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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:

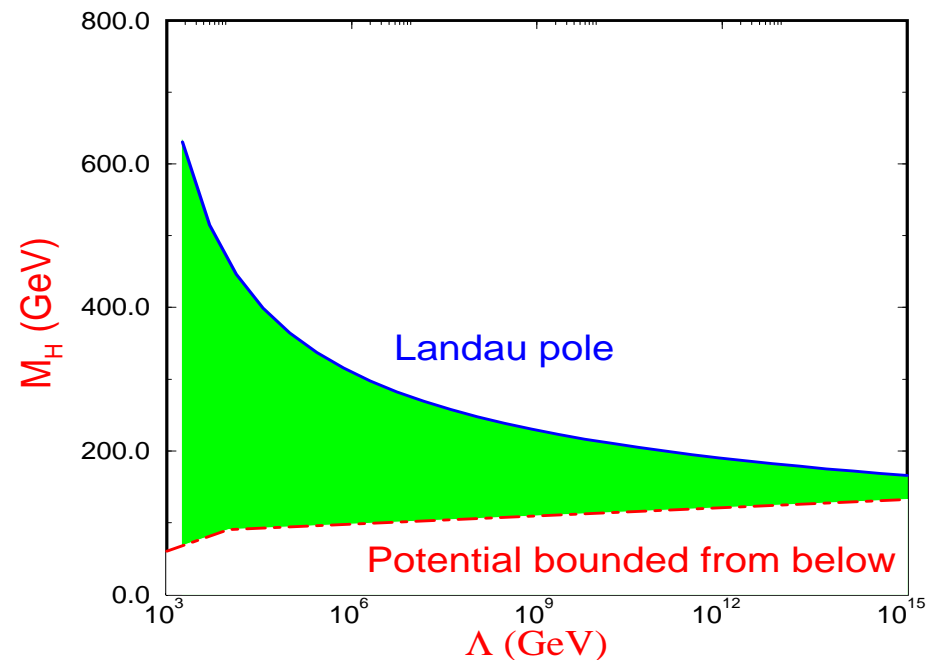
The Standard Model (SM) cannot be the ultimate theory

- 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?

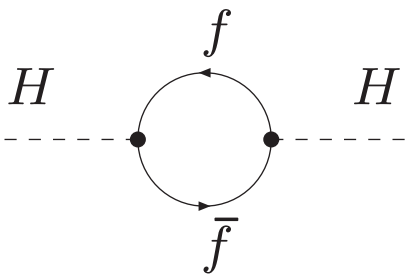
- $\Lambda < M_{\text{Pl}}$: inclusion of gravity effects necessary
- stability of Higgs potential:
- **Hierarchy problem** :
Higgs mass unstable w.r.t. quantum corrections
 $\delta M_H^2 \sim \Lambda^2$

\Rightarrow



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

Free propagation: $\text{---} \overset{H}{\text{---}} \text{---}$ 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:

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

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

\Rightarrow quadratically divergent!

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

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

(for $M_H \lesssim 1 \text{ TeV}$)

- no additional symmetry for $M_H = 0$
- no protection against large corrections

⇒ 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): $\delta M_H^2 \approx M_{\text{GUT}}^2$

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

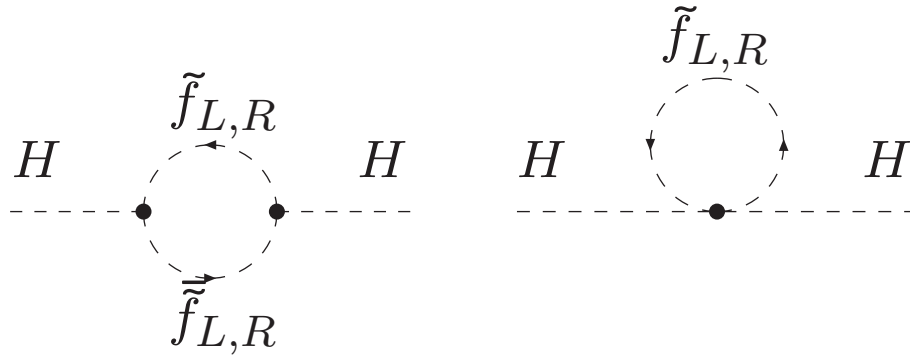
Supersymmetry:

Symmetry between fermions and bosons

$$\begin{aligned} Q|\text{boson}\rangle &= |\text{fermion}\rangle \\ Q|\text{fermion}\rangle &= |\text{boson}\rangle \end{aligned}$$

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

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 $\Lambda \rightarrow \infty$: $\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}} \lambda_{\tilde{f}}^2 \Lambda^2$

⇒ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} = N_f$$
$$\lambda_{\tilde{f}}^2 = \lambda_f^2$$

complete correction vanishes if furthermore

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

Soft SUSY breaking: $m_{\tilde{f}}^2 = m_f^2 + \Delta^2, \quad \lambda_{\tilde{f}}^2 = \lambda_f^2$

$$\Rightarrow \Sigma_H^{f+\tilde{f}} \sim N_f \lambda_f^2 \Delta^2 + \dots$$

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

⇒ realized if mass scale of SUSY partners

$$M_{\text{SUSY}} \lesssim 1 \text{ TeV}$$

⇒ 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

$$\begin{aligned} & \text{Bosons} \leftrightarrow \text{Fermions} \\ Q \text{ } | \text{Fermion} \rangle & \rightarrow | \text{Boson} \rangle \\ Q \text{ } | \text{Boson} \rangle & \rightarrow | \text{Fermion} \rangle \end{aligned}$$

Simplified examples:

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

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

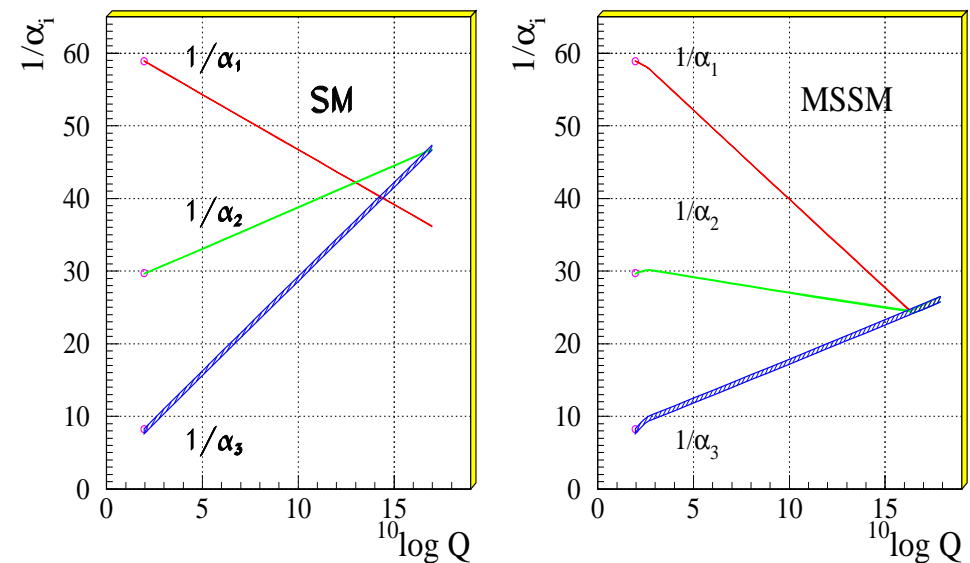
Supersymmetry: Motivation

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.) ...

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



[Amaldi, de Boer, Fürstenauf '92]

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\begin{array}{llll} [u, d, c, s, t, b]_{L,R} & [e, \mu, \tau]_{L,R} & [\nu_{e,\mu,\tau}]_L & \text{Spin } \frac{1}{2} \\ [\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R} & [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} & [\tilde{\nu}_{e,\mu,\tau}]_L & \text{Spin } 0 \\ g & \underbrace{W^\pm, H^\pm} & \underbrace{\gamma, Z, H_1^0, H_2^0} & \text{Spin } 1 / \text{Spin } 0 \\ \tilde{g} & \tilde{\chi}_{1,2}^\pm & \tilde{\chi}_{1,2,3,4}^0 & \text{Spin } \frac{1}{2} \end{array}$$

