Electroweak and Theory

(SM and MSSM)

Sven Heinemeyer, IFCA (CSIC, Santander)

St. Andrews, 08/2012

1. Higgs and Electroweak in The Standard Model (I)

2. Higgs and Electroweak in The Standard Model (II)

3. Higgs and Electroweak in the MSSM

Electroweak and Theory (III):
Higgs and Electroweak in the MSSM

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1. Introduction and Motivation

2. The Higgs sector of the MSSM

3. Electroweak precision observables in the MSSM

4. Comparison to "the discovery"

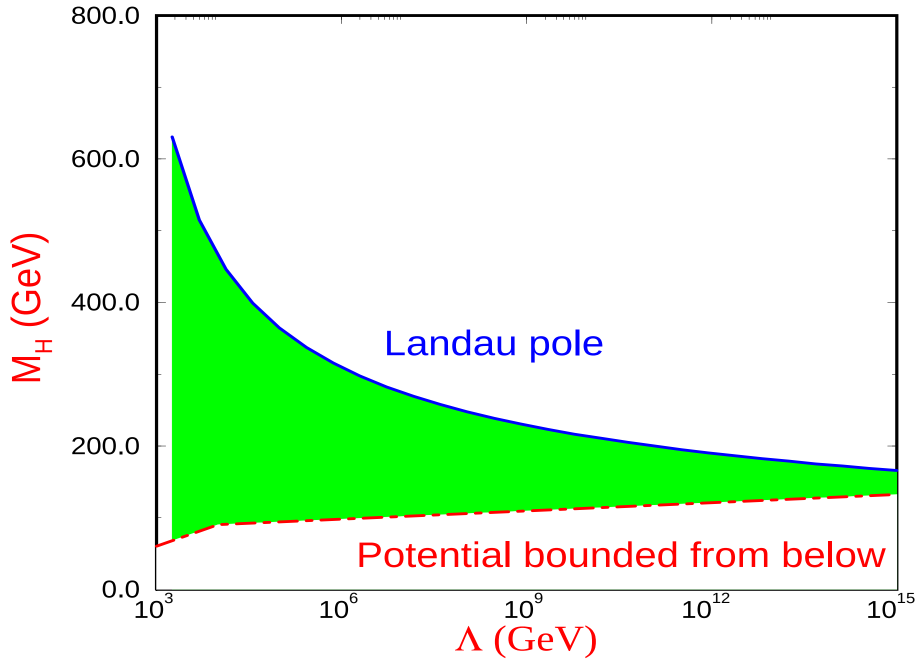
Introduction and Motivation:

The Standard Model (SM) cannot be the ultimate theory

- The SM does not contain gravity
- Further problems: Hierarchy problem
- And another one: SM does not provide Cold Dark Matter candidate

Up to which energy scale Λ can the SM be valid?

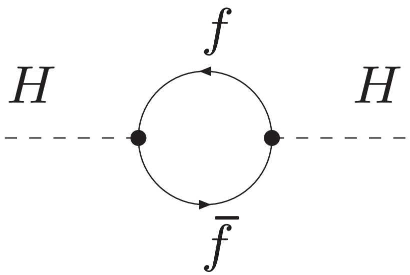
- $\Lambda < M_{\text{Pl}}$: inclusion of gravity effects necessary
- stability of Higgs potential: $\Rightarrow$
- Hierarchy problem : Higgs mass unstable w.r.t. quantum corrections $\delta M_H^2 \sim \Lambda^2$



Mass is what determines the properties of the free propagation of a particle

Free propagation: 

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections: 

inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

QM: integration over all possible loop momenta k

dimensional analysis:

$$\Sigma_H^f \sim N_f \, \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

$$\text{for } \Lambda \to \infty : \quad \Sigma_H^f \sim N_f \, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

$\Rightarrow$ quadratically divergent!

For $\Lambda = M_{\mathrm{Pl}}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\mathrm{Pl}}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

– no additional symmetry for $M_H = 0$

– no protection against large corrections

$\Rightarrow$ Hierarchy problem is instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale

E.g.: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\mathrm{GUT}}^2$

Note however: there is another fine-tuning problem in nature, for which we have no clue so far – cosmological constant

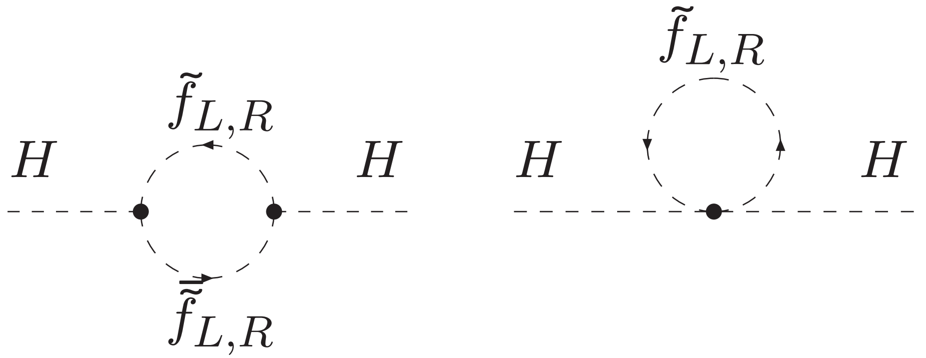
Supersymmetry:

Symmetry between fermions and bosons

$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$
$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}}^2 \int d^4k \left(\frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2} \right) + \text{ terms without quadratic div.}$$

for $\Lambda \to \infty$: $\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}}^2\, \Lambda^2$

⇒ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} \;=\; N_f$$
$$\lambda^2_{\tilde{f}} \;=\; \lambda^2_f$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

Soft SUSY breaking: $m^2_{\tilde{f}} = m^2_f + \Delta^2, \quad \lambda^2_{\tilde{f}} = \lambda^2_f$

$$\Rightarrow \; \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda^2_f \, \Delta^2 + \ldots$$

⇒ correction stays acceptably small if mass splitting is of weak scale

⇒ realized if mass scale of SUSY partners

$$M_{\mathrm{SUSY}} \lesssim 1 \,\mathrm{TeV}$$

⇒ SUSY at TeV scale provides attractive solution of hierarchy problem

Physics beyond the SM:

Interesting (new) physics models :

- 2HDM:
  - two Higgs doublets more natural than one
- MSSM:
  - solves hierarchy problem
  - automatic electroweak symmetry breaking
  - gauge coupling unification
  - cold dark matter candidate
- Little Higgs:
  - (partially) solves the hierarchy problem
  - cold dark matter candidate
- Extra dimensions:
  - solves the hierarchy problem
  - cold dark matter candidate
- . . .

⇒ pick your favorite model now (I pick the MSSM)

Supersymmetry:

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 (added by hand)

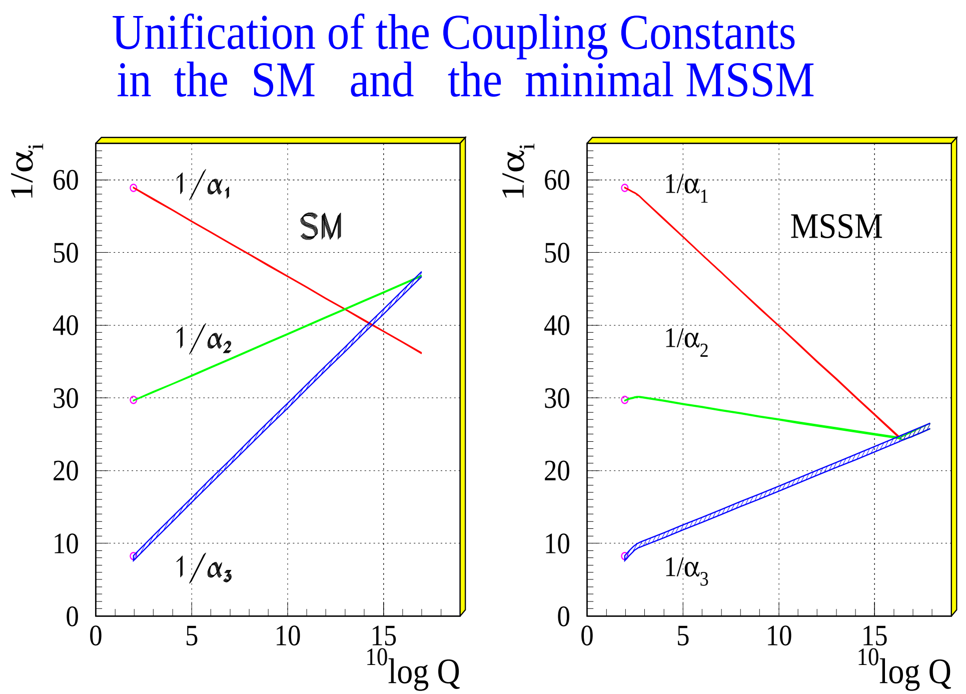
SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1\ \text{TeV})}$

Supersymmetry: Motivation

The SM is in a pretty good shape.

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

1.) Stability of the Higgs mass against higher-order corr.
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)
3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs
4.) SUSY provides CDM candidate
5.) ...



[*Amaldi, de Boer, Fürstenau '92*]

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

SUSY breaking:

“Hidden sector”:	$\longrightarrow$	Visible sector:
SUSY breaking		MSSM

“Gravity-mediated”: CMSSM/mSUGRA
“Gauge-mediated”: GMSB
“Anomaly-mediated”: AMSB
“Gaugino-mediated”
...

CMSSM/mSUGRA: mediating interactions are gravitational

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

AMSB, Gaugino-mediation: SUSY breaking happens on a different brane in a higher-dimensional theory

$\Rightarrow$ all new low-energy parameters expressed through a few GUT scale parameters!

