SUSY Higgs Bosons at LEP, Tevatron, LHC, . . .

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Santander, 12/2005

1. Motivation for the Higgs and Supersymmetry
2. The final LEP results
3. MSSM Higgs bosons at the Tevatron
4. MSSM Higgs bosons at the LHC
5. Prospects for the ILC
6. Conclusions

1. Motivation for the Higgs and Supersymmetry

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

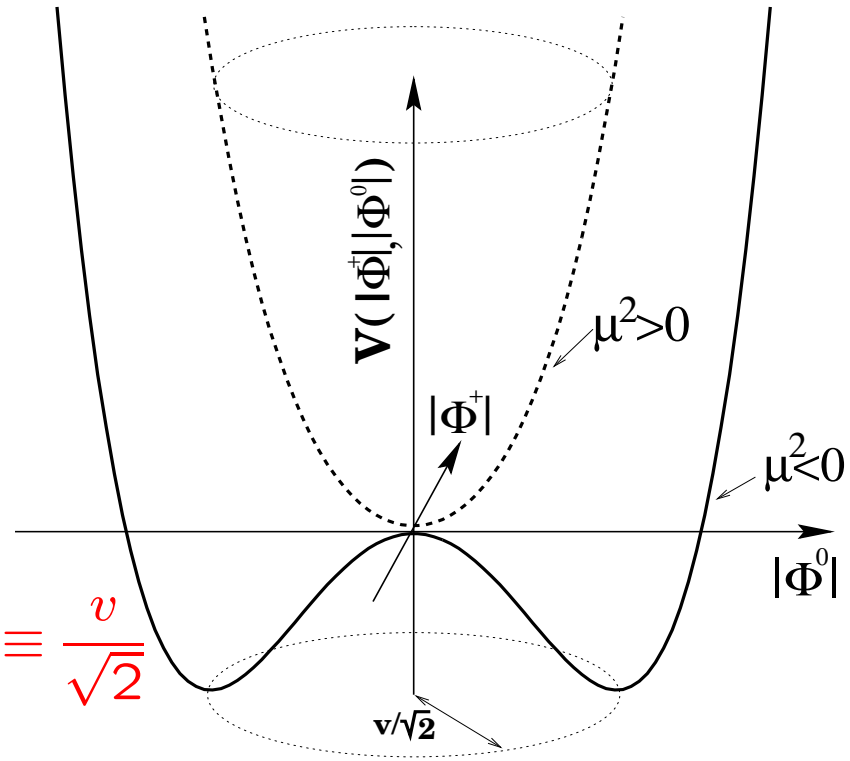
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

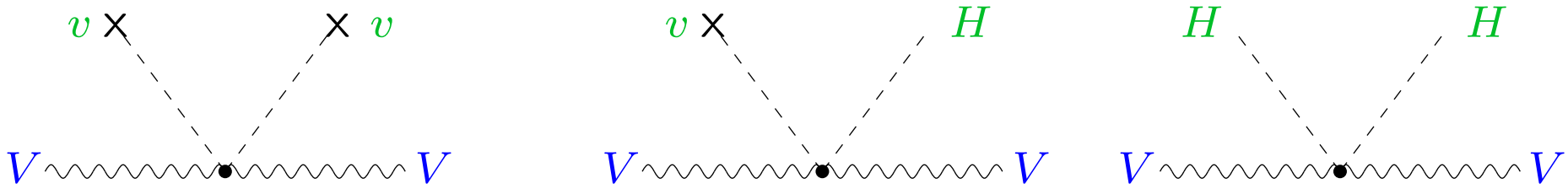
Lagrange density:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

Gauge invariant coupling to gauge fields

$\Rightarrow$ mass terms for gauge bosons and fermions

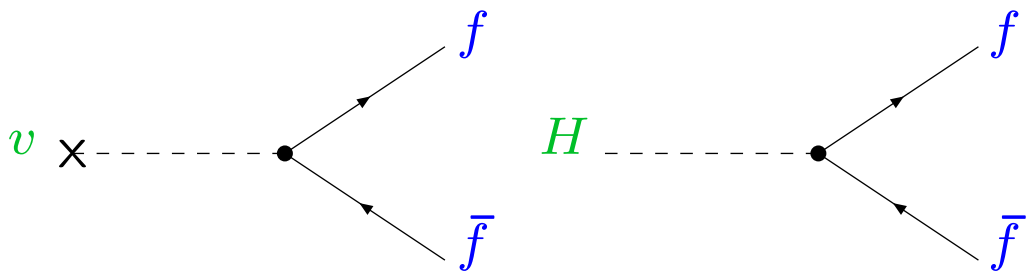
1.) $VV\Phi\Phi$ coupling:



$\Rightarrow$ VV mass terms $\qquad$ $\Rightarrow$ triple/quartic couplings to gauge bosons

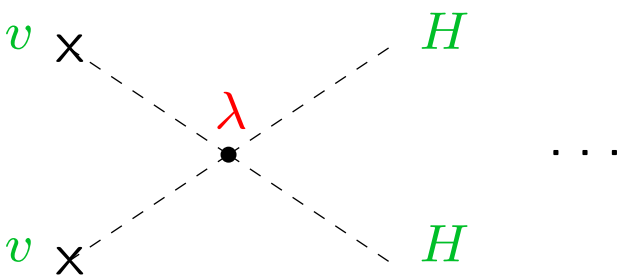
$g_2^2 v^2/2 \equiv M_W^2$, $(g_1^2 + g_2^2) v^2/2 \equiv M_Z^2$ $\Rightarrow$ coupling $\propto$ masses

2.) fermion mass terms: Yukawa couplings



$m_f = v\, g_f \Rightarrow$ coupling $\propto$ masses

3.) mass of the Higgs boson: self coupling



$\ldots$

$\lambda = M_H^2/v$

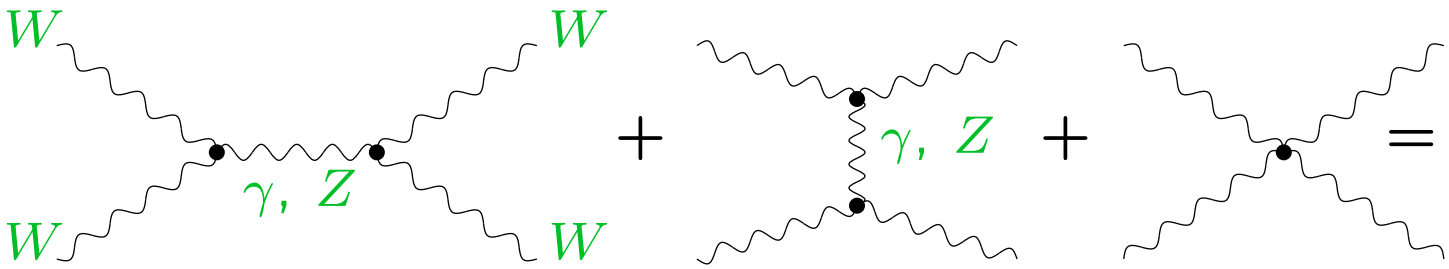
$M_H = v\sqrt{\lambda}$ free parameter

$\longrightarrow$ last unknown parameter of the SM

$\boxed{\Rightarrow \text{establish Higgs mechanism} \equiv \text{find the Higgs} \oplus \text{measure its couplings}}$

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \to W_L W_L$

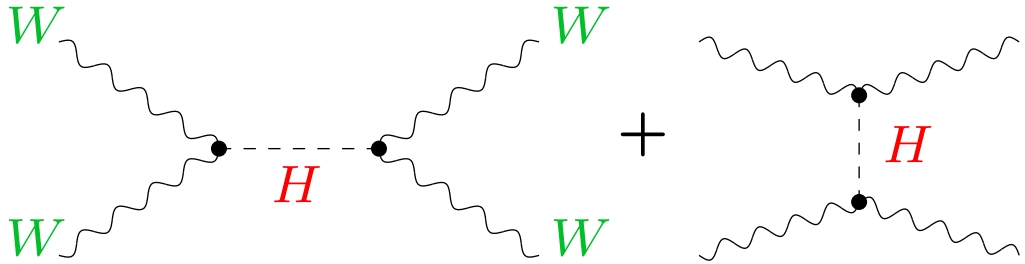
$\mathcal{M}_V =$ 

$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$

for $E \to \infty$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$\mathcal{M}_S =$ 

$= g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$

for $E \to \infty$

$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4} \left(g_{WWH}^2 - g^2 M_W^2 \right) + \ldots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g\, M_W$$

What else do we know about the Higgs boson?

SM at high energies

– upper limit on M_H:

$\longrightarrow$ dependence of coupling λ_{HHHH} from energy scale Λ

$\Rightarrow$ divergence: Landau pole

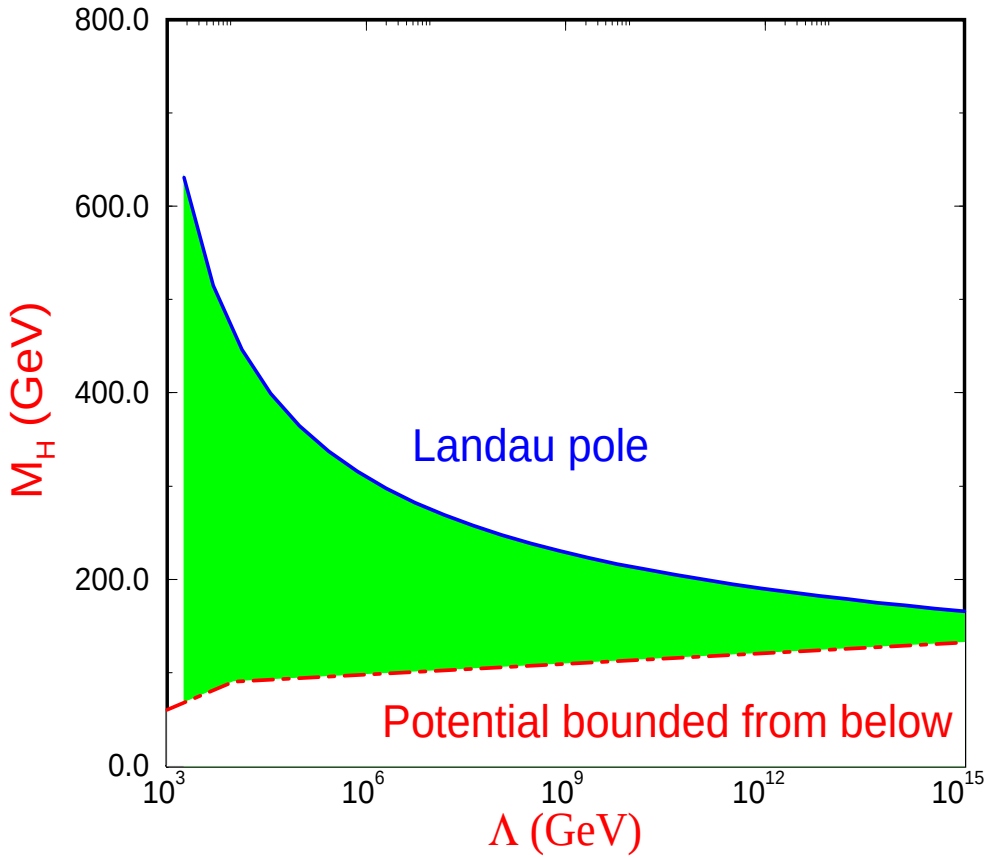
– lower limit on M_H:

$\longrightarrow$ stability of the vacuum :

$V(v) < V(0)$

[*Coleman, Weinberg '73*]

– combined $\Rightarrow$



Λ: scale up to which the SM is valid

$\Lambda = M_{\text{GUT}} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$

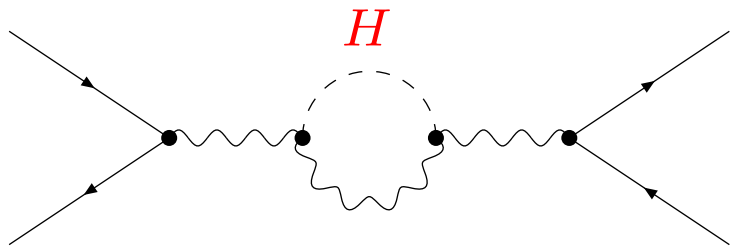
Indirect measurements via precision observables (POs):

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\text{eff}}, \ldots$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections



$\Downarrow$

All parameters of the model enter

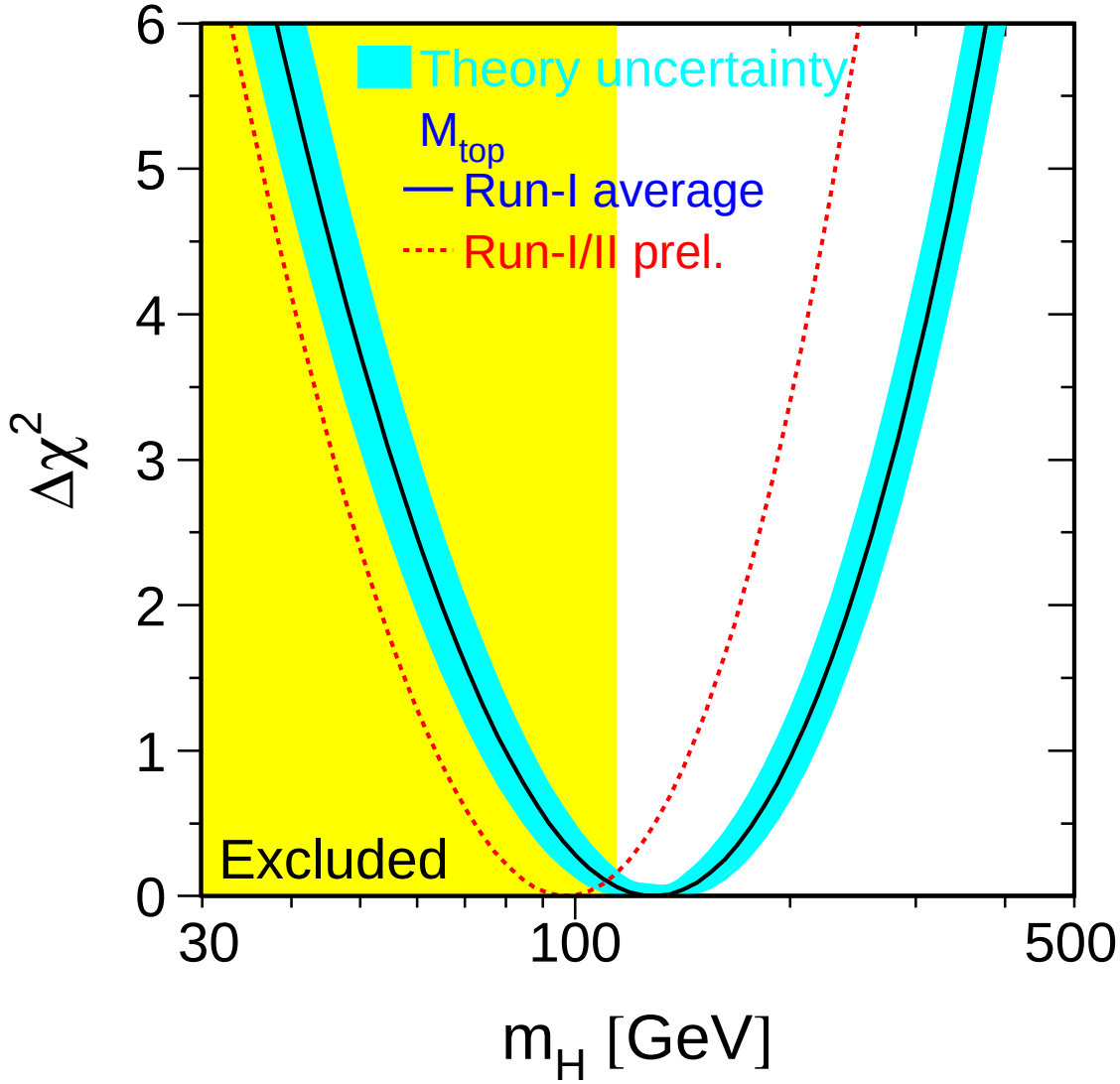
limits on M_H

Global fit to all SM data:

[*LEPEWWG '05*]

$\Rightarrow M_H = 91^{+45}_{-32}$ GeV

$M_H < 186$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 200$ GeV

Motivation for SUSY

Supersymmetry (SUSY) : Symmetry between

$$\text{Bosons} \leftrightarrow \text{Fermions}$$

$$Q\ |\text{Fermion}\rangle \rightarrow |\text{Boson}\rangle$$
$$Q\ |\text{Boson}\rangle \rightarrow |\text{Fermion}\rangle$$

Simplified examples:

$$Q\ |\text{top},\ t\rangle \rightarrow |\text{scalar top},\ \tilde{t}\rangle$$
$$Q\ |\text{gluon},\ g\rangle \rightarrow |\text{gluino},\ \tilde{g}\rangle$$

$\Rightarrow$ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}} \Rightarrow$ SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian

SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1\ \text{TeV})}$

Supersymmetry: Motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

$\rightarrow$ more than 9 reasons as a motivation:
(incl. 3 1/2 exp. verified SUSY predictions!)

1.) (Original motivation:) Stability of Higgs mass against higher order corrections in the MSSM

$\boxed{\Rightarrow M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})}$

2.) Haag-Lopuszanski-Sohnius theorem:
maximal gauge symmetry for a QFT:
inner gauge symmetry $\otimes$ (local) Susy

3.) Lorentz algebra $\subset$ Susy algebra (local)
$\rightarrow$ connection to general relativity
Superstring theories contain $N = 1$ Susy as low energy limit.

