Higgs physics in the MSSM: looking beyond LEP

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1. Introduction

2. Present status of m_{h} predictions in the MSSM

3. LEP results: benchmarks and beyond

4. Prospects for the future

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1. Introduction

Higgs sector of the MSSM:

Two Higgs doublets H_1, H_2:

$$\begin{pmatrix} v_1 + (\phi_1^0 + i\chi_1^0)/\sqrt{2} \\ \phi_1^- \end{pmatrix}, \quad \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + i\chi_2^0)/\sqrt{2} \end{pmatrix}$$

Physical states: $h^0, H^0, A^0, H^\pm$

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

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

MSSM, lowest order: $m_\mathrm{h} < M_\mathrm{Z}$

Large radiative corrections:

Dominant one-loop corrections: $\sim G_\mu m_\mathrm{t}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_\mathrm{t}^2}\right)$

Two-loop result

[*S. Heinemeyer, W. Hollik, G. W. '99*]

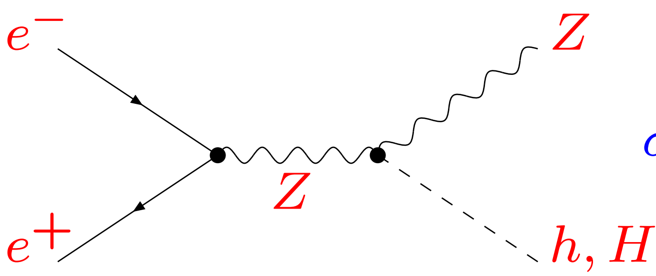
$$\Rightarrow m_\mathrm{h} \lesssim 135 \text{ GeV}$$

Measurement of m_h, Higgs couplings

$\Rightarrow$ test of the theory (more directly than in SM)

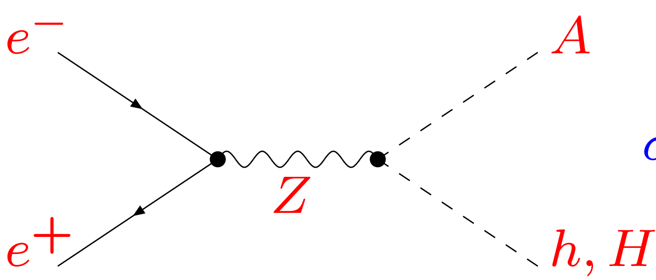
Production of neutral MSSM Higgs bosons at LEP:

$e^+e^- \to Zh, ZH$



$\sigma_{\rm hZ} \approx \sin^2(\beta - \alpha_{\rm eff})\sigma_{\rm hZ}^{\rm SM}$

$e^+e^- \to Ah, AH$



$\sigma_{\rm hA} \propto \cos^2(\beta - \alpha_{\rm eff})\sigma_{\rm hZ}^{\rm SM}$

Interpretation of LEP excess within MSSM:

– $M_{\rm A} \gg M_{\rm Z} \Rightarrow h$ with SM-type couplings

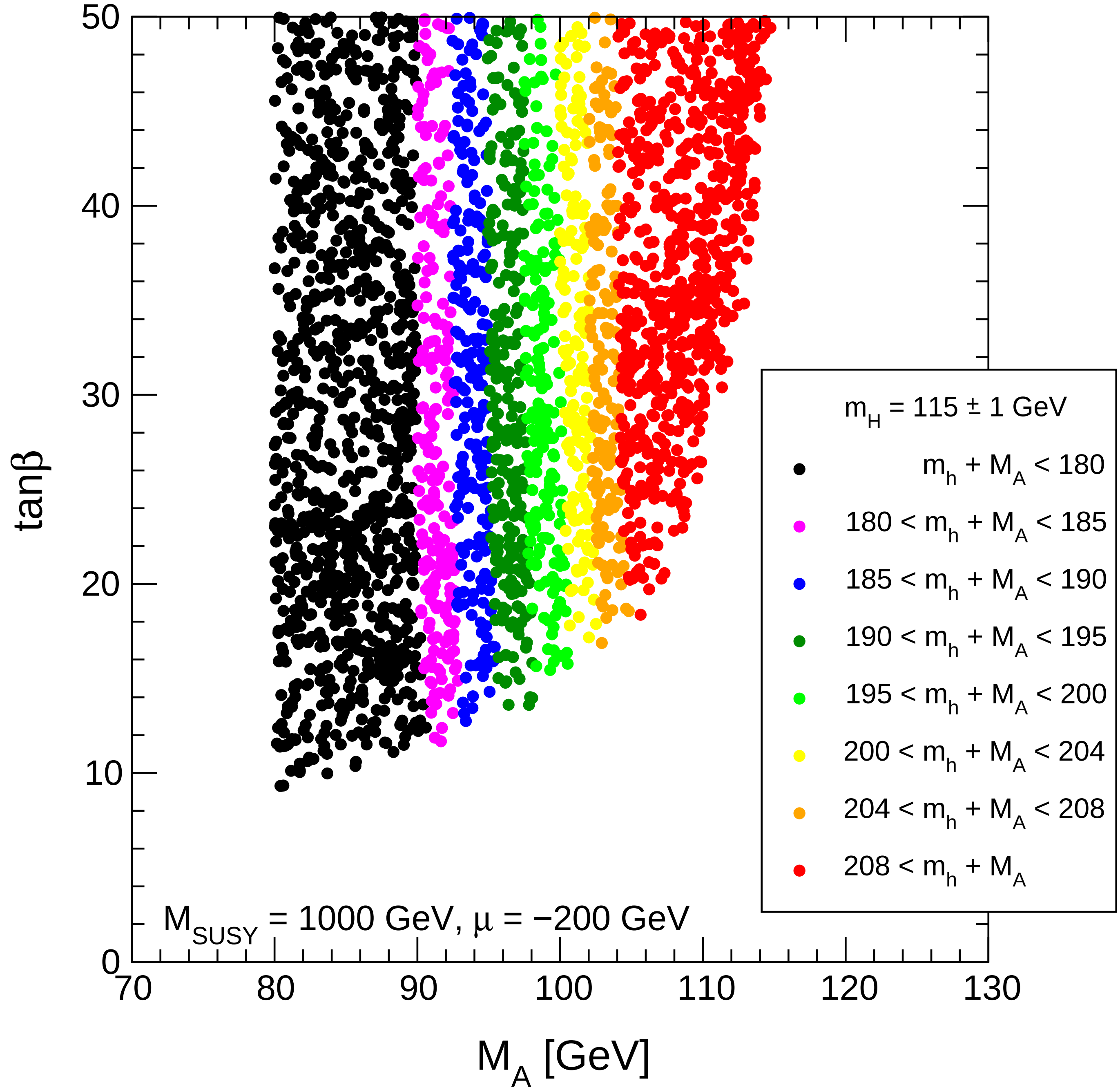
– other possibility:

$m_{\rm h}, M_{\rm A} \approx 100$ GeV, $\sin^2(\beta - \alpha_{\rm eff}) \ll 1$
$m_{\rm H} \approx 115$ GeV

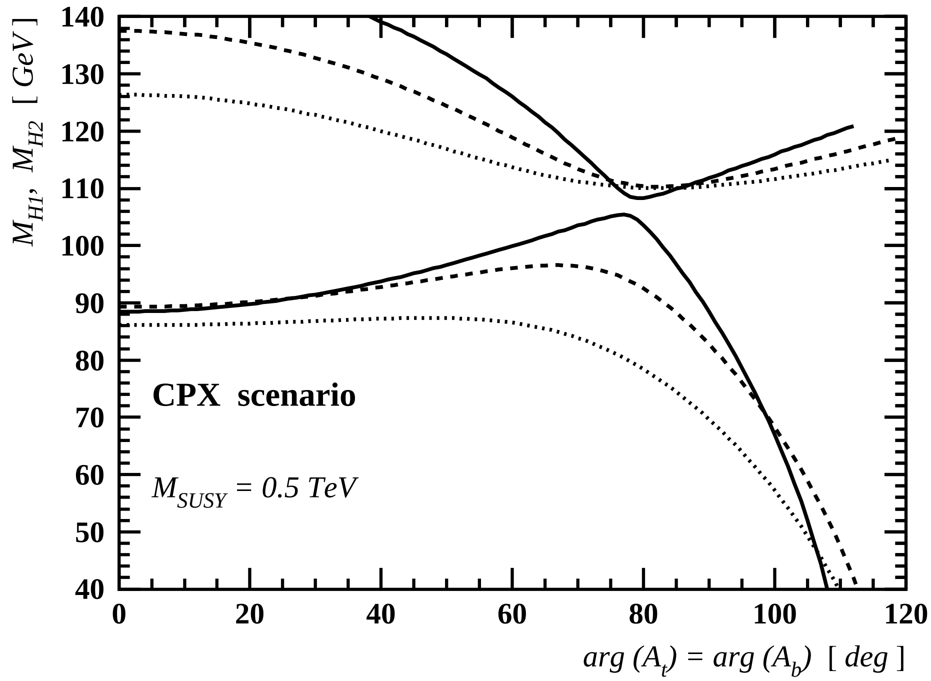
$\Rightarrow H$ with SM-type couplings

Allowed parameter space in M_A–$\tan\beta$ plane with $m_H = 115 \pm 1$ GeV, $\sin^2(\beta - \alpha_{eff}) < 0.2$:

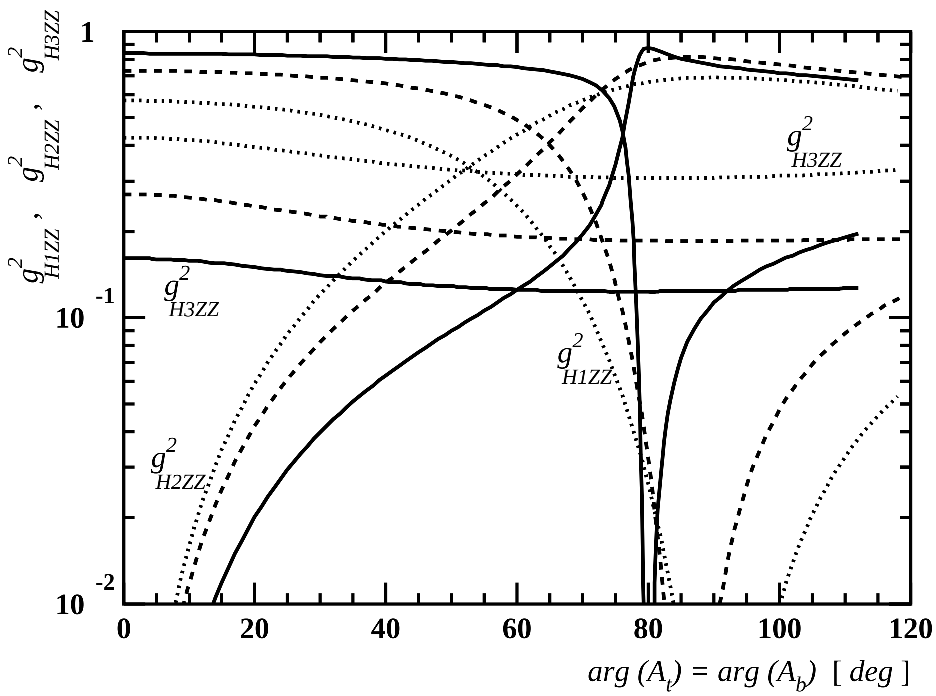
[*S. Heinemeyer, G. W. '00*]



Similar behavior also possible in $\mathcal{CP}$-violating case:
[*M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '00*]



(a)



(b)

2. Present status of m_h predictions in the MSSM

Different approaches for radiative corrections to m_h:

Effective potential, renormalization group (RG),
Feynman-diagrammatic (FD) approach

[*H. Haber, R. Hempfling '91*]
[*Y. Okada, M. Yamaguchi, T. Yanagida '91*]
[*J. Ellis, G. Ridolfi, F. Zwirner '91*]
[*R. Barbieri, M. Frigeni '91*]
[*P. Chankowski, S. Pokorski, J. Rosiek '94*]
[*A. Dabelstein '95*]
[*D. Pierce, J. Bagger, K. Matchev, R. Zhang '97*]

[*J. Casas, J. Espinosa, M. Quirós, A. Riotto '95*]
[*M. Carena, M. Quirós, C. Wagner '95*]
[*H. Haber, R. Hempfling, A. Hoang '97*]

[*R. Hempfling, A. Hoang '93*]
[*R. Zhang '99*]
[*J. Espinosa, R. Zhang '00*]
[*J. Espinosa, I. Navarro '01*]

[*S. Heinemeyer, W. Hollik, G. W. '98, '99*]

...