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

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

m_0 : universal scalar mass parameter

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

A_0 : universal trilinear coupling

} at the GUT scale

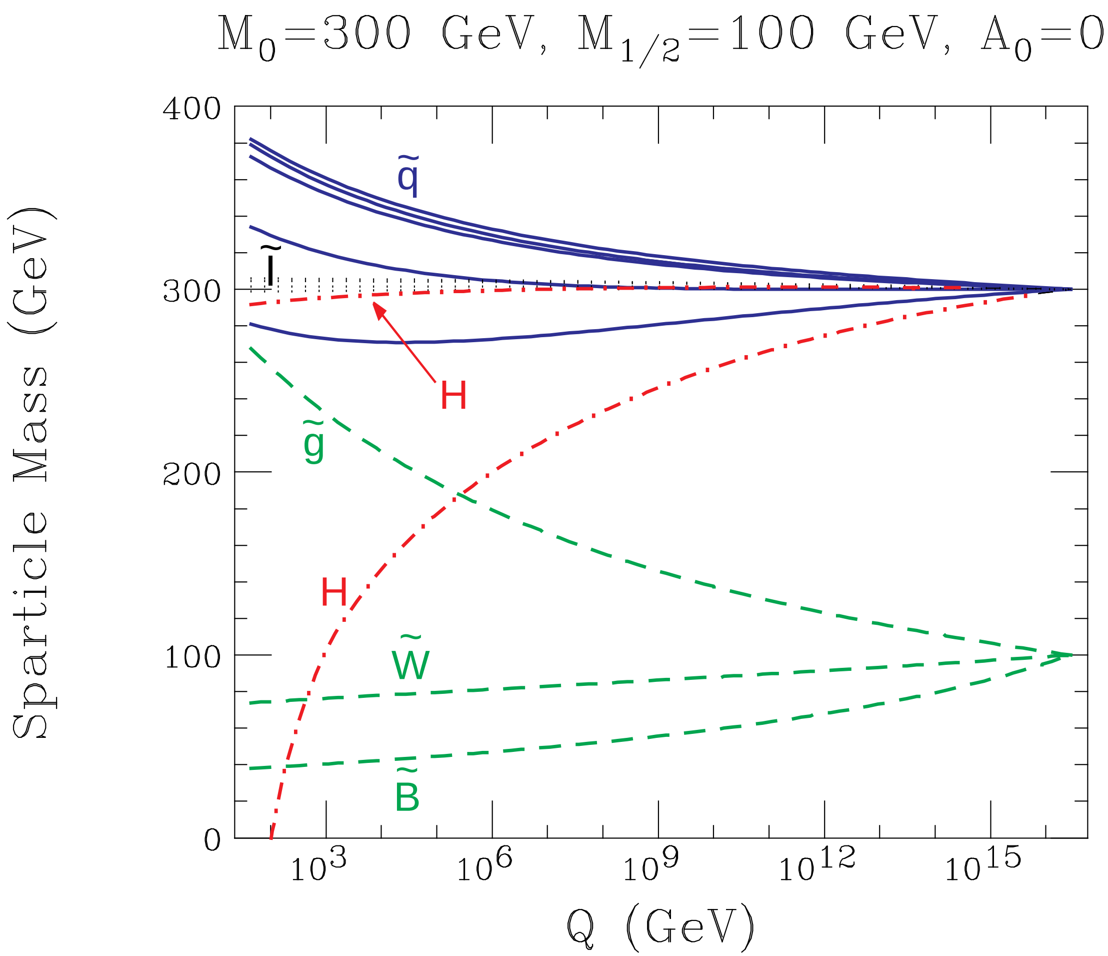
$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino

⇒ particle spectra from renormalization group running to weak scale



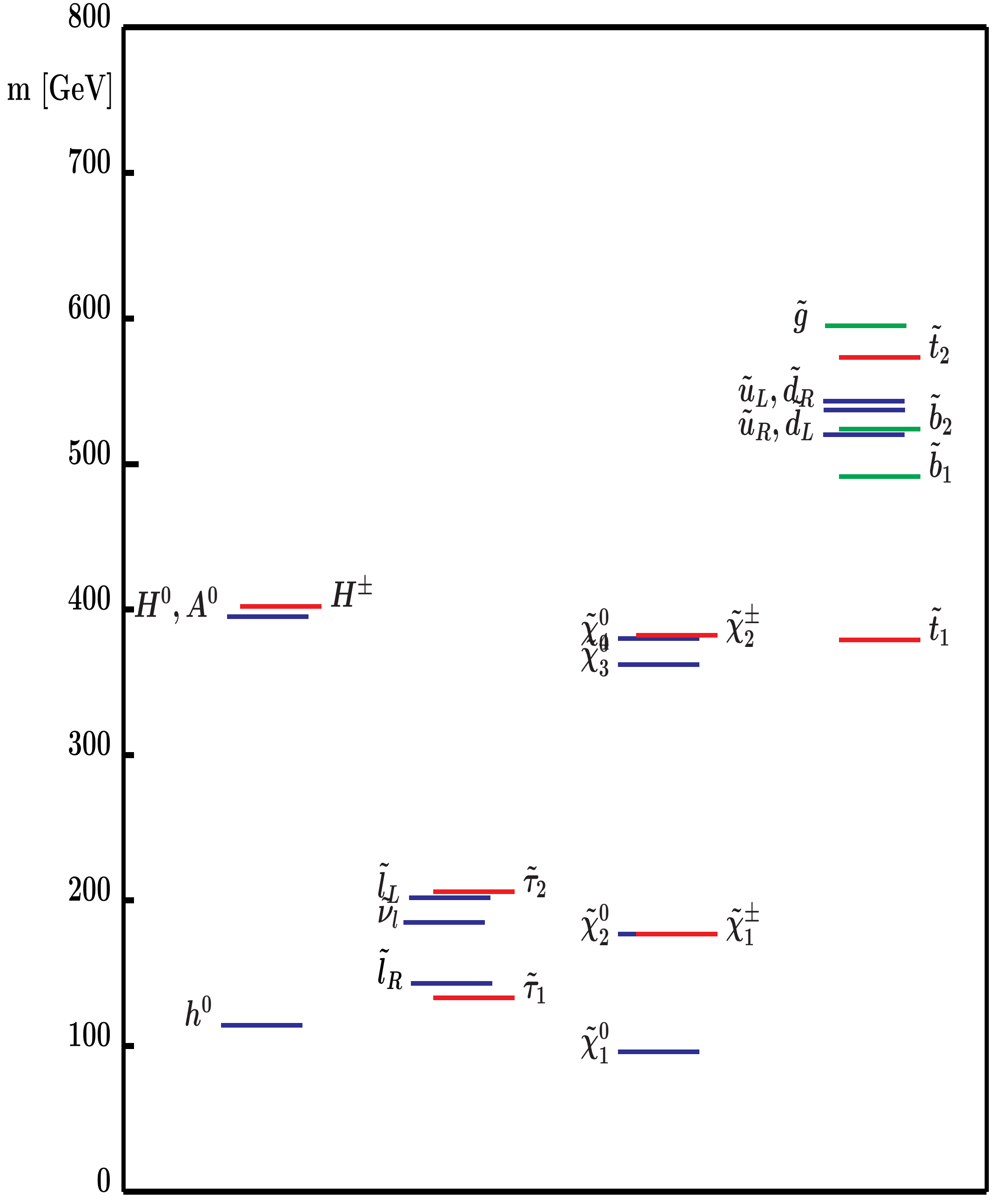
⇒ one parameter turns negative ⇒ Higgs mechanism for free

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

all the sectors



GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A or μ as free parameters at the EW scale

$\Rightarrow$ besides the CMSSM parameters

$$M_A \text{ or } \mu$$

And there is more: 3.) VCMSSM
4.) mSUGRA
5.) NUHM2

. . . no time here . . .

The Higgs sector of the MSSM

Enlarged Higgs sector: Two Higgs doublets

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}
\end{aligned}
$$

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

gauge couplings, in contrast to SM $\Rightarrow m_h \leq M_Z$

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

Input parameters: (to be determined experimentally)

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

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \qquad \tan(2\alpha) = \tan(2\beta)\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}, \qquad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

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:

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

Parameters in MSSM 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

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

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

In lowest order:

$$m_{\mathrm{H}^\pm}^2 = M_A^2 + M_W^2$$

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

$\phi_1 - \phi_2$ basis:

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

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

$$\Bigg\Downarrow \quad \leftarrow \text{ Diagonalization}, \alpha$$

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

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

Measurement of m_h, Higgs couplings

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

The lightest MSSM Higgs boson

MSSM predicts upper bound on M_h:

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

Large radiative corrections:

Yukawa couplings: $\frac{e\, m_t}{2 M_W s_W}, \frac{e\, m_t^2}{M_W s_W}, \ldots$

$\Rightarrow$ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

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

Present status of M_h prediction in the MSSM:

Complete one-loop and 'almost complete' two-loop result available

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 $m_t = 173.2 \pm 0.9\,\text{GeV}$

(including theoretical uncertainties from unknown higher orders)

$\Rightarrow$ observable at the LHC

Obtained with:

FeynHiggs

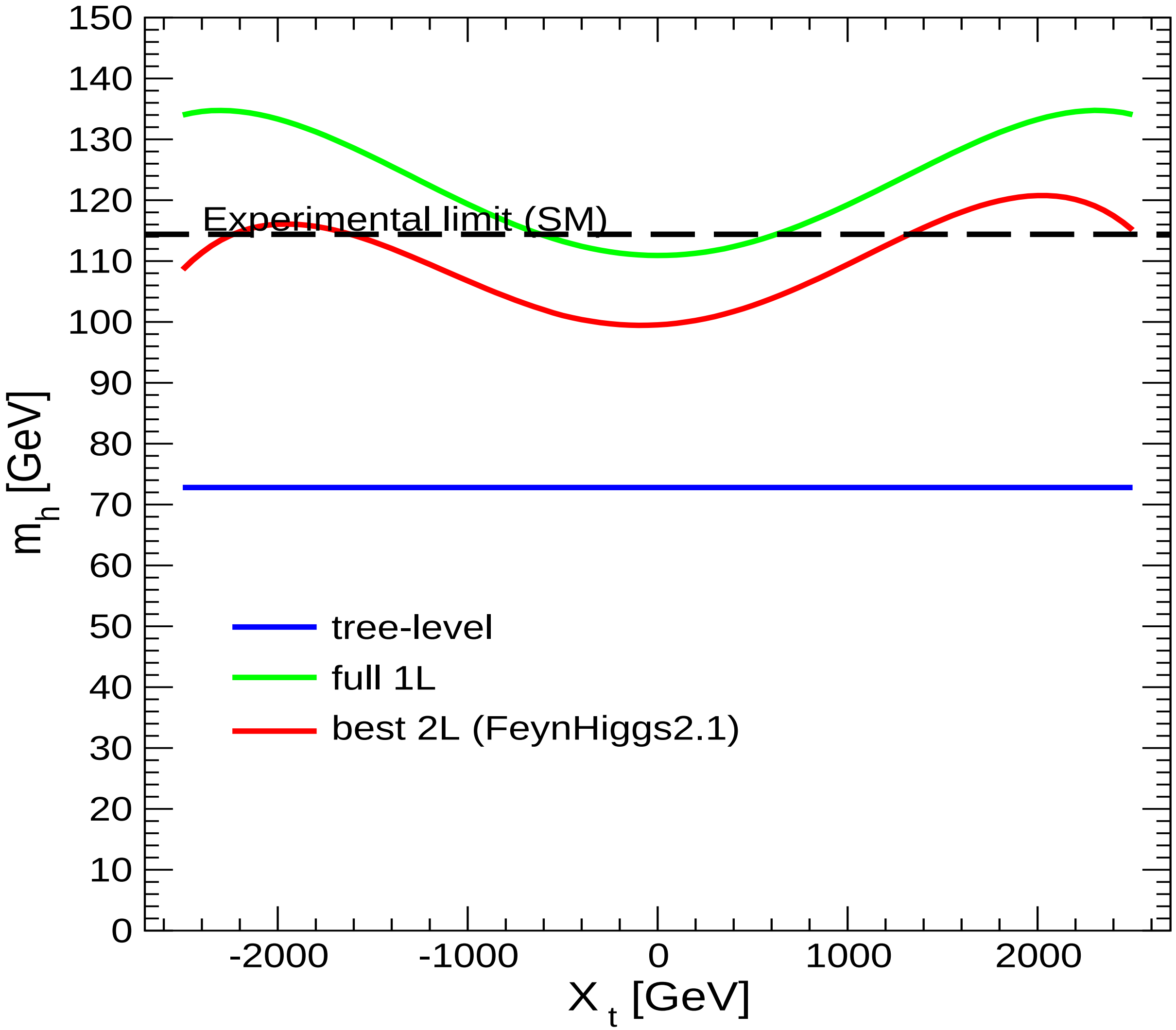
`www.feynhiggs.de`

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein K. Williams '98 – '12*]

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

Effects of the two-loop corrections to the lightest Higgs mass:

Example for one set of MSSM parameters



Comparison with experimental limits

⇒ strong impact on bound on SUSY parameters

Higgs couplings, tree level:

$$g_{hVV} = \sin(\beta - \alpha)\, g_{HVV}^{\text{SM}}, \quad V = W^{\pm}, Z$$

$$g_{HVV} = \cos(\beta - \alpha)\, g_{HVV}^{\text{SM}}$$

$$g_{hAZ} = \cos(\beta - \alpha)\, \frac{g'}{2\cos\theta_W}$$

$$g_{hb\bar{b}}, g_{h\tau^+\tau^-} = -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{\text{SM}}$$

$$g_{ht\bar{t}} = \frac{\cos\alpha}{\sin\beta}\, g_{Ht\bar{t}}^{\text{SM}}$$

$$g_{Ab\bar{b}}, g_{A\tau^+\tau^-} = \gamma_5 \tan\beta\, g_{Hb\bar{b}}^{\text{SM}}$$

$\Rightarrow$ $g_{hVV} \leq g_{HVV}^{\text{SM}}$, g_{hVV}, g_{HVV}, g_{hAZ} cannot all be small

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

The decoupling limit:

For $M_A \gtrsim 150$ GeV:

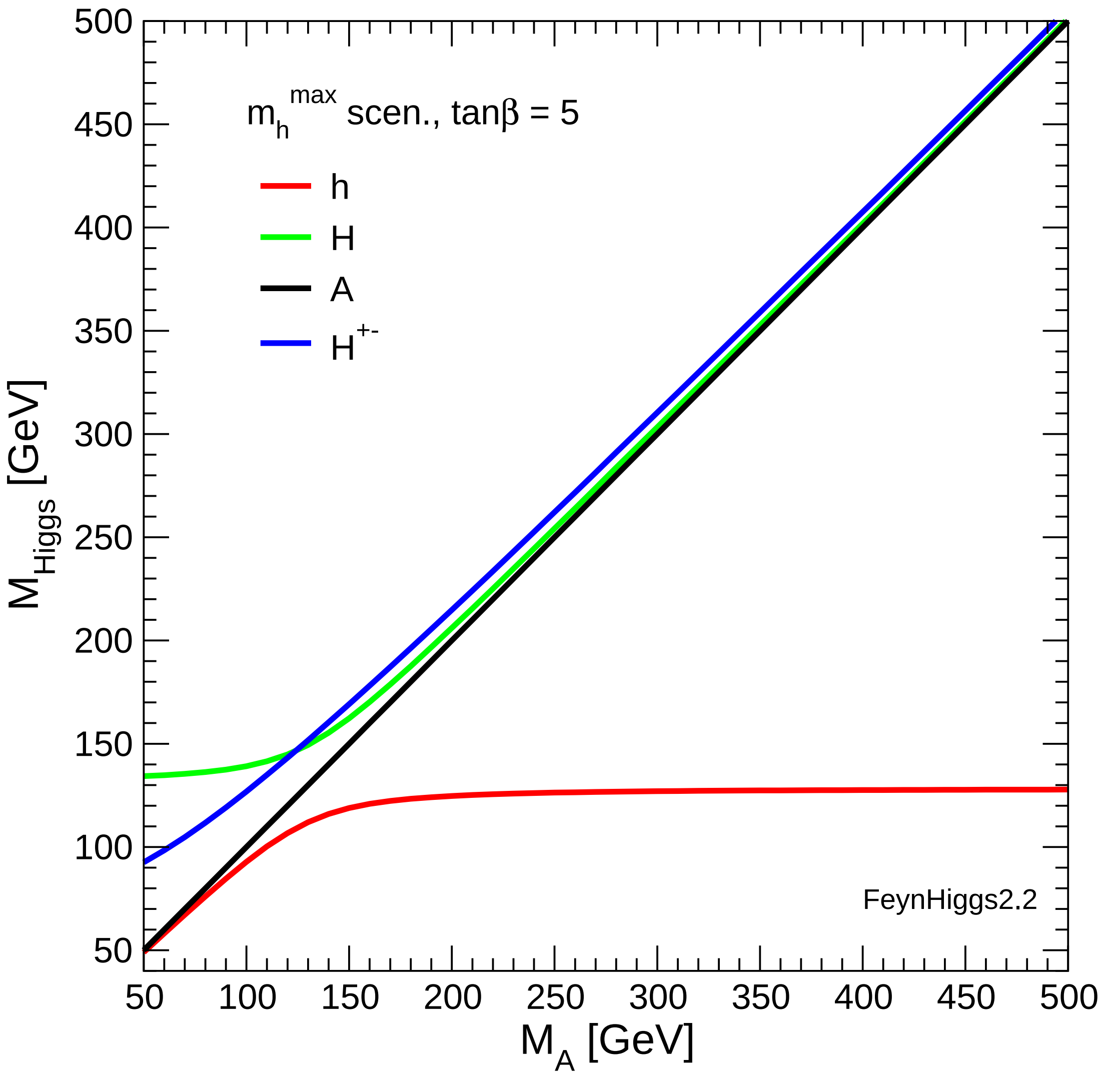
The lightest MSSM Higgs
is SM-like

$\Rightarrow$ SM analysis applies!

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

$\to$ coupling to gauge bosons ~ 0

$\Rightarrow$ no production via $WH, \ldots$



Remaining theoretical uncertainties in prediction for M_h in the MSSM:

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

– From unknown higher-order corrections:
  $\Rightarrow \Delta M_h \approx 3$ GeV

– From uncertainties in input parameters

  $m_t, \ldots, M_A, \tan\beta, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{g}}, \ldots$

  $\Delta m_t \approx 1$ GeV $\Rightarrow \Delta M_h \approx 1$ GeV

Higgs couplings, production cross sections

$\Rightarrow$ also affected by large SUSY loop corrections

Extreme example: $\Gamma(h \to b\bar{b}) \to 0$ via loop corrections possible

MSSM Higgs boson searches at the LHC

Overview about MSSM Higgs boson searches at the LHC:

1. Light MSSM Higgs boson in the decoupling limit:
   $\rightarrow$ SM Higgs searches apply
   $\rightarrow$ keep in mind the upper limit of 135 GeV
   $\Rightarrow$ no limits beyond LEP so far!

2. Light MSSM Higgs boson "before" the decoupling limit:
   $\rightarrow$ dedicated search necessary
   $\rightarrow$ SM-like search with reduced couplings
   $\rightarrow$ $p_0 \oplus \mu$ with reduced $\sigma \times$ BR

3. Hevay MSSM Higgs boson:
   $\rightarrow$ dedicated search
   $\Rightarrow$ model independent results on $\sigma \times$ BR
   $\Rightarrow$ specific MSSM results for H/A

Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

$\rightarrow$ investigate benchmark scenarios:

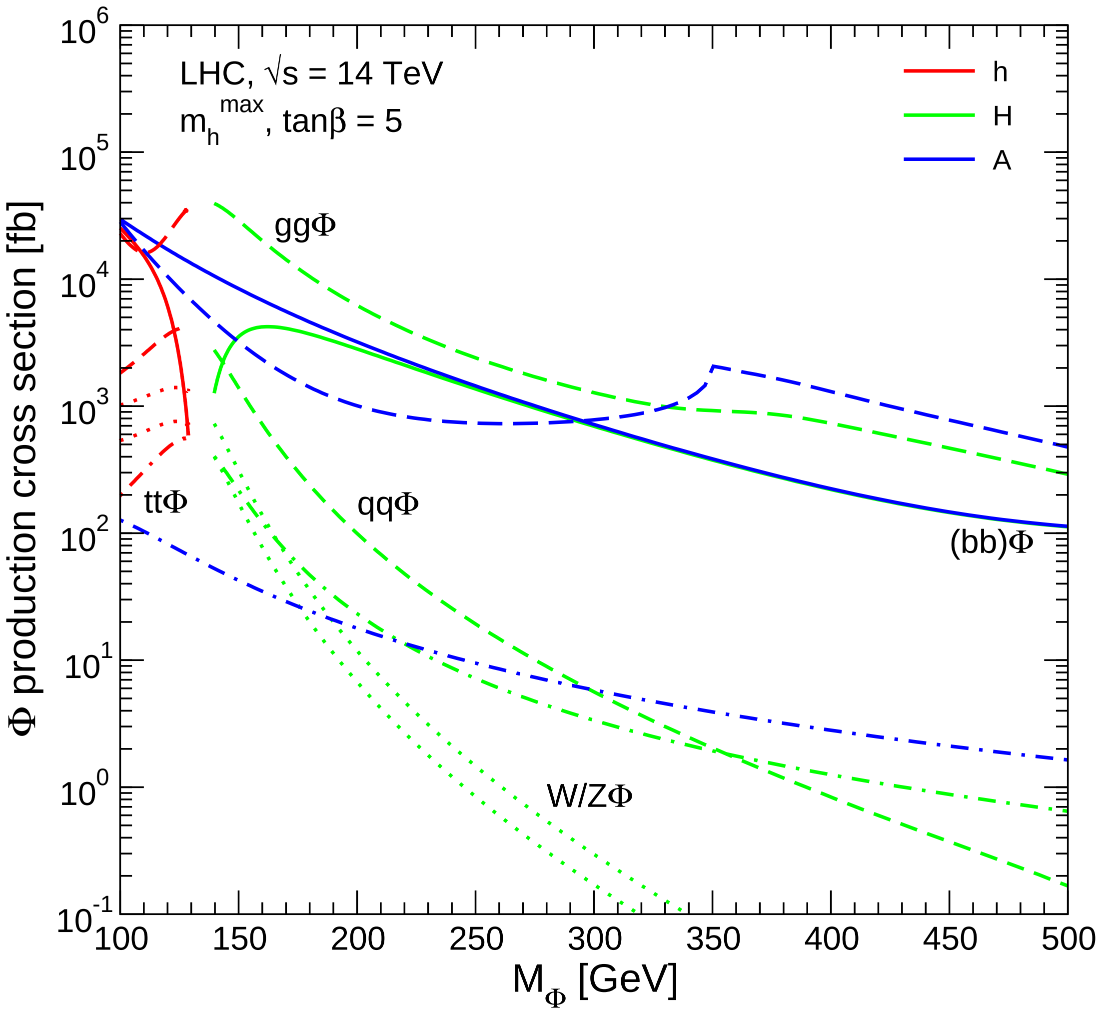
> $\rightarrow$ Vary only M_A and $\tan\beta$
> $\rightarrow$ Keep all other SUSY parameters fixed

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

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

Overview about SUSY Higgs production cross sections ($\phi = h, H, A$)

[*Tev4LHC Higgs working group report '06*]



gluon fusion: $gg \to \phi$

weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'\phi$

top quark associated production: $gg, q\bar{q} \to t\bar{t}\phi$

weak boson associated production: $q\bar{q}' \to W\phi, Z\phi$

NEW: $b\bar{b}\phi$

Search for the lightest MSSM Higgs at the LHC:

$\Rightarrow$ full parameter accessible   But there might be problems . . .