4.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)

$\boxed{\Rightarrow M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})}$

5.) Lifetime of the proton: for SU(5) GUTs:

$\tau_{p,\text{SM}} < \tau_{p,\text{exp}} < \tau_{p,\text{SUSY}}$

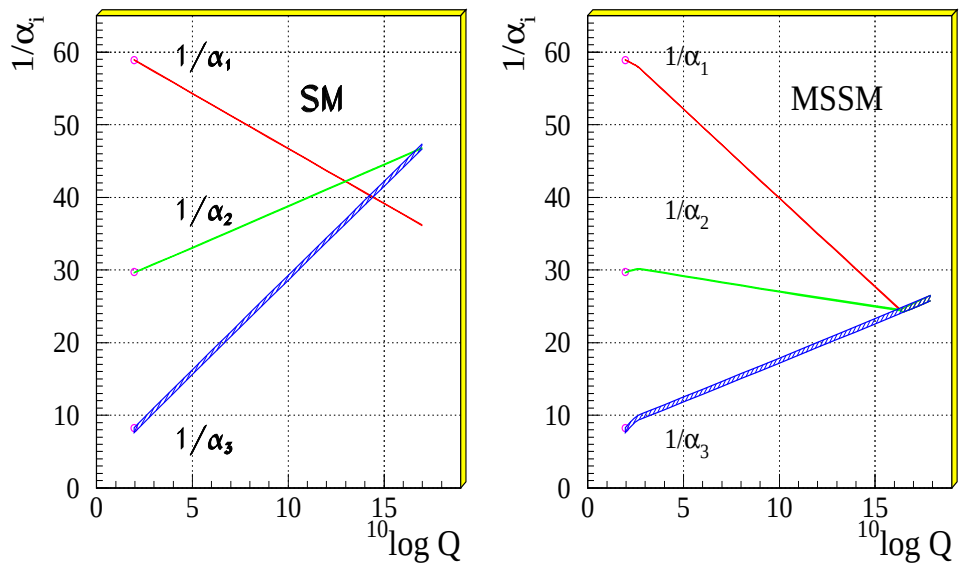
6.) Spontaneous symmetry breaking via Higgs mechanism is automatically achieved in SUSY GUTs

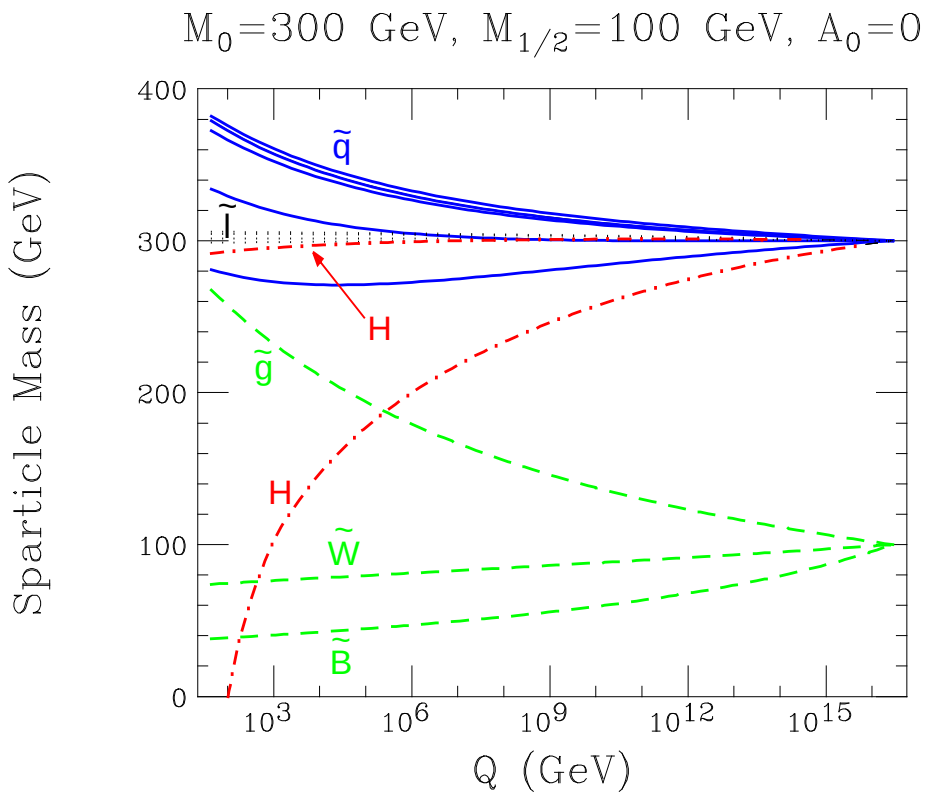
$\rightarrow$ T

SUSY prediction #1 experimentally verified:

$m_t = 150 - 200$ GeV

Unification of the Coupling Constants in the SM and the minimal MSSM




M_0=300 GeV, $M_{1/2}$=100 GeV, A_0=0
Sparticle Mass (GeV)
Q (GeV)
$\tilde{q}$
$\tilde{l}$
H
$\tilde{g}$
H
$\tilde{W}$
$\tilde{B}$

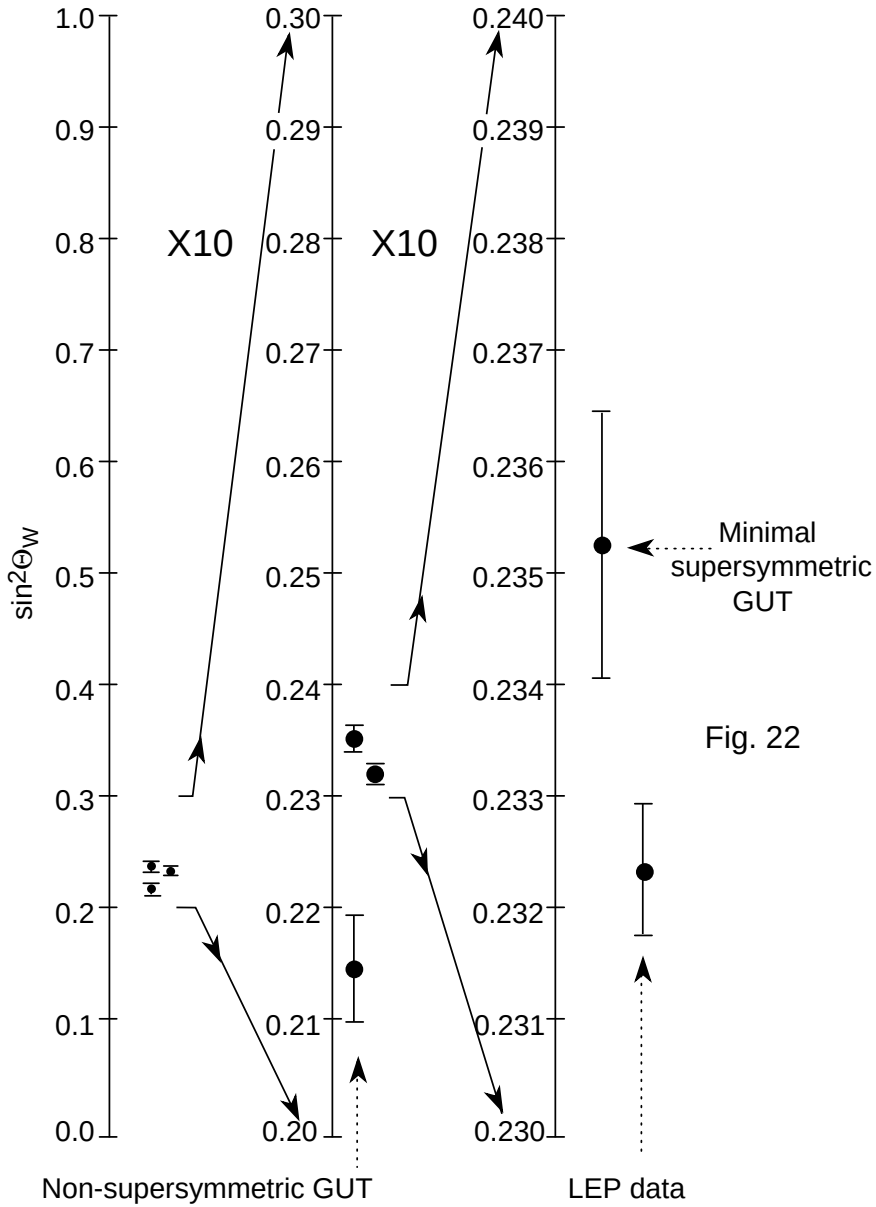

$\sin^2\Theta_W$
X10
X10
Minimal supersymmetric GUT
Non-supersymmetric GUT
LEP data

Fig. 22

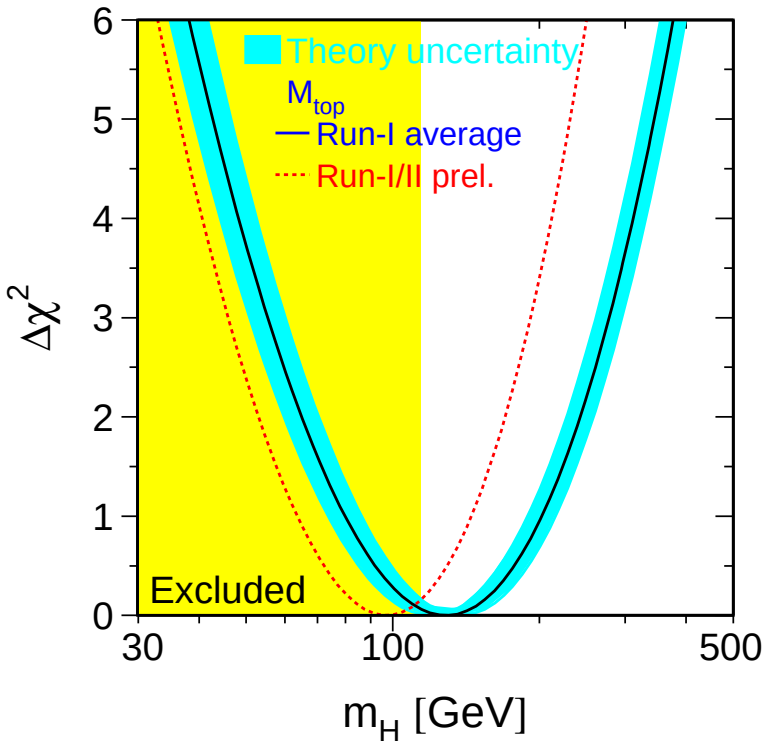
7.) Prediction for $\sin\theta_{W|M_{GUT}} = \frac{3}{8}$
low energy prediction via RGE $\rightarrow$ T

SUSY prediction #2 exp. verified:
$\sin^2\theta_{\text{eff}} \approx 0.232$

8.) LSP (lightest SUSY particle) is stable
SUSY prediction #3 exp. verified:
cold dark matter
(with correct properties)

9.) Prediction of a light Higgs boson in the MSSM (see below): $m_h \lesssim 135$ GeV
Indirect search: Global fit to SM data:
[*LEPEWWG '05*]

SUSY prediction #3 1/2 exp. verified:
$m_h \lesssim 135$ GeV



...) Solution for Flavor problem? Solution for Baryogenesis?

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

$\rightarrow$ CPV will be neglected throughout this talk!

Enlarged Higgs sector: Two Higgs doublets

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

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

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

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

Contrary to the SM:

m_h is not a free parameter

MSSM tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta m_h^2 \sim G_\mu m_t^4 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of m_h, Higgs couplings $\Rightarrow$ test of the theory

LHC: $\Delta m_h \approx 0.2$ GeV

ILC: $\Delta m_h \approx 0.05$ GeV

$\Rightarrow m_h$ will be (the best?) electroweak precision observable

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

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

for $m_t = 172.7$ GeV

(including theoretical uncertainties from unknown higher orders)

$\Rightarrow$ observable at the LHC

Obtained with:

FeynHiggs

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

[*T. Hahn, S.H., W. Hollik, G. Weiglein '03, '04*]

`www.feynhiggs.de`

$\rightarrow$ all Higgs masses, couplings, BRs (easy to link, easy to use :-)

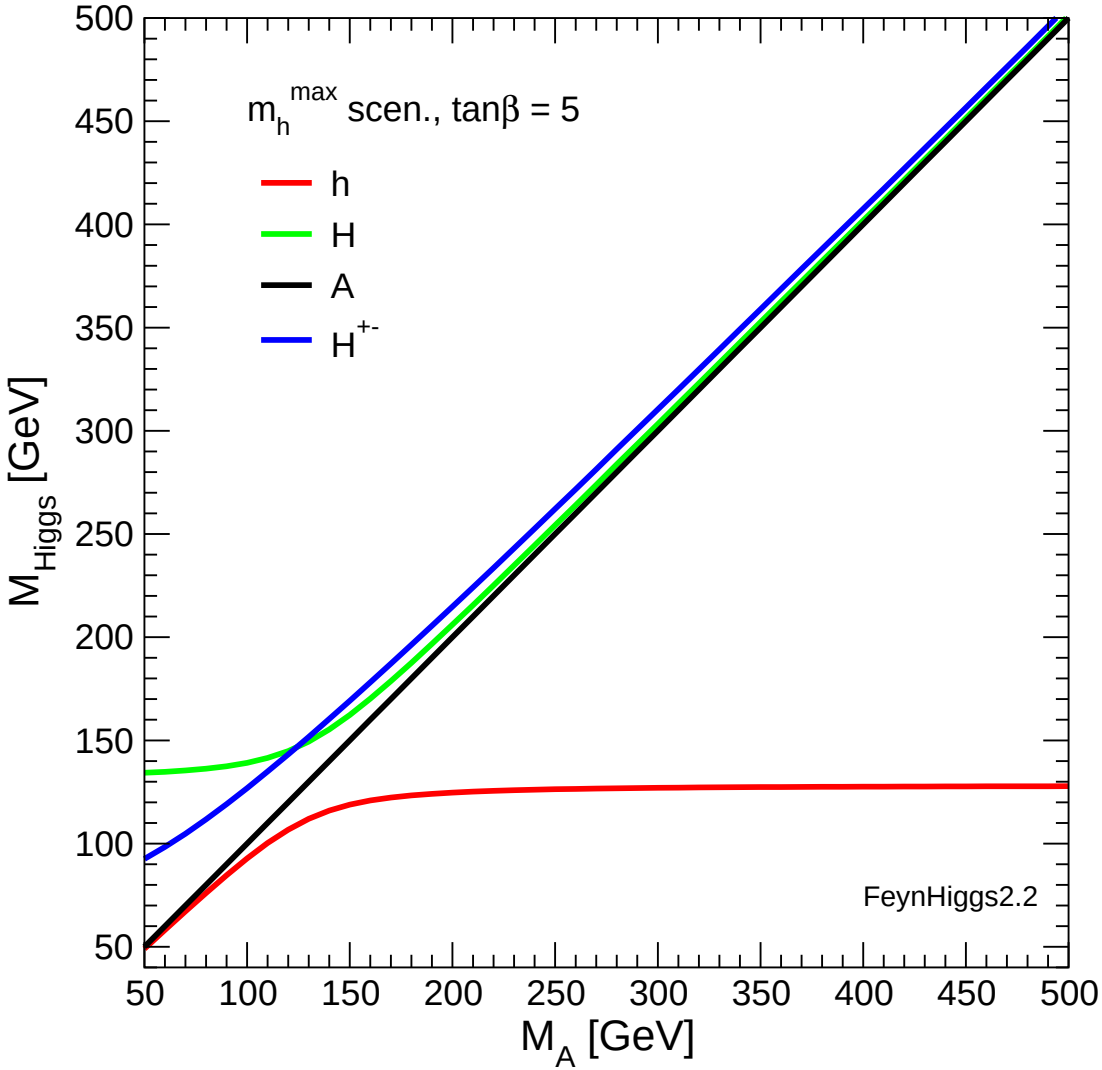
The decoupling limit:

For $M_A \gtrsim 150$ GeV:

The lightest MSSM Higgs is SM-like

The heavy MSSM Higgses: $M_A \approx M_H \approx M_{H^\pm}$

of course there are exceptions . . .



