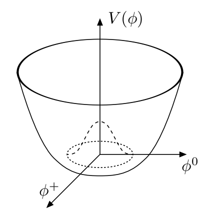
Creation of particle masses without violating gauge principles

Test of the Higgs mechanism

- Discovery – m
- Interaction with a scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



- Spin- and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$

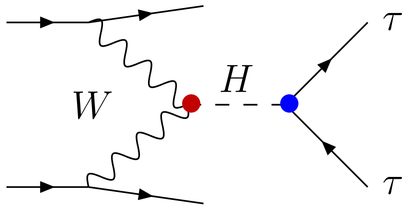


$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{C}$ouplings

Strategy

Combination of the Higgs production and decay channels $\Rightarrow$ Higgs decay rates, absolute couplings

E.g.:



$\sim \Gamma_{WW}\ \text{BR}(H \to \tau\tau)$

Problem

- total Higgs production cross section not measurable
- some Higgs decay channels not observable

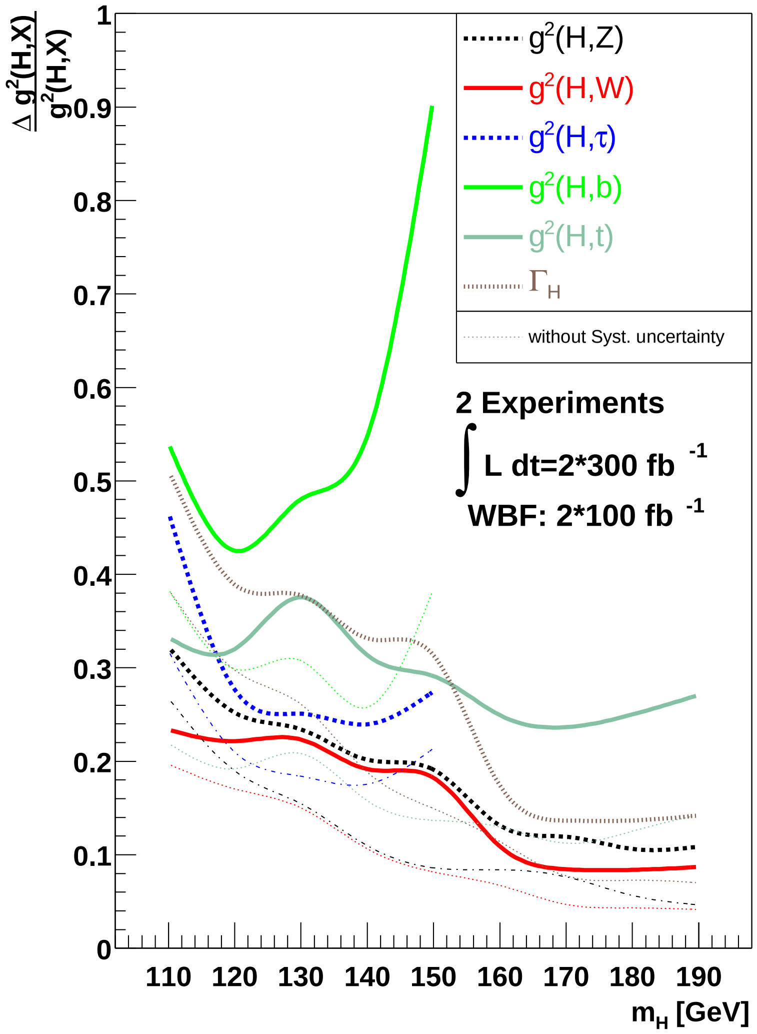
$\Rightarrow$ only ratios of couplings are measurable

Ansatz

Mild theoretical assumptions $\Rightarrow$ total Higgs width and absolute couplings

- Light Higgs with SM-like couplings   Kinnunen,Nikitenko,Richter-Was,Zeppenfeld
- General two-Higgs doublet model   Dührssen,Heinemeyer,Logan,Rainwater,Weiglein, Zeppenfeld

Dührssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld



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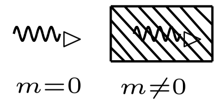
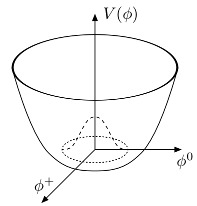


- Spin- and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$



Higgs boson quantum numbers

Quantum numbers of the Higgs boson: J^{PC}

- J spin
- P parity
- C charge conjugation

$\diamond$ $\gamma\gamma \to H$ or $H \to \gamma\gamma \rightsquigarrow J \neq 1$.

Spin and CP quantum numbers: angular correlations, threshold effects

- angular correlations in production: Hjj in vector boson fusion, gluon gluon fusion

  Plehn,Rainwater,Zeppenfeld; Hankele,Klämke,Zeppenfeld Campanario eal; Del Duca eal

- angular correlations in Higgs decays, e.g. $H \to ZZ \to l^+l^-l^+l^-$

  Dell'Aquila,Nelson; Kramer,Kühn,Stong,Zerwas; Choi,Miller,MMM,Zerwas;Bluj; Buszello,Fleck,Marquard,van der Bij; Englert,Hackstein,Spannowsky: $lljj$

  CP-violation

  Buszello,Marquard,van der Bij Godbole,Miller,MMM

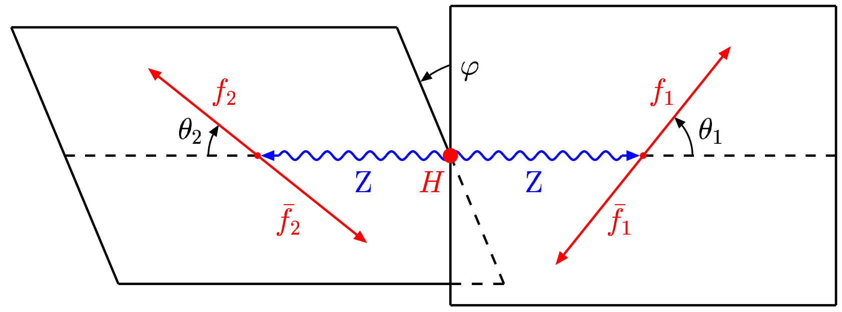
- below ZZ threshold: angular correlations, threshold effects

  Choi,Miller,MMM,Zerwas Buszello,Marquard,van der Bij

Higgs boson quantum numbers

◇ Determination of spin and parity in

$$gg \to H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$$



◇ Helicity methods: general HZZ coupling for arbitrary spin and parity

Differential distributions

◇ Double polar angular distribution ($\mathcal{CP}$ invariant theory)

$$\frac{d\Gamma_H}{d\cos\theta_1 d\cos\theta_2} \sim \sin^2\theta_1 \sin^2\theta_2 \, |\mathcal{T}_{00}|^2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)\left[|\mathcal{T}_{11}|^2 + |\mathcal{T}_{1,-1}|^2\right]$$
$$+(1+\cos^2\theta_1)\,\sin^2\theta_2\,|\mathcal{T}_{10}|^2 + \sin^2\theta_1\,(1+\cos^2\theta_2)\,|\mathcal{T}_{01}|^2$$
$$+2\,\eta_1\eta_2\cos\theta_1\cos\theta_2\left[|\mathcal{T}_{11}|^2 - |\mathcal{T}_{1,-1}|^2\right]$$

SM: $\mathcal{T}_{00} = M_H^2/(2M_Z^2) - 1,\ \mathcal{T}_{11} = -1,\ \mathcal{T}_{10} = \mathcal{T}_{01} = \mathcal{T}_{1,-1} = 0$

$\eta_i = 2v_i a_i/(v_i^2 + a_i^2),\ v_i = 2I_{3i} - 4e_i \sin^2\theta_W,\ a_i = 2I_{3i}$

◇ Azimuthal angular distribution ($\mathcal{CP}$ invariant theory)

$$\frac{d\Gamma_H}{d\varphi} \sim |\mathcal{T}_{11}|^2 + |\mathcal{T}_{10}|^2 + |\mathcal{T}_{1,-1}|^2 + |\mathcal{T}_{01}|^2 + |\mathcal{T}_{00}|^2/2$$
$$+\eta_1\eta_2\left(\frac{3\pi}{8}\right)^2 \Re\mathrm{e}(\mathcal{T}_{11}\mathcal{T}_{00}^* + \mathcal{T}_{10}\mathcal{T}_{0,-1}^*)\cos\varphi + \frac{1}{4}\Re\mathrm{e}(\mathcal{T}_{11}\mathcal{T}_{-1,-1}^*)\cos 2\varphi$$

Determination of spin and parity

- **$M_H < 2M_Z$:** $d\Gamma/dM_*^2 \sim \beta$ for $\mathcal{J}^{\mathcal{P}} = 0^+$
  - ◇ $d\Gamma/dM_*^2$ rules out $\mathcal{J}^{\mathcal{P}} = 0^-, 1^-, 2^-, 3^\pm, 4^\pm$
  - ◇ $d\Gamma/dM_*^2$ and no $[1+\cos^2\theta_1]\sin^2\theta_2$
    $[1+\cos^2\theta_2]\sin^2\theta_1$ rules out $\mathcal{J}^{\mathcal{P}} = 1^+, 2^+$

- **$M_H > 2M_Z$:**
  - ◇ odd normality: $\mathcal{J}^{\mathcal{P}} = 0^-, 1^+, 2^-, 3^+, \ldots$ excluded by non-zero $\sin^2\theta_1 \sin^2\theta_2$
  - ◇ even normality: $\mathcal{J}^{\mathcal{P}} = 1^-, 3^-, \ldots$ excluded by non-zero $\sin^2\theta_1 \sin^2\theta_2$
  - ◇ rule out $\mathcal{J}^{\mathcal{P}} = 2^+, 4^+$ with:
    $\frac{d\sigma}{d\cos\theta}[gg/\gamma\gamma \to H \to ZZ]$ only isotropic for spin 0

- Caveat: HO corrections to $H \to WW/ZZ \to 4f$ distort the shapes of the distributions

