Higgs Physics at a e^+e^- Linear Collider

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On behalf of the ECFA/DESY Higgs boson study group
with contributions from US and Asian Higgs study groups

Many thanks for contributions from: M.Battaglia, J.-C. Brient, K.Desch, F.Gianotti, A.Gay, E.Gross, J.Guasch, A.Kiiskinen, R.Van Kooten, N.Meyer, S.Penaranda, J.Schreiber, M.Schumacher, S.Yamashita

Outline

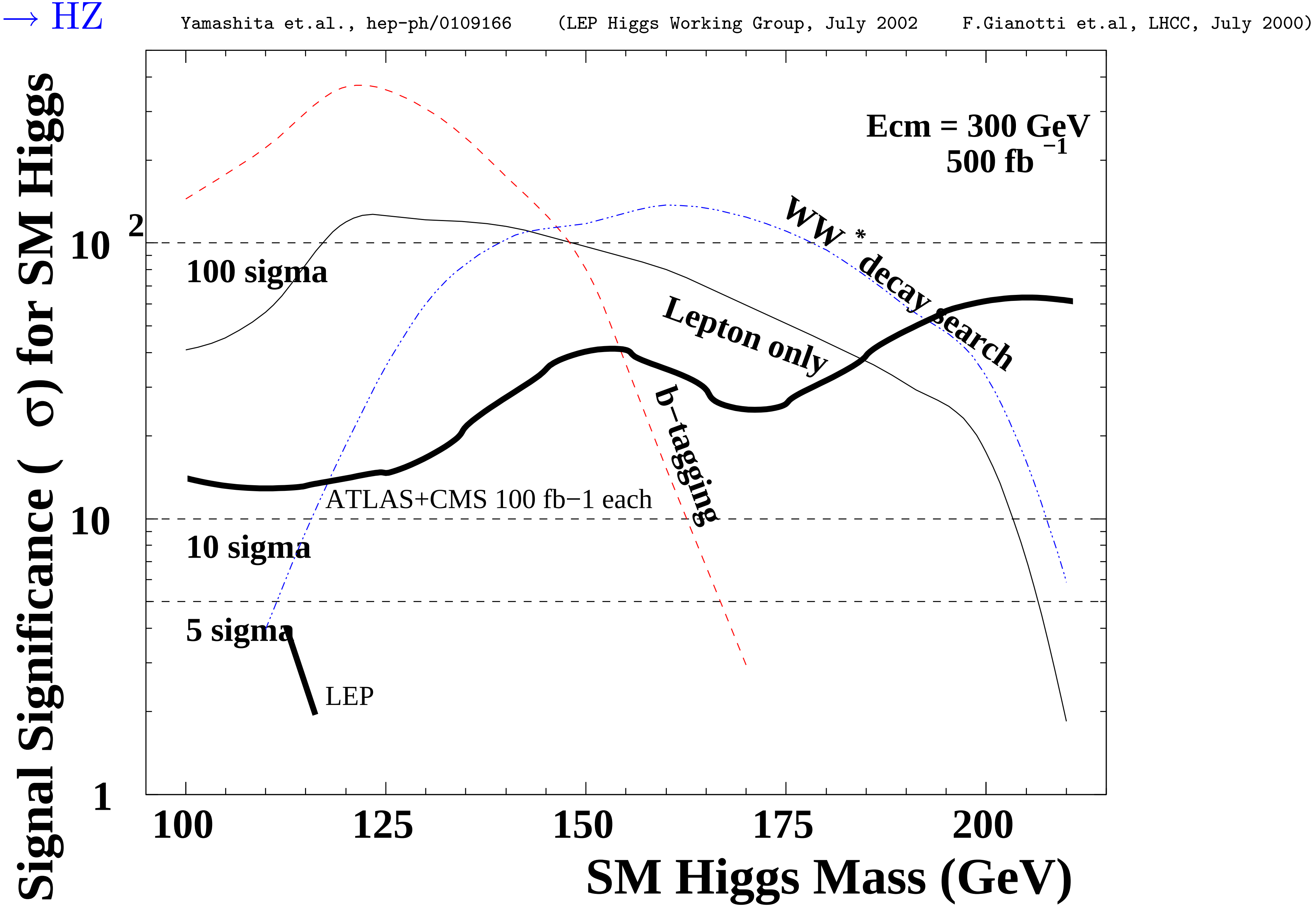
- Standard Model Physics
  - Higgs boson production mechanism
  - Indirect and direct branching ratio measurements
  - Characterization of the Higgs boson potential
  - Higgs boson strahlung from top quarks
- The General Two-Doublet Higgs Model
  - Charged Higgs bosons
  - Determination of the ratio of the VEV $\tan\beta$
- MSSM and beyond
  - Invisible Higgs boson decays
  - Higgs boson parity
  - Distinction of Higgs boson models
- Conclusions

Introduction

- Linear e^+e^- Collider of at least $\sqrt{s} = 500$ GeV and high luminosity: large potential to study Higgs bosons and understand electroweak symmetry-breaking and mass generation.
- e^+e^- collider, LEP: immense progress for Higgs boson searches, almost background free at LEP-1 and sensitivity beyond expectations at LEP-2.
- 10 years of Linear Collider Higgs studies: from discovery to precision measurements.
- New milestones: TESLA TDR 2001, Snowmass 2001, next Korea LCWS 2002.
- Recommendation to build TESLA by the German Science Council, July 2002.
- Review with focus on new results and developments.

SM Higgs Significance

$e^+e^- \to Z \to HZ$



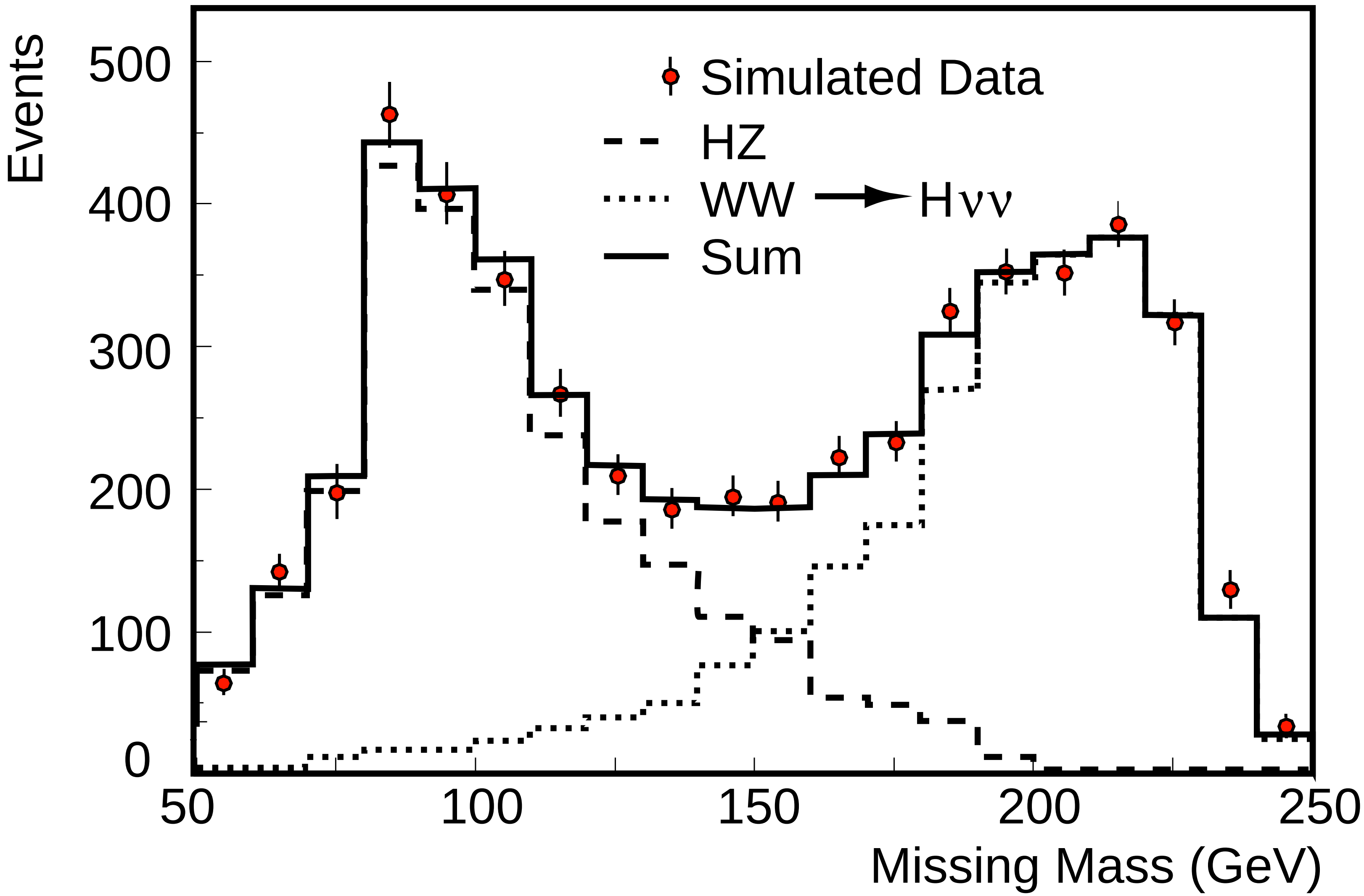
Very high sensitivity at a LC, and extended mass reach at the LHC.

