Higgs Studies at a LC

Higgs boson precision physics at a high energy e^+e^- collider

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LoopFest, 9-10 May 2002

- very accurate experimental measurements for M_H, Γ_H, $Br(H \to XX)$, ... available
- emphasis on precision of existing theoretical predictions for Higgs mass(es) and couplings:
  $\longrightarrow$ Higgs e^+e^- production cross sections
  $\longrightarrow$ Higgs branching ratios
- comparison between theory and experiments (at the % level) always tricky

SM Higgs boson: H

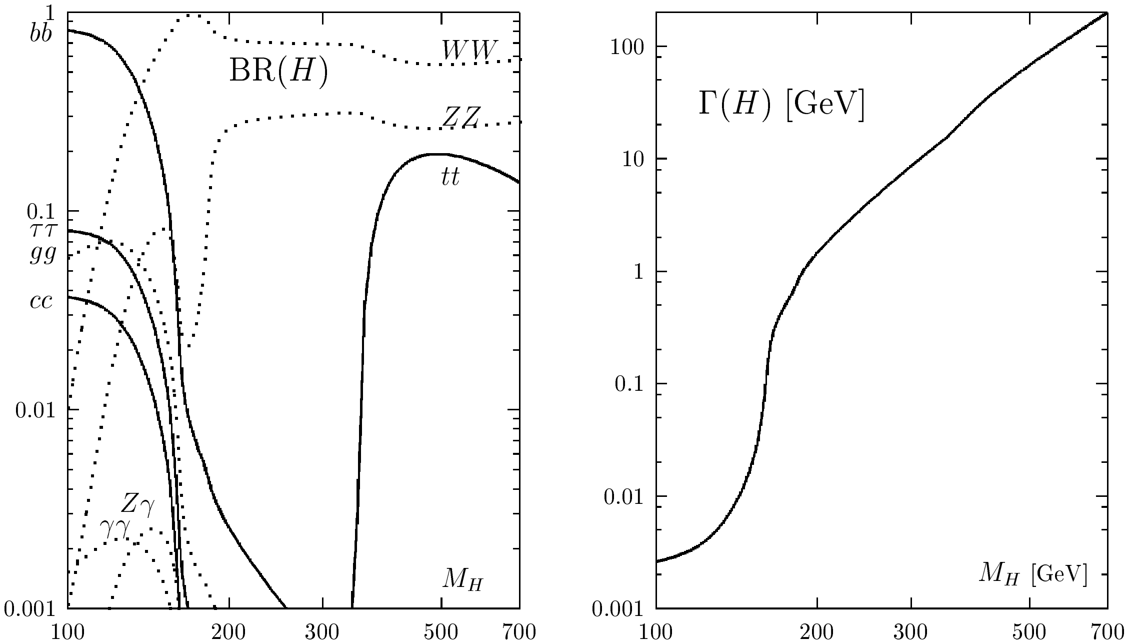
$$v = (G_F\sqrt{2})^{-1/2} \longrightarrow m_H^2 = (2\lambda v^2)$$

- gauge/Higgs sector: only one free parameter

$$\begin{aligned} g_{HVV} &= \frac{2M_V^2}{v} \quad , \quad g_{HHVV} = \frac{2M_V^2}{v^2} \\ g_{3H} &= 6v\lambda \quad , \quad g_{4H} = 6\lambda \end{aligned}$$

- fermion sector: more arbitrariness

$$g_{Hff} = \frac{m_f}{v}$$

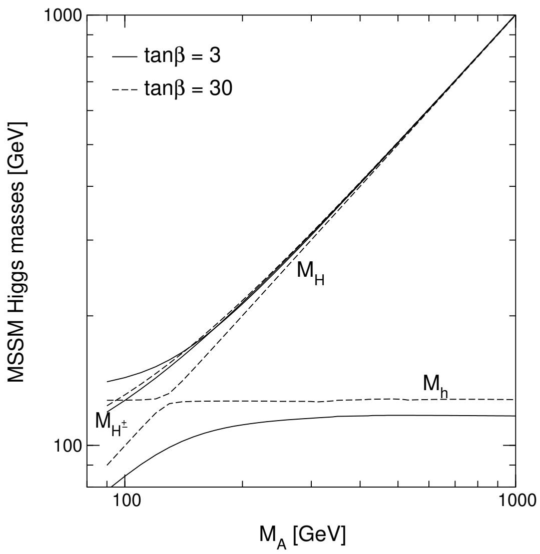


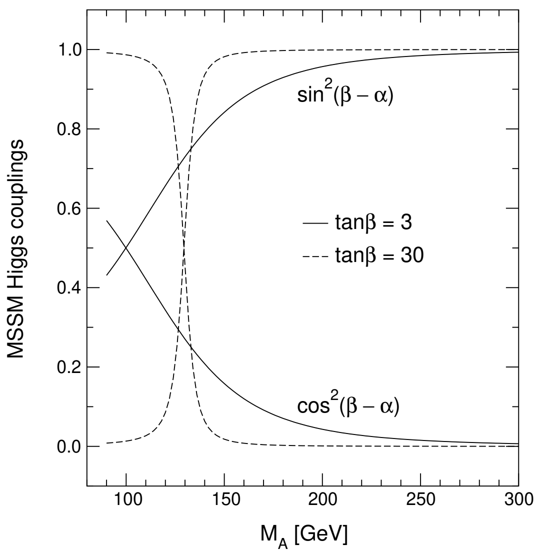
$$\begin{cases} M_H > 113.5\,\text{GeV (95\%c.l.) (direct)} \\ M_H < 196\,\text{GeV (95\%c.l.) (indirect)} \end{cases}$$

Focus on light/intermediate Higgs.

MSSM Higgs bosons: h^0, H^0, A^0, H^+

Masses and couplings depend on two parameters, $(M_A, \tan\beta)$, where $\tan\beta = v_1/v_2$.