Used for LEP analyses until 1999:

RG improved one-loop effective potential result

⇒ Leading logs at two-loop level

program: *subhpole*

[*M. Carena, M. Quirós, C. Wagner '95*]

New result:

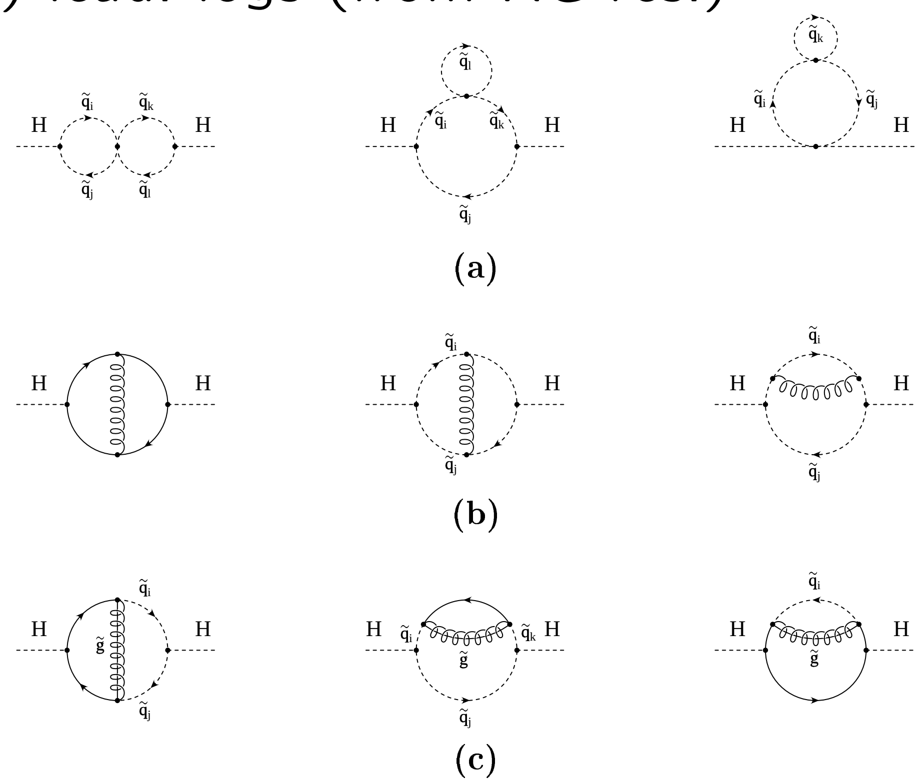
Feynman-diagrammatic two-loop result

⇒ Complete one-loop

+ dominant two-loop corrections: $\mathcal{O}(\alpha\alpha_s)$

+ $\mathcal{O}(\alpha^2)$ lead. logs (from RG res.)

$\mathcal{O}(\alpha\alpha_s)$:



program: *FeynHiggs*

[*S. Heinemeyer, W. Hollik, G. W. '98, '00*]

`http://www.feynhiggs.de`

Comparison of Feynman-diagrammatic two-loop result for m_{h} with RG result:

– Agreement in leading logs at two-loop order
[*M. Carena, H. Haber, S. Heinemeyer, W. Hollik, C. Wagner, G. W. '00*]

– Diagrammatic result contains new genuine two-loop contributions:

$\Rightarrow$ Sizable numerical effect

Increase in $m_{\mathrm{h}}^{\mathrm{max}}$ by ≈ 4 GeV

New genuine two-loop terms confirmed by independent calculation
[*R. Zhang '99*] [*J. Espinosa, R. Zhang '00*]

Recent result on $\mathcal{O}(\alpha^2)$ corrections:

Leading non-logarithmic Yukawa corrections
[*J. Espinosa, R. Zhang '00*]

$\Rightarrow$ upward shift of m_{h} by up to 1–2 GeV

Not yet confirmed by independent calculation, not yet included in experimental analyses

Remaining theoretical uncertainties in prediction for m_{h}:

– From unknown higher-order corrections:

Comparison of results using different renormalization schemes

[*S. Heinemeyer, W. Hollik, M. Frank, G. W. '01*]

Analysis not as sophisticated yet as for SM precision observables ("blue band" for M_{H})

rough estimate: $\Delta m_{\mathrm{h}} \approx 3$ GeV

– From uncertainties in input parameters

$m_{\mathrm{t}}, \ldots, M_{\mathrm{A}}, \tan\beta, m_{\tilde{\mathrm{t}}_1}, m_{\tilde{\mathrm{t}}_2}, \theta_{\tilde{\mathrm{t}}}, m_{\tilde{\mathrm{g}}}, \ldots$

$\Delta m_{\mathrm{t}} \approx 5$ GeV $\Rightarrow$ $\Delta m_{\mathrm{h}} \approx 5$ GeV

Upper bound on m_h in the MSSM:

"Unconstrained MSSM" :

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

Diagrammatic result: *FeynHiggs*
[*S. Heinemeyer, W. Hollik, G. W. '99*]

$$m_h \lesssim 130\,\text{GeV}$$

for $m_t = 175\,\text{GeV}$, no theory uncertainties

holds also for $\mathcal{CP}$-violation [*A. Pilaftsis, C. Wagner '99*]

Parameter scan for different SUSY-breaking scenarios:

mSUGRA, GMSB, AMSB
[*S. Ambrosanio, A. Dedes, S Heinemeyer, S. Su, G. W. '01*]

$$m_h \lesssim 124,\ 119,\ 122\ \text{GeV}$$

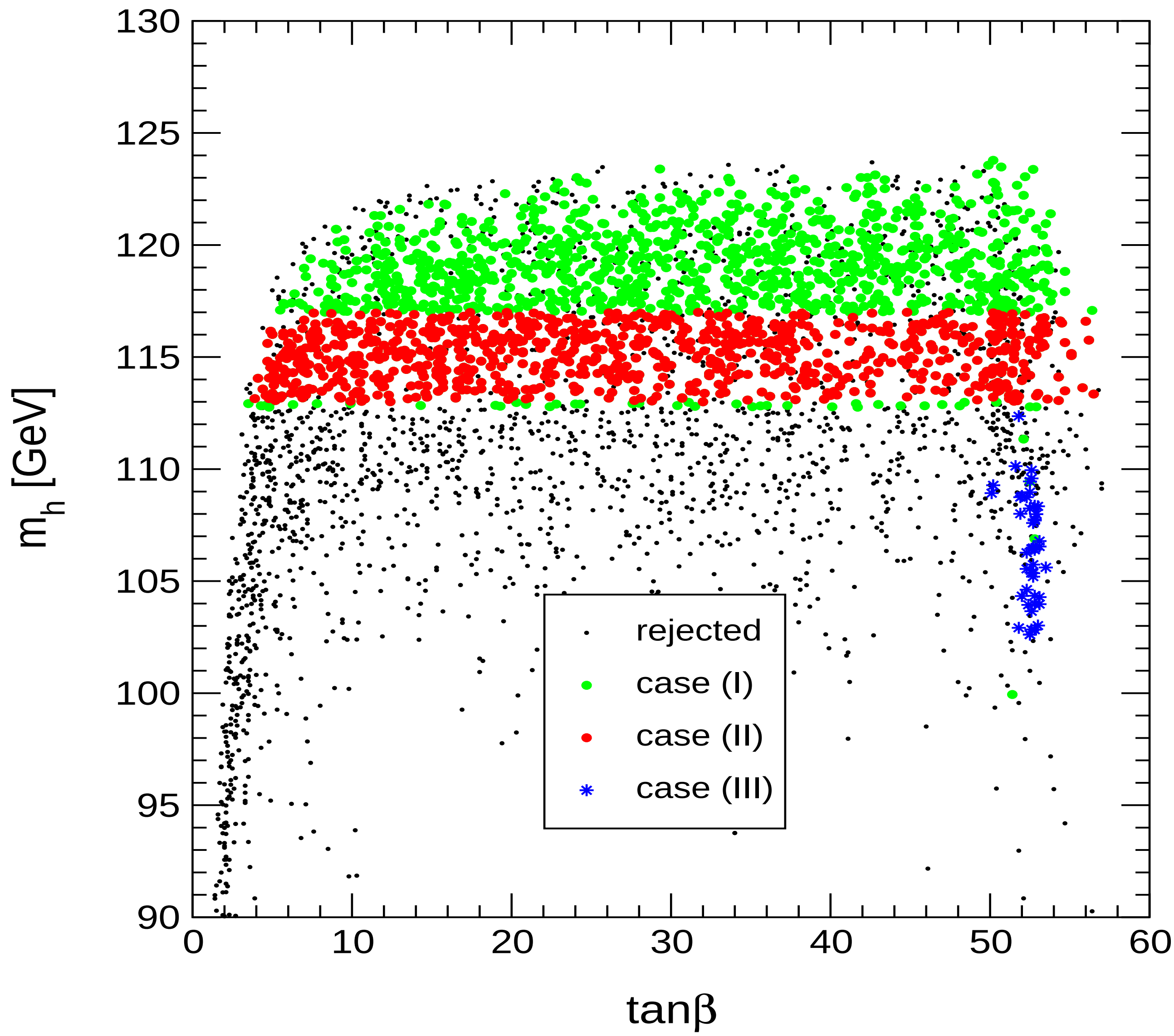
Upper bound on m_h in extensions of MSSM:

[*G. Kane, C. Kolda, J. Wells '93*]
[*J. Espinosa, M. Quirós '93, '98*]

$$m_h \lesssim 200\ \text{GeV}$$

Allowed parameter space in mSUGRA scenario:

[*S. Ambrosanio, A. Dedes, S Heinemeyer, S. Su, G. W. '01*]



Case 2: LEP excess interpreted as $m_{\mathrm{h}} \approx 115$ GeV

Case 3: LEP excess interpreted as $m_{\mathrm{H}} \approx 115$ GeV
(only possible in mSUGRA, not realised
in GMSB, AMSB)

Higgs couplings, production cross sections

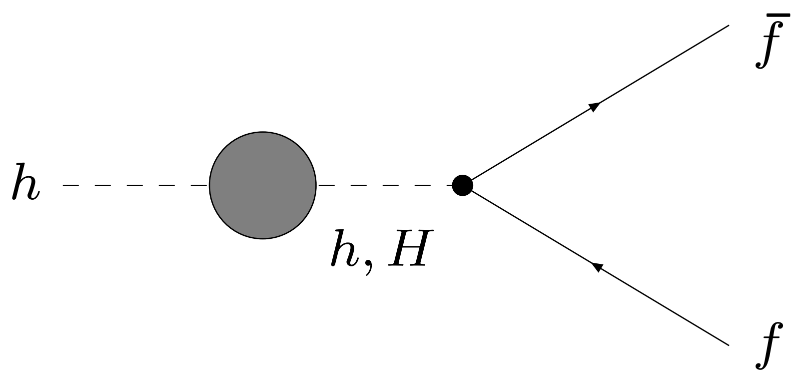
Also affected by large SUSY loop corrections

FD two-loop corrections implemented in results for $h \to f\bar{f}$, $e^+e^- \to hZ, hA$

[S. Heinemeyer, W. Hollik, G. W. '00]

[S. Heinemeyer, W. Hollik, J. Rosiek, G. W. '01]

$hf\bar{f}$ coupling:



$$A(h \to f\bar{f}) = \sqrt{Z_h}\left(\Gamma_h - \frac{\hat{\Sigma}_{\mathrm{hH}}(m_\mathrm{h}^2)}{m_\mathrm{h}^2 - m_\mathrm{H}^2 + \hat{\Sigma}_{\mathrm{HH}}(m_\mathrm{h}^2)}\Gamma_H\right)$$

Effective $hf\bar{f}$ coupling for $\hat{\Sigma}(q^2) \approx \hat{\Sigma}(0)$:

$$\Rightarrow\ A(h \to f\bar{f}) \approx C_f \sin\alpha_{\mathrm{eff}}, \quad C_f \sim \frac{1}{\cos\beta}, f = b, \tau, \mu$$