Higgs Boson Strahlung/Fusion

$e^+e^- \rightarrow ZH \rightarrow \nu\bar{\nu}H \rightarrow \nu\bar{\nu}b\bar{b}$

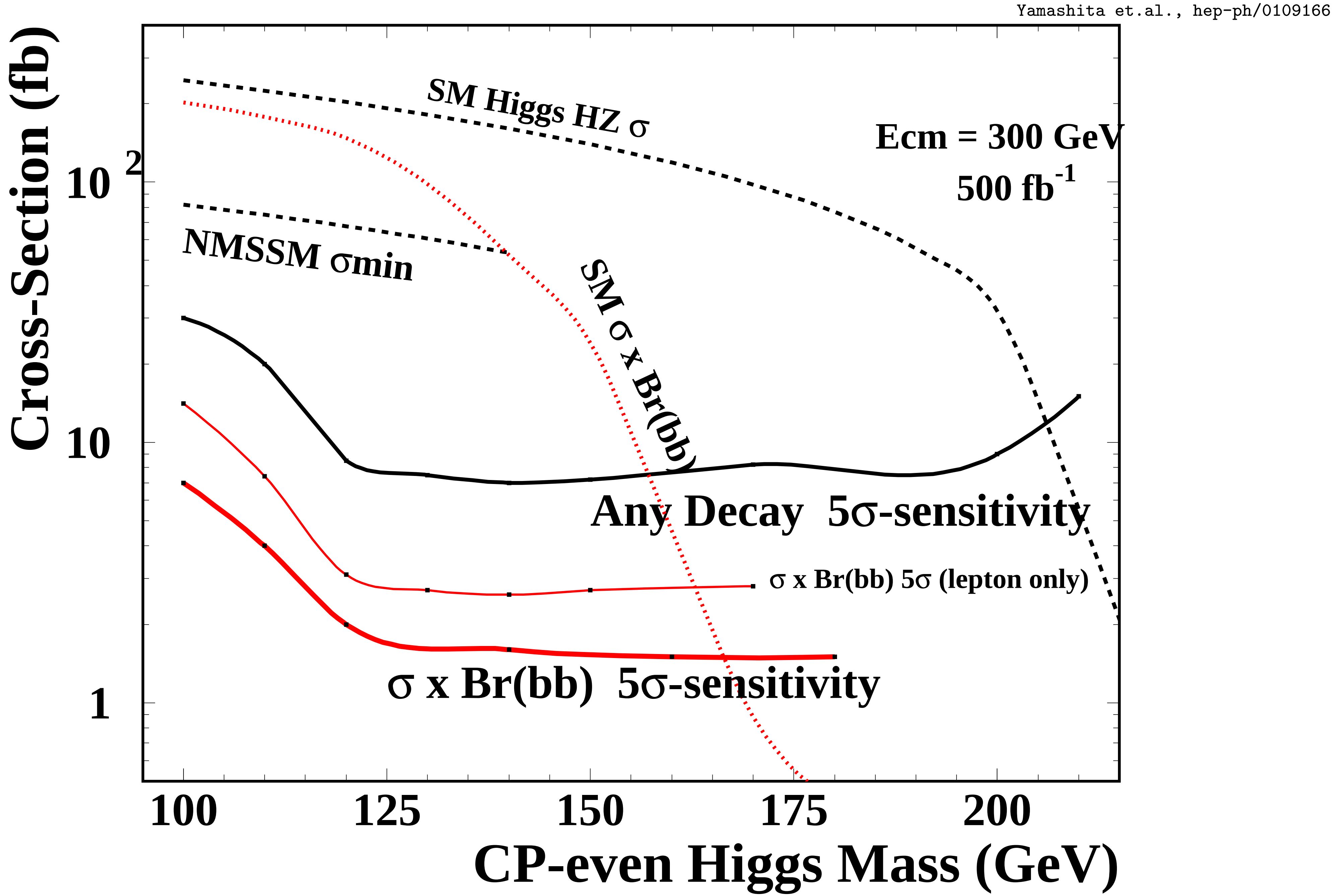
$e^+e^- \rightarrow W^+W^-\nu\bar{\nu} \rightarrow \nu\bar{\nu}H \rightarrow \nu\bar{\nu}b\bar{b}$

Van Kooten, LCWS, Baltimore, March 2001



Detailed determination of Higgs boson production mechanism.

General Cross Section Sensitivity



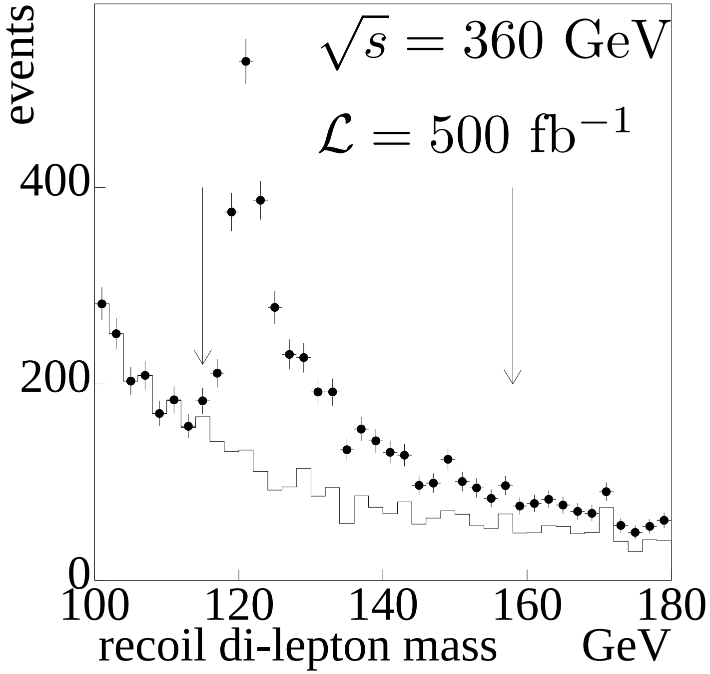
SM Decay Branching Ratios

$e^+e^- \to HZ \to H\ell^+\ell^-$

- Indirect $BR(H \to X)$ determination:
  Inclusive: $\sigma_{inc} = \sigma_{HZ} BR(Z \to \ell^+\ell^-)$
  Individual: $\sigma(X) = \sigma_{HZ} BR(Z \to Y) BR(H \to X)$
- Direct $BR(H \to X)$ determination:

Brient, LC-PHSM-2002-003

Selection of a HZ sample $Z \to \ell^+\ell^-$, where $m_H = m^{recoil}_{\ell^+\ell^-}$.
Selection in this sample of individual Higgs decay modes.



