Lectures on Phenomenology

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Lecture 4:

- Prospects for SUSY searches at the next generation of colliders

- Higgs mass bounds in SUSY theories

- Precision physics in the MSSM Higgs sector

Prospects for SUSY searches at the next generation of colliders

SUSY searches at the Tevatron

Best prospects for:

- light SUSY Higgs h

- $\tilde{t}$, $\tilde{b}$ searches

SUSY searches at the LHC

- MSSM Higgs bosons:

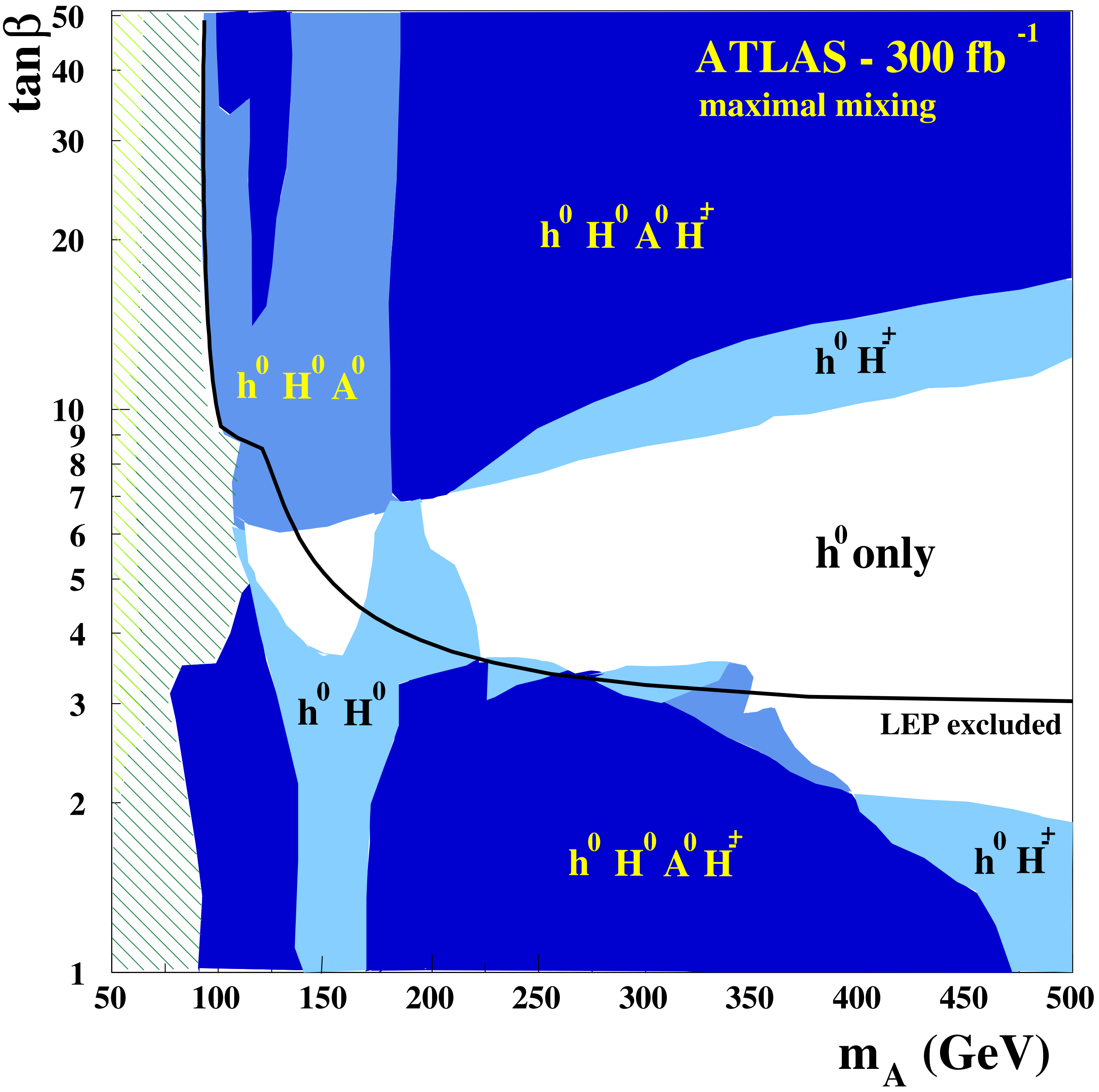
  good prospects for detecting light Higgs h

  H/A discovery possible in significant part of parameter space

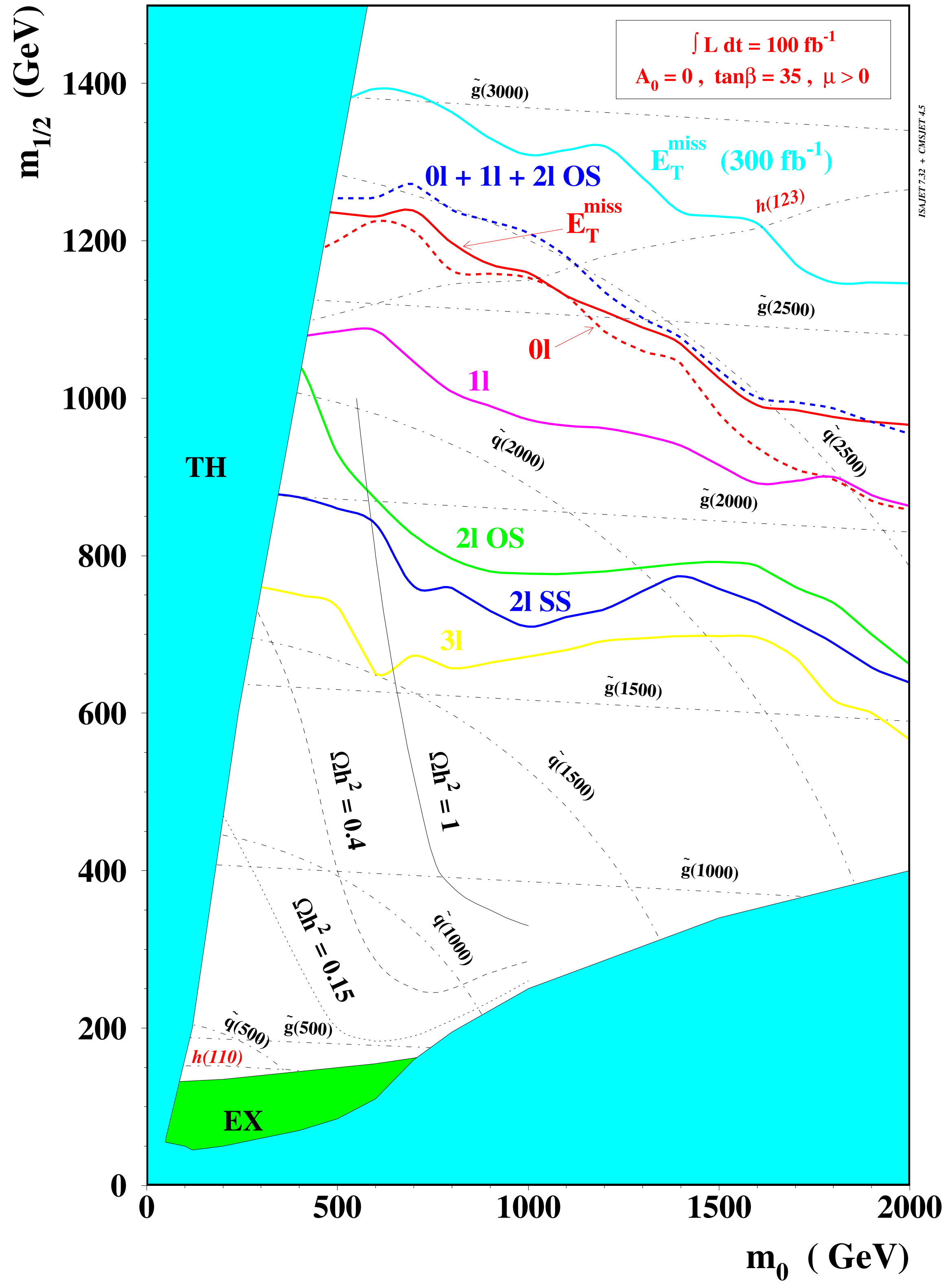
- discovery of SUSY particles expected if low-energy SUSY is realized:
  - mass reach for squarks, gluino 2–3 TeV
  - SUSY particles can be produced via cascade decays of heavy squarks etc.
  - ...

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane (MSSM, m_h^{max} benchmark scenario):

[*ATLAS '99*]



Discovery reach contours in m_0–$m_{1/2}$ plane (mSUGRA scenario) for various final states with 100 fb^{-1}:
[*CMS '99*]



In order to establish SUSY experimentally:

Need to demonstrate that:

– every particle has superpartner

– their spins differ by 1/2

– their gauge quantum numbers are the same

– their couplings are identical

– mass relations hold

. . .

$\Rightarrow$ Precise measurements of masses, branching ratios, cross sections, angular distributions, . . . mandatory for

- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

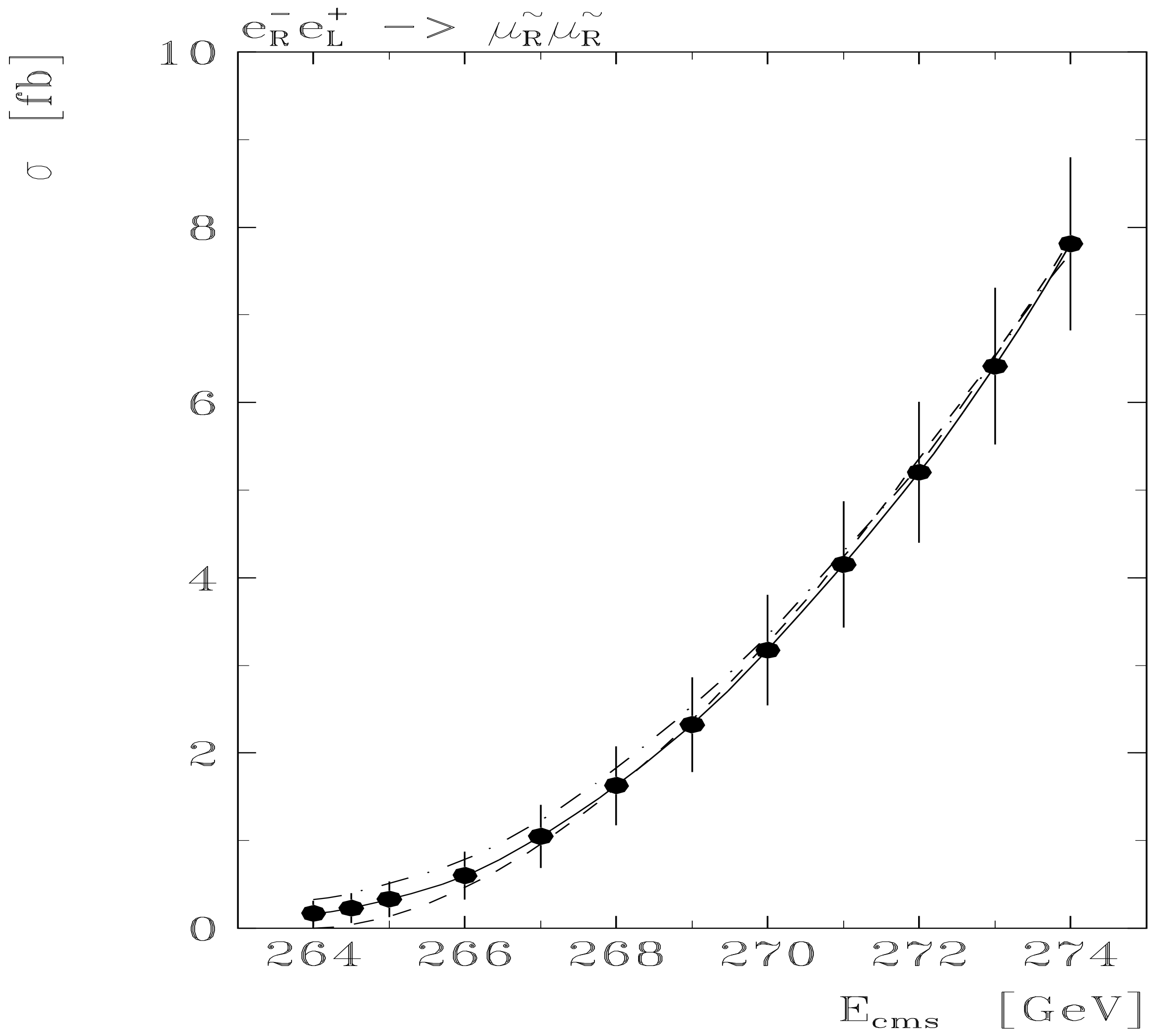
Requires clean experimental environment, high luminosity, beam polarization, . . .