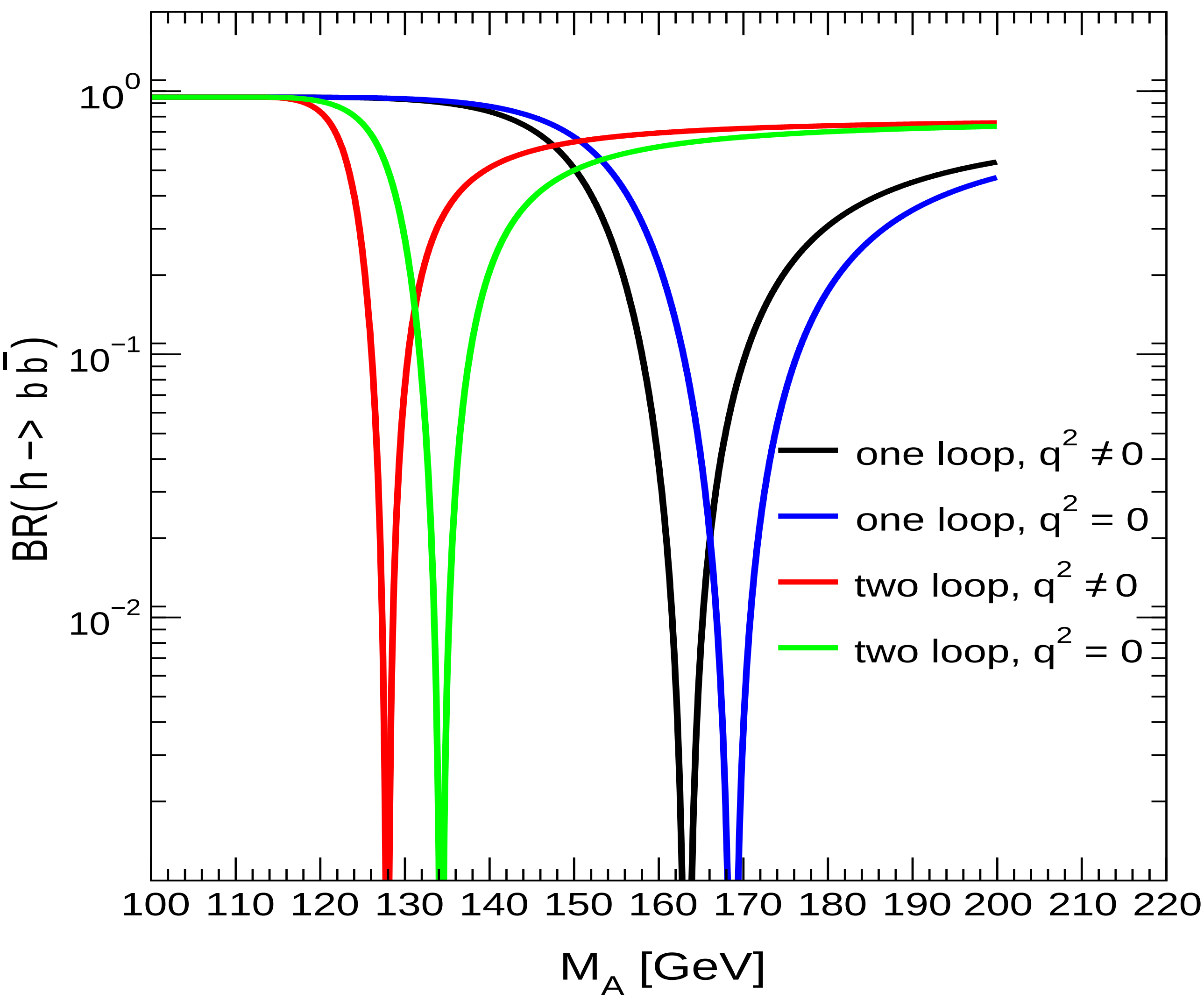
Effective hff coupling can go to zero for large Σ_{hH}

⇒ "Pathological regions"

[*W. Loinaz, J. Wells '98*]

[*M. Carena, S. Mrenna, C. Wagner '99*]

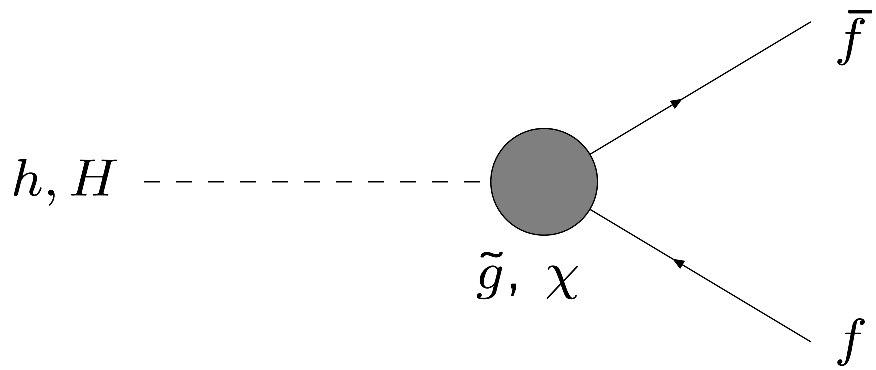
⇒ Suppression of BR($h \to b\bar{b}$), BR($h \to \tau\tau$), ...



[*S. Heinemeyer, W. Hollik, G. W. '00*]

$hq\bar{q}$ coupling:

large gluino/higgsino corrections possible for large $\tan\beta$



Gluino vertex corrections to $h \to q\bar{q}$:

$\Rightarrow$ ratio $\Gamma(h \to \tau^+\tau^-)/\Gamma(h \to b\bar{b})$ can significantly differ from SM value

Resummation of leading corrections for large $\tan\beta$ to all orders

[*M. Carena, S. Mrenna, C. Wagner '99*]

[*M. Carena, D. Garcia, U. Nierste, C. Wagner '00*]

Absorption of the dominant $\mathcal{O}(\alpha_s)$ corrections into effective tree-level couplings

[*H. Eberl, K. Hidaka, S. Kraml, W. Majerotto, Y. Yamada '99*]

2. LEP results: benchmarks and beyond

Constraints from Higgs search at LEP:

LEP benchmarks (used since 2000):
[*M. Carena, S. Heinemeyer, C. Wagner, G. W. '99*]

- $m_h^{\rm max}$-scenario:

$$m_t = m_t^{\rm exp} = 174.3 \text{ GeV}, \quad M_{\rm SUSY} = 1 \text{ TeV}$$

$$M_2 = 200 \text{ GeV}, \; M_A = 1 \text{ TeV},$$
$$\overline{m}_t = 1/(1 + \tfrac{4}{3\pi}\alpha_s),$$
$$X_t = \sqrt{6} M_{\rm SUSY} \text{ (RG)}, \; X_t = 2 M_{\rm SUSY} \text{ (FD)}$$

  $\Rightarrow$ maximal $m_h(\tan\beta)$ for fixed m_t, $M_{\rm SUSY}$

- no-mixing scenario:
  $X_t = 0$

- large μ scenario:
  $\mu = 1\,\text{TeV}, \; M_{\rm SUSY} = 400\,\text{GeV}, \; X_t = -300\,\text{GeV}$

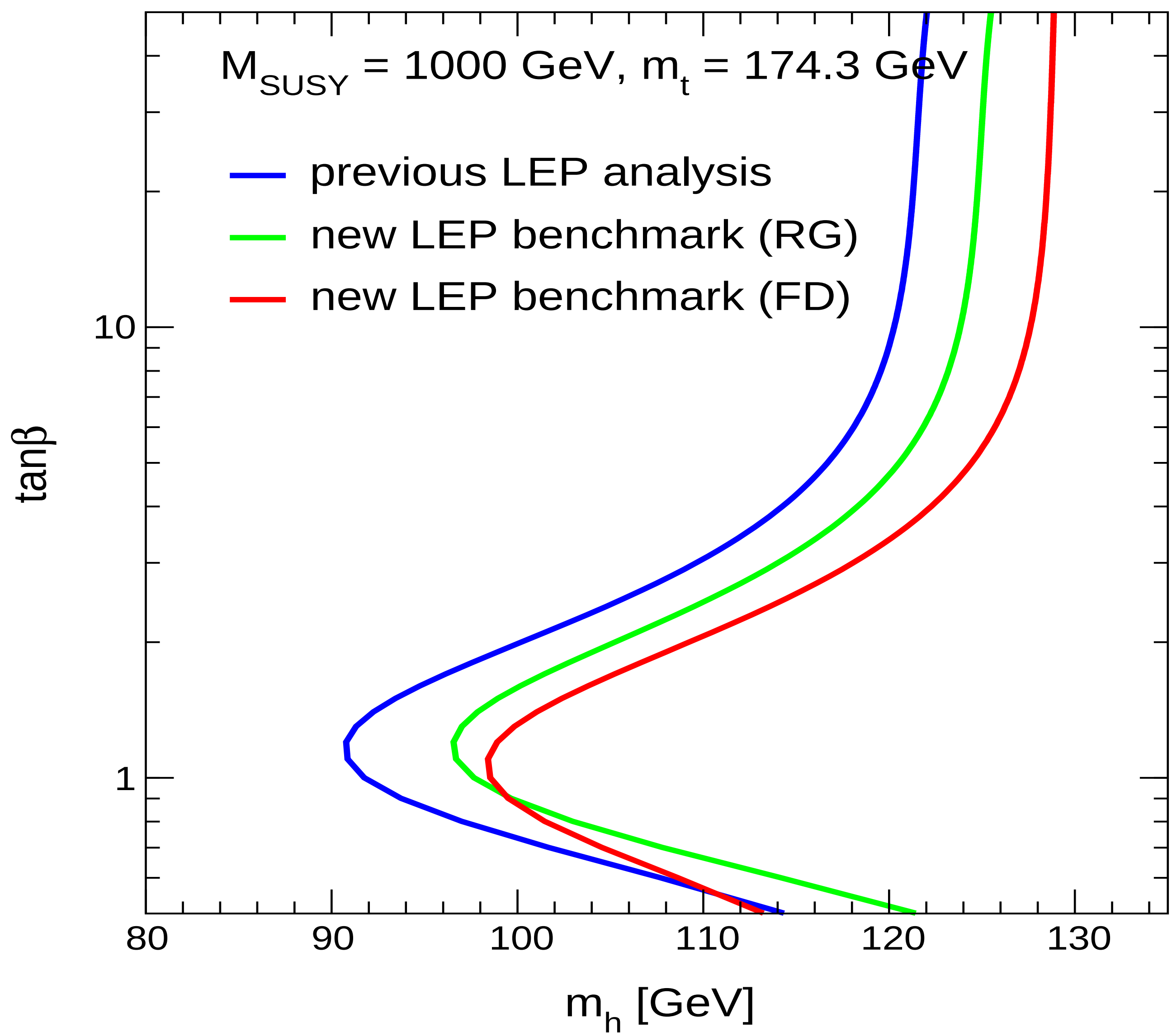
Scans performed with *FeynHiggs*, *subhpole2*

$\Rightarrow$ output: m_h, m_H, $\alpha_{\rm eff}$

implemented into *HZHA* [*P. Janot '96*] [*A. Quadt '00*]

$m_h^{max}(\tan\beta)$: Prev. analysis, RG vs. FD result:

[S. Heinemeyer, W. Hollik, G. W. '00]



m_h^{max} increased: by $\approx$ 5 GeV: prev. an. $\rightarrow$ m_h^{max} scen.

