Electroweak Physics: Preparing for TESLA

Georg Weiglein

IPPP Durham

DESY Academic Training Lectures

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Lecture 3:

- Prospects for SUSY searches at the next generation of colliders
- Observables, pseudo-observables and electroweak parameters
- 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.
  - ...

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

...

⇒ 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, ...

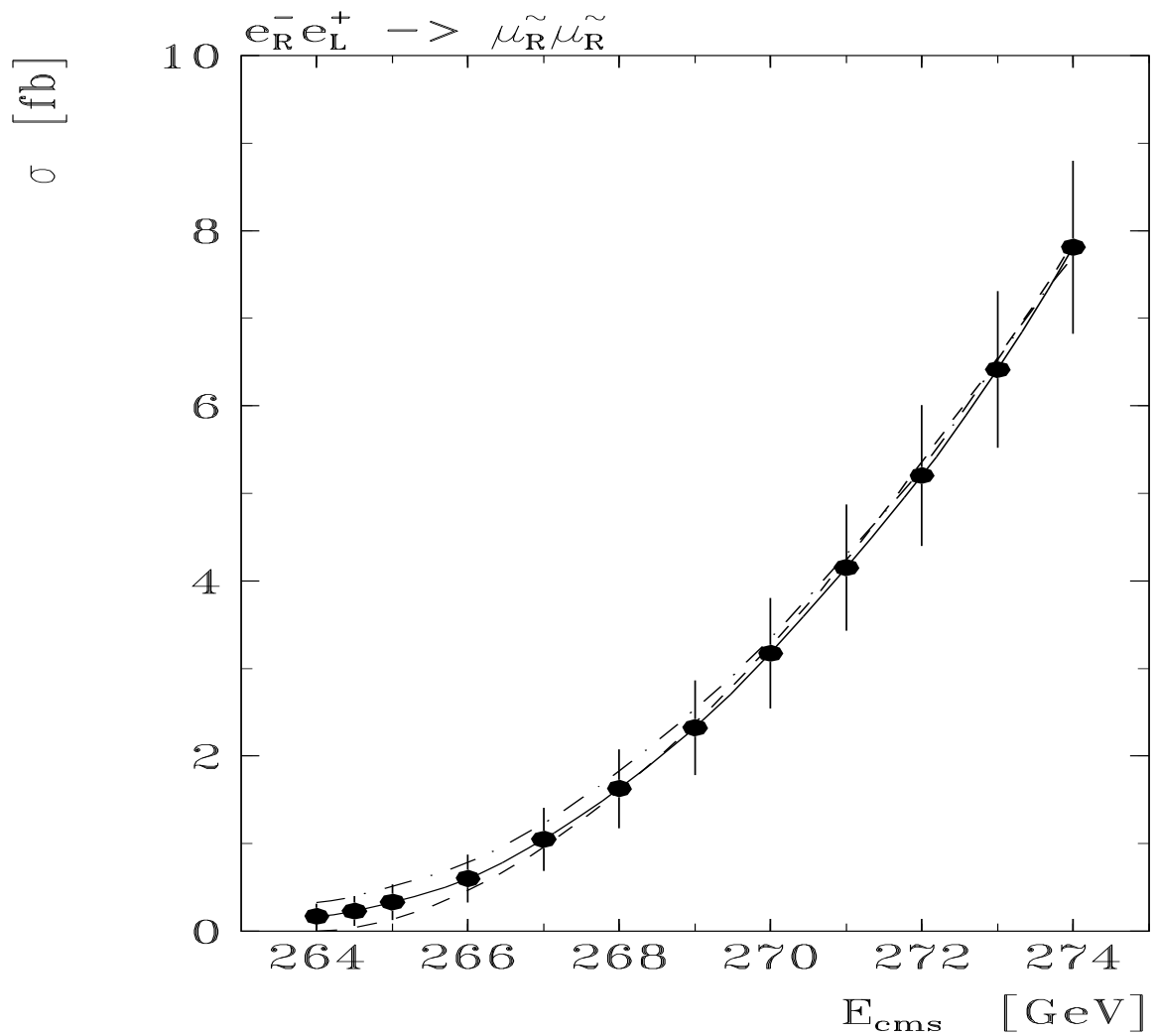
⇒ High luminosity LC necessary,

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*]

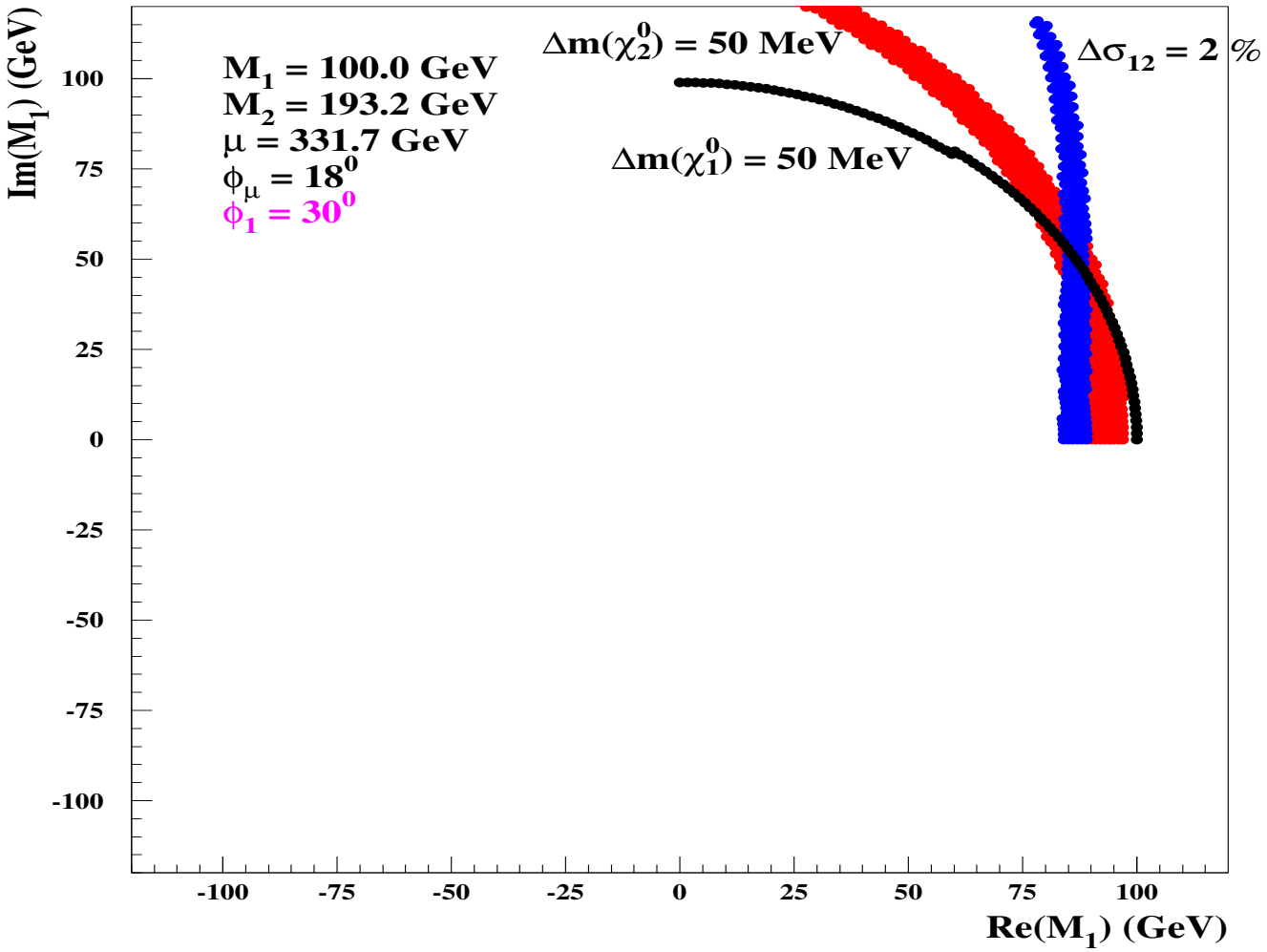


$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

test of $J = 0$ hypothesis

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

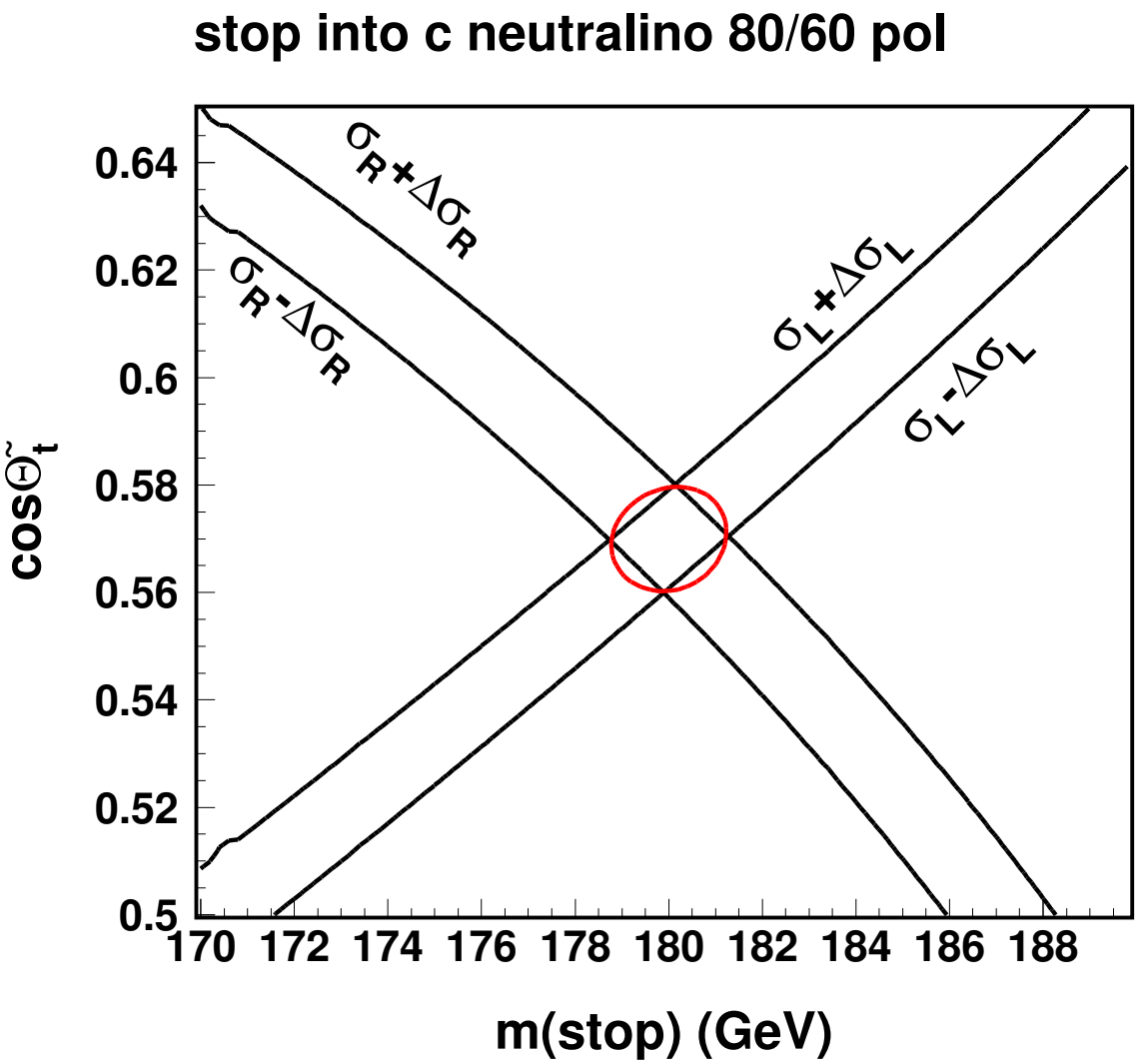
$m_{\tilde{\chi}_1^0} = 96.12 \pm 0.05$ GeV, $m_{\tilde{\chi}_2^0} = 177.13 \pm 0.05$ GeV,
$m_{\tilde{\chi}_1^\pm} = 174.90 \pm 0.05$ GeV, $\Delta\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0) = \pm 2\%$
[*K. Desch, G. Moortgat-Pick '02*]



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

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:

⇒ 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

  ⇒ determination of Z' couplings at LC

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

- ...

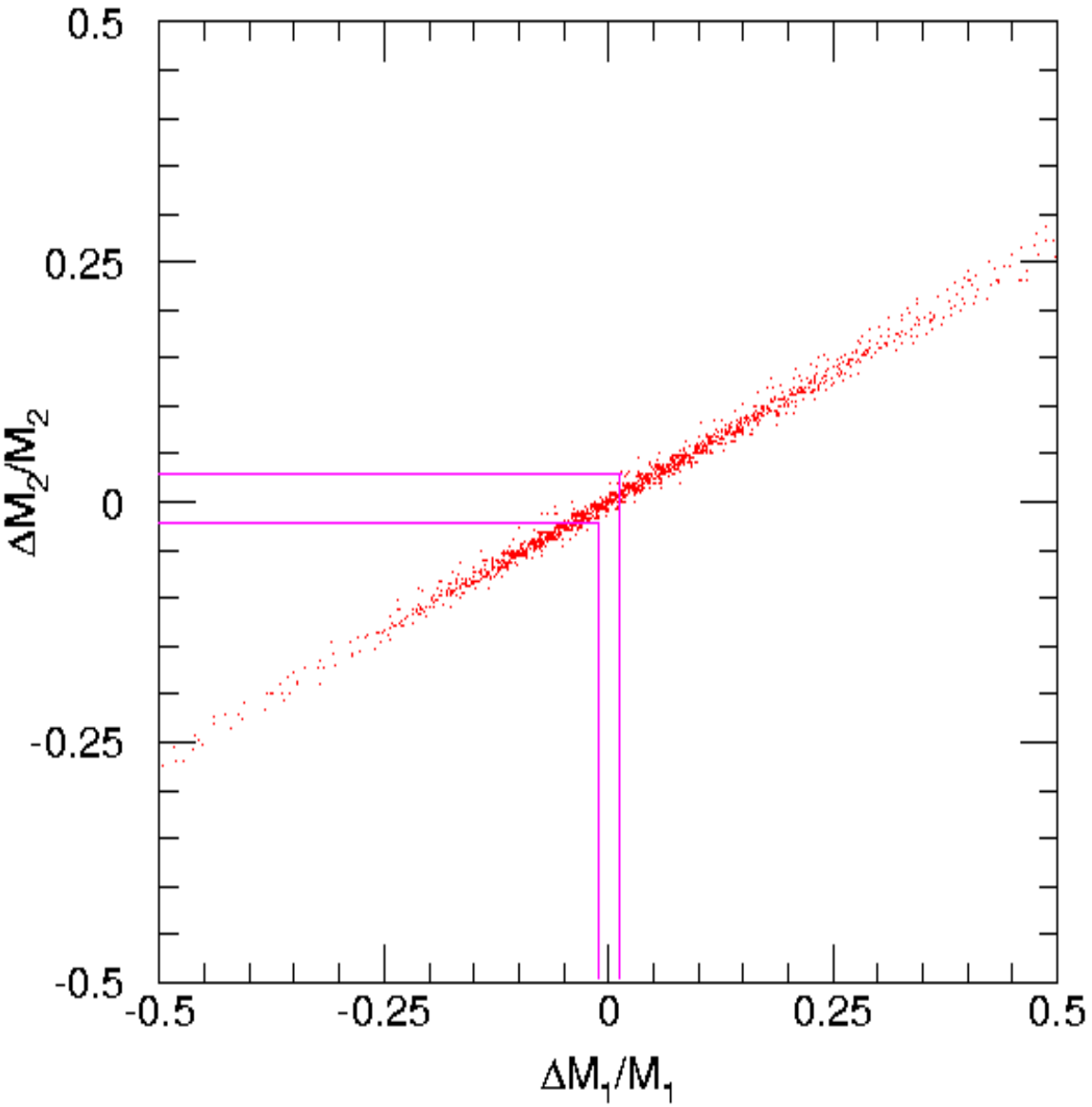
⇒ investigated in "LHC / LC Study Group"

`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]



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

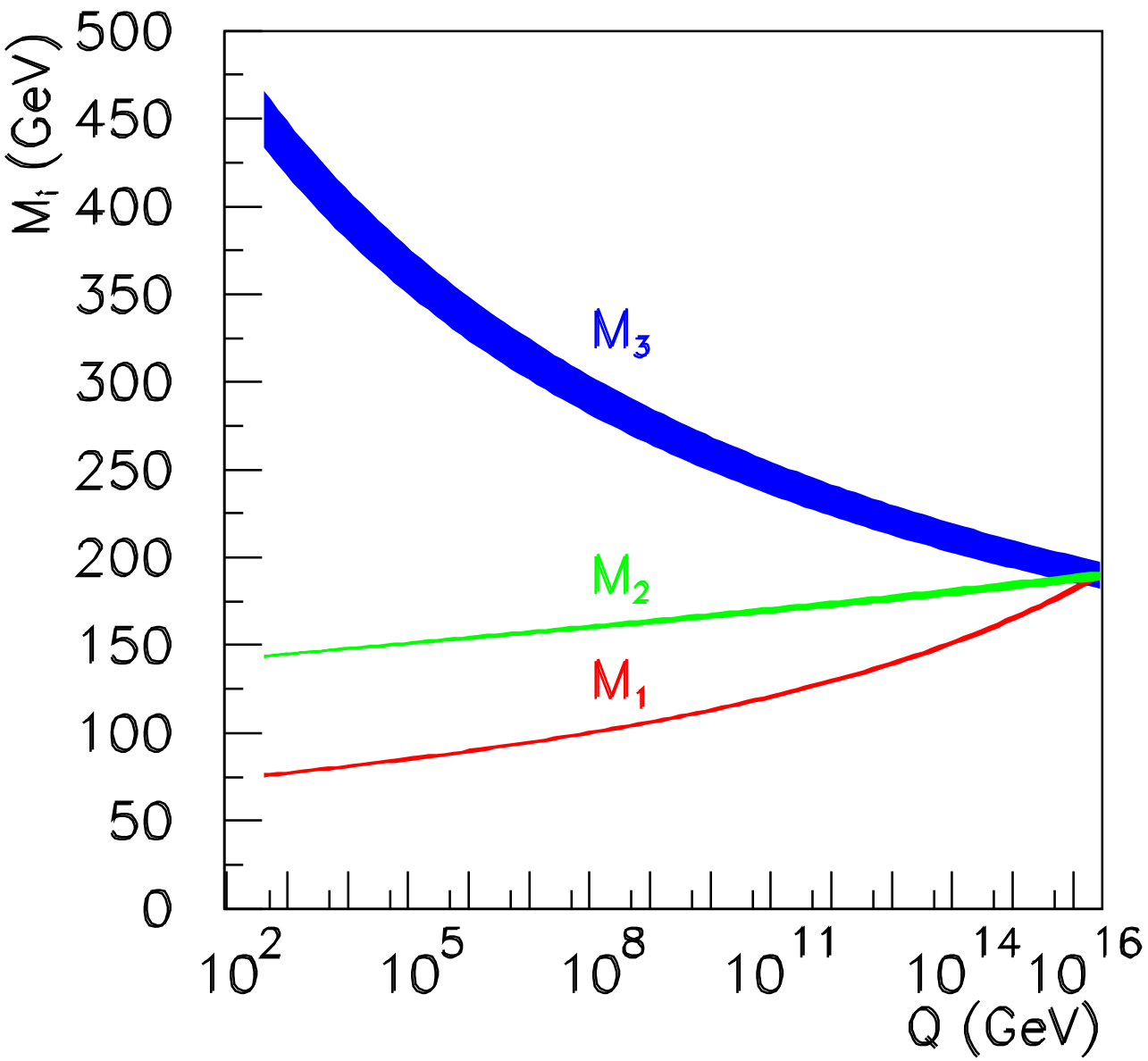
From combination of LHC and LC results, precise measurement of masses of SUSY particles, couplings:

⇒ 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*]



Observables, pseudo-observables and electroweak parameters

Precise measurements of cross sections, BRs at LC:

$\Rightarrow$ parameter determination with accuracy 10^{-2}–10^{-3}

Precise determination requires precise definition of parameters!

Note: couplings, masses, mixing angles, etc. are not (directly) physical observables

$\Rightarrow$ "pseudo-observables"

Actual observables:
cross sections, BRs, asymmetries

Need deconvolution procedure (unfolding) in order to determine masses, partial widths, etc. from measured cross sections

$\Rightarrow$ pseudo-observables are not strictly model-independent

What is a suitable definition of model parameters?

need some compromise between

– simple interpretaion within given model

– model independence

In principle possible (extreme case):

fit model with n free parameters to n observables

$\Rightarrow M_{\mathrm{W}}^{\mathrm{exp,SM}} = M_{\mathrm{W}}^{\mathrm{exp,SM}}(m_{\mathrm{t}}, M_{\mathrm{H}}, \ldots)$

However: want to define particle masses such that they are (approximately) model-independent, easy to relate to measurable quantities

– reconstruction of decay products

– from cross section near threshold

...

Example: what is M_{W}?

Theorist point of view:

Mass determined by pole of propagator

Which pole?

– real part of complex pole, $\mathcal{M}^2 = \overline{M}^2 - i\overline{M}\,\overline{\Gamma}$, or

– pole of real part, $\widetilde{M}^2$

From 2-loop order on:

real part of complex pole $\neq$ pole of real part

$$\delta\overline{M}^2_{(2)} = \delta\widetilde{M}^2_{(2)} + \underbrace{\mathrm{Im}\left\{\Sigma'_{\mathrm{T},(1)}(M^2)\right\}\,\mathrm{Im}\left\{\Sigma_{\mathrm{T},(1)}(M^2)\right\}}_{\text{gauge-parameter dependent!}}$$

S-matrix theory

[*A. Sirlin '91*], [*R.G. Stuart '91*], [*H. Veltman '94*]

[*P. Gambino, P.A. Grassi '99*]

Explicit 2-loop calculation in general R_ξ-gauge:

[*A. Freitas, W. Hollik, W. Walter, G.W. '00*]

$\Rightarrow$ Complex pole gauge-invariant

How does one measure the pole of a propagator?