Bredenstein, Denner, Dittmaier, Walser

$\mathcal{CP}$ Violation

- **$\mathcal{CP}$ Violation:** Examine behaviour with

  most general vertex $=$
  sum of even and odd normality tensors

- **Case spin 0:** $p = p_{Z_1} + p_{Z_2}$, $k = p_{Z_1} - p_{Z_2}$

$$\boxed{\text{Vertex } HZZ: \quad \frac{igM_Z}{\cos\theta_W}\left[a\, g_{\mu\nu} + \frac{b}{M_Z^2}\, p_\mu p_\nu + i\, \frac{c}{M_Z^2}\, \epsilon_{\mu\nu\alpha\beta}\, p^\alpha k^\beta \right]}$$

  ◇ $a = 1,\ b = c = 0$: SM

  ◇ $(a \neq 0 \wedge c \neq 0) \quad \vee \quad (b \neq 0 \wedge c \neq 0)$: $\mathcal{CP}$-violation

- **Observables sensitive to $\mathcal{CP}$**

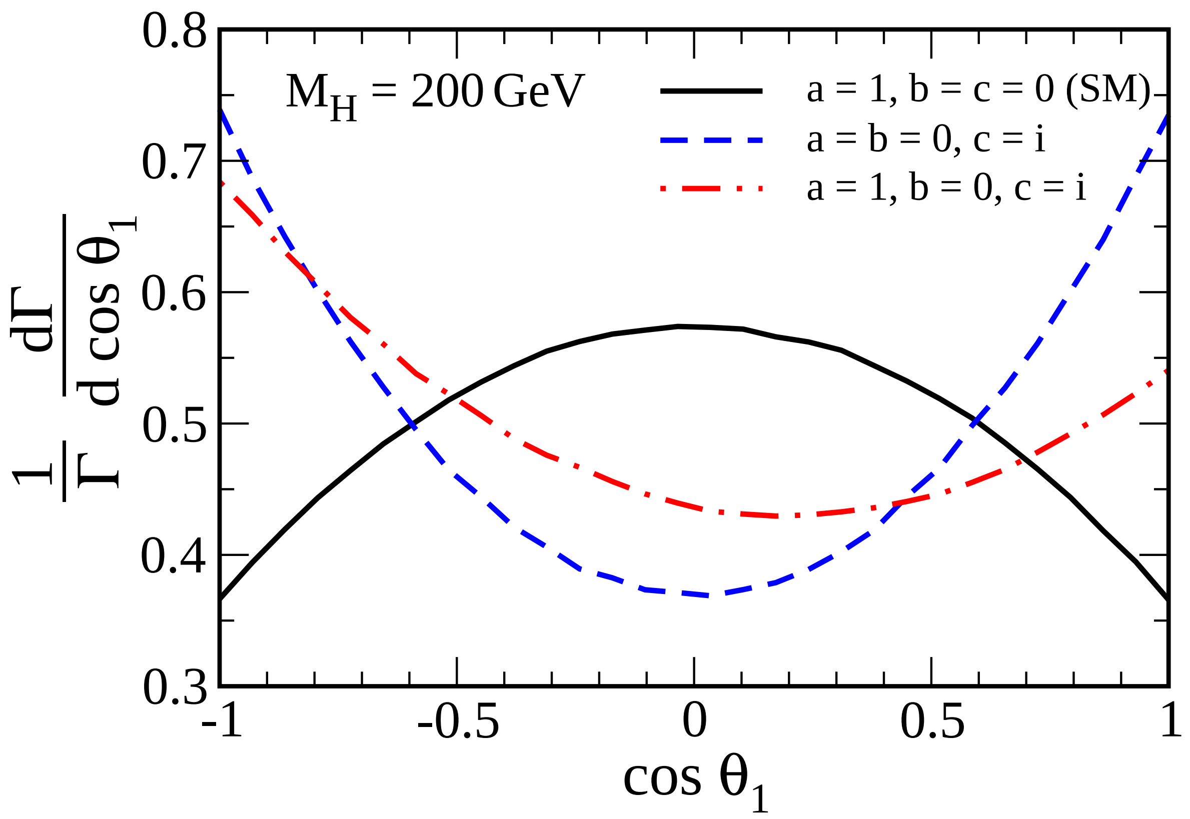
  ◇ angle ϕ between oriented Z decay planes in the Higgs rest frame

  ◇ cos of the fermion polar angle θ in the Z rest frame

Higgs boson quantum numbers

angular distribution in $\cos\theta$

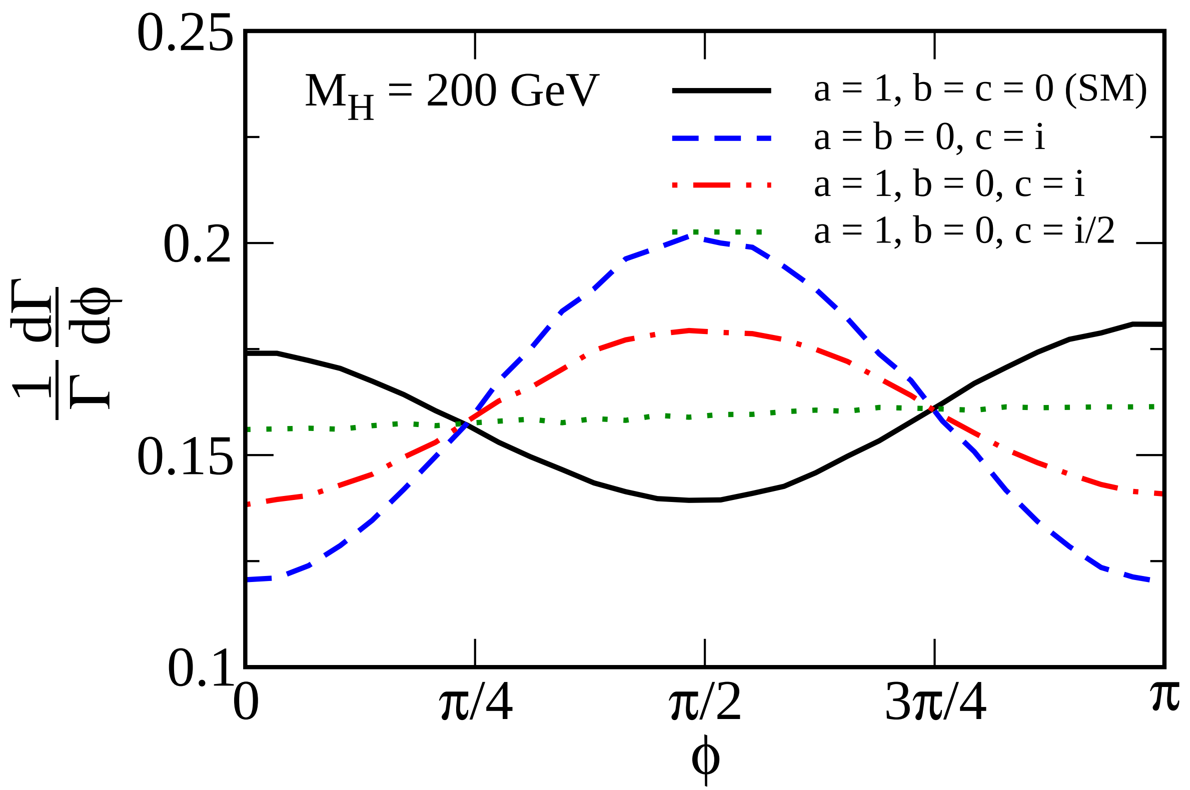
Godbole,Miller,MMM



Higgs boson quantum numbers

angular distribution in ϕ

Godbole,Miller,MMM



Higgs boson quantum numbers

Asymmetries sensitive to $\mathcal{CP}$

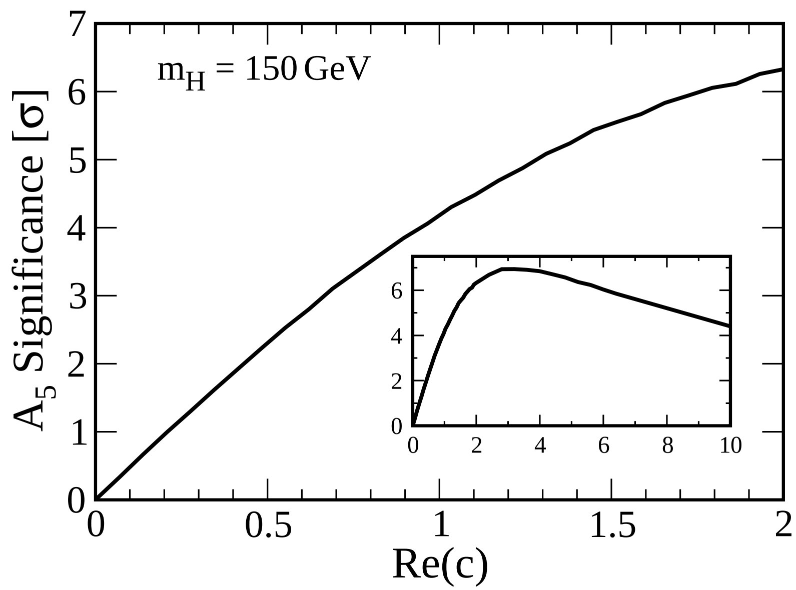
Godbole,Miller,MMM

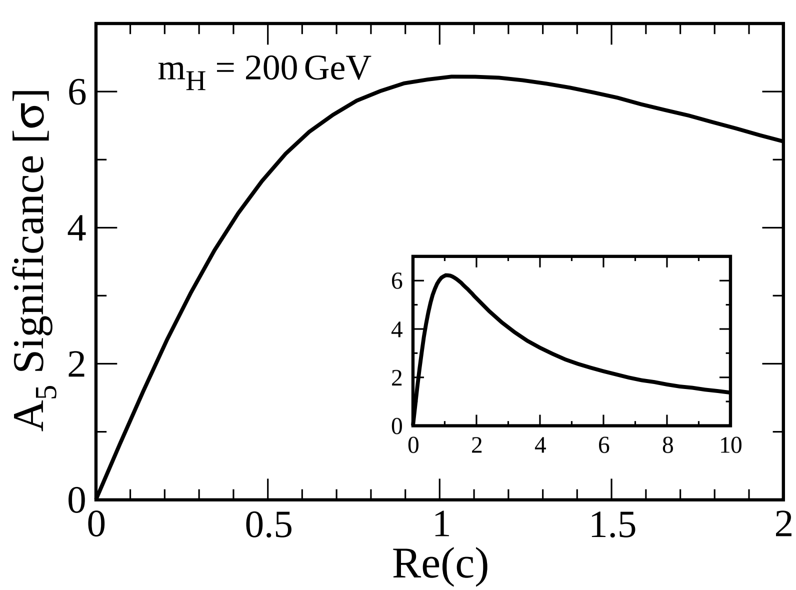
◇ Example:

$$O_5 = \sin\theta_1 \sin\theta_2 \sin\phi[\sin\theta_1 \sin\theta_2 \cos\phi - \cos\theta_1 \cos\theta_2]$$

$$O_5 = \frac{[(\vec{p}_{4H} \times \vec{p}_{3H}) \cdot \vec{p}_{1H}][(\vec{p}_{1Z} - \vec{p}_{2Z}) \cdot \vec{p}_{3Z}]}{|\vec{p}_{3H} + \vec{p}_{4H}||\vec{p}_{3Z} - \vec{p}_{4Z}|^2|\vec{p}_{1Z} - \vec{p}_{2Z}|^2/8}$$

$$\mathcal{A}_5 = \frac{\Gamma(O_5 > 0) - \Gamma(O_5 > 0)}{\Gamma(O_5 > 0) + \Gamma(O_5 > 0)}$$





Higgs boson quantum numbers

gluon gluon fusion	CP-even Htt can be distinguished from CP-odd at $> 5\sigma$ ($M_H = 160$ GeV)	Klämke,Zeppenfeld
$H \to ZZ \to 4l$	consistency with SM; $0^-/1^\pm$ excluded ($\int \mathcal{L} = 100\text{fb}^{-1}$, $M_H = 200/\gtrsim 230$ GeV)	Buszello,Fleck, Marquard,van der Bij
CMS: $H \to ZZ \to 4l$	scalar, pseudoscalar can be distinguished at 3σ ($\int \mathcal{L} = 60\text{fb}^{-1}$, $M_H = 300$ GeV)	CMS
ALTAS: $H \to ZZ \to 4l$	strong limits to anomalous couplings	Buszello,Marquard, van der Bij
	$\triangleright$ CP-odd excluded at 8.7σ (2.9σ) for $M_H = 200$ GeV (130 GeV), $\int \mathcal{L} = 100\text{fb}^{-1}$	Strässner
	$\triangleright$ b/c w/ precision 1 (0.35/0.2) for $M_H = 130$ GeV (higher M_H)	
	$\triangleright$ include info from measured signal cxn	
	$\rightsquigarrow$ further increase in precision	

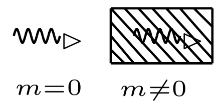
Experimental verification of the Higgs mechanism

Higgs mechanism:

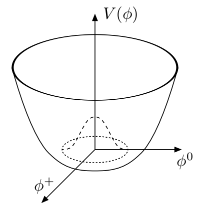
Creation of particle masses without violating gauge principles

Test of the Higgs mechanism

- Discovery – m
- Interaction with a scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



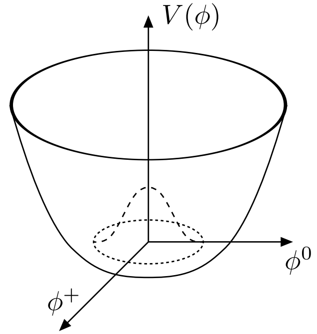
- Spin- and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$

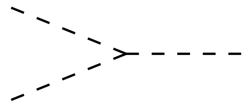
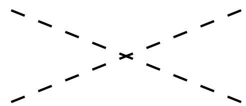


$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$ouplings

The Higgs potential:

$$\boxed{V(H) = \frac{1}{2!}\lambda_{HH}H^2 + \frac{1}{3!}\lambda_{HHH}H^3 + \frac{1}{4!}\lambda_{HHHH}H^4}$$



$\mathcal{T}$rilinear coupling	$\lambda_{HHH} = 3\frac{M_H^2}{v}$	
$\mathcal{Q}$uartic coupling	$\lambda_{HHHH} = 3\frac{M_H^2}{v^2}$	

$\mathcal{M}$easurement of the Higgs self-couplings and $\mathcal{R}$econstruction of the Higgs potential } $\mathcal{E}$xperimental verification $\mathcal{O}$f the scalar sector of the $\mathcal{H}$iggs mechanism

Determination of the Higgs self-couplings at colliders:

$\boldsymbol{\lambda_{HHH}}$ via Higgs pair production

$\boldsymbol{\lambda_{HHHH}}$ via triple Higgs production

Higgs-strahlung, WW/ZZ fusion, gg fusion

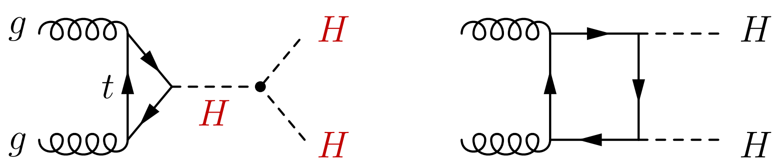
$\mathcal{T}$he $\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling at the $\mathcal{LHC}$

Determination of λ_{HHH} at the LHC

Djouadi,Kilian,MMM,Zerwas;
Lafaye,Miller,Moretti,MMM

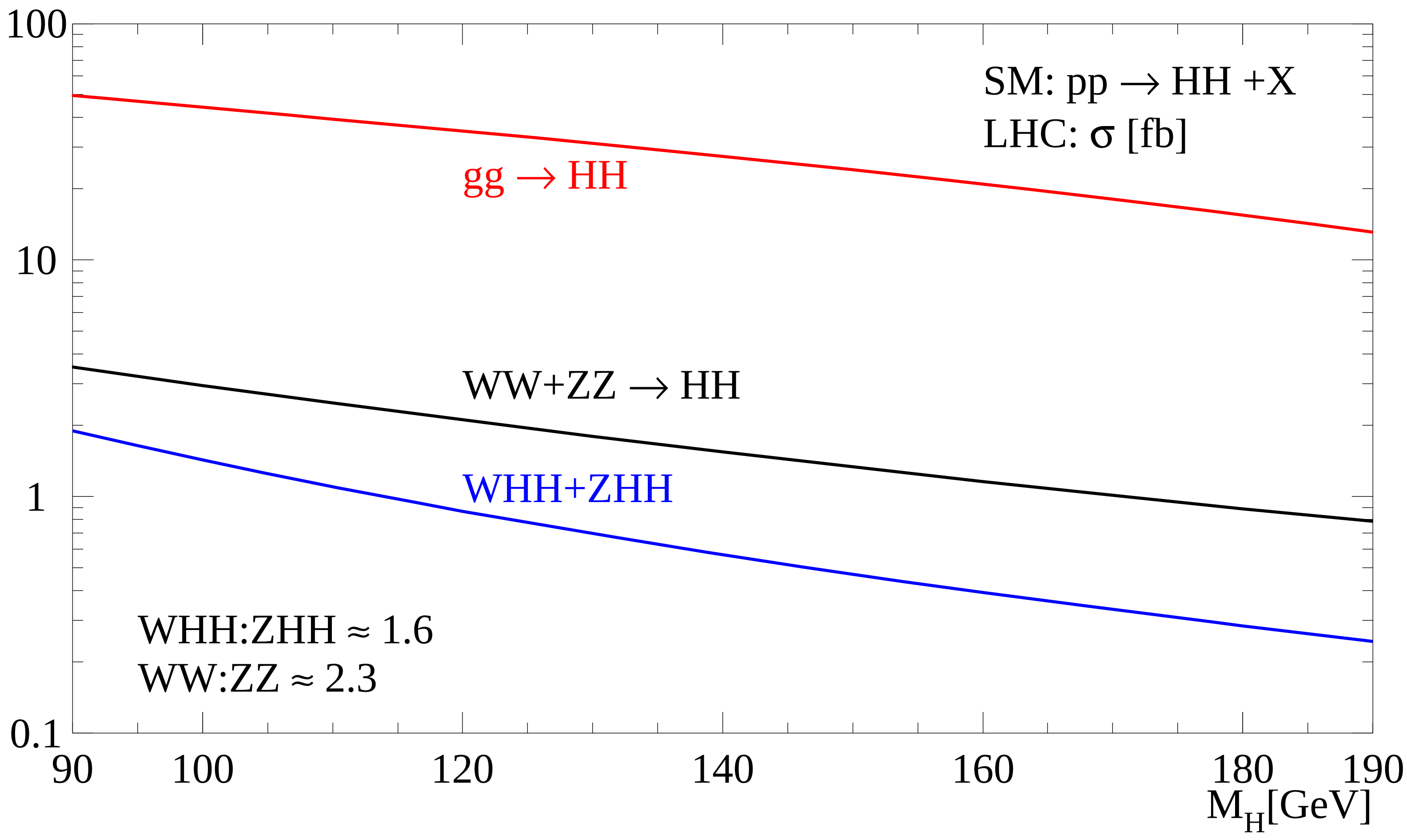
double Higgs-strahlung:	$q\bar{q} \longrightarrow W/Z + HH$	Barger,Han,Phillips
WW/ZZ fusion:	$qq \longrightarrow qq + HH$	Dicus,Kallianpur,Willenbrock Abbasabadi,Repko,Dicus,Vega Dobrovolskaya,Novikov Eboli,Marques,Novaes,Natale
gluon gluon fusion:	$gg \longrightarrow HH$	Glover,van der Bij Plehn,Spira,Zerwas Dawson,Dittmaier,Spira

gluon gluon fusion - dominant process



Double $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{P}$roduction at the $\mathcal{LHC}$

Djouadi,Kilian,MMM,Zerwas



$\mathcal{E}$xpected $\mathcal{A}$ccuracies in λ_{HHH} at the $\mathcal{LHC}$

small signal + large QCD background $\rightsquigarrow$ challenge!