by $\approx$ 4 GeV: RG $\rightarrow$ FD result

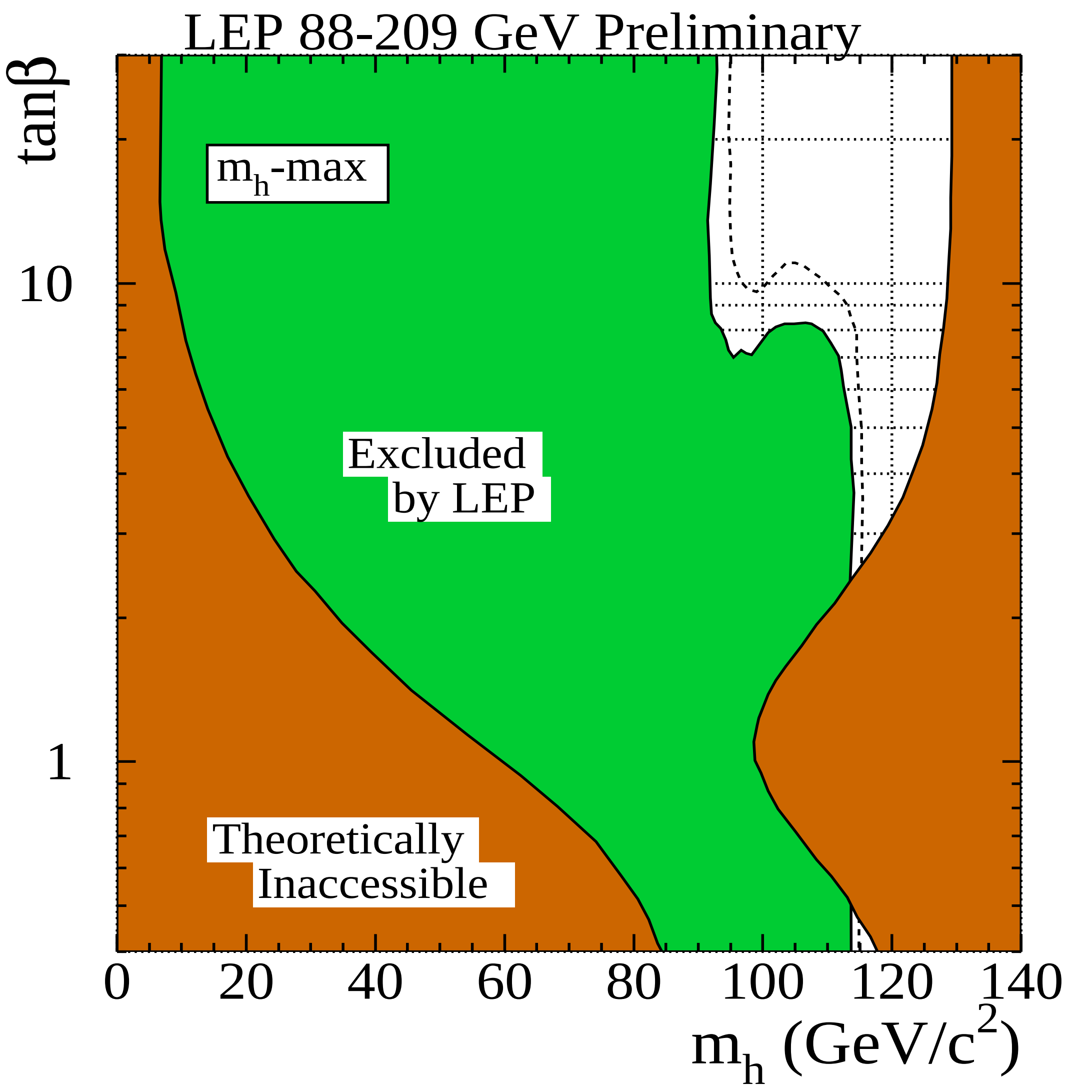
$\Rightarrow$ m_h^{max} higher by up to $\approx$ 9 GeV

Excluded $\tan\beta$ region decreased

Experimental search vs. upper m_h-bound (*FeynHiggs*)

[*LEP Higgs Working Group '01*]

m_h^{max}-scenario:



$$m_h > 91.0\,\text{GeV (expected: } 94.6\,\text{GeV)}, \quad 95\%\ \text{C.L.}$$

$$M_A > 91.9\,\text{GeV (expected: } 95.0\,\text{GeV)}$$

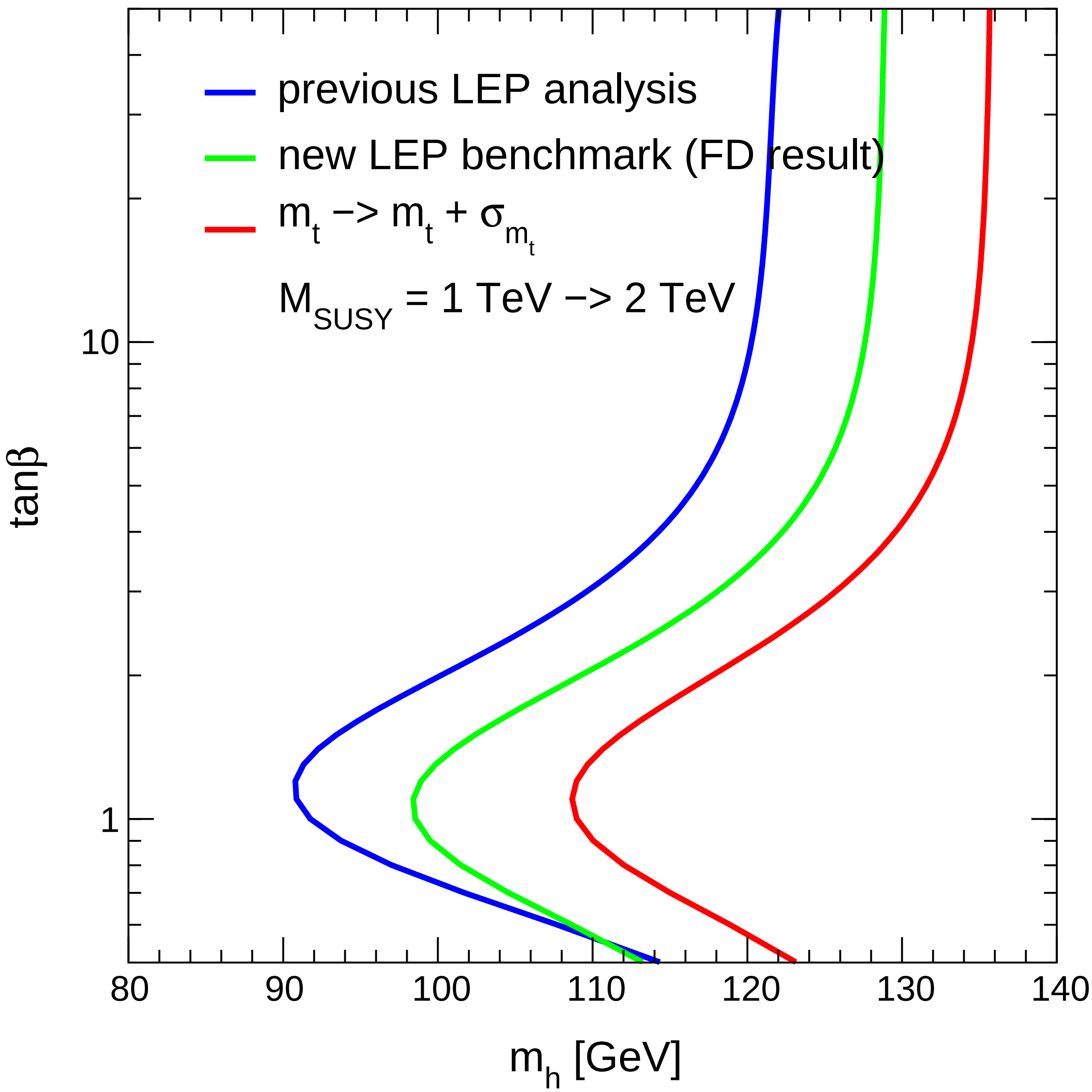
Excluded $\tan\beta$ region:

$$0.5 < \tan\beta < 2.4$$

for $m_t = 174.3$ GeV, $M_{SUSY} = 1$ TeV

Effect of: $m_\mathrm{t} \to m_\mathrm{t} + \sigma_{m_\mathrm{t}}$, $M_\mathrm{SUSY} = 1$ TeV $\to$ 2 TeV

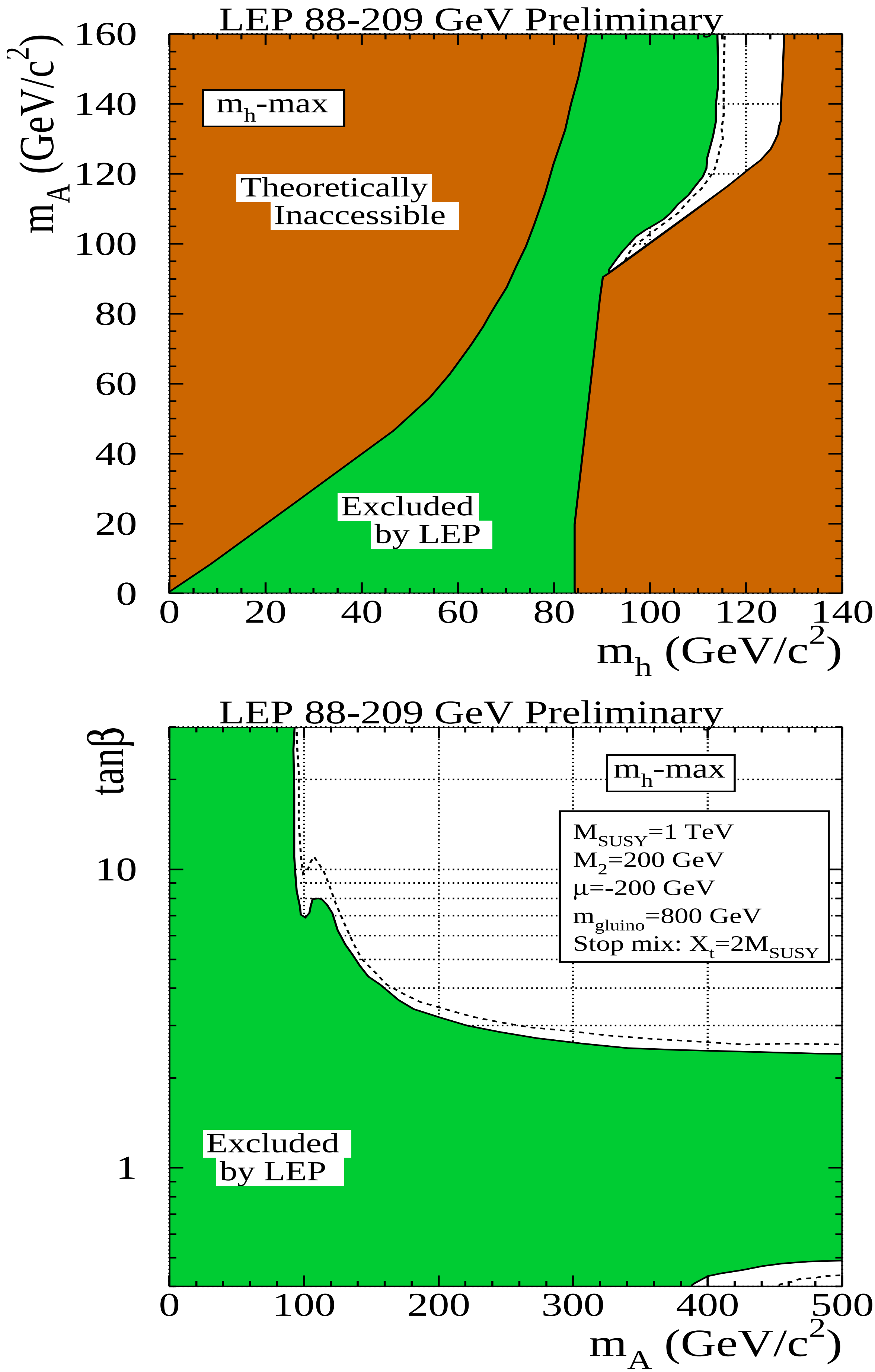
[*S. Heinemeyer, W. Hollik, G. W. '00*]



$\Rightarrow$ precise knowledge of m_t important!

Experimental search vs. upper m_h-bound (*FeynHiggs*)

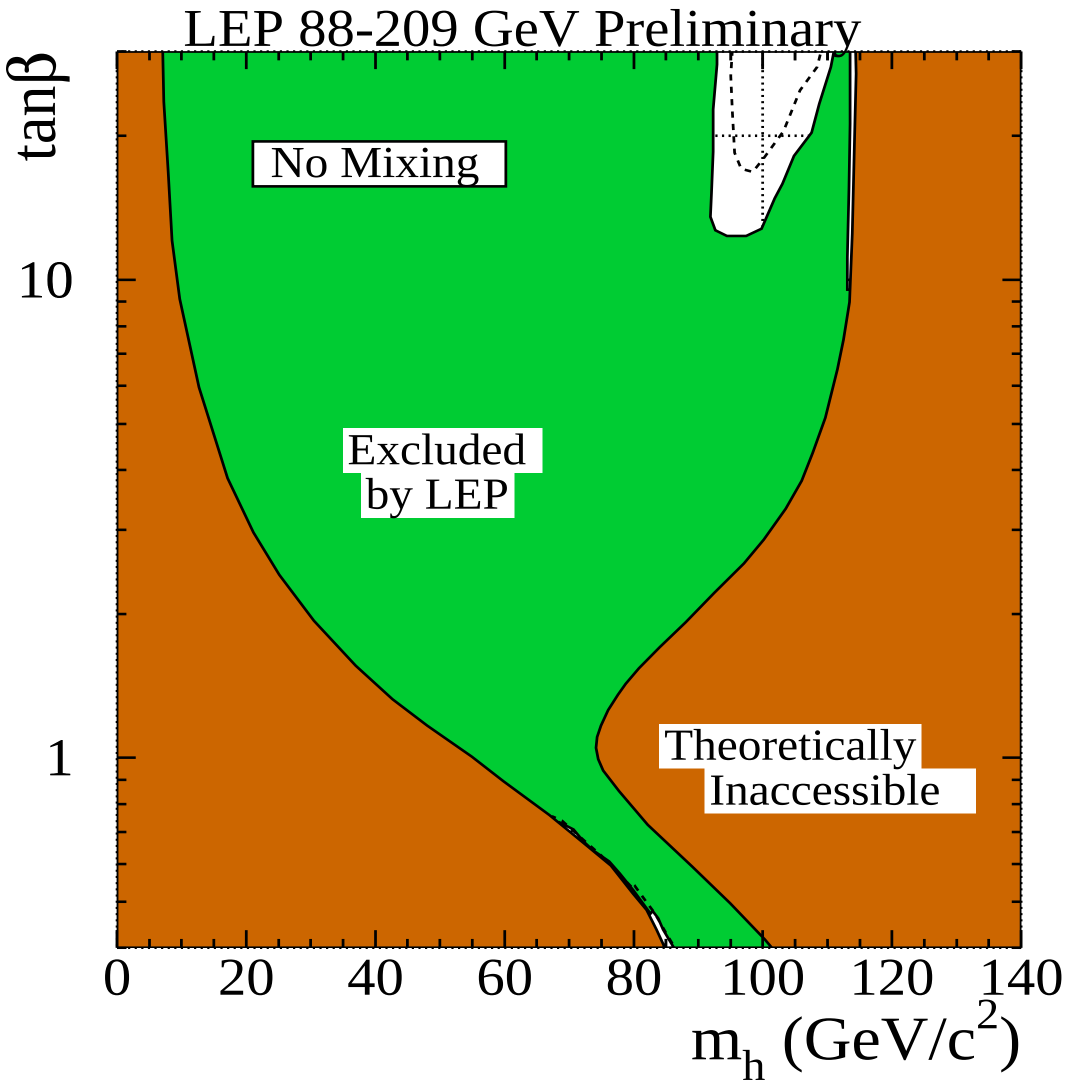
[*LEP Higgs Working Group '01*]