Experimentalist point of view:

In practice: comparison data – Monte Carlo

$\Rightarrow$ "M_{W} is what is implemented in Monte Carlo program"

Comparison theory prediction – experimental result:

Definition via real part of complex pole:

$$\Rightarrow \sigma(s) \sim \frac{s}{(s - \overline{M}^2)^2 + \overline{M}^2\overline{\Gamma}^2}$$

$\Rightarrow$ Breit–Wigner shape with constant width

Experimental determinations at LEP/Tevatron use:

$$\sigma(s) \sim \frac{s}{(s - M^2)^2 + s^2\Gamma^2/M^2}$$

$\Rightarrow$ Breit–Wigner shape with running width

Relation:

$$M^2 = \overline{M}^2 + \overline{\Gamma}^2 \quad \Rightarrow \underbrace{\Delta M_{\mathrm{W}} \approx 27\,\mathrm{MeV}}_{\text{formally a 2-loop effect!}}$$

$\Rightarrow$ For theoretical prediction of M_{W}:
need prediction for $\overline{M}_{\mathrm{W}}$ and $\overline{\Gamma}_{\mathrm{W}}$

$\Rightarrow$ (Slightly) larger theoretical uncertainty for M_{W} than for $\overline{M}_{\mathrm{W}}$

Quark masses: on-shell (pole) masses affected by large QCD uncertainties

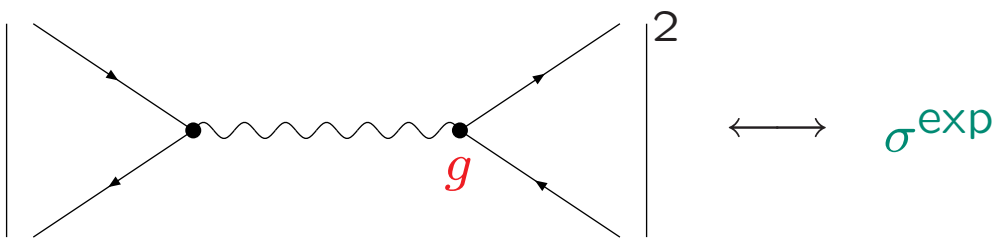
$\Rightarrow$ $\overline{\mathrm{MS}}$ masses usually preferable

Particle masses: relatively small model dependence

Couplings, mixing angles, etc.:
relatively large model dependence

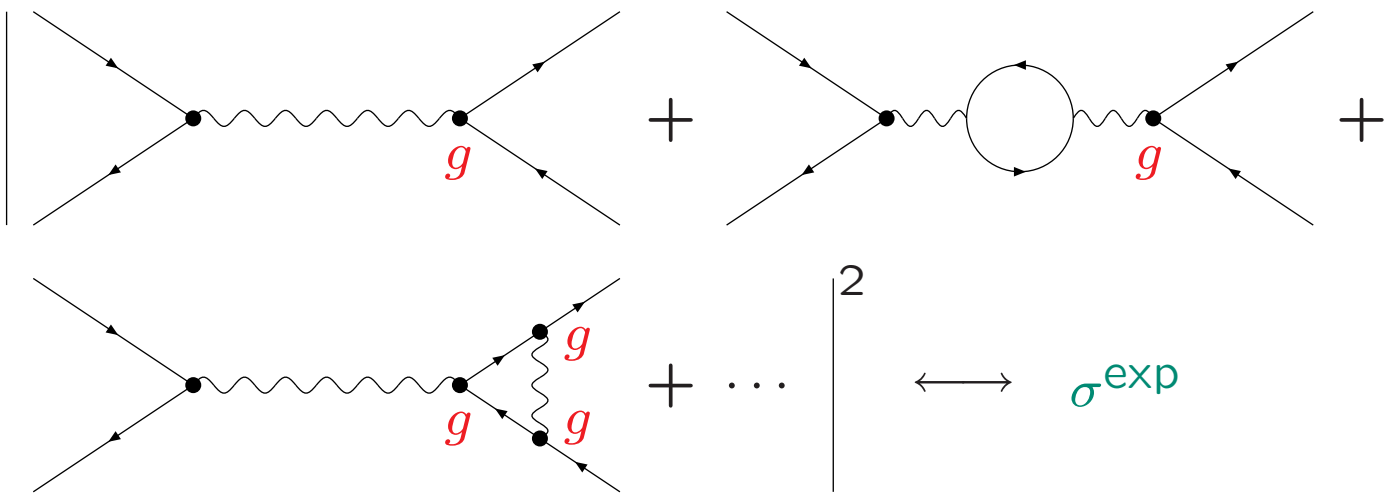
E.g.: determination of coupling g from cross section measurement

accuracy of $\mathcal{O}(10\%)$:



accuracy $\lesssim 1\%$:

need instead



$\Rightarrow$ need precise and unambigous definition of parameters

used by both experimentalists and theorists

The Higgs sector of the MSSM

Two Higgs doublets:

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1^0 + i\chi_1^0)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + i\chi_2^0)/\sqrt{2} \end{pmatrix}$$

Higgs potential:

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

Mixing of $\mathcal{CP}$-even, $\mathcal{CP}$-odd, charged fields:

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

$$\tan(2\alpha) = \tan(2\beta)\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

Three Goldstone bosons (as in SM): G^0, $G^\pm$

$\longrightarrow$ longitudinal components of $W^\pm$, Z

$\Rightarrow$ Five physical states: $h^0, H^0, A^0, H^\pm$

h, H: neutral, $\mathcal{CP}$-even

A^0: neutral, $\mathcal{CP}$-odd

$H^\pm$: charged

Gauge-boson masses:

$$M_W^2 = \frac{1}{2}g'^2(v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_1^2 + v_2^2),$$
$$M_\gamma = 0$$

Parameters in Higgs potential V (besides g, g'):

$$v_1,\ v_2,\ m_1,\ m_2,\ m_{12}$$

relation for M_{W}^2, M_{Z}^2
$\Rightarrow$ 1 condition

minimization of V w.r.t. neutral Higgs fields H_1^1, H_2^2
$\Rightarrow$ 2 conditions

$\Rightarrow$ only two free parameters remain in V
conventionally chosen as

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{\mathrm{A}}^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

$\Rightarrow$ m_{h}, m_{H}, mixing angle α, $m_{\mathrm{H}^\pm}$:

no free parameters, can be predicted

In lowest order:

$$M_{\mathrm{H}^\pm}^2 = M_{\mathrm{A}}^2 + M_{\mathrm{W}}^2$$

Predictions for m_h, m_H from diagonalization of tree-level mass matrix:

$\phi_1 - \phi_2$ basis:

$$M_{\text{Higgs}}^{2,\text{tree}} = \begin{pmatrix} m_{\phi_1}^2 & m_{\phi_1\phi_2}^2 \\ m_{\phi_1\phi_2}^2 & m_{\phi_2}^2 \end{pmatrix} =$$

$$\begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2\cos^2\beta + M_Z^2\sin^2\beta \end{pmatrix}$$

$$\Big\Downarrow \leftarrow \text{Diagonalization, } \alpha$$

$$\begin{pmatrix} m_H^{2,\text{tree}} & 0 \\ 0 & m_h^{2,\text{tree}} \end{pmatrix}$$

Tree-level result for m_h, m_H:

$$m_{H,h}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$\Rightarrow m_h \leq M_Z$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

Higgs couplings, tree level:

$$
\begin{aligned}
g_{\mathrm{hVV}} &= \sin(\beta-\alpha)\, g^{\mathrm{SM}}_{\mathrm{HVV}}, \quad V = W^{\pm}, Z \\
g_{\mathrm{HVV}} &= \cos(\beta-\alpha)\, g^{\mathrm{SM}}_{\mathrm{HVV}} \\
g_{\mathrm{hAZ}} &= \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_{\mathrm{W}}} \\
g_{\mathrm{hb\bar{b}}}, g_{\mathrm{h}\tau^+\tau^-} &= -\frac{\sin\alpha}{\cos\beta}\, g^{\mathrm{SM}}_{\mathrm{Hb\bar{b}},\mathrm{H}\tau^+\tau^-} \\
g_{\mathrm{ht\bar{t}}} &= \frac{\cos\alpha}{\sin\beta}\, g^{\mathrm{SM}}_{\mathrm{Ht\bar{t}}} \\
g_{\mathrm{Ab\bar{b}}}, g_{\mathrm{A}\tau^+\tau^-} &= \gamma_5 \tan\beta\, g^{\mathrm{SM}}_{\mathrm{Ab\bar{b}}}
\end{aligned}
$$

$\Rightarrow g_{\mathrm{hVV}} \leq g^{\mathrm{SM}}_{\mathrm{HVV}}$

g_{hVV}, g_{HVV}, g_{hAZ} cannot all be small

$g_{\mathrm{hb\bar{b}}}, g_{\mathrm{h}\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

Measurement of m_{h}, Higgs couplings

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

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

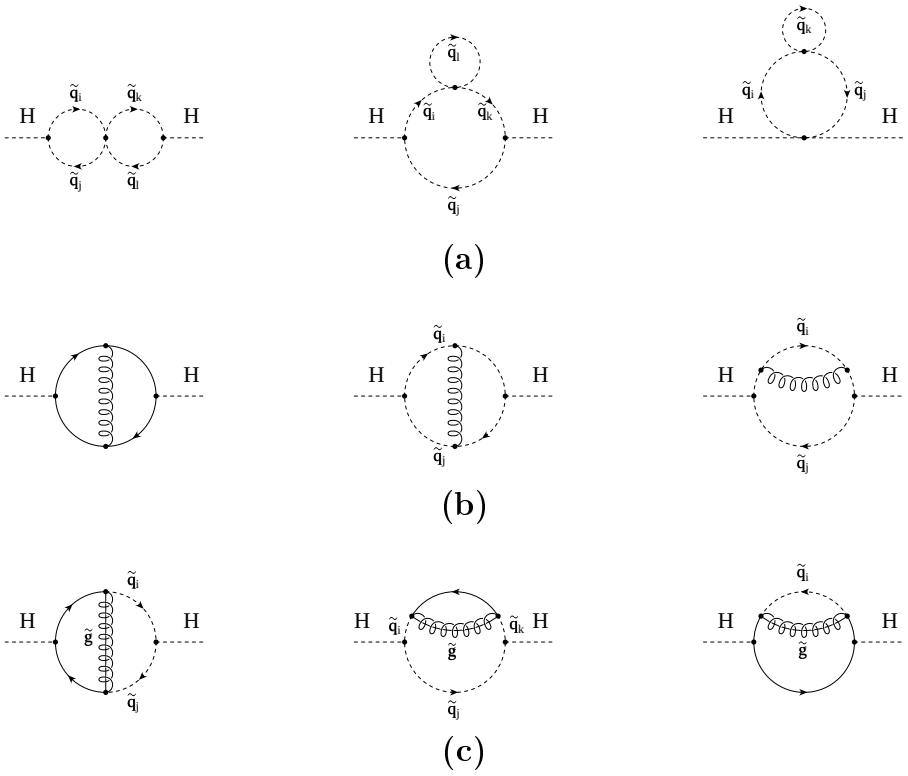
Input parameters: $M_{\tilde{t}_L}$, $M_{\tilde{t}_R}$, X_{t}

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



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

Upper bound on m_h:

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

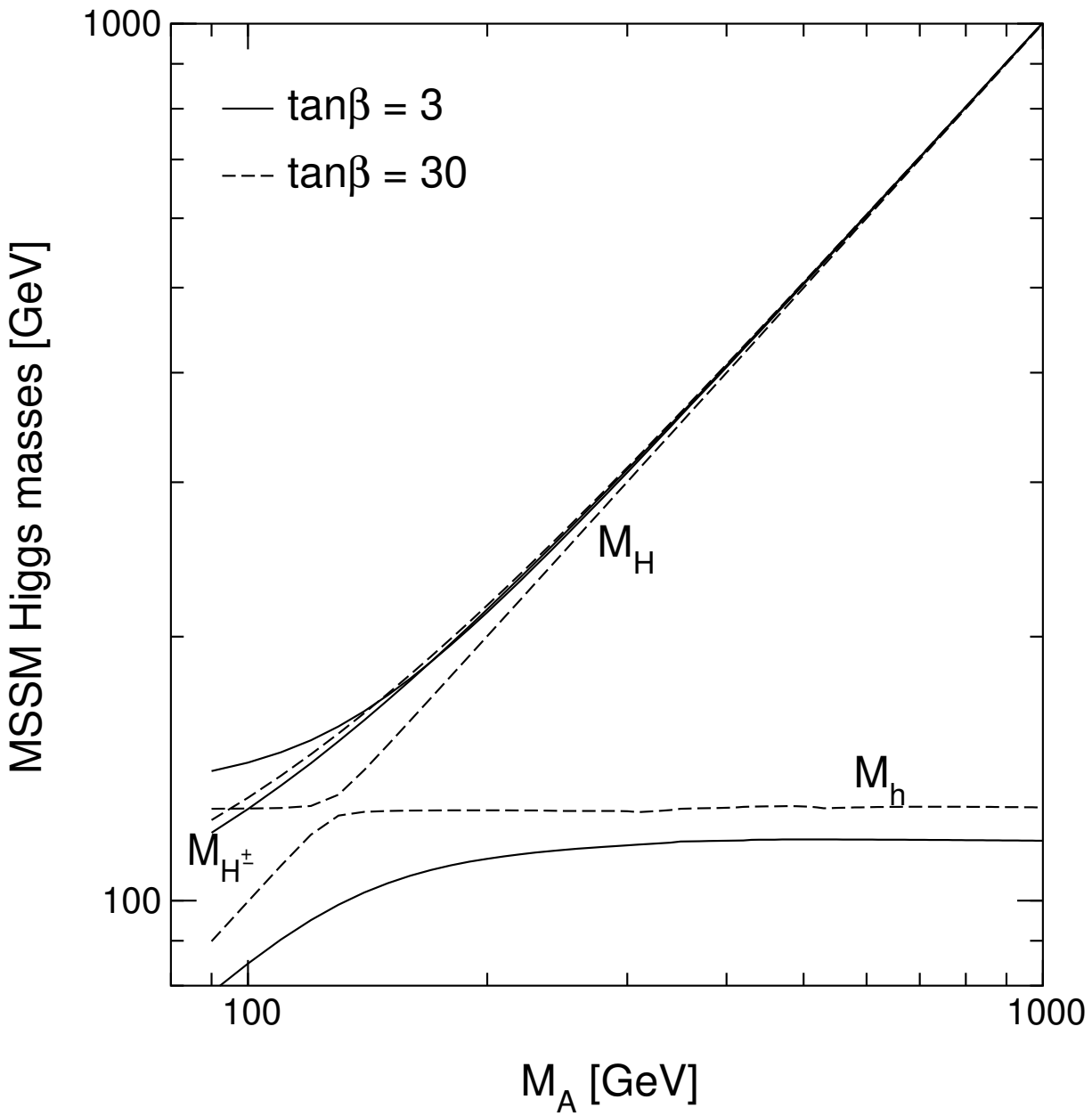
$$m_h \lesssim 135\,\text{GeV}$$

for $m_t = 175\,\text{GeV}$

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*]

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

$\Rightarrow$ **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:
$\Rightarrow \Delta m_{\mathsf{h}} \approx 3$ GeV

– From uncertainties in input parameters

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

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

Higgs couplings, production cross sections

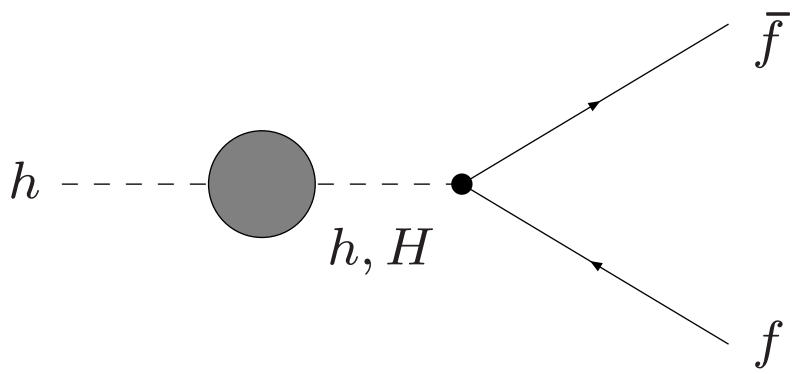
Also affected by large SUSY loop corrections

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:



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

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

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 $\tan\beta$

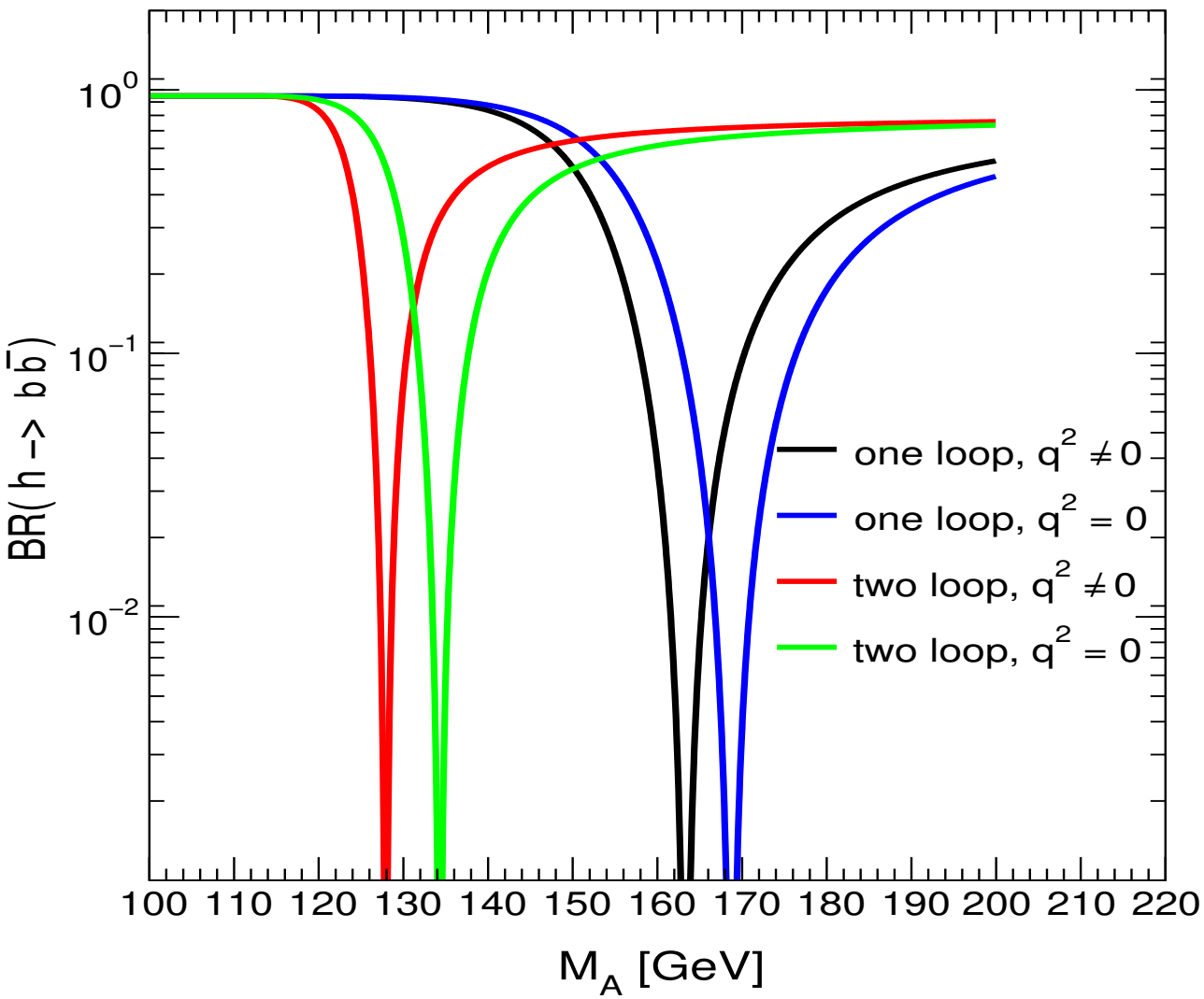
Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{hH}$

$\Rightarrow$ "Pathological regions"

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

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

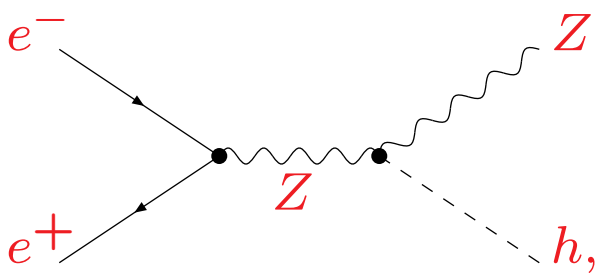
$\Rightarrow$ Suppression of BR($h \to b\bar{b}$), BR($h \to \tau\tau$), ...



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

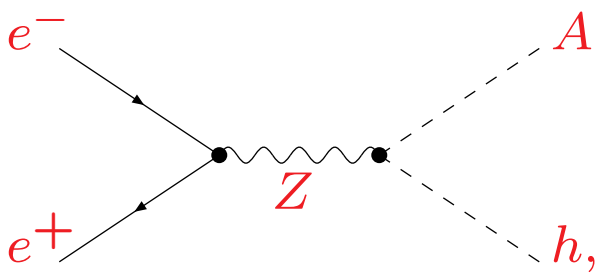
Search for neutral MSSM Higgs bosons at LEP:

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



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

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



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

Interpretation of LEP excess within MSSM:

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

– other possibility:

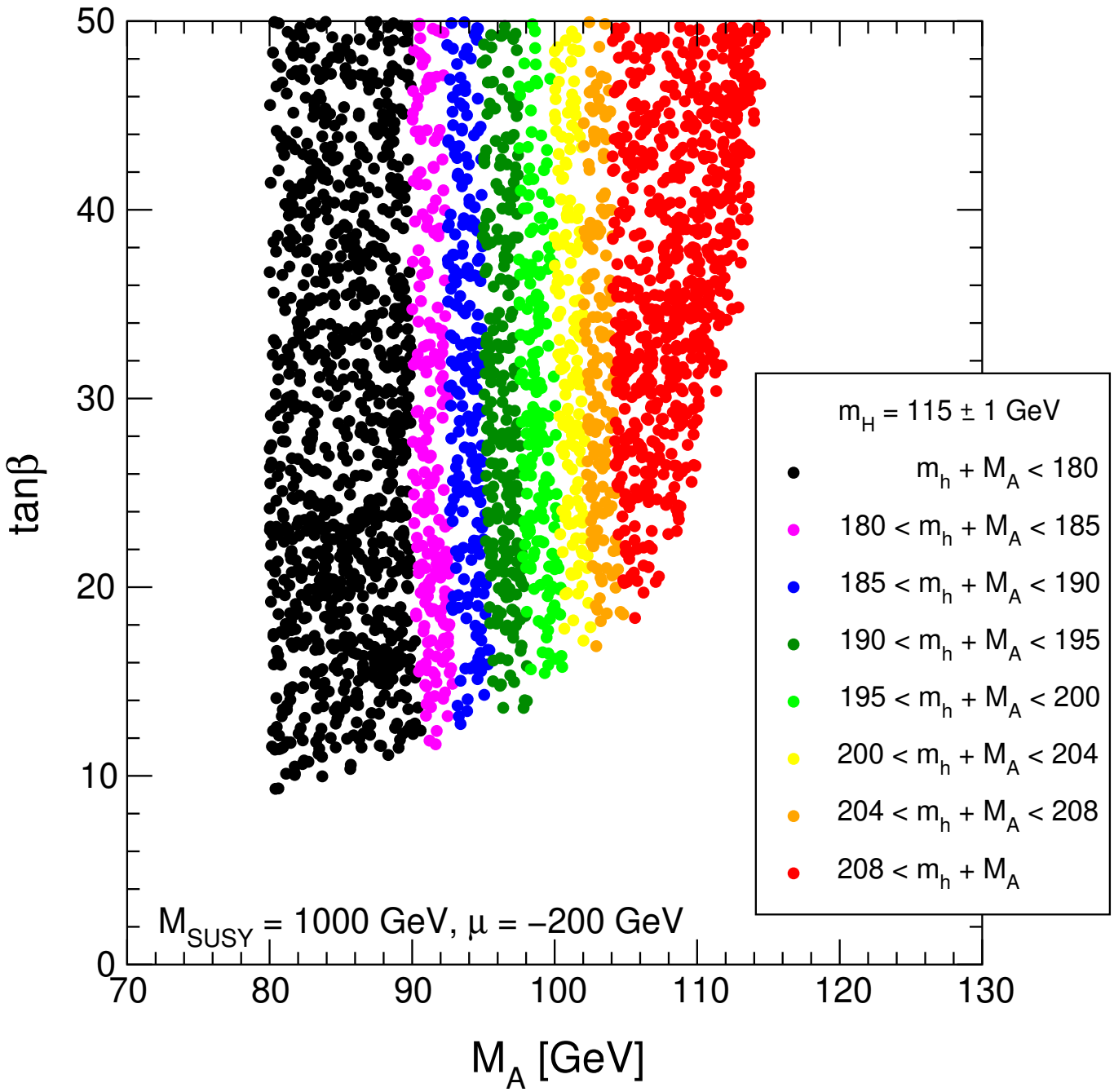
$m_h, M_A \approx 100$ GeV, $\sin^2(\beta - \alpha_{eff}) \ll 1$