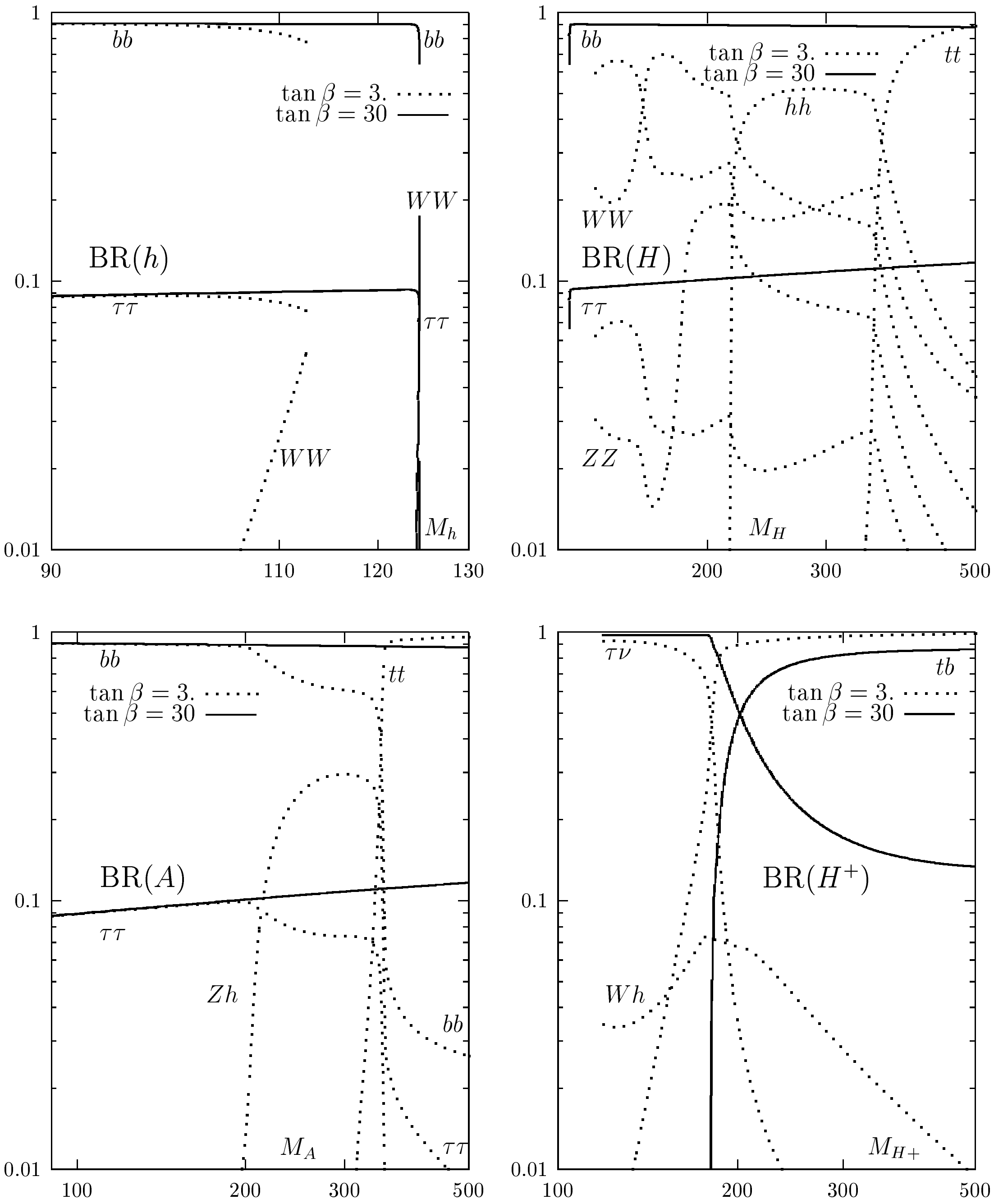
- gauge sector

$$
\begin{aligned}
g_{h^0VV} &= g_{HVV}\sin(\beta-\alpha) \quad , \\
g_{H^0VV} &= g_{HVV}\cos(\beta-\alpha) \quad , \quad g_{A^0VV} = 0
\end{aligned}
$$

- fermion sector

$$
\begin{aligned}
g_{h^0uu} &= g_{Huu}\frac{\cos\alpha}{\sin\beta} \quad , \quad g_{h^0dd} = g_{Hdd}\frac{-\sin\alpha}{\cos\beta} \quad , \\
g_{H^0uu} &= g_{Huu}\frac{\sin\alpha}{\sin\beta} \quad , \quad g_{H^0dd} = g_{Hdd}\frac{\cos\alpha}{\cos\beta} \quad , \\
g_{A^0uu} &= g_{Huu}\frac{1}{\tan\beta} \quad , \quad g_{A^0dd} = g_{Hdd}\tan\beta \quad ,
\end{aligned}
$$

plus loop effects



Much more complicated scenario, but

$$M_{h^0} < 135\,\mathrm{GeV}$$

i.e., in the low mass region we can learn a lot by comparing H to h^0.

Approaching the decoupling limit...

(See H.Logan talk tomorrow)

gauge bosons

$$\frac{g^2_{h^0VV}}{g^2_{HVV}} \simeq 1 - \frac{c^2 M_Z^4 \sin^2 4\beta}{4 M_A^4}$$

and fermions

$$\begin{aligned}
\frac{g^2_{h^0tt}}{g^2_{Htt}} &\simeq 1 & -\frac{c M_Z^2 \sin 4\beta \cot\beta}{M_A^2} \\
\frac{g^2_{h^0bb}}{g^2_{Hbb}} &\simeq 1 & -\frac{4 c M_Z^2 \cos 2\beta}{M_A^2}\left[\sin^2\beta - \frac{\Delta_b}{1+\Delta_b}\right]
\end{aligned}$$

from one-loop one-loop improved and dominant two-loop ($O(G_F m_t^4)$, $O(\alpha_s G_F m_t^4)$, $O(G_F^2 m_t^6)$)

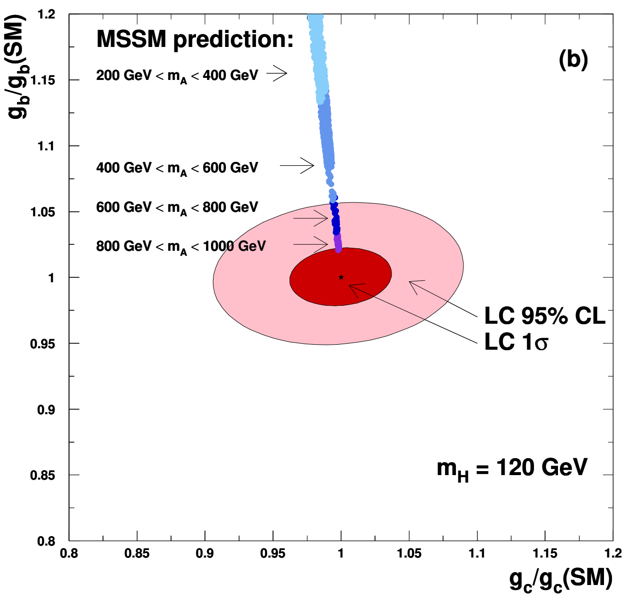
- radiative corrections to the Higgs squared-mass matrix
- vertex corrections to the Higgs-fermion Yukawa couplings

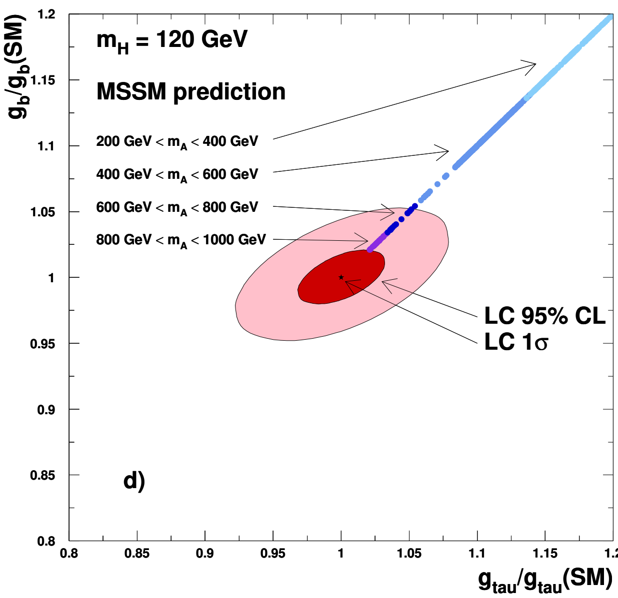
Chankowski, Pokorski, Rosiek, Carena, Haber, Hempling, Heinemeyer, Hollik, Wagner, Weiglein, Dobado, Herrero, Peñaranda, ...