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

⇒ 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

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

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

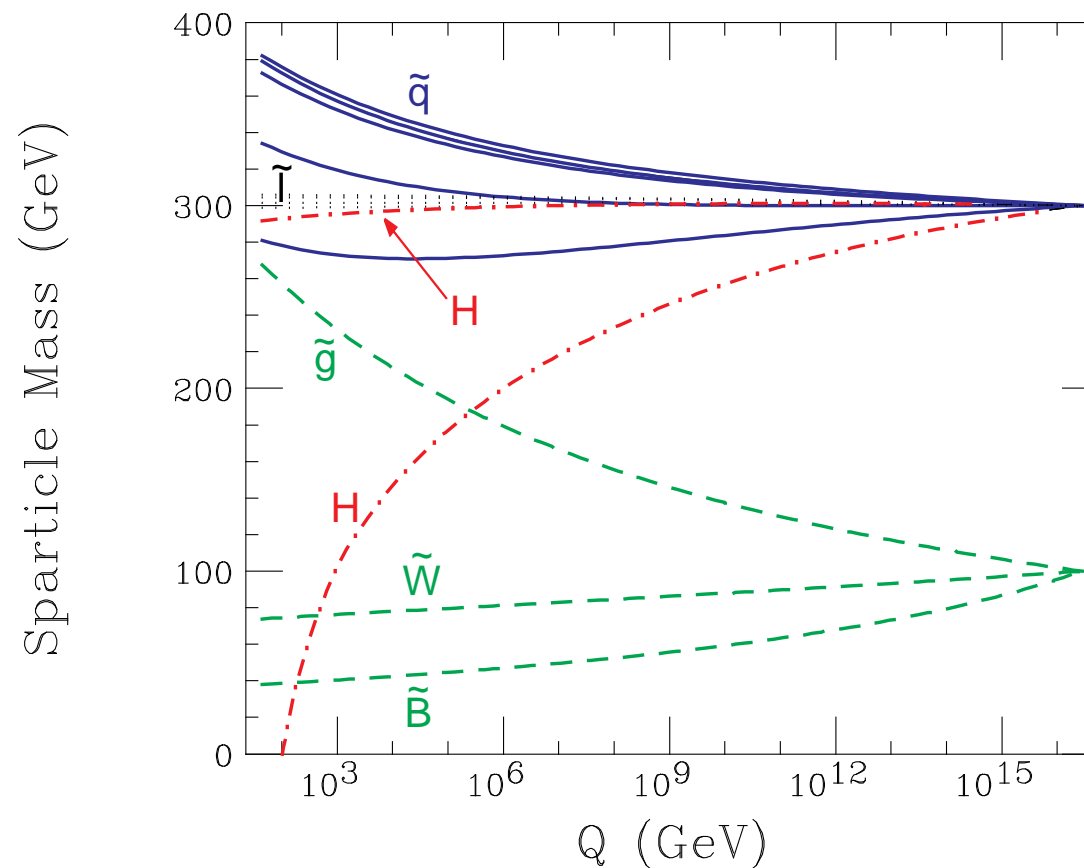
} at the GUT scale

⇒ 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

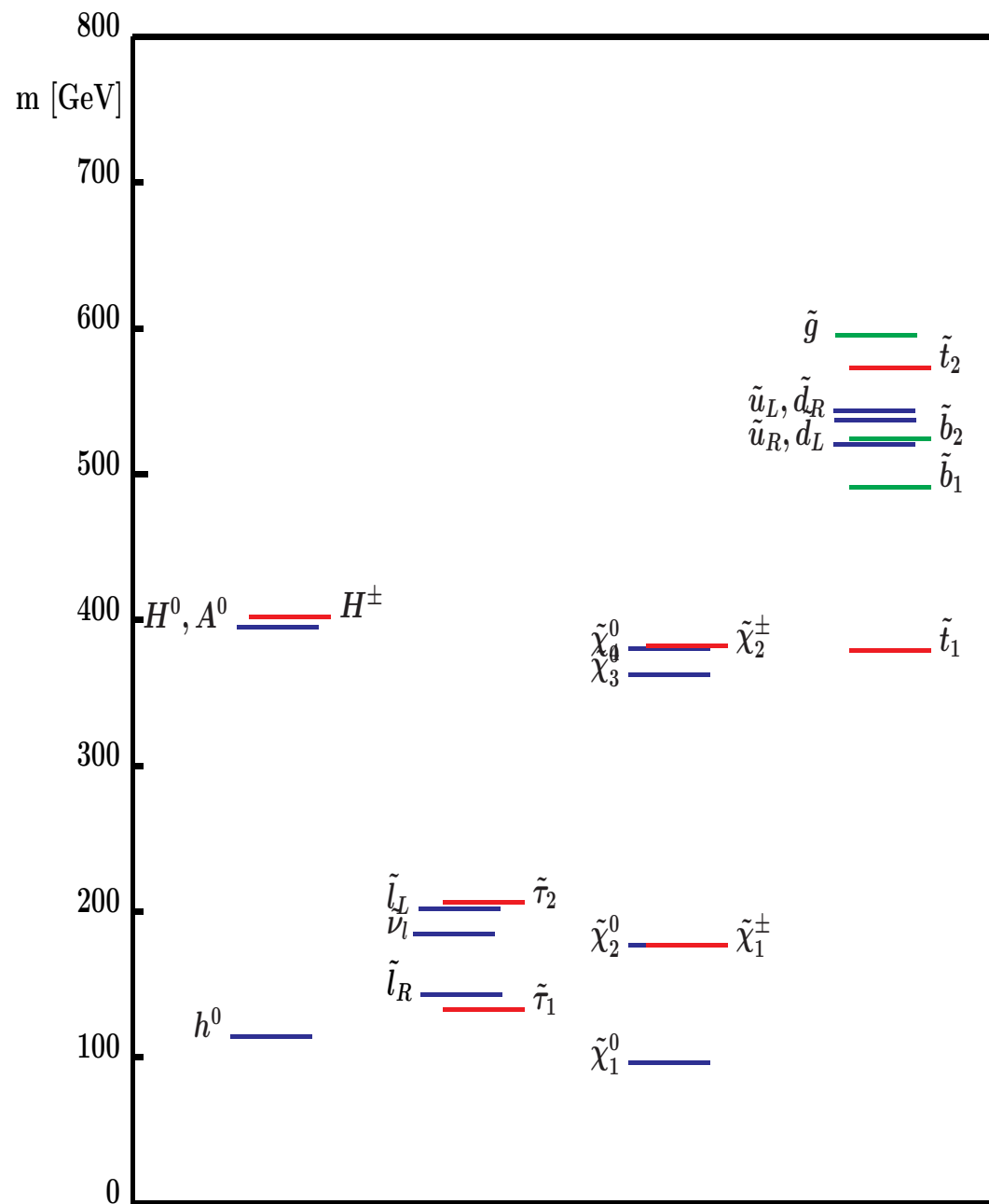
$$M_0 = 300 \text{ GeV}, M_{1/2} = 100 \text{ GeV}, A_0 = 0$$



⇒ 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

⇒ effectively M_A or μ as free parameters at the EW scale

⇒ besides the CMSSM parameters

M_A or μ

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

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

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

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

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

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)

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

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

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

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

→ longitudinal components of W^\pm, Z

⇒ 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

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

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

In lowest order:

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

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

$\phi_1 - \phi_2$ basis:

$$M_{\text{Higgs}}^{2,\text{tree}} = \begin{pmatrix} m_{\phi_1}^2 & m_{\phi_1\phi_2}^2 \\ m_{\phi_1\phi_2}^2 & m_{\phi_2}^2 \end{pmatrix} =$$
$$\begin{pmatrix} M_A^2 \sin^2 \beta + M_Z^2 \cos^2 \beta & -(M_A^2 + M_Z^2) \sin \beta \cos \beta \\ -(M_A^2 + M_Z^2) \sin \beta \cos \beta & M_A^2 \cos^2 \beta + M_Z^2 \sin^2 \beta \end{pmatrix}$$

⇓ ← Diagonalization, α

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

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: $\frac{e m_t}{2M_W s_W}$, $\frac{e m_t^2}{M_W s_W}$, \dots

\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

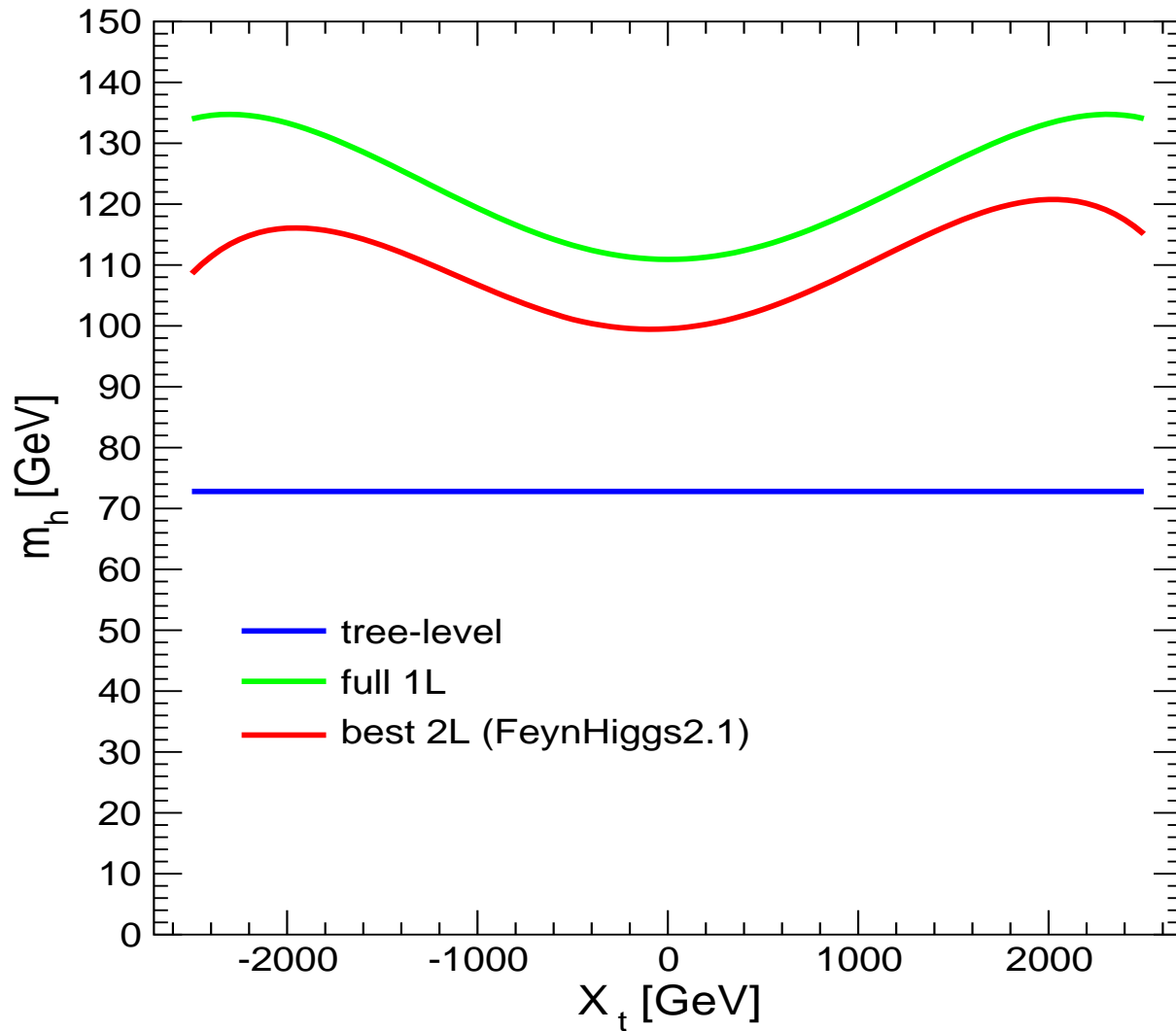
www.feynhiggs.de

[*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 :-)

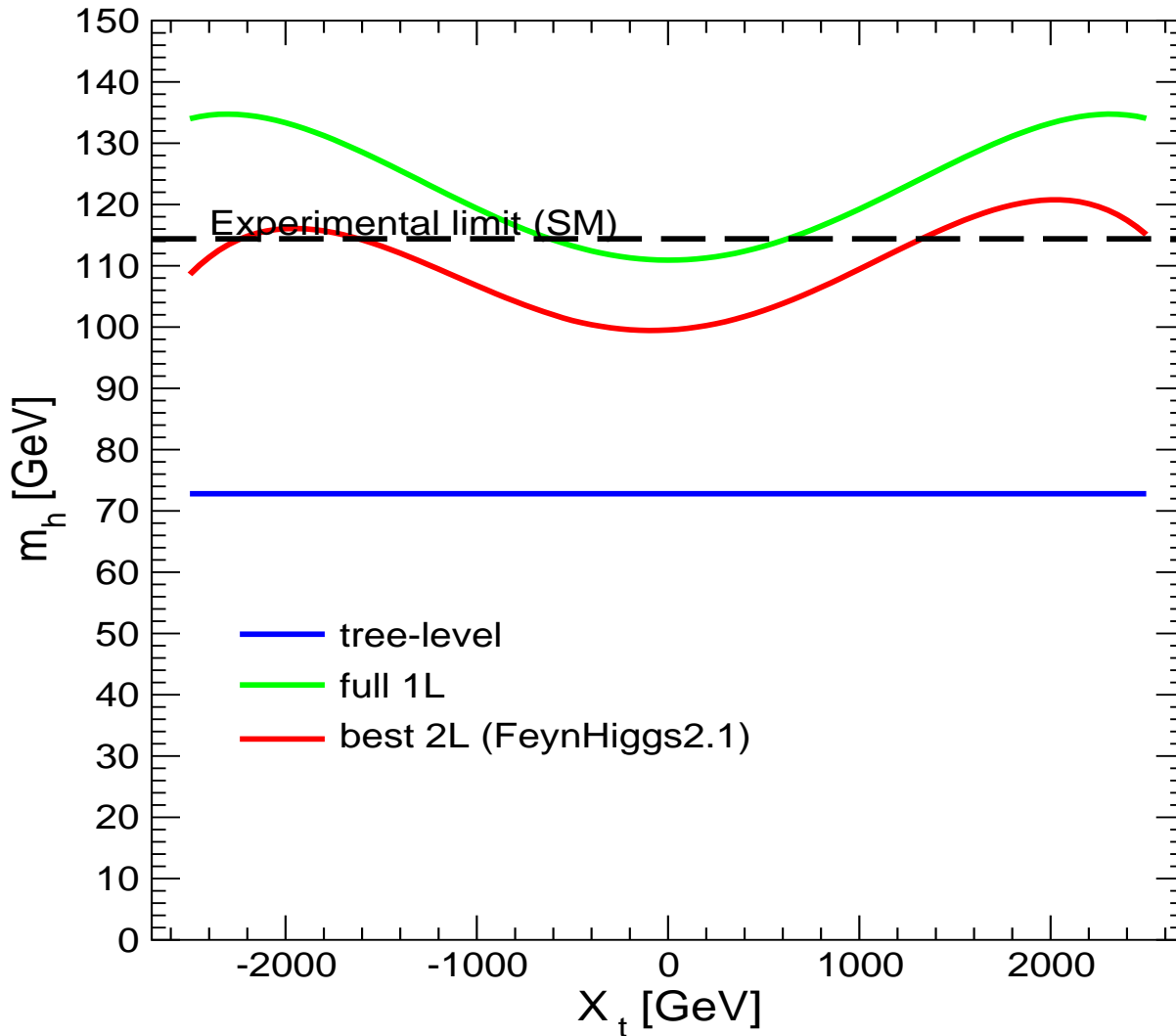
Effects of the two-loop corrections to the lightest Higgs mass:

Example for one set of MSSM parameters



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

Example for one set of MSSM parameters



Comparison with
experimental limits

\Rightarrow strong impact on
bound on SUSY parameters

Higgs couplings, tree level:

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

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

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

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

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

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

$\Rightarrow g_{hVV} \leq g_{HVV}^{\text{SM}}, \quad g_{hVV}, g_{HVV}, g_{hAZ}$ 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

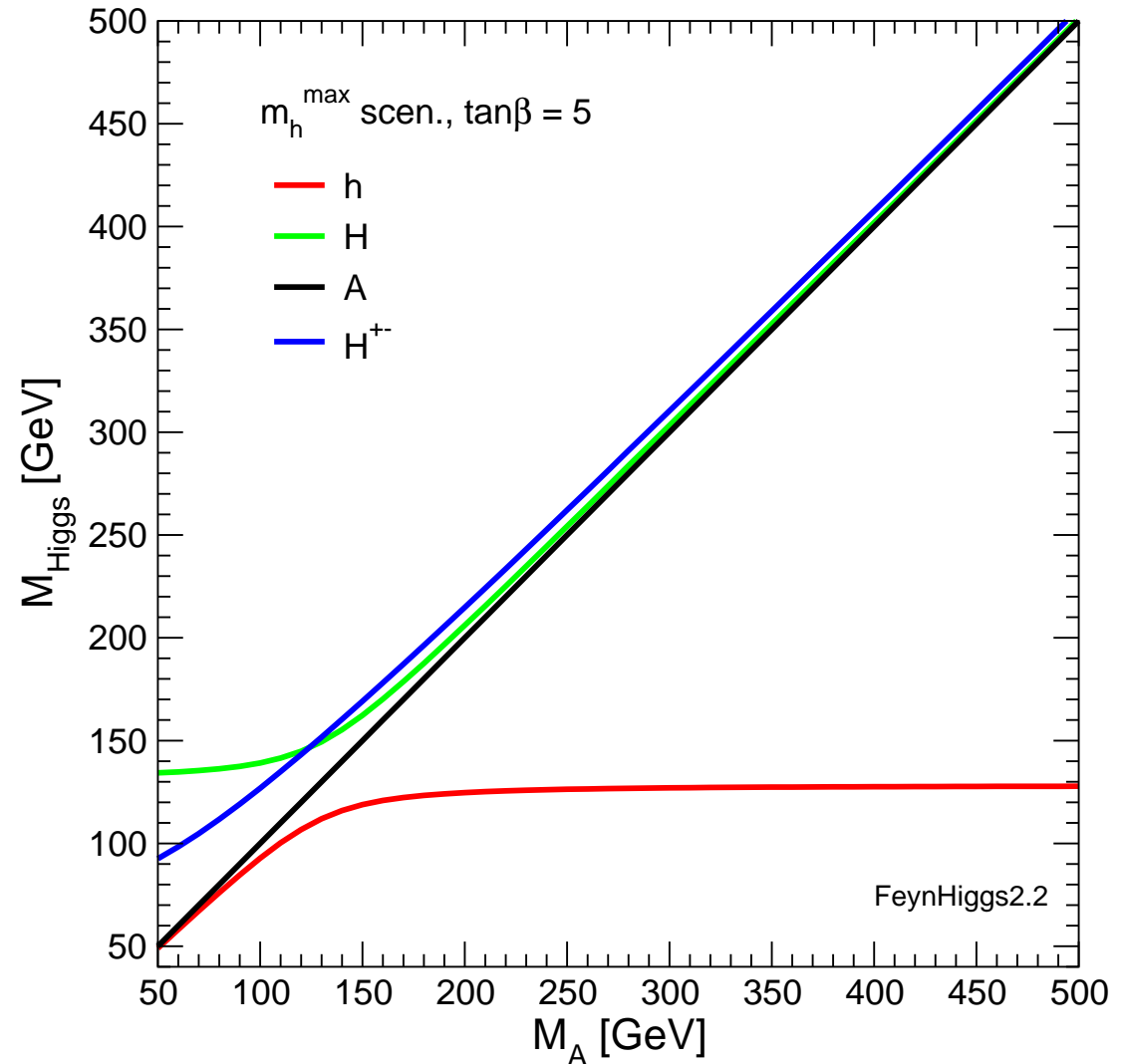
⇒ SM analysis applies!

The heavy MSSM Higgses:

$$M_A \approx M_H \approx M_{H^\pm}$$

→ coupling to gauge bosons ~ 0

⇒ no production via WH, \dots



Remaining theoretical uncertainties in prediction for M_h in the MSSM:

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

- From unknown higher-order corrections:

$$\Rightarrow \Delta M_h \approx 3 \text{ GeV}$$

- From uncertainties in input parameters

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

$$\Delta m_t \approx 1 \text{ GeV} \Rightarrow \Delta M_h \approx 1 \text{ GeV}$$

Higgs couplings, production cross sections

\Rightarrow also affected by large SUSY loop corrections

Extreme example: $\Gamma(h \rightarrow b\bar{b}) \rightarrow 0$ 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:
 - SM Higgs searches apply
 - keep in mind the upper limit of 135 GeV
2. Light MSSM Higgs boson “before” the decoupling limit:
 - dedicated search necessary
 - SM-like search with reduced couplings
 - $p_0 \oplus \mu$ with reduced $\sigma \times \text{BR}$
3. Heavy MSSM Higgs boson:
 - dedicated search
 - ⇒ model independent results on $\sigma \times \text{BR}$
 - ⇒ specific MSSM results for H/A

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: $\alpha_{\text{eff}} \rightarrow 0$:
main decay mode vanishes, important search channel vanishes

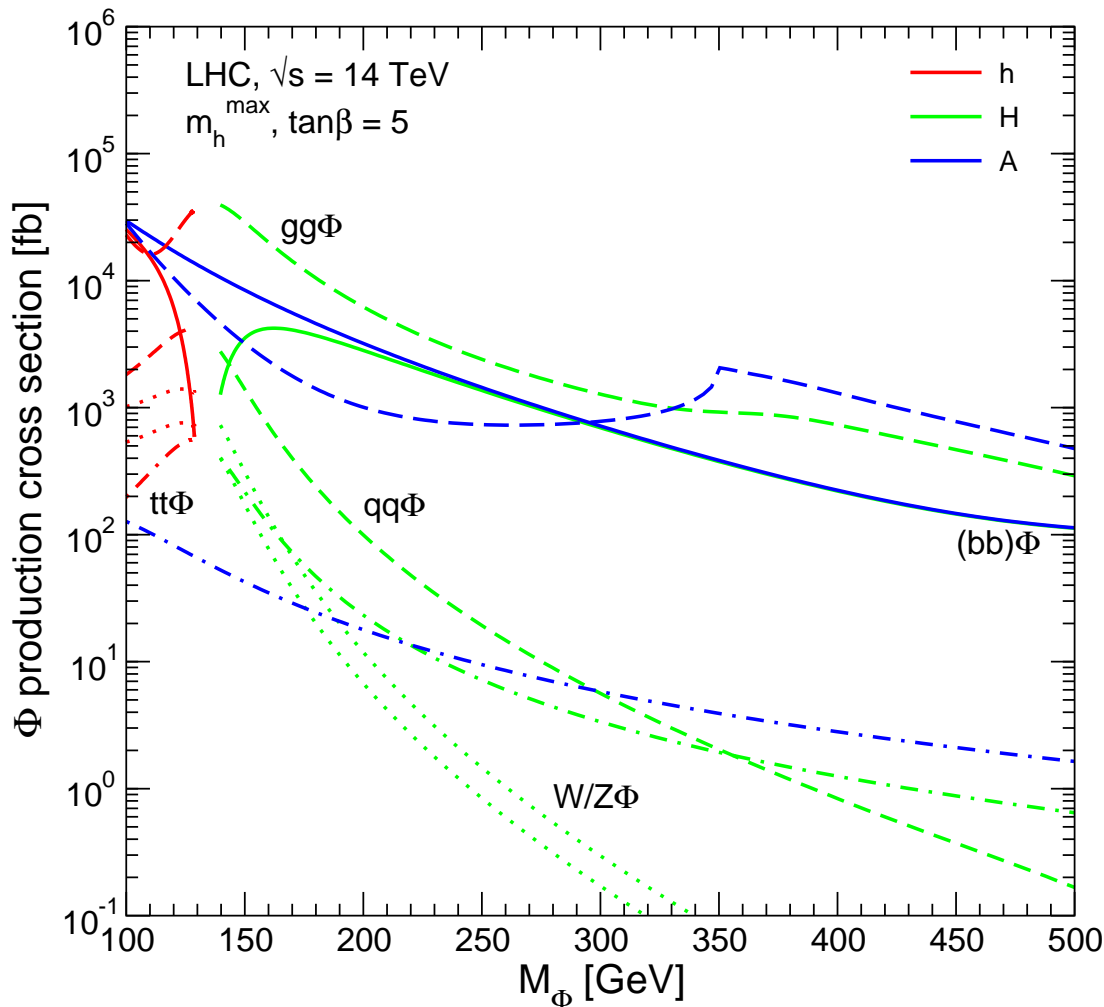
4. gluophobic Higgs scenario

→ hgg coupling is small: main LHC production mode vanishes

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

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

[*Tev4LHC Higgs working group report '06*]



gluon fusion: $gg \rightarrow \phi$

weak boson fusion (WBF):

$q\bar{q} \rightarrow q'\bar{q}'\phi$

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

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

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:

$$h \rightarrow b\bar{b}$$

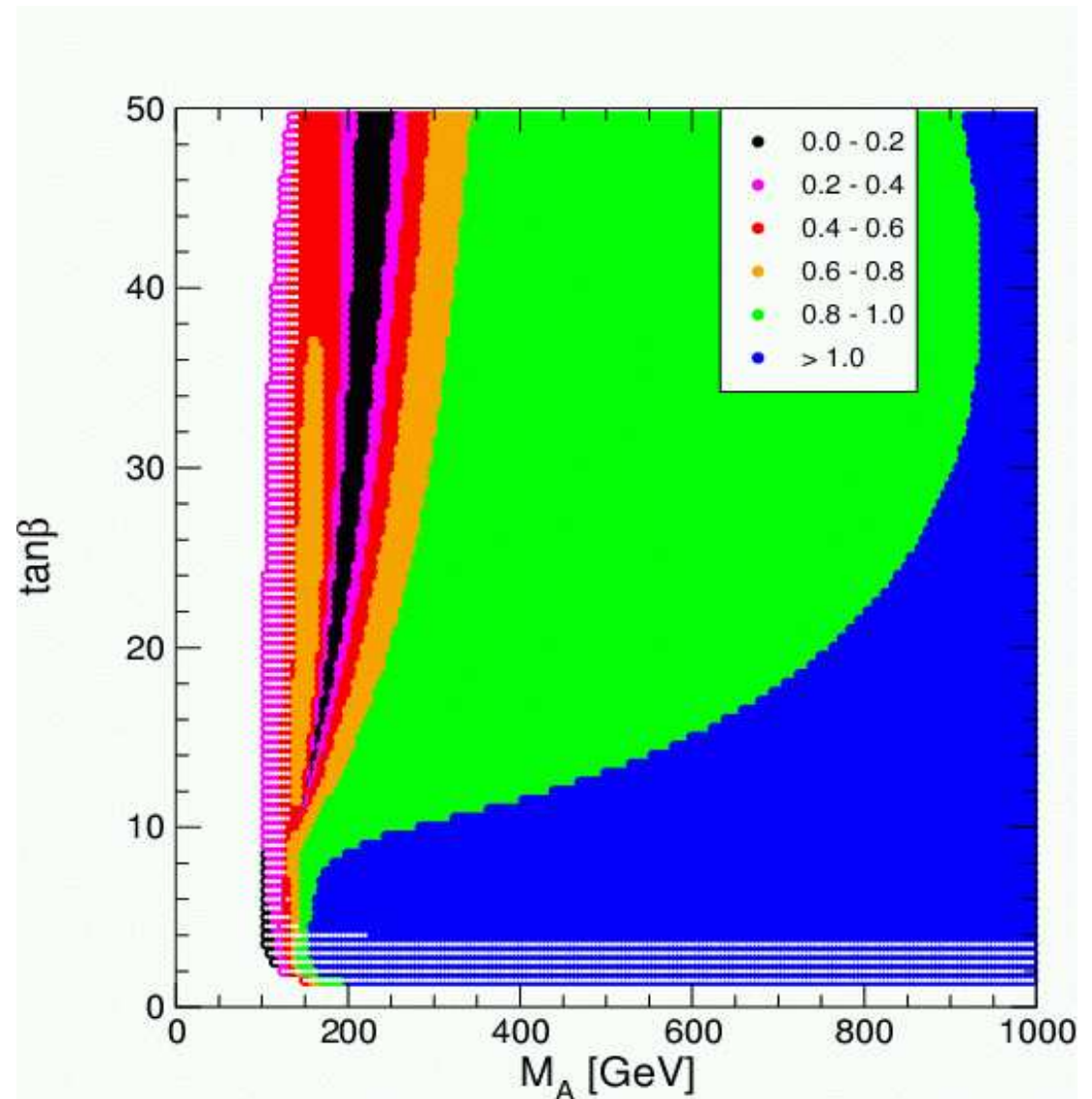
can be **strongly suppressed**

→ “Small α_{eff} scenario”

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

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

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



Possible problem in SUSY:

$$gg \rightarrow h \rightarrow \gamma\gamma$$

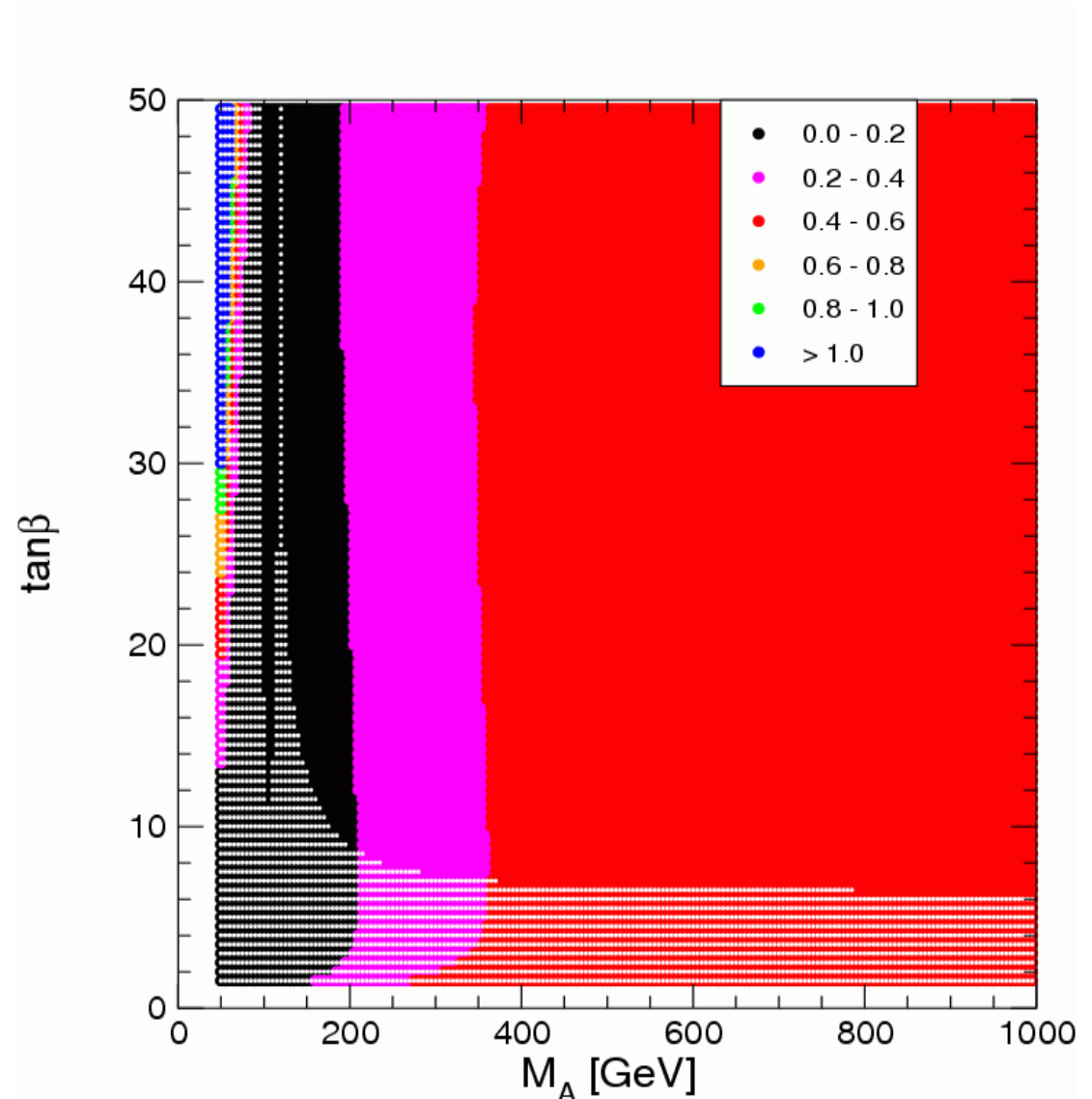
can be **strongly suppressed**

→ “gluophobic Higgs scenario”

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

⇒ Strong suppression of
 $gg \rightarrow h \rightarrow \gamma\gamma$ possible
over the whole parameter space

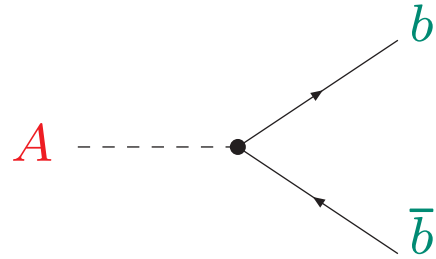
(not realized in
CMSSM, GMSB, AMSB, ...)



The heavy MSSM Higgs bosons

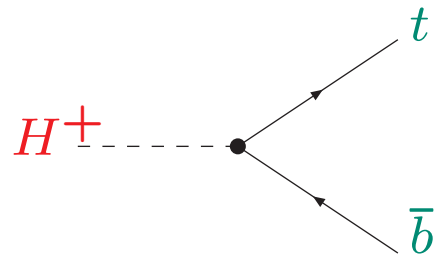
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



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

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:

$$\begin{aligned} b\bar{b} &\rightarrow H/A \rightarrow \tau^+\tau^- + X \\ gb &\rightarrow tH^\pm + X, \quad H^\pm \rightarrow \tau\nu_\tau \\ pp &\rightarrow t\bar{t} \rightarrow H^\pm + X, \quad H^\pm \rightarrow \tau\nu_\tau \end{aligned}$$

Enhancement factors compared to the SM case:

$$\begin{aligned} H/A &: \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{\text{BR}(H \rightarrow \tau^+\tau^-) + \text{BR}(A \rightarrow \tau^+\tau^-)}{\text{BR}(H \rightarrow \tau^+\tau^-)_{\text{SM}}} \\ H^\pm &: \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \text{BR}(H^\pm \rightarrow \tau\nu_\tau) \end{aligned}$$

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

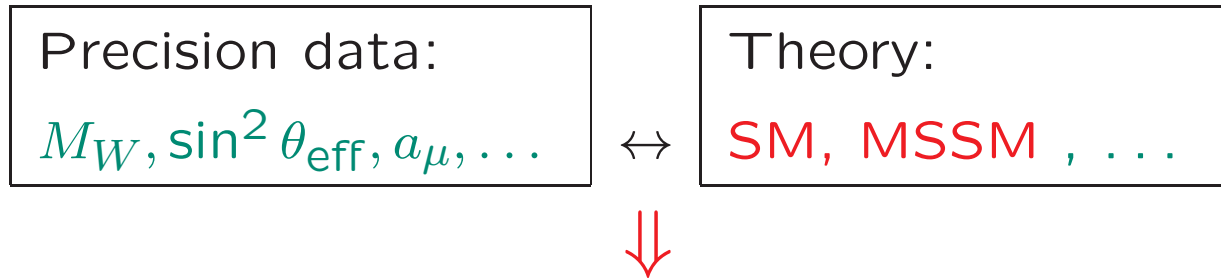
also relevant for $\text{BR}(H/A \rightarrow \tau^+\tau^-)$, $\text{BR}(H^\pm \rightarrow \tau\nu_\tau)$