$m_H \approx 115$ GeV

$\Rightarrow H$ with SM-type couplings

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

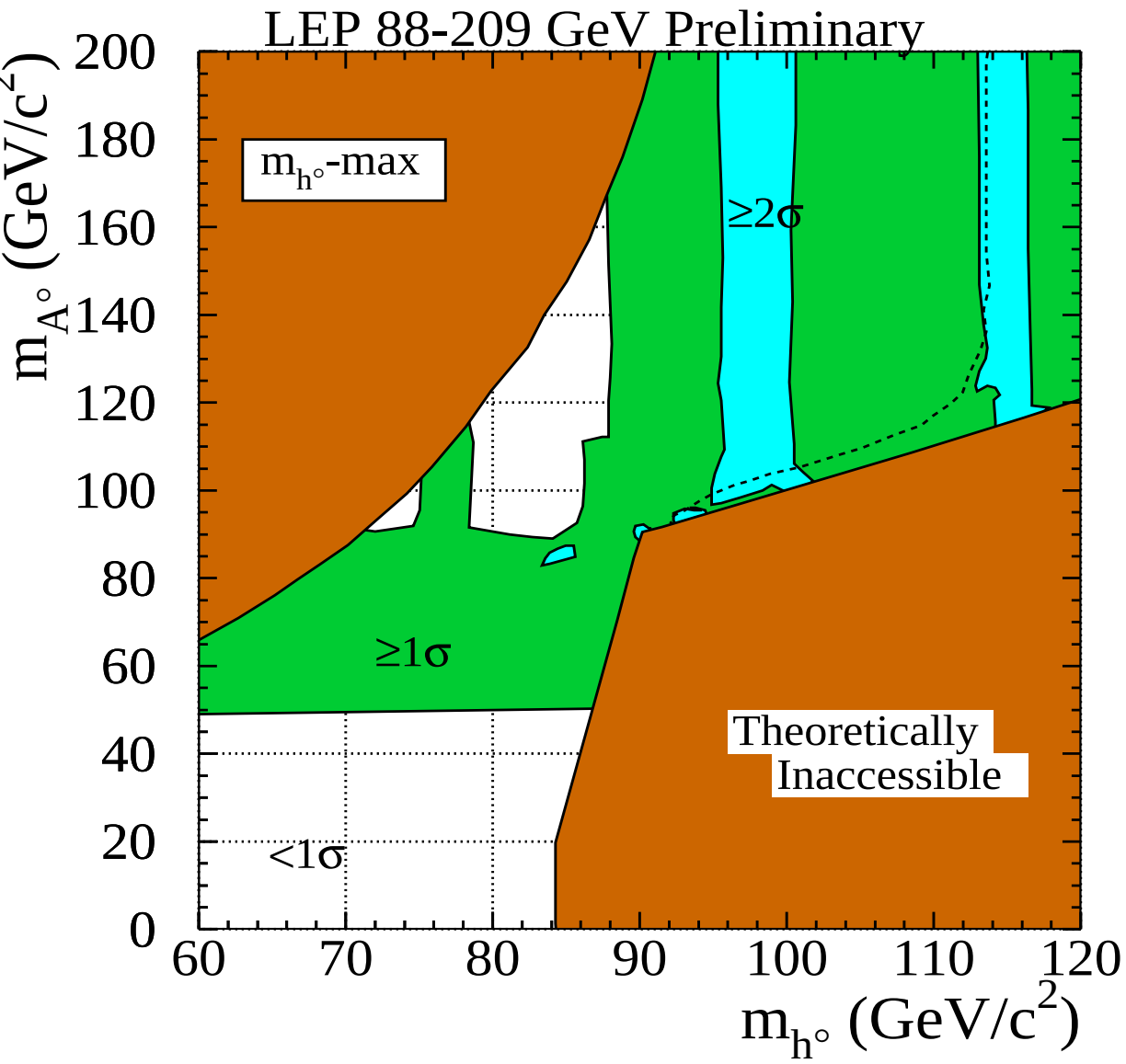
[*S. Heinemeyer, G. W. '00*]



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

[*LEP Higgs Working Group '01*]

$m_{\mathrm{h}}^{\mathrm{max}}$-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:
  $\mu = 1\,\text{TeV}$, $M_{SUSY} = 400\,\text{GeV}$, $X_t = -300\,\text{GeV}$

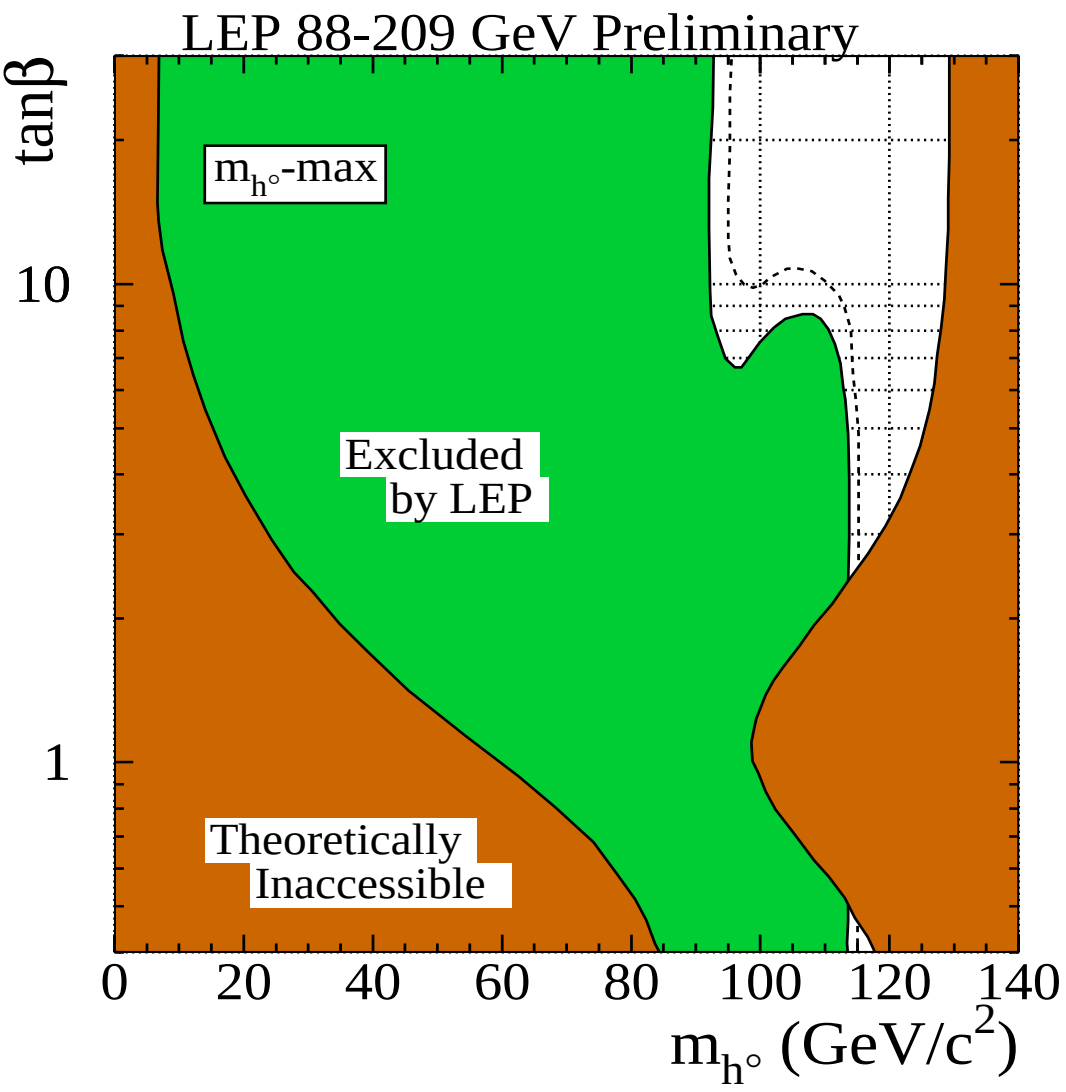
  $\Rightarrow$ m_h within kinematical reach of LEP
  parameter regions with strong suppression of BR($h \to b\bar{b}$), BR($h \to \tau\tau$)

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

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 GeV), 95% C.L.

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

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

"Excluded" $\tan\beta$ region:

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

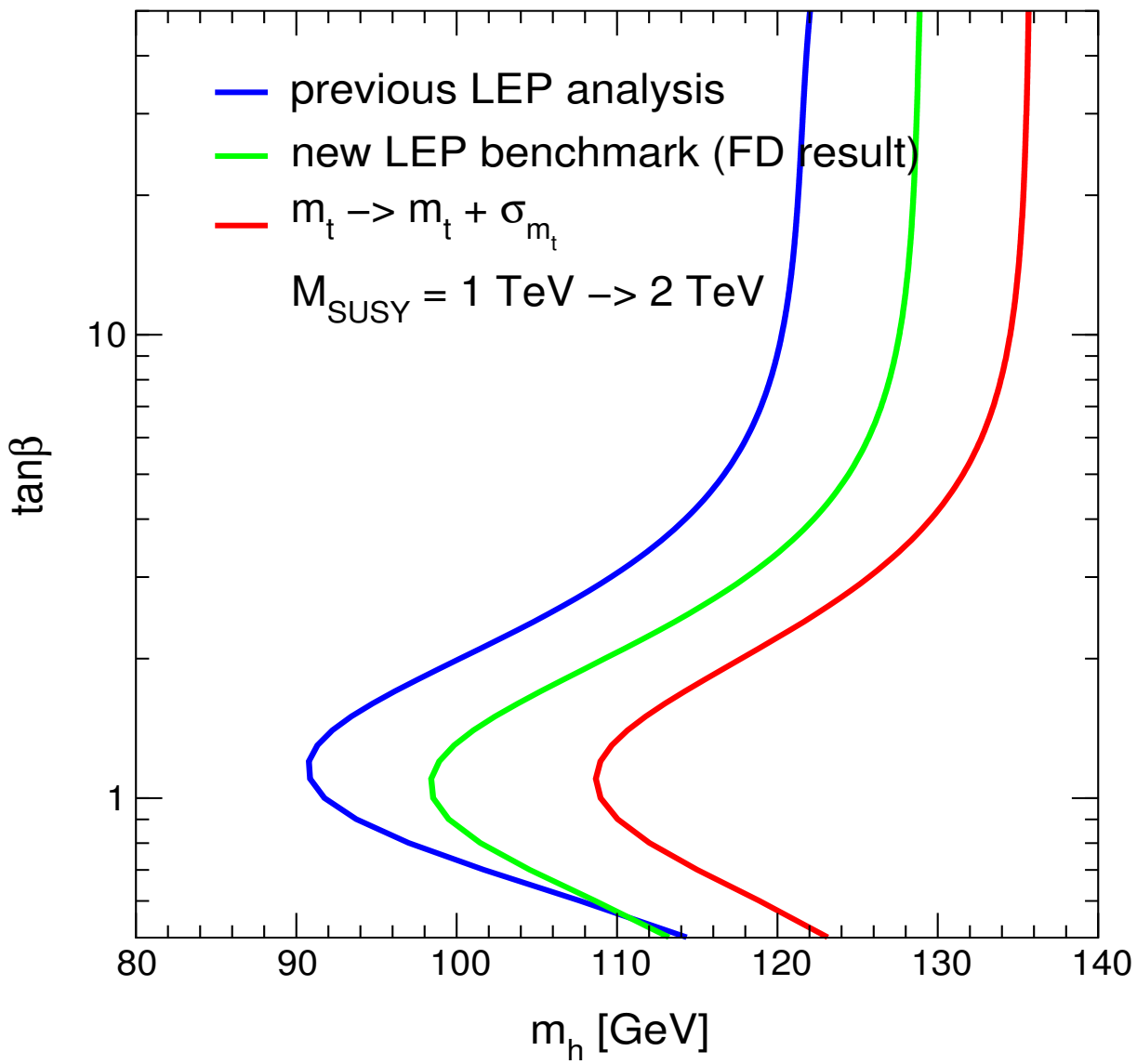
Note: this exclusion bound assumes

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

no theoretical uncertainties included

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

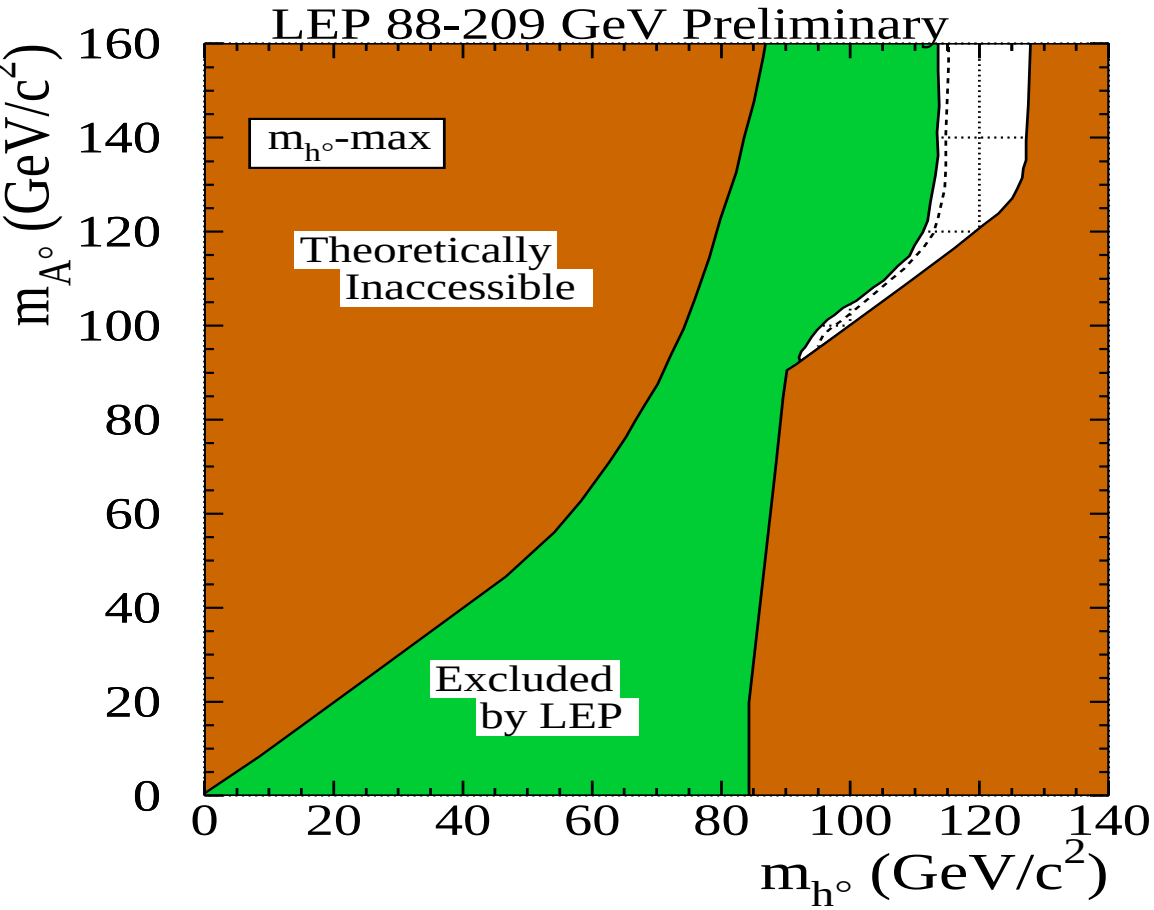
[*S. Heinemeyer, W. Hollik, G. W. '00*]

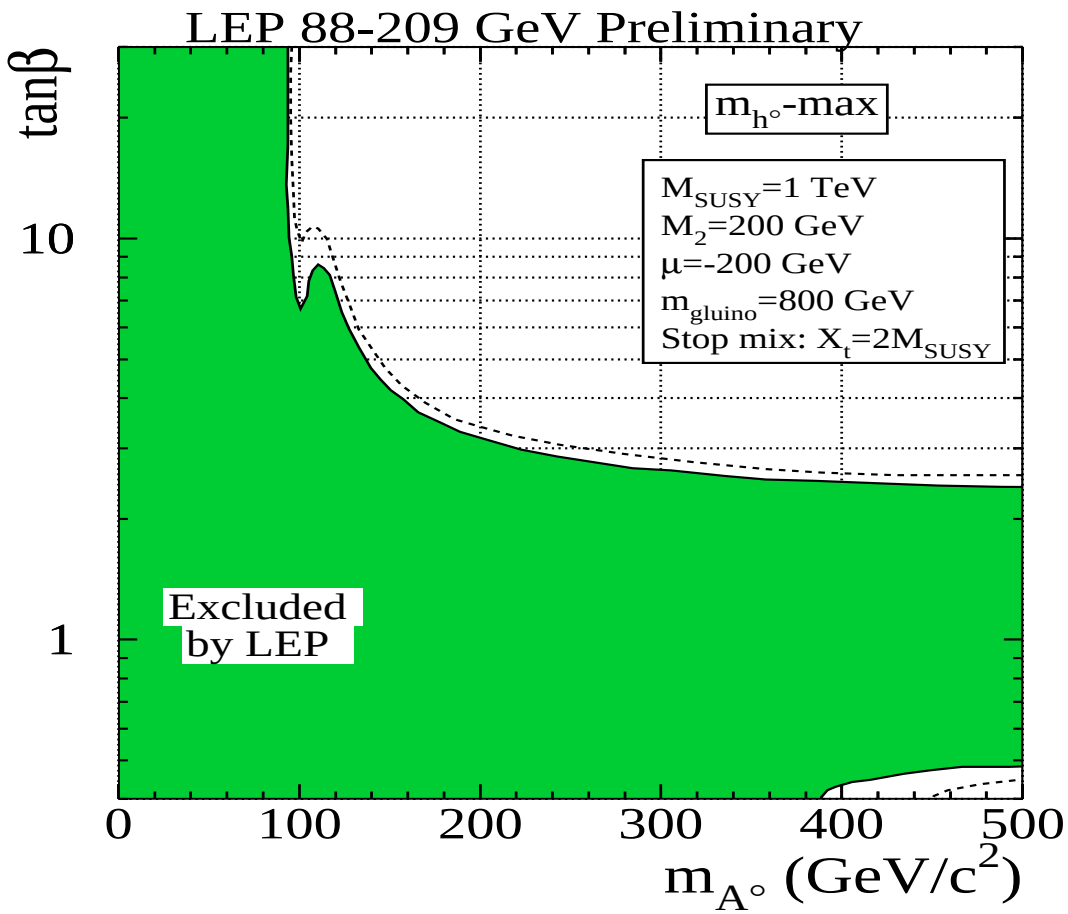


$\Rightarrow$ precise knowledge of m_t important!

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

[*LEP Higgs Working Group '01*]

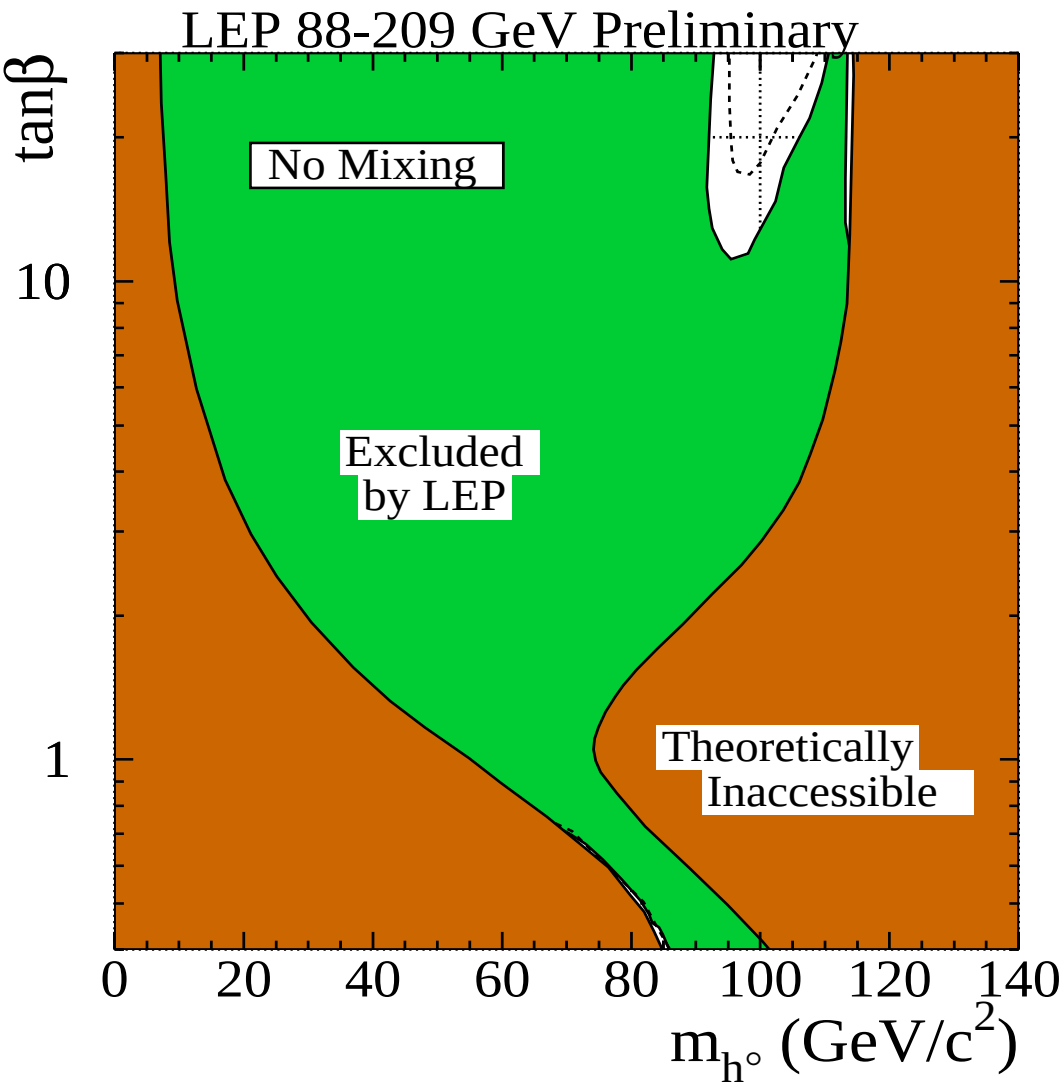




Experimental search vs. upper m_{h}-bound (*FeynHiggs*)