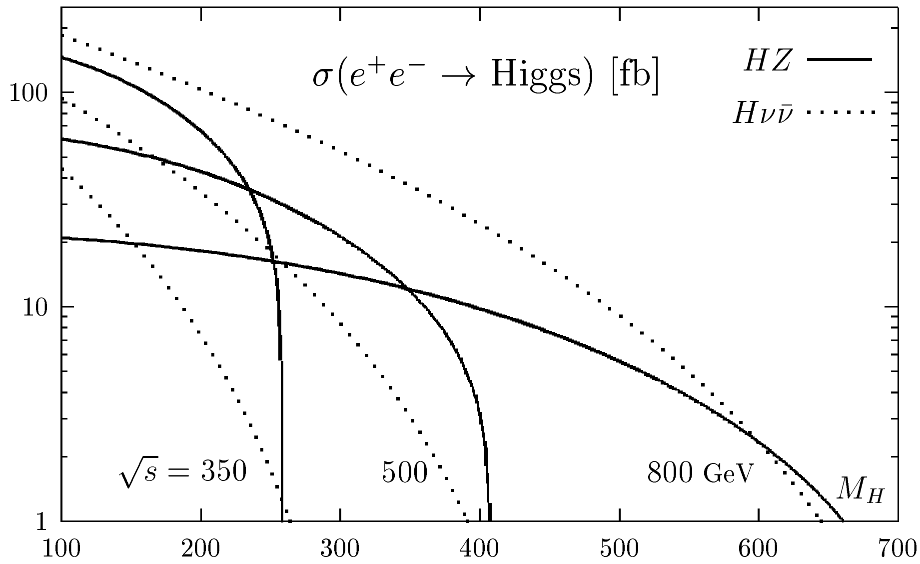
M.Battaglia, K.Desch : HFITTER

($\sqrt{s}$=500 GeV, 500 fb^{-1})

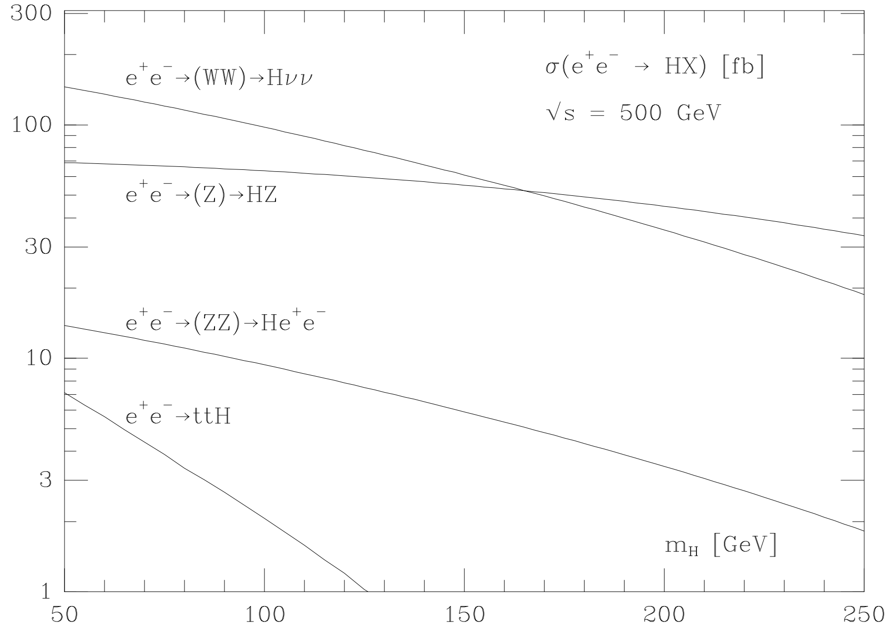
Coupling	M_H = 120GeV	140GeV
g_{HWW}	± 0.012	± 0.020
g_{HZZ}	± 0.012	± 0.013
g_{Htt}	± 0.030	± 0.061
g_{Hbb}	± 0.022	± 0.022
g_{Hcc}	± 0.037	± 0.102
$g_{H\tau\tau}$	± 0.033	± 0.048
g_{HWW}/g_{HZZ}	± 0.017	± 0.024
g_{Htt}/g_{HWW}	± 0.029	± 0.052
g_{Hbb}/g_{HWW}	± 0.012	± 0.022
$g_{H\tau\tau}/g_{HWW}$	± 0.033	± 0.041
g_{Htt}/g_{Hbb}	± 0.026	± 0.057
g_{Hcc}/g_{Hbb}	± 0.041	± 0.100
$g_{H\tau\tau}/g_{Hbb}$	± 0.027	± 0.042