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

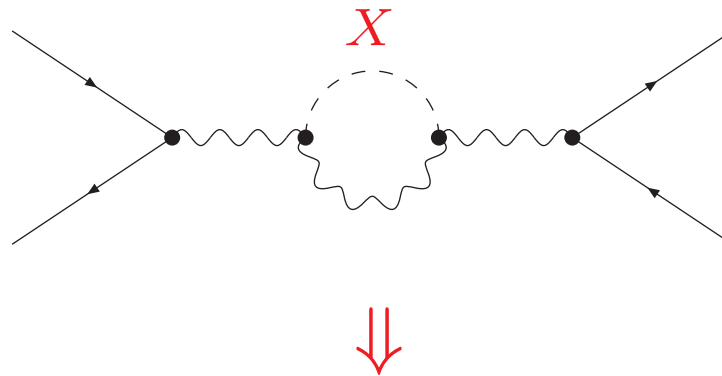
\Rightarrow additional effects on $\text{BR}(H/A \rightarrow \tau^+\tau^-)$, $\text{BR}(H^\pm \rightarrow \tau\nu_\tau)$

Electroweak Precision observables in the MSSM

Comparison of precision observables with theory:



Test of theory at quantum level: Sensitivity to loop corrections

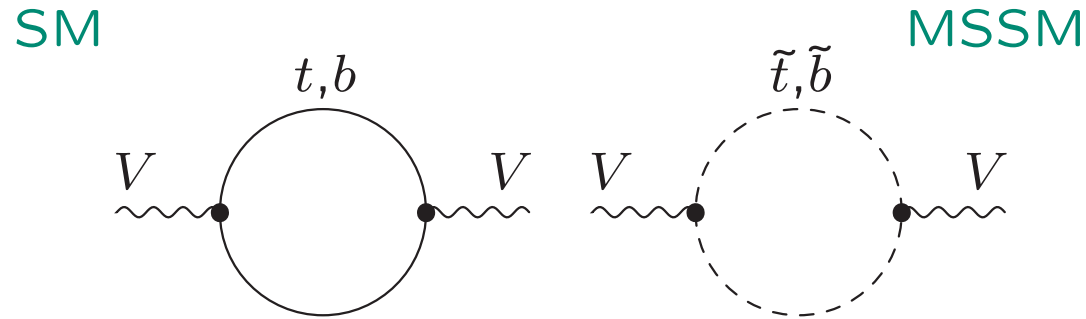


⇒ Information about unknown parameters

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 , $\sin^2 \theta_{\text{eff}}$ \rightarrow approximation via the ρ -parameter:

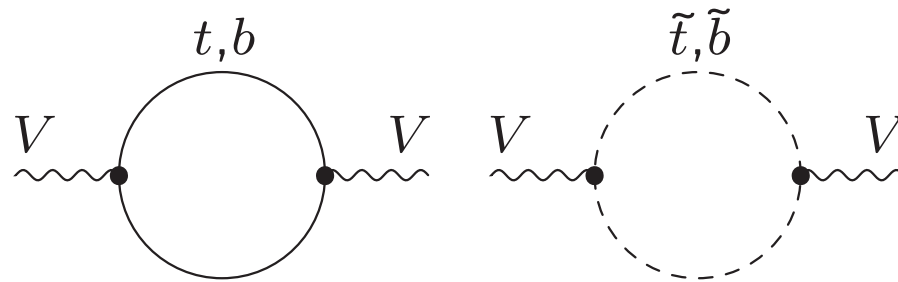
ρ measures the relative strength between
neutral current interaction and charged current interaction

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

(leading, process independent terms)

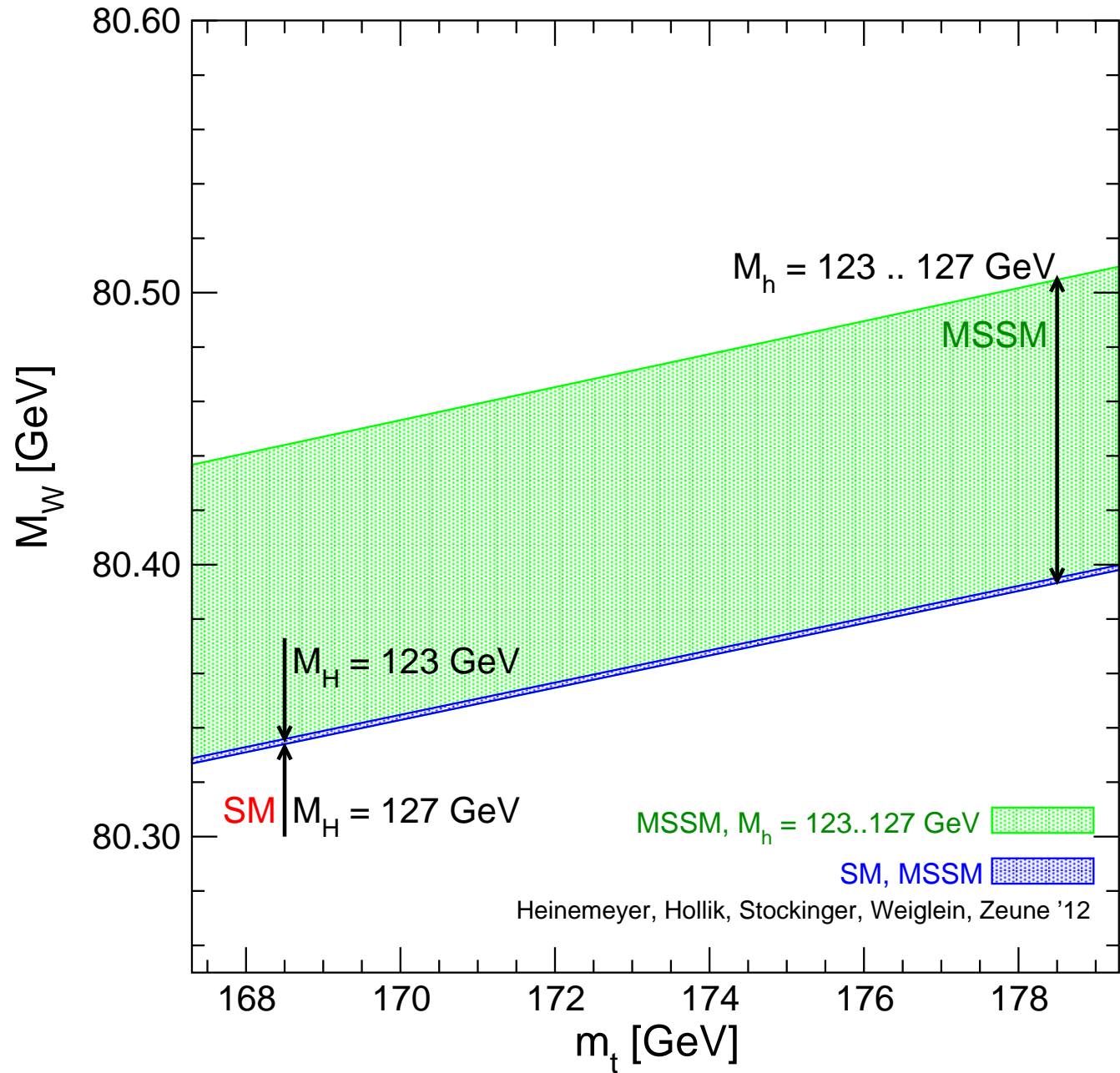
$\Delta\rho$ gives the main contribution to EW observables:

$$\Delta M_W \approx \frac{M_W}{2} \frac{c_W^2}{c_W^2 - s_W^2} \Delta\rho, \quad \Delta \sin^2 \theta_W^{\text{eff}} \approx -\frac{c_W^2 s_W^2}{c_W^2 - s_W^2} \Delta\rho$$

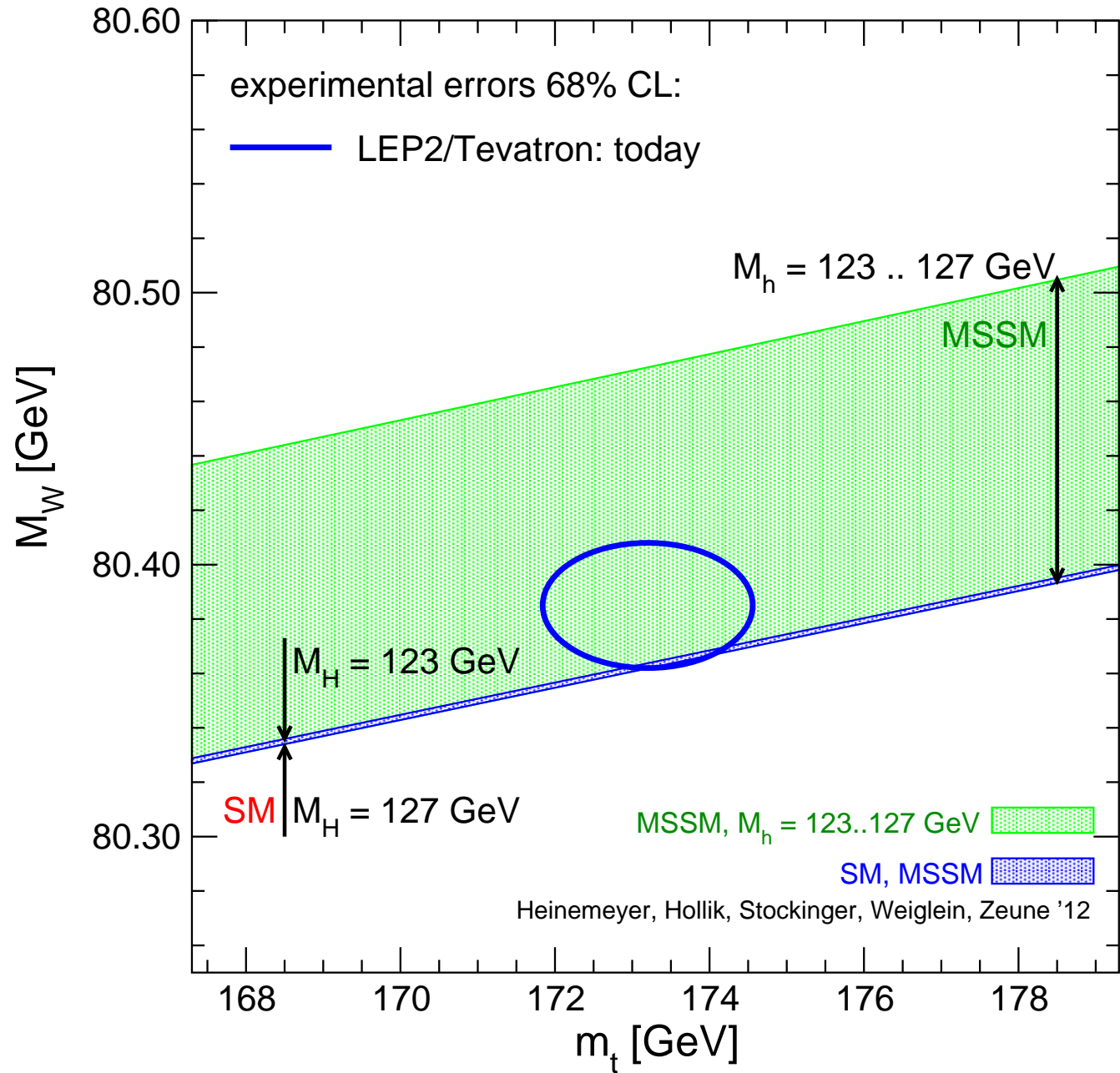


$$\Delta\rho^{\text{SUSY}} \text{ from } \tilde{t}/\tilde{b} \text{ loops} > 0 \quad \Rightarrow \quad M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$$

The most beautiful example:



The most beautiful example:



Remember 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

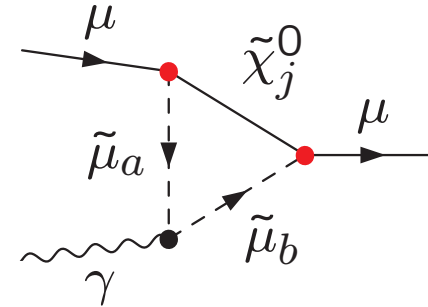
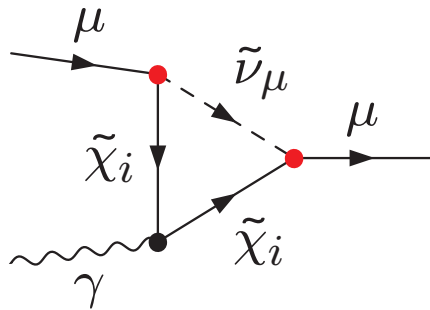


3 σ deviation has now been definitely established

(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:

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

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

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

SUSY corrections at 1L:

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

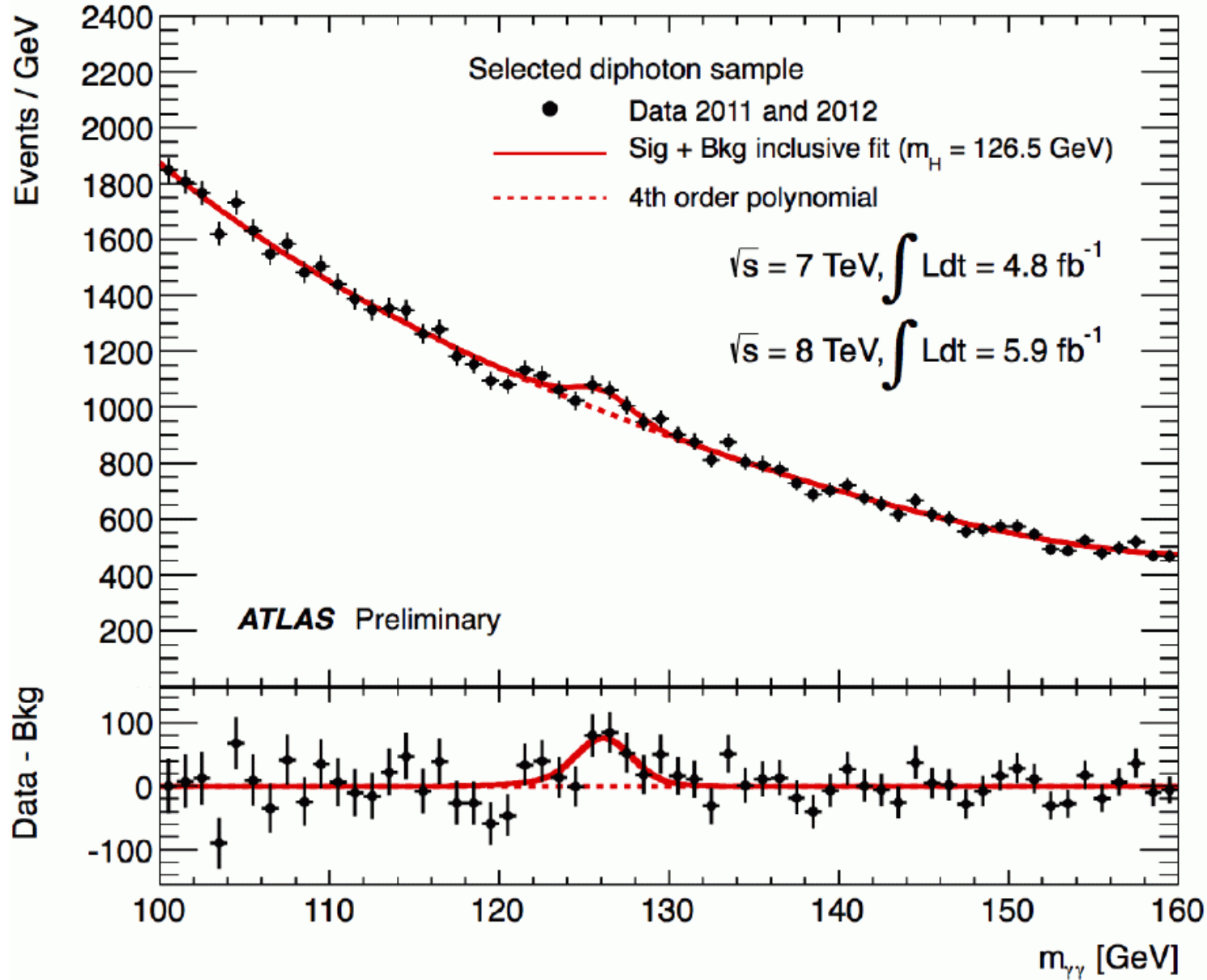
$M_{\text{SUSY}} (= m_{\tilde{\mu}} = m_{\tilde{\nu}} = m_{\tilde{\chi}})$: generic SUSY mass scale

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

⇒ SUSY could easily explain the “discrepancy”

⇒ a_{μ} can provide bounds on SUSY parameter space
(by requiring agreement at the 95% C.L.)

⇒ limits on M_h



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

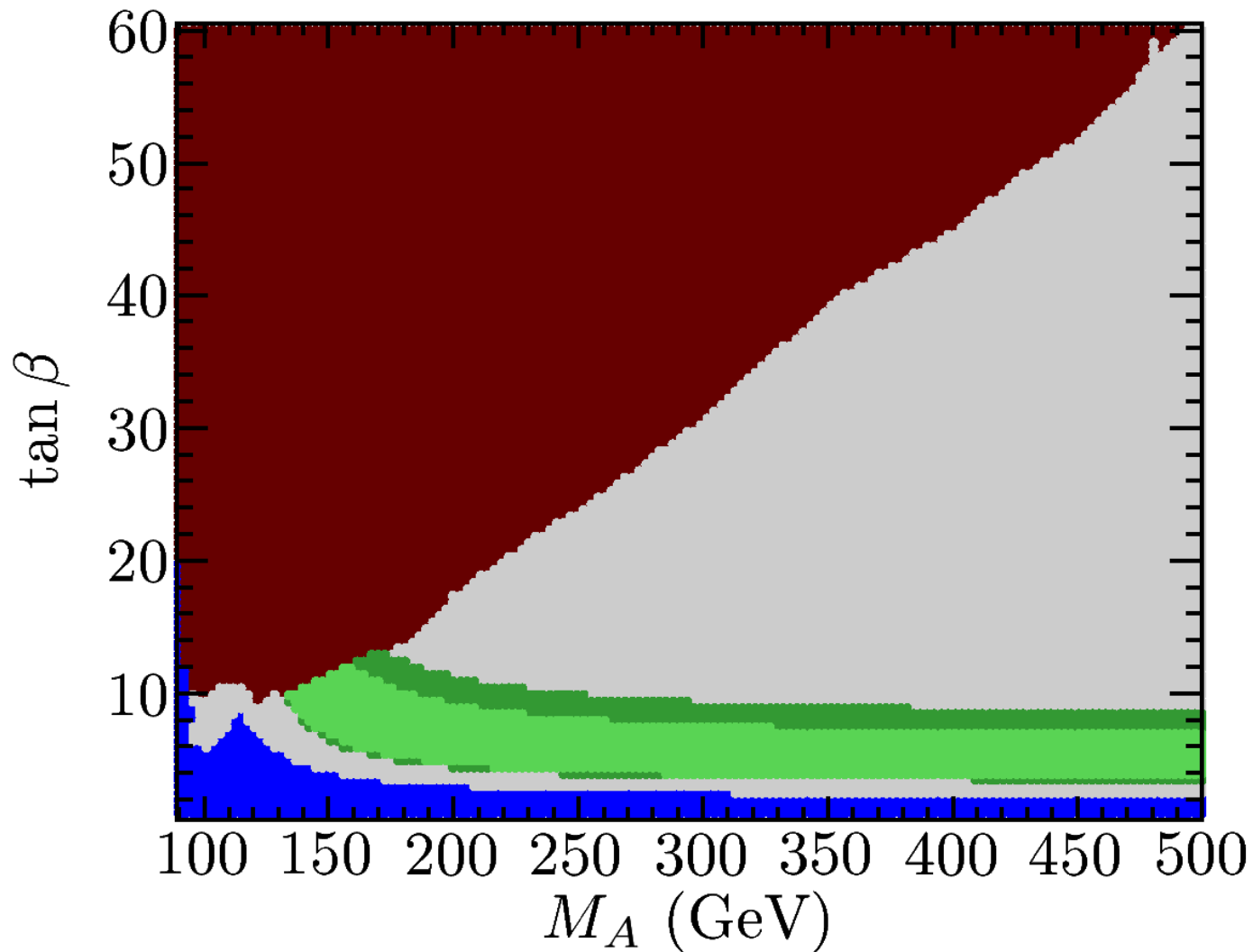
Here a few results from one randomly picked article:

[[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”

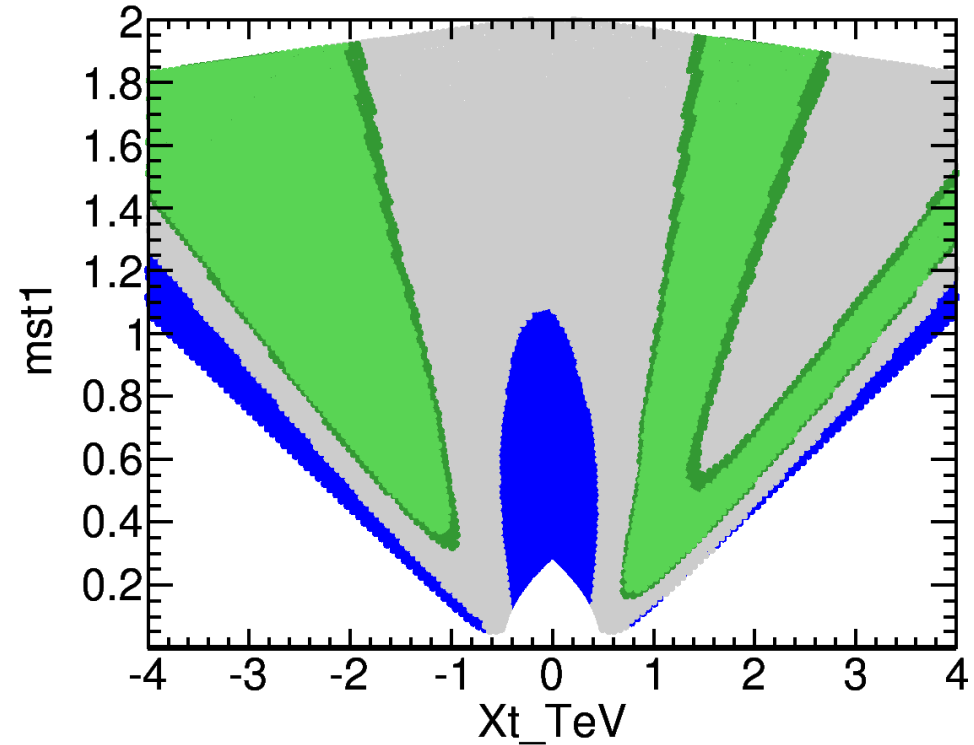
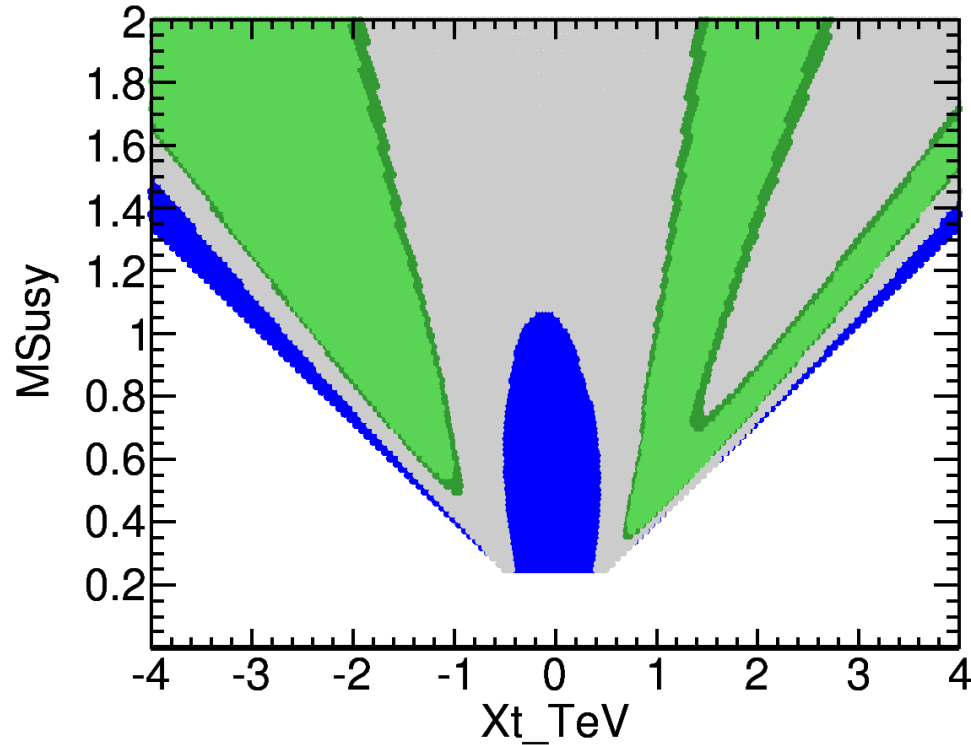
First idea: new lower bounds on M_A and $\tan\beta$ [S.H., O. Stal, G. Weiglein '11]

| M_{SUSY} | Limits without $M_h = 125$ | | | Limits with $M_h = 125$ | | |
|-------------------|----------------------------|-------|-------------|-------------------------|-------|-------------|
| | $\tan\beta$ | 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 |

⇒ new conservative limits obtained!

⇒ only small margin left for $t \rightarrow H^+b$

m_h^{\max} scenario:

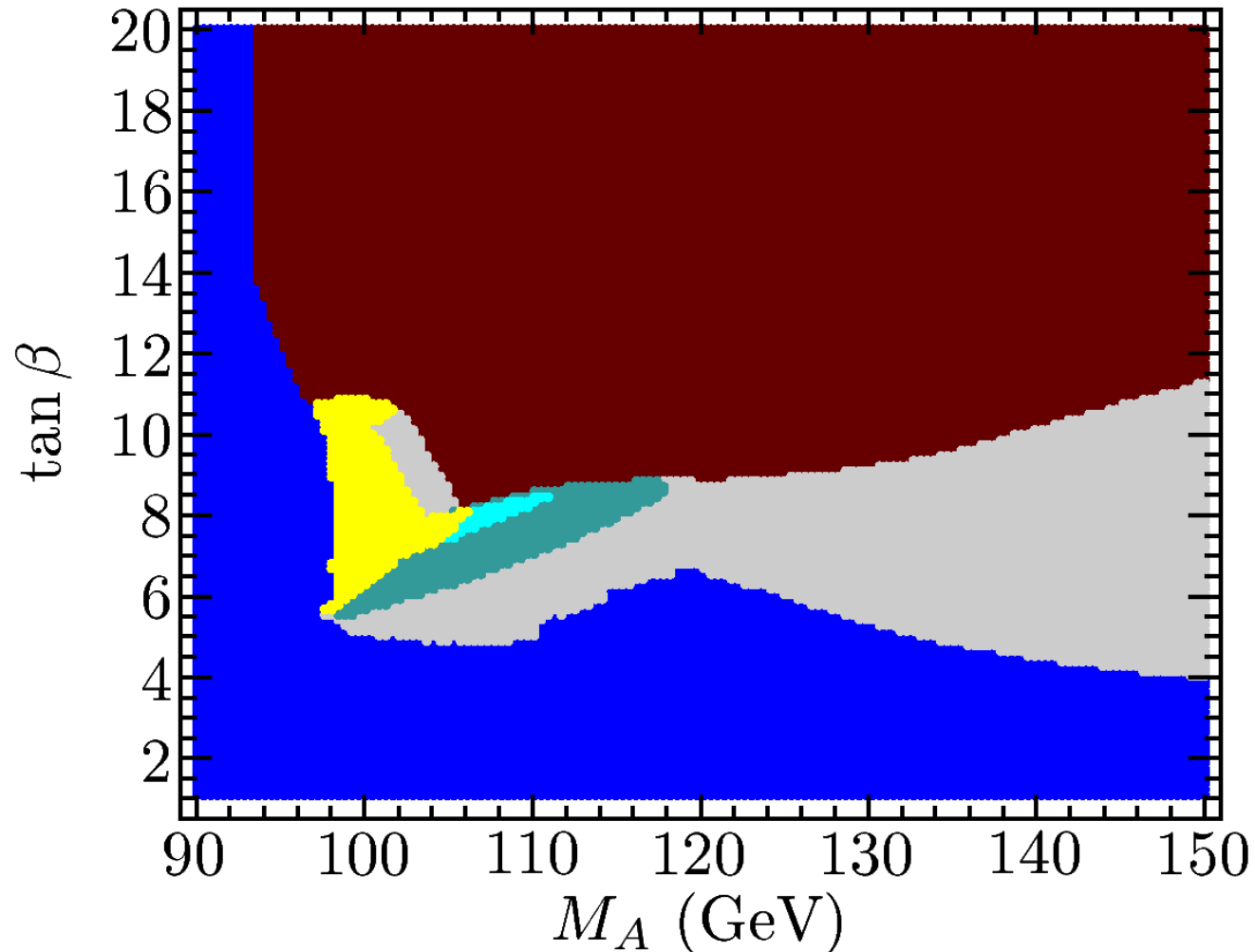


⇒ green are allowed by Higgs “excess”

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

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

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



Possible: $M_h = 98 \text{ GeV}$, $M_H = 125 \text{ GeV}$, ...

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]

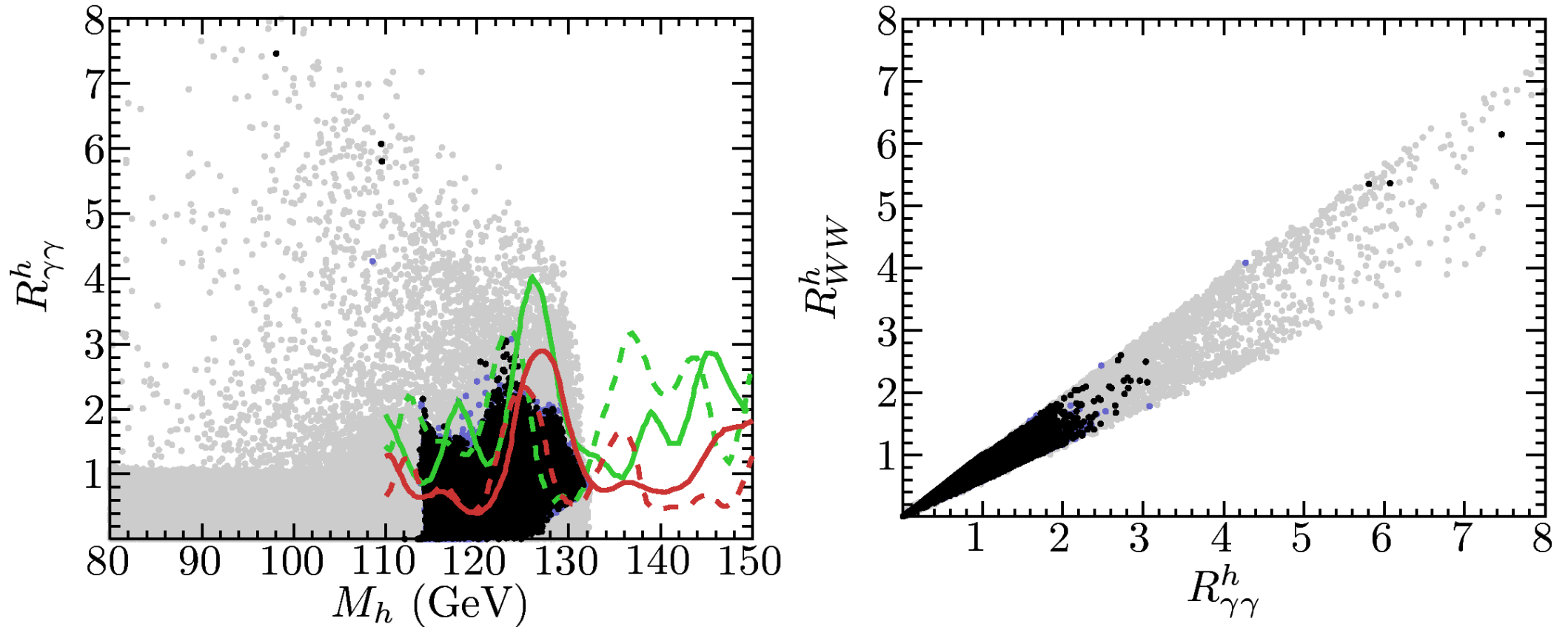
(R. Benbrik, M. Gomez Bock, S.H., O. Stal, G. Weiglein, L. Zeune)]

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

Possible MSSM interpretation:

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

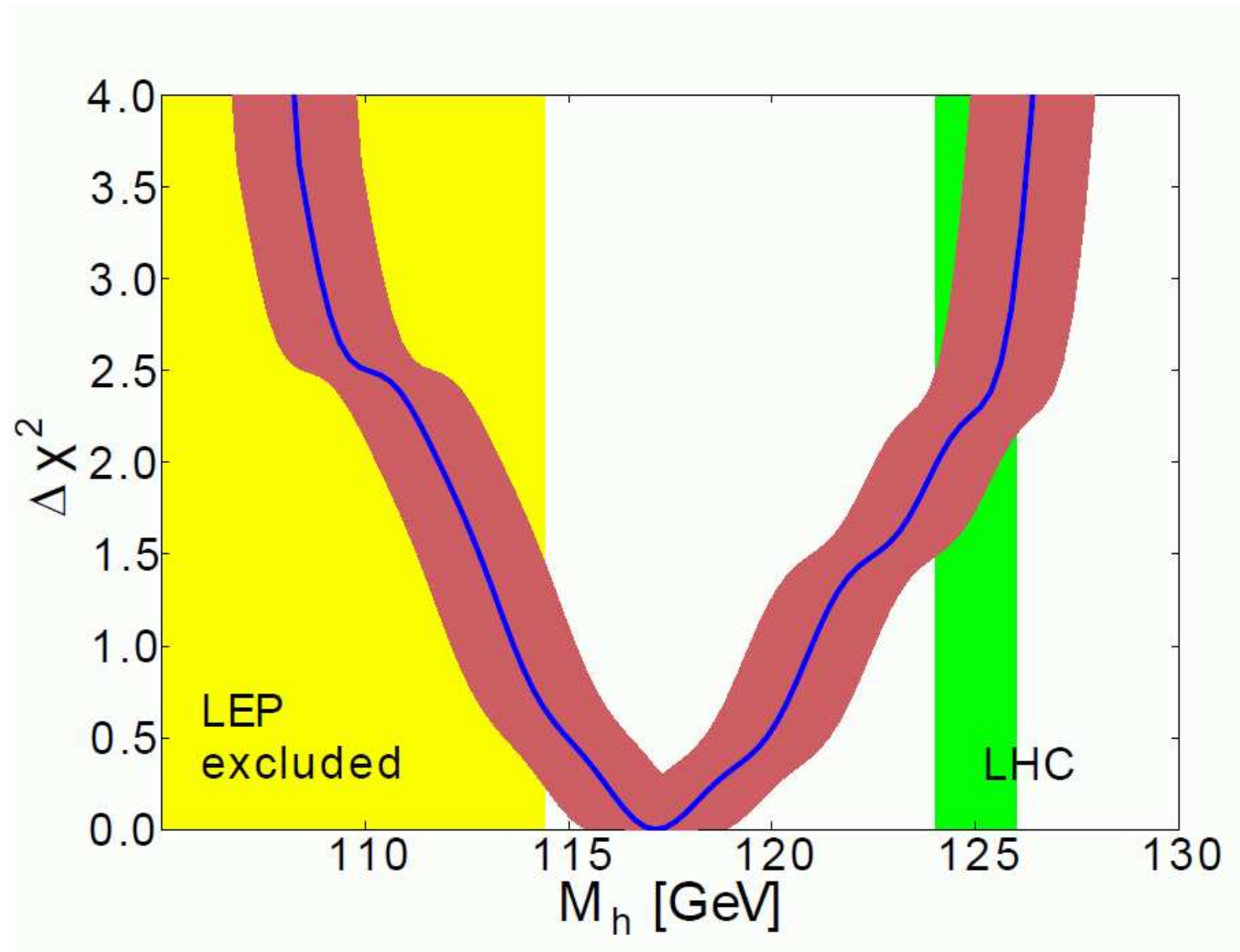
Scan over the MSSM parameter space:



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

CMSSM: post-LHC (5+5 fb⁻¹) red band plot:

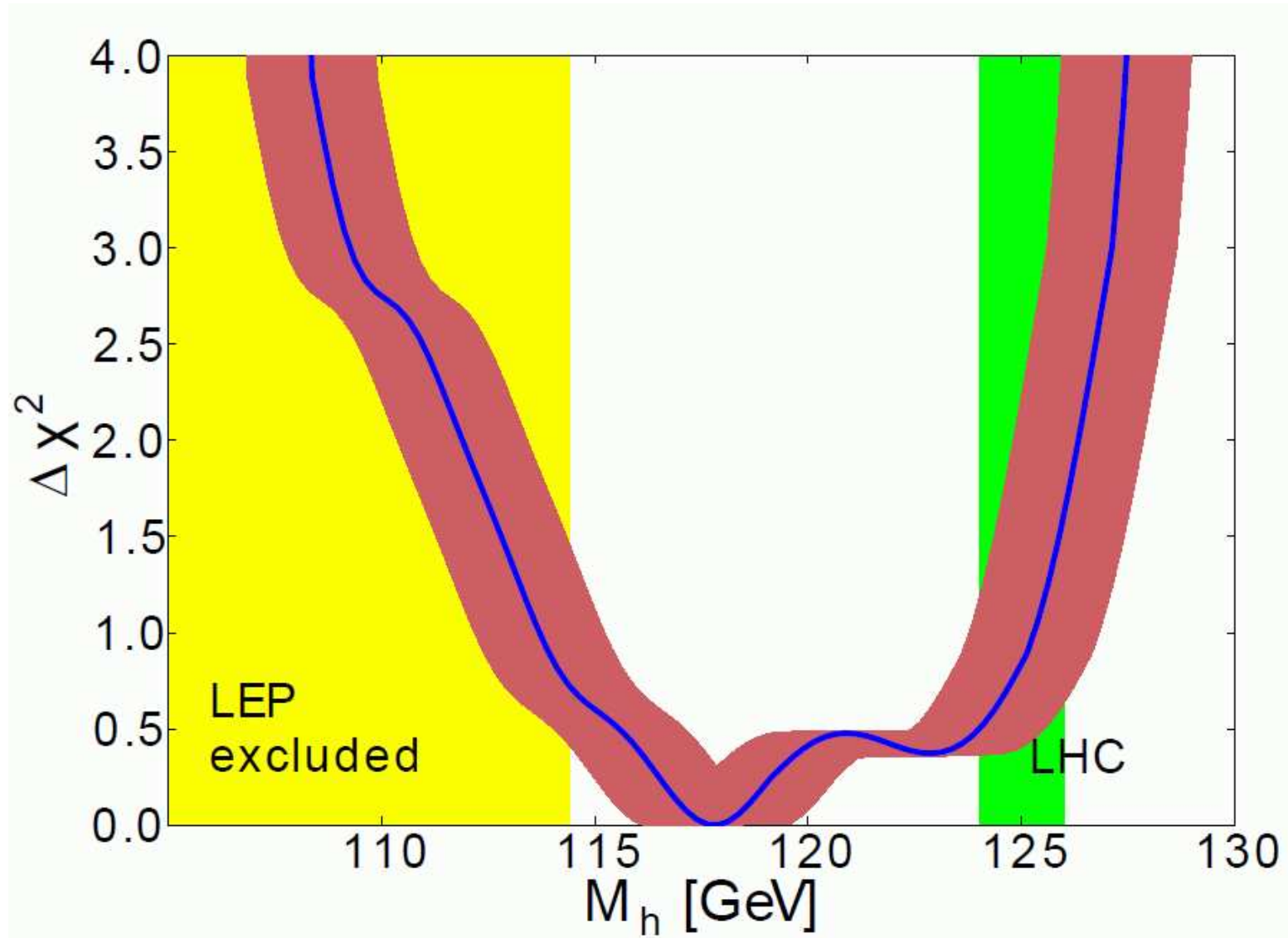
[2012]



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

NUHM1: post-LHC (5+5 fb⁻¹) red band plot:

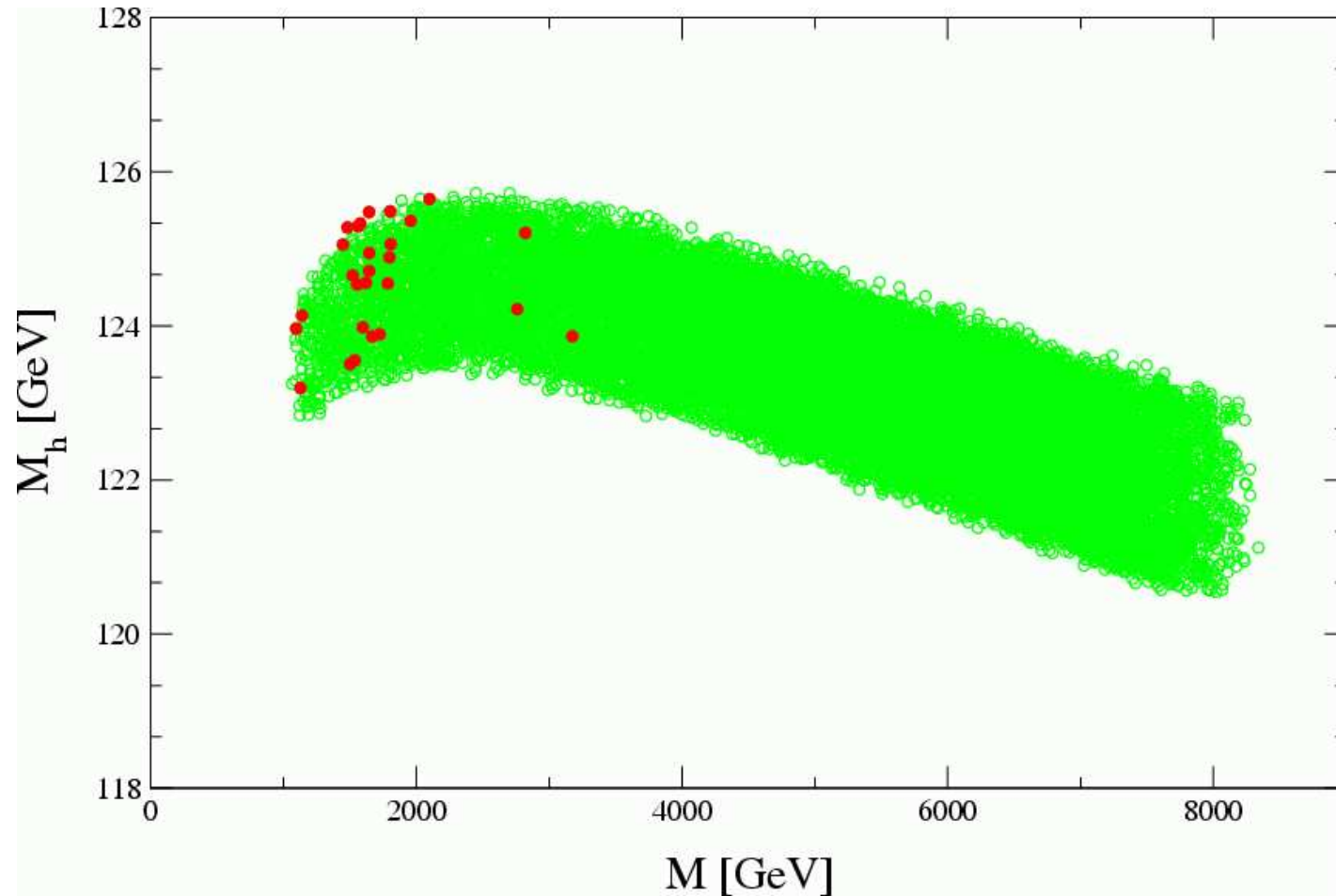
[2012]



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

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

$\Rightarrow 120 \text{ GeV} \leq M_h \leq 126 \text{ GeV}$ (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



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<http://www.ifca.es/HDays12>