Baur,Plehn,Rainwater

$M_H < 140$ GeV: $gg \to HH \to b\bar{b}\gamma\gamma$:

- SLHC [$\int \mathcal{L} = 6$ ab^{-1}]:

  $M_H = 120$ GeV $\quad \lambda_{HHH} = 0$ exclusion $\quad$ at 90% CL

- VLHC [$\sqrt{s} = 200$ TeV]:

  $M_H = 120$ GeV: $\quad \delta\lambda_{HHH}/\lambda_{HHH} = 20 - 40\%$ $\quad$ at 1 σ

Gianotti et al.;Blondel,Clark,Mazzucato
Baur,Plehn,Rainwater
Dahlhoff

$M_H > 140$ GeV: $gg \to HH \to W^+W^-W^+W^-$:

- LHC [$\int \mathcal{L} = 300$ fb^{-1}]:

  $150 \lesssim M_H \lesssim 200$ GeV: $\quad \lambda_{HHH} = 0$ exclusion $\quad$ at 95% CL

- SLHC [$\int \mathcal{L} = 3$ ab^{-1}]:

  $150 < M_H < 200$ GeV $\quad \delta\lambda_{HHH}/\lambda_{HHH} = 20 - 30\%$ $\quad$ at 1 σ

Higgs self-couplings in the MSSM

Djouadi,Kilian,MM,Zerwas;Pandita,Osland;Boudjema,Semenov

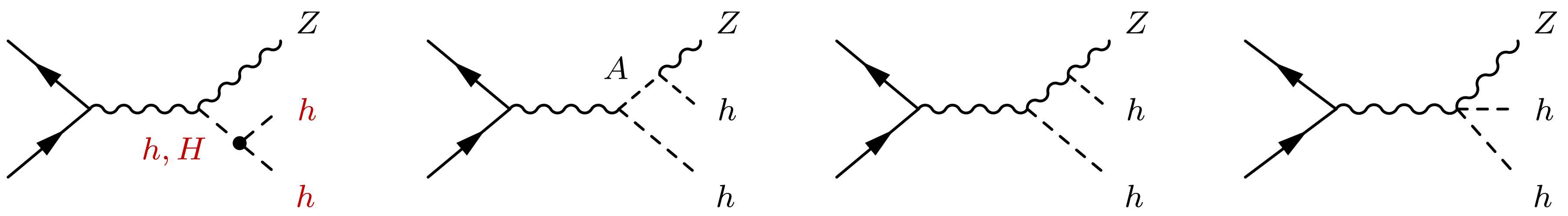
6 CP-invariant trilinear couplings between neutral Higgs bosons

λ_{hhh}	λ_{Hhh}	λ_{HHh}
λ_{HHH}	λ_{hAA}	λ_{HAA}

Determination of $\lambda_{3\Phi}$ at e^+e^- colliders

- ⋆ WW/ZZ fusion
- ⋆ double Higgs-strahlung
- ⋆ triple Higgs production

For example $e^+e^- \to Zhh$



sensitive to $\lambda_{hhh}, \lambda_{Hhh}$

Sensitivity regions

Processes sensitive to $\lambda_{3\Phi}$

λ	double Higgs−strahlung Zhh	ZHh	ZHH	ZAA	triple Higgs−production Ahh	AHh	AHH	AAA
hhh	$\times$				$\times$			
Hhh	$\times$	$\times$			$\times$	$\times$		
HHh		$\times$	$\times$			$\times$	$\times$	
HHH			$\times$				$\times$	
hAA				$\times$	$\times$	$\times$		$\times$
HAA				$\times$		$\times$	$\times$	$\times$

system can be solved for all λ apart from discrete ambiguities

Sensitivity regions

Djouadi,Kilian,MM,Zerwas

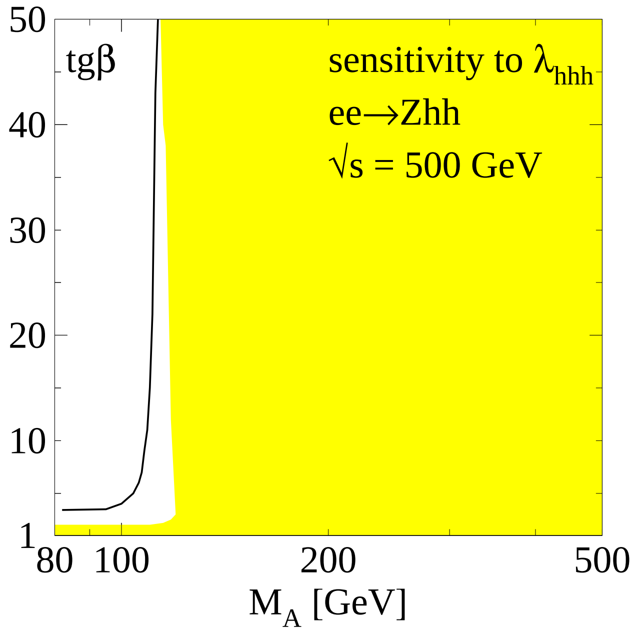
(i) $\sigma[\lambda] > 0.01$ fb [and 0.1 fb]

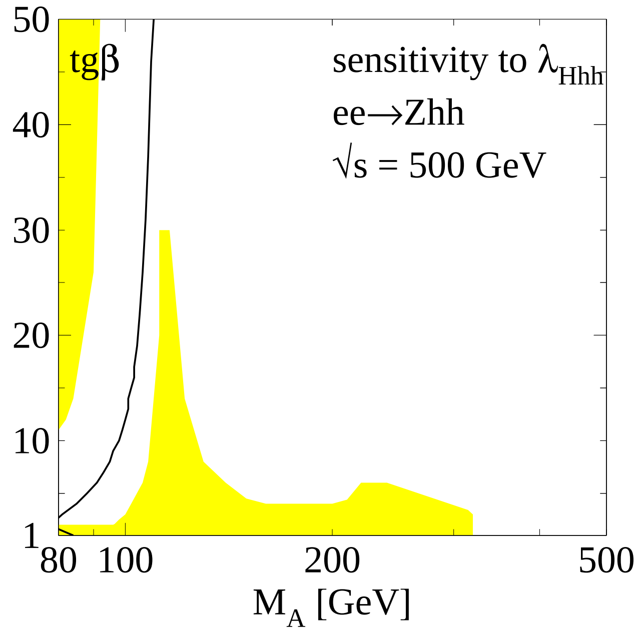
(ii) $\mathrm{eff}\{\lambda \to 0\} > 2$ st.dev. for $\int \mathcal{L} = 2$ ab^{-1}

Sensitivity regions for $\lambda_{hhh}, \lambda_{Hhh}$

Processes sensitive to: λ_{hhh} : Zhh, Ahh

λ_{Hhh} : Zhh, ZHh, Ahh





regions without sensitivity: $\lambda \sin(\beta-\alpha), \lambda \cos(\beta-\alpha)$ small

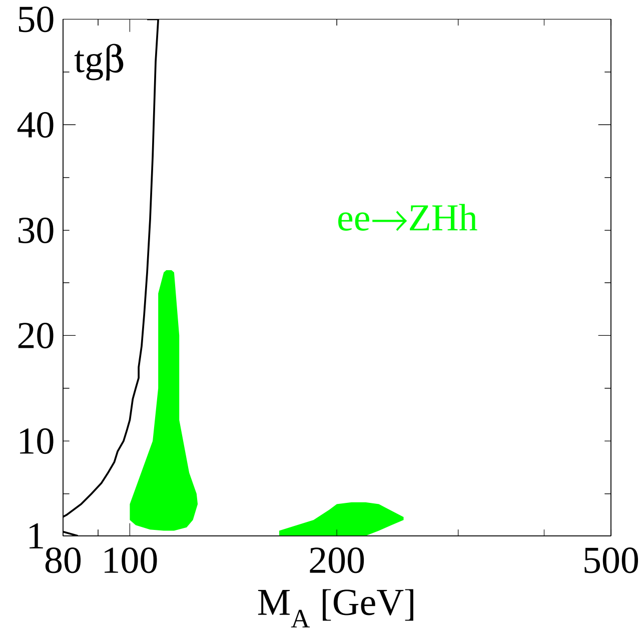
large M_A: sensitivity criteria not fulfilled because of

- phase space effects
- suppression of the H, A propagators for heavy masses

Sensitivity regions for $\lambda_{hhh}, \lambda_{Hhh}$

Processes sensitive to: $\lambda_{hhh}: \quad Zhh, Ahh$

$\lambda_{Hhh}: \quad Zhh, ZHh, Ahh$



regions without sensitivity: $\lambda \sin(\beta - \alpha), \lambda \cos(\beta - \alpha)$ small

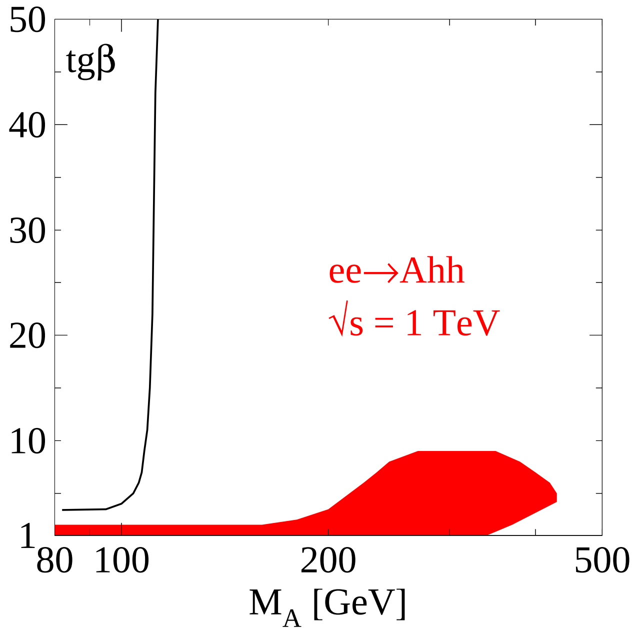
large M_A: sensitivity criteria not fulfilled because of

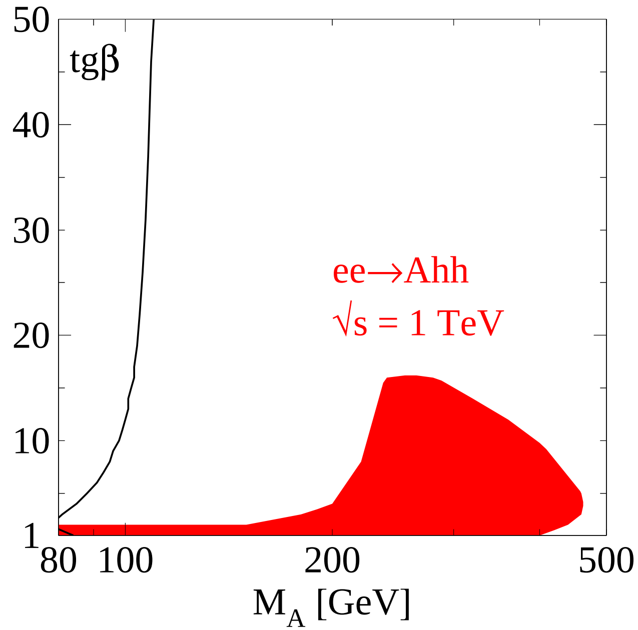
- ○ phase space effects
- ○ suppression of the H, A propagators for heavy masses

Sensitivity regions for $\lambda_{hhh}, \lambda_{Hhh}$

Processes sensitive to: λ_{hhh} : Zhh, Ahh

λ_{Hhh} : Zhh, ZHh, Ahh





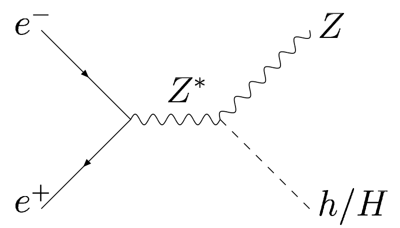
regions without sensitivity: $\lambda \sin(\beta - \alpha), \lambda \cos(\beta - \alpha)$ small

large M_A: sensitivity criteria not fulfilled because of

- phase space effects
- suppression of the H, A propagators for heavy masses

Higgs production b) e^+e^- Collider

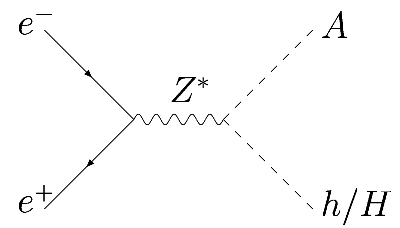
- Higgs strahlung: $e^+e^- \to Z + h/H$



$$\sigma_h \sim \sin^2(\beta-\alpha)$$
$$\sigma_H \sim \cos^2(\beta-\alpha)$$

ELW corrections $\sim -5 ... -10$ %

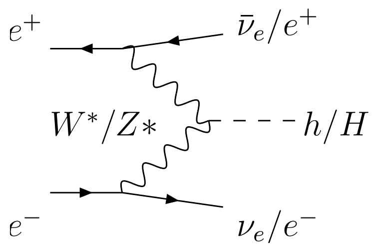
- Pair production: $e^+e^- \to A + h/H$



$$\sigma_h \sim \cos^2(\beta-\alpha)$$
$$\sigma_H \sim \sin^2(\beta-\alpha)$$

Complementarity!

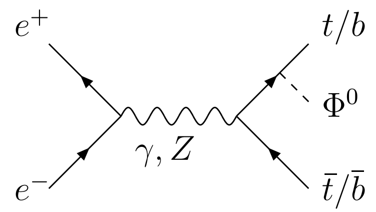
- W/Z fusion: $e^+e^- \to \nu_e\bar{\nu}_e/e^+e^- + h/H$



important at high energies

ELW corrections: $\sim -2 ... -10$ %

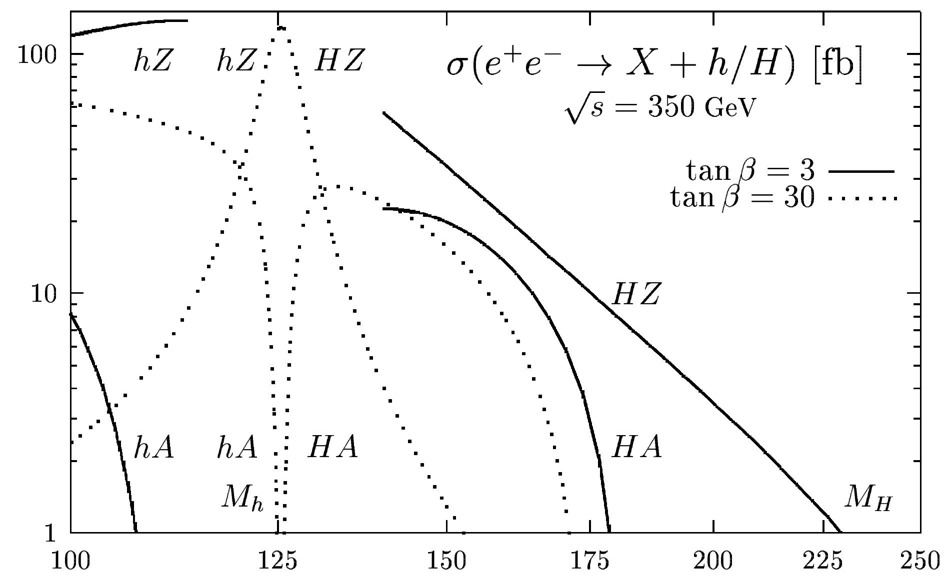
- Assoc prod w/ $q\bar{q}$: $e^+e^- \to t\bar{t}/b\bar{b} + h/H/A$

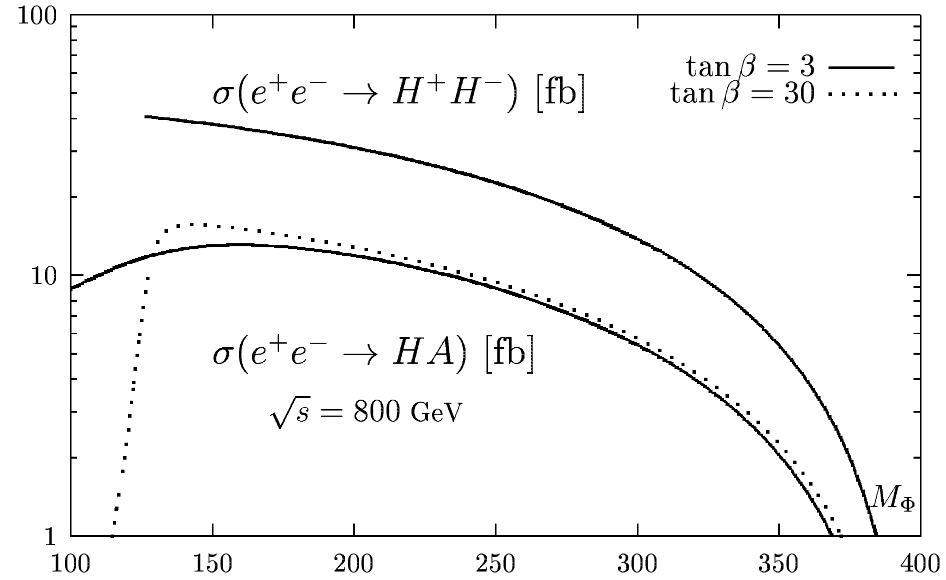


measurement of the Yukawa couplings

QCD corrections: $\sim -10 ... +50$ %

ELW corrections: $\sim +10$ %





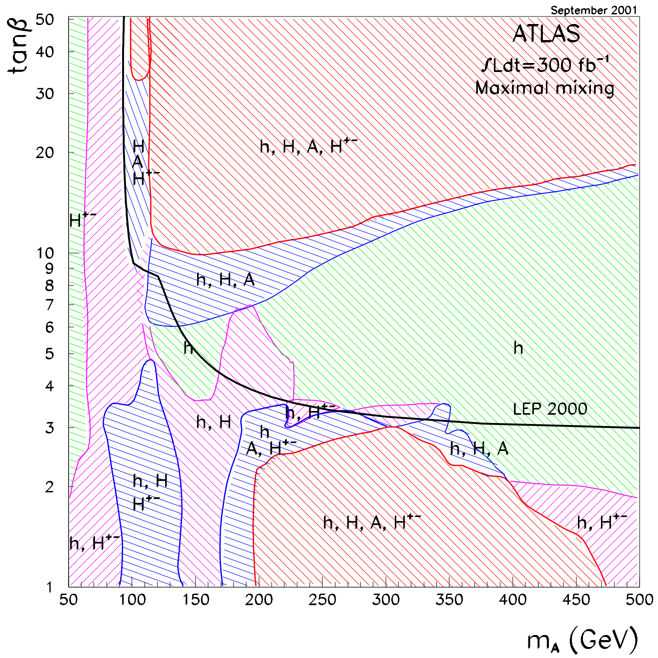
Djouadi, Kalinowski, Zerwas

* h can be discovered in the entire MSSM parameter range: Zh or Ah
* All SUSY Higgs bosons can be discovered @ 500 GeV if $M_A, M_H, M_{H^\pm} \lesssim 230$ GeV
* If decay modes are very complicated $\rightsquigarrow$ missing mass tech. $\rightsquigarrow$ detection

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction in $\gamma\gamma$ $\mathcal{C}$ollisions

Krämer,MM,Spira,Zerwas, Phys.Lett.B508(2001)311-316

▷ Search for H, A at the **LHC**:



Higgs particles H, A with masses $M_{H/A} \gtrsim 200$ GeV and centered around $\tan\beta \sim 7$ may escape discovery at the LHC

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction in $\gamma\gamma$ $\mathcal{C}$ollisions