$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu/\tan\beta$, $X_b = A_b - \mu\tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ-$\tilde{t}/\tilde{b}$ couplings

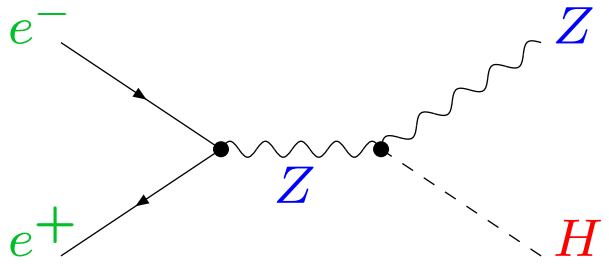
$$SU(2) \text{ relation} \Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$$

$\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

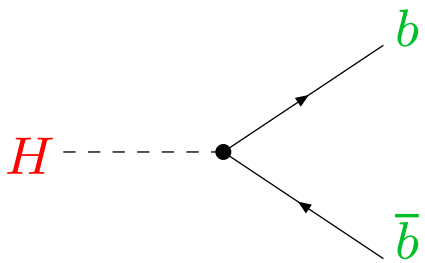
2. The final LEP results [*LEP Higgs WG '03, '04, '05*]

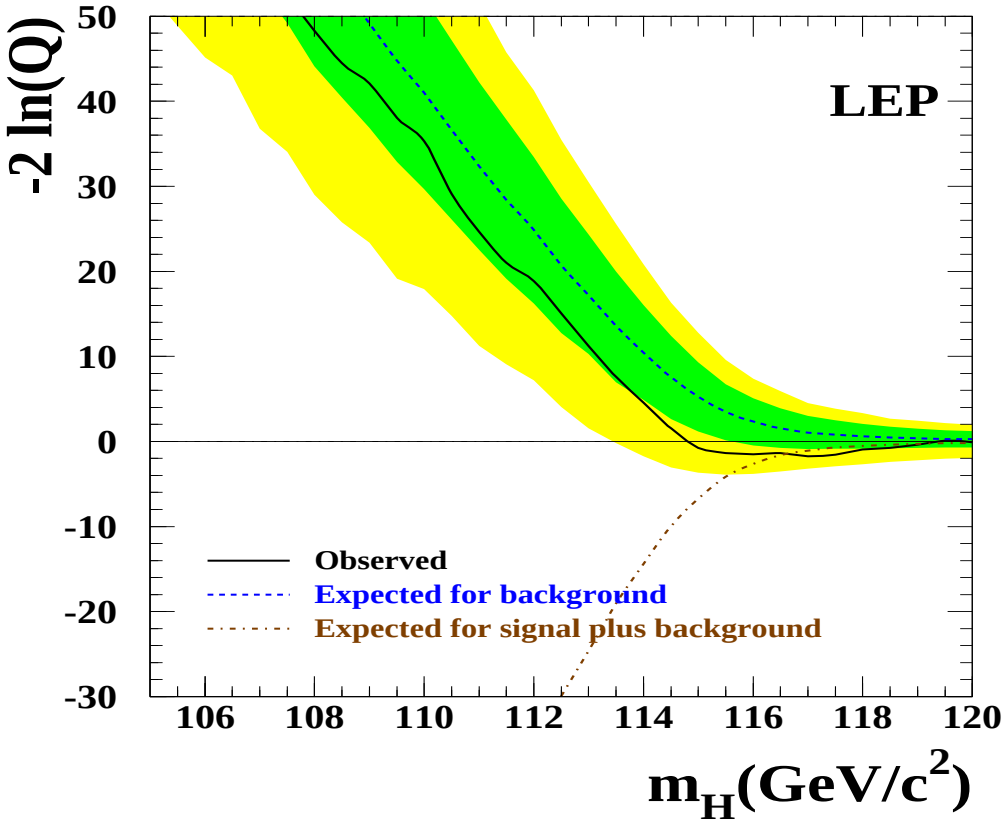
Search for the Standard Model Higgs at LEP:

Dominant production process:
$e^+e^- \to ZH$:



Dominant decay process: $H \to b\bar{b}$





Exclusion limit, 95% C.L.: $M_H > 114.4$ GeV (expected: 115.3 GeV)

Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

→ investigate benchmark scenarios:

→ Vary only M_A and $\tan\beta$
→ Keep all other SUSY parameters fixed

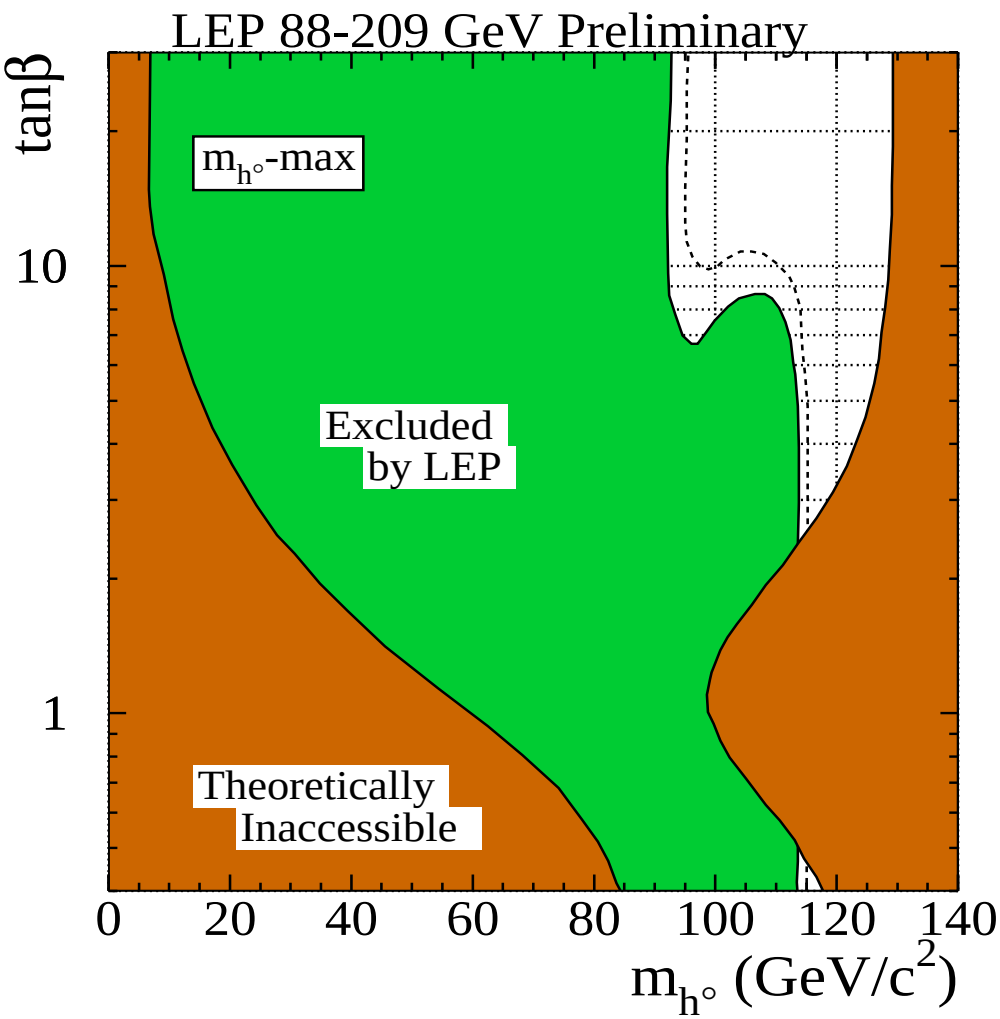
1. $m_h^{\max}$ scenario:
   → obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\text{SUSY}}$)
2. no-mixing scenario
   → no mixing in the scalar top sector ($X_t = 0$)
3. small α_{eff} scenario
   → $hb\bar{b}$ coupling $\sim \sin\alpha_{\text{eff}}/\cos\beta$ can be zero: $\alpha_{\text{eff}} \to 0$:
   main decay mode vanishes, important search channel vanishes
4. gluophobic Higgs scenario
   → hgg coupling is small: main LHC production mode vanishes

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

Results in the $m_h^{\max}$ scenario: [*LEP Higgs Working Group '04*]

Experimental search vs. upper m_h-bound (`FeynHiggs2.0`)

$m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV:



$m_h > 92.7$ GeV
(expected: 94.8 GeV), 95% C.L.

$M_A > 93.1$ GeV
(expected: 95.1 GeV)

Parameter region where experimental lower bound on m_h is significantly lower than SM bound, $M_H > 114.4$ GeV, corresponds to $\sin^2(\beta - \alpha_{\text{eff}}) \ll 1$

"Excluded" $\tan\beta$ region:

$$0.7 < \tan\beta < 2.2$$

Note: this exclusion bound assumes

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

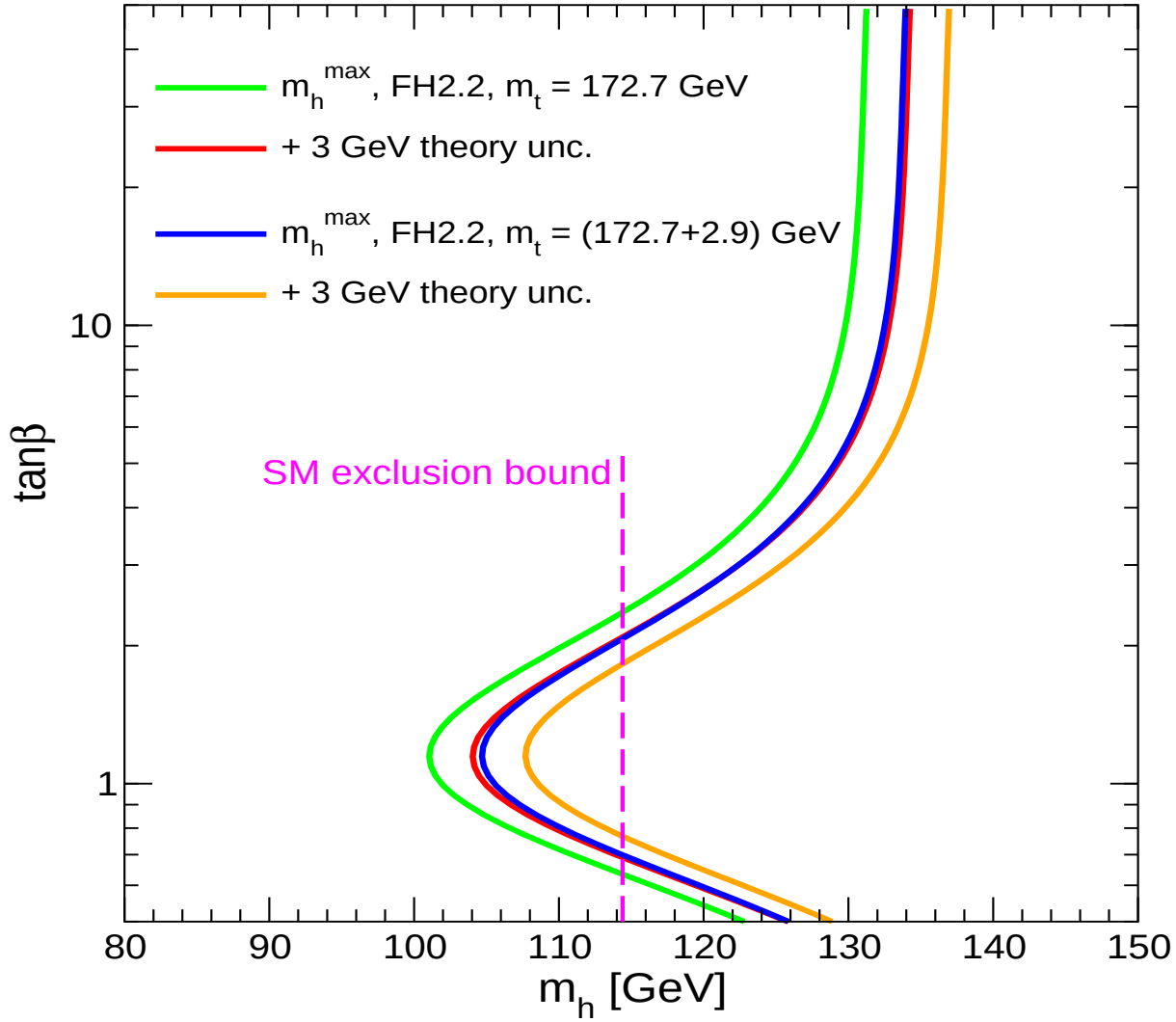
no theoretical uncertainties included

Note: new m_t value: $m_t = 172.7 \pm 2.9$ GeV

parametric uncertainty: $\delta m_h^{\text{para}} \approx \delta m_t$

Effect of new corrections and $m_t \to m_t + \sigma_{m_t}$

[*S.H., W. Hollik, G. Weiglein '05*]



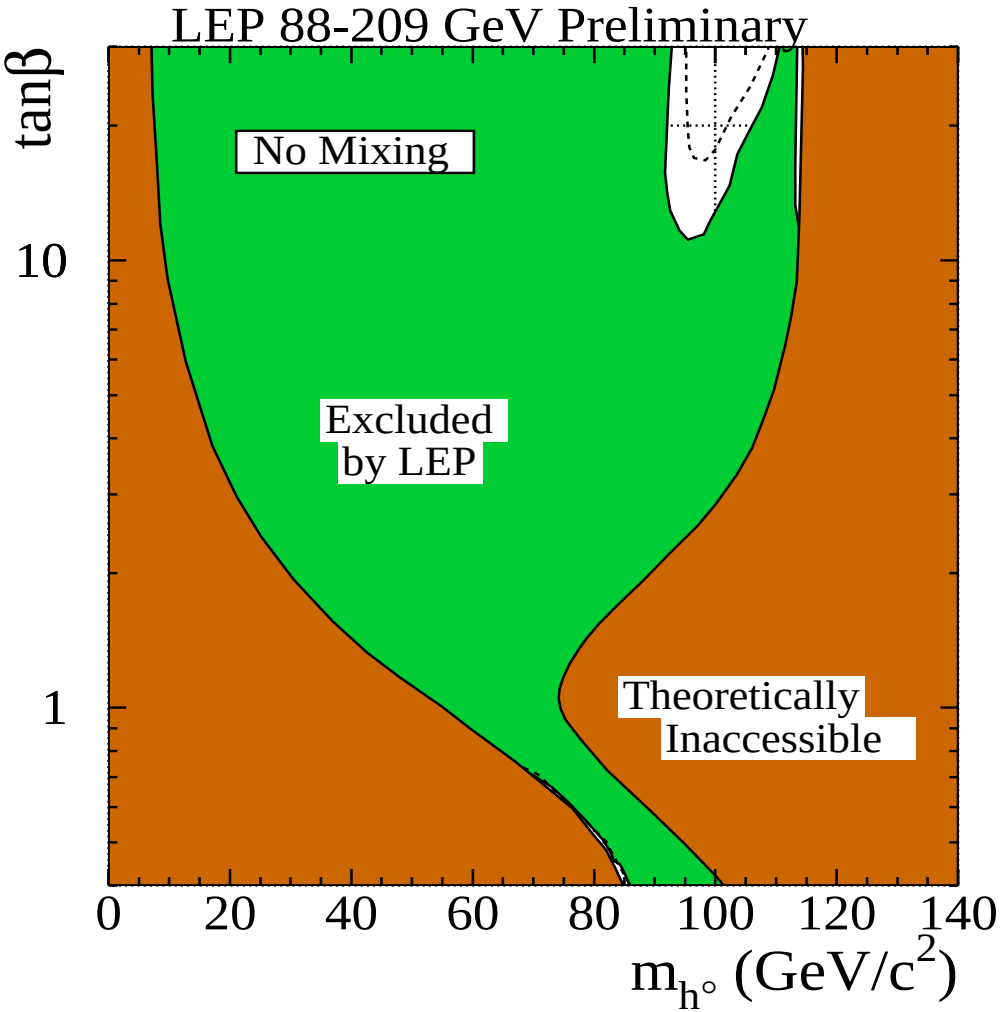
$\Rightarrow$ precise knowledge of m_t important!

$\Rightarrow$ Low $\tan\beta$ region not fully excluded by LEP!

Results in the no-mixing scenario [*LEP Higgs Working Group '04*]

Experimental search vs. upper m_h-bound (`FeynHiggs2.0`)

$m_t = 174.3$ GeV, $M_{\mathrm{SUSY}} = 1$ TeV:



$m_h > 92.8$ GeV
(expected: 94.9 GeV), 95% C.L.

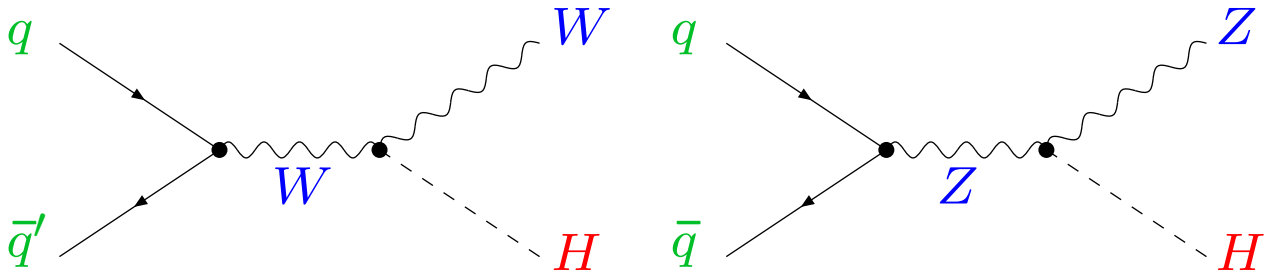
$M_A > 93.1$ GeV
(expected: 95.1 GeV)

$0.7 \leq \tan\beta \leq 4.6$ excluded

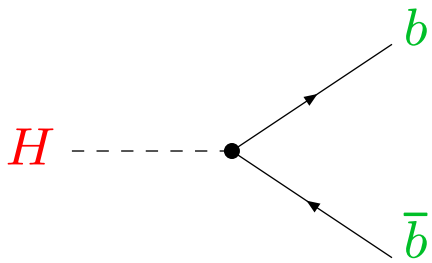
3. MSSM Higgs bosons at the Tevatron

Search for the SM Higgs:

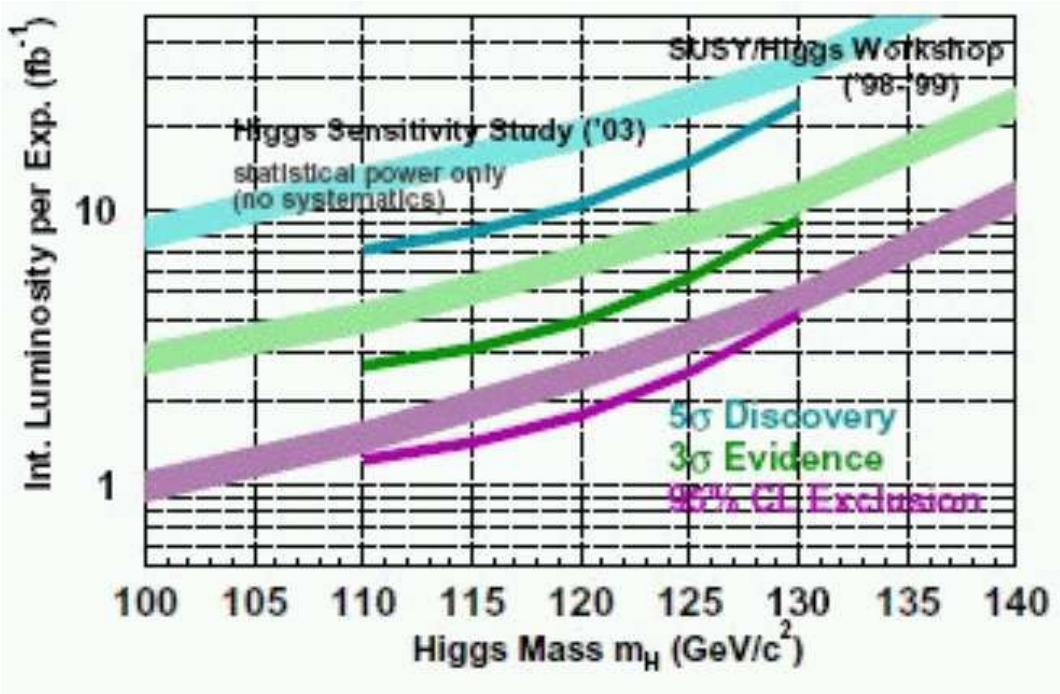
Dominant production processes:



Dominant decays: $H \to b\bar{b}$



Expectations for Higgs discovery at the Tevatron:



Unfortunately: luminosity problems $\Rightarrow$ progress remains unclear

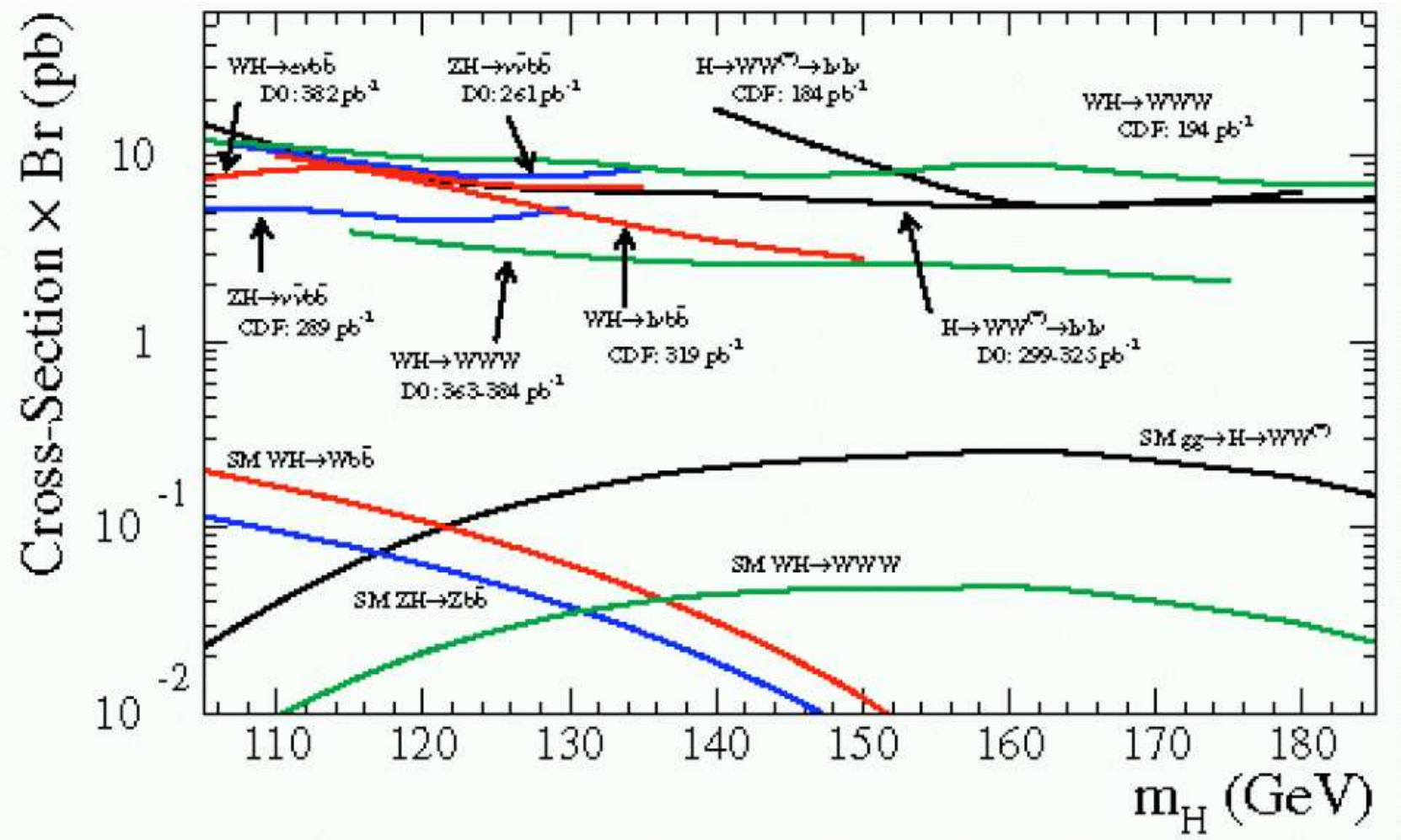
$\approx$ 2006/07: sensitivity for 95% C.L. exclusion for $M_H \approx 120$ GeV

$\approx$ 2008/09: sensitivity for 3σ evidence for $M_H \approx 120$ GeV

SM Higgs up to $M_H \approx 130$ GeV can be excluded at 95% C.L.

Current status of SM Higgs search:

[*CDF, D0 '05*]



Can they close the gap?

MSSM Higgs searches (I): Search for a "SM-like" light Higgs:

Prediction in "simplified" versions of the MSSM:
($m_t^{\rm exp} = 172.7$ GeV, $\delta m_t^{\rm exp} = 2.9$ GeV)
[*A. Dedes, S.H., S. Su, G. Weiglein '03*] [*S.H., W. Hollik, G. Weiglein '04,'05*]

	max. m_h [GeV]	$\delta m_h/\delta m_t$	for $m_t^{\rm exp} + 2\delta m_t$
mSUGRA/CMSSM	125.6	0.65	129.4
mGMSB	120.0	0.70	124.1
mAMSB	121.5	0.58	124.9

Exclusion potential of the Tevatron: $M_H^{\rm SM} \lesssim 130$ GeV

$\Rightarrow$ Tevatron can exclude mSUGRA/CMSSM, mGMSB, mAMSB, ...

Possible problem in SUSY:

$h \to b\bar{b}$

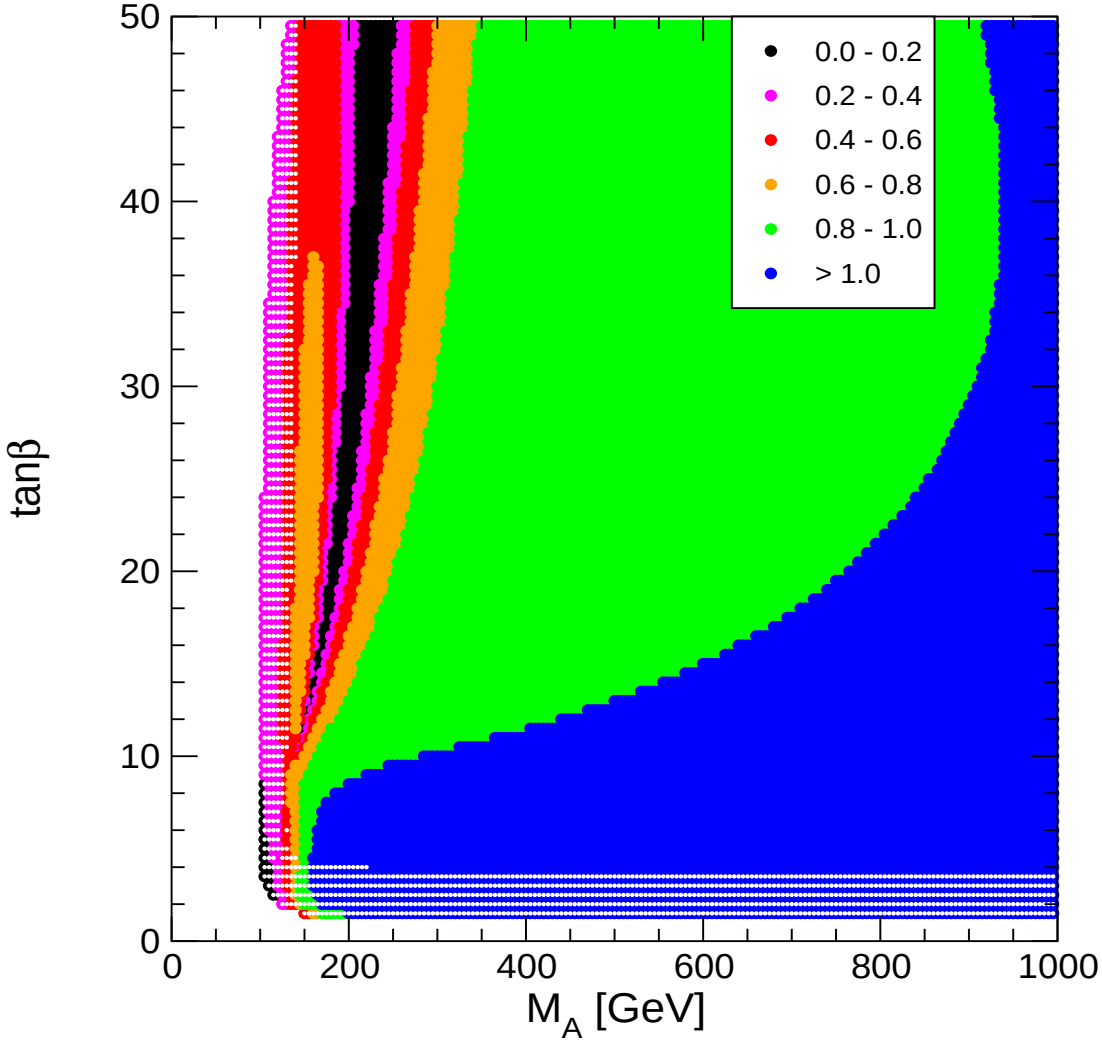
can be strongly suppressed

$\to$ "Small α_{eff} scenario"

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

$\Rightarrow$ Strong suppression of $h \to b\bar{b}$ possible, up to $M_A \lesssim 350$ GeV

(not realized in mSUGRA/CMSSM, GMSB, AMSB, . . .)



MSSM Higgs searches (II): "Heavy" MSSM Higgs bosons

Search modes:

$$b\,\bar{b} \to \phi\, b\,\bar{b}\ , \quad \phi = h, H, A$$
$$p\,\bar{p} \to \phi \to \tau^+\,\tau^-\ , \quad \phi = h, H, A$$

Strong enhancement compared to the SM:

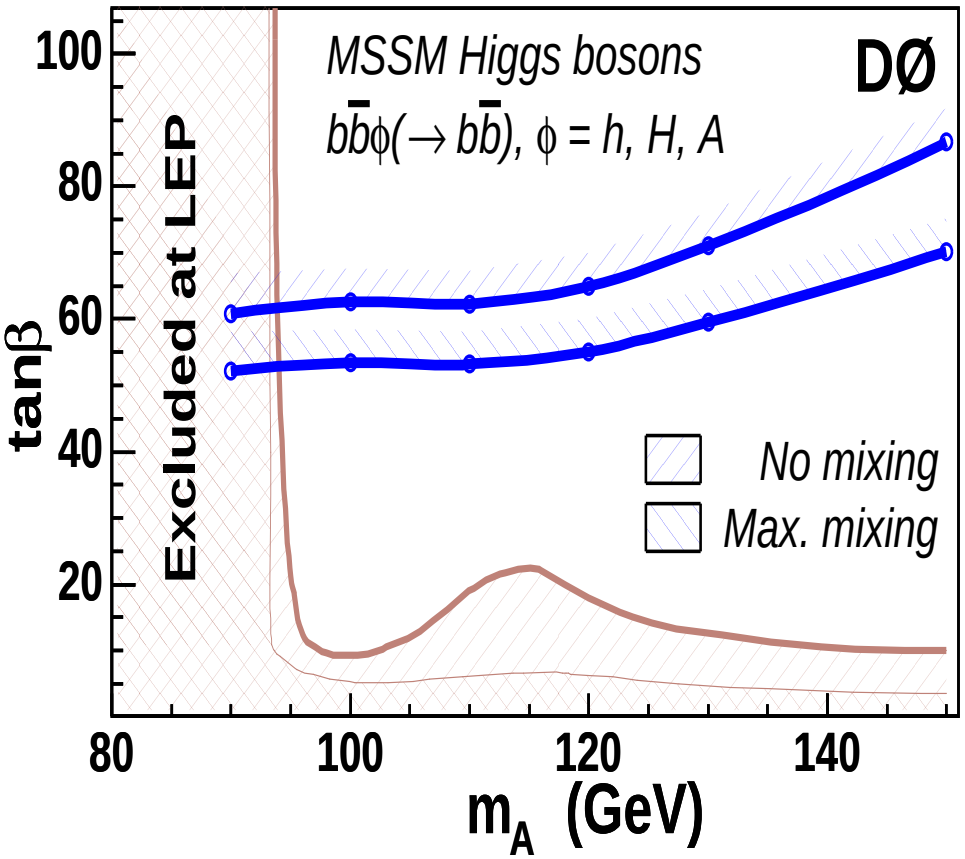
$$\sigma(b\bar{b}A) \times \mathrm{BR}(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

$$\sigma(gg, b\bar{b} \to A) \times \mathrm{BR}(A \to \tau^+\tau^-) \simeq \sigma(gg, b\bar{b} \to A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

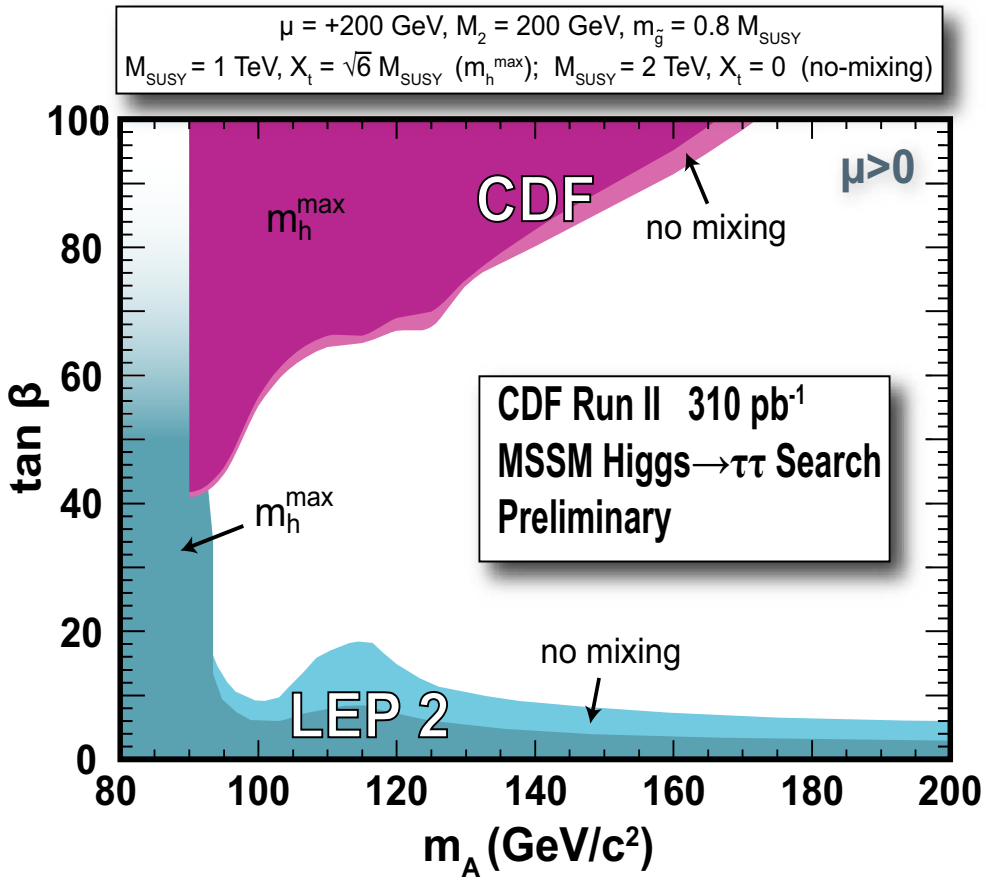
$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}}\,\mu\,\tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\pi} A_t\,\mu\,\tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

Either $H \approx A$ or $h \approx A \Rightarrow$ another factor of 2

Existing Tevatron data allows bounds on SUSY parameter space:



[D0 '05]