$\Rightarrow$ High luminosity LC necessary,

complementary to hadron machines

Examples for SUSY physics at the LC:

Determination of mass and spin of $\tilde{\mu}_R$ from production at threshold:
[TESLA TDR '01]



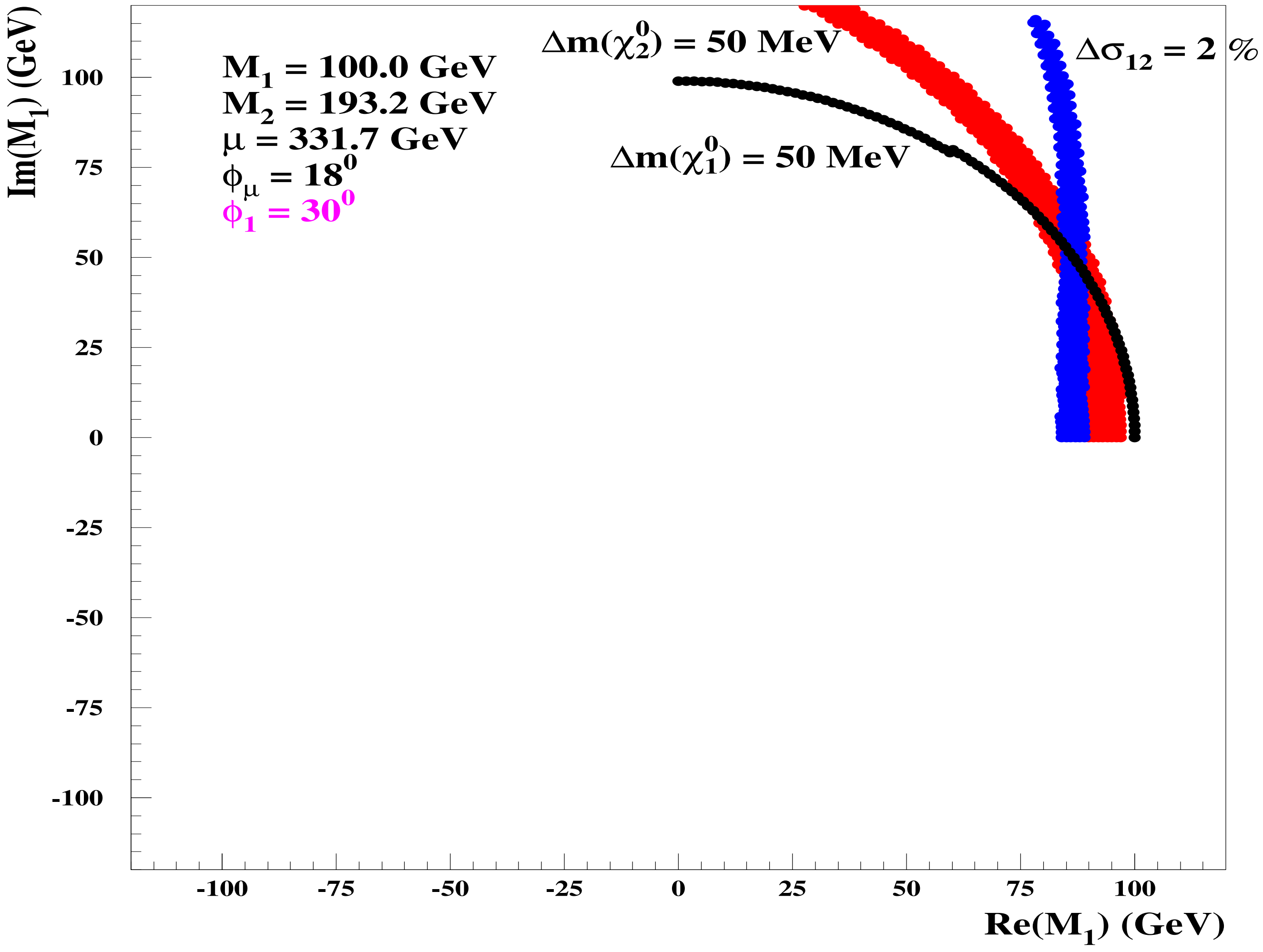
$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

test of $J = 0$ hypothesis

Determination of phase ϕ_1 in neutralino sector from measurement of $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ and $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$, $\mathcal{L} = 500\ \mathrm{fb}^{-1}$:

$m_{\tilde{\chi}^0_1} = 96.12 \pm 0.05$ GeV, $m_{\tilde{\chi}^0_2} = 177.13 \pm 0.05$ GeV, $m_{\tilde{\chi}^\pm_1} = 174.90 \pm 0.05$ GeV, $\Delta\sigma(\tilde{\chi}^0_1\tilde{\chi}^0_2) = \pm 2\%$

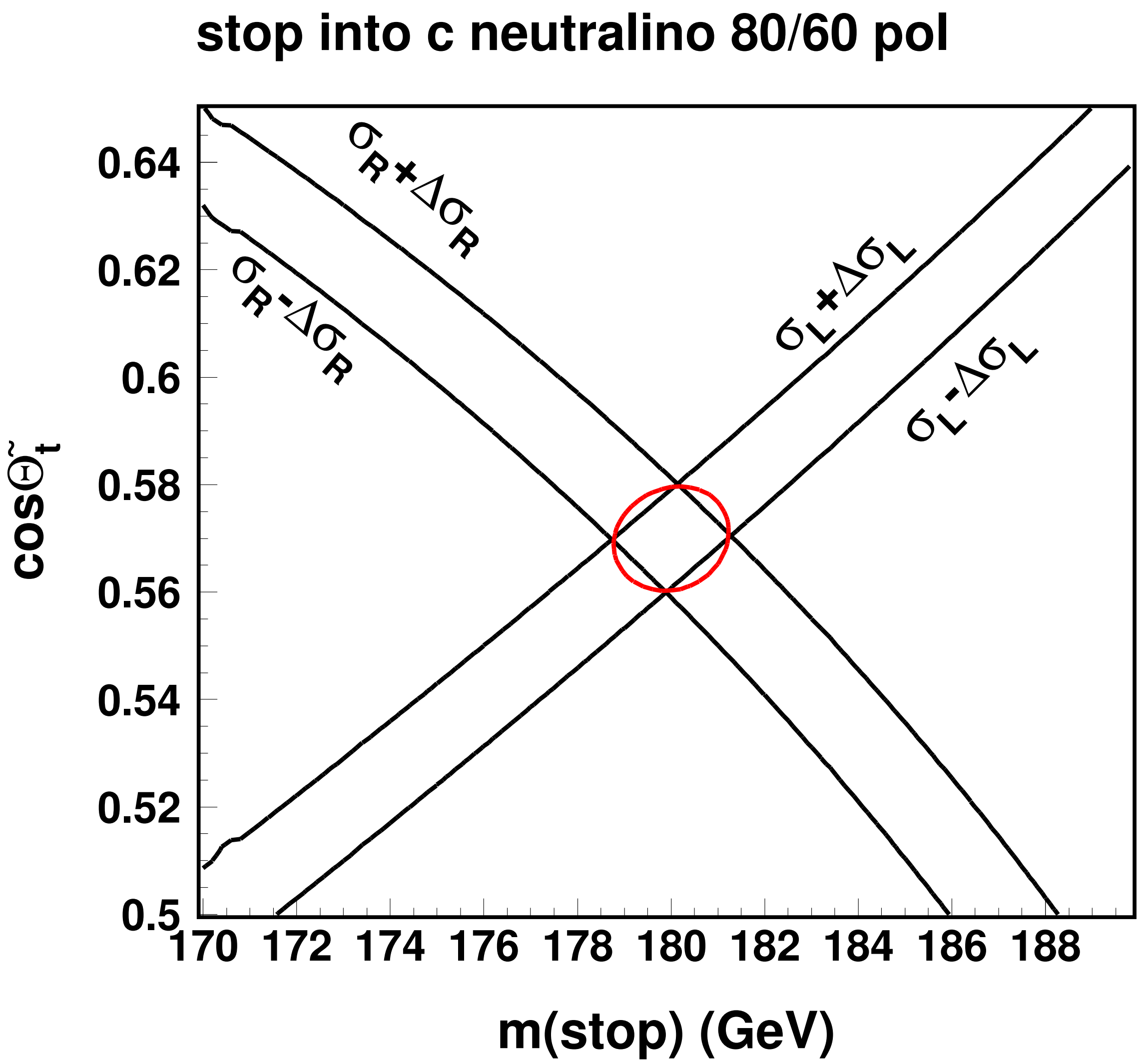
[*K. Desch, G. Moortgat-Pick '02*]



$\Rightarrow \Phi_1 = 30^0 \pm 3^0$

Determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$ from $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1)$ with polarized beams:

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



$$\Rightarrow \quad \frac{\Delta m_{\tilde{t}_1}}{m_{\tilde{t}_1}} \approx 0.5\%, \qquad \frac{\Delta \cos\theta_{\tilde{t}}}{\cos\theta_{\tilde{t}}} \approx 1.5\%$$

Complementarity of LHC and LC:

$\Rightarrow$ Results obtained at one collider can be used for improving experimental analyses at the other

- SUSY example:

  LC results for masses and BR's of SUSY particles as input for analyzing cascade decays at LHC

- Alternative theory example:

  Measurement of Z' mass at LHC

  $\Rightarrow$ determination of Z' couplings at LC

  Z': extended gauge group or Kaluza–Klein excitation ($\rightarrow$ large extra dimensions)?

- . . .

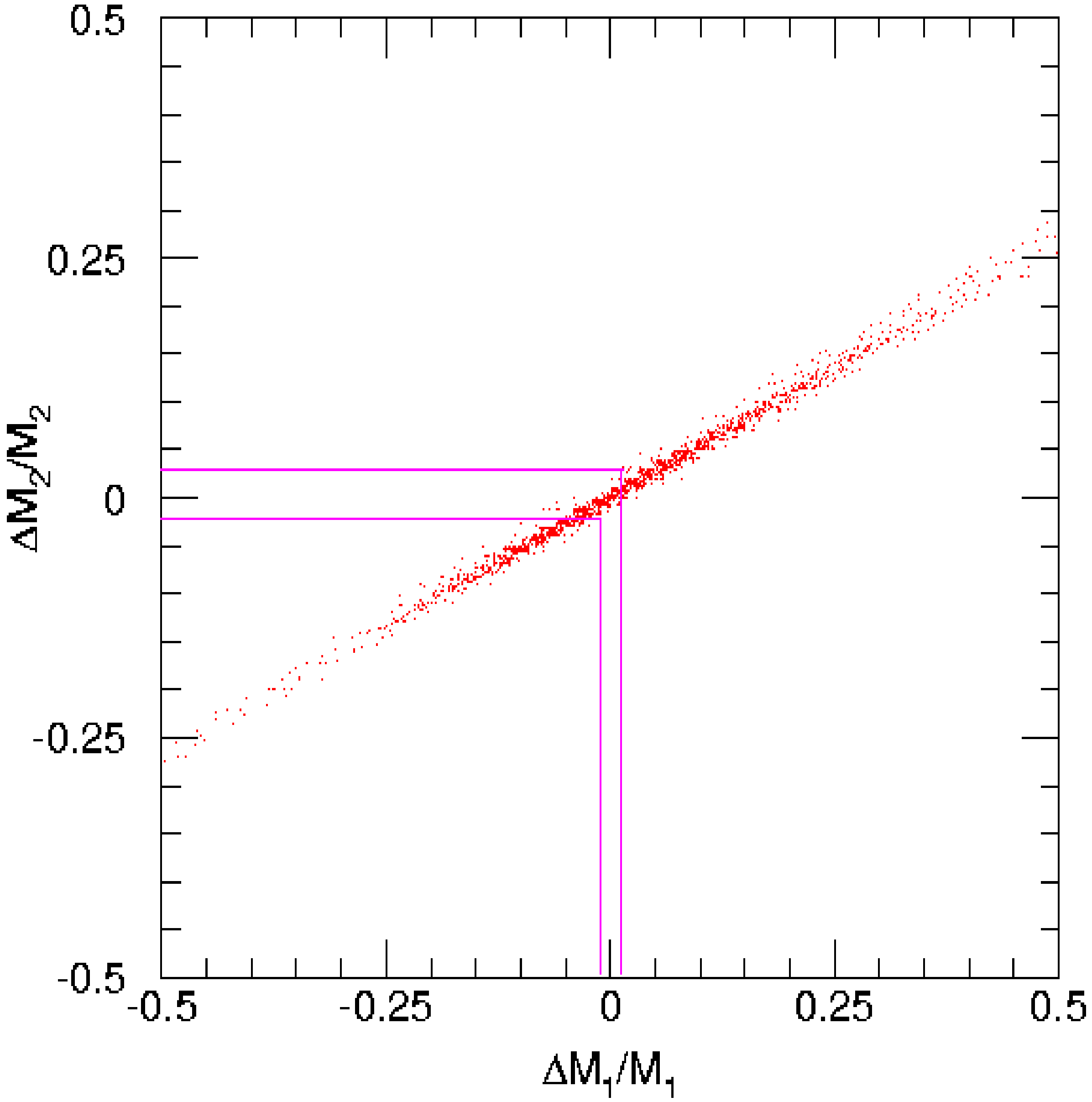
$\Rightarrow$ investigated in "LHC / LC Study Group"

`www.ippp.dur.ac.uk/~georg/lhclc`

E.g.: Impact of precise measurement of LSP mass on LHC analyses

Determination of $m_{\tilde{\chi}_2}$:

[*ATLAS TDR*]