Decays mode	SM branching ratio(%)	$\Delta BR/BR$(%)
bb	68	1.5
$\tau\tau$	6.9	4.1
cc	3.1	5.8
gluons	7.0	3.6
$\gamma\gamma$	0.22	21
$WW^\star$	13	2.7

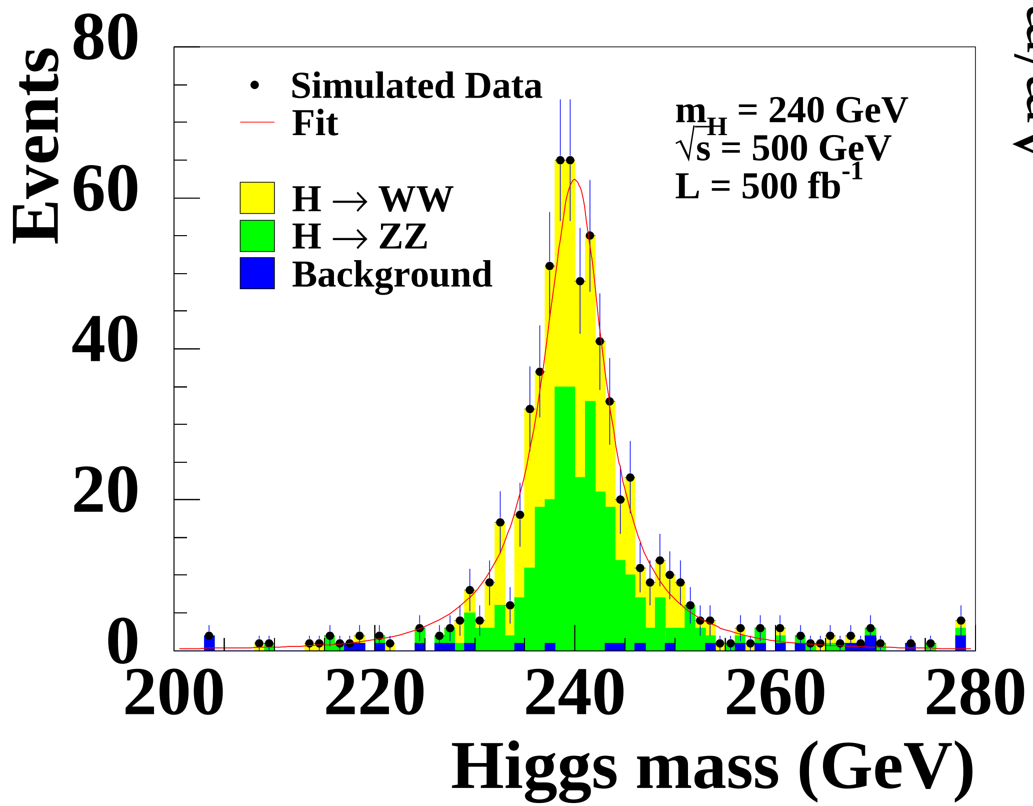
Complementarity with LHC, higher precision and all decay modes. Test: $g_{Hff} \propto m_f$

SM Higgs Mass and Decay Width

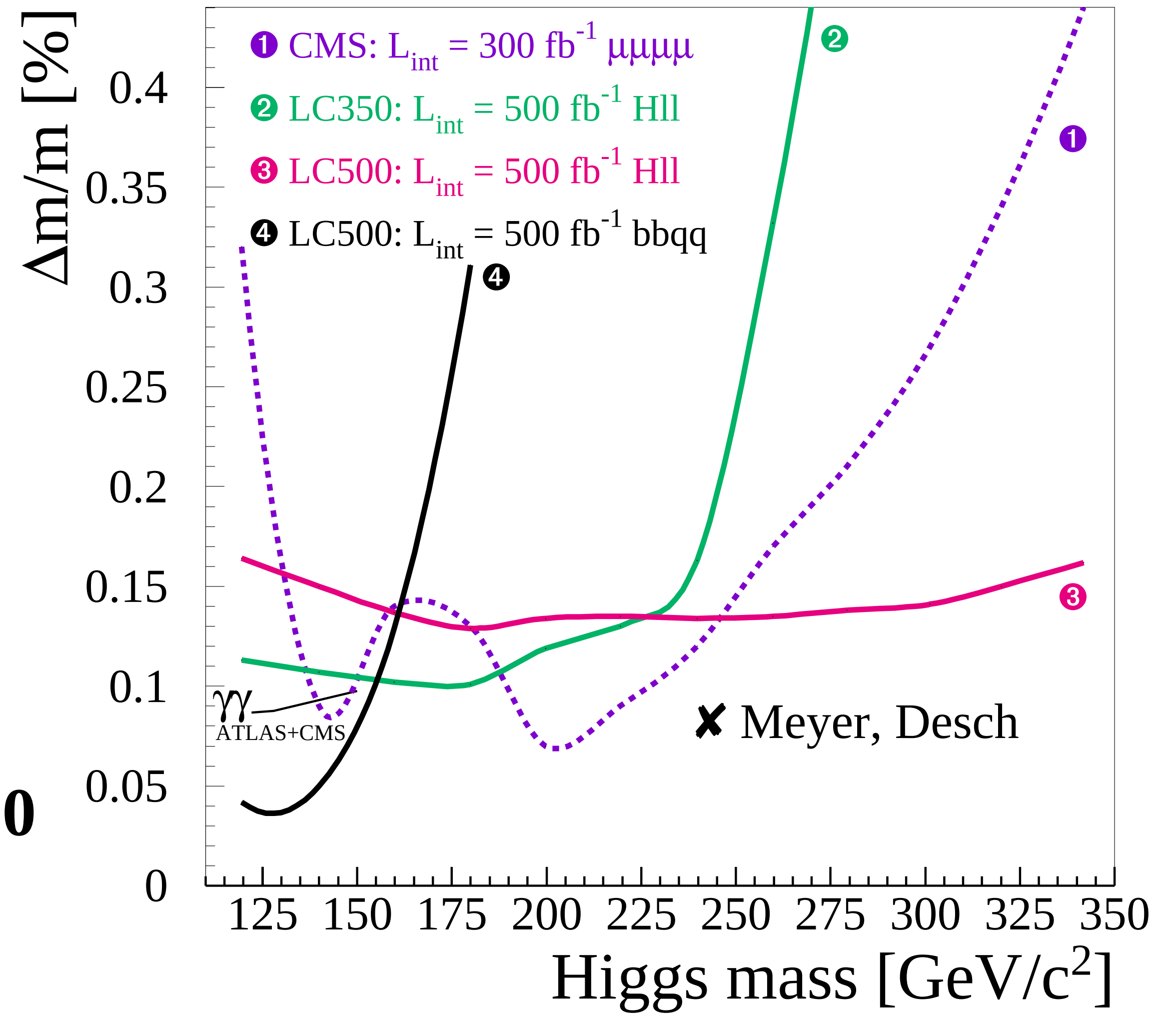
$e^+e^- \to HZ \to WWZ$

$e^+e^- \to HZ \to ZZZ$

Meyer, Desch, LCWS St.Malo, March 2002



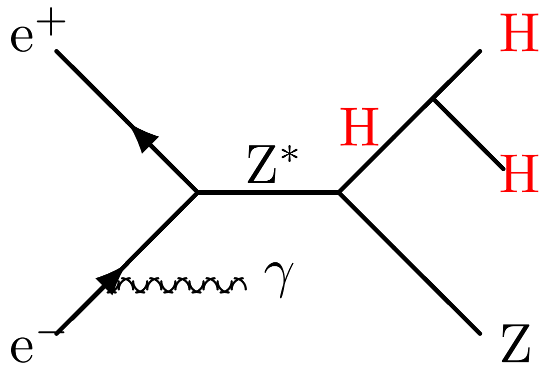
Drollinger, Sopczak, EPJdirect C-N1 (2001) 1



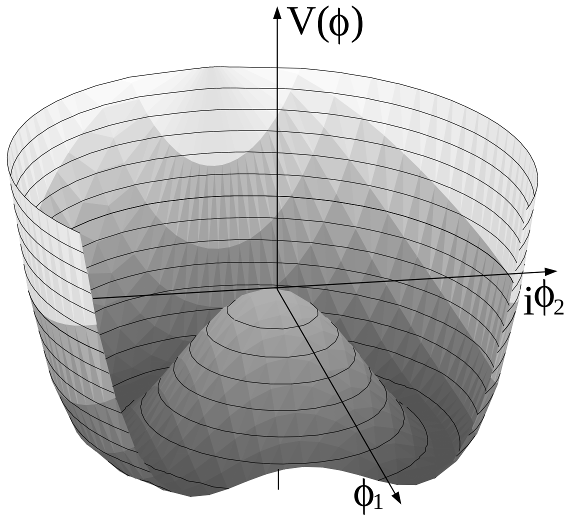
$\Delta m_H/m_H = 0.08\%$ $\quad \Delta\Gamma_H/\Gamma_H = 11\%$

SM Higgs Boson Potential

$e^+e^- \to HZ \to HHZ$:



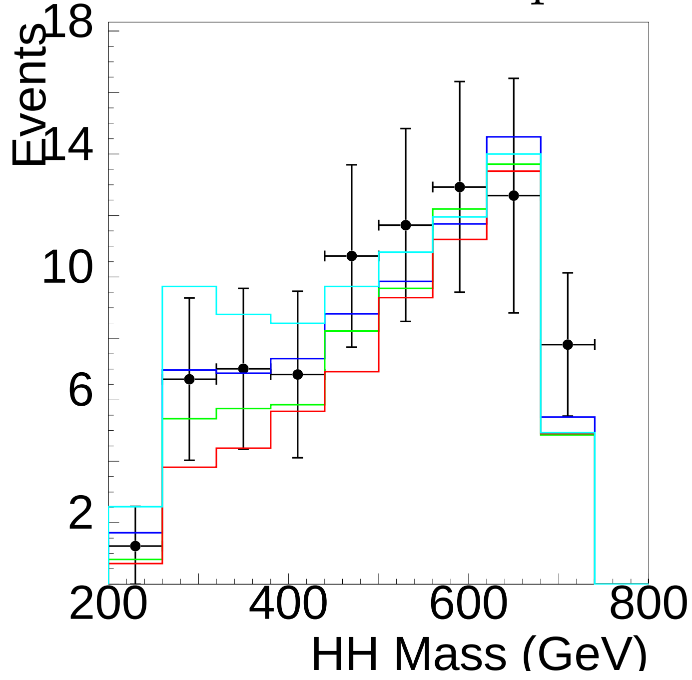
Probing shape of potential



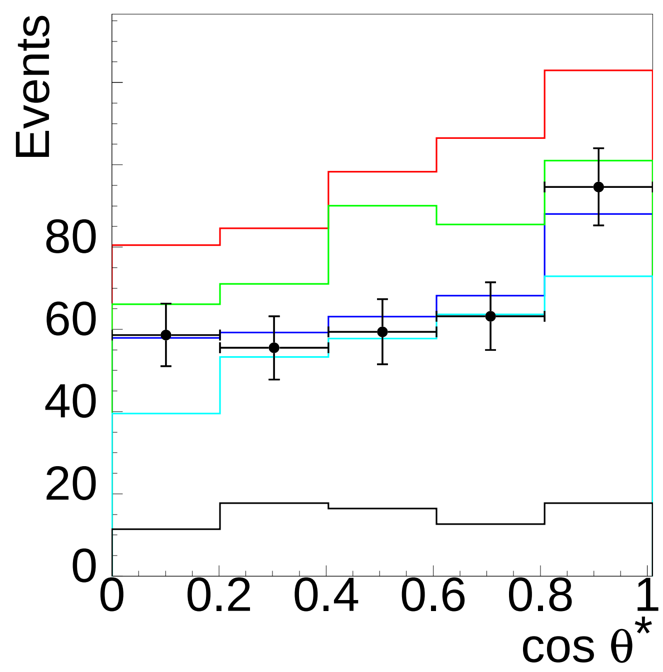
Triple Higgs boson coupling: $g_{\rm HHH} = 3m_H^2/2v$, where $v = 246$ GeV.

Battaglia, Boos, Yao, hep-ph/0111276

$\sqrt{s}$=800 GeV $\mathcal{L}$=1000 fb^{-1} invariant mass of HH pair



$\sqrt{s}$=3 TeV $\mathcal{L}$=5000 fb^{-1} angle between H and HH



Lines indicate $g_{\rm HHH}/g_{\rm HHH}^{\rm SM} = 1.25,\ 1.00,\ 0.75,\ 0.50$

Sensitivity $\Delta g/g = 29\%$

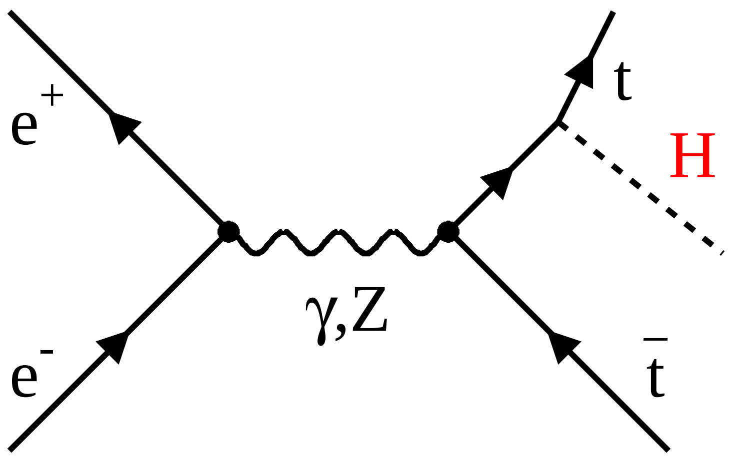
Sensitivity $\Delta g/g = 7\%$

SM Higgsstrahlung ttH

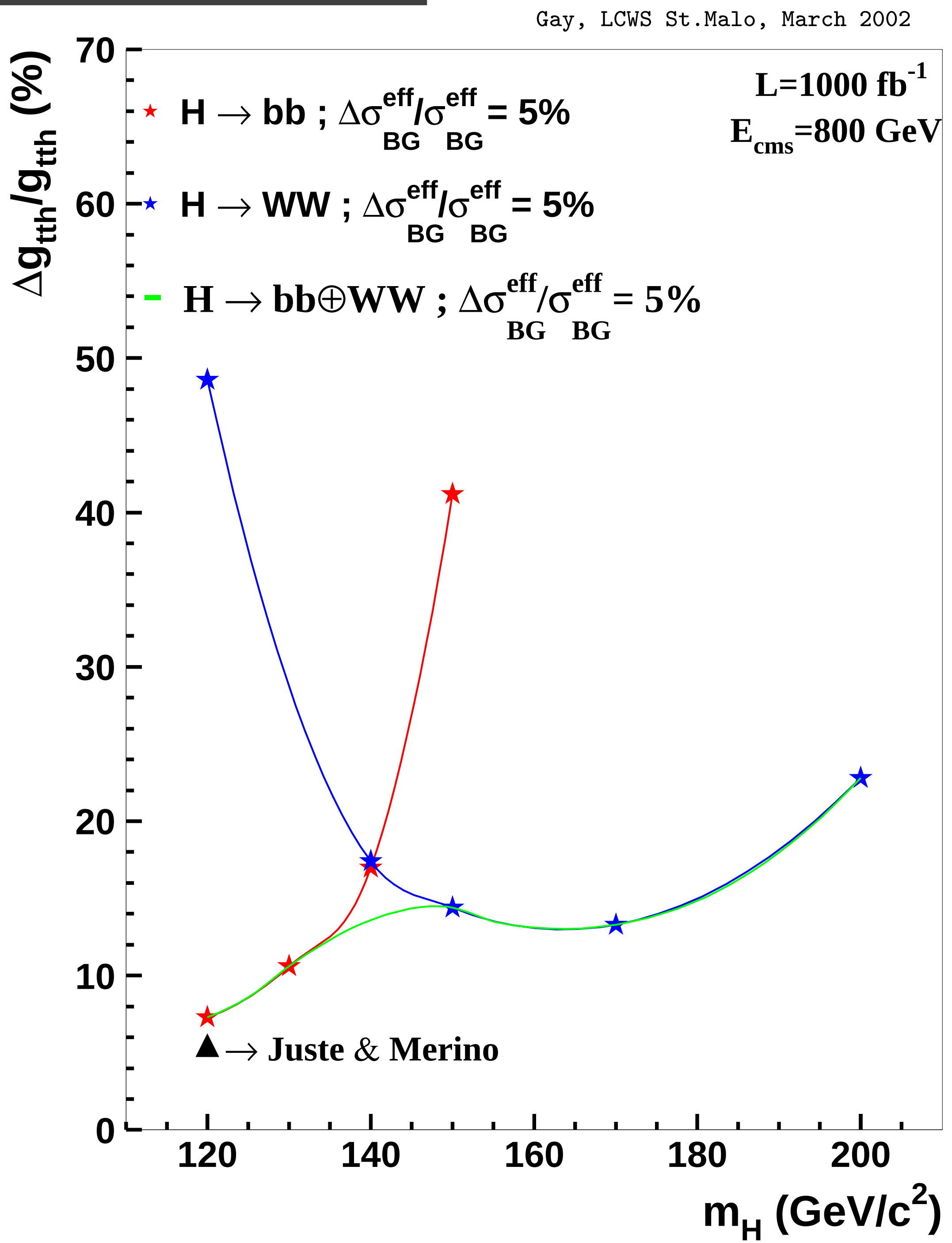
$e^+e^- \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

$e^+e^- \rightarrow t\bar{t}H \rightarrow t\bar{t}W^+W^-$

Challenge: 5% precision on the background.



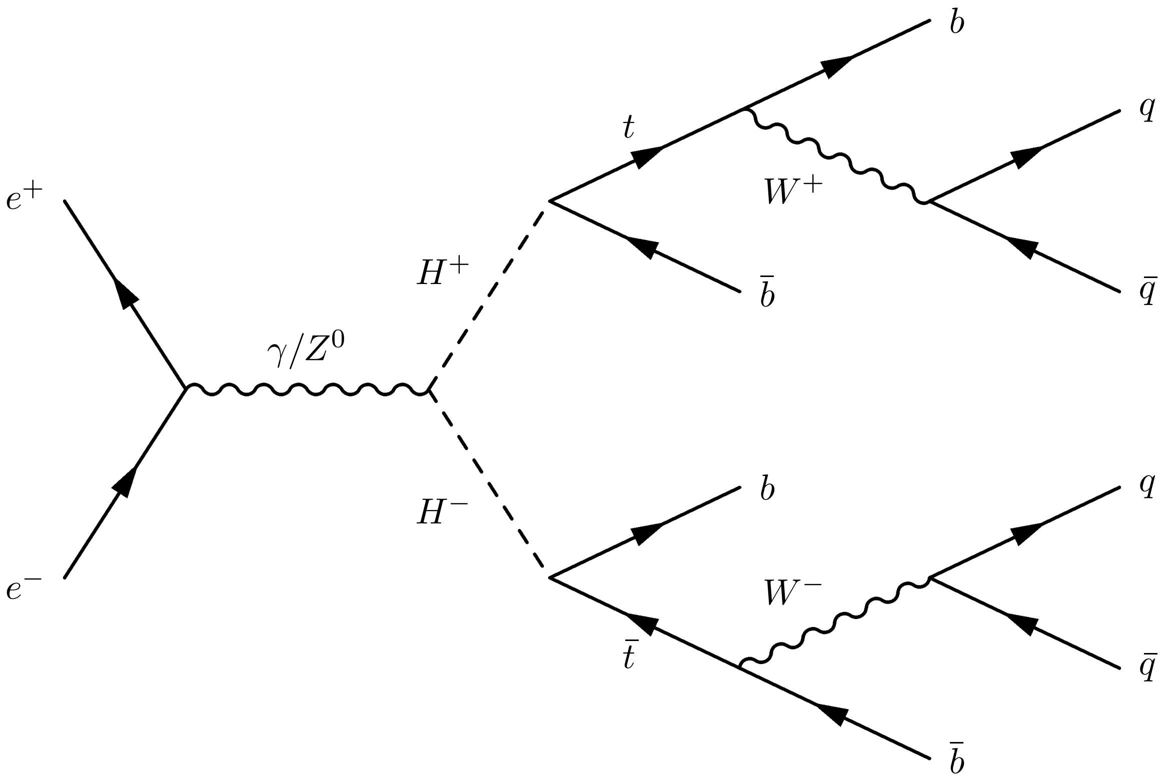
$\Delta g_{\rm ttH}/g_{\rm ttH} = 5$ to 20%



2DHM Charged Higgs Bosons

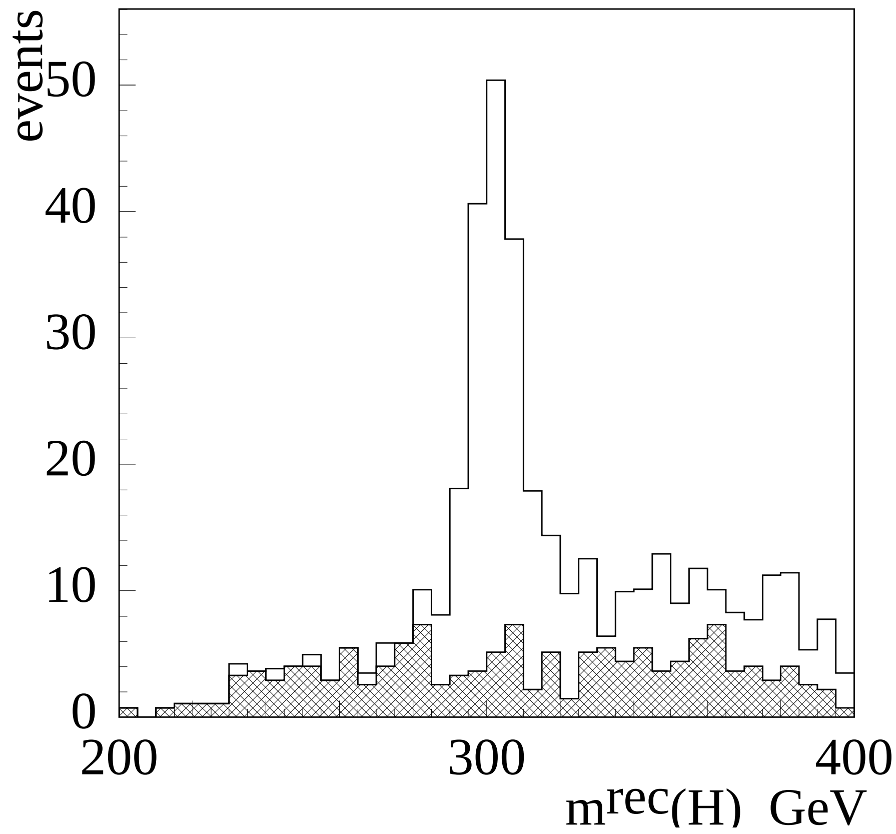
$e^+e^- \to Z \to H^+H^- \to t\bar{b}\bar{t}b$

Detailed reconstruction
of the entire decay chain.



Battaglia, Ferrari, Kiiskinen, hep-ph/0112015

$\sqrt{s} = 800$ GeV and $\mathcal{L} = 1000$ fb^{-1}

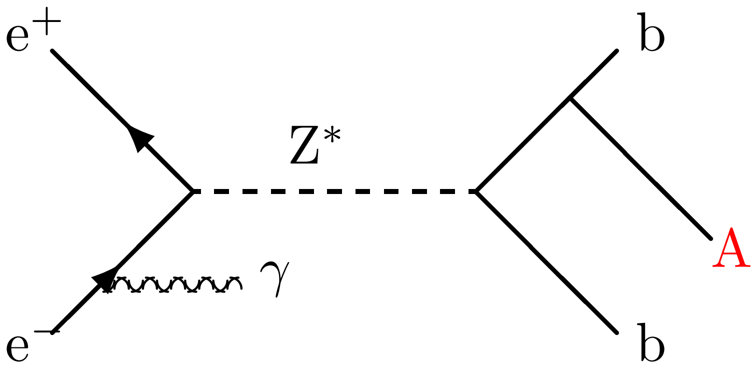


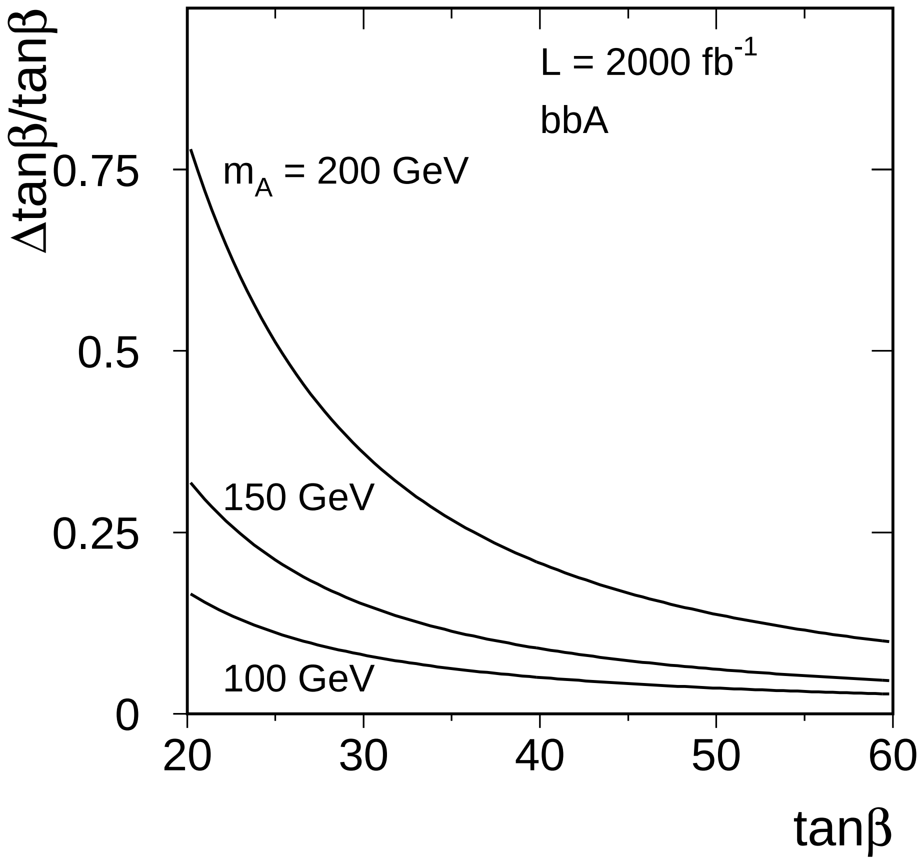
$\Delta(\sigma BR(H^+ \to t\bar{b}))/\sigma BR(H^+ \to t\bar{b}) = 8.8\%$

2DHM Higgsstrahlung bbA

Gunion, Han, Jiang, Mrenna, Sopczak hep-ph/0112334

$e^+e^- \rightarrow b\bar{b} \rightarrow b\bar{b}A \rightarrow b\bar{b}b\bar{b}$





Measure $\tan\beta \equiv \mathrm{VEV}_1/\mathrm{VEV}_2$

1) bbA rate $\propto g^2_{\mathrm{bbA}} \propto \tan^2\beta$

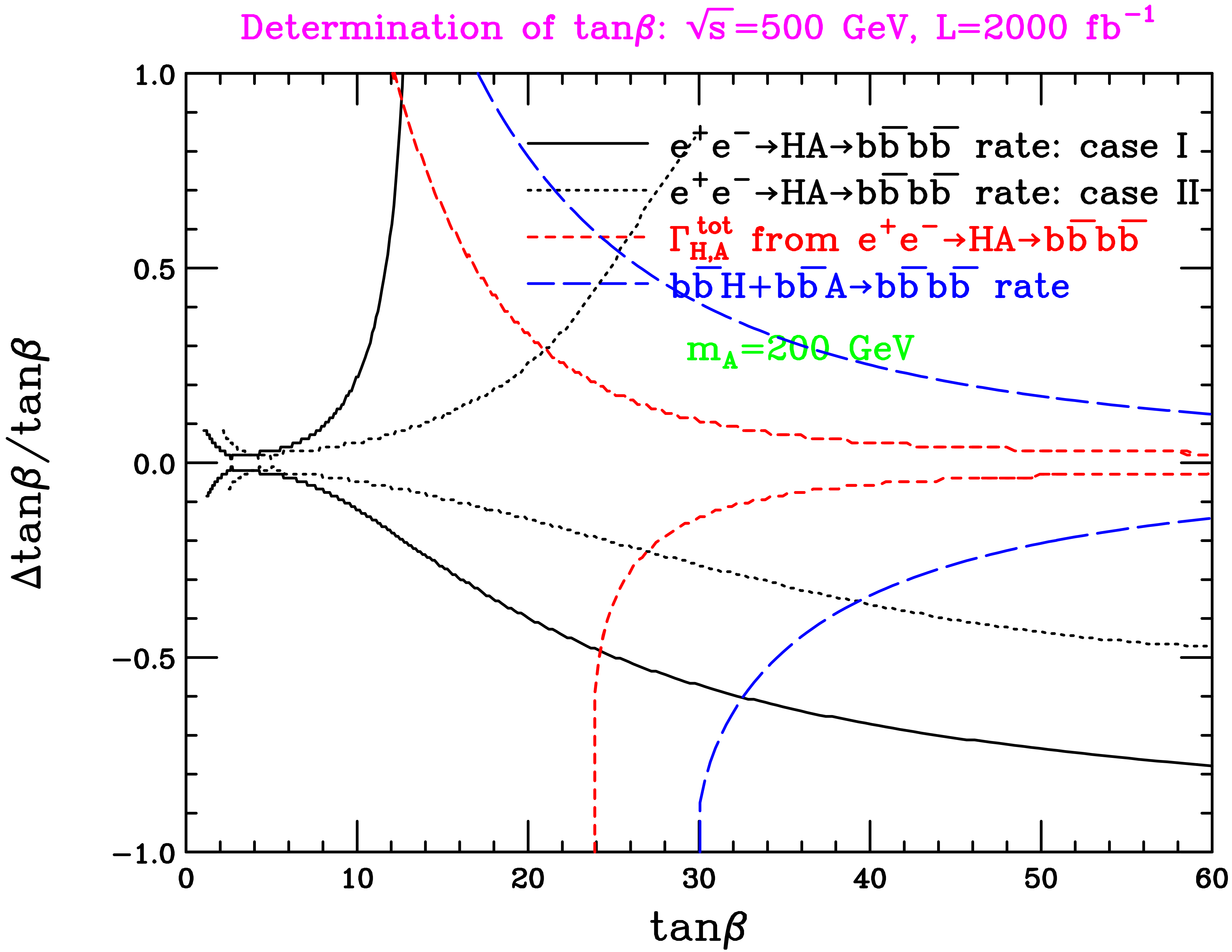
Further methods:

2) $e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$ rate

3) H,A decay width

4) H^+ decay width

MSSM Higgsstrahlung bbH



MSSM Invisible Higgs Boson Decays

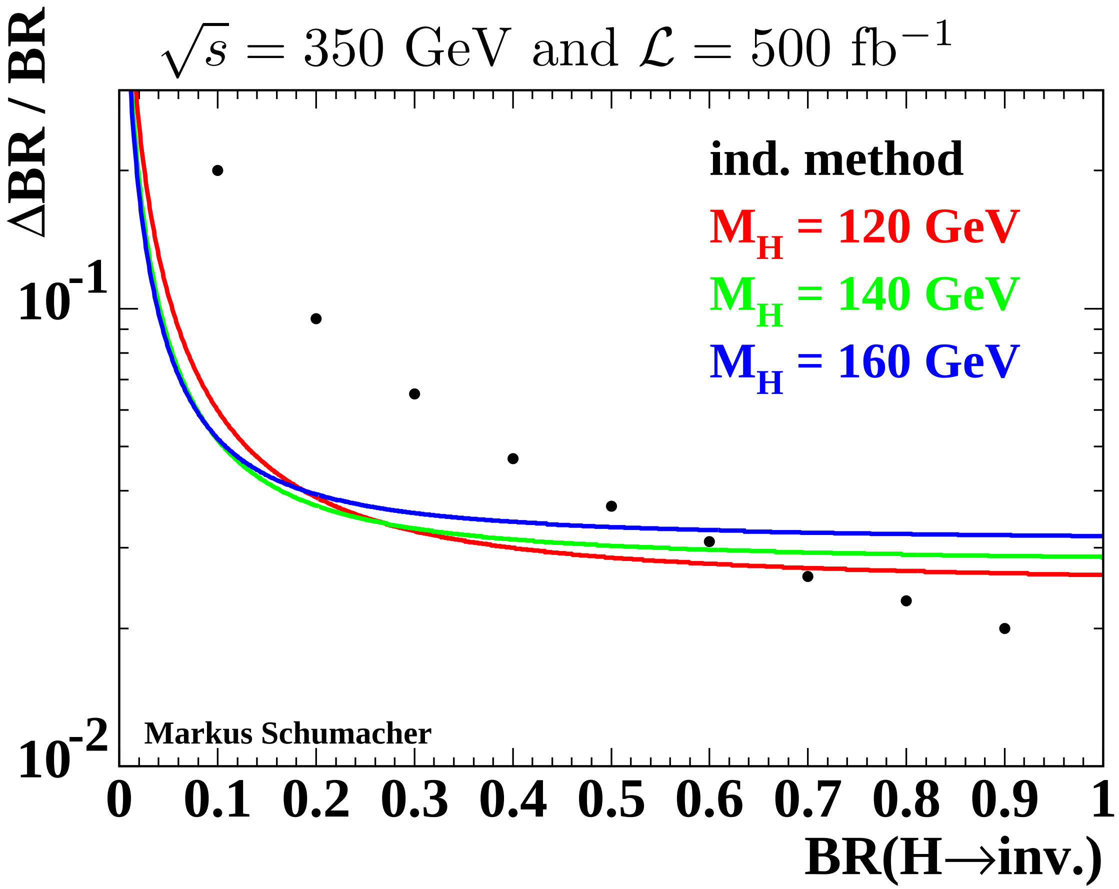
$e^+e^- \to ZH \to Z\tilde{\chi}^0\tilde{\chi}^0$: $m_H = m_Z^{recoil}$

Schumacher, LCWS, Cracow, Sep. 2001

LEP: All Z decay modes, here first $Z \to q\bar{q}$.

Higher sensitivity cf. indirect method (1− sum of visible H decay modes).

$\sqrt{s} = 350$ GeV and $\mathcal{L} = 500$ fb^{-1}



$\Delta BR/BR < 4\%$ for $BR(H \to inv.) > 20\%$ and SM production rate.

Higgs Boson Parity

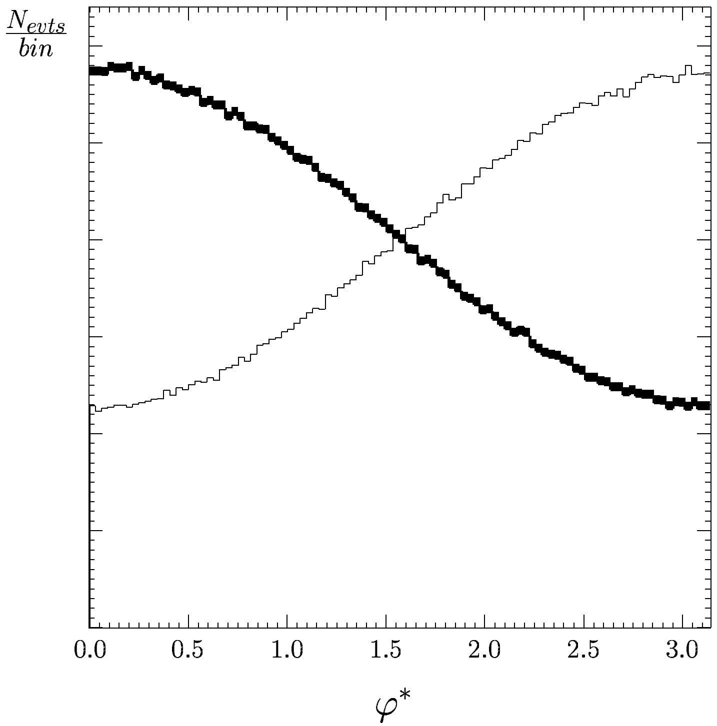
H: CP-even

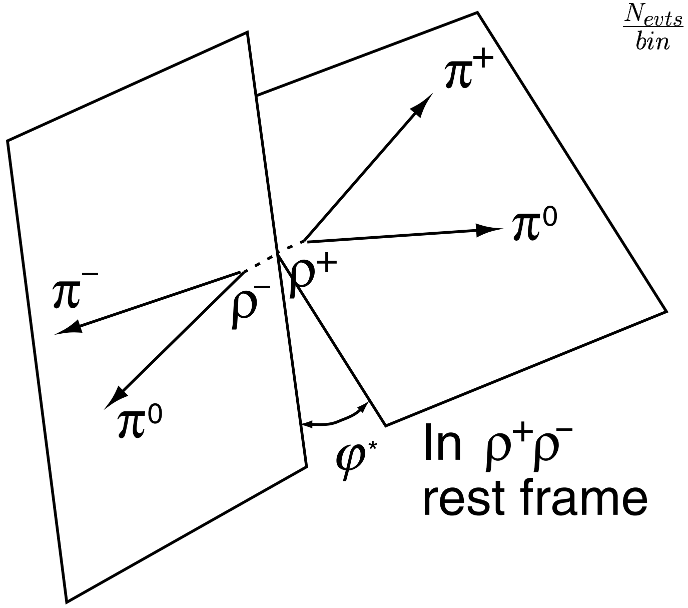
A: CP-odd

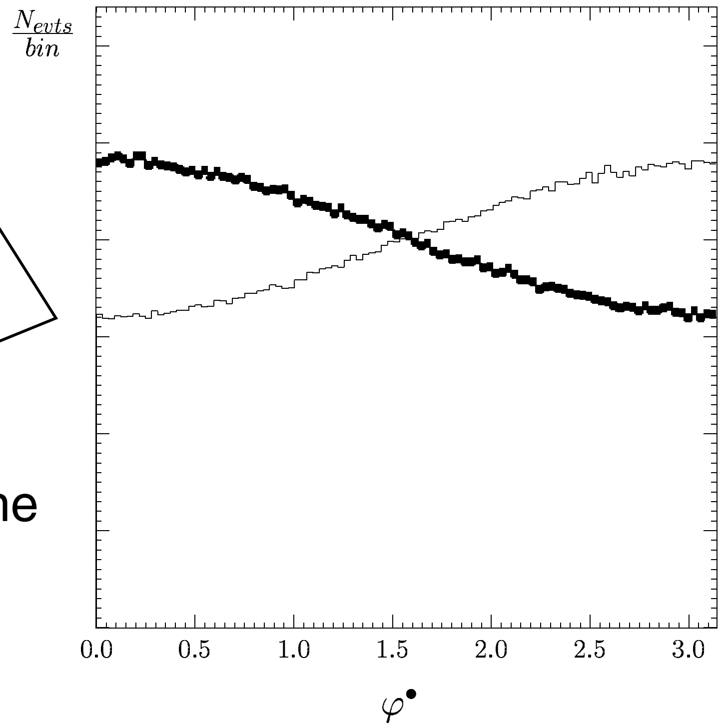
$$H/A \to \tau^+\tau^- \to \rho^+\bar{\nu}_\tau\rho^-\nu_\tau \to \pi^+\pi^0\bar{\nu}_\tau\pi^-\pi^0\nu_\tau$$

Bower, Pierzchal, Wąs, Worek, hep-ph/0204292

$\rho^+\rho^-$ acoplanarity angle before and after detector simulation







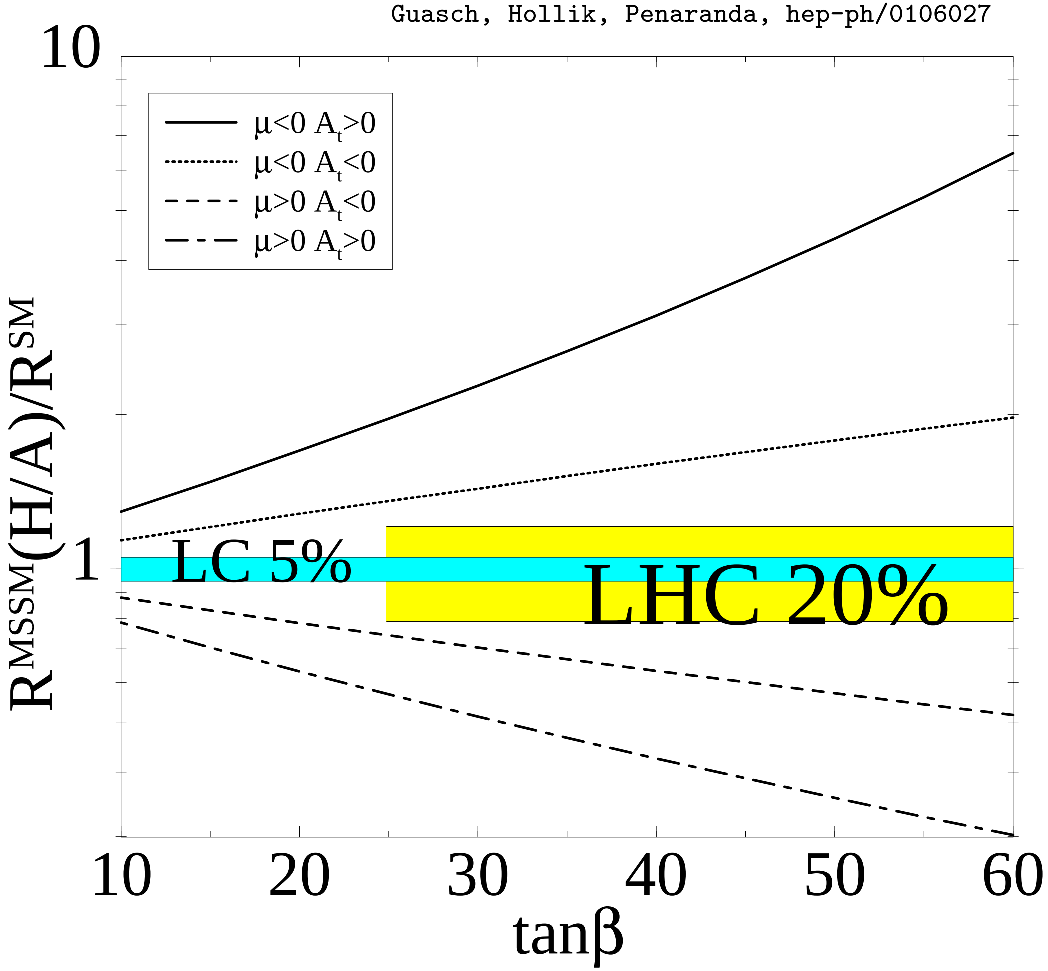
Difference between scalar (thick line)

and pseusoscalar (thin line) Higgs bosons can be determined.

Distinction of Models

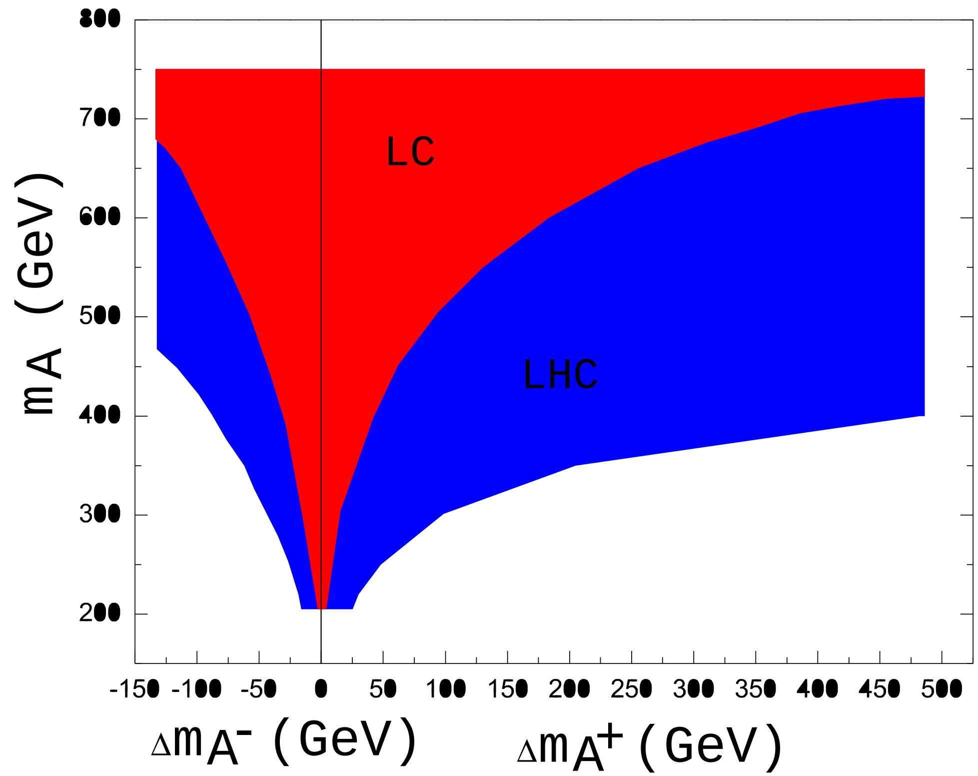
$R = BR(\mathrm{H} \to \mathrm{b\bar{b}})/BR(\mathrm{H} \to \tau^+\tau^-)$

Guasch, Hollik, Penaranda, hep-ph/0106027



$\frac{BR(\mathrm{H\to b\bar{b}})/BR^{\mathrm{SM}}_{\mathrm{b\bar{b}}}}{BR(\mathrm{H\to W^+W^-})/BR^{\mathrm{SM}}_{\mathrm{W^+W^-}}} < 3.5\% < 20\%$

Gross, Heinemeyer, Weiglein, private communications



$\Rightarrow$ stronger A mass prediction at a LC

MSSM predicts large effects in all scenarios:

LHC large $\tan\beta$, LC all $\tan\beta$

Miller, Nevzorov, Zerwas, SUSY02, June 2002

NMSSM: extra singlet $\lambda N H_1 H_2$

e.g. $m^2_{\mathrm{H}+} = m^2_{\mathrm{A}} + m^2_{\mathrm{W}+} - 0.5\lambda^2\, v^2$

Measurement of $m_{\mathrm{H}+}$ and m_{A}

$\Rightarrow$ MSSM or beyond

Conclusions

- After a first discovery at the Tevatron or the LHC and initial precision measurements, already in the first phase of a LC, all Higgs boson decay modes will be measured with very high precision.
- Models like the SM, the general 2DHM, the MSSM or the NMSSM will be distinguished for a wide range of parameters.
- The underlying mechanism of symmetry breaking and mass generation will be tested.
- The model parameters will be measured and the Higgs boson might be known as precisely as is the Z boson today.
- Like for the top quark (LEP mass prediction, Tevatron observation), important consistencies of the model can be probed with combined LC and LHC physics.
- After 10 years of preparational studies the LC has a solid case and the HEP community is prepared to answer fundamental questions over the next decades.