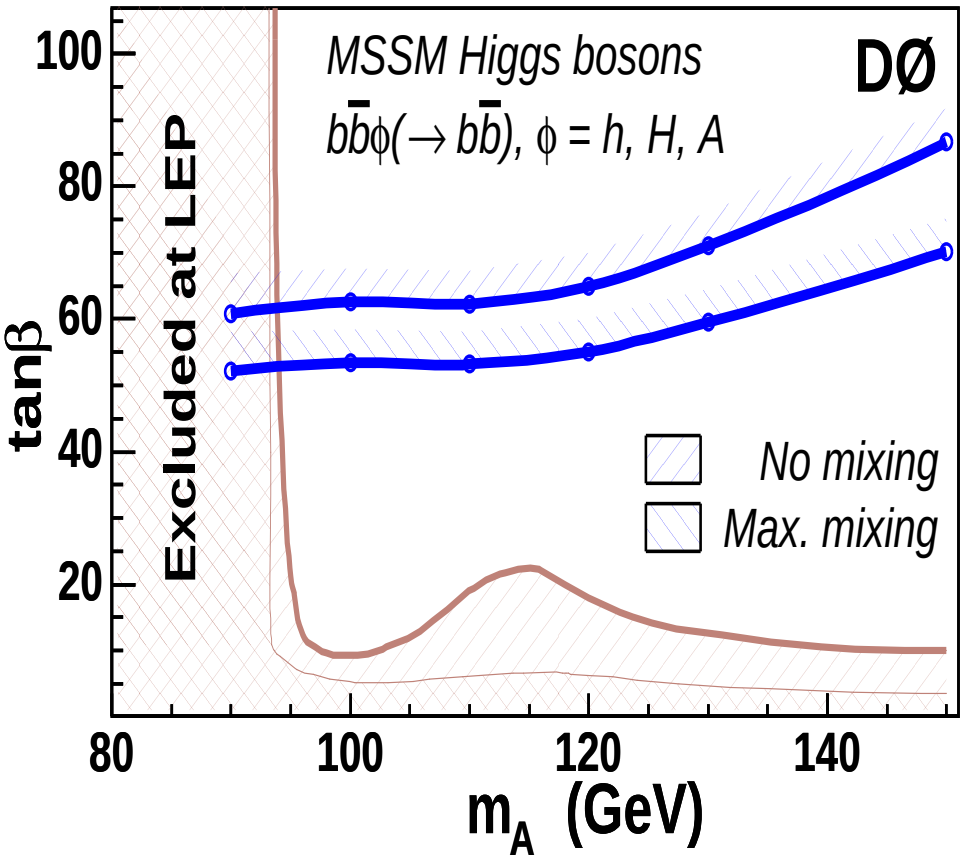


[CDF '05]

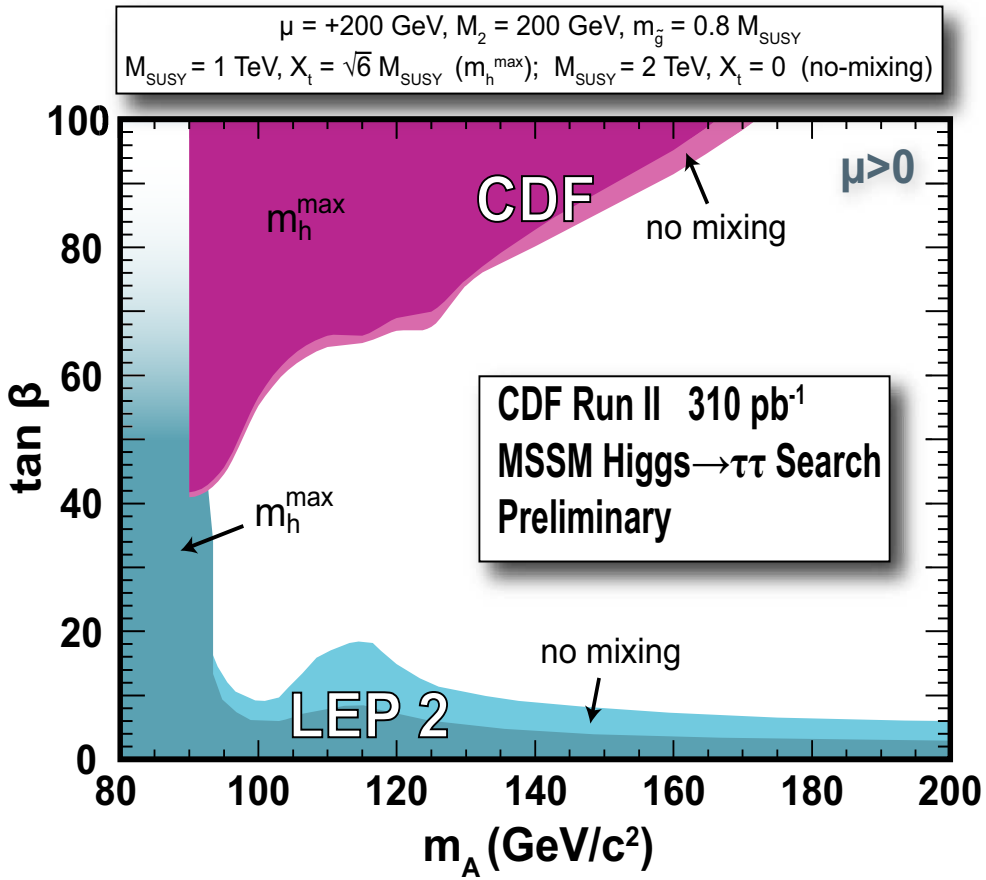
⇒ Bounds on the MSSM parameter space for low M_A, high $\tan\beta$:

$\tan\beta \approx 50$ excluded for $M_A \approx 100$ GeV

Existing Tevatron data allows bounds on SUSY parameter space:



[D0 '05]



[CDF '05]

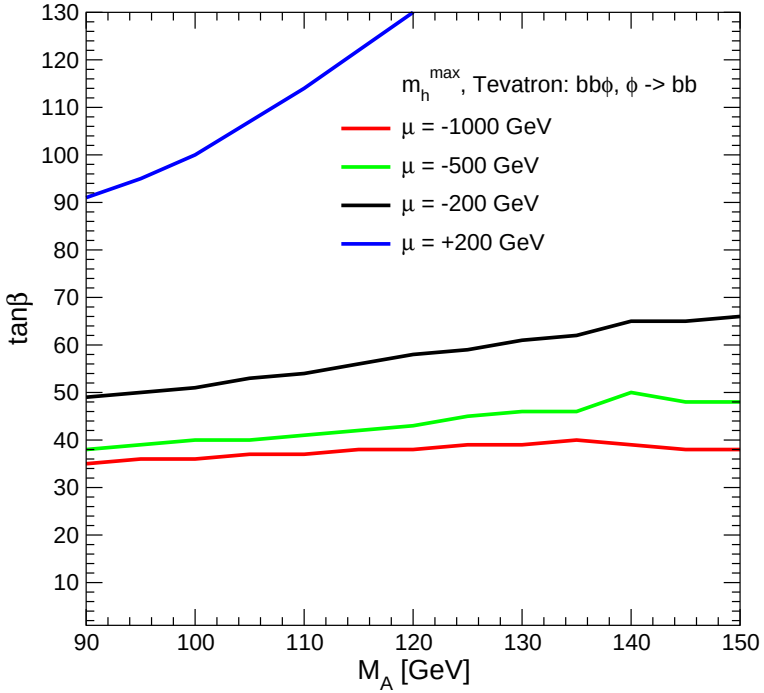
⇒ Bounds on the MSSM parameter space for low M_A, high $\tan\beta$:

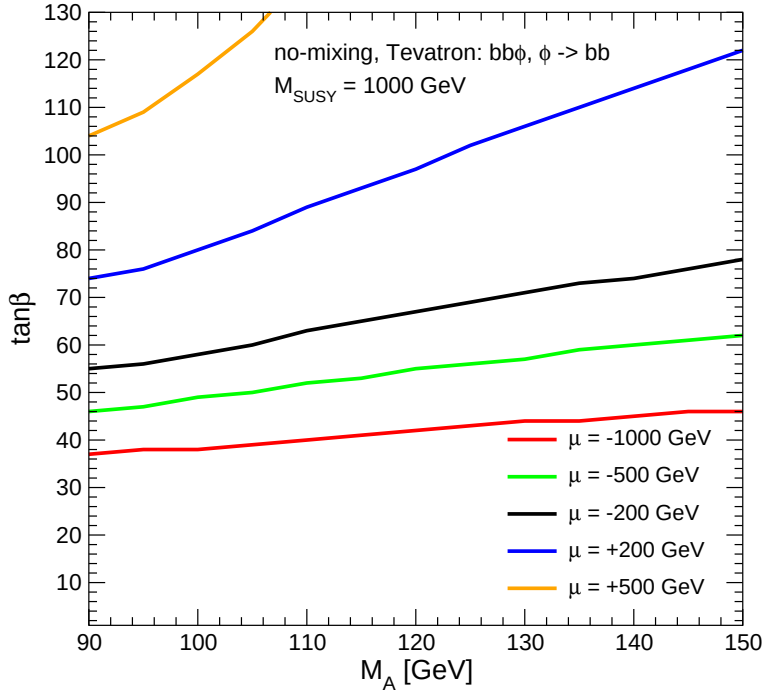
$\tan\beta \approx 50$ excluded for $M_A \approx 100$ GeV

in certain benchmark scenarios!

Dependence of Tevatron bounds from $b\bar{b}\phi, \phi \to b\bar{b}$ on μ:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]





$\Rightarrow$ strong variation with the sign and absolute value of μ

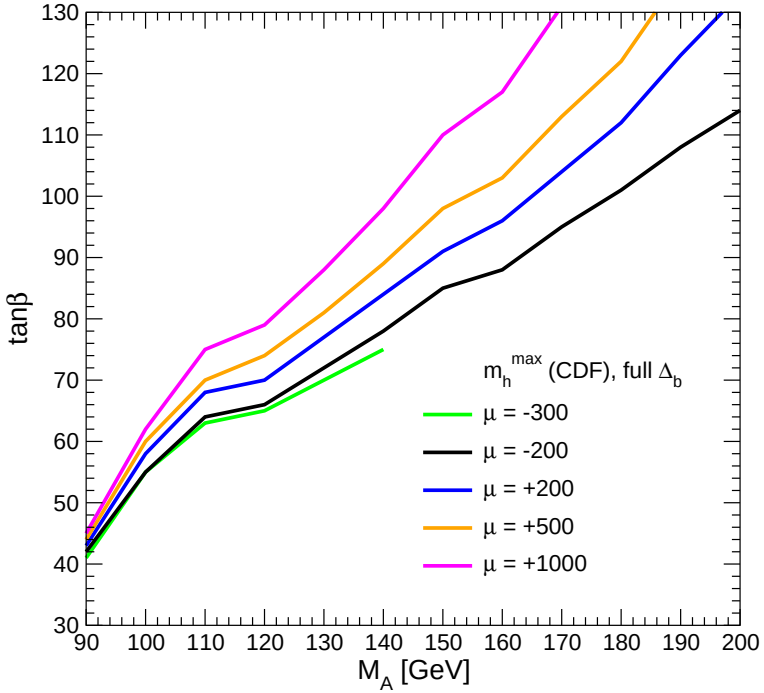
$\Rightarrow$ much stronger or weaker bounds possible

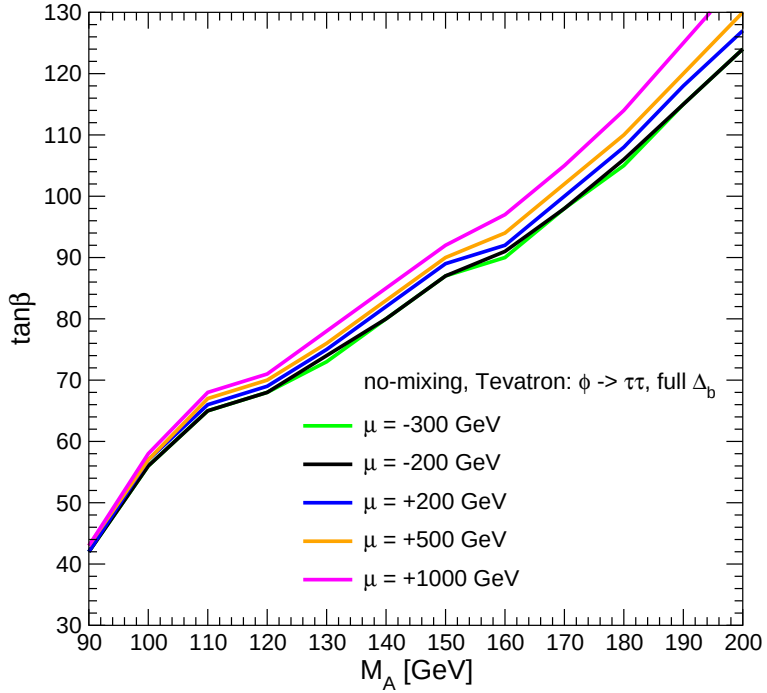
no bounds for $\mu \gtrsim 200$ GeV

(positive μ preferred by $(g-2)_\mu$)

Dependence of Tevatron bounds from $p\bar{p} \to \phi, \phi \to \tau^+\tau^-$ on μ:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]





⇒ less strong variation with the sign and absolute value of μ

(→ numerical compensations in production and decay)

⇒ still much stronger or weaker bounds possible

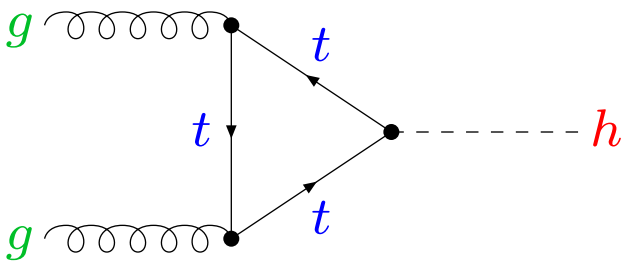
strong dependence on benchmark scenario

4. MSSM Higgs bosons at the LHC

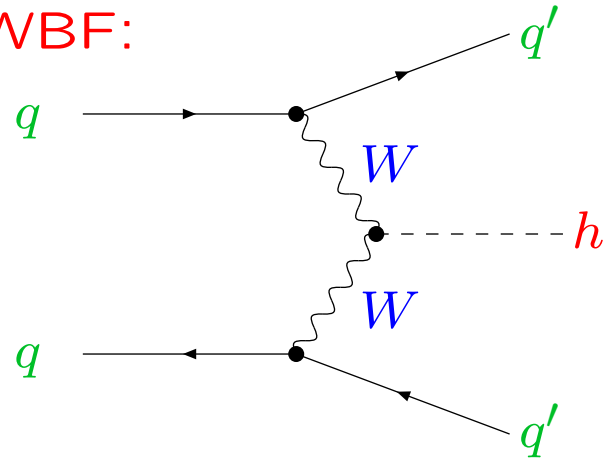
Higgs search in the SM:

Important production channel at the LHC:

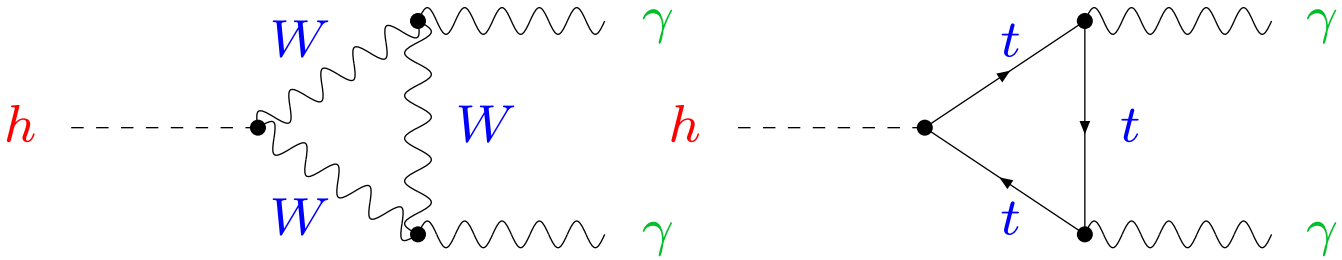
Gluon-Fusion:



WBF:

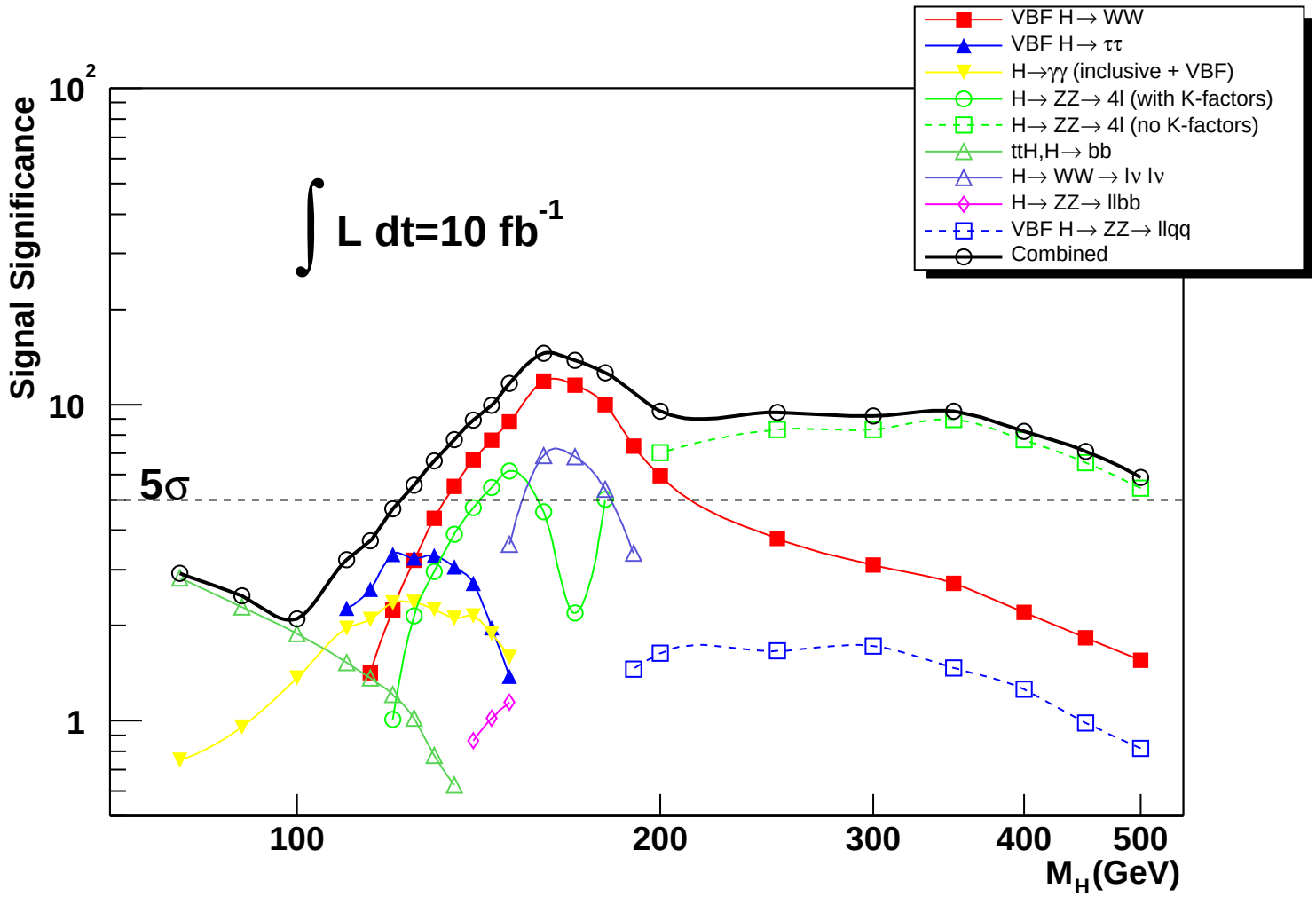


Important decay for Higgs mass measurement:



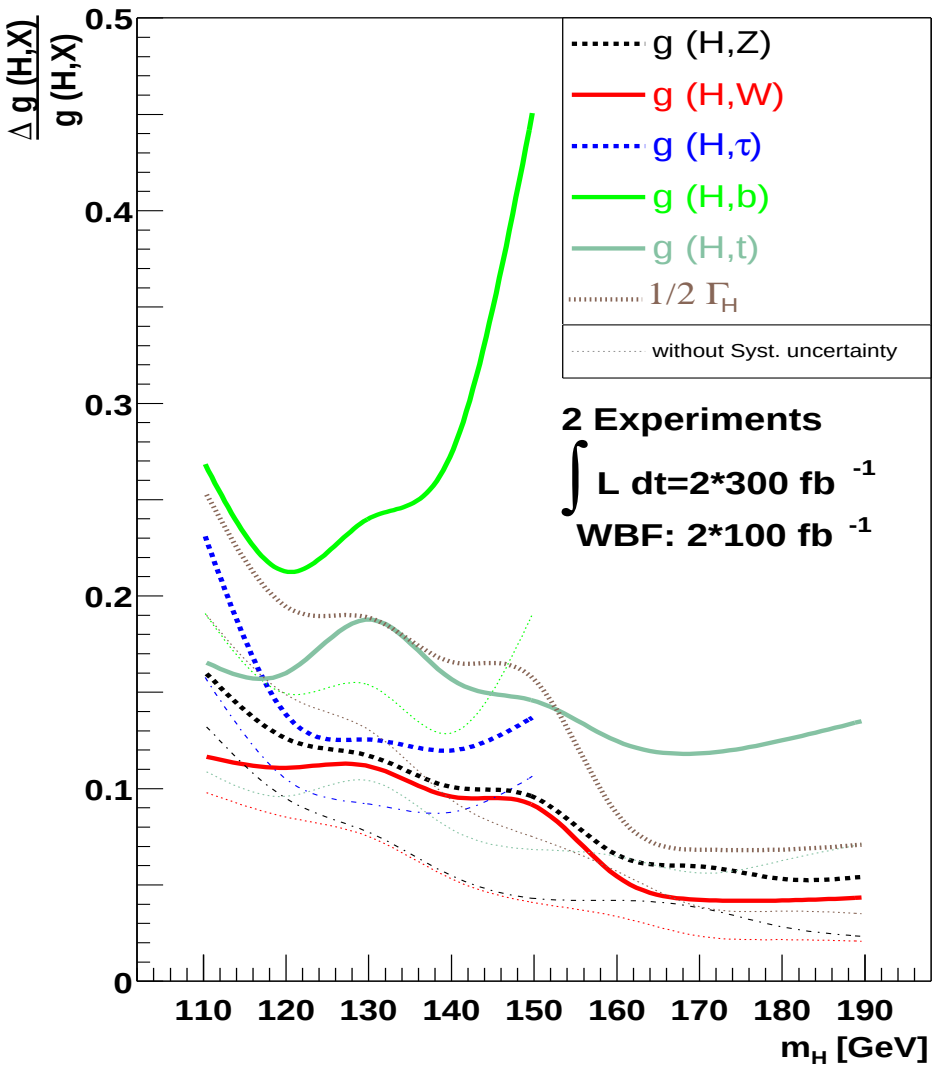
SM Higgs search at the LHC: ⇒ full parameter accessible

[*ATLAS '05*]



Higgs coupling determination at the LHC:

[*M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04*]



With mild theory assumptions:

- typical accuracies of 10-15% for $m_H \leq 150$ GeV
- 5% accuracies for HVV couplings above WW threshold
- Systematic errors contribute up to half of the total error, especially at high luminosity

MSSM Higgs searches (I): light SM-like Higgs bosons

Possible problem in SUSY:

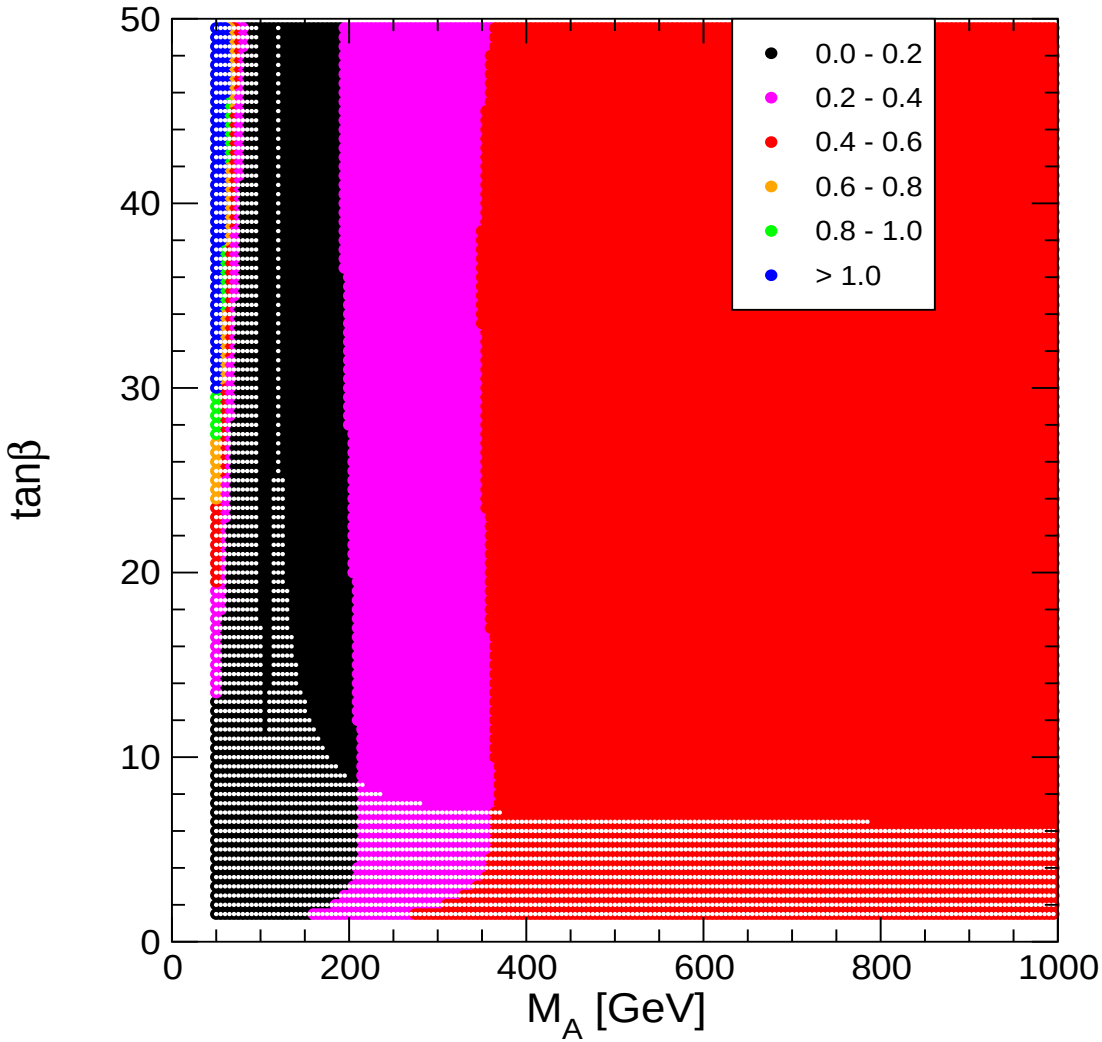
$$gg \to h \to \gamma\gamma$$

can be strongly suppressed

$\longrightarrow$ "gluophobic Higgs scenario"

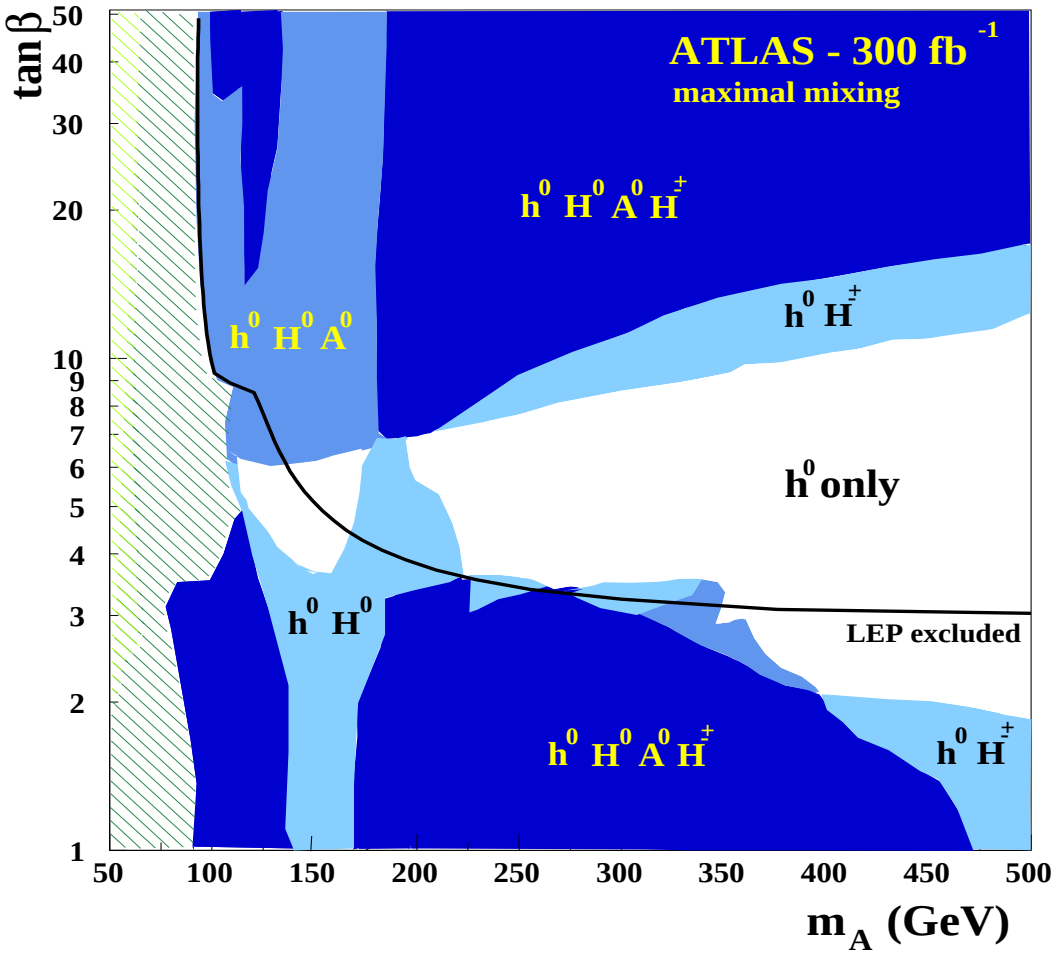
[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

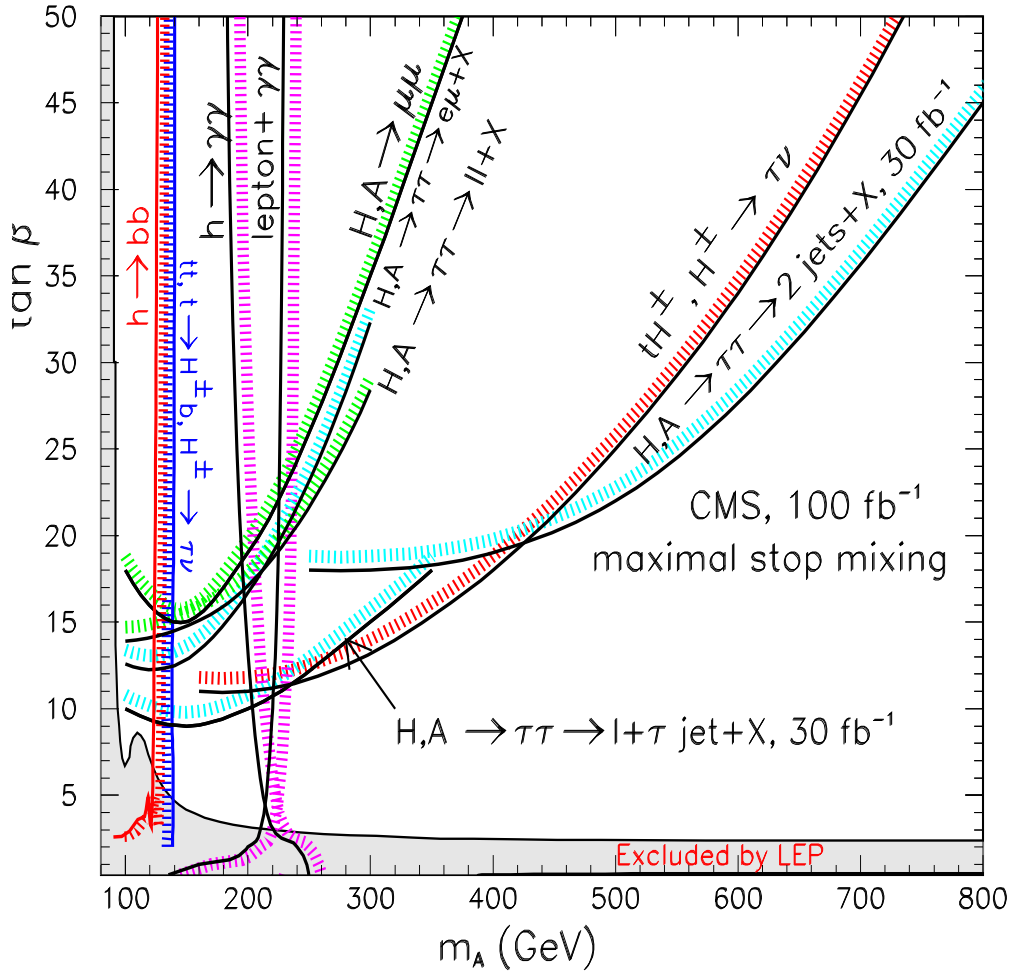
$\Rightarrow$ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space



MSSM Higgs searches (II): "Heavy" MSSM Higgs bosons

MSSM Higgs discovery contours in M_A–tan β plane
($m_h^{\max}$ benchmark scenario): [ATLAS '99] [CMS '03]





Most powerful search modes for heavy MSSM Higgs bosons:

$$b\bar{b} \to H/A \to \tau^+\tau^- + X$$
$$pp \to tH^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$

Enhancement factors compared to the SM case:

$$H/A \;\; : \;\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{\mathrm{BR}(H \to \tau^+\tau^-) + \mathrm{BR}(A \to \tau^+\tau^-)}{\mathrm{BR}(H \to \tau^+\tau^-)_{\mathrm{SM}}}$$

$$H^\pm \;\; : \;\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \mathrm{BR}(H^\pm \to \tau\nu_\tau)$$

$\Rightarrow$ Δ_b effects so far neglected by ATLAS/CMS

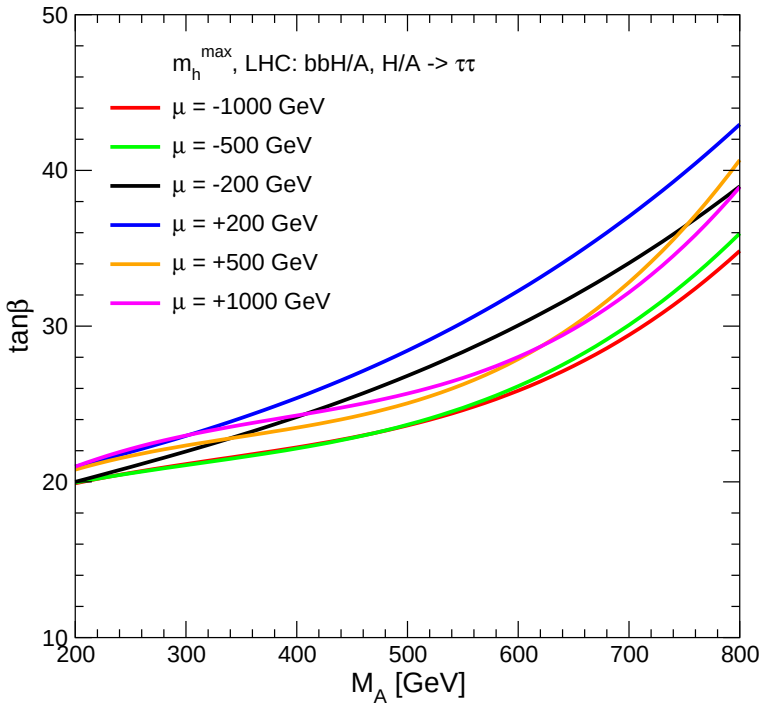
also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