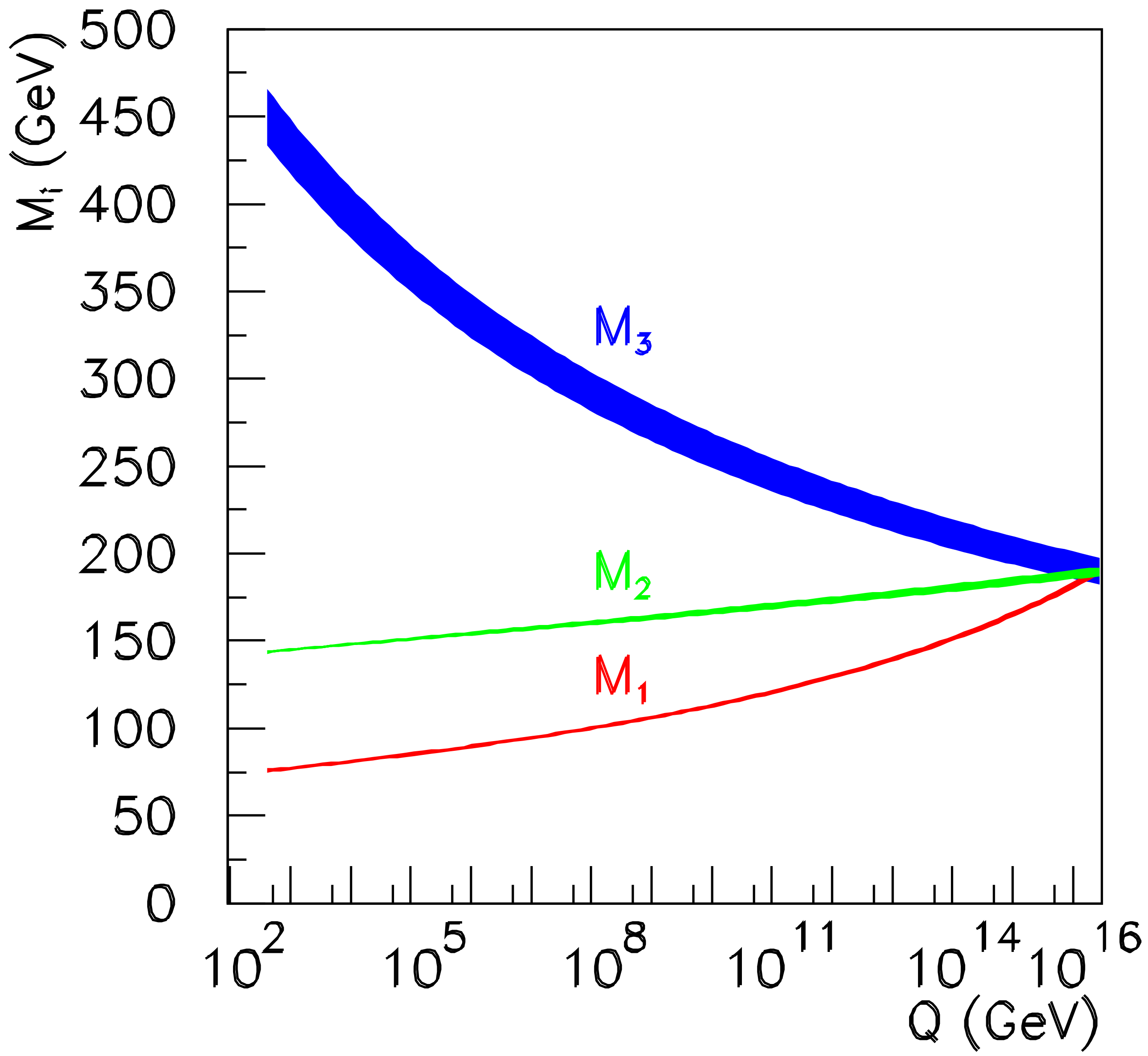
$\Rightarrow$ LC accuracy on $m_{\tilde{\chi}_1}$ yields drastic improvements

From combination of LHC and LC results, precise measurement of masses of SUSY particles, couplings:

⇒ Determination of underlying SUSY parameters, test of SUSY-breaking scenarios

⇒ Extrapolation to high energy scales possible

E.g.: Test of gaugino mass unification
[*G. Blair, W. Porod, P. Zerwas '01*]



Higgs mass bounds in SUSY theories

MSSM predicts upper bound on m_{h}:

tree-level bound:

$m_{\mathrm{h}} < M_{\mathrm{Z}}$, excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings: $\frac{\mathrm{e}\, m_{\mathrm{t}}}{2 M_{\mathrm{W}} s_{\mathrm{W}}}$, $\frac{\mathrm{e}\, m_{\mathrm{t}}^2}{M_{\mathrm{W}} s_{\mathrm{W}}}$, ...

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

$\tilde{\mathrm{t}}$ sector:

$$M_{\tilde{\mathrm{t}}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_{\mathrm{t}}^2 + DT_1 & m_{\mathrm{t}} X_{\mathrm{t}} \\ m_{\mathrm{t}} X_{\mathrm{t}} & M_{\tilde{t}_R}^2 + m_{\mathrm{t}}^2 + DT_2 \end{pmatrix}$$

$X_{\mathrm{t}} = A_{\mathrm{t}} - \mu \cot\beta$; large mixing possible

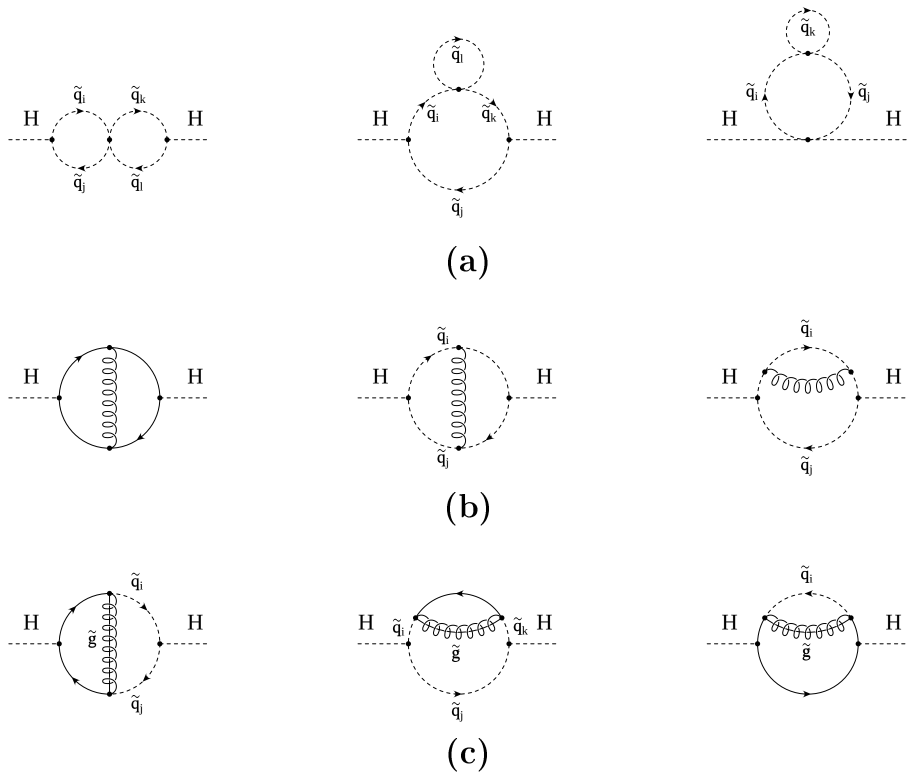
Input parameters: $M_{\tilde{t}_L}$, $M_{\tilde{t}_R}$, X_{t}

$\Rightarrow$ Physical parameters: $m_{\tilde{\mathrm{t}}_1}$, $m_{\tilde{\mathrm{t}}_2}$, $\theta_{\tilde{\mathrm{t}}}$

Present status of m_h prediction in the MSSM:

Complete one-loop result available

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



+ leading $\mathcal{O}(\alpha^2)$ corrections

Upper bound on m_h:

[*S. Heinemeyer, W. Hollik, G. W. '98, '00, '02*]

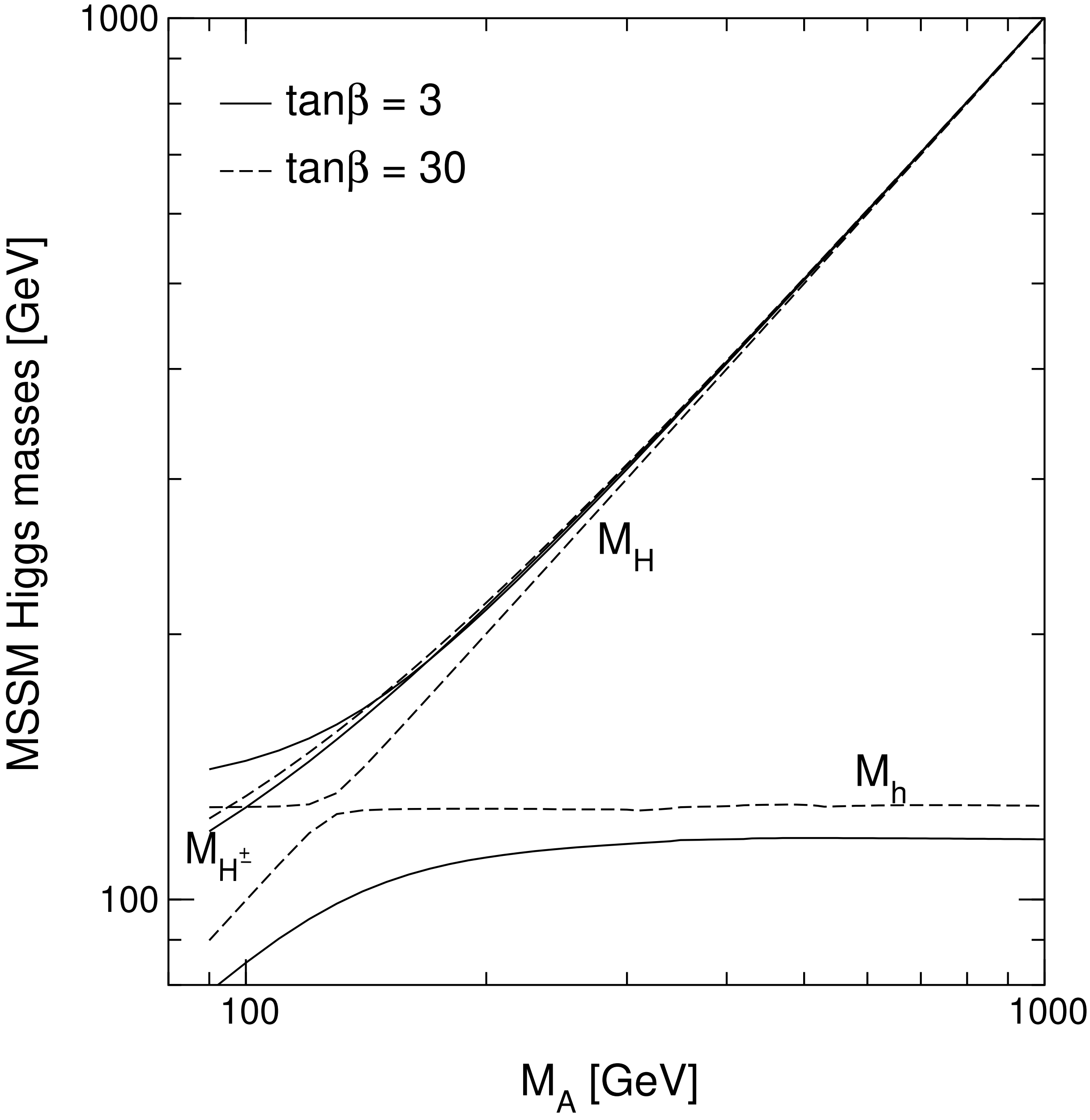
$$m_\mathrm{h} \lesssim 135\,\mathrm{GeV}$$

for $m_\mathrm{t} = 175\,\mathrm{GeV}$

no theoretical uncertainties from unknown higher orders included

Upper bound on m_{h} saturated for large M_{A}, large $\tan\beta$, significant mixing in $\tilde{\mathrm{t}}$ sector

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



Upper bound reduced by

$\approx 6, 11, 8$ GeV in mSUGRA, GMSB, AMSB scenarios

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

Upper bound on m_{h} in extensions of MSSM:

[*G. Kane, C. Kolda, J. Wells '93*]

[*J. Espinosa, M. Quirós '93, '98*]

$$m_{\mathrm{h}} \lesssim 200 \text{ GeV}$$

$\Rightarrow$ **SUSY requires light Higgs boson:**

definite and robust prediction of SUSY models

testable at next generation of colliders

Remaining theoretical uncertainties in prediction for m_{h} in the MSSM:

– From unknown higher-order corrections:
$\Rightarrow \Delta m_{\mathrm{h}} \approx 3$ 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

Higgs couplings, production cross sections

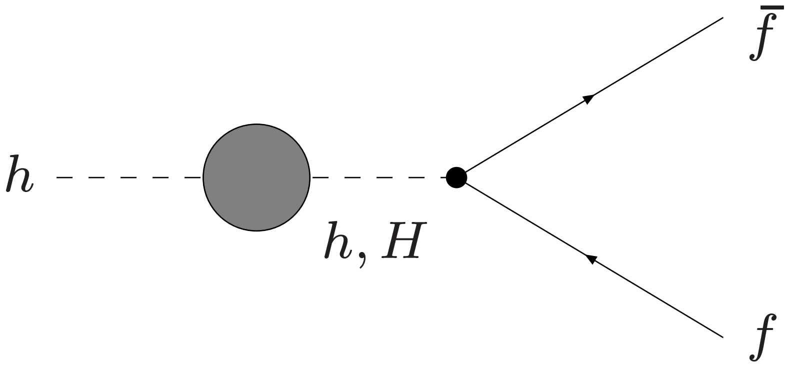
Also affected by large SUSY loop corrections

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:



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

$\Rightarrow$ Effective $hf\bar{f}$ coupling can vanish for large $\hat{\Sigma}_{\mathrm{hH}}$