Experimental search vs. upper $m_{\rm h}$-bound (*FeynHiggs*)

[*LEP Higgs Working Group '01*]

no-mixing scenario:



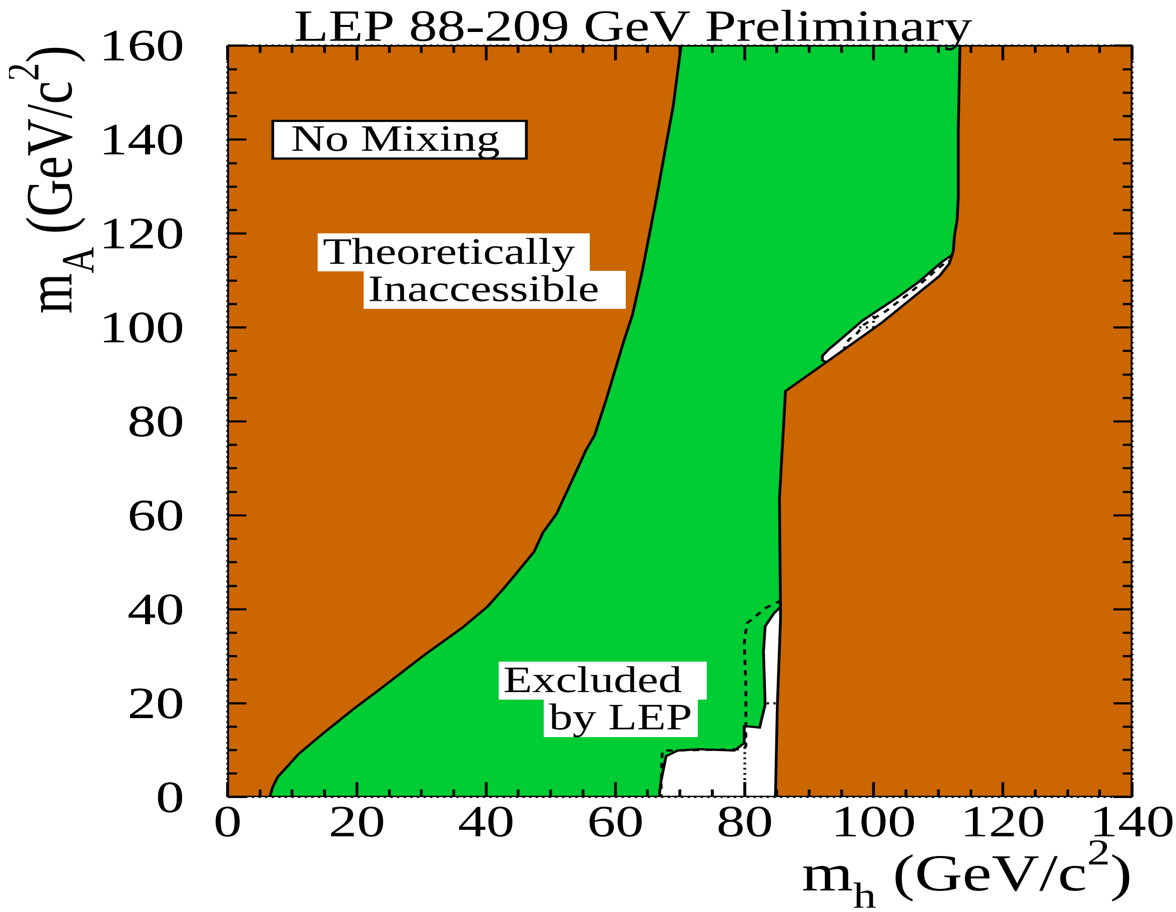
Excluded $\tan\beta$ region:

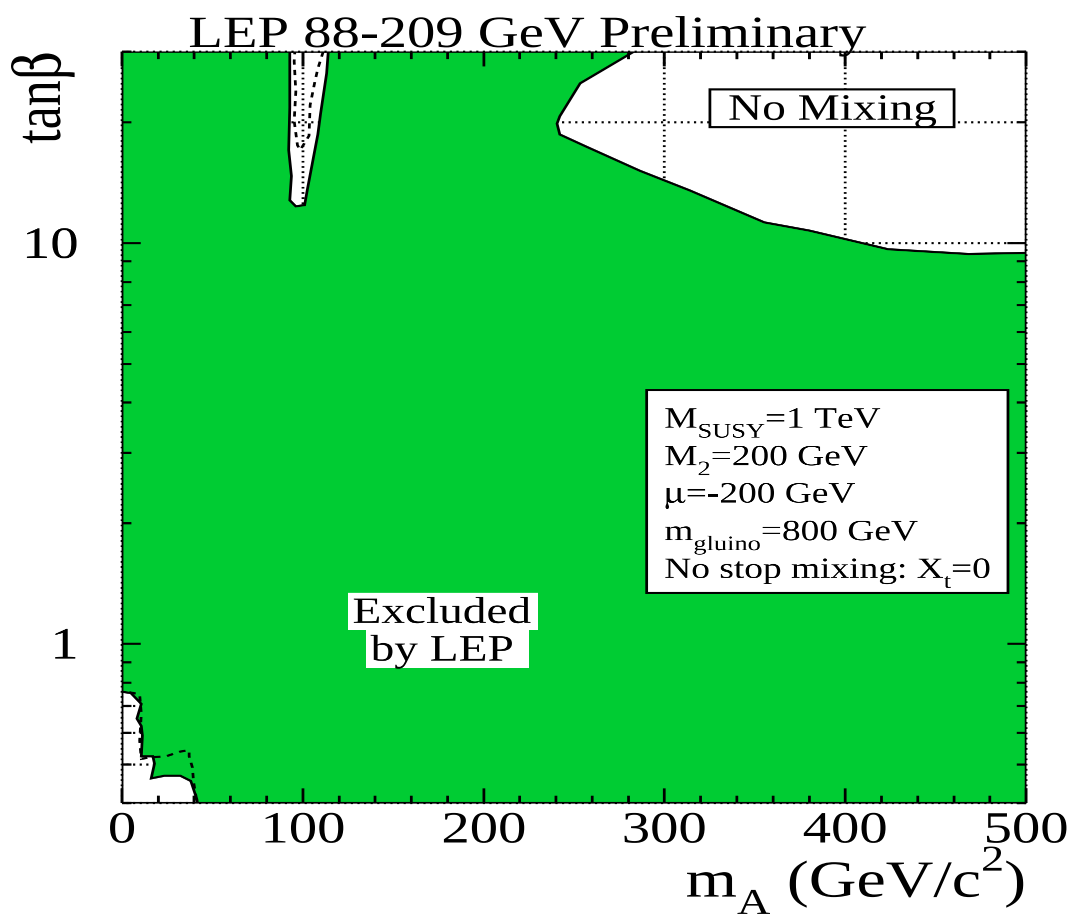
$$0.8 < \tan\beta < 9.6$$

for $m_{\rm t} = 174.3$ GeV, $M_{\rm SUSY} = 1$ TeV

Experimental search vs. upper m_h-bound (*FeynHiggs*)

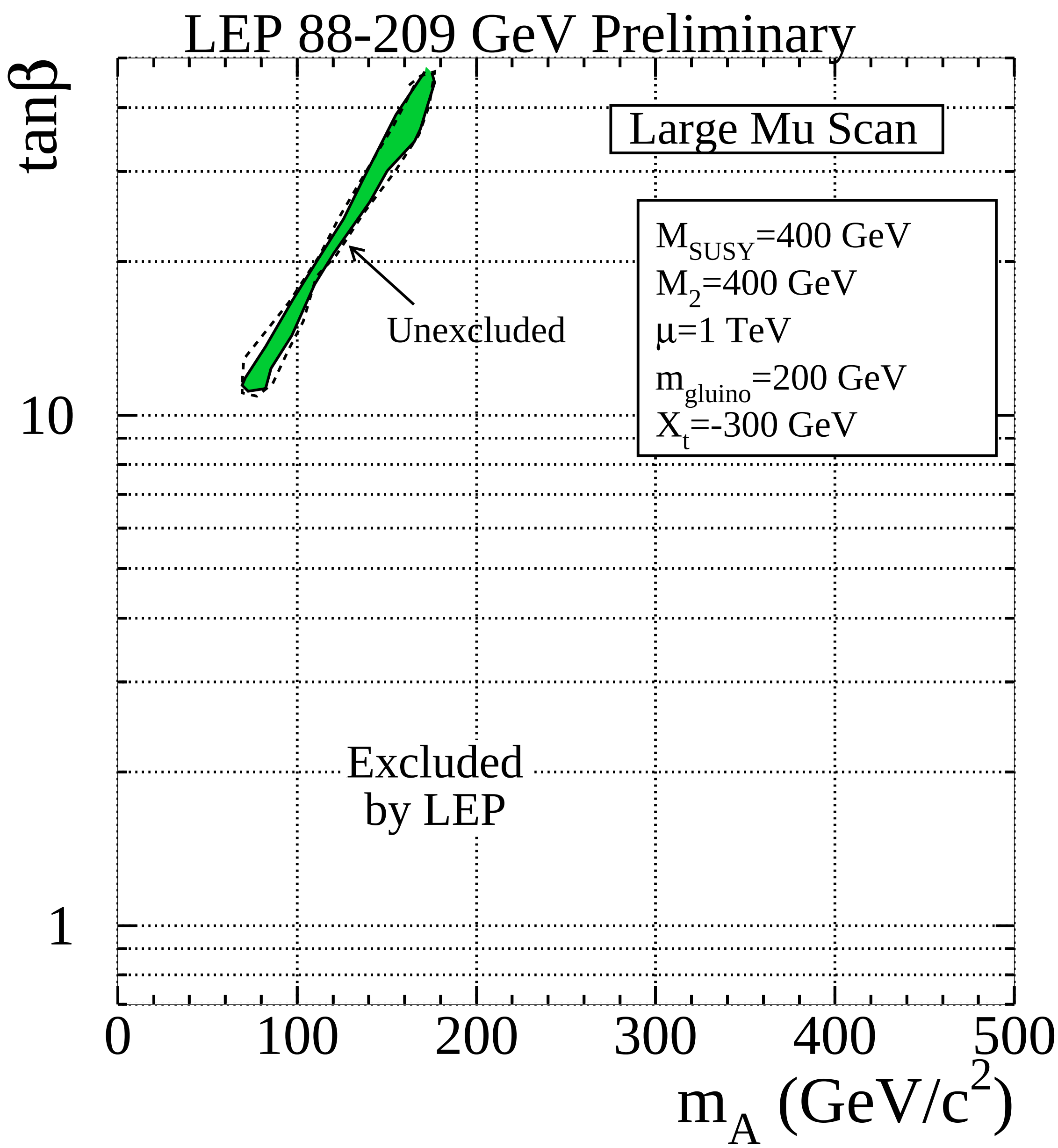
[*LEP Higgs Working Group '01*]





Unexcluded region in large μ scenario:

[*LEP Higgs Working Group '01*]



m_{h} everywhere kinematically accessible

Unexcluded region where BR($h \to b\bar{b}$), BR($h \to \tau\tau$) strongly suppressed

Preparation of final LEP results

LEP Higgs Workshop ongoing

`http://lephiggs.web.cern.ch/LEPHIGGS`

- Seven working groups for different channels

- 'Physics scope' working group
  - further LEP-wide combinations of final results
  - investigation of exp./theo. problems in large $\tan\beta$ region
  - interpretation of LEP results: constraints from electroweak precision data, $b \to s\gamma$, $g_\mu - 2$, cosmology, ...