[*LEP Higgs Working Group '01*]

no-mixing scenario:



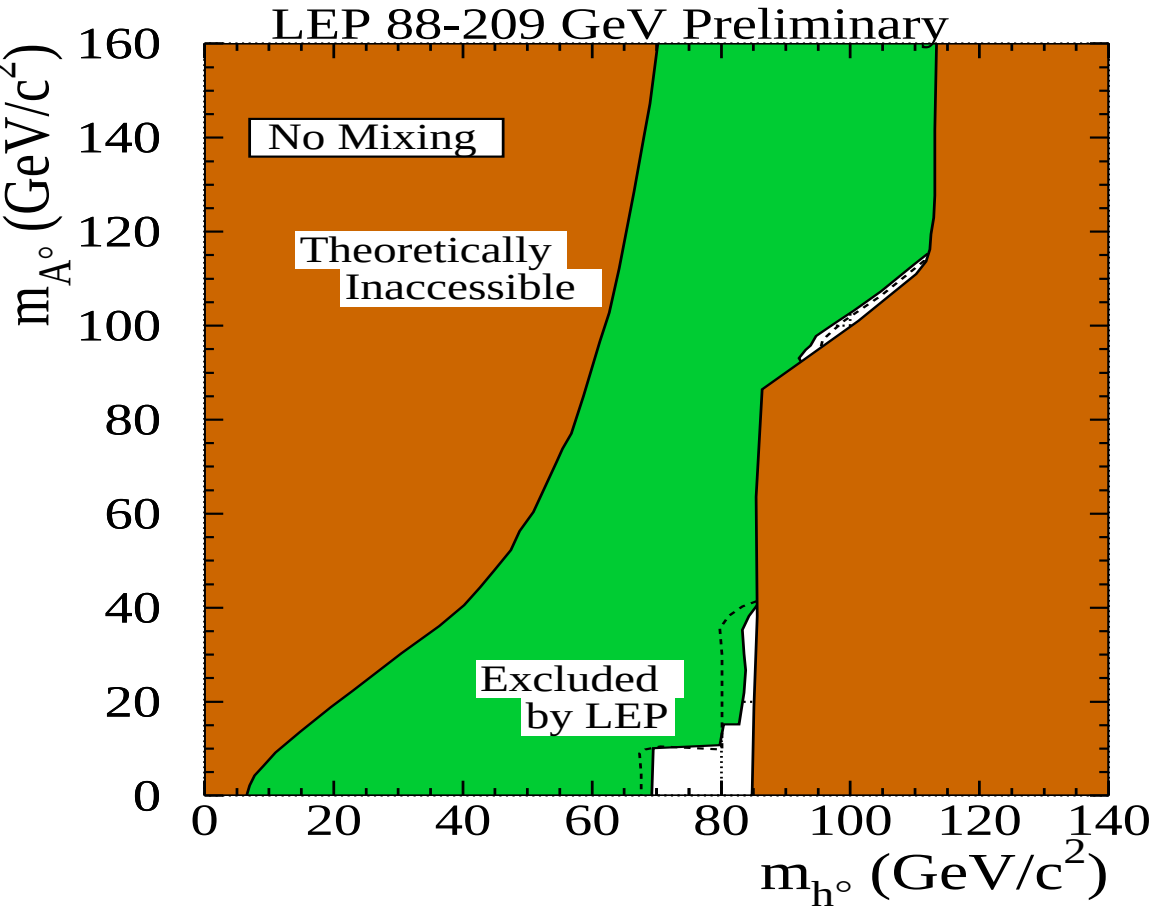
Excluded $\tan\beta$ region:

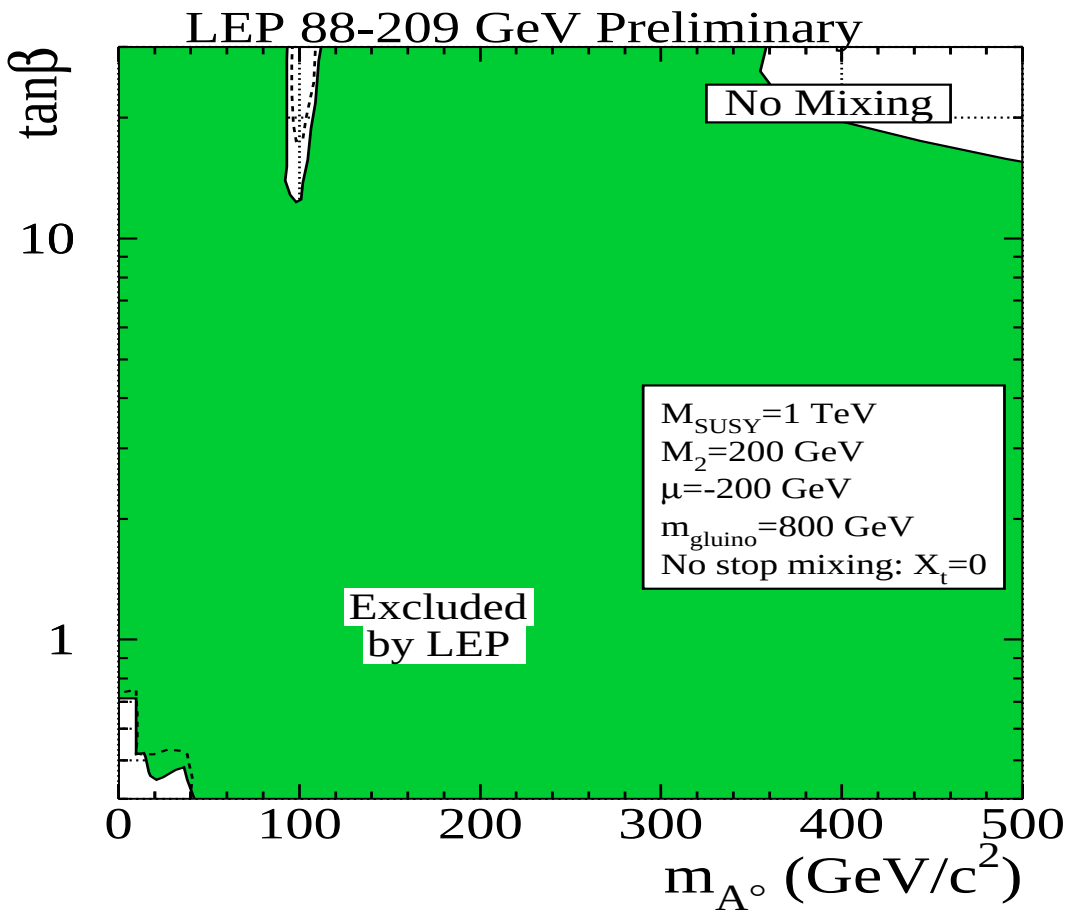
$$0.7 < \tan\beta < 10.5$$

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

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

[*LEP Higgs Working Group '01*]





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

Preparation of final LEP results

[LEP Higgs Working Group '02]

Particular focus on 'model-independent' results:

– Cross section limits

– Limits on

$$s^2 \equiv \frac{\sigma(hZ) \times \mathrm{BR}}{\Big[\sigma(hZ) \times \mathrm{BR}\Big]_{\mathrm{SM}}} \ldots$$

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 $m_{\mathrm{h}}^{\mathrm{max}}$ scenario
(constraints from $g_\mu - 2$, $b \to s\gamma$, . . . respected)

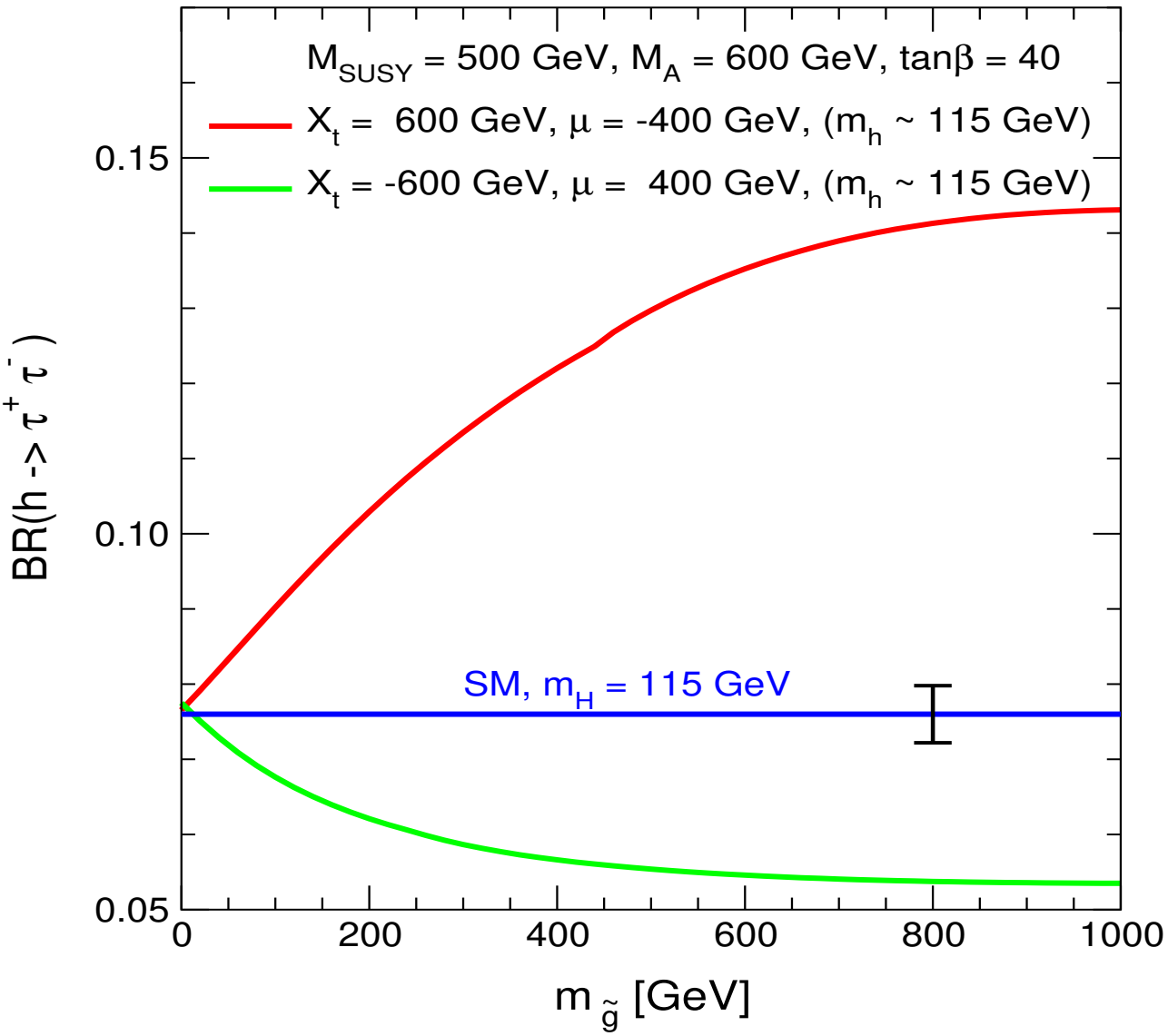
Precision physics in the MSSM Higgs sector