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 for large $\tan\beta$

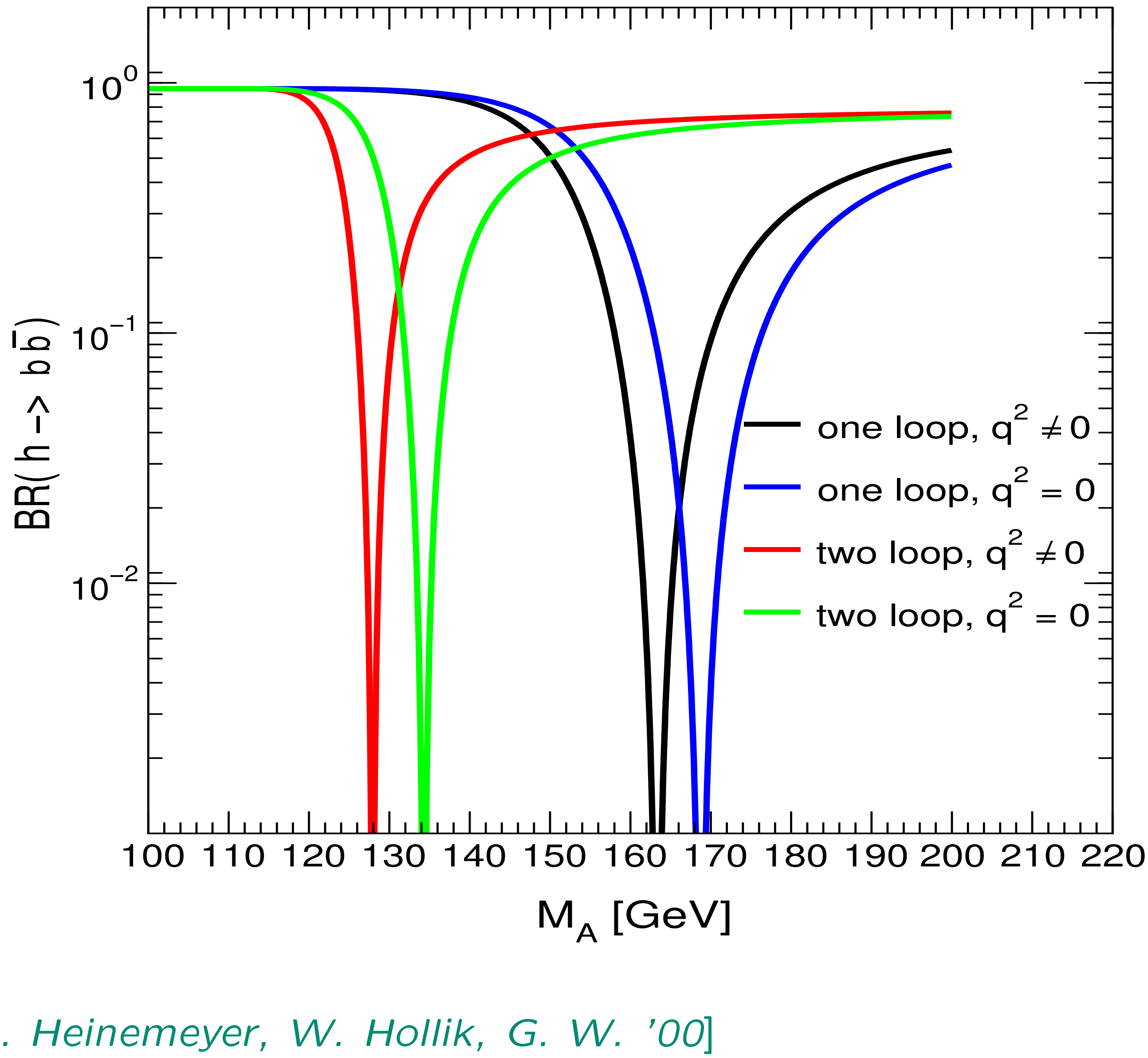
Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{hH}$

$\Rightarrow$ "Pathological regions"

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

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

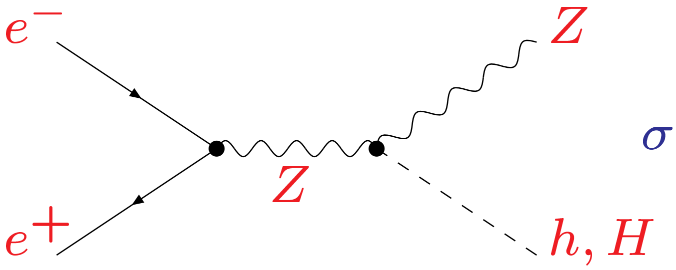
$\Rightarrow$ Suppression of BR($h \to b\bar{b}$), BR($h \to \tau\tau$), ...



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

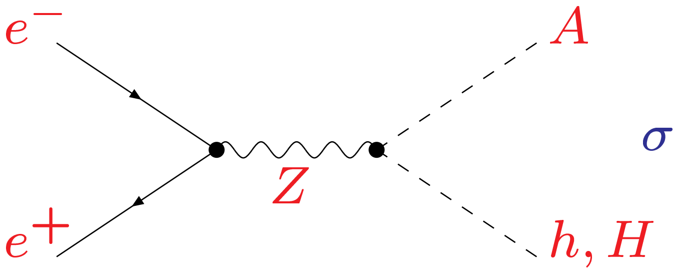
Search for neutral MSSM Higgs bosons at LEP:

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



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

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



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

Interpretation of LEP excess within MSSM:

– $M_A \gg M_Z \Rightarrow h$ with SM-type couplings

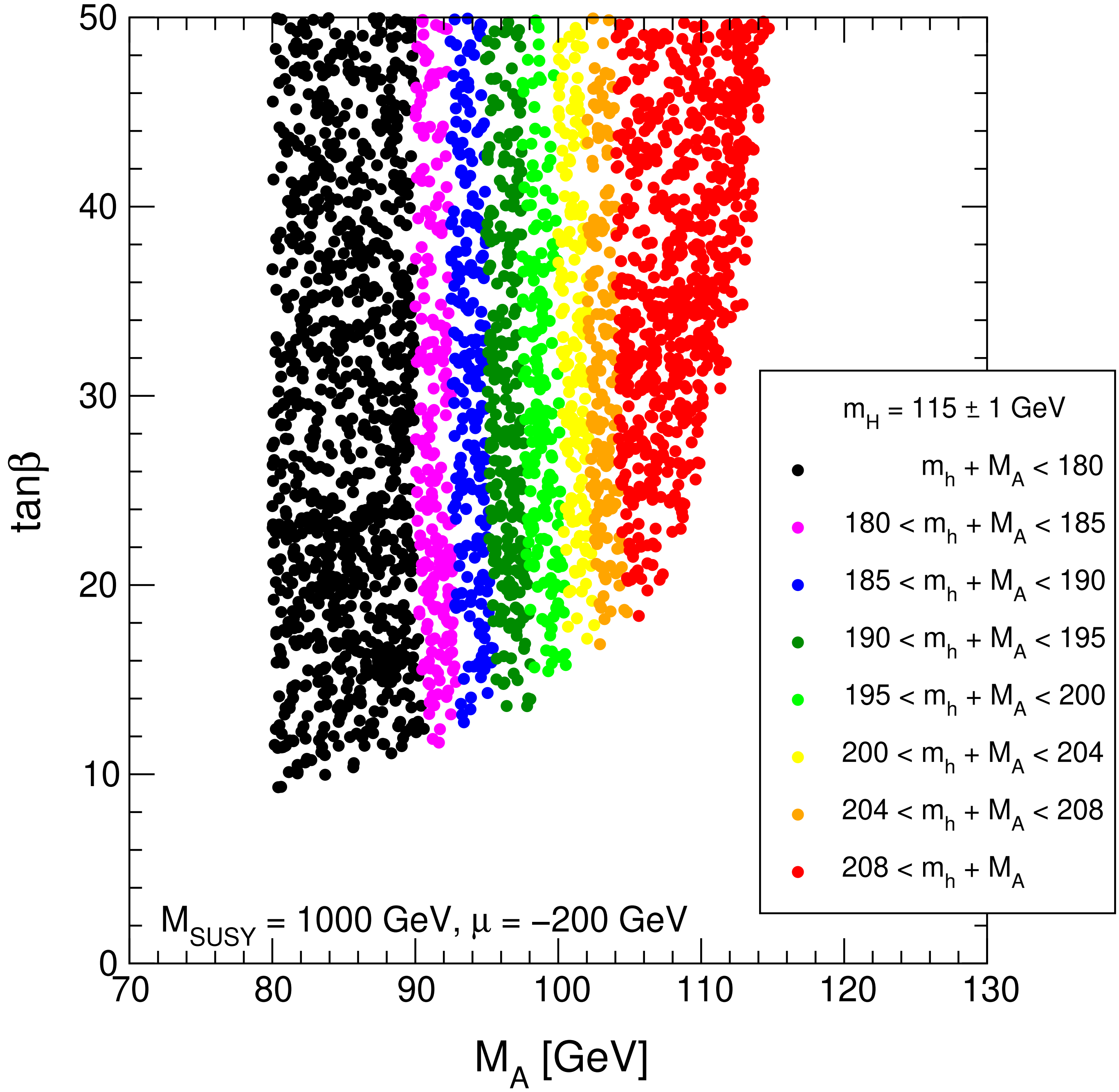
– other possibility:

$m_h, M_A \approx 100$ GeV, $\sin^2(\beta - \alpha_{eff}) \ll 1$
$m_H \approx 115$ GeV

$\Rightarrow H$ with SM-type couplings

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

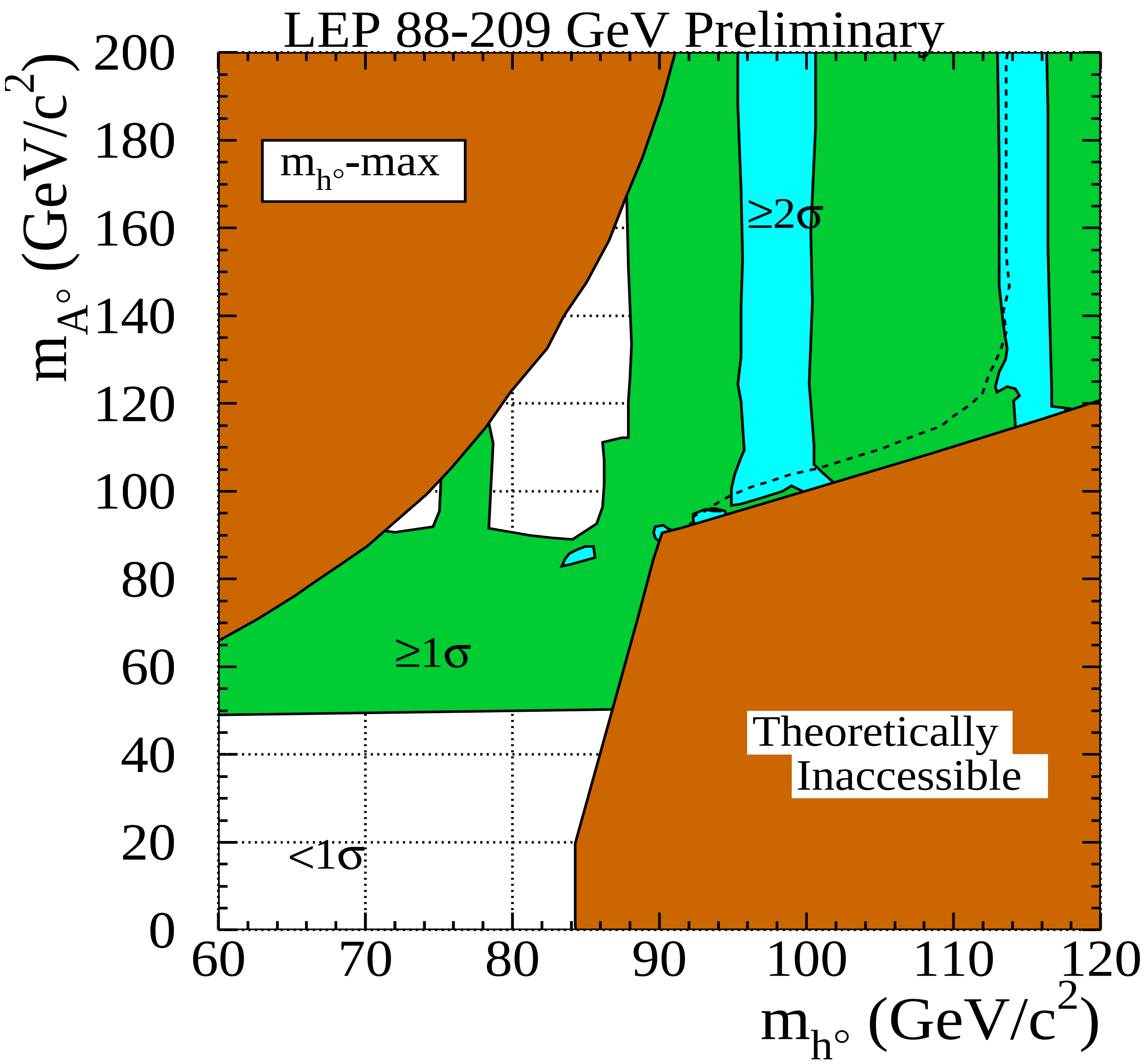
[*S. Heinemeyer, G. W. '00*]



Parameter regions in $(m_\mathsf{h},\ M_\mathsf{A})$ plane where observation is more than 1σ or more than 2σ above background expectation:

[*LEP Higgs Working Group '01*]

$m_\mathsf{h}^\mathsf{max}$-scenario:



Constraints from the Higgs search at LEP

LEP benchmarks (used since 2000):

[*M. Carena, S. Heinemeyer, C. Wagner, G. W. '99*]

- m_h^{max}-scenario:

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

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

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

- no-mixing scenario:
  $X_t = 0$

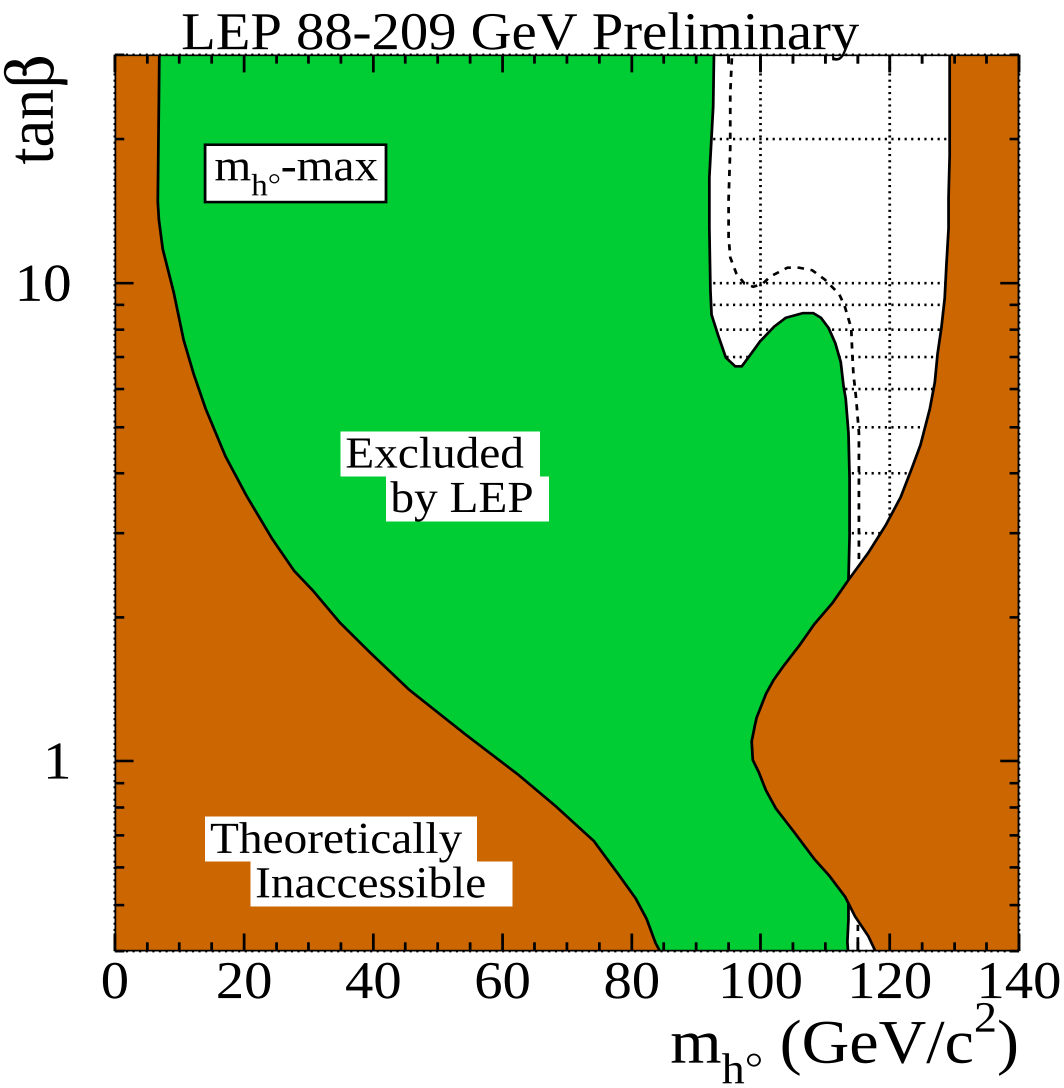
- large μ scenario:
  $\mu = 1\,\text{TeV}$, $M_{SUSY} = 400\,\text{GeV}$, $X_t = -300\,\text{GeV}$

  $\Rightarrow$ m_h within kinematical reach of LEP
  parameter regions with strong suppression
  of $\text{BR}(h \to b\bar{b})$, $\text{BR}(h \to \tau\tau)$

  $\Rightarrow$ Flavor-independent, decay-mode independent
  search channels needed

Experimental search vs. upper m_{h}-bound(*FeynHiggs*1.0)
[*LEP Higgs Working Group '01*]

$m_{\text{h}}^{\text{max}}$-scenario:



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

$M_{\text{A}} > 91.9$ GeV (expected: 95.0 GeV)

Parameter region where experimental lower bound on m_{h} is significantly lower than SM bound, $M_{\text{H}} > 114.1$ GeV, corresponds to $\sin^2(\beta - \alpha_{\text{eff}}) \ll 1$

"Excluded" $\tan\beta$ region:

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

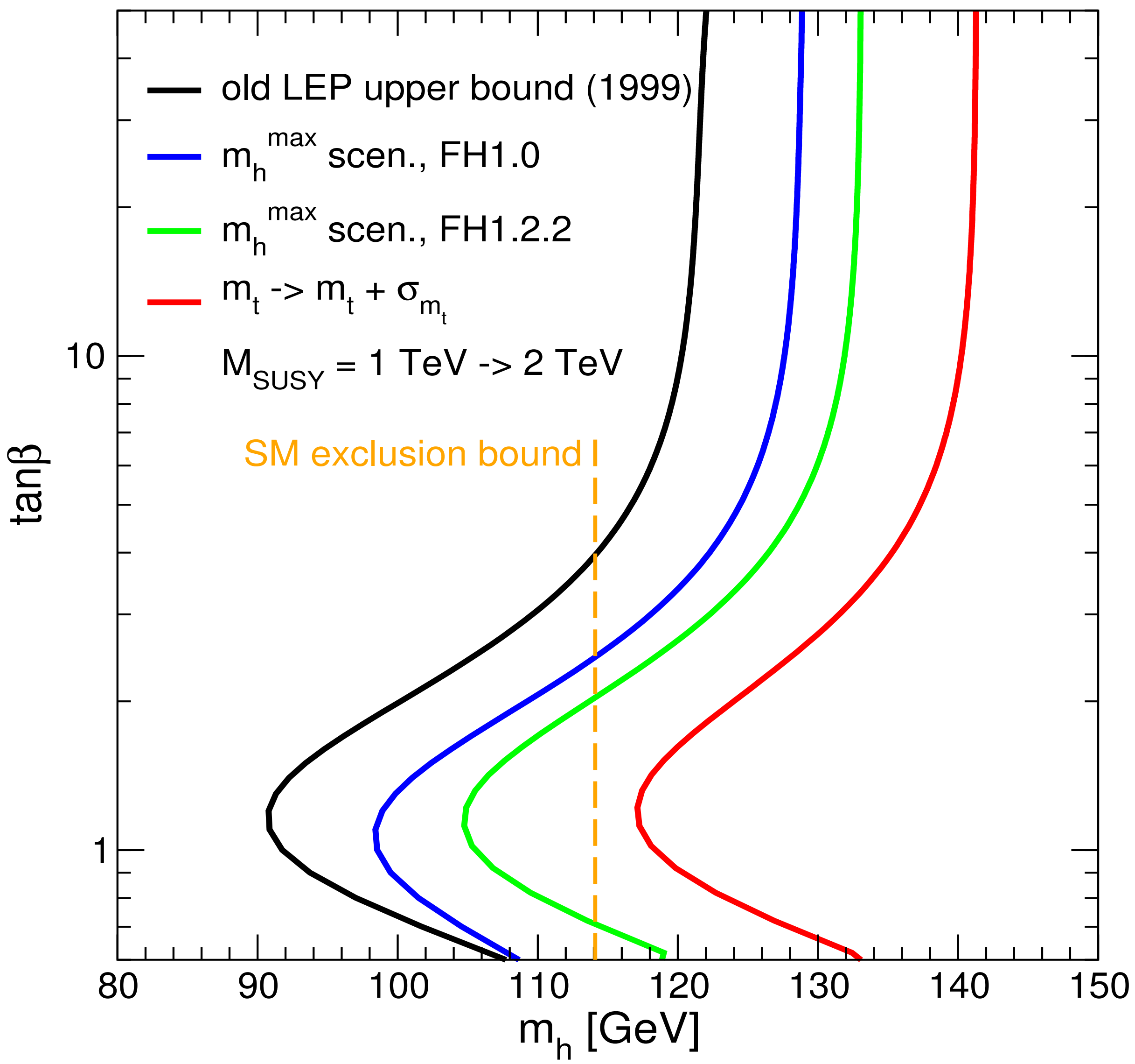
Note: this exclusion bound assumes

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

no theoretical uncertainties included

Effect of new corrections and $m_t \to m_t + \sigma_{m_t}$, $M_{SUSY} = 1$ TeV $\to$ 2 TeV

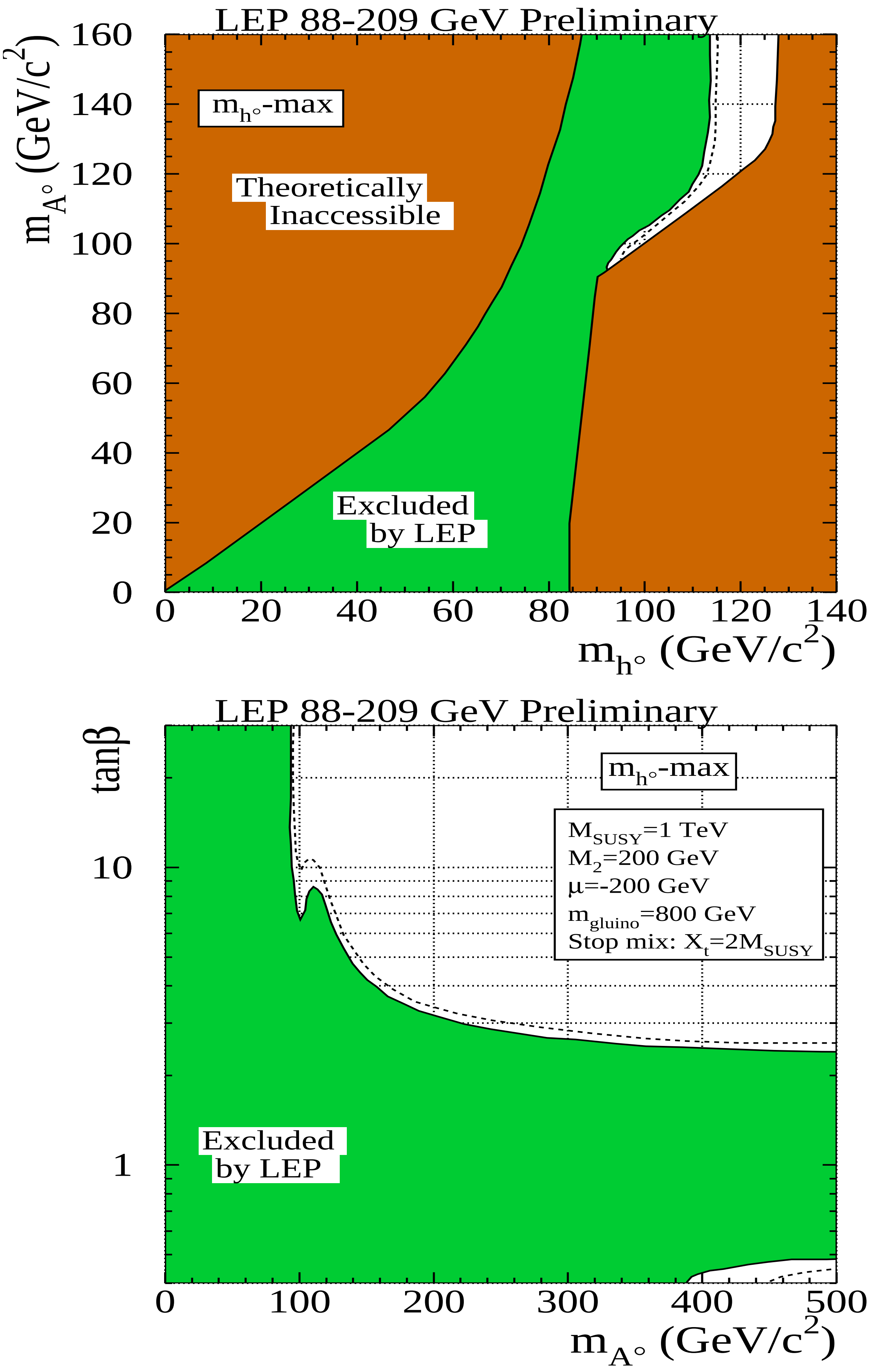
[*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]



$\Rightarrow$ no $\tan\beta$ exclusion for $m_t \to m_t + \sigma_{m_t}$, $M_{SUSY} = 1$ TeV $\to$ 2 TeV

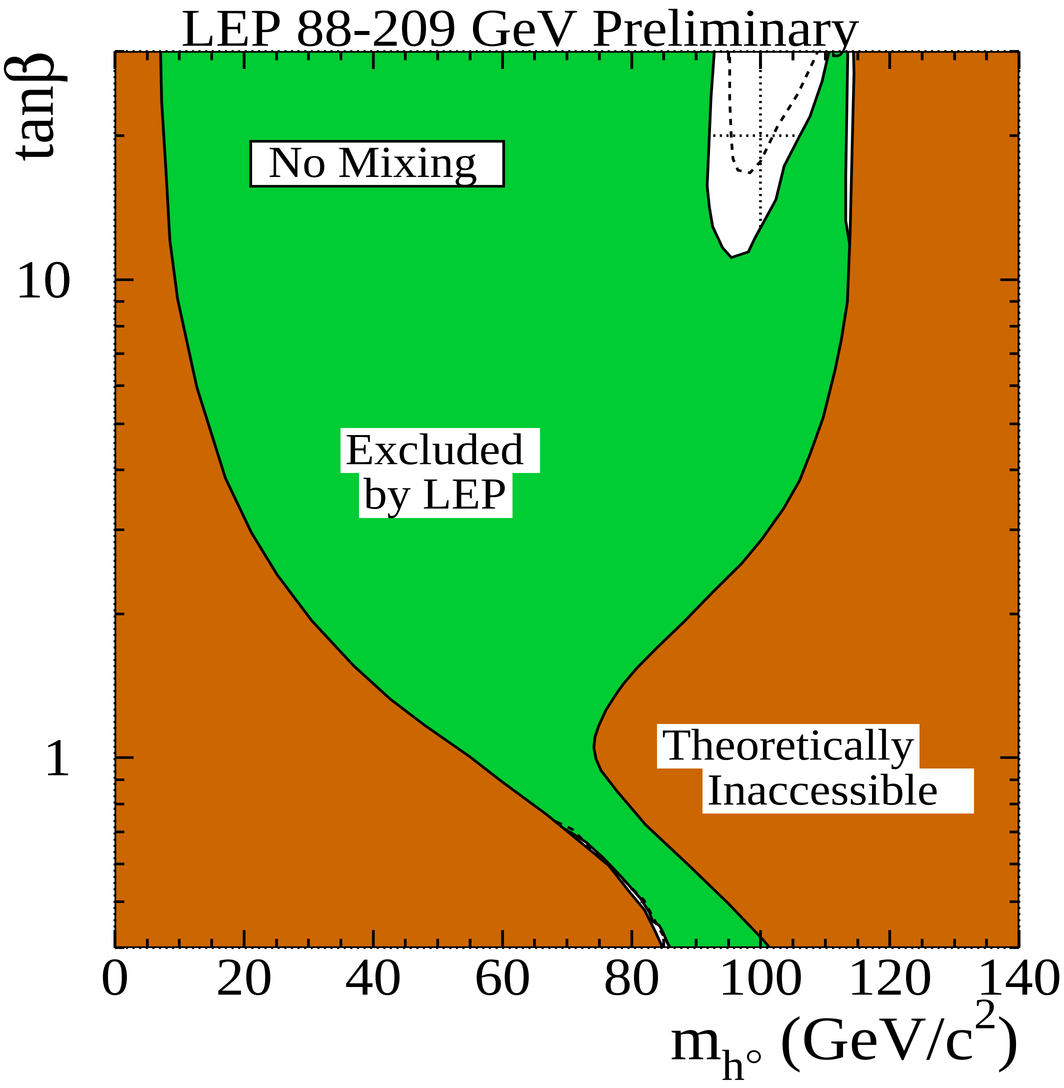
Experimental search vs. upper m_h-bound (*FeynHiggs*)