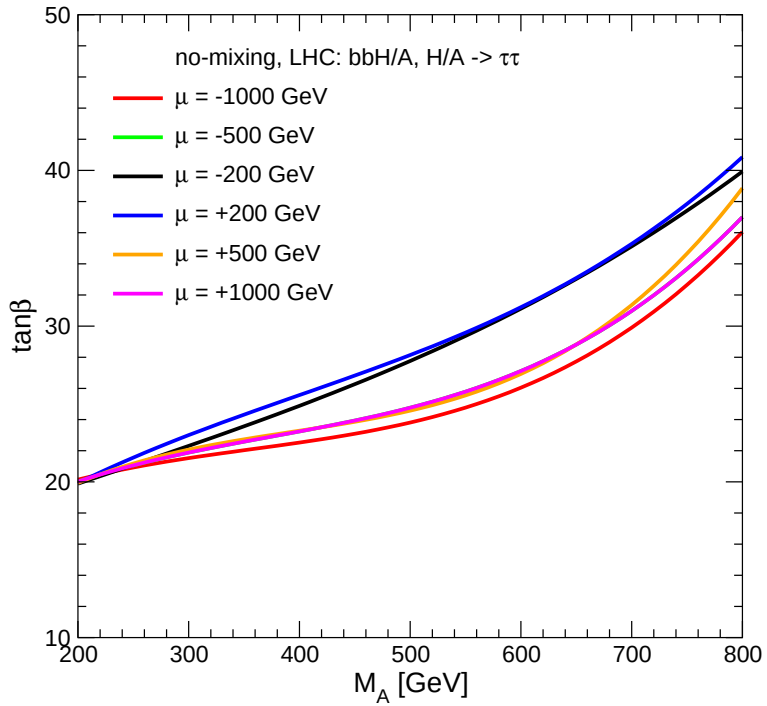
also relevant: correct evaluation of $\Gamma(H/A/H^\pm \to \mathrm{SUSY})$

$\Rightarrow$ additional effects on $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

Dependence of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^-$ on μ:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]





⇒ non-negligible variation with the sign and absolute value of μ

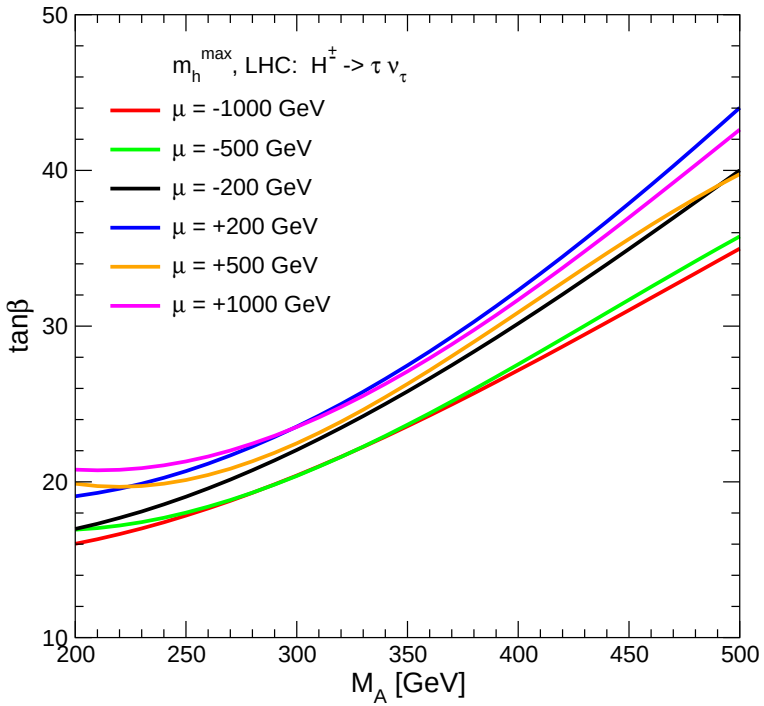
(→ numerical compensations in production and decay)

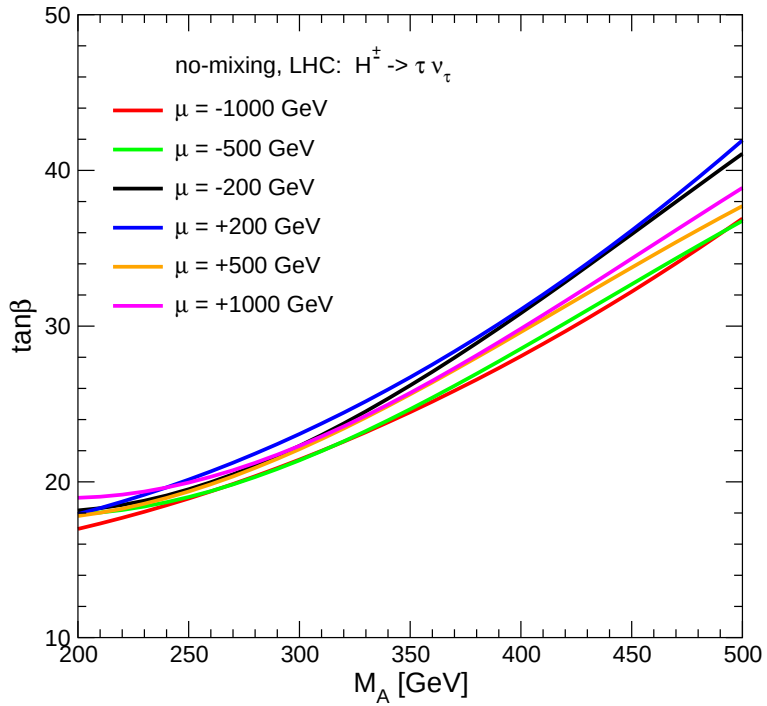
⇒ much stronger or weaker bounds possible

than in existing analysis

Dependence of the LHC wedge from $pp \to tH^\pm, H^\pm \to \tau\nu_\tau$ on μ:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]





$\Rightarrow$ non-negligible variation with the sign and absolute value of μ

($\to$ numerical compensations in production and decay)

$\Rightarrow$ much stronger or weaker bounds possible

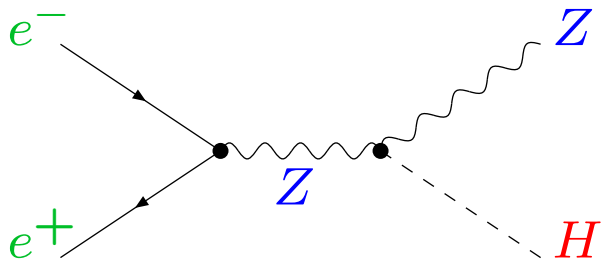
than in existing analysis

5. Prospects for the ILC

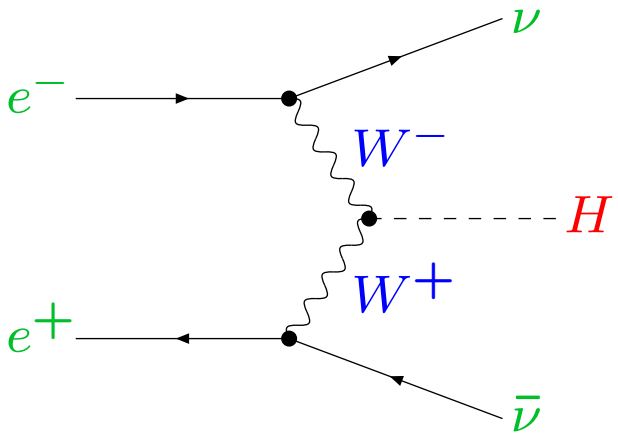
ILC: e^+e^- accelerator: possible start: 2015

SM Higgs boson at the ILC:

Higgs-Strahlung:



Weak boson fusion:

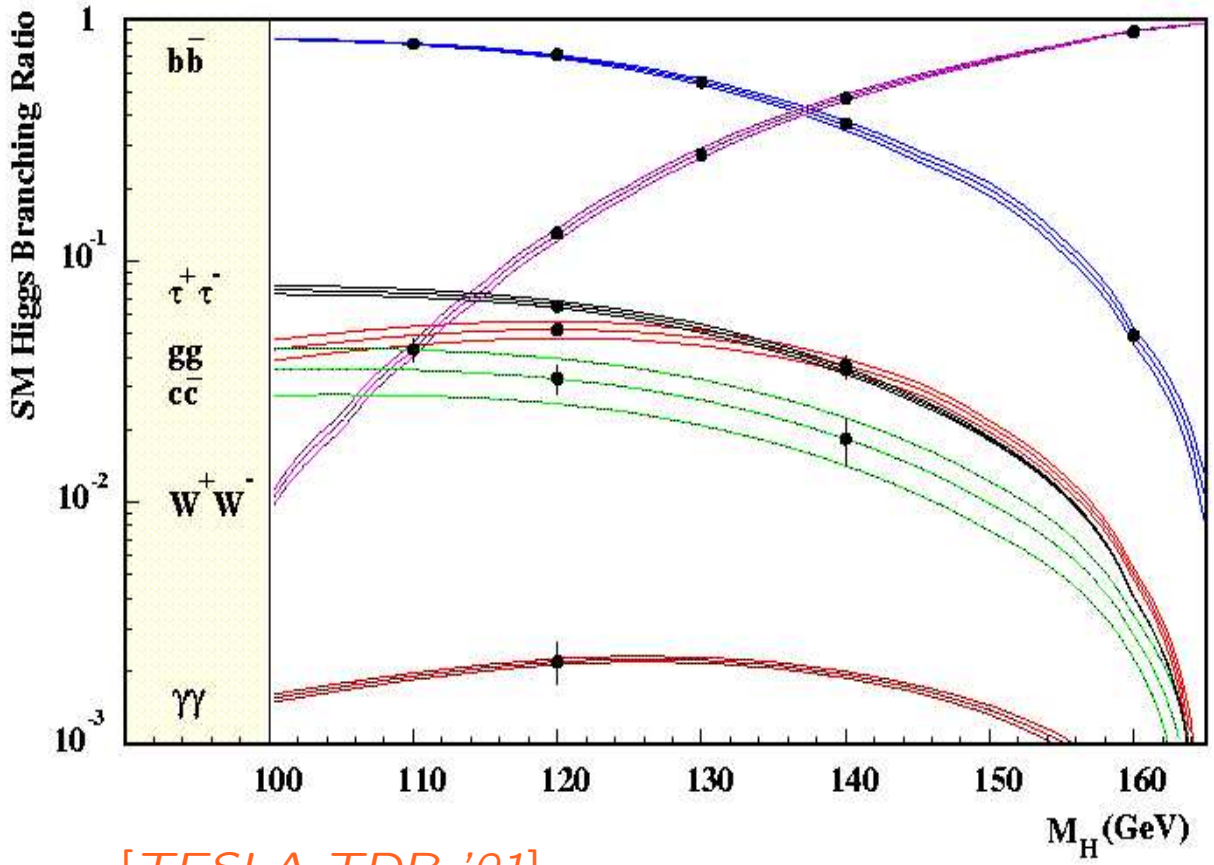


$\Rightarrow$ Measurement of masses, couplings, ... in per cent/per mille

SM Higgs boson precision measurements at the ILC:

Precise measurement of:

1. Higgs boson mass, $\delta M_H \approx 50$ MeV
2. Higgs boson width (direct/indirect)
3. Higgs boson couplings, $\mathcal{O}$ (few%) $\Rightarrow$
4. Higgs boson quantum numbers: spin, . . .



[*TESLA TDR '01*]

MSSM: similar precision expected (possible problems from loop corrections)

Precision physics in the MSSM Higgs sector

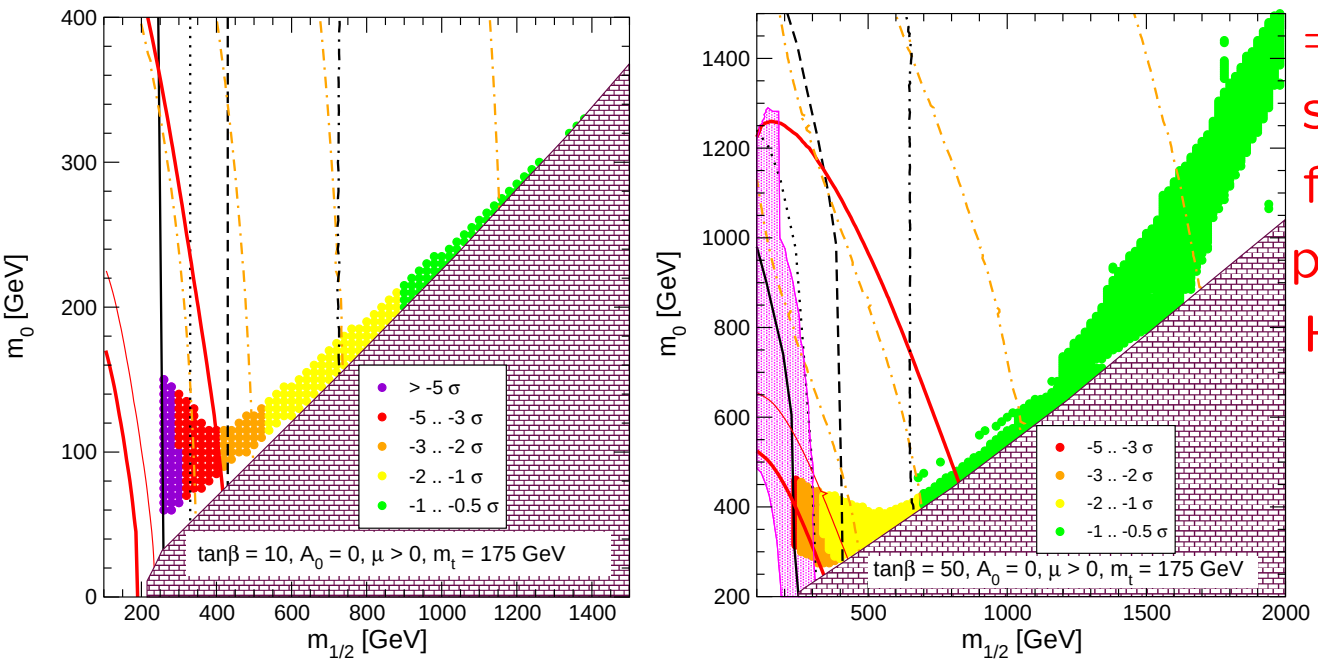
Precise measurement of Higgs branching ratios

⇒ Sensitivity to deviations SM / MSSM

E.g.: Prediction for $\sigma(e^+e^- \to Zh) \times \mathrm{BR}(h \to WW^*)$ in parameter region allowed by cosmology: comparison mSUGRA – SM:

[*J. Ellis, S.H., K. Olive, G. Weiglein '02*]

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



⇒ In allowed parameter space: sizable deviations from SM predictions for precision observables in the Higgs sector possible

Experimental situation:

Tevatron/LHC/ILC will provide high accuracy measurements !
(Same holds for astro-physics experiments like PLANCK, . . .)

Theory situation:

measured observables have to be compared with theoretical predictions (in the MSSM)

High precision of experimental data can only fully be exploited
if it is matched with
theoretical calculations (masses, couplings) at the same level of accuracy

Theoretical calculations should be viewed as
an essential part of all future High Energy
Physics programs

6. Conclusinos

- – Higgs mechanism is the most attractive solution for EWSB
  – SUSY is the most attractive extension of the SM

- The LEP results are finally ready
  MSSM: search in certain benchmark scenarios
  ⇒ no significant deviation found in the SM/MSSM search

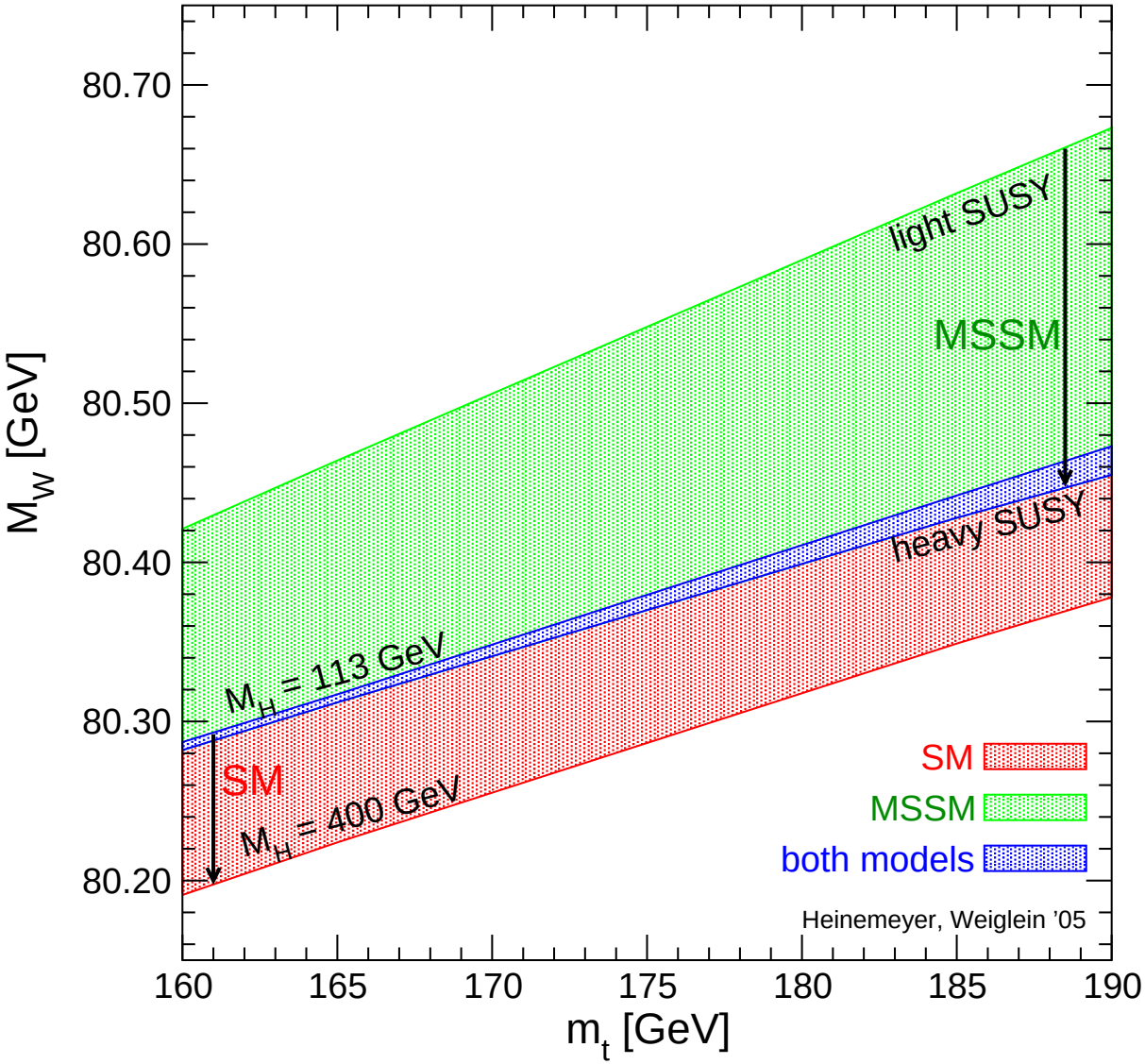
- Tevatron is actively searching for the Higgs:
  SM: no sensitivity yet; with 8 fb^{-1}: $M_H^{\rm SM} \lesssim 130$ GeV can be excluded
  MSSM: current data allows to set bounds on the parameter space
  important: strong dependence on μ
  mSUGRA/CMSSM, mGMSB, mAMSB can be excluded!