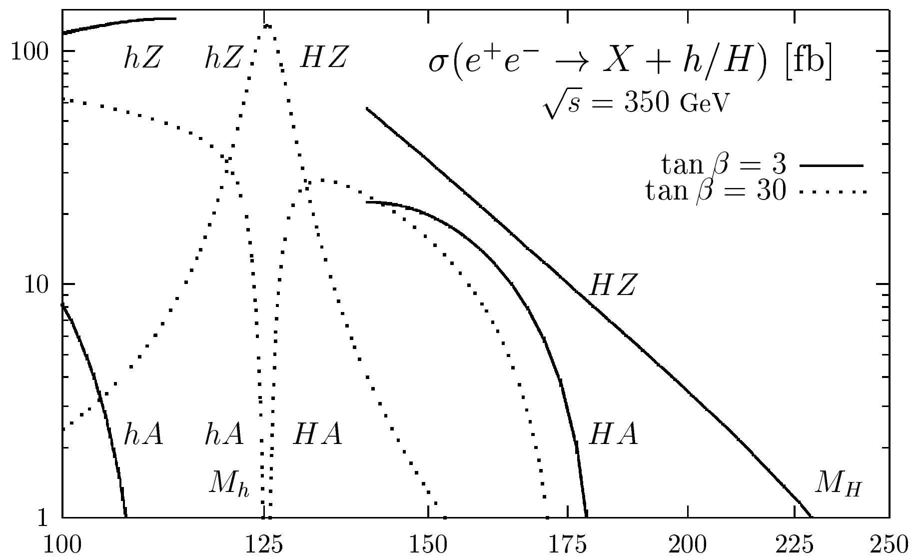


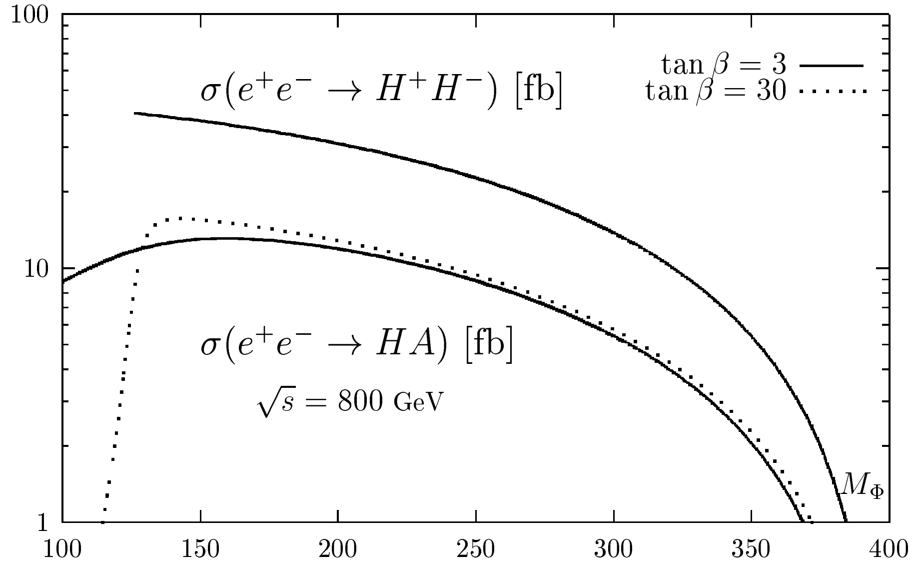


$\sigma(e^+e^- \to \text{Higgs})$ [fb]
HZ
$H\nu\bar{\nu}$
100
10
1
$\sqrt{s} = 350$
500
800 GeV
M_H
100
200
300
400
500
600
700



300
100
30
10
3
1
$e^+e^- \to (WW) \to H\nu\nu$
$\sigma(e^+e^- \to HX)$ [fb]
$\sqrt{s}$ = 500 GeV
$e^+e^- \to (Z) \to HZ$
$e^+e^- \to (ZZ) \to He^+e^-$
$e^+e^- \to ttH$
m_H [GeV]
50
100
150
200
250


$\sigma(e^+e^- \to X + h/H)$ [fb]
$\sqrt{s} = 350$ GeV
$\tan\beta = 3$
$\tan\beta = 30$
hZ
hZ
HZ
HZ
hA
hA
HA
HA
M_h
M_H
100
10
1
100
125
150
175
200
225
250


$\sigma(e^+e^- \to H^+H^-)$ [fb]
$\tan\beta = 3$
$\tan\beta = 30$
$\sigma(e^+e^- \to HA)$ [fb]
$\sqrt{s} = 800$ GeV
M_Φ
100
10
1
100
150
200
250
300
350
400

SM Production Cross Sections

- $e^+e^- \to ZH$: one-loop EW corrections known (Kniehl,Berends,Kleiss,Fleisher,Jegerlehner,Denner,...)

  crucial observable for
  $\longrightarrow$ model independent measurement of M_H
  $\longrightarrow$ model independent measurement of g_{ZZH}
  $\longrightarrow$ model independent measurement of $Br(H \to f\bar{f})$

- $e^+e^- \to H\nu_e\bar{\nu}_e$, one-loop EW corrections still incomplete. Possible to
  $\longrightarrow$ include IS bremsstrahlung (structure functions at $\mathcal{O}(\alpha^2)$, soft-photon exponentiation)
  $\longrightarrow$ Improved Born Approximation (IBA): leading corrections included in $\Delta\rho$ and $\Delta\alpha$:

$$\alpha \to \bar{\alpha} = \frac{\alpha}{1 - \Delta\alpha}$$

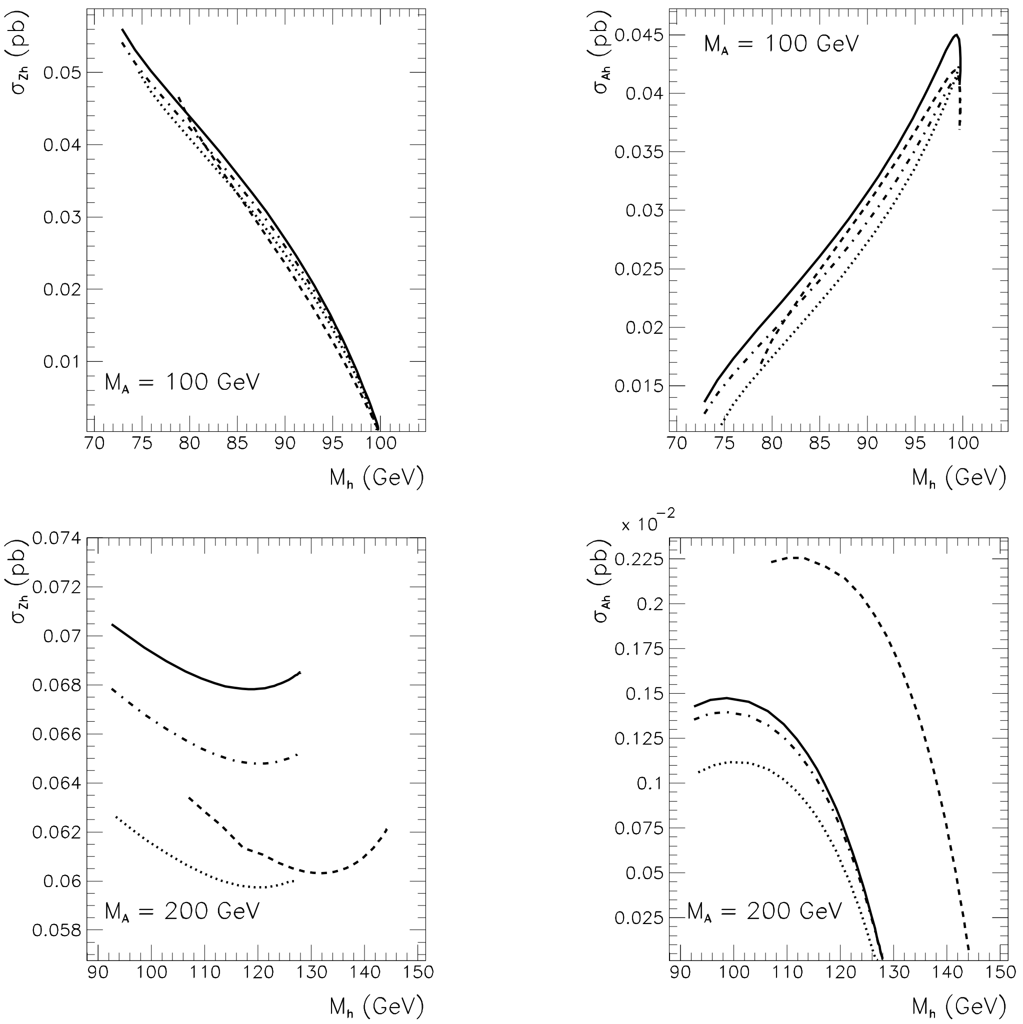
$$c_w^2 \to \bar{c}_w^2 = 1 - \bar{s}_w^2 = c_w^2(1 - \Delta\rho)$$