[*LEP Higgs Working Group '01*]



Experimental search vs. upper m_h-bound (*FeynHiggs*)
[*LEP Higgs Working Group '01*]

no-mixing scenario:



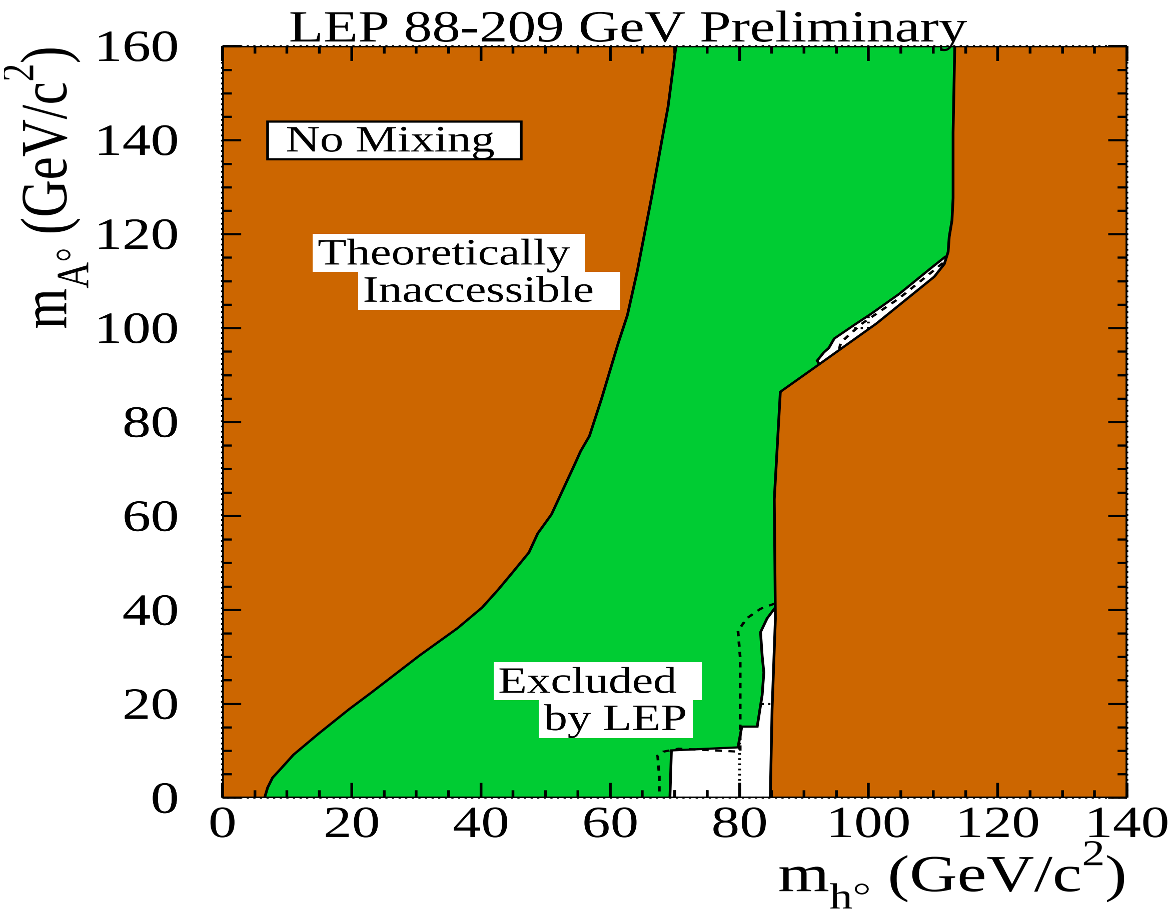
Excluded $\tan\beta$ region:

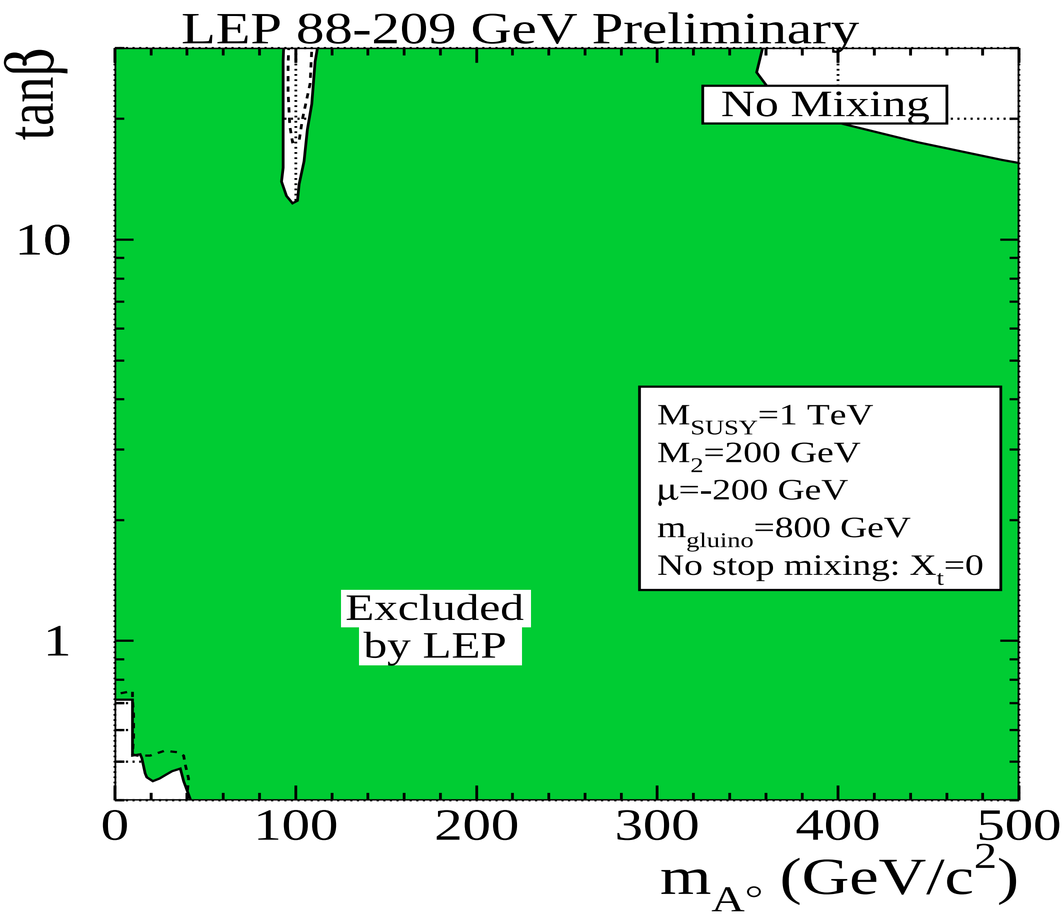
$$0.7 < \tan\beta < 10.5$$

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

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

[*LEP Higgs Working Group '01*]





Preparation of final LEP results

[*LEP Higgs Working Group '02*]

Particular focus on 'model-independent' results:

– Cross section limits

– Limits on

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

separately for different decay channels
$h \to b\bar{b}$, $h \to q\bar{q}$ (flavor-independent), . . . ,
$h \to X$ (decay-mode independent)

Benchmark scenarios:

– Inclusion of $H^\pm$ information

– Benchmark scan for $\mathcal{CP}$-violating case

– 2HDM scans

– External constraint m_h^{max} scenario
(constraints from $g_\mu - 2$, $b \to s\gamma$, . . . respected)

Suggested benchmarks for Higgs searches at the Tevatron and the LHC

[*M. Carena, S. Heinemeyer, C. Wagner, G. W. '02*]

Scenarios for general MSSM
no specific SUSY-breaking scenario assumed
no indirect constraints
M_A, $\tan\beta$ varied

- m_h^{max}-scenario:
  $X_t = 2\,M_{SUSY}$ (FD), $M_{SUSY} = 1$ TeV
  $\Rightarrow$ maximal $m_h(\tan\beta)$ for fixed m_t, M_{SUSY}

- no-mixing scenario:
  $X_t = 0$, $M_{SUSY} = 2$ TeV

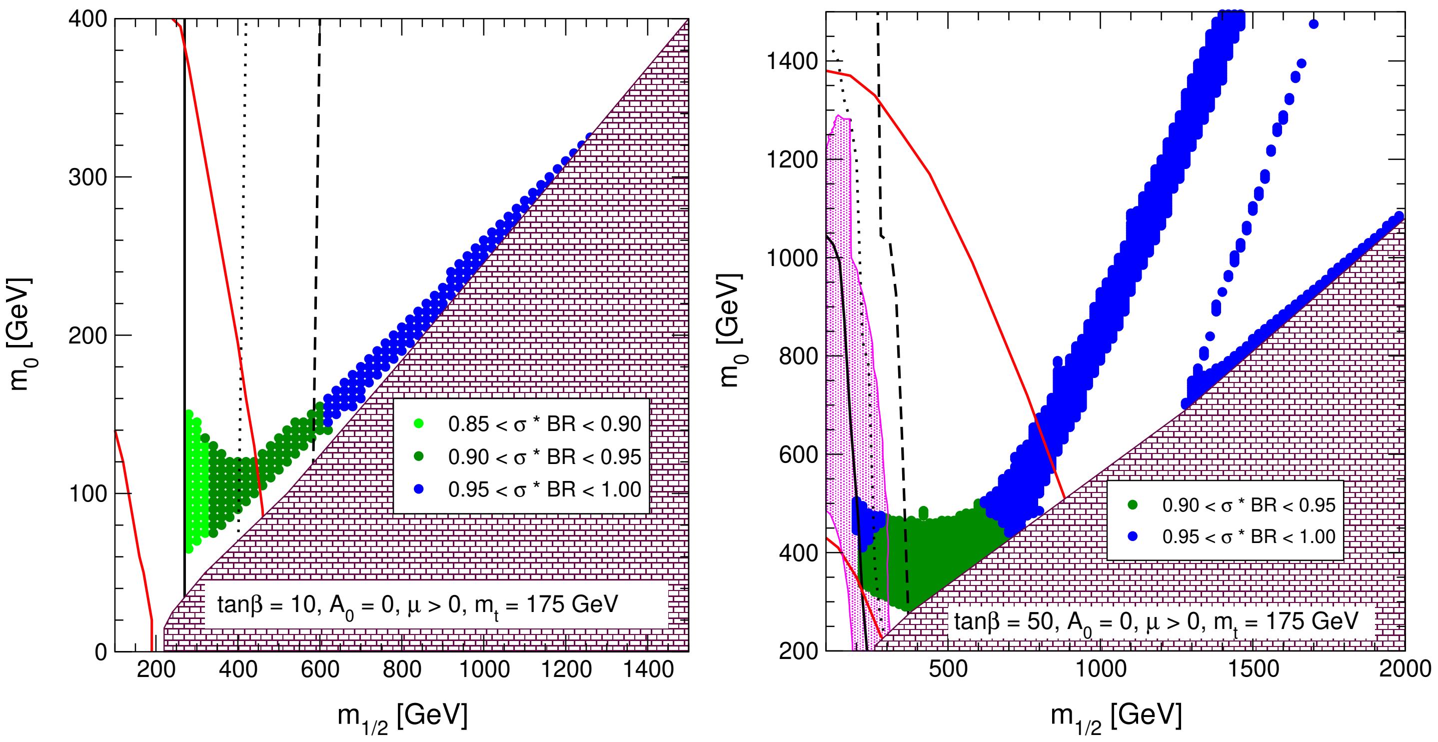
- gluophobic Higgs scenario:
  $M_{SUSY} = 350$ GeV, $X_t = -750$ GeV (FD)
  $\Rightarrow$ suppression of $gg \to h$

- small α_{eff} scenario:
  $M_{SUSY} = 800\,\text{GeV}$, $\mu = 2.5\,M_{SUSY}$,
  $X_t = -1100$ GeV (FD)
  $\Rightarrow$ suppression of $h \to b\bar{b}$, $h \to \tau\tau$

mSUGRA scenario combined with constraints from Higgs search, CDM, $(g_\mu - 2)$, $b \to s\gamma$:
prospects for Tevatron and LHC
[J. Ellis, S. Heinemeyer, K. Olive, G. W. '01]