- Prospects for LHC Higgs searches:
  SM: no problem; coupling determination at the 5-15% level
  MSSM: LHC wedge: only the light h can be found
  → strong dependence on μ

- ILC Higgs measurements:
  SM/MSSM: very good prospects; precise theory calculations needed

Back-up

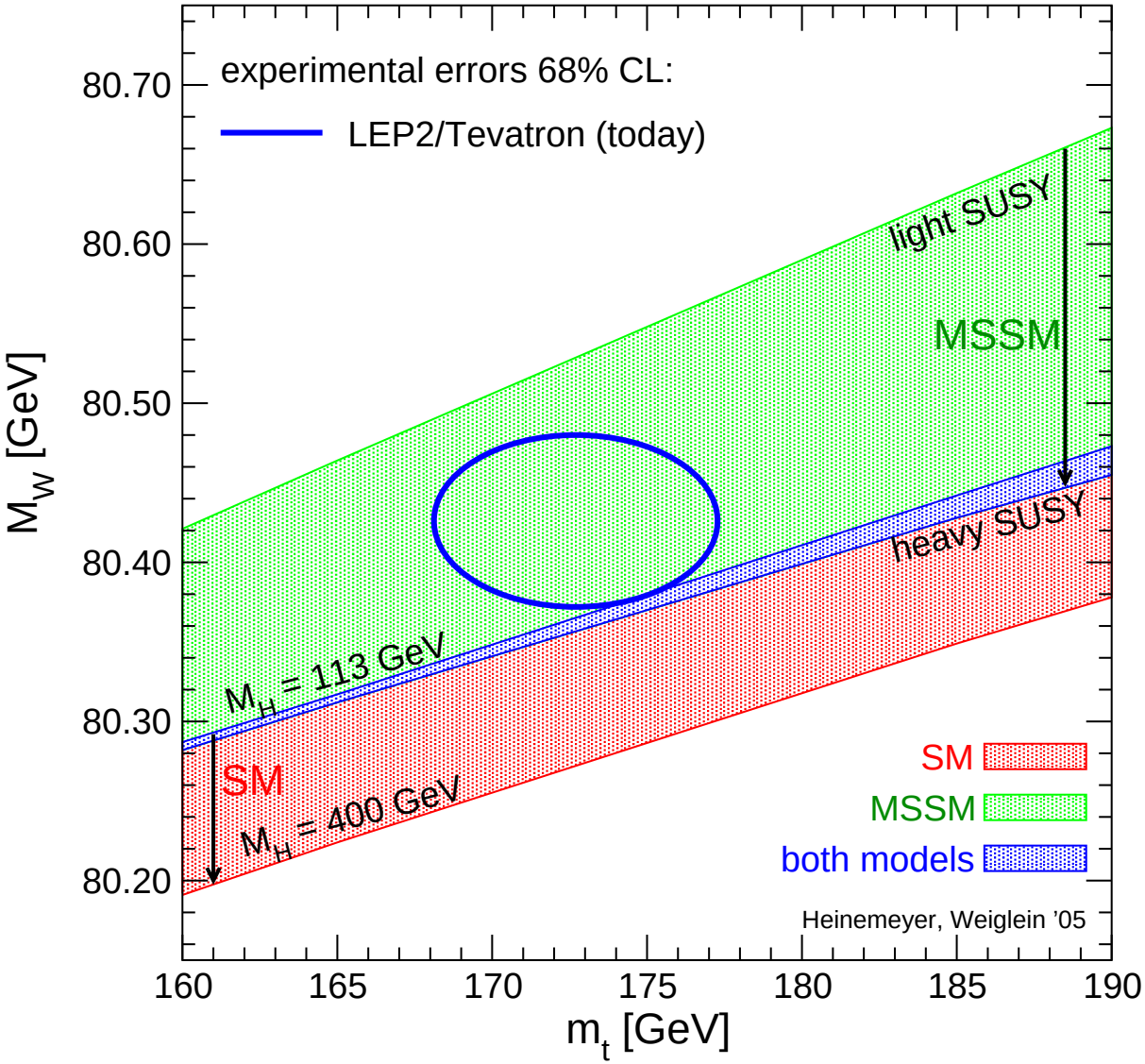
MSSM Example: Prediction for M_W in the SM and the MSSM :



MSSM uncertainty:
unknown masses
of SUSY particles

SM uncertainty:
unknown Higgs mass

MSSM Example: Prediction for M_W in the SM and the MSSM :



MSSM uncertainty:
unknown masses
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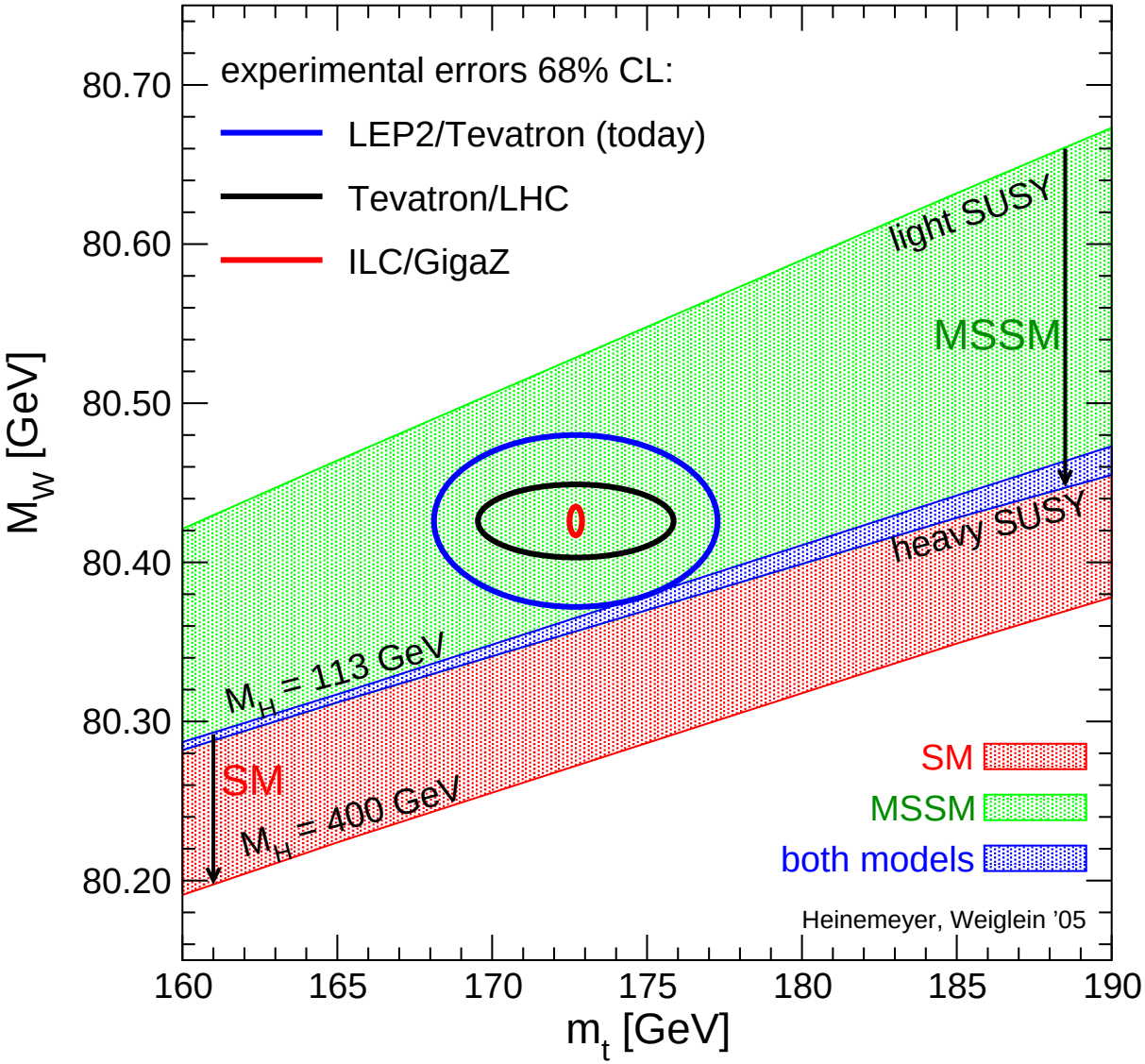
SM uncertainty:
unknown Higgs mass

MSSM Example: Prediction for M_W in the SM and the MSSM :



MSSM uncertainty:
unknown masses
of SUSY particles

SM uncertainty:
unknown Higgs mass

What is the "CMSSM" or "mSUGRA" ?

$\Rightarrow$ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

} at the GUT scale

$\tan\beta$: ratio of Higgs vacuum expectation values

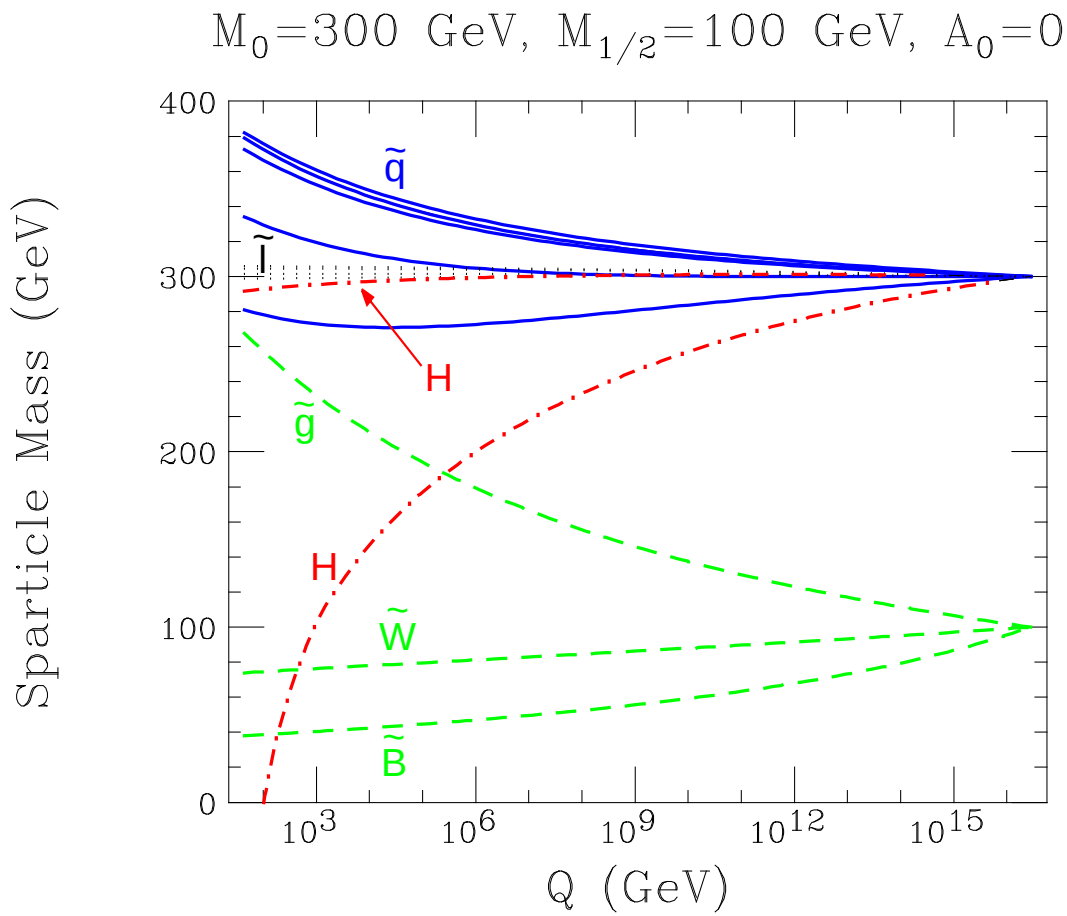
$\mathrm{sign}(\mu)$: sign of supersymmetric Higgs parameter

$\Rightarrow$ particle spectra from renormalization group running to weak scale

Lightest SUSY particle (LSP) is usually lightest neutralino

Low-energy parameters (at the electroweak (EW) scale) via
"Renormalization group equations" (RGEs)

[RGE: equations that connect parameters at different energy scales]



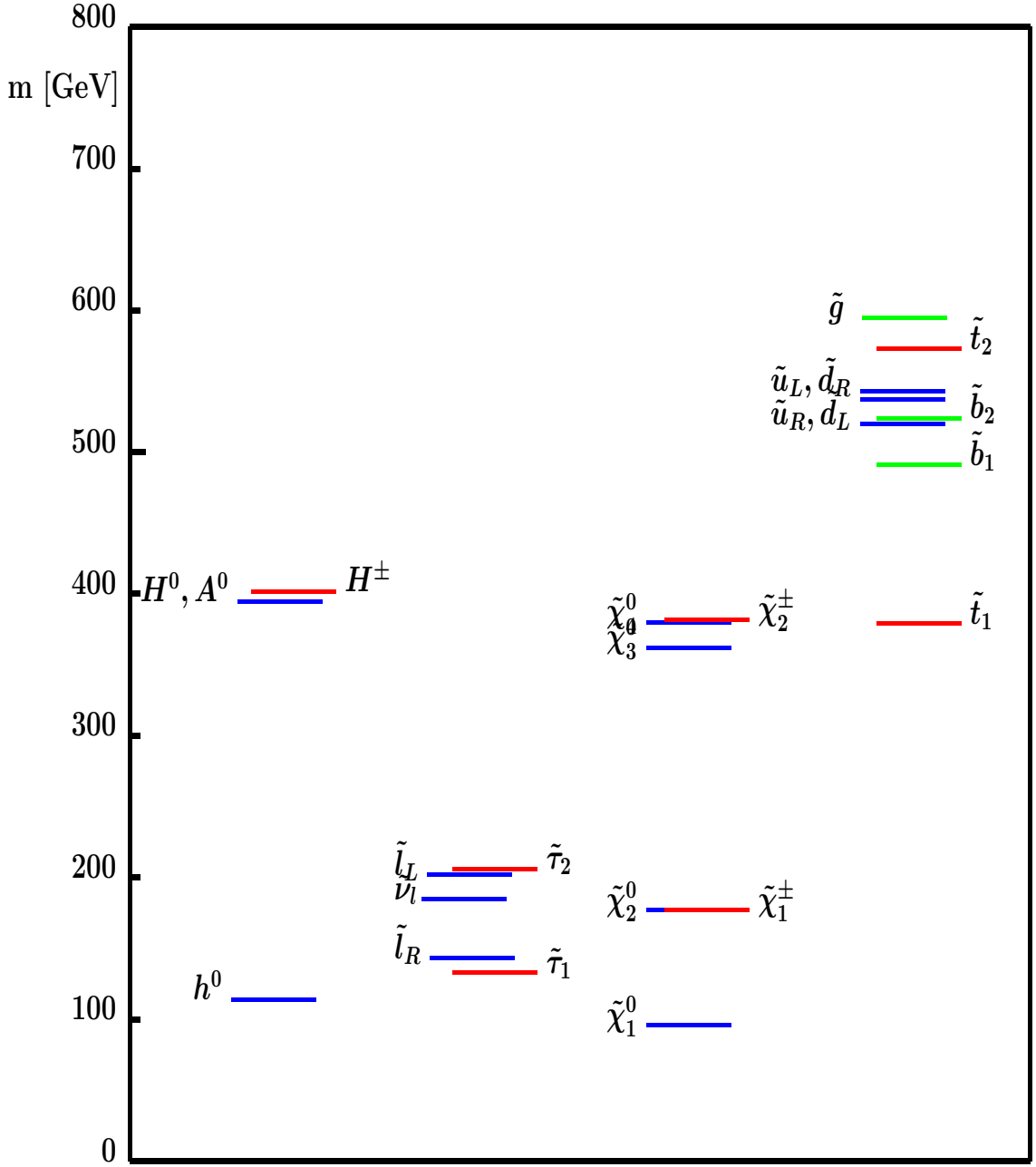
Note: one parameter in the Higgs potential becomes negative
$\Rightarrow$ Higgs mechanism for free

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

SPS home page:

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

$\Rightarrow m_h \lesssim 130$ GeV

$\Rightarrow$ observable at the Tevatron