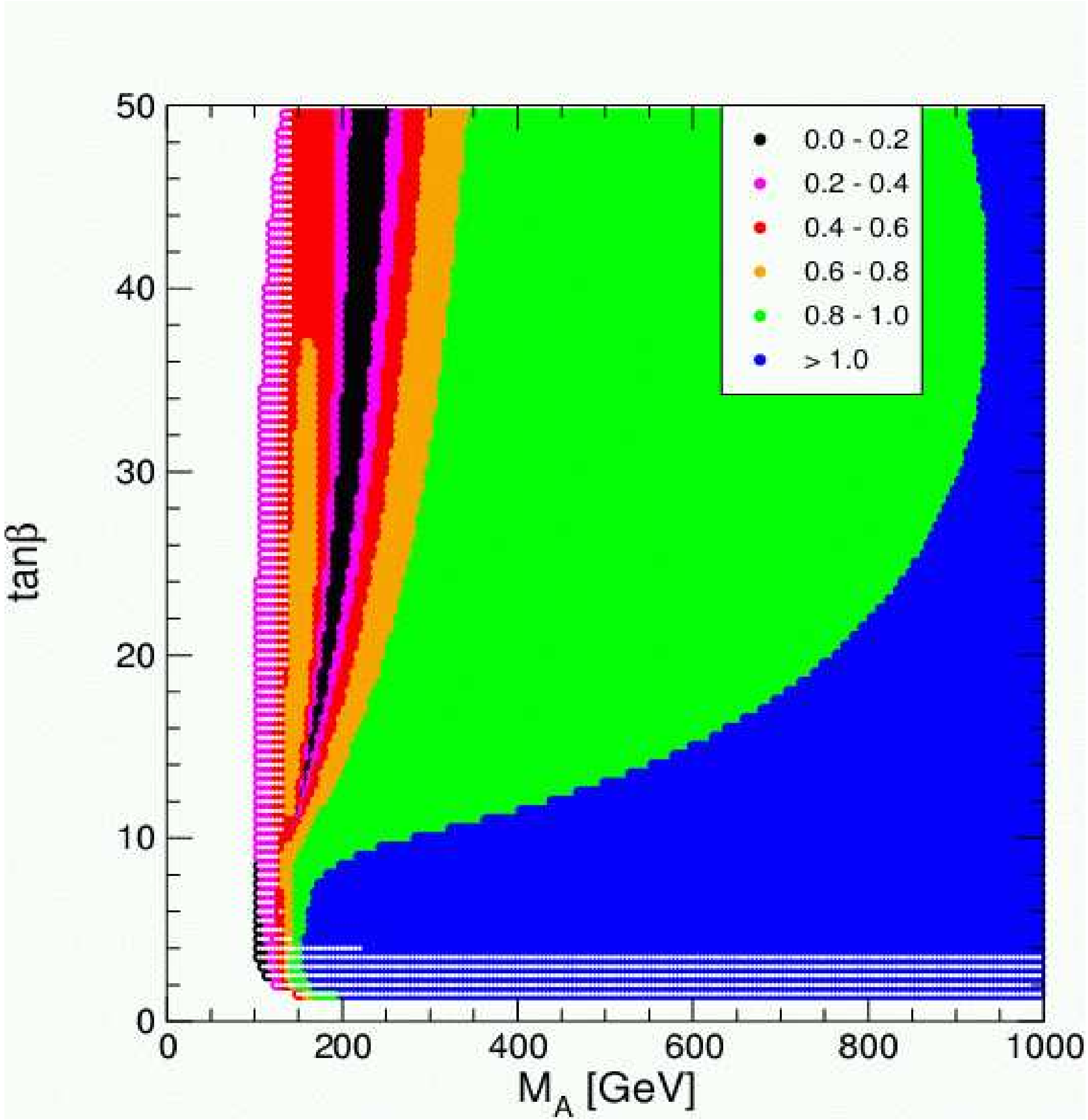
Possible problem in SUSY:

$$h \to b\bar{b}$$

can be strongly suppressed

→ "Small α_{eff} scenario"

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



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

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

Possible problem in SUSY:

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

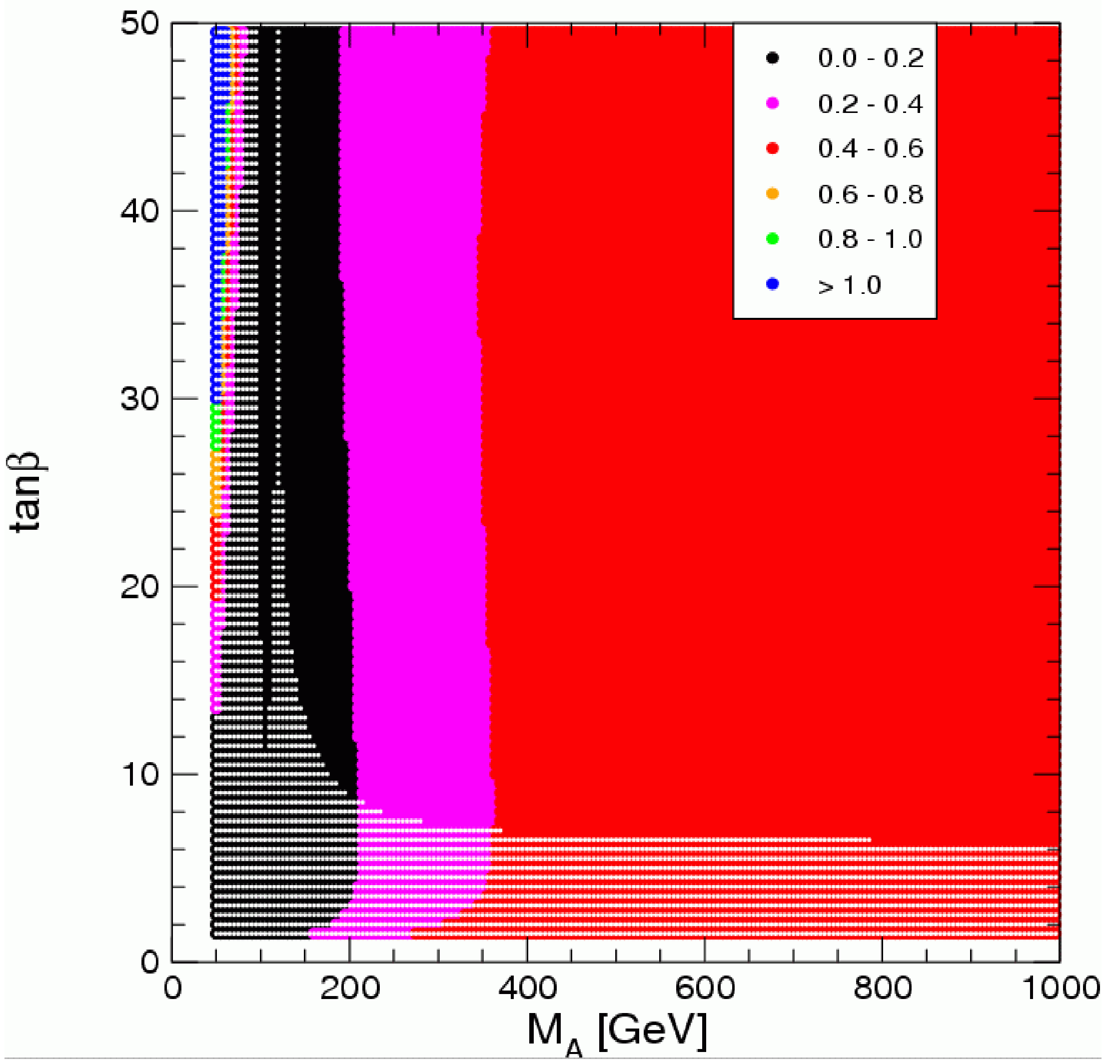
can be strongly suppressed

$\to$ "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

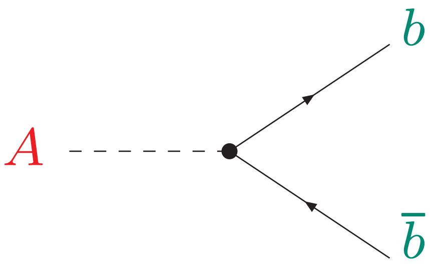
(not realized in CMSSM, GMSB, AMSB, ...)



The heavy MSSM Higgs bosons

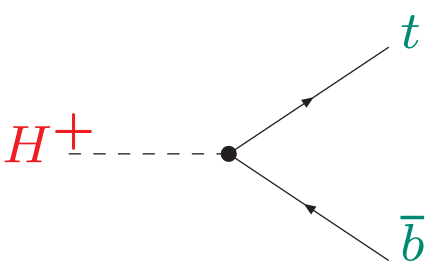
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



$$y_b \quad \to \quad y_b \, \frac{\tan\beta}{1+\Delta_b}$$

At large $\tan\beta$: either $H \approx A$ or $h \approx A$



$$y_b \, \frac{\tan\beta}{1+\Delta_b}$$

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

$\Rightarrow$ other parameters enter $\Rightarrow$ strong μ dependence

Most powerful LHC search modes for heavy MSSM Higgs bosons:

$$
\begin{array}{l}
b\bar{b} \to H/A \to \tau^+\tau^- + X \\
gb \to tH^\pm + X,\ \ H^\pm \to \tau\nu_\tau \\
pp \to t\bar{t} \to H^\pm + X,\ \ H^\pm \to \tau\nu_\tau
\end{array}
$$

Enhancement factors compared to the SM case:

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

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

$\Rightarrow$ Δ_b effects (often neglected by ATLAS/CMS analyses)

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

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

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

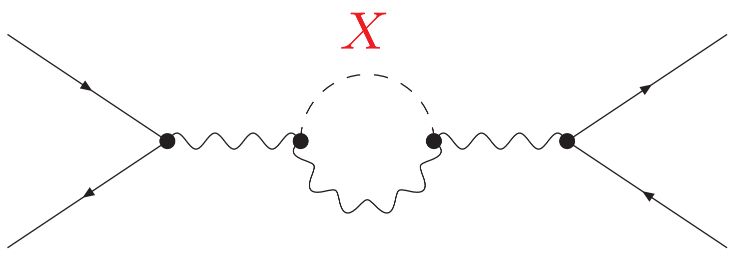
Electroweak Precision observables in the MSSM

Comparison of precision observables with theory:

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

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections



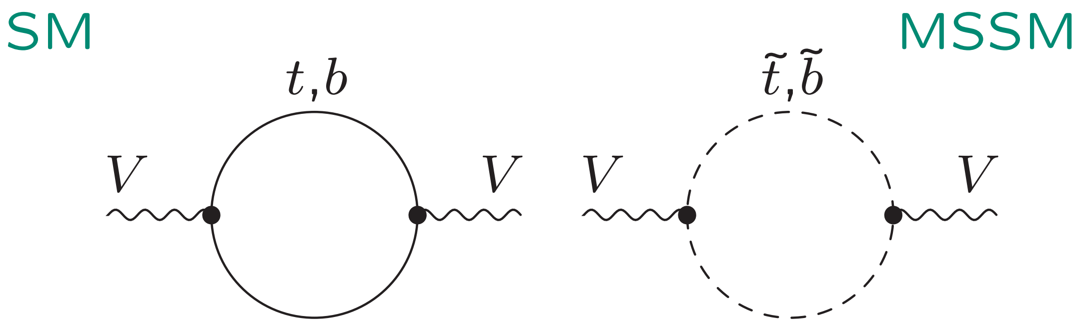
$\Downarrow$

$\Rightarrow$ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed

Differences between the MSSM and the SM:

1.) New contributions from SUSY particles:



2.) CPV effects via new complex phases

3.) large Yukawa corrections: $\sim m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

4.) large corrections from the $b/\tilde{b}$ sector for large $\tan\beta$

5.) non-decoupling SUSY effects: $\sim \log \frac{M_{\text{SUSY}}}{M_W}$

Corrections to M_W, $\sin^2\theta_{\rm eff}$ → approximation via the ρ-parameter:

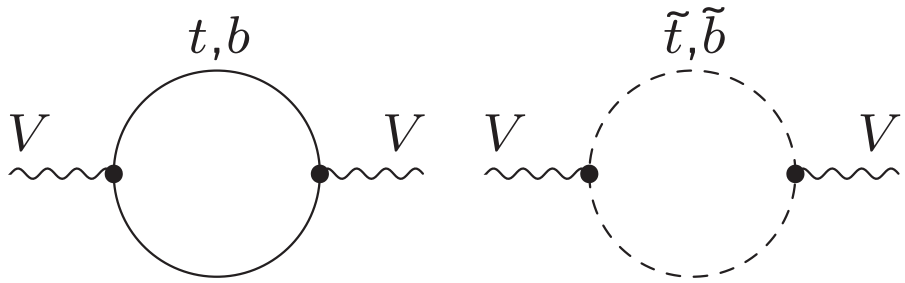
ρ measures the relative strength between
neutral current interaction and charged current interaction

$$\rho = \frac{1}{1 - \Delta\rho} \qquad \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

(leading, process independent terms)

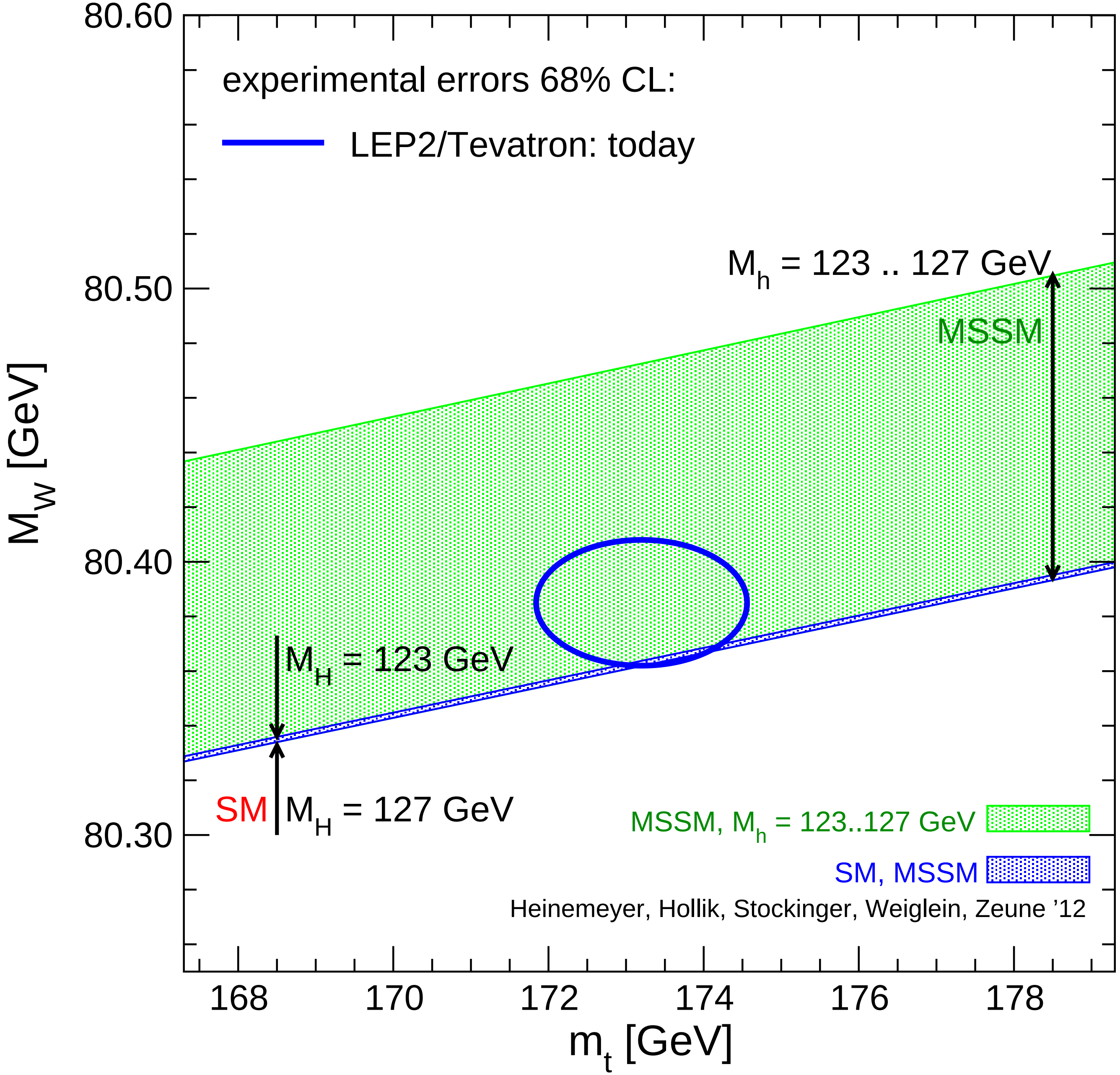
$\Delta\rho$ gives the main contribution to EW observables:

$$\Delta M_W \approx \frac{M_W}{2} \frac{c_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2} \Delta\rho, \qquad \Delta \sin^2\theta_W^{\rm eff} \approx -\frac{c_{\rm W}^2 s_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2} \Delta\rho$$



$\Delta\rho^{\rm SUSY}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\quad\Rightarrow M_W^{\rm SUSY} \gtrsim M_W^{\rm SM}$

The most beautiful example:



Remeber the anomalous magnetic moment of the muon:

$$a_\mu(\text{Exp-SM}) = \left\{ \begin{array}{ll} [\text{HMNT '06}] & 28(8) \\ [\text{DEHZ '06}] & 28(8) \\ [\text{FJ '07}] & 29(9) \\ [\text{MRR '07}] & 29(9) \\ [\text{DH '10}] & 28.7(8.0) \end{array} \right\} \times 10^{-10}$$

better agreement between evaluations, more precise,

larger deviation from exp than ever before

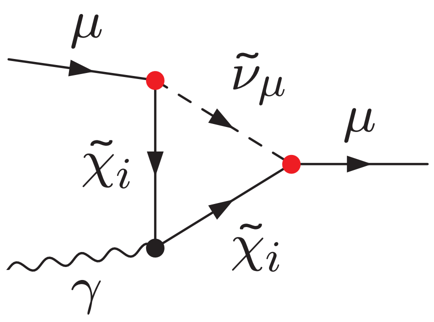
$\Downarrow$

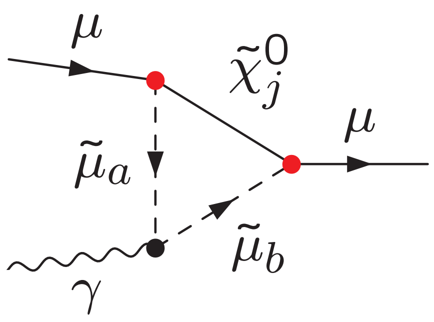
3σ deviation has now been definitely established

(based on e^+e^- data)

SUSY can easily explain the deviation:

Feynman diagrams for MSSM 1L corrections:





– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}_i^\pm - \tilde{\nu}_\mu \quad : \quad \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a \quad : \quad \sim m_\mu \tan\beta$$

SM, EW 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$

MSSM, 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan\beta$

SUSY corrections at 1L:

$$a_\mu^{\text{SUSY,1L}} \approx 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2 \tan\beta \, \text{sign}(\mu)$$

$M_{\text{SUSY}}(= m_{\tilde{\mu}} = m_{\tilde{\nu}} = m_{\tilde{\chi}})$: generic SUSY mass scale

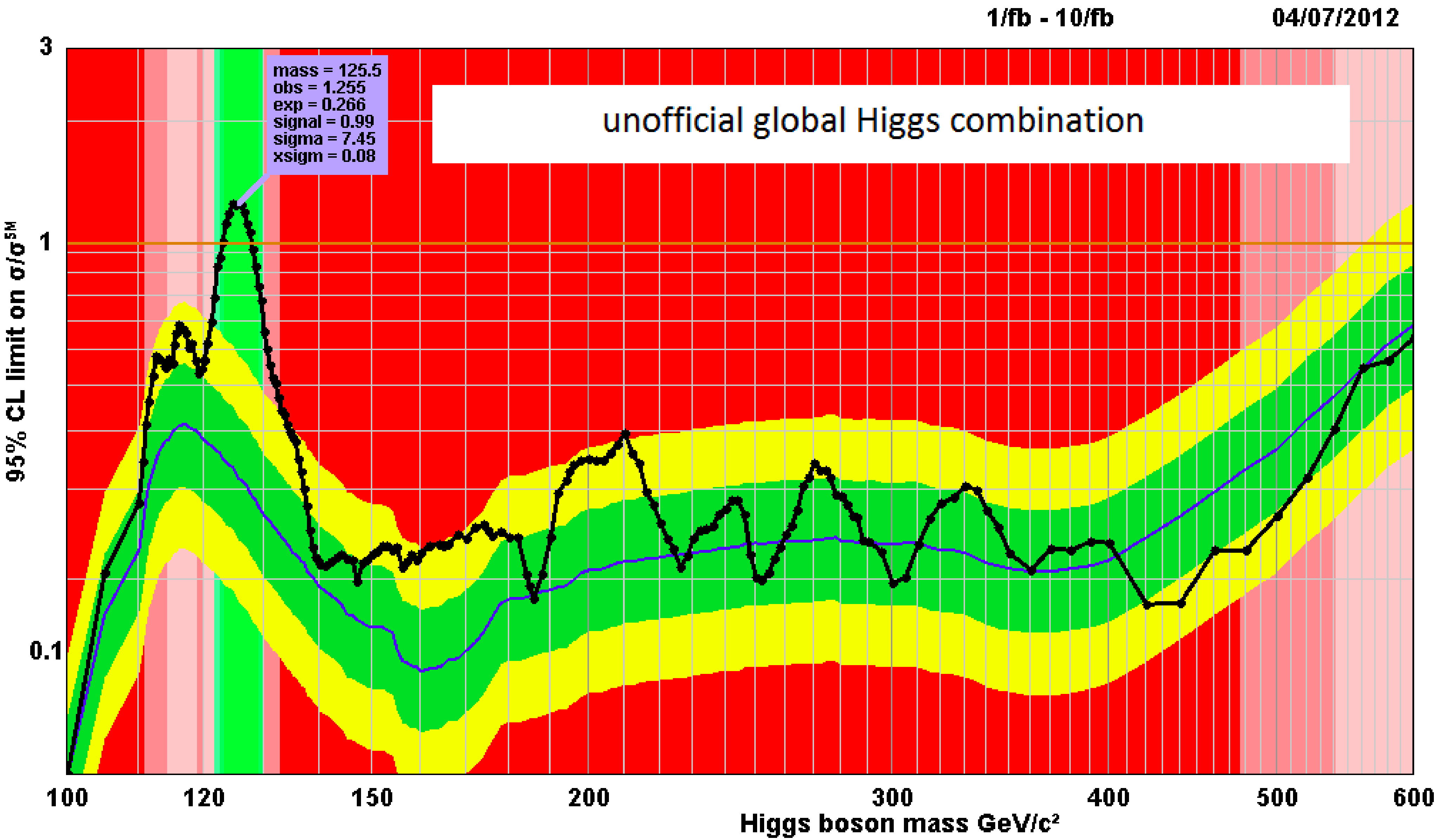
$$\begin{aligned} a_\mu^{\text{SUSY,1L}} &= (-100 \ldots +100) \times 10^{-10} \\ a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} &\approx (28 \pm 8) \times 10^{-10} \end{aligned}$$

⇒ SUSY could easily explain the "discrepancy"

⇒ a_μ can provide bounds on SUSY parameter space
(by requiering agreement at the 95% C.L.)