  crucial observable for
  $\longrightarrow$ measurement of $\Gamma(H \to WW) \longrightarrow \Gamma_H$

MSSM Production Cross Sections
$e^+e^- \to Zh^0(H^0)$ and $e^+e^- \to Ah^0(H^0)$

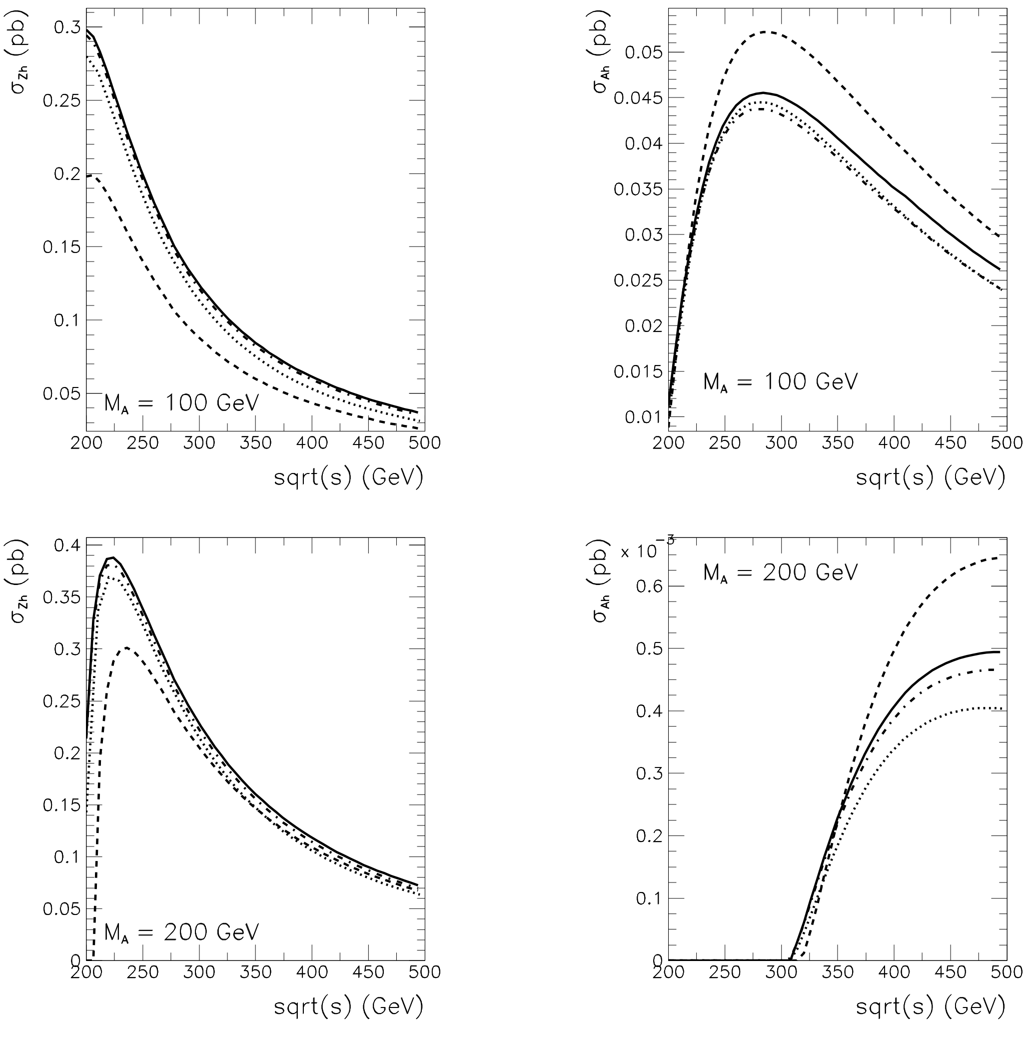
(Heinemeyer,Hollik,Rosiek,Weiglein)

- complete one-loop contributions
- dominant ($\mathcal{O}(G_F \alpha_s M_t^4)$) and further sub-dominant two-loop contributions