Krämer,MM,Spira,Zerwas, Phys.Lett.B508(2001)311-316

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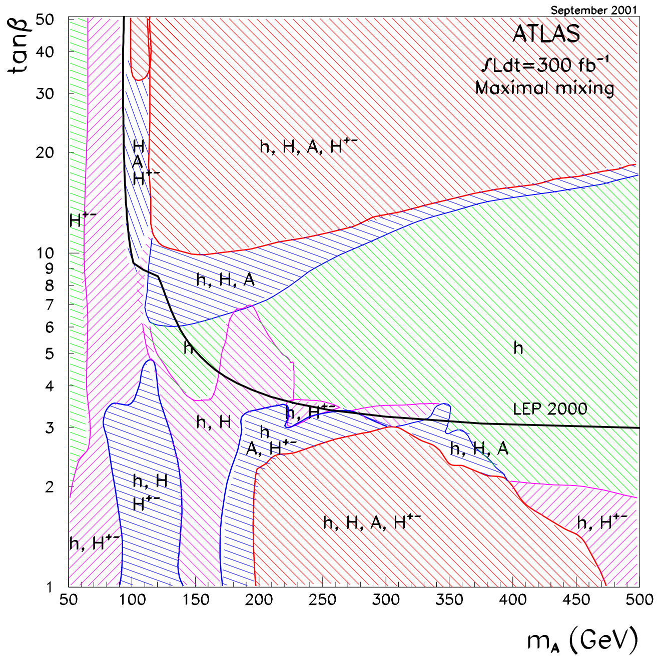

Higgs particles H, A with masses $M_{H/A} \gtrsim 200$ GeV and centered around $\tan\beta \sim 7$ may escape discovery at the LHC

▷ At e^+e^- **linear colliders:** Production of H, A with masses $M_{H,A} \lesssim 0.5\sqrt{s_{ee}}$

$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction in $\gamma\gamma$ $\mathcal{C}$ollisions

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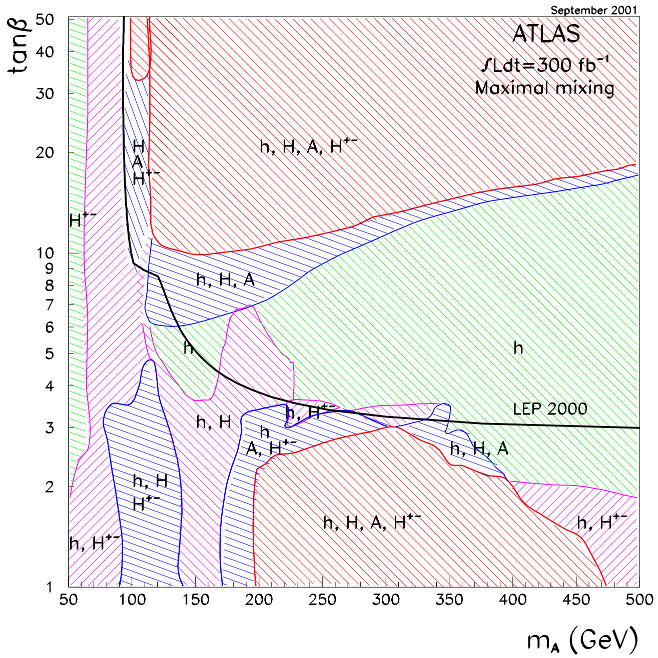


Higgs particles H, A with masses $M_{H/A} \gtrsim 200$ GeV and centered around $\tan\beta \sim 7$ may escape discovery at the LHC

▷ At e^+e^- **linear colliders:** Production of H, A with masses $M_{H,A} \lesssim 0.5\sqrt{s_{ee}}$

▷ Alternative: Search for H, A at **future $\gamma\gamma$ colliders**

Ginzburg,Kotkin,Panfil, Serbo,Telnov

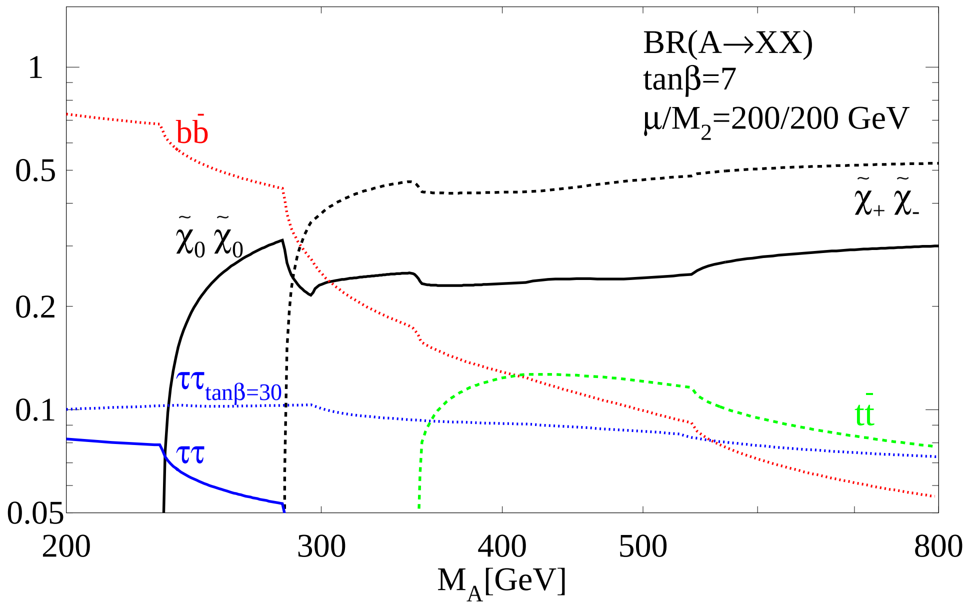
high luminosity ($\int \mathcal{L} = 300$ fb^{-1} in 2 years)

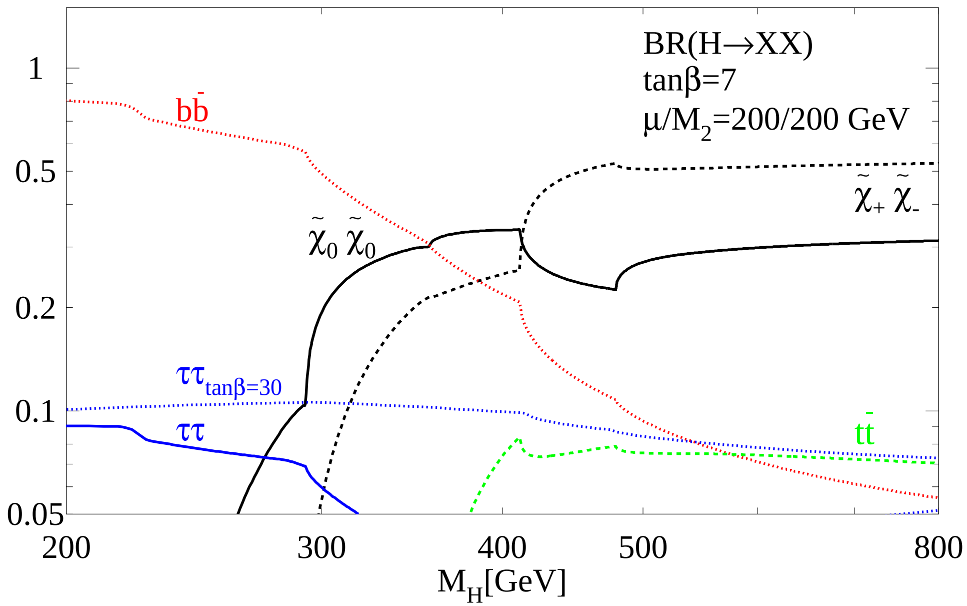
high energy, high degree of polarisation

H, A can be produced with masses up to $M_{H,A} \lesssim 0.8\sqrt{s_{ee}}$

Decay Modes

HDECAY

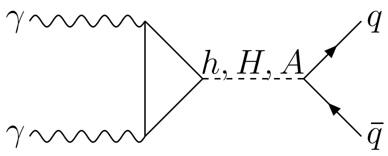




$\mathcal{P}$rocess $\gamma\gamma \to q\bar{q}$ – signal

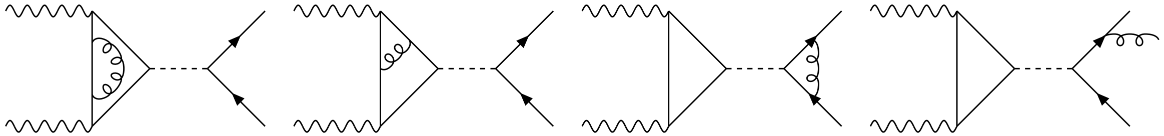
Signal process

LO



Spira,Djouadi,Graudenz,Zerwas
Melnikov,Yakovlev
Inoue et al.
Braaten,Leveille
Drees,Hikasa;...

NLO



$$\frac{d\sigma_{\rm LO}^{++/--}}{d\cos\theta} = \frac{N_c G_F^2 \alpha^2 \beta m_q^2}{128\pi^3}\left[g_{hqq}^2 \beta^2 |\mathcal{G}_h|^2 + g_{Hqq}^2 \beta^2 |\mathcal{G}_H|^2 + g_{Aqq}^2 |\mathcal{G}_A|^2 + 2 g_{hqq} g_{Hqq} \beta^2 {\rm Re}(\mathcal{G}_h \mathcal{G}_H)\right]$$

$$\frac{d\sigma_{\rm LO}^{+-/-+}}{d\cos\theta} = 0$$

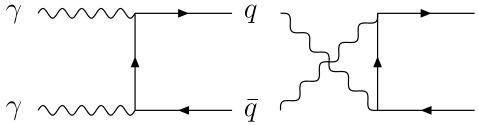
$$\mathcal{G}_\Phi = \mathcal{M}_\Phi/(1 - m_\Phi^2/s + i m_\Phi \Gamma_\Phi/s) \qquad \Phi = h, H, A \qquad \mathcal{M}_\Phi : \ \gamma\gamma\Phi - \text{form factor}$$

$$\beta = (1 - 4m_q^2/s)^{1/2}$$

$\mathcal{P}$rocess $\gamma\gamma \to q\bar{q}$ – bkg & interference

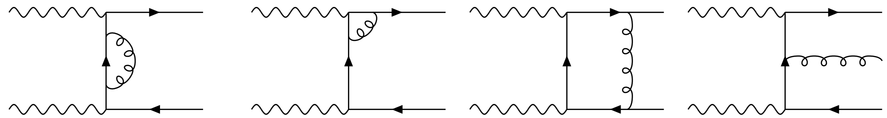
Background process

LO



Jikia,Tkabladze
Kamal,Merebashvili,Conogouris

NLO



$$\frac{d\sigma_{\rm LO}^{++/--}}{d\cos\theta} = \frac{N_c \alpha^2 Q_q^4 16\pi\beta(1+\beta^2)}{s} \frac{m_q^2}{s} \frac{1}{(1-\beta^2\cos^2\theta)^2}$$

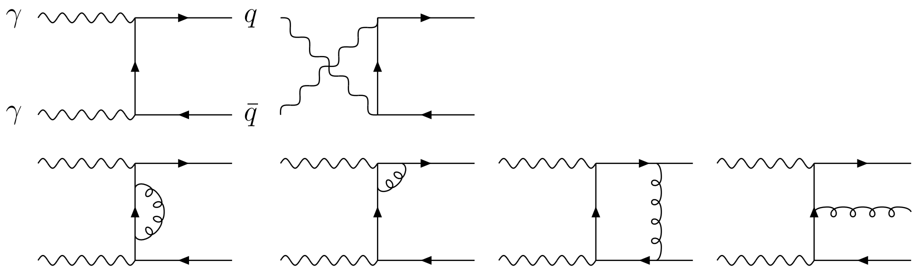
$$\frac{d\sigma_{\rm LO}^{+-/-+}}{d\cos\theta} = \frac{N_c \alpha^2 Q_q^4 4\pi\beta^3}{s} \frac{\sin^2\theta(2-\beta^2\sin^2\theta)}{(1-\beta^2\cos^2\theta)^2}$$

$\mathcal{P}$rocess $\gamma\gamma \to q\bar{q}$ – bkg & interference

Background process

LO

NLO



Jikia, Tkabladze
Kamal, Merebashvili, Conogouris

$$\frac{d\sigma_{\rm LO}^{++/--}}{d\cos\theta} = \frac{N_c\alpha^2 Q_q^4 16\pi\beta(1+\beta^2)}{s}\frac{m_q^2}{s}\frac{1}{(1-\beta^2\cos^2\theta)^2}$$

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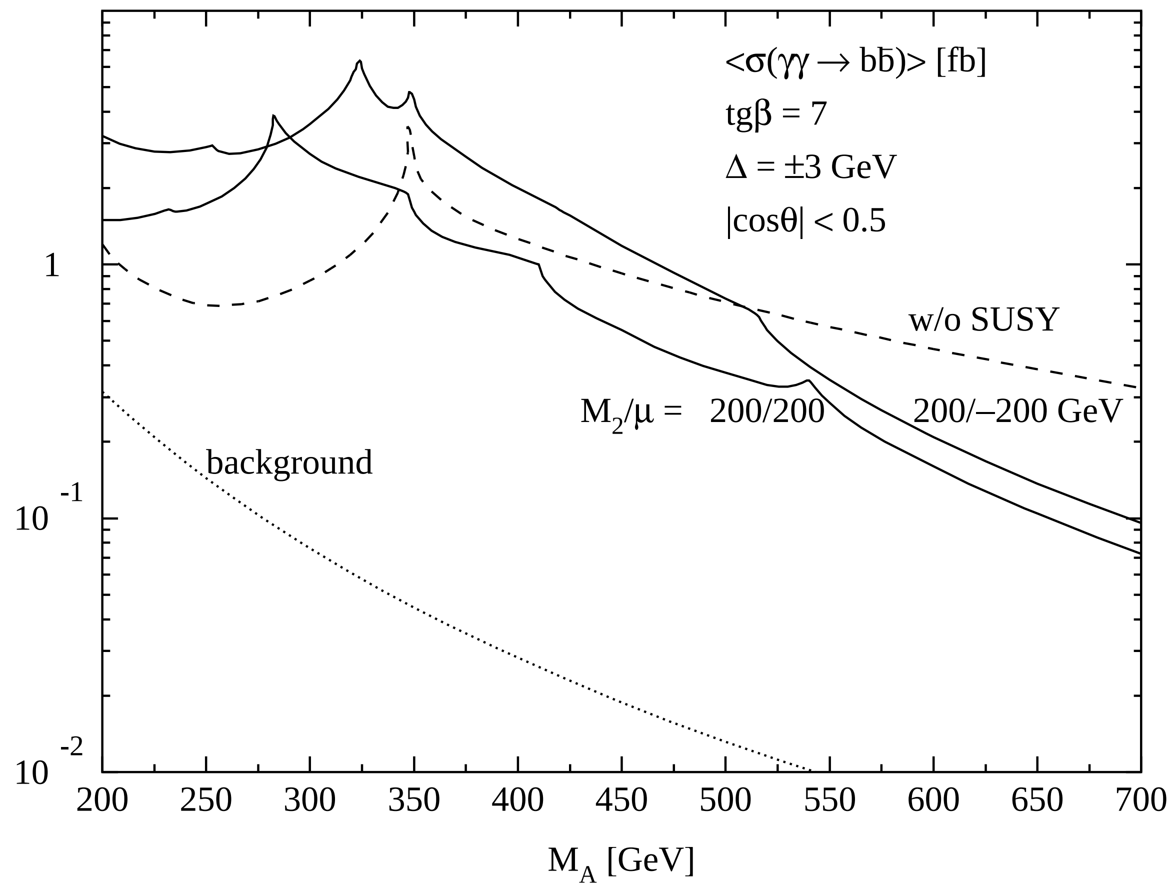
Interference process

$$\frac{d\sigma_{\rm LO}^{++/--}}{d\cos\theta} = \frac{N_c G_F\alpha^2 Q_q^2\beta}{\sqrt{2}\pi}\frac{m_q^2}{s}\frac{1}{1-\beta^2\cos^2\theta}\left[g_{hqq}\beta^2{\rm Re}(\mathcal{G}_h) + g_{Hqq}\beta^2{\rm Re}(\mathcal{G}_H) - g_{Aqq}{\rm Re}(\mathcal{G}_A)\right]$$

$$\frac{d\sigma_{\rm LO}^{+-/-+}}{d\cos\theta} = 0$$

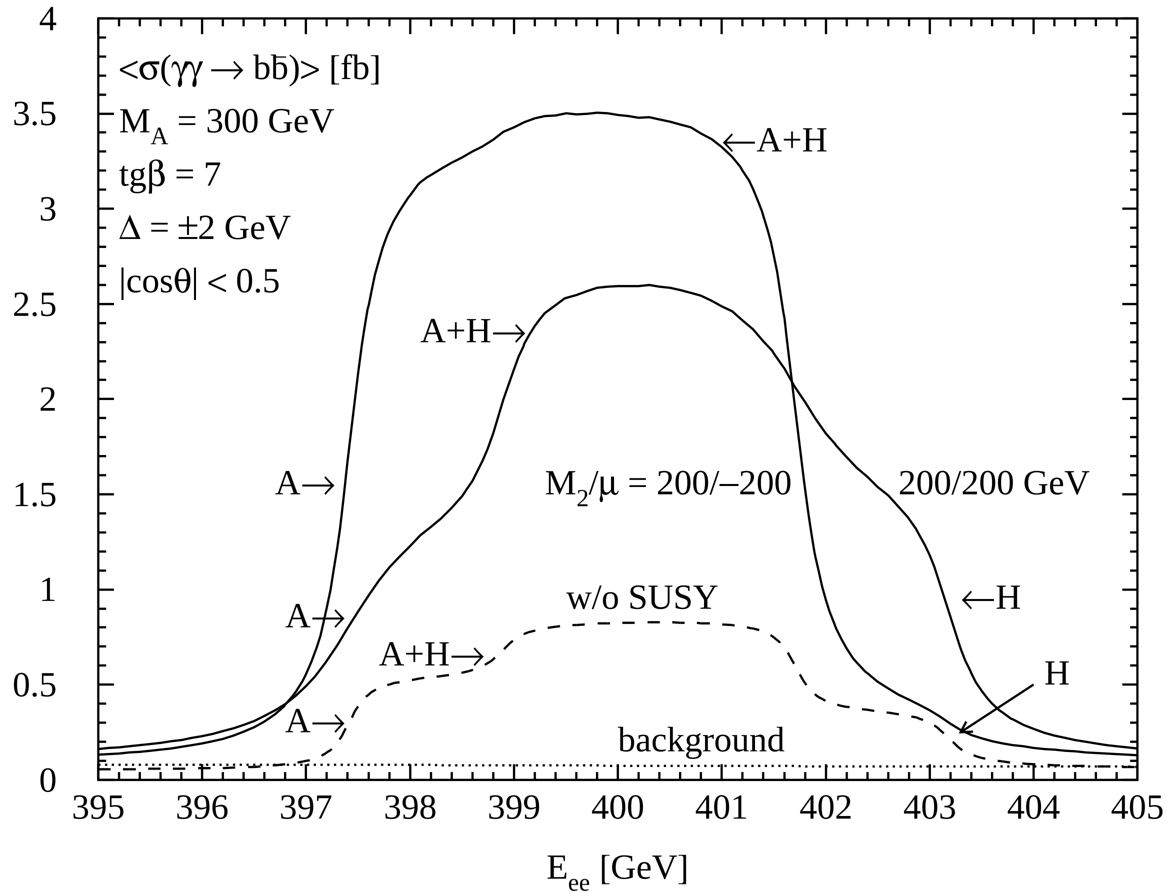
NLO corrections have been calculated

$\mathcal{R}$esult $e^+e^- \to \gamma\gamma \to b\bar{b}$



- ▷ Cut in $\cos\theta$ enhances S/B
- ▷ $\sigma_{\text{bkg}} \lesssim 0.3$ fb; $\sigma_{\text{signal}} \gtrsim 0.1$ fb for $M_A \lesssim 600$ GeV
- ▷ Peaks/kinks: behaviour of $\gamma\gamma A$ form factor/BR($H/A \to b\bar{b}$) at the gaugino/$t\bar{t}$ thresholds

Separation of H and A



▷ $M_A = 300$ GeV, $M_H = 301.37$ GeV for large SUSY particle masses

▷ Change of cross section at the H, A production thresholds $\Rightarrow$ separation of H and A via threshold scan of the H, A production cross section

$\tau\tau$ $\mathcal{F}$usion to $\mathcal{SUSY}$ $\mathcal{H}$iggs $\mathcal{B}$osons at a $\mathcal{P}$hoton $\mathcal{C}$ollider

Choi,Kalinowski,Lee,MM,Spira,Zerwas, Phys.Lett.B606(2005)164

- **Motivation:** $\delta \tan\beta / \tan\beta \sim 10$ % at e^+e^-/pp colliders

Choi et al.;Boos et al.;Gunion et al.;Kinnunen et al.
Nieżurawski et al.;Velasco et al.

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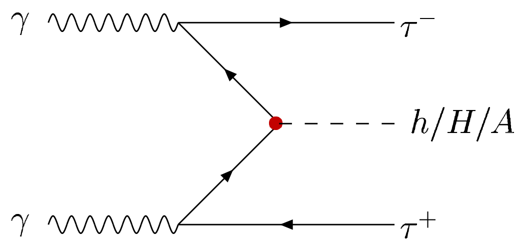
- **$\tau\tau$ Fusion to h, H, A at a $\gamma\gamma$ Collider: Signal**



Couplings: for large $\tan\beta$

$A\tau\tau = \tan\beta$, $H\tau\tau \approx \tan\beta$	heavy H/A
$h\tau\tau \approx \tan\beta$	light A

Higgs decays: $h/H/A \to b\bar{b}$ at 90% (SPS1b)

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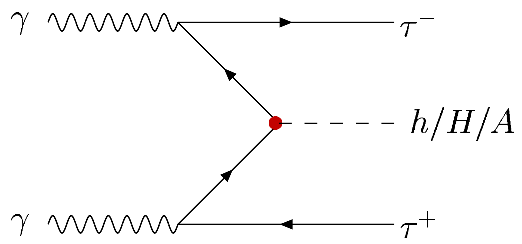

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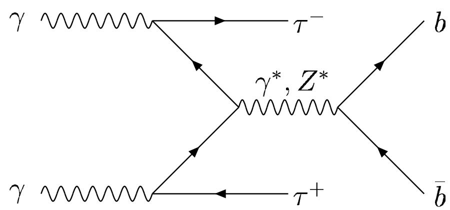
- **Bkg - Annihilation: $\tau^+\tau^- \longrightarrow b\bar{b}$ and $b\bar{b} \to \tau^+\tau^-$ via γ, Z**



suppressed $\sim g^2$ except for $M_{bb} \sim M_Z$, $M_{\tau\tau} \sim M_Z$

$\tau\tau$ $\mathcal{F}$usion to $\mathcal{SUSY}$ $\mathcal{H}$iggs $\mathcal{B}$osons at a $\mathcal{P}$hoton $\mathcal{C}$ollider

Choi, Kalinowski, Lee, MM, Spira, Zerwas, Phys.Lett.B606(2005)164

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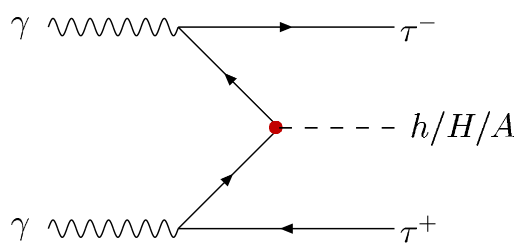

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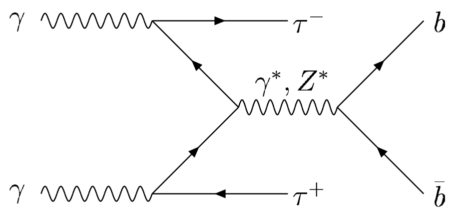
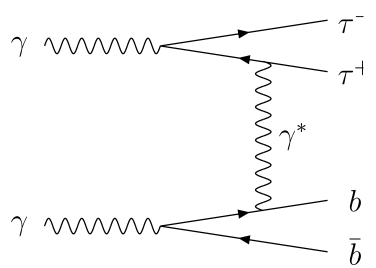


suppressed $\sim g^2$ except for $M_{bb} \sim M_Z$, $M_{\tau\tau} \sim M_Z$

- **Bkg - diffractive: $\gamma\gamma \longrightarrow (\tau\tau)(bb)$**



suppressed by event topology:

$\tau\tau$ small invariant mass/same direction

bb dito/close to γ axes

$\tau\tau$ $\mathcal{F}$usion to $\mathcal{SUSY}$ $\mathcal{H}$iggs $\mathcal{B}$osons at a $\mathcal{P}$hoton $\mathcal{C}$ollider

Choi,Kalinowski,Lee,MM,Spira,Zerwas, Phys.Lett.B606(2005)164

Analysis: Full set of signal and bkg diagrams ($\rightarrow$ CompHEP Boos,Pukhov,...)

Cuts: $M_{bb} = M_\Phi \pm \Delta$ with $\Delta = \text{max}[\Gamma_\phi/2, \Delta_{\text{ex}}] \rightarrow \Delta_{\text{ex}} = 0.05 M_\Phi$

τ polar angle	≥ 130 mrad [shielding: dead mask]
τ energy	≥ 5 GeV
τ^+ and τ^-	assumed in opposite directions

Efficiencies: $\epsilon_{bb} \sim 0.7$ and $\epsilon_{\tau\tau} \sim 0.5 \rightsquigarrow \epsilon \sim 0.35$

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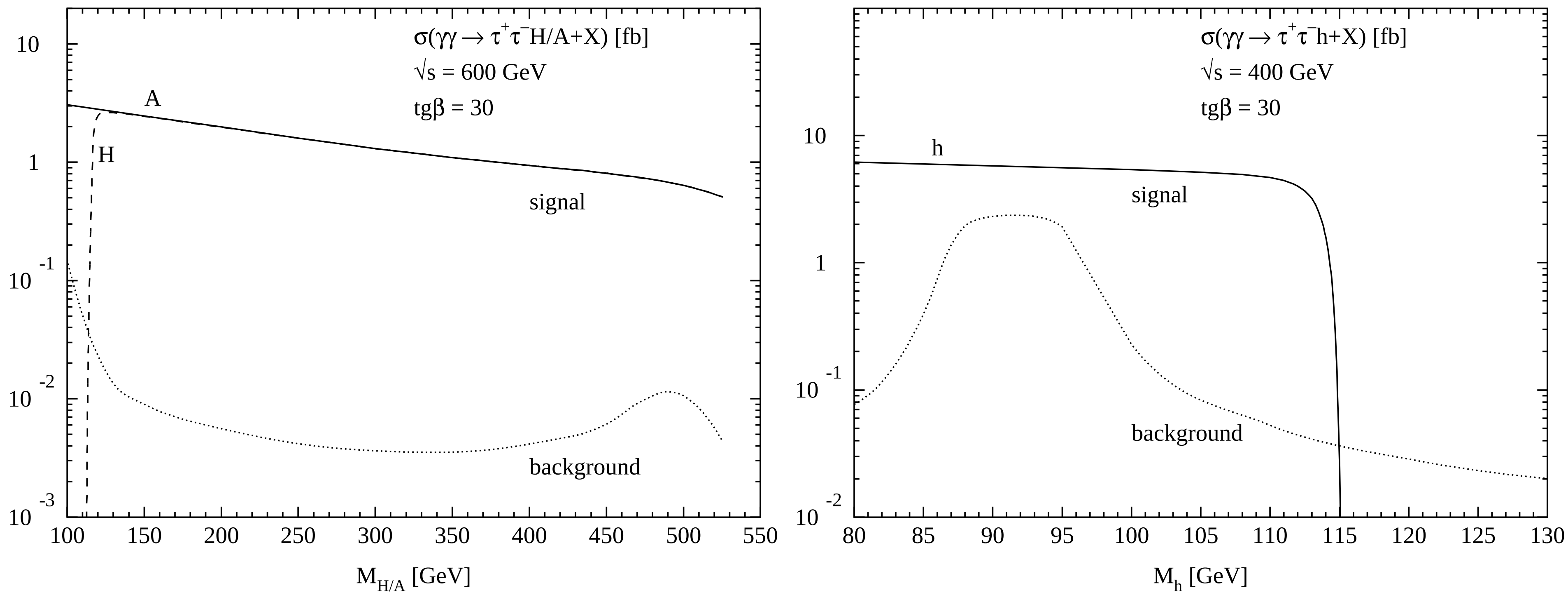
$E_{e^\pm e^-} = 800/500$ GeV $\Rightarrow E_{\gamma\gamma} = 600/400$ GeV, $\mathcal{L} = 200/100$ fb^{-1}



- $\sigma(H/A) = 3$ to 1 fb for $M_{A/H} = 100...500$ GeV and $\tan\beta = 30$
- $\sigma(h) = 5$ fb for $M_h = 110$ GeV and $\tan\beta = 30$
- $\Delta\tan\beta \approx 0.9$-$1.3$ uniformly for $\tan\beta \gtrsim 10$

$\mathcal{P}$rocess $\gamma\gamma \longrightarrow b\bar{b}$ - technical details

- $b\bar{b}$ final state most promising
- Restriction to 2-jet final states $\rightsquigarrow$ enhance S/B
- Higher order corrections (in 2-jet) are accounted for by resummation Fadin,Khoze,Martin Melles,Stirling
- Polarisation of $e^{\pm}$ and laser beams $\rightsquigarrow$ enhance S/B
  [For leading order with realistic photon spectra see also Gunion et al.]

$\gamma\gamma$ luminosity $d\mathcal{L}^{\gamma\gamma}/dz$ Ginzburg et al. Kühn et al.

"P": pol.; $\sqrt{s_{ee}} = 500$ GeV

For this helicity combination:
$d\mathcal{L}^{\gamma\gamma}/dz$ max. for $J_z = 0$
peaked towards high energies