Precise measurement of Higgs branching ratios

⇒ Sensitivity to deviations SM / MSSM

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

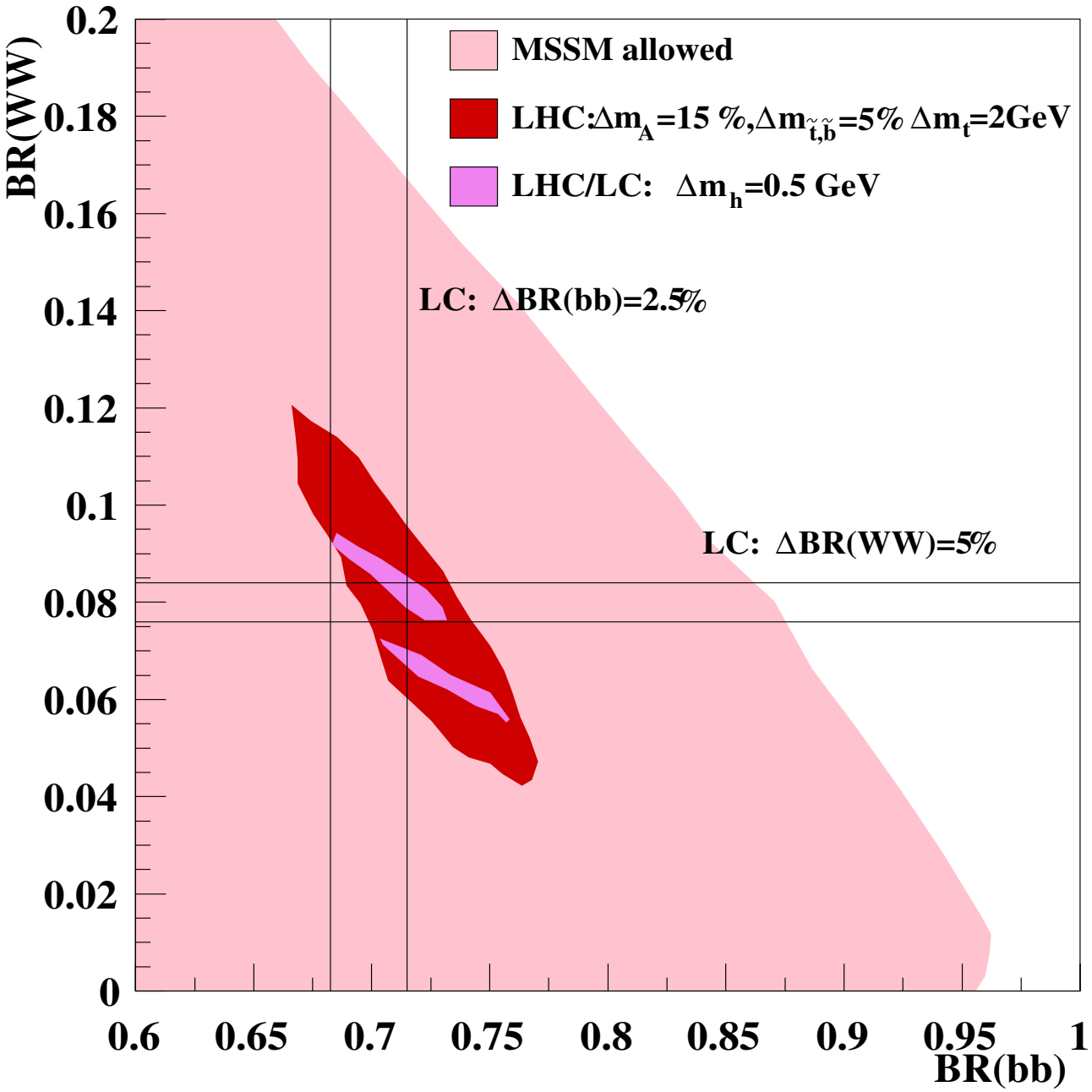
[*S. Heinemeyer, G.W. '01*]



⇒ 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*]



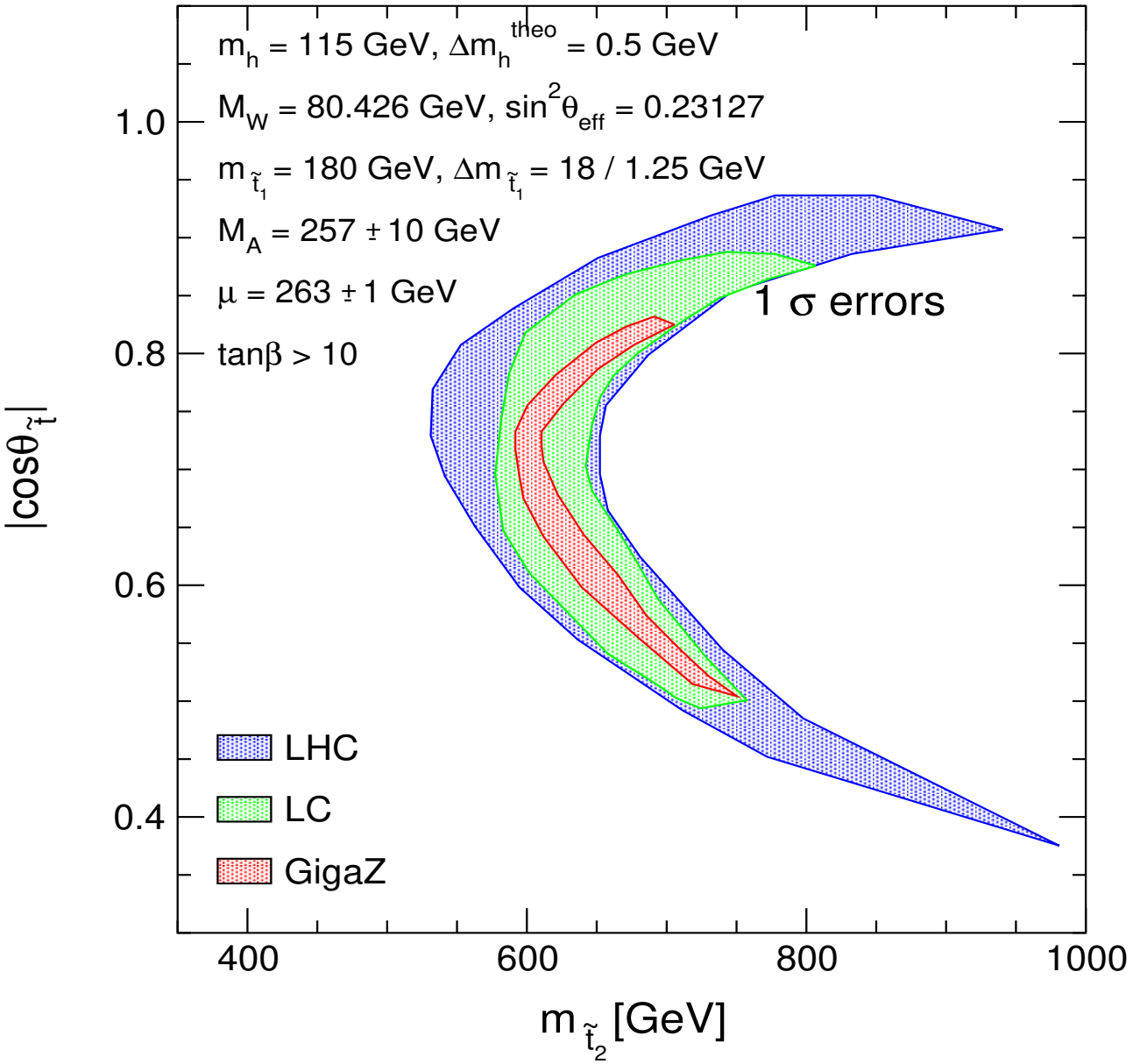
⇒ very sensitive test of the model

From precise measurement of m_h

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

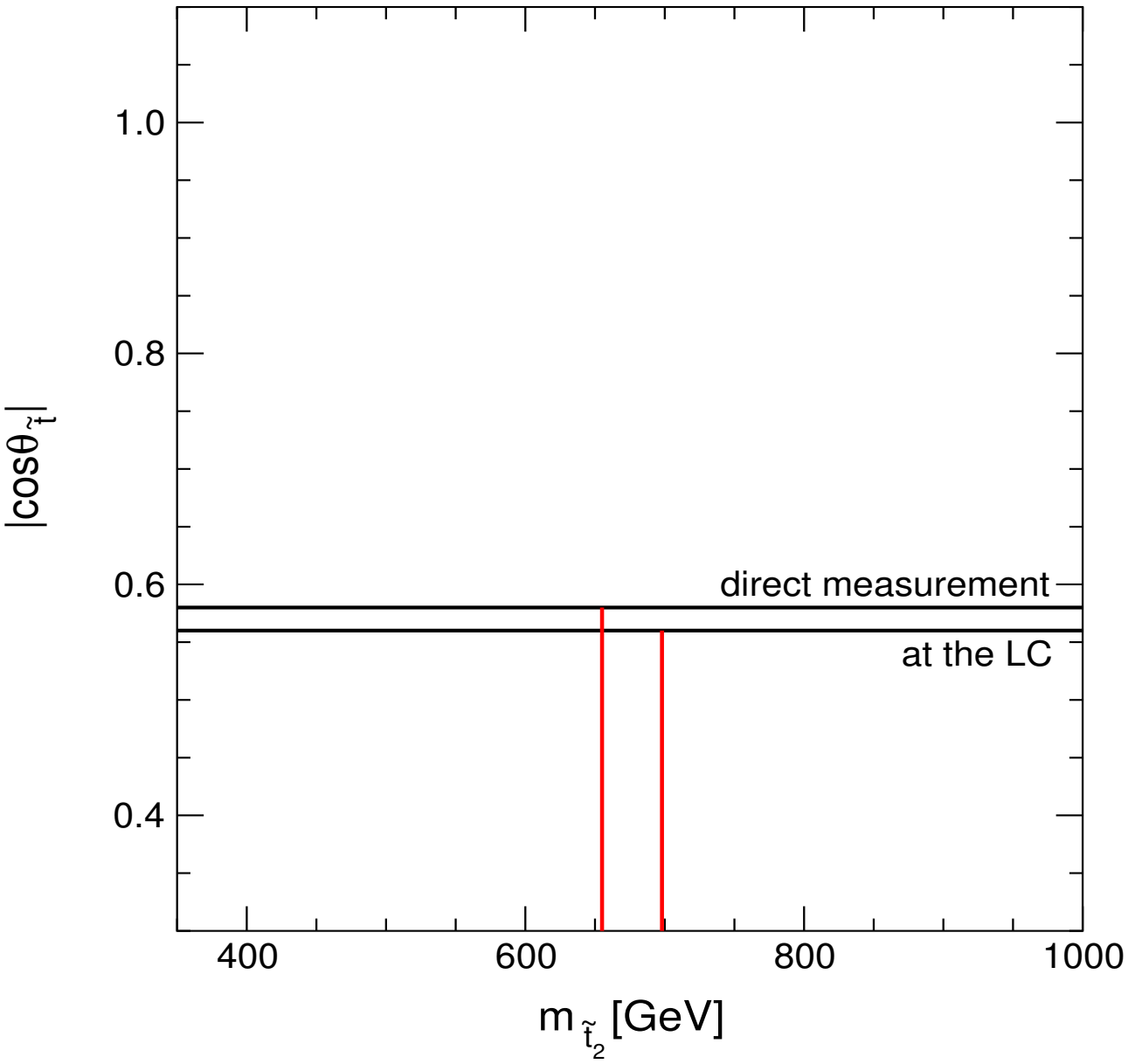
E.g.: Indirect constraints on $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$ from precision measurements of m_h, M_W, $\sin^2\theta_{\rm eff}$ at LC/GigaZ:
[*S. Heinemeyer, G.W. '01*]

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 3:

- LC physics essential for
  - establishing SUSY experimentally
  - disentangling patterns of SUSY breaking

- LC physics program will require efficient communication between experimentalists and theorists, careful treatment of higher-order effects, model dependence, etc.

- 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 $m_{\rm h}$ in the MSSM: $m_{\rm h} \lesssim 135$ GeV

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

- LC has potential for performing high-precision SUSY Higgs physics

  Needed in order to fully exploit LC potential:
  - $\delta m_{\rm t}^{\rm exp} \lesssim 0.2$ GeV
  - more than factor 10 improvement in uncertainties from unknown higher-orders