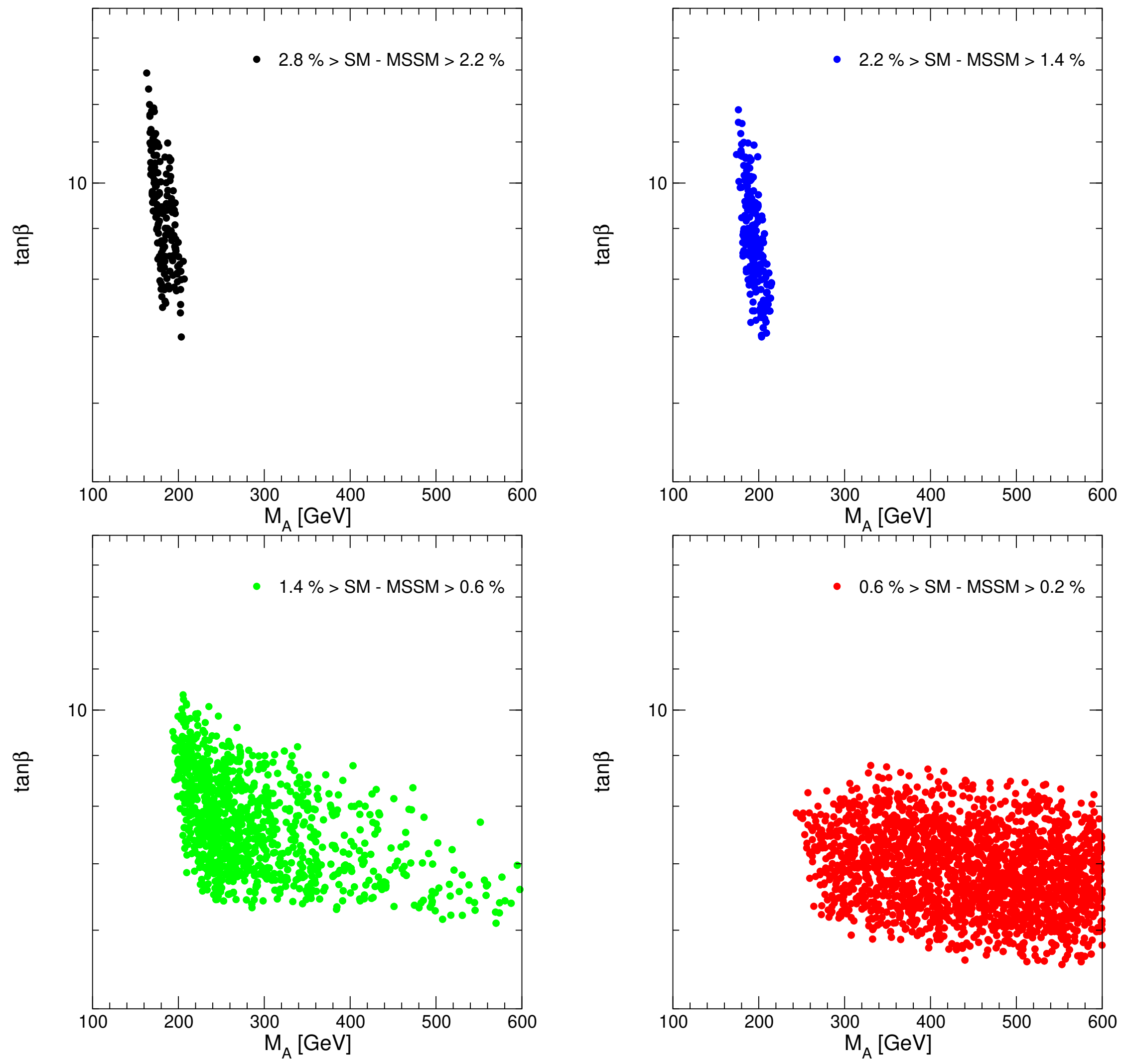
($\tan\beta = 5$, $M_{\tilde{q}} = 1$ TeV, $M_{\tilde{l}} = 300$ TeV

$X_t = 0$, $A_b = A_t$, $\mu = 200$, $M_2 = 200$ GeV, $\tilde{m}_g = 500$ GeV)


σZh (pb)
MA = 100 GeV
sqrt(s) (GeV)
σAh (pb)
MA = 100 GeV
sqrt(s) (GeV)
σZh (pb)
MA = 200 GeV
sqrt(s) (GeV)
σAh (pb)
x 10−3
MA = 200 GeV
sqrt(s) (GeV)

Can $\sigma(e^+e^- \to ZH/h^0)$ be used as a precision observable?

(Dawson,Heinemeyer)



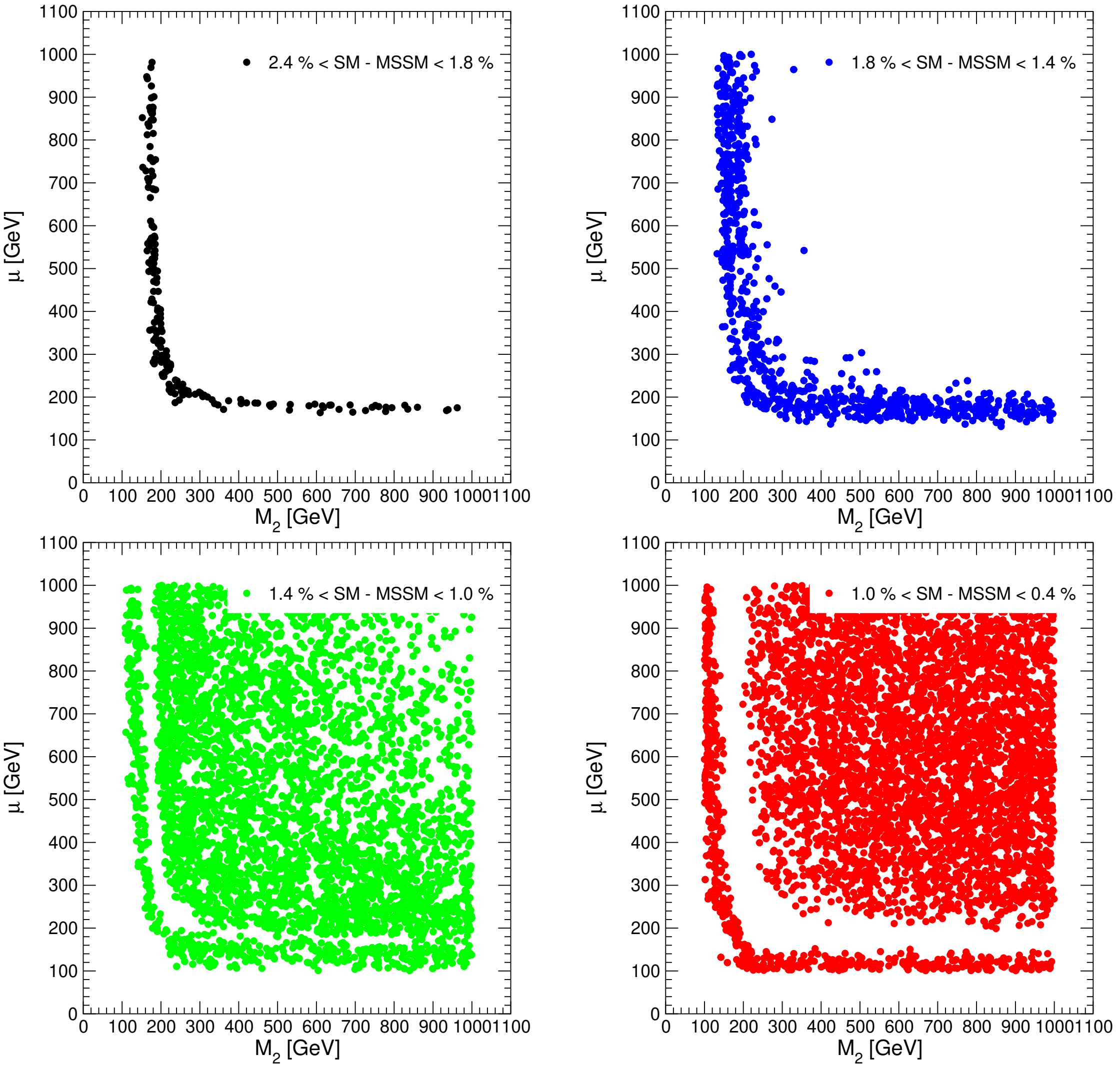
The Higgs sector scenario: ($m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $\sin\theta_{\tilde{t}}$ measured)