- 'LEP legacy' working group
  - Technical aspects of archiving data and programs
  - 'Political' aspects

Towards final LEP-combined results

[A. Quadt, G. W. '01]

Main focus on 'model-independent' results:

- Cross section limits
- Limits on

$$s^2 \equiv \frac{\sigma(hZ) \times \text{BR}}{\left[\sigma(hZ) \times \text{BR}\right]_{\text{SM}}}$$

$$c^2 \equiv \frac{\sigma(hA) \times \text{BR}}{\left[\sigma(hA)/\cos^2(\beta - \alpha_{\text{eff}})\right]_{\text{MSSM}}}$$

Separately for different decay channels

Planned to include/investigate: decay-mode independent search, flavor-independent, Yukawa searches

Benchmark scenarios:

- Inclusion of $H^\pm$ information
- Benchmark scan for $\mathcal{CP}$-violating case
- 2HDM scans

Long list of goals; actual realization severely restricted by decreasing manpower

Large $\tan\beta$ region:

Experimental problem:

For $\tan\beta \gtrsim 30$: very large values of Γ_h, Γ_A possible

$\Rightarrow$ larger than resolution of reconstructed masses

$\Rightarrow$ loss of efficiency

Theoretical predictions for signal processes:

$e^+e^- \to hf\bar{f}$, $e^+e^- \to hA$

Used by LEP collaborations: *HZHA*:

[*P. Janot '96*]

α_eff approximation for SUSY loop corrections

on-shell production of h, A

effects of non-zero Γ_h, Γ_A approximated by folding

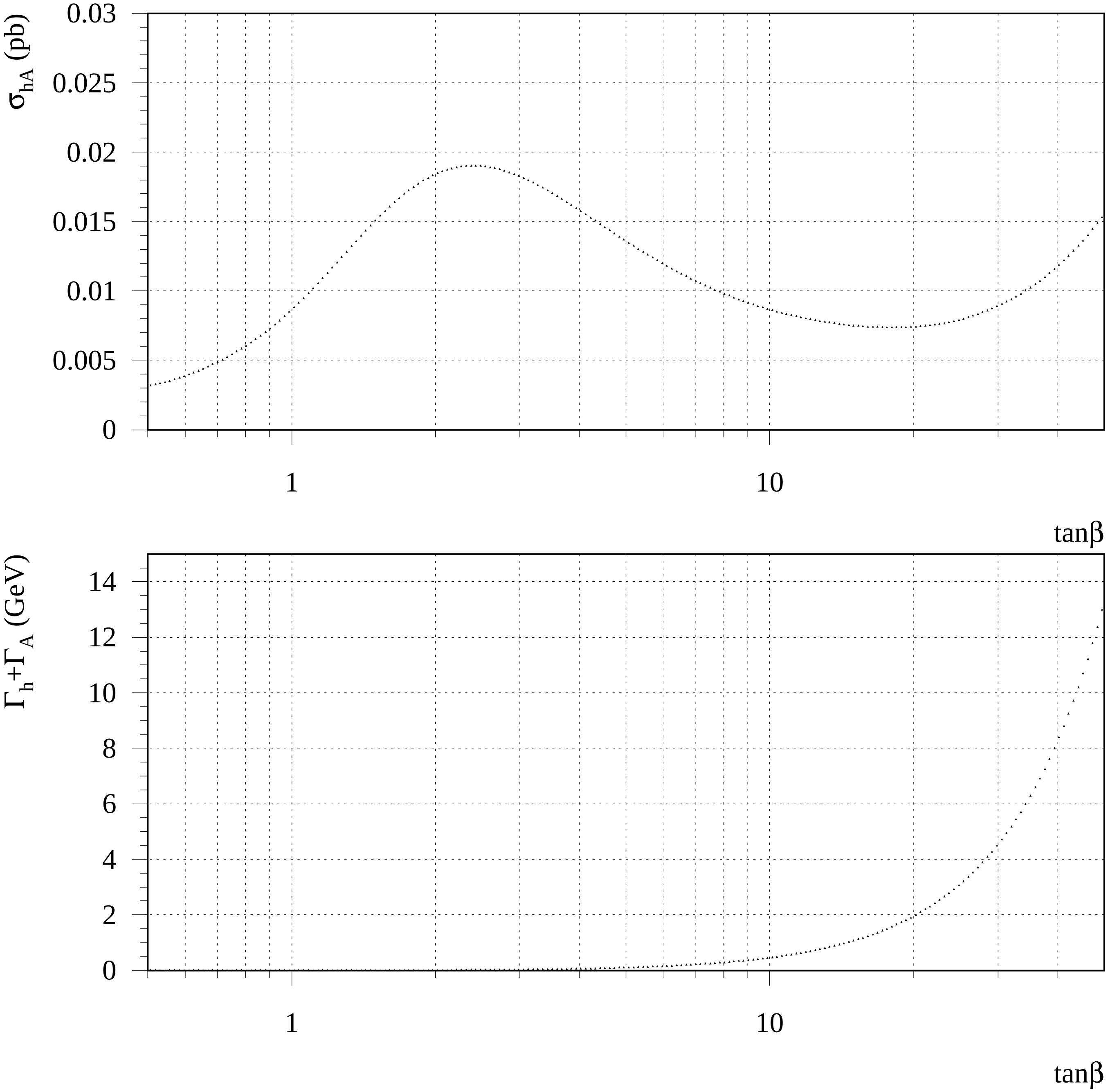
(on-shell cross section) $\times$ (Breit-Wigner shape)

Theoretical problem:

Validity of on-shell approximation for h, A?

HZHA prediction for σ_{hA}:

[*P. Janot '00*]



Theoretical uncertainty in large $\tan\beta$ region?

Comparison with result for complete $2 \to 4$ process:

$e^+e^- \to 4b$

[*A. Freitas, G. W. '01*]

4. Prospects for the future

Possible benchmark scenarios for Tevatron and LHC:

- $m_{\mathrm{h}}^{\mathrm{max}}$-scenario

- no-mixing scenario:

  Highly constrained by LEP results, but not completely excluded

- "Difficult" scenarios:

  Similar to large μ scenario at LEP

  Tevatron:
  E.g.: Suppression of $hb\bar{b}$ coupling
  [*Tevatron Higgs Working Group Report '00*]

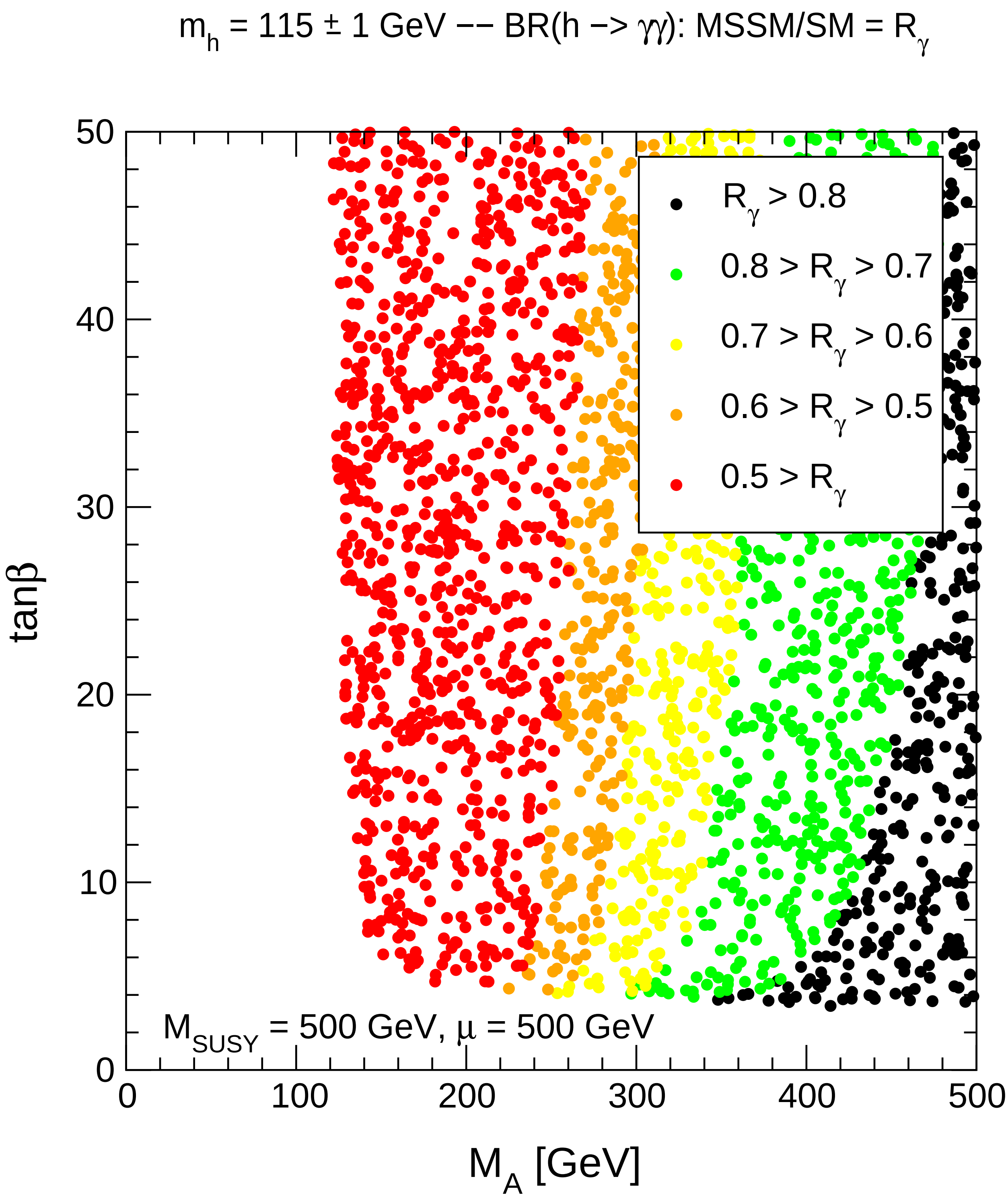
  LHC:
  E.g.: $m_{\mathrm{h}} \approx 115$ GeV, BR($h \to \gamma\gamma$) or BR($h \to b\bar{b}$)
  strongly suppressed,
  large BR into invisible decay modes ...

- $\mathcal{CP}$-violating case

- ...

Suppression of BR($h \to \gamma\gamma$) in unconstrained MSSM:

[*S. Heinemeyer, G. W. '00*]



$\Rightarrow$ significant suppression possible over wide parameter space

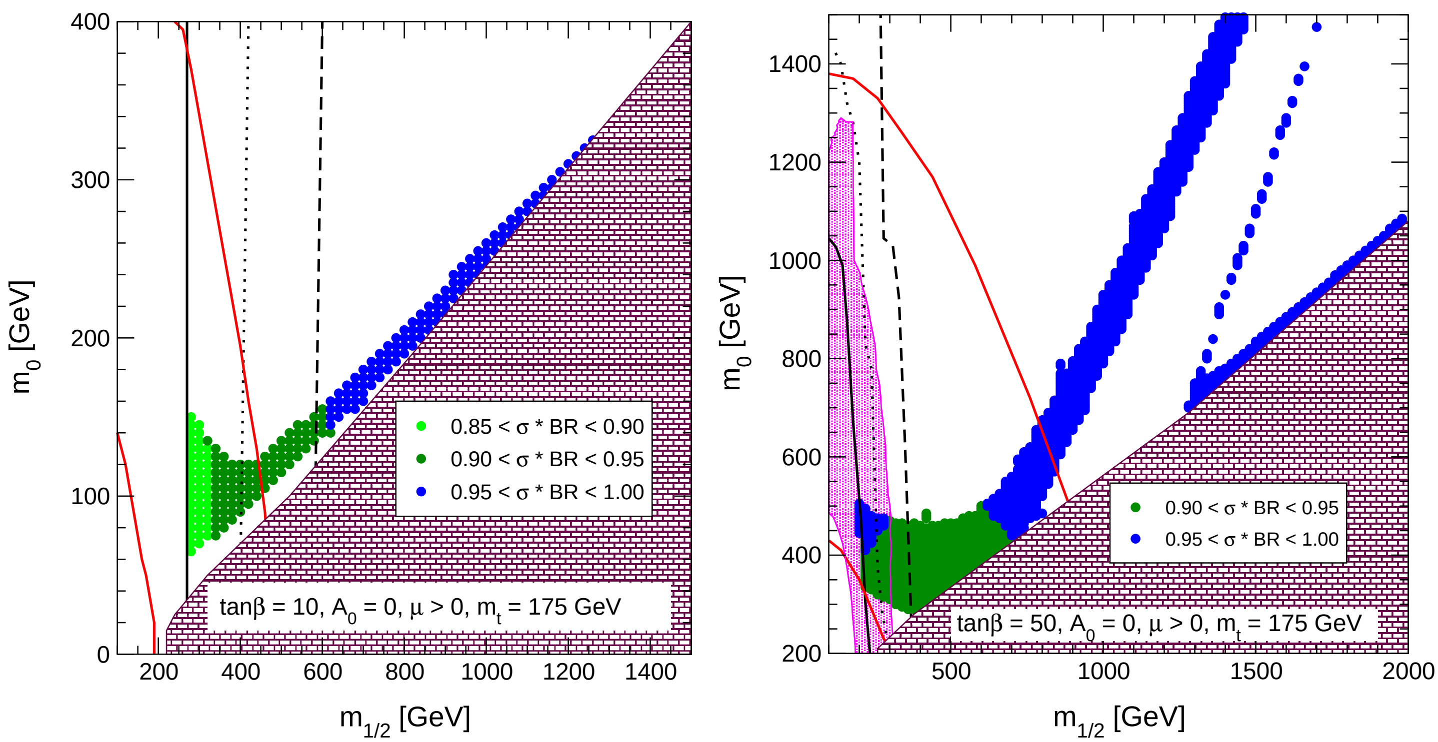
Observability of lightest Higgs at Tevatron and LHC:

CMSSM (mSUGRA) combined with constraints from Higgs search, CDM, $(g_\mu - 2)$, $b \to s\gamma$

[J. Ellis, S. Heinemeyer, K. Olive, G. W. '01]

$\mu > 0$, $\tan\beta = 10, 50$:

$$\Big[\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)\Big]_{\rm CMSSM} \Big/ \Big[\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)\Big]_{\rm SM}:$$

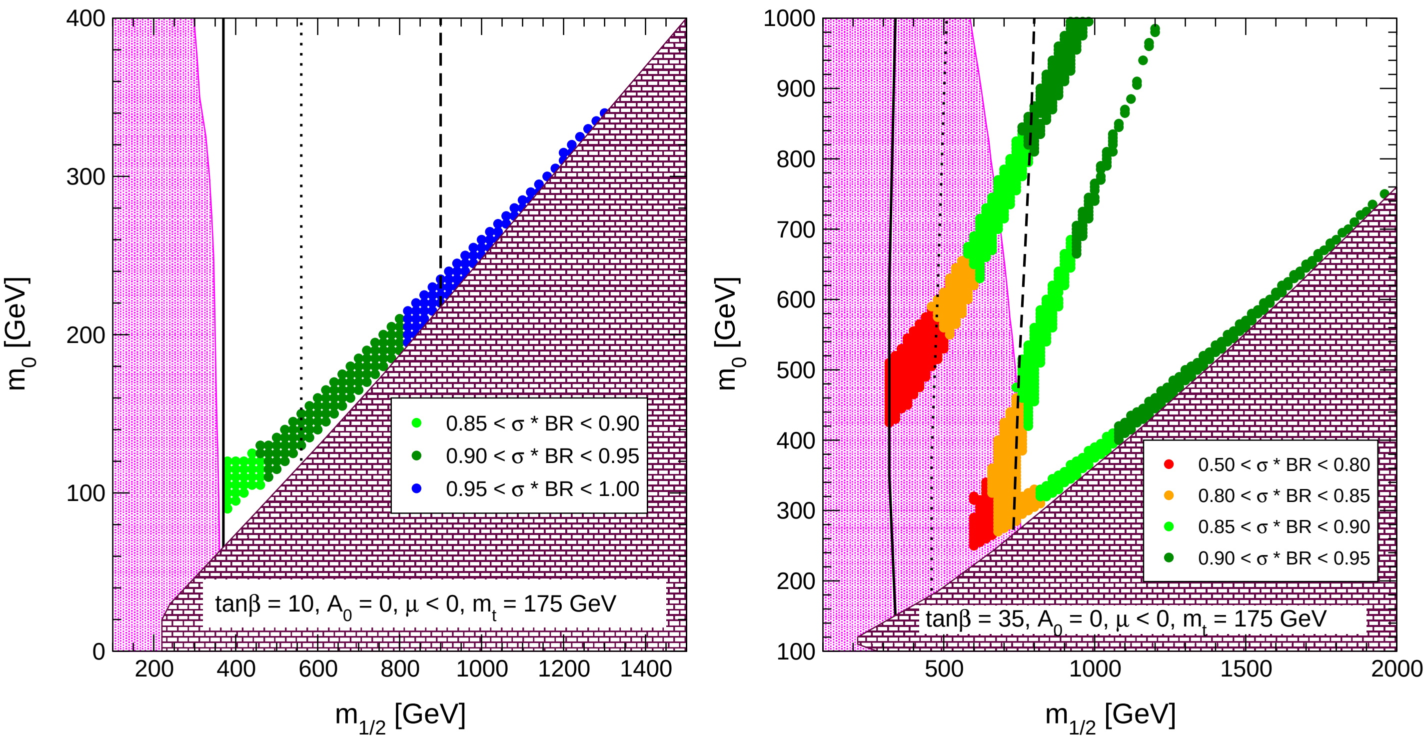


⇒ Model consistent with all constraints

no significant suppression of $\sigma(gg \to h) \times \text{BR}(h \to \gamma\gamma)$ compared to SM case

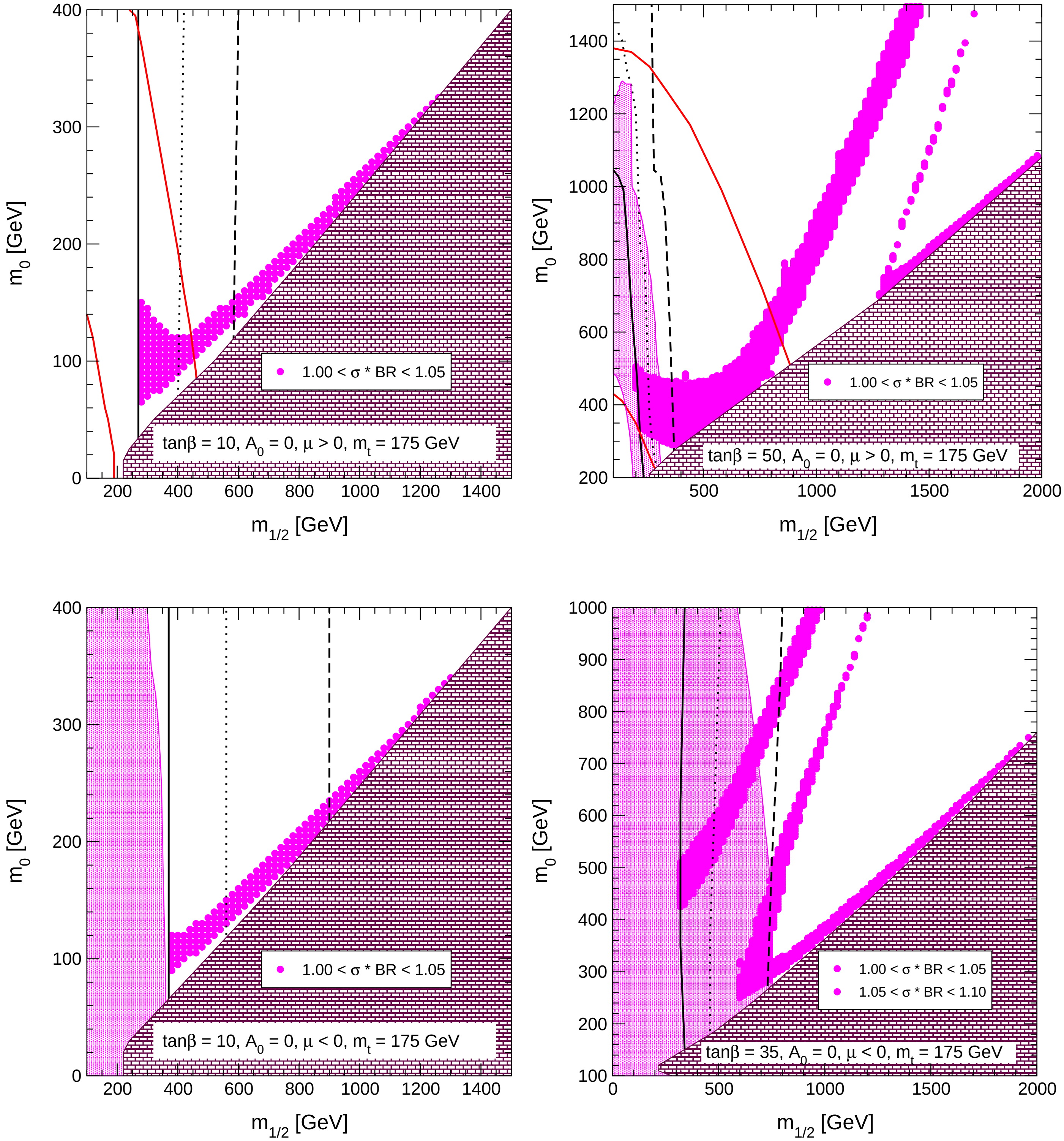
$\mu < 0$, $\tan\beta = 10, 35$:

$$\left[\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)\right]_{\text{CMSSM}} / \left[\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)\right]_{\text{SM}}:$$



⇒ Larger suppression possible in regions disfavored by $(g_\mu - 2)$ and $b \to s\gamma$ constraints

$\left[\sigma(V/\bar{t}t + h) \times \mathcal{B}(h \to bb)\right]_{\text{CMSSM}} / \left[\sigma(V/\bar{t}t + h) \times \mathcal{B}(h \to bb)\right]_{\text{SM}}$:



$\Rightarrow$ Vh and $t\bar{t}h$ production unsuppressed

Good prospects for discovering lightest CMSSM Higgs with 15 fb^{-1} at Tevatron (for $m_h \approx 115$ GeV) and with 10 fb^{-1} at LHC (in whole mass range)

From precise measurement of m_h

$\Rightarrow$ Constraints on $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$, M_A, $\tan\beta$, ...

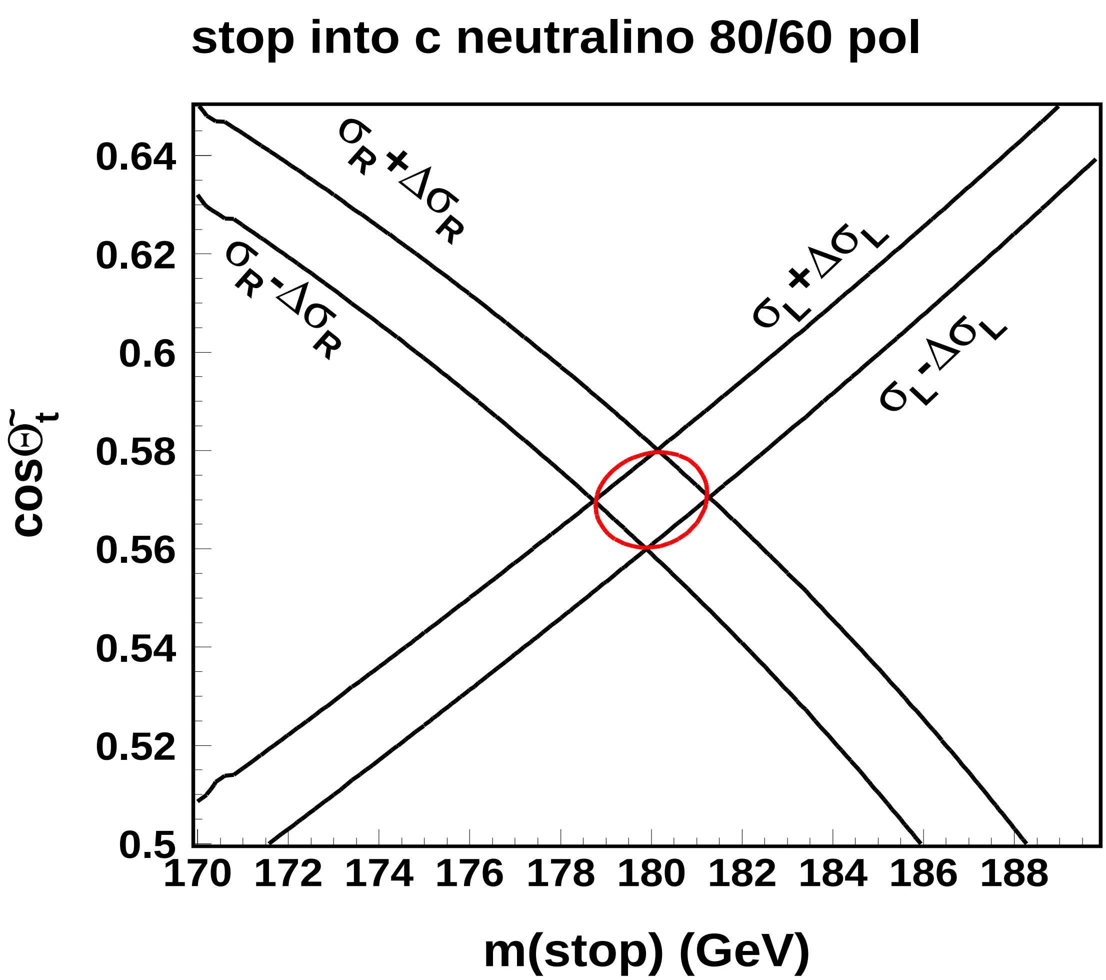
Example: Combination of direct and indirect information on $\tilde{t}$ sector parameters

Direct information:

$e^+e^- \to \tilde{t}_1\tilde{t}_1$ at LC, $\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb^{-1}

80% pol. e^- beam, 60% pol. e^+ beam

[*R. Keränen, H. Nowak, A. Sopczak '00*]

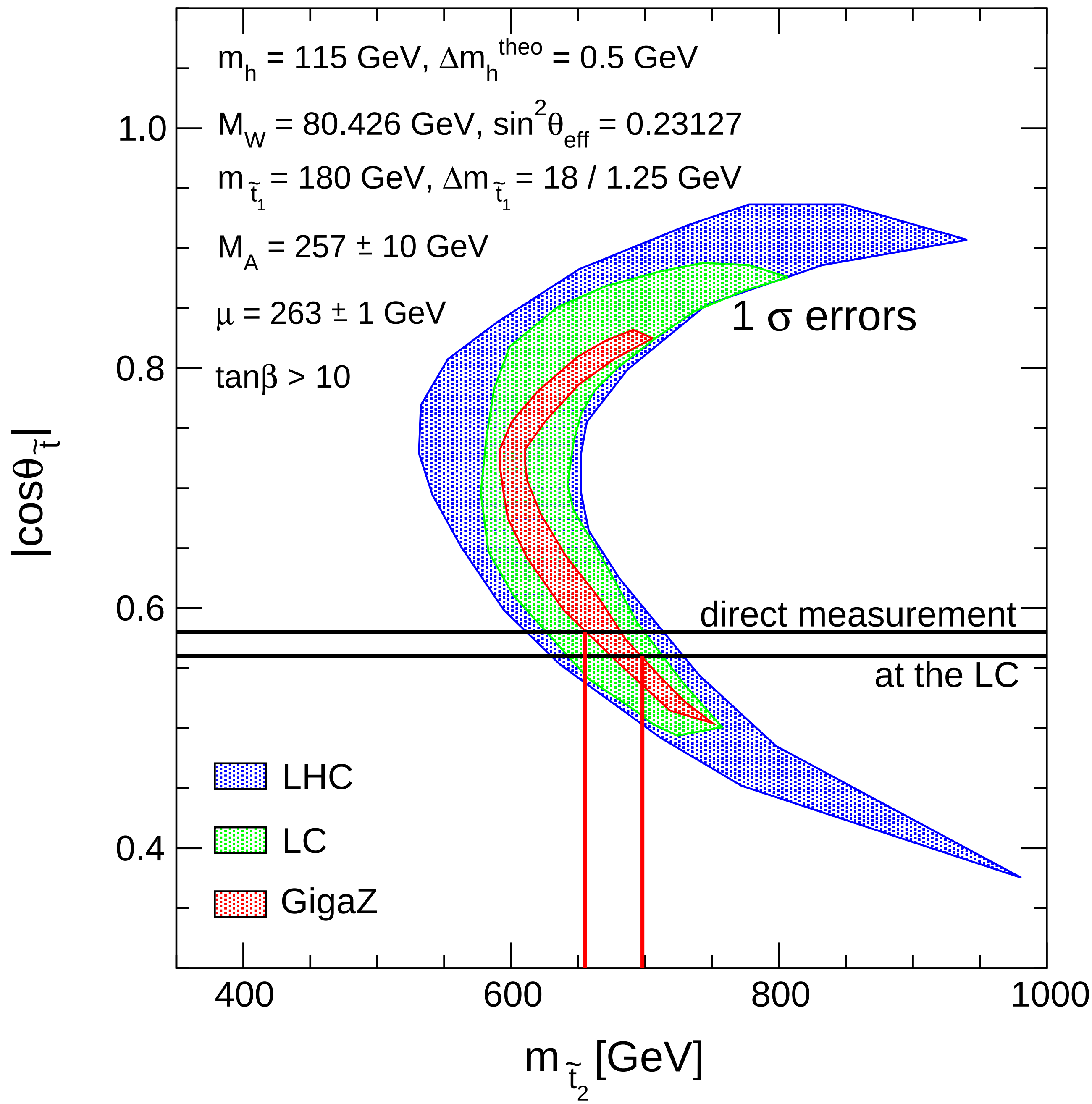


$\Rightarrow$ Precise determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$

Indirect constraints on $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$ from precise measurement of m_h, M_W, $\sin^2\theta_{eff}$ at LC/GigaZ:

[S. Heinemeyer, G.W. '00]

Allowed region in $m_{\tilde{t}_2}$–$\theta_{\tilde{t}}$ plane:

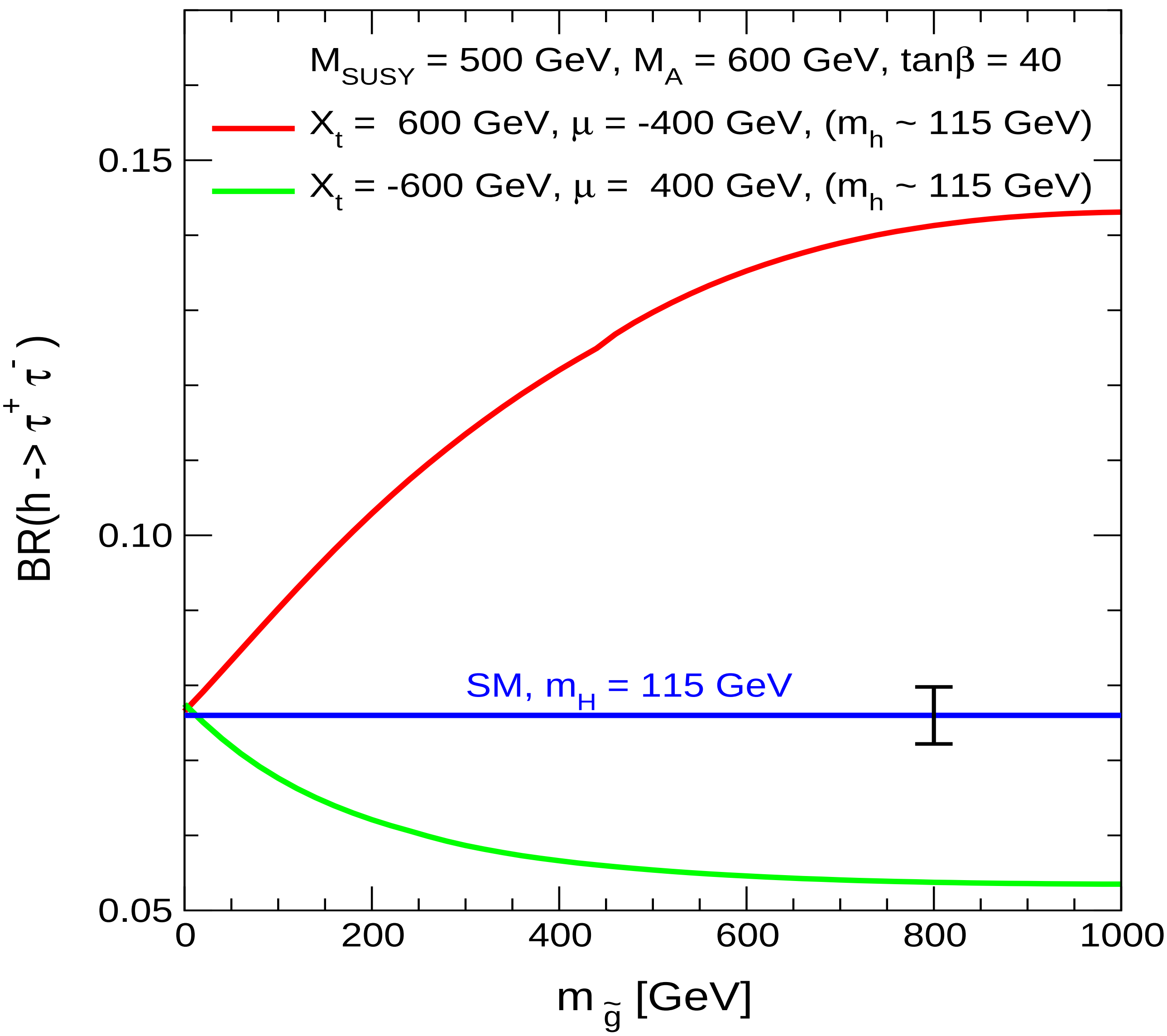


⇒ Direct/indirect information is complementary

Indirect determination of $m_{\tilde{t}_2}$ with high precision

$hq\bar{q}$ coupling:

Effect of gluino vertex corrections on BR($h \to \tau^+\tau^-$):
[*S. Heinemeyer, G.W. '01*]



Large effects possible for large tan β,

even for relatively large M_A

Precise measurement of τ branching ratio

⇒ Sensitivity to deviations SM/MSSM

What remains to be done?

A lot ...

- Explore full structure of SUSY:

  $\mathcal{CP}$ violation, non-minimal models, ...

- Improve estimate of theoretical uncertainties:

  $\Rightarrow$ "blue band" for m_{h}, ...

- More precise results needed for signal and background processes

- Try to match experimental precision at LHC with accuracy of theoretical prediction

  Much calculational effort needed

  Complementarity example:

  in order to match $\delta m_{\mathrm{h}}^{\mathrm{exp}} \approx 0.2$ GeV (from LHC)

  need $\delta m_{\mathrm{t}}^{\mathrm{exp}} \lesssim 0.2$ GeV (from LC)

- Muon Collider with $\Delta m_{\mathrm{h}}/m_{\mathrm{h}} = 10^{-6}$

  $\Rightarrow$ m_{h} will be electroweak high-precision observable, even more precise than G_μ, M_{Z}

  Use m_{h} as input to determine m_{t}?
  (like at present $G_\mu \leftrightarrow M_{\mathrm{W}}$)

5. Conclusions

- LEP MSSM benchmark scans and more model-independent LEP-combined results:

  Important input for Higgs search at Tevatron/LHC

- Theory predictions in the MSSM Higgs sector:

  Still a lot of work to be done in preparation for Tevatron RunII, LHC, LC, ...

- Prediction for m_{h}, $h \to f\bar{f}$, $e^+e^- \to hZ, hA$:

  Dominant diagrammatic two-loop corrections combined with one-loop on-shell result

  Upper bound for m_{h} in the MSSM:

  $m_{\mathrm{h}} \lesssim 130$ GeV in unconstrained MSSM

  $m_{\mathrm{h}} \lesssim 124, 119, 122$ GeV: mSUGRA, GMSB, AMSB

- CMSSM with CDM, m_{h}, $g_\mu - 2$, $b \to s\gamma$ constr.:

  h should be discoverable at LHC with ≈ 10 fb^{-1}

- m_{h}, Higgs couplings as precision observables:

  At TevII/LHC/LC: improved accuracy of precision observables m_{h}, M_{W}, $\sin^2\theta_{\mathrm{eff}}$, ... and input parameters m_{t}, $m_{\tilde{\mathrm{t}}}$, ...

  $\Rightarrow$ Highly sensitive test of SM and MSSM