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

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



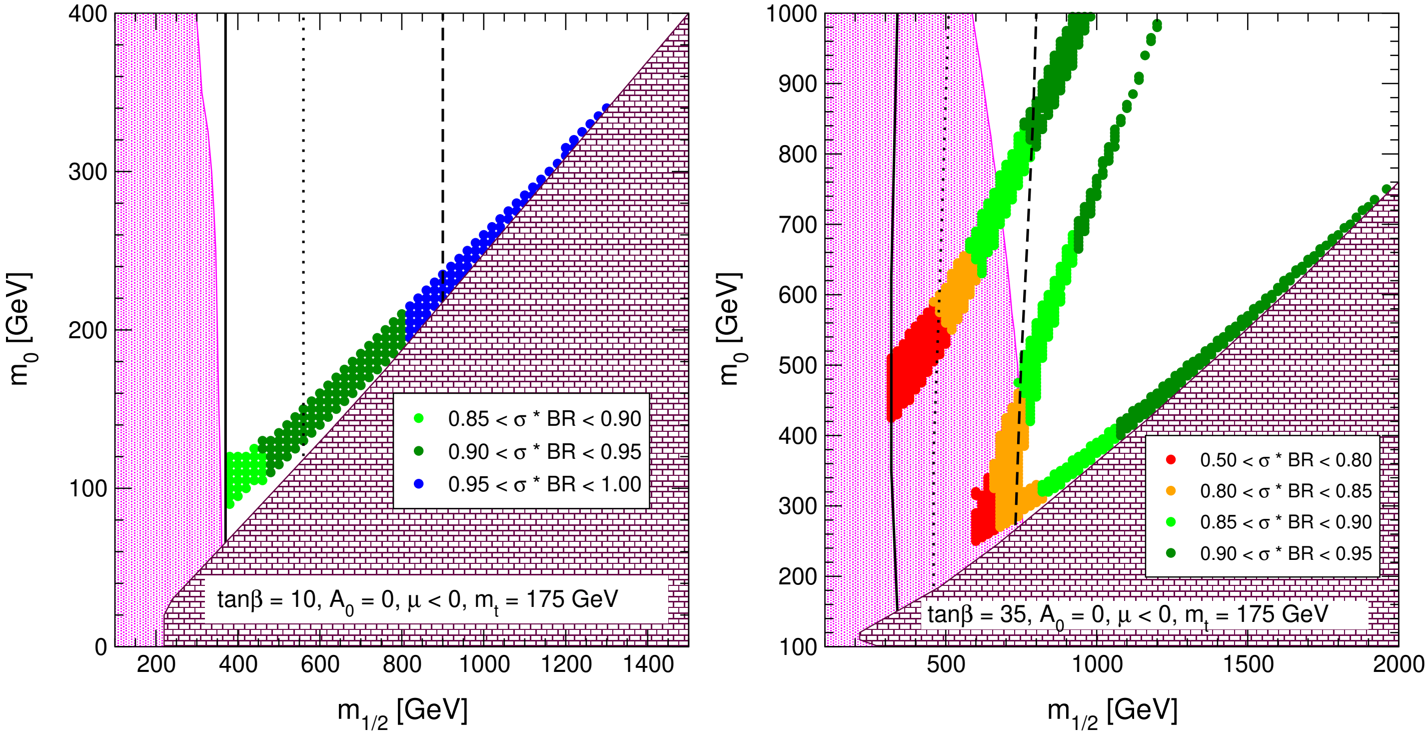
⇒ mSUGRA scenario consistent with all experimental constraints

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

⇒ Discovery of lightest Higgs boson within about one year at LHC possible

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

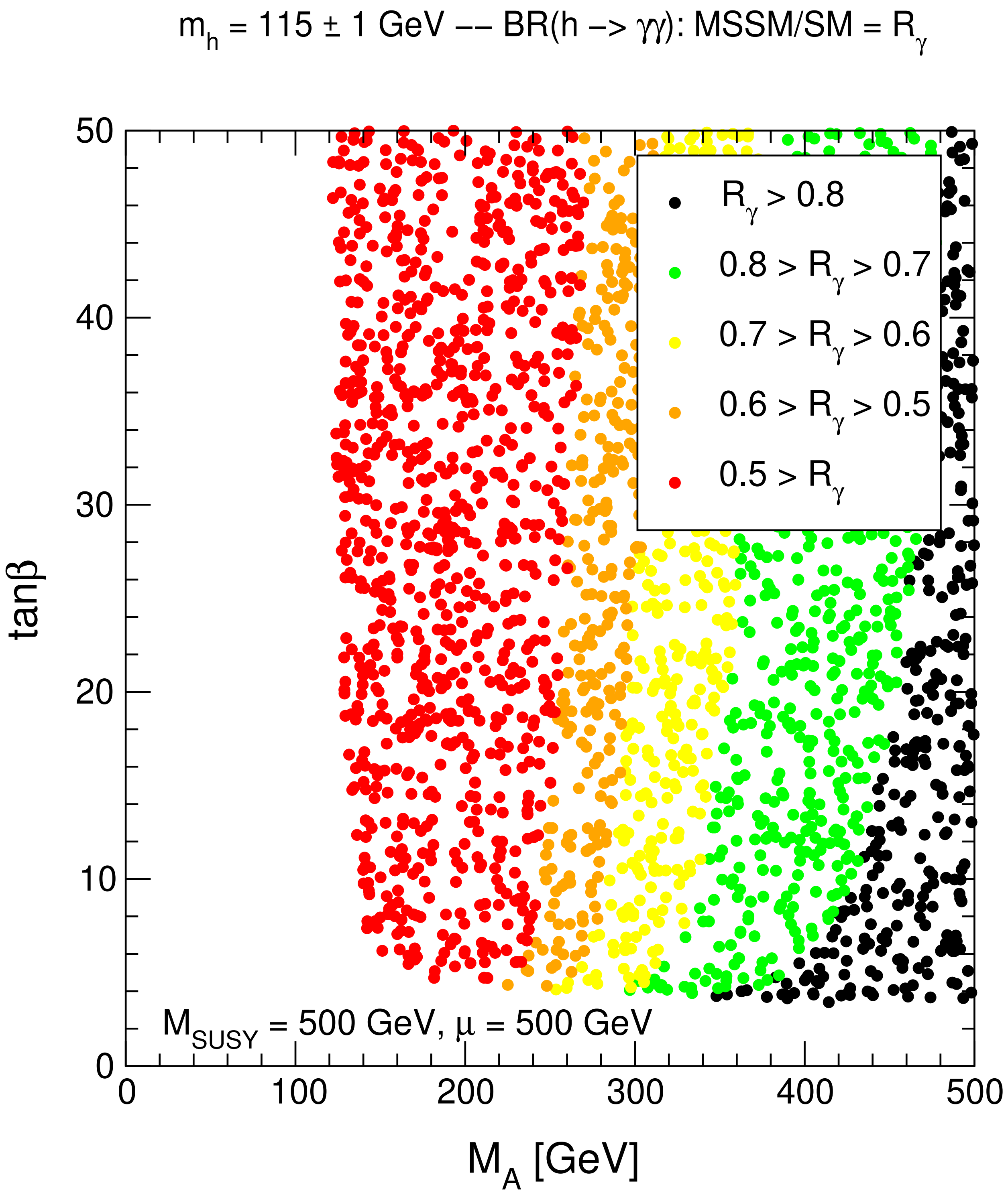
$$\Big[\sigma(gg \to h) \times \text{BR}(h \to \gamma\gamma)\Big]_{\text{CMSSM}} \Big/ \Big[\sigma(gg \to h) \times \text{BR}(h \to \gamma\gamma)\Big]_{\text{SM}}:$$



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

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

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

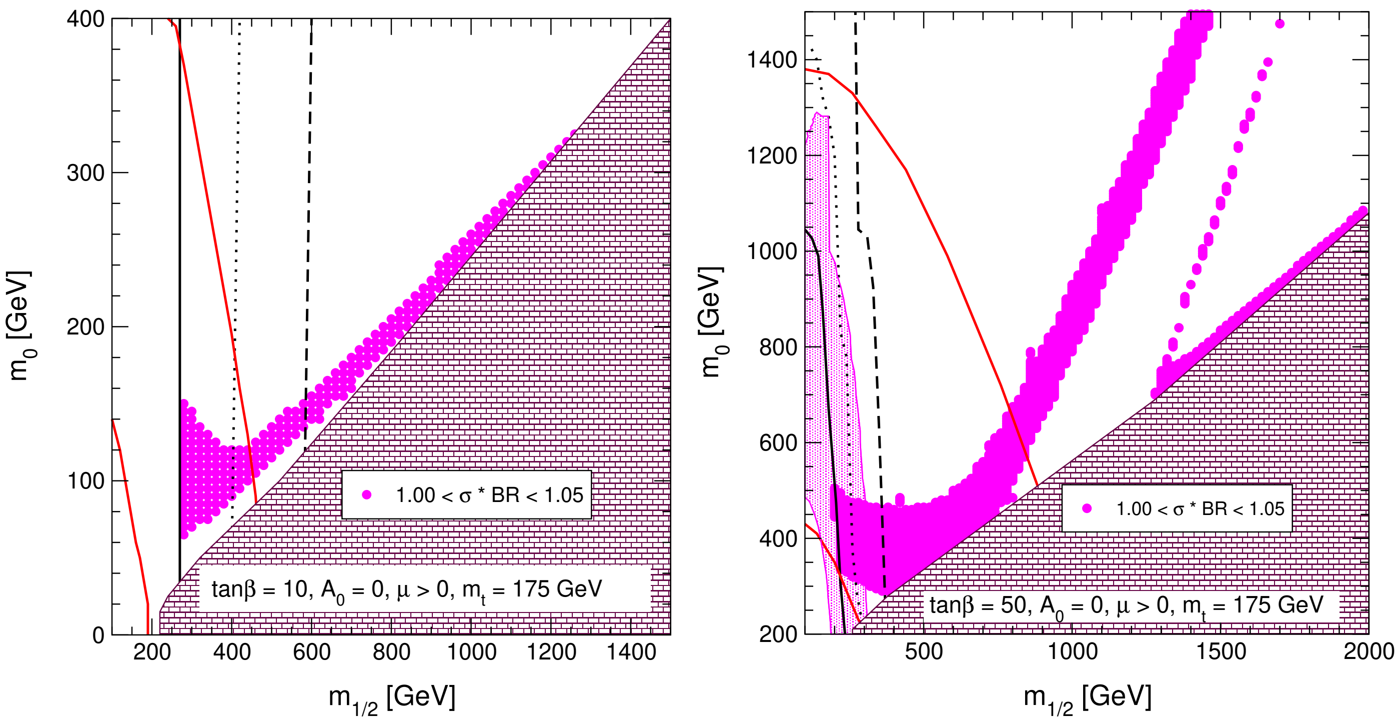


$\Rightarrow$ significant suppression possible over wide parameter space

Higgs production in mSUGRA via W/Z-fusion and associated production with top quark:

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

$$\left[\sigma(V/\bar{t}t+h)\times \mathrm{BR}(h\to\bar{b}b)\right]_{\mathrm{CMSSM}}\Big/\left[\sigma(V/\bar{t}t+h)\times \mathrm{BR}(h\to\bar{b}b)\right]_{\mathrm{SM}}:$$



No suppression of $\sigma \times$ BR compared to SM case

$\Rightarrow$ For $m_{\mathrm{h}} \approx 115$ GeV:

Discovery at Tevatron with ≈ 15 fb^{-1} possible

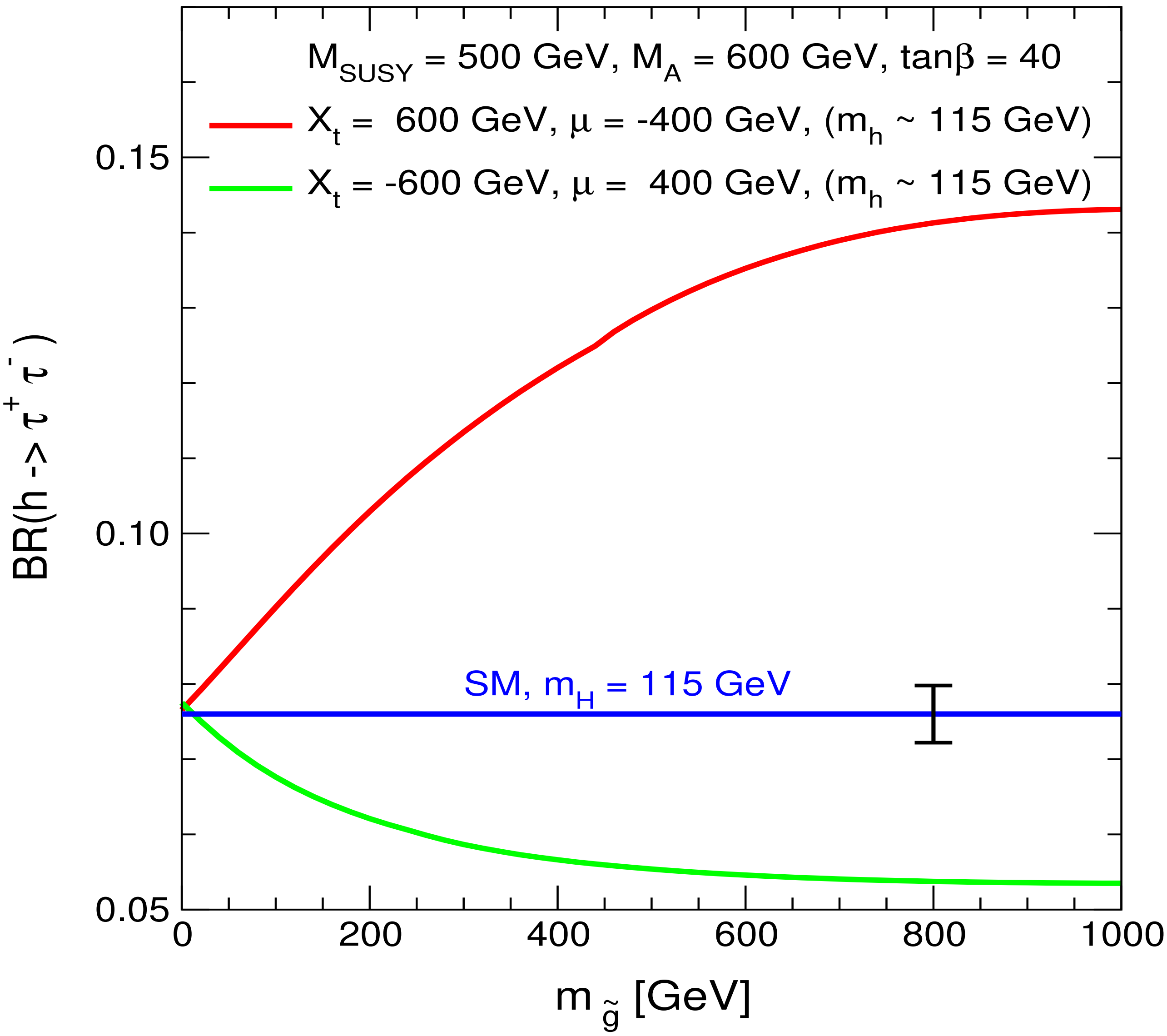
Precision physics in the MSSM Higgs sector

Precise measurement of Higgs branching ratios

$\Rightarrow$ Sensitivity to deviations SM / MSSM

E.g.: Comparison of SM / MSSM prediction for BR($h \to \tau^+\tau^-$) with experimental precision at LC:

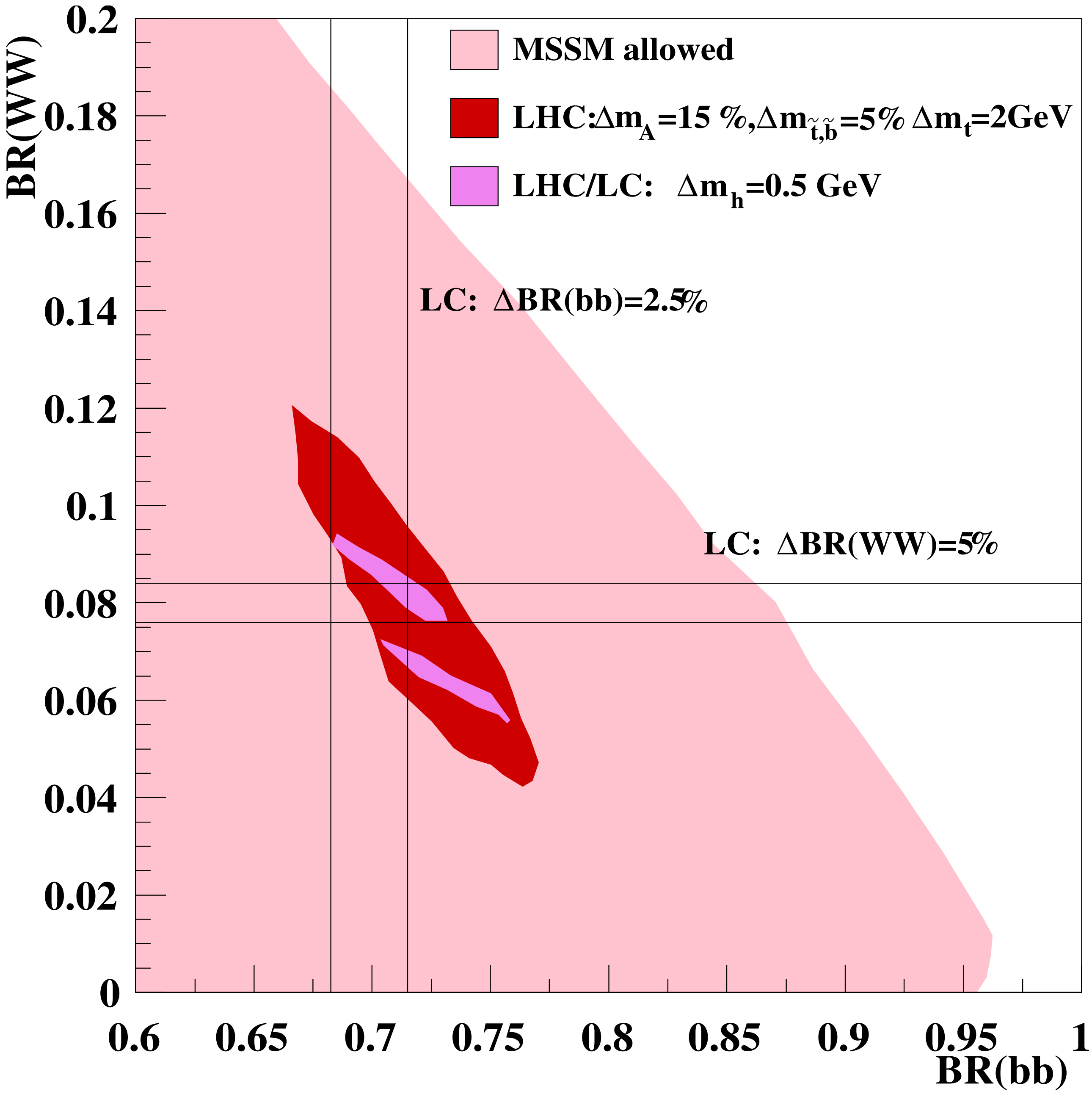
[*S. Heinemeyer, G.W. '01*]



$\Rightarrow$ Large deviations from SM prediction possible even for relatively large M_A

Comparison: Prediction of light Higgs BRs from measurements of heavy Higgs properties at the LHC vs. experimental precision at the LC

[*K. Desch, S. Heinemeyer, G.W. '02*]



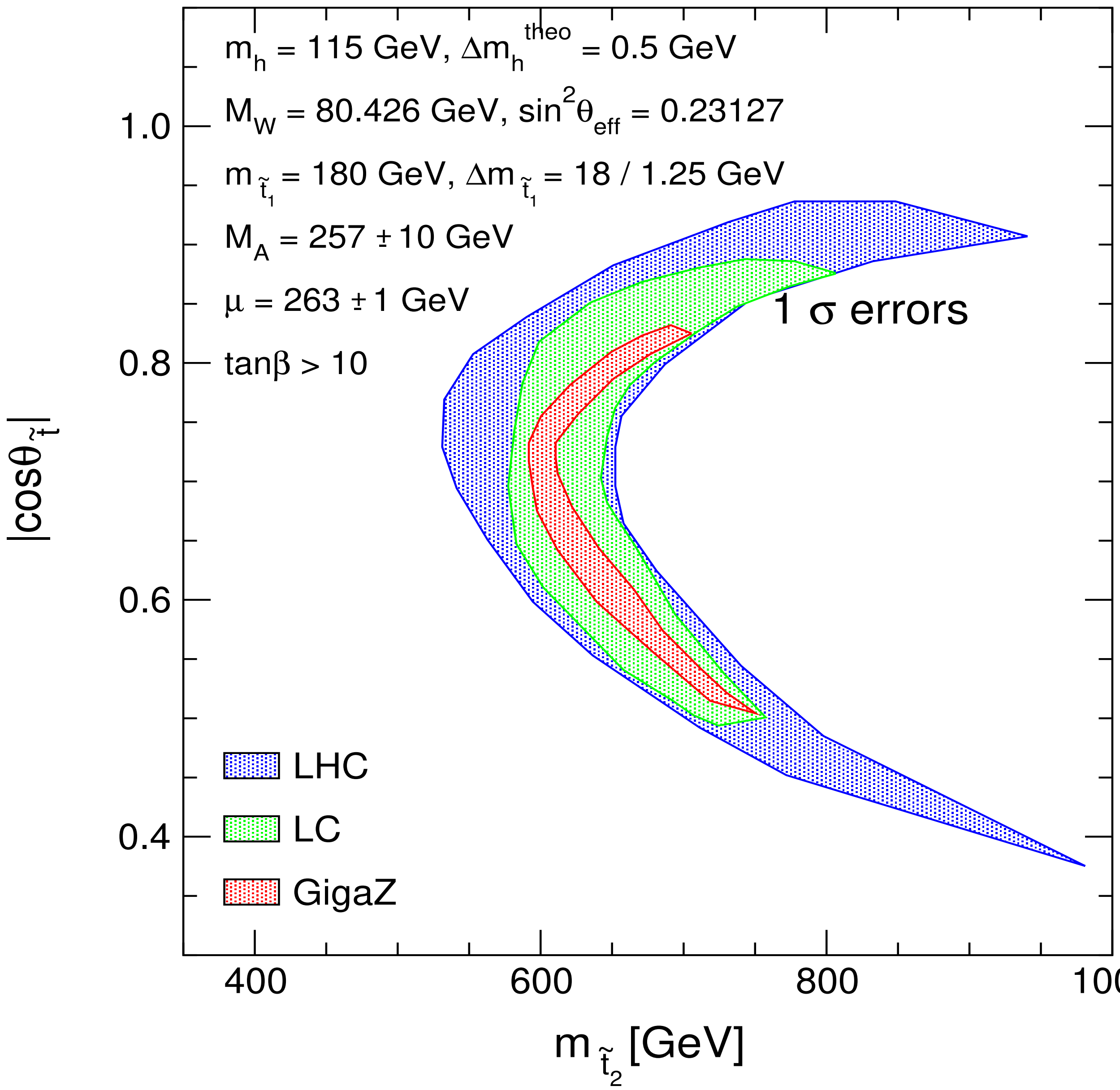
⇒ very sensitive test of the model

From precise measurement of m_{h}

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

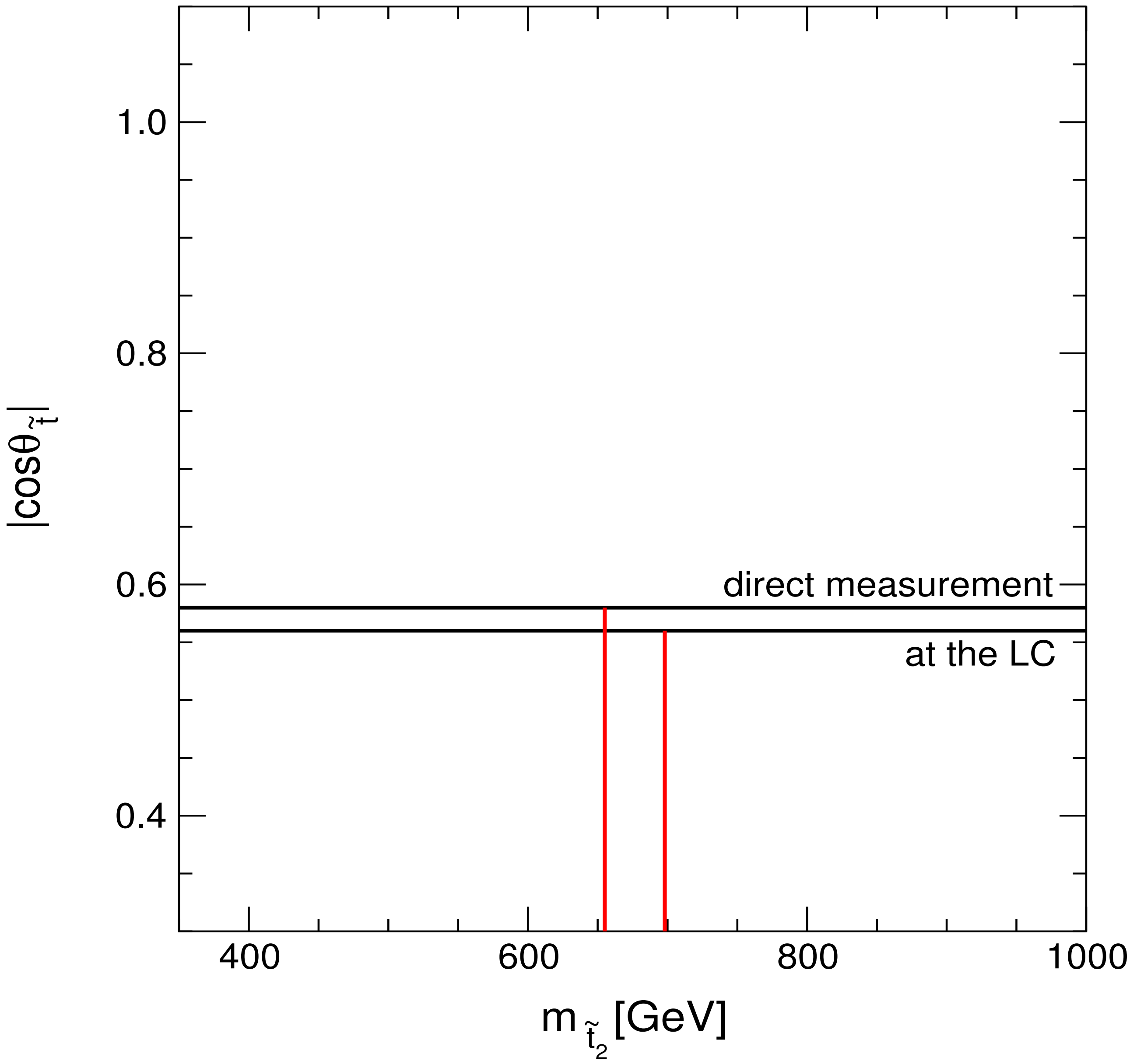
E.g.: Indirect constraints on $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$ from precision measurements of m_{h}, M_{W}, $\sin^2\theta_{\mathrm{eff}}$ at LC/GigaZ:
[S. Heinemeyer, G.W. '01]

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



$\Rightarrow$ Direct/indirect information is complementary

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



1.0
0.8
0.6
0.4
$|\cos\theta_{\tilde{t}}|$
direct measurement
at the LC
400
600
800
1000
$m_{\tilde{t}_2}$ [GeV]

Necessary improvements in accuracy of theoretical prediction in order to match experimental precision at LHC, $\delta m_\mathrm{h}^\mathrm{exp} \approx 0.2$ GeV:

- Uncertainty from experimental errors of input parameters:

  $\Rightarrow$ Complementarity example:

  In order to match

  experimental precision at LHC, $\delta m_\mathrm{h}^\mathrm{exp} \approx 0.2$ GeV

  need

  LC precision on m_t, $\delta m_\mathrm{t}^\mathrm{exp} \lesssim 0.2$ GeV

- Uncertainty from unknown higher-order corrections:

  $\Rightarrow$ Need improvement by more than a factor 10!

Summary of Lecture 4:

- SUSY searches (same for other kinds of new physics) at next generation of colliders:

  Tevatron and LHC: big discovery potential

  LC: high-precision physics

  $\Rightarrow$ need both to

  - establish SUSY experimentally
  - disentangle patterns of SUSY breaking

- Complementarity LHC / LC can be exploited for improving analyses at both machines

- Light Higgs boson is definite and robust prediction of SUSY theories, testable at next generation of colliders

  Upper bound on m_{h} in the MSSM: $m_{\mathrm{h}} \lesssim 135$ GeV

  reduced by 5–10 GeV in mSUGRA, GMSB, AMSB

- Precision physics in the Higgs sector:

  $\Rightarrow$ Very sensitive test of SM, MSSM, . . .

$\Rightarrow$ Golden era of Standard Model is likely to end soon

Data rules: expect the unexpected

$\Rightarrow$ Very exciting prospects for high-energy physics!