$\longrightarrow$ SM uncertainties: m_t

$\longrightarrow$ MSSM parameter uncertainties: as from LHC and/or LC

$\longrightarrow$ uncertainty on M_h: ± 0.5 GeV

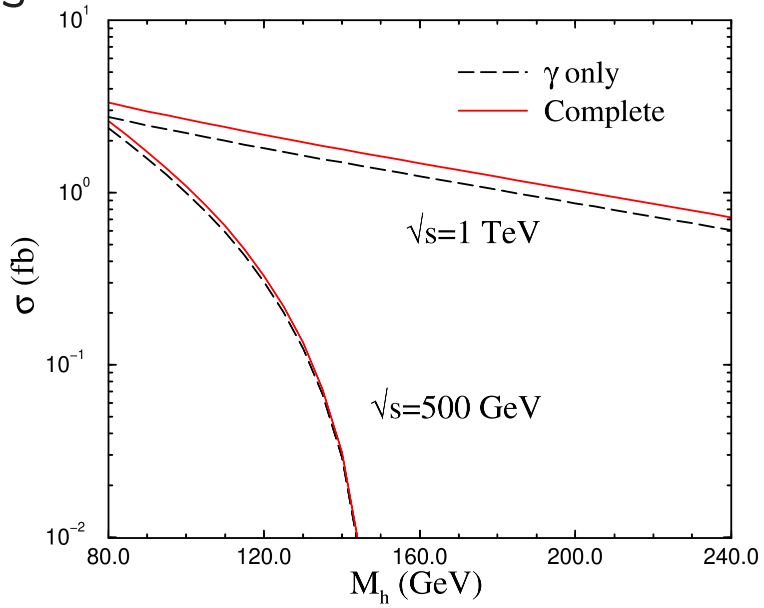
$\longrightarrow$ theoretical uncertainties: 1%



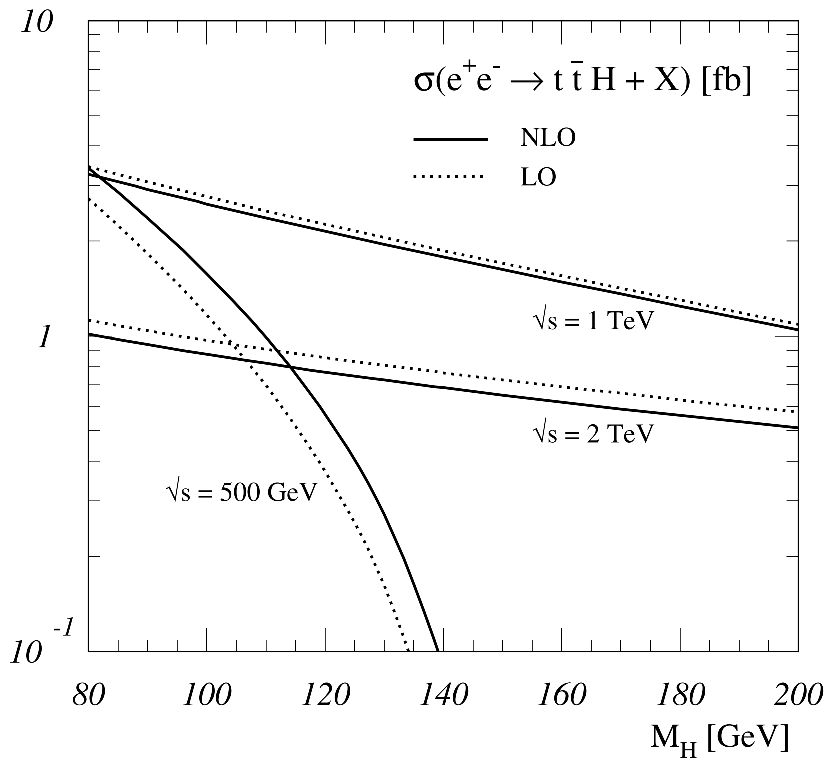
The gaugino scenario: $\tan\beta$ and M_A measured

A sub-leading mode: $e^+e^- \to t\bar{t}H$ Crucial to measure g_{Htt}

- Higgs bremsstrahlung off top quarks dominates



- $\mathcal{O}(\alpha_s)$ corrections computed (Dawson,Reina; Dittmaier,Krämer,Liao,Spira,Zerwas)

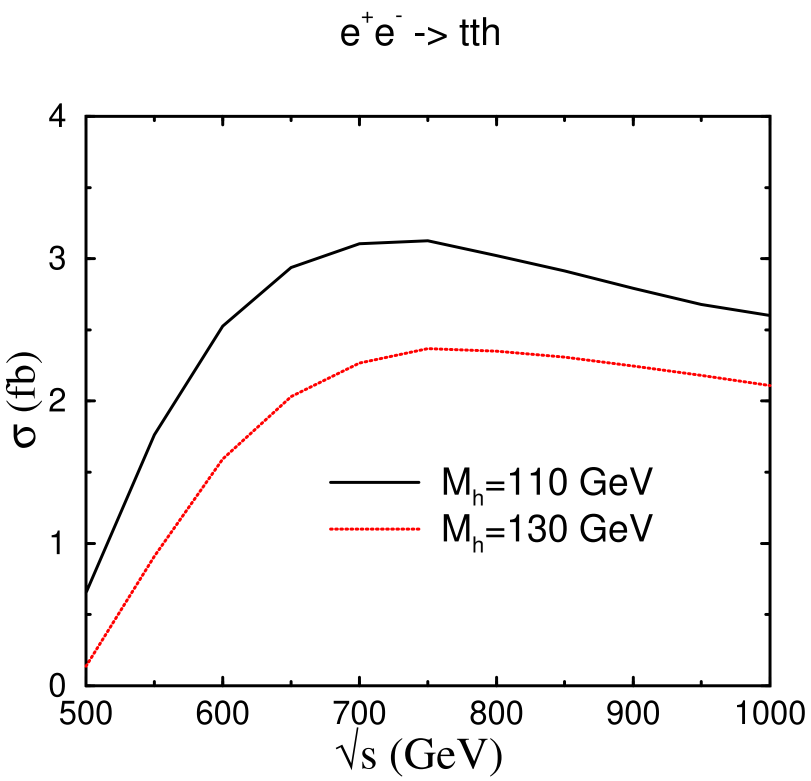


- one-loop EW corrections not available yet
- $O(\alpha_s)$ computed for MSSM ($e^+e^- \to t\bar{t}\phi^0, b\bar{b}\phi^0$), not full MSSM

Note

Both previous corrections relevant for $e^+e^- \to t\bar{t}$

- Optimal scale $\sqrt{s} \simeq 700 - 800$ GeV: Dilution of the coupling?



SM Higgs Decay rates

Tree level decays

$$\Gamma(H \to f\bar{f}) = \frac{g^2_{hff}}{4\pi}\frac{N_c M_H}{2}\beta_f^3$$

$$\Gamma(H \to VV) = \frac{g^2_{hVV}}{4\pi}\frac{3\delta_V}{8M_H}\left(1 - \frac{4}{3}\frac{1}{\tau_V} + \frac{4}{3}\frac{1}{\tau_V^2}\right)\beta_V$$

$(\tau_i = 4m_i^2/M_H^2,\ \beta_i = \sqrt{1-\tau_f})$

- one-loop: complete EW and QCD corrections
- beyond one-loop: dominant corrections $(\alpha_s,\ g_{ttH},\ \lambda)$

  $\longrightarrow$ two-loop and three-loop QCD corrections

  $\longrightarrow$ $O(g^2_{htt})$, $O(g^4_{htt})$, $O(\alpha_s(m_t)g^2_{htt})$, $O(\alpha_s^2(m_t)g^2_{htt})$ corrections computed in the low-mass Higgs approximation

$$\lim_{p_H \to 0} \mathcal{A}(X \to Y + H) = \frac{1}{v}\sum_i m_i \frac{\partial}{\partial m_i}\mathcal{A}(X \to Y)$$

  $\longrightarrow$ $\mathcal{O}(\lambda^2)$ corrections for $M_H \gg 2M_Z$

Chetyrkin, Kniehl, Sirlin, Steinhauser, Djouadi, Spira, Zerwas, Melnikov, Marciano, Willenbrock, Ghinculov, ...

Loop induced decays

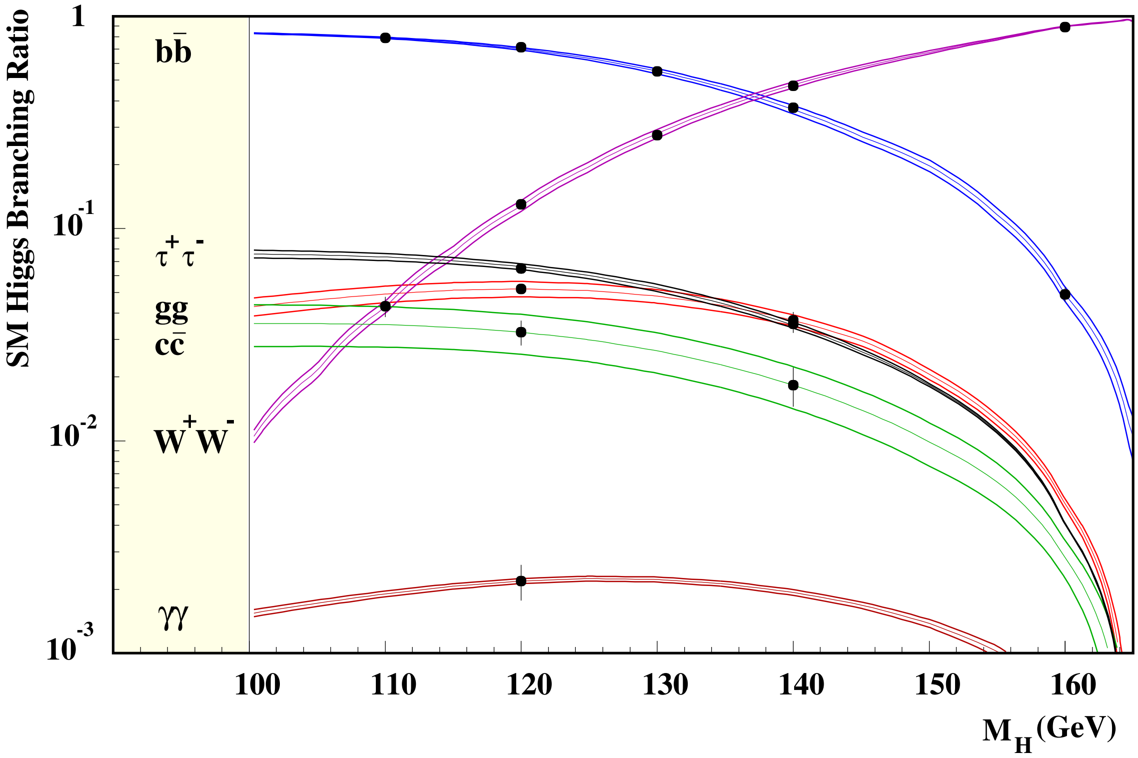
$$\Gamma(H \to gg) = \frac{G_F \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3} \left| \sum_Q A_Q^H(\tau_Q) \right|$$

- QCD corrections up to three loops (15-20% à la BLM)
- $\mathcal{O}(G_F M_t^2)$ EW corrections very small

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_{cf} e_f^2 A_f^H(\tau_f) + A_W^H(\tau_W) \right|^2$$

- QCD corrections up to three loops (3% for light Higgs)
- $\mathcal{O}(G_F M_t^2)$ EW small (1%)

$\Gamma(H \to \gamma Z) \longrightarrow$ similar to $\Gamma(H \to \gamma\gamma)$



For $M_H = 120$ GeV, $\sqrt{s} = 350, 500$ GeV and 500 fb^{-1}

Decay mode:	$b\bar{b}$	WW^*	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$
HFITTER (350)	2.4%	5.1%	5.0%	8.5%	5.5%	19%
HFITTER (500)	2.9%	9.3%	7.9%	39%	18%	
Theory	1.4%	2.3%	2.3%	23%	5.7%	2.3%

Mainly due to: m_c, m_b, and $\alpha_s(\mu)$.

From HDECAY when (Carena etal., hep-ph/0106116):

$$\alpha_s(M_Z) = 0.1185 \pm 0.0020$$
$$m_c(m_c) = 1.23 \pm 0.09 \text{ GeV}$$
$$m_b(m_b) = 4.17 \pm 0.05 \text{ GeV}$$

MSSM Higgs Decay rates

A part from obvious rescaling of the couplings...

- $\Gamma(\Phi^0 \to f\bar{f})$ and $\Gamma(H^\pm \to f'\bar{f})$
  $\longrightarrow$ QCD corrections as SM
  $\longrightarrow$ full MSSM EW and QCD corrections: usually $< 10\%$, except large gluino contributions for large $\tan\beta$ and $M_{\tilde{q}} < 300$ GeV.

- $\Gamma(\Phi^0 \to gg)$: b-quark loop and squark loop can be important
  $\longrightarrow$ QCD corrections as SM

- $\Gamma(\Phi^0 \to \gamma\gamma)$: additional sfermion, chargino, and charged Higgs loops
  $\longrightarrow$ QCD corrections normally small
  $\longrightarrow$ no complete MSSM corrections

- Decays to MSSM particles

Conclusions

- Incredible amount of work done for e^+e^-, both SM and MSSM, allows us to claim that a LC can do precision Higgs boson physics

- $2 \to 3$ production processes: EW and MSSM corrections still missing

- Study of distributions at precision level

- Study of background at precision level

- Careful interface between available theoretical predictions and precision fits: need to show drastic improvement with respect to the LHC (see Zeppenfeld's talk, tomorrow)

- This sounds like a good start: more from further studies of the LC potential!