⇒ limits on M_h

Comparison to “the discovery” [vixra.org]



Implications of Higgs searches for SUSY

The latest results on ATLAS/CMS Higgs searches were presented on 13.12.2011 before 4pm

On 14.12.2011 about 6 articles appeared on the arXiv, analyzing the implications

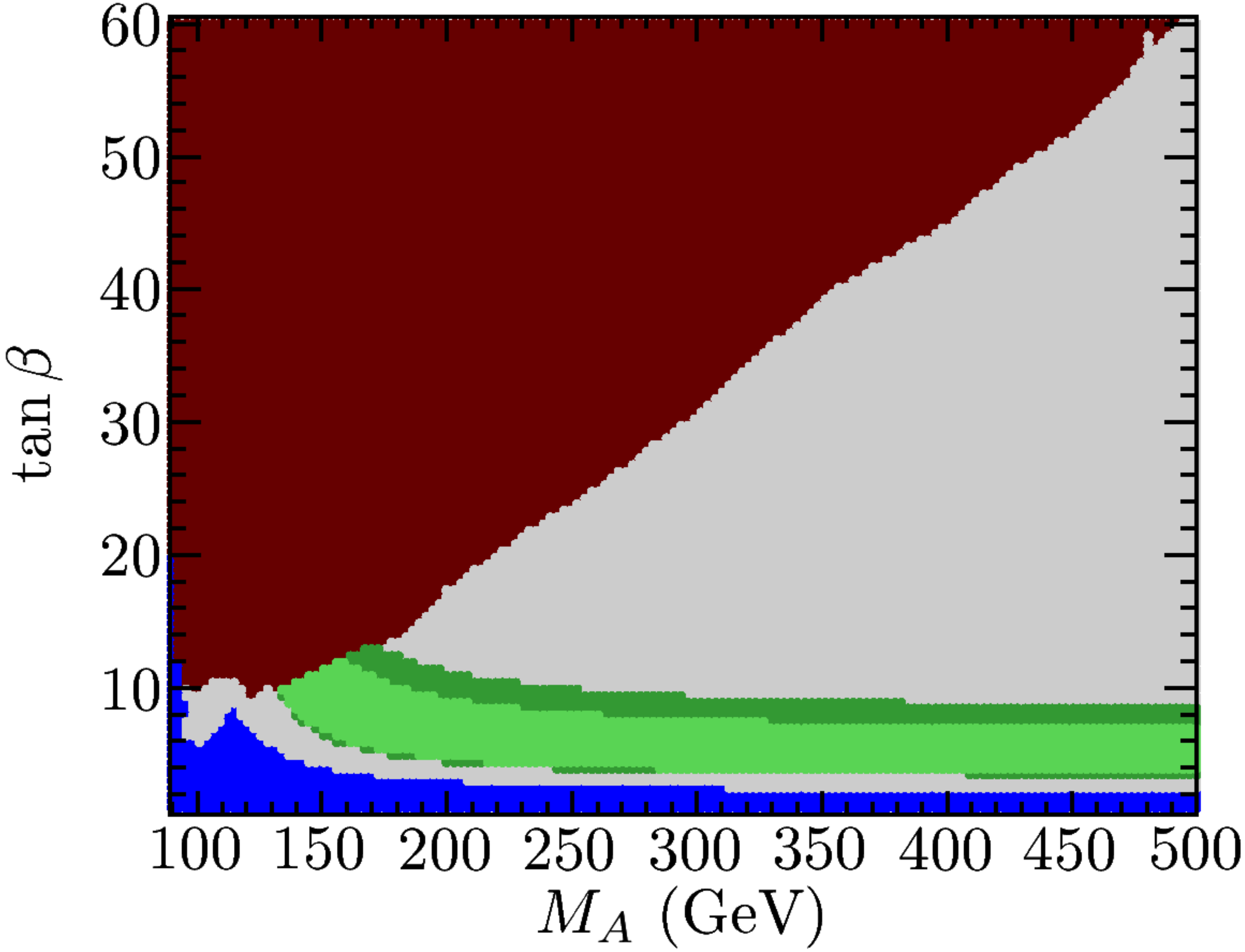
Most of them analyzed them in the framework of SUSY

Here a few results from one randomly picked article:
[*arXiv:1112.3026 [hep-ph] (S.H., O. Stal, G. Weiglein)*]

$$M_h = 125 \pm 1(\text{exp.}) \pm 2(\text{theo.})\ \text{GeV}$$

First idea: new lower bounds on M_A and $\tan\beta$ [*S.H., O. Stal, G. Weiglein '11*]

⇒ maximize all contributions: m_h^{max} scenario



⇒ green are allowed by Higgs "excess"

First idea: new lower bounds on M_A and $\tan\beta$ [S.H., O. Stal, G. Weiglein '11]

	Limits without $M_h = 125$			Limits with $M_h = 125$		
M_{SUSY}	$\tan\beta$	M_A	$M_{H^\pm}$	$\tan\beta$	M_A	$M_{H^\pm}$
500	2.7	94.5	123	4.5	139	159
1000	2.2	94.5	123	3.2	133	155
2000	2.0	94.5	123	2.9	130	152

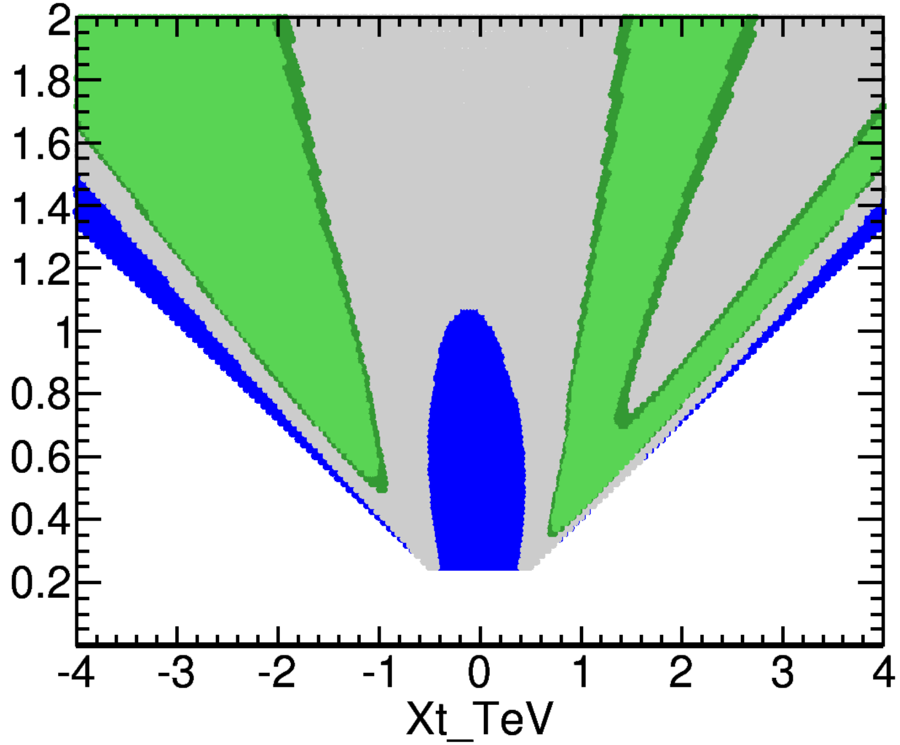
$\Rightarrow$ new conservative limits obtained!

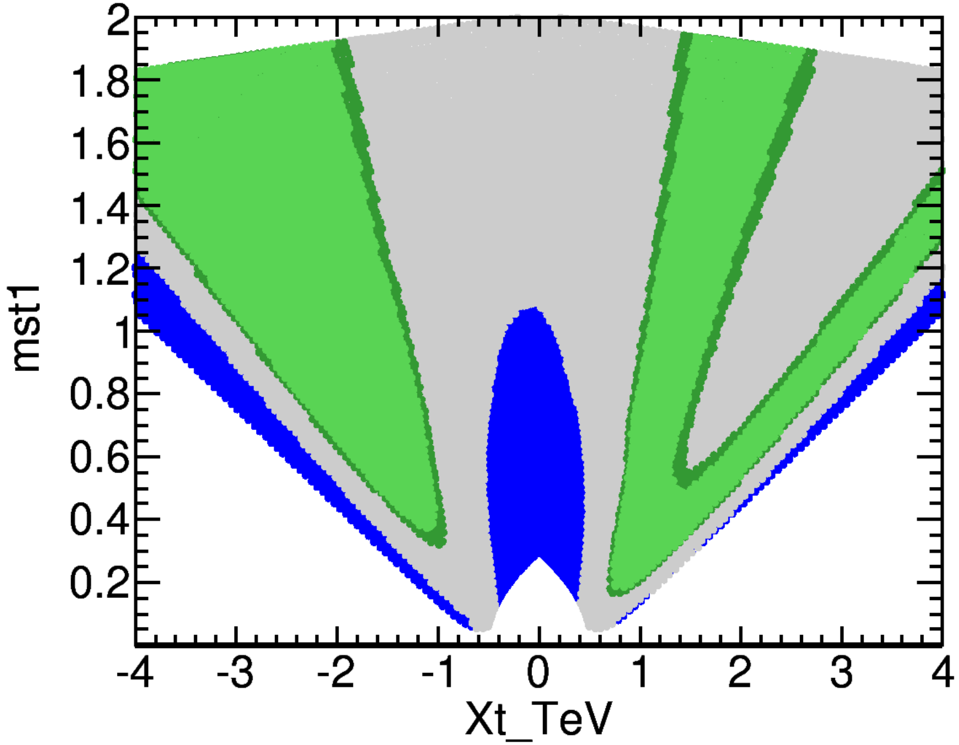
$\Rightarrow$ only small margin left for $t \to H^+ b$

Limits on stop masses:

[S.H., O. Stal, G. Weigleip '11]

m_h^{max} scenario:





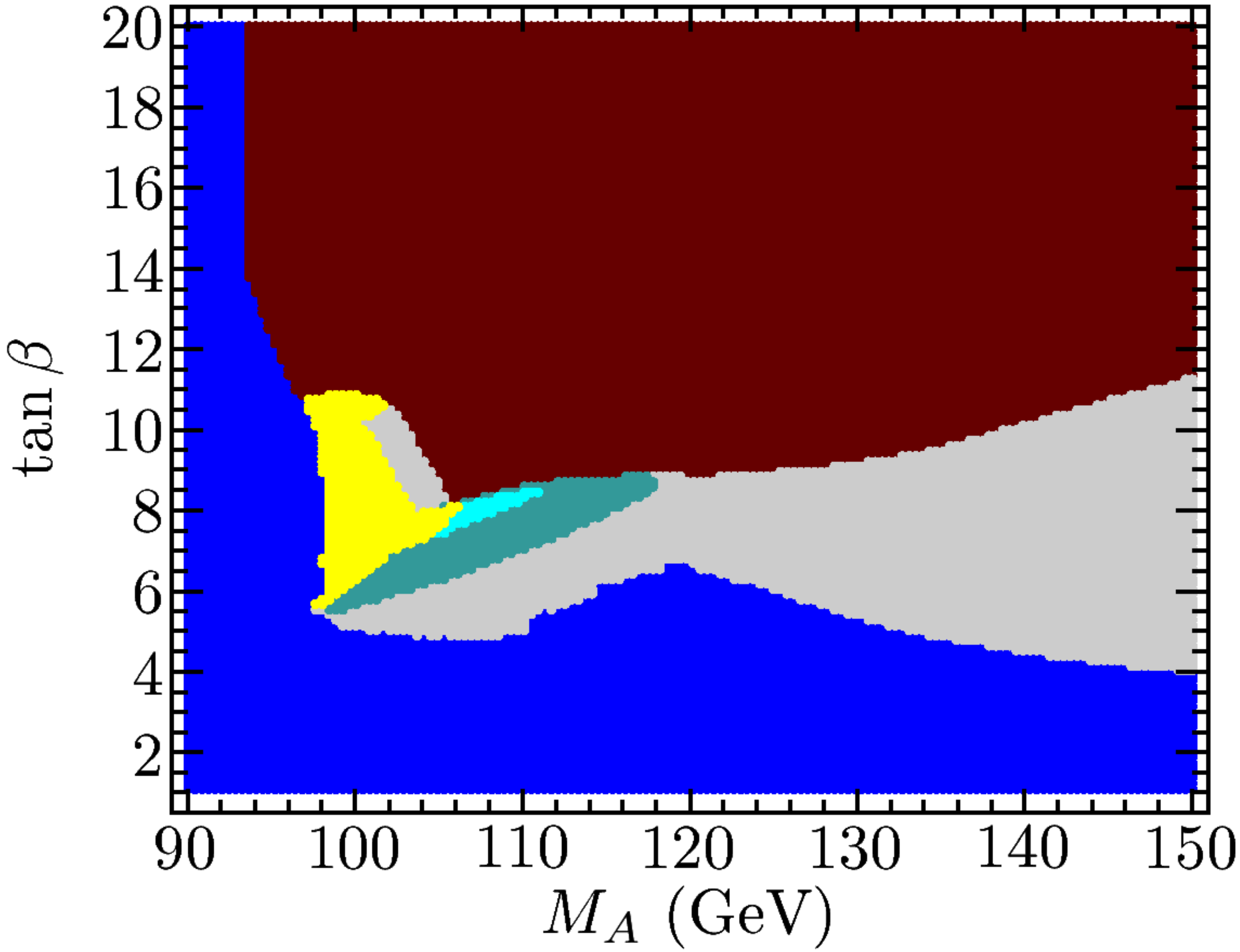
$\Rightarrow$ green are allowed by Higgs "excess"

$m_{\tilde{t}_1} \gtrsim 150$ GeV $(X_t > 0)$

$m_{\tilde{t}_1} \gtrsim 300$ GeV $(X_t < 0)$ (preferred by BR$(b \to s\gamma)$)

A "heavy" SUSY Higgs at 125 GeV? [S.H., O. Stal, G. Weiglein '11]

$M_{\text{SUSY}} = \mu = 1$ TeV, $X_t = 2.3$ TeV, all Higgs limits taken into account:



Possible: $M_h = 98$ GeV, $M_H = 125$ GeV, . . .

Implications of Higgs searches for SUSY

The latest results on ATLAS/CMS Higgs searches were presented on 04.07.2012 before 11am

On 05.07.2011 about 3 articles appeared on the arXiv, analyzing the implications

Most of them analyzed them in the framework of SUSY

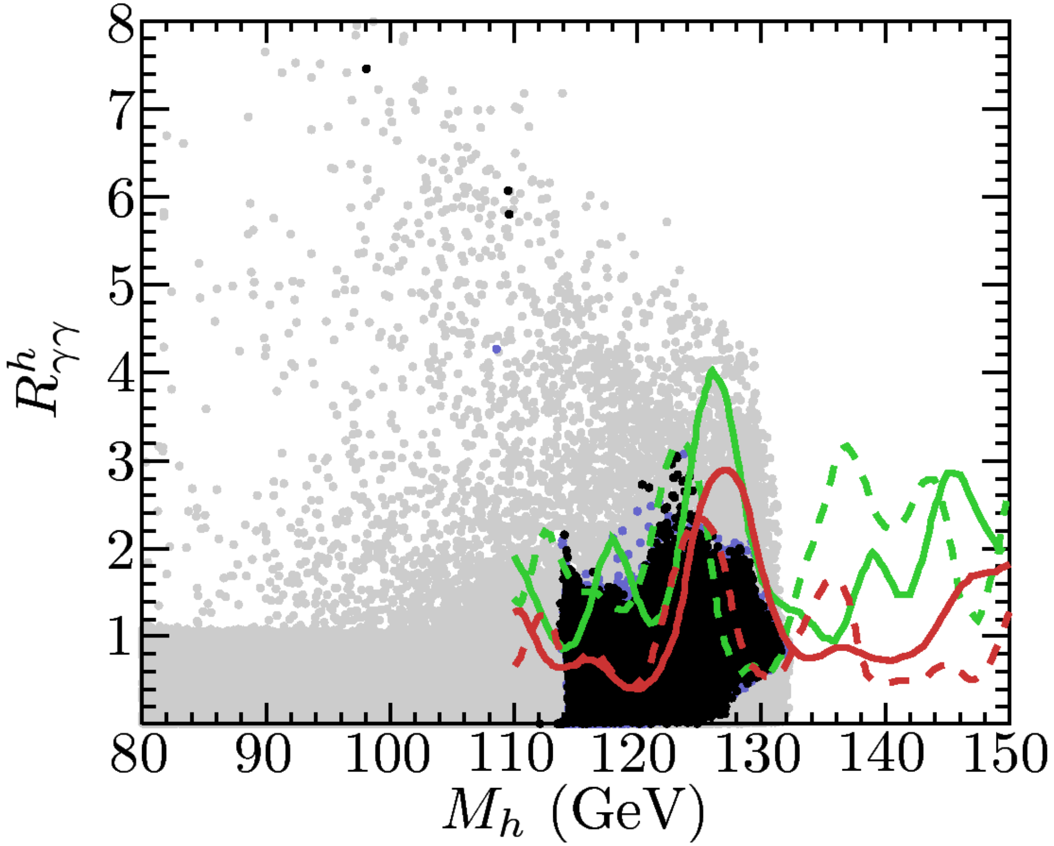
Here a few results from one randomly picked article:
[arXiv:1207.1096 [hep-ph]
(R. Benbrik, M. Gomez Bock, S.H., O. Stal, G. Weiglein, L. Zeune)]

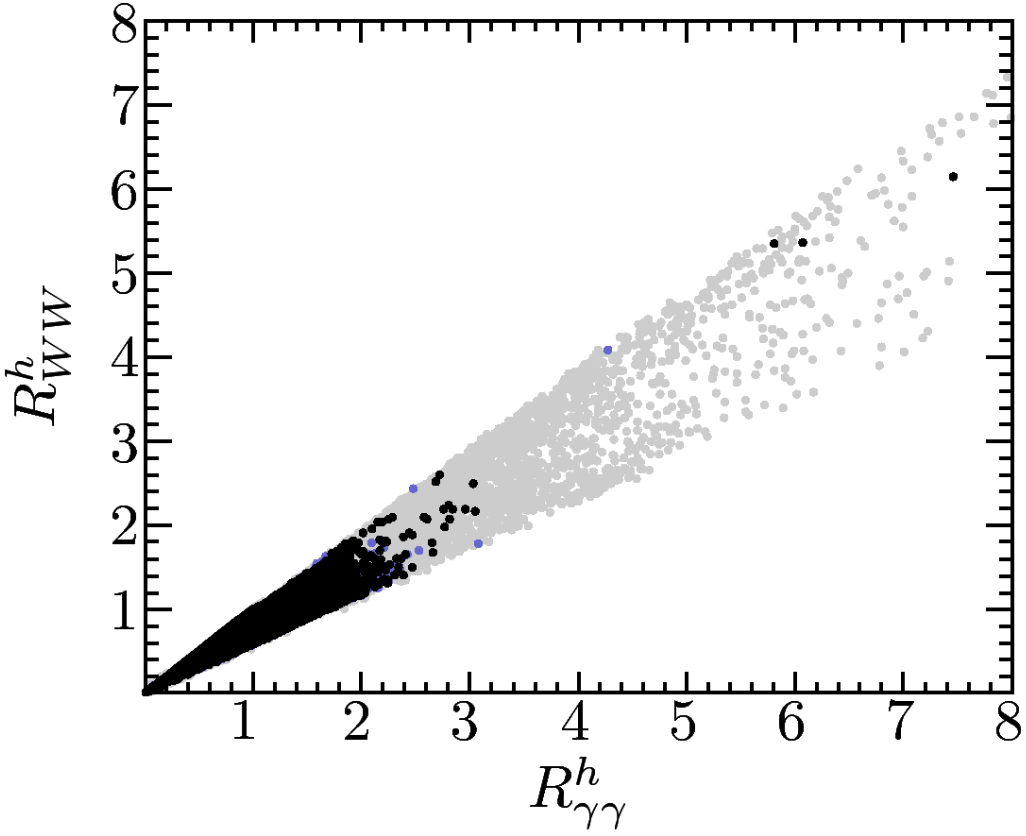
$$M_h = 125 \pm 1(\text{exp.}) \pm 2(\text{theo.})\ \text{GeV}$$

Possible MSSM interpretation:

[*R. Benbrik, M. Gomez Bock, S.H., O. Stal, G. Weiglein, L. Zeune '12*]

Scan over the MSSM parameter space:

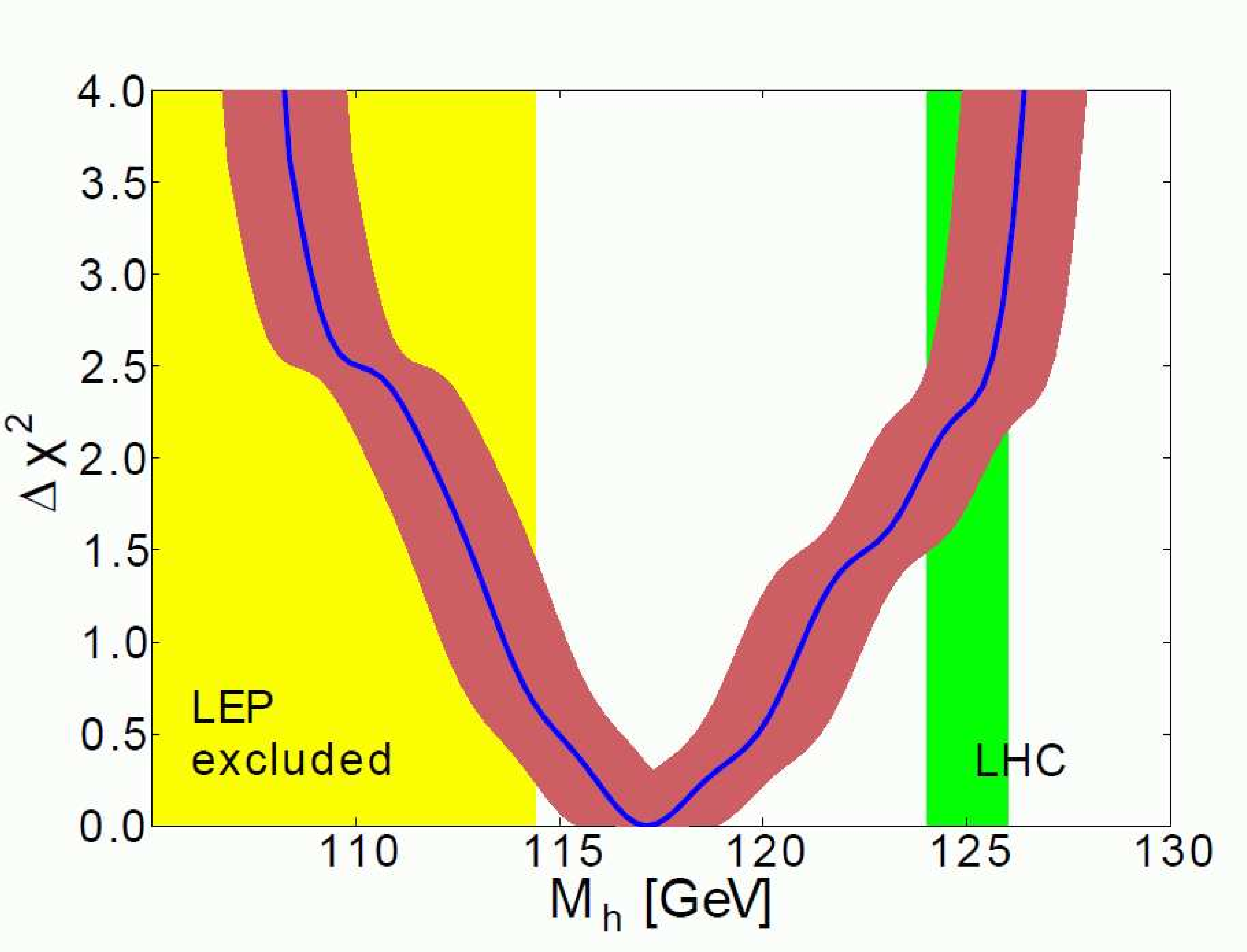




$\Rightarrow$ enhanced $\gamma\gamma$ rate, suppressed WW, $b\bar{b}$ rate possible!

CMSSM: post-LHC (5+5 fb^{-1}) red band plot:

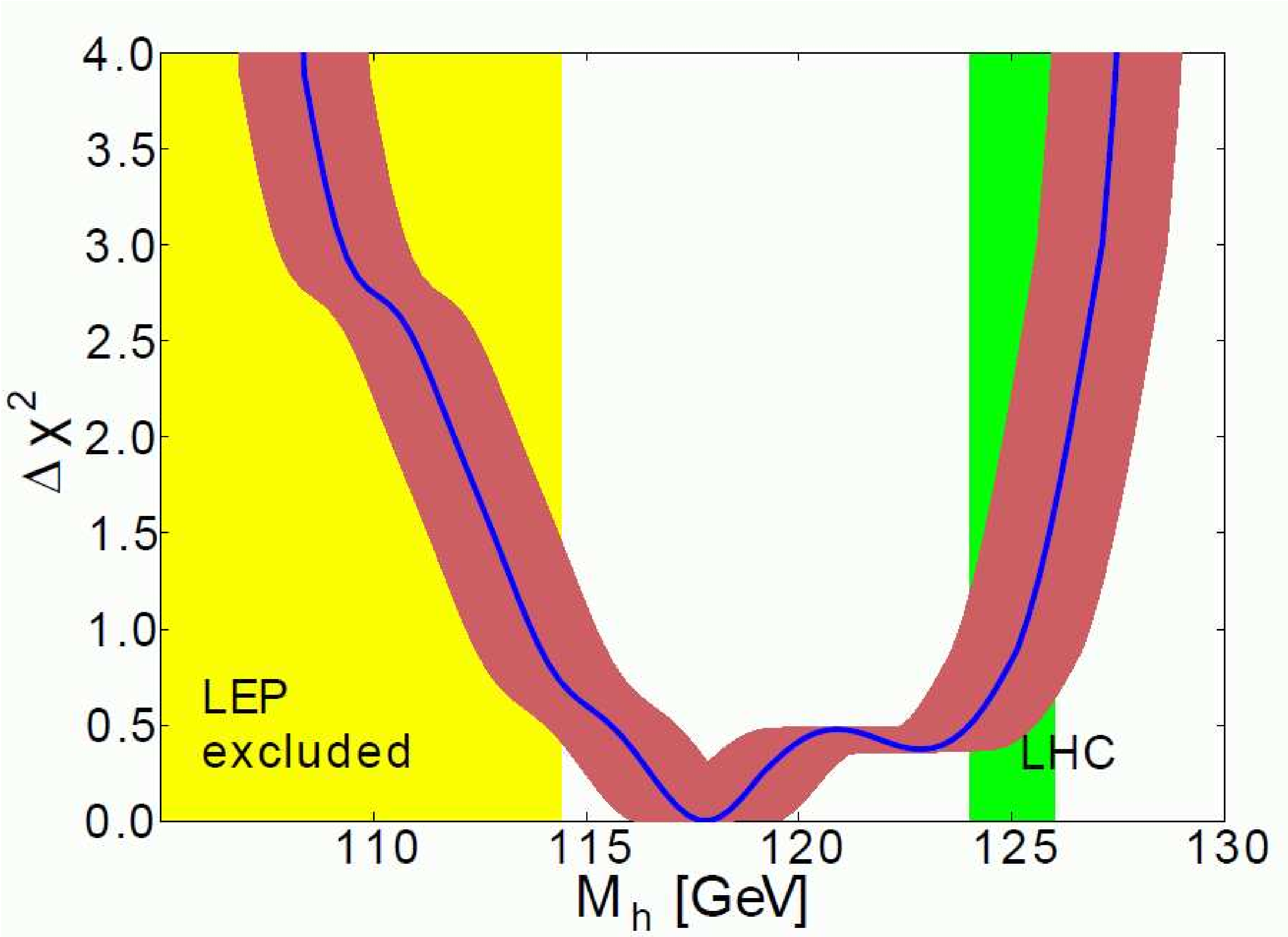
[2012]



$M_h = 117 \pm 4\,(\text{exp}) \pm 1.5(\text{theo})$ GeV $\Delta\chi^2(M_h = 125 \text{ GeV}) \lesssim 2$

NUHM1: post-LHC (5+5 fb^{-1}) red band plot:

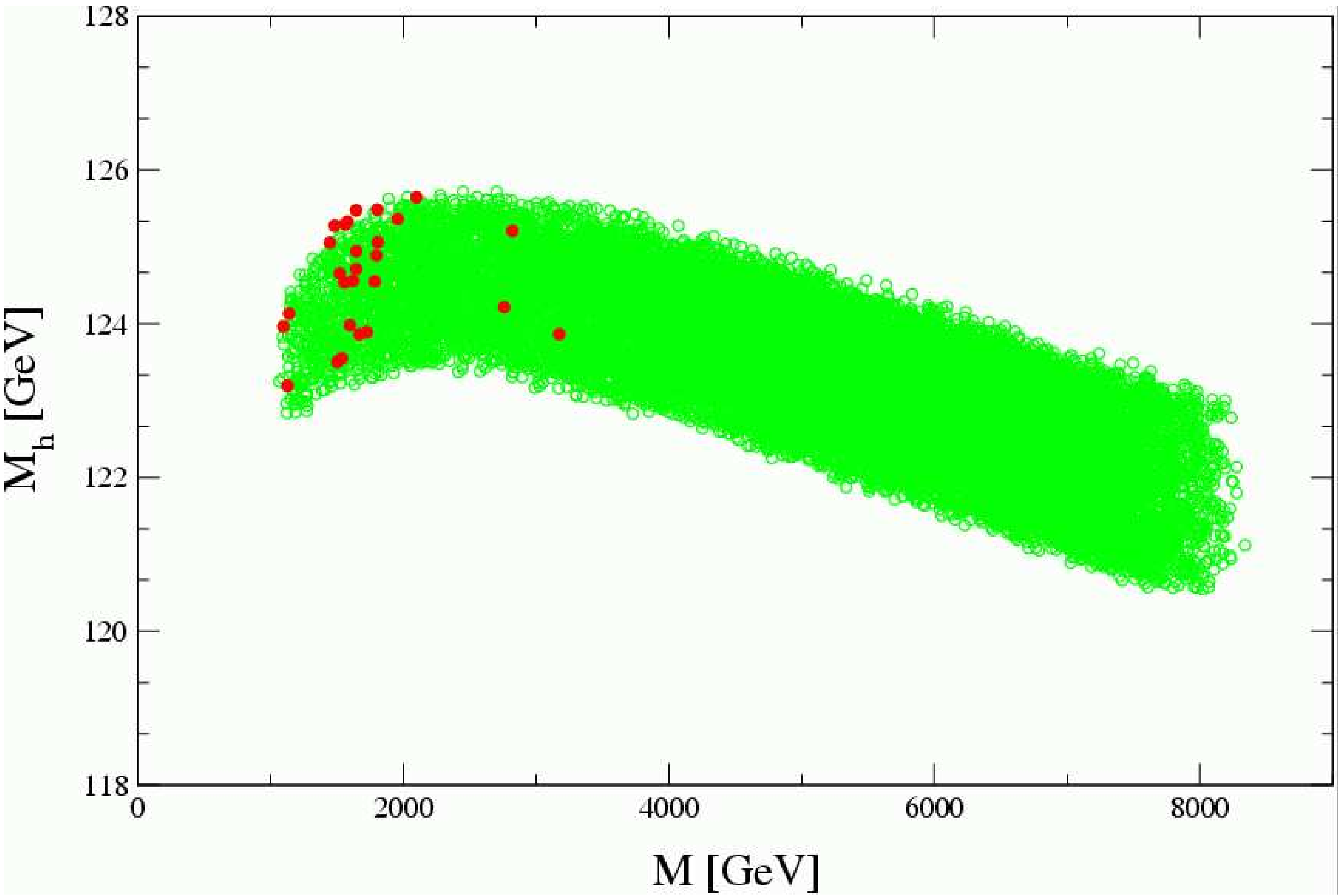
[2012]



$M_h \approx 118^{+7}_{-4}$ (exp) $\pm\, 1.5$(theo) GeV $\quad \Delta\chi^2(M_h = 125 \text{ GeV}) \approx 0.5$

Randomly picked analysis: Finite Unified MSSM prediction (2008)

[*S.H., M. Mondragon, G. Zoupanos '08*]



green: consistent with B physics constraints

red: agreement with (loose) CDM bound

$\Rightarrow$ 120 GeV $\leq M_h \leq$ 126 GeV (no theory error incl. yet)

Summary

- The Standard Model (SM) of particle physics: rock-solid foundation
  - Higgs sector works well
  - Clear and precise predictions, depending only on M_H
  - Precision observables predict a light Higgs boson

- Interesting alternative: Supersymmetry

  → Minimal Supersymmetric Standard Model (MSSM)
  (Dark Matter candidate: $\tilde{\chi}_1^0$, coupling constant unification, . . .)
  - extended Higgs sector, $M_h \lesssim 135$ GeV
  - decoupling limit: lightest Higgs boson is SM-like
  - Precision observables potentially better (M_W, $(g-2)_\mu$, . . .)

- Higgs searches at the LHC: we have a **DISCOVERY !!! :-)**

  ⇒ compatible with $M_H \simeq 125$ GeV

- SM interpretation: fits well
  MSSM interpretation: fits equally well – or even better?

  ⇒ slowly approaching coupling determination


Higgs Days at Santander 2012
Theory meets Experiment
17.-21. September
MultiDark
IFCA
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
CPAN
Ingenio 2010
contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays12