SUSY: From the Basics to Collider Phenomenology

Sven Heinemeyer, IFCA (Santander)

Louvain, 05/2007

1. Introduction to SUSY
2. SUSY Lagrangians and the MSSM
3. “Simplified versions” and special sectors
4. SUSY Phenomenology

SUSY: From the Basics to Collider Phenomenology

Sven Heinemeyer, IFCA (Santander)

Louvain, 05/2007

1. Introduction to SUSY

2. SUSY Lagrangians and the MSSM

3. “Simplified versions” and special sectors

4. SUSY Phenomenology

SUSY lectures (III):
"Simplified Versions" and Special Sectors

Sven Heinemeyer, IFCA (Santander)

Louvain, 05/2007

1. Constrained Models:
   - CMSSM/mSUGRA
   - mGMSB
   - mAMSB

2. The MSSM Higgs Sector with real parameters

3. The MSSM Higgs Sector with complex parameters

1. Constrained Models: CMSSM/mSUGRA, mGMSB, mAMSB

Remember:

$\Rightarrow$ phenomenology depends mainly on mechanism for communicating SUSY breaking rather than on SUSY-breaking mechanism itself

"Hidden sector":	$\longrightarrow$	Visible sector:
SUSY breaking		MSSM

"Gravity-mediated": CMSSM, mSUGRA
"Gauge-mediated": GMSB
"Anomaly-mediated": AMSB
...

SUGRA: mediating interactions are gravitational

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

AMSB: SUSY breaking on a different brane in a higher-dimensional theory

$\boxed{\text{All constrained models are special versions of the MSSM !!!}}$

1A. Gravity-mediated SUSY breaking

⇒ Quantum field theory of supergravity: graviton and gravitino

QFT with spin 2 and spin $\frac{3}{2}$ field is not renormalizable

⇒ cannot be extended to arbitrarily high energies

⇒ QFT of supergravity has to be interpreted as effective theory

contains non-renormalizable terms prop. to inverse powers of $M_{\rm Pl}$

Best candidate for fundamental theory: string theory

SUSY breaking in hidden sector:

⇒ supergravity Lagrangian contains non-renormalizable terms that communicate between hidden and visible sector $\sim 1/M_{\rm Pl}^n$

Dimensional analysis:

SUSY breaking in hidden sector by v.e.v. $\langle F \rangle$ (dim $\langle F \rangle$ = mass^2)
coupling $\sim 1/M_{\text{Pl}}$

require $m_{\text{soft}} \to 0$ for $\langle F \rangle \to 0$ (no SUSY breaking) and for
$M_{\text{Pl}} \to \infty$ (vanishing gravitational interaction)

$$\Rightarrow \quad m_{\text{soft}} \approx \frac{\langle F \rangle}{M_{\text{Pl}}}$$

Wanted: $m_{\text{soft}} \lesssim 1$ TeV (hierarchy problem)

$\Rightarrow \sqrt{\langle F \rangle} \approx 10^{11}$ GeV : scale of SUSY breaking in hidden sector

In general: $m_{\text{gravitino}} = m_{\frac{3}{2}} \approx \frac{\langle F \rangle}{M_{\text{Pl}}}$

$\Rightarrow$ $m_{\frac{3}{2}} \approx m_{\text{soft}}$, gravitational interactions

$\Rightarrow$ gravitino not important for collider phenomenology

Non-renormalizable terms in supergravity Lagrangian:

$$\mathcal{L}_{\mathrm{NR}} = -\frac{1}{M_{\mathrm{Pl}}} F_X \sum_a \frac{1}{2} f_a \lambda^a \lambda^a + \text{h.c.} - \frac{1}{M_{\mathrm{Pl}}^2} F_X F_X^* \, k^i_j \varphi_i \varphi^{*j}$$
$$- \frac{1}{M_{\mathrm{Pl}}} F_X \left(\frac{1}{6} y'^{ijk} \varphi_i \varphi_j \varphi_k + \frac{1}{2} \mu'^{ij} \varphi_i \varphi_j\right) + \text{h.c.}$$

F_X : (auxiliary) field for a chiral supermultiplet X in the hidden sector

φ_i, λ^a: scalar and gaugino fields in the MSSM

If $\sqrt{\langle F_X \rangle} \sim 10^{10}$–$10^{11}$ GeV

$\Rightarrow$ soft SUSY-breaking terms of MSSM with $m_{\mathrm{soft}} \approx 10^2$–$10^3$ GeV

Assumption of a "minimal" form of the supergravity Lagrangian

$\Rightarrow$ soft-breaking terms which obey "universality" and "proportionality"

Results in exactly the known MSSM Lagrangian (**??**)

$$\begin{aligned}\mathcal{L}_{\text{soft}} &= -\frac{1}{2}\Big(M_1\tilde{B}\tilde{B} + M_2\widetilde{W}\widetilde{W} + M_3\tilde{g}\tilde{g}\Big) + \text{h.c.} \\ &\quad - (m^2_{H_u} + |\mu|^2)H_u^+ H_u - (m^2_{H_d} + |\mu|^2)H_d^+ H_d - (bH_uH_d + \text{h.c.}) \\ &\quad - \Big(\tilde{u}_R\mathbf{a_u}\tilde{Q}H_u - \tilde{d}_R\mathbf{a_d}\tilde{Q}H_d - \tilde{e}_R\mathbf{a_e}\tilde{L}H_d\Big) + \text{h.c.} \\ &\quad - \tilde{Q}^+\mathbf{m^2_Q}\tilde{Q} - \tilde{L}^+\mathbf{m^2_L}\tilde{L} - \tilde{u}_R\mathbf{m^2_u}\tilde{u}^*_R - \tilde{d}_R\mathbf{m^2_d}\tilde{d}^*_R - \tilde{e}_R\mathbf{m^2_e}\tilde{e}^*_R\end{aligned}$$

with 5 independent parameters at the GUT scale:

$$\begin{aligned} M_1 = M_2 = M_3 &= m_{1/2} \\ m^2_{H_u} = m^2_{H_d} = \mathbf{m^2_Q} = \mathbf{m^2_L} = \mathbf{m^2_u} = \mathbf{m^2_d} = \mathbf{m^2_e} &= m_0 \\ \mathbf{a_u} = \mathbf{a_d} = \mathbf{a_e} &= A_0 \\ & \quad b \\ & \quad |\mu|^2 \end{aligned}$$

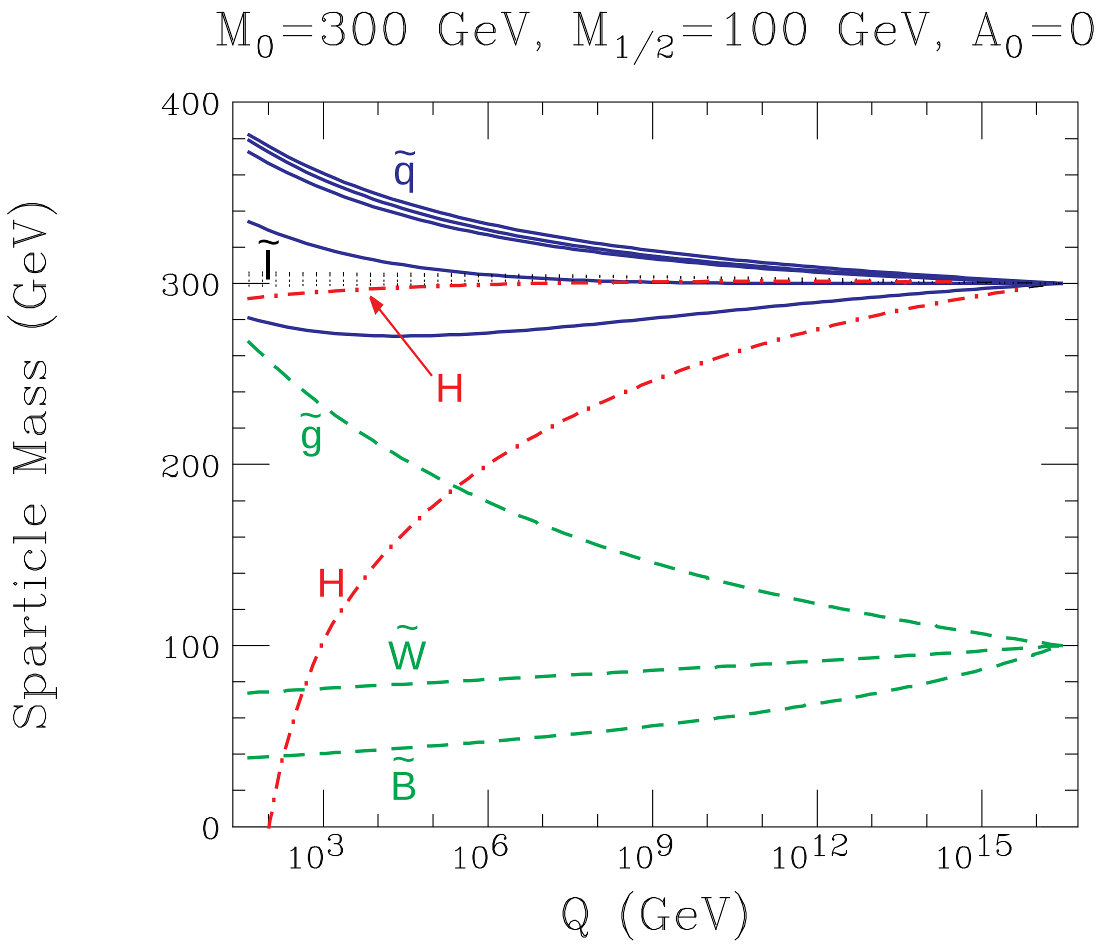
Still to do: parameter(Q_{GUT}) $\to$ parameter($Q_{\text{electroweak}}$)

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

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

$\Rightarrow M_1, M_2, M_3, m_{H_u}^2, m_{H_d}^2, \mathbf{m_Q^2}, \mathbf{m_L^2}, \mathbf{m_u^2}, \mathbf{m_d^2}, \mathbf{m_e^2}, \mathbf{a_u}, \mathbf{a_d}, \mathbf{a_e}, b, |\mu|^2$ at the EW scale

Example:



Five new parameters, if possible phases are ignored:

$$m_0^2,\ m_{1/2},\ A_0,\ b,\ \mu$$

Final "trick": require radiative electroweak symmetry breaking:
Require correct value of M_Z at the EW scale:

$$\begin{aligned}
|\mu|^2 + m_{H_d}^2 &= b \tan\beta - M_Z^2/2 \cos 2\beta \\
|\mu|^2 + m_{H_u}^2 &= b \cot\beta + M_Z^2/2 \cos 2\beta
\end{aligned}$$

$\Rightarrow$ $|\mu|$, b given in terms of $\tan\beta$, sign μ

$\Rightarrow$ Scenario characterized by

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

Usually called 'CMSSM' (constrained MSSM) or 'mSUGRA'

In agreement with all phenomenological constraints (see below)

Summary: "supergravity inspired scenario", "mSUGRA"
characterized by five parameters:

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

m_0: universal scalar mass parameter

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

A_0: universal trilinear coupling

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

sign(μ): sign of supersymmetric Higgs parameter

m_0, $m_{1/2}$, A_0: GUT scale parameters

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

Lightest SUSY particle (LSP) is usually lightest neutralino

gaugino masses run in same way as gauge couplings

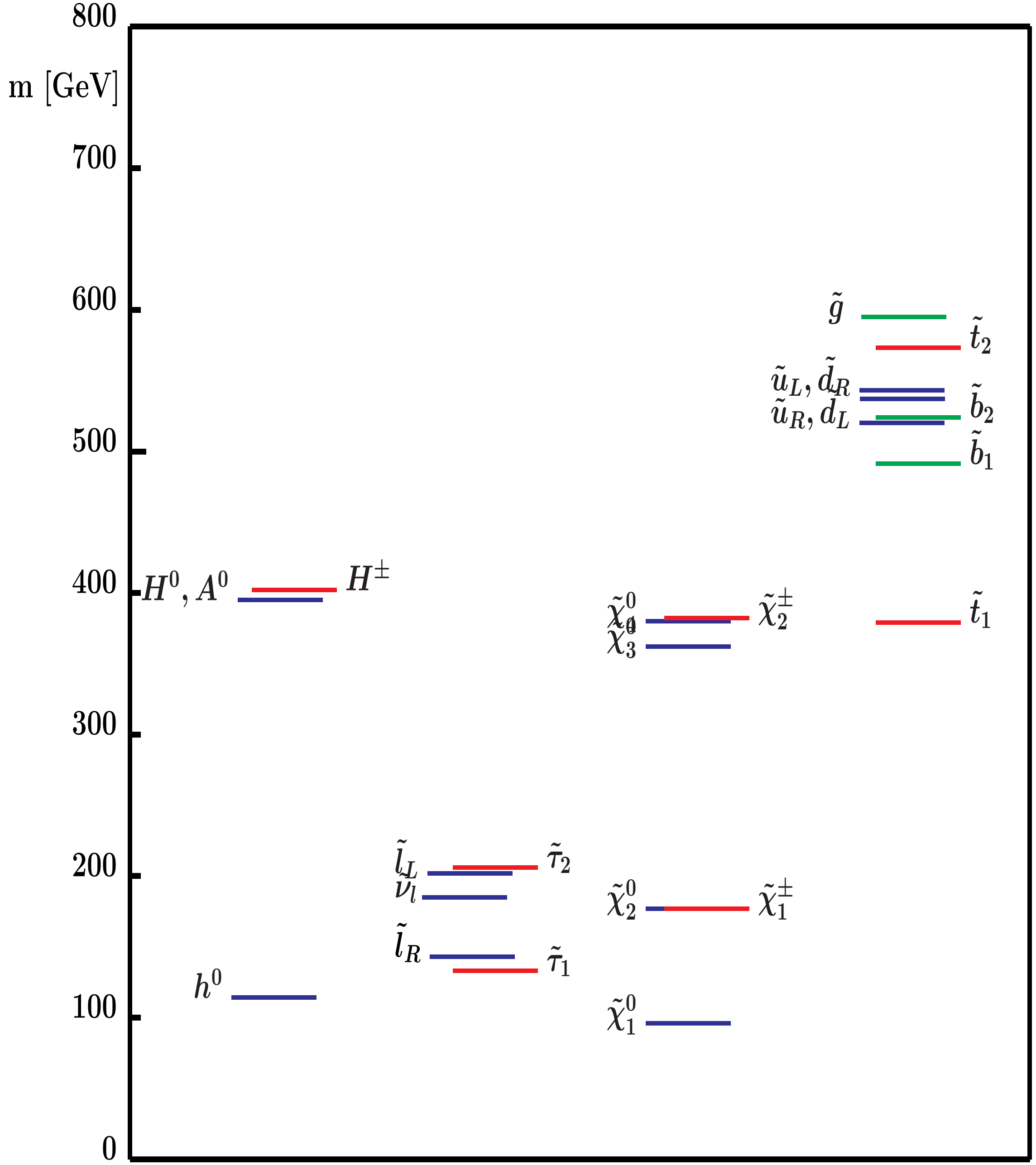
$\Rightarrow$ gluino heavier than charginos, neutralinos

"Typical" mSUGRA scenario

(SPS 1a benchmark scenario):

SPS home page:

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



1B. (minimal) gauge mediated SUSY breaking: mGMSB

New chiral supermultiplets, "messengers" , couple to SUSY breaking in hidden sector

Couple indirectly to MSSM fields via gauge interactions

$\Rightarrow$ mediation of SUSY breaking via electroweak and QCD gauge interactions

$\Rightarrow$ $\approx$ flavor-diagonal

SUSY breaking already in messenger spectrum

$\Rightarrow$ masses of SUSY particles from loop diagrams with messenger particles, gauge-interaction strength

$$\Rightarrow \quad m_{\text{soft}} \approx \frac{\alpha_i}{4\pi} \frac{\langle F \rangle}{M_{\text{mess}}}, \quad M_{\text{mess}} \sim \sqrt{\langle F \rangle}$$

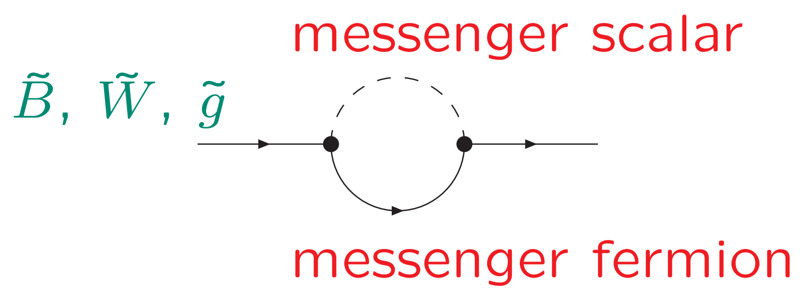
For $m_{\text{soft}} \lesssim 1$ TeV $\Rightarrow \sqrt{\langle F \rangle} \approx 10^4$–$10^5$ GeV

$\Rightarrow$ scale of SUSY breaking in hidden sector much lower than in SUGRA

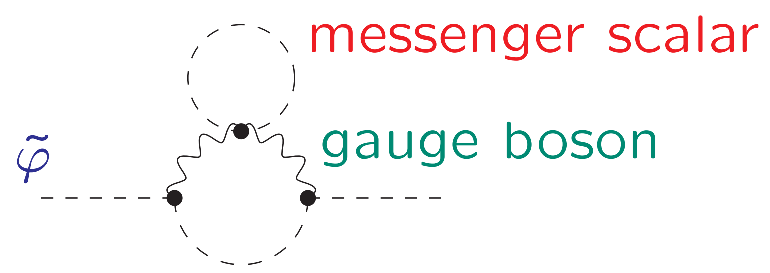
Gravitino mass: $m_{\frac{3}{2}} \approx \frac{\langle F \rangle}{M_{\rm Pl}} \approx 10^{-9}$ GeV

$\Rightarrow$ Gravitino is always the lightest SUSY particle (LSP)

Gaugino masses generated at one-loop order, $m_\lambda \approx \frac{\alpha_i}{4\pi}$



Scalar masses generated at two-loop order, $m^2_\varphi \approx \left(\frac{\alpha_i}{4\pi}\right)^2$



$\Rightarrow$ Typical mass hierarchy in GMSB scenario between strongly interacting and weakly interacting particles $\sim \alpha_3/\alpha_2/\alpha_1$

GMSB scenario characterized by

$$M_{\text{mess}}, N_{\text{mess}}, \Lambda, \tan\beta, \text{sign}(\mu)$$

M_{mess}: messenger mass scale

N_{mess}: messenger index (number of messenger multiplets)

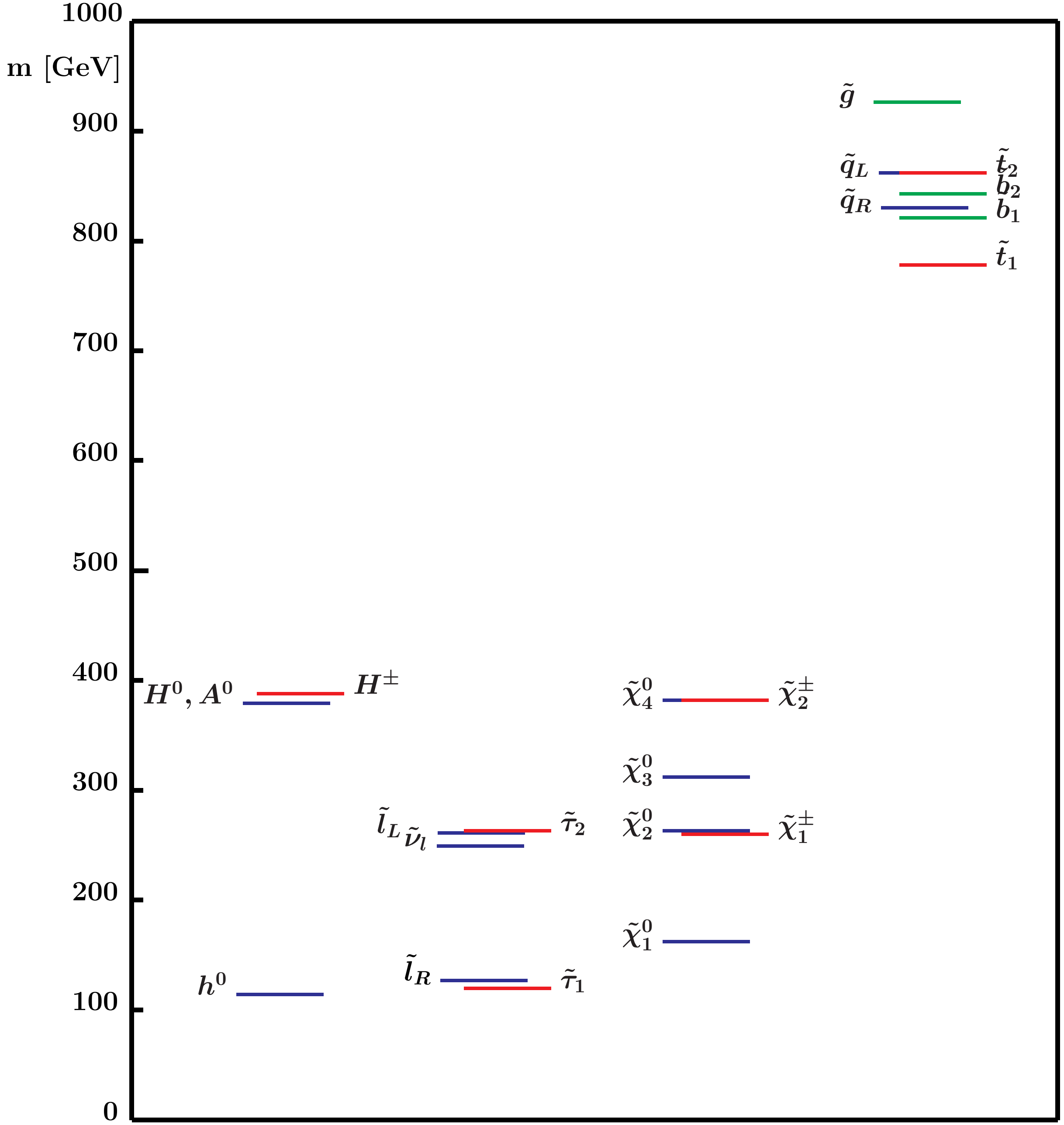
$\Lambda = \langle F \rangle / M_{\text{mess}}$: universal soft SUSY breaking mass scale felt by low-energy sector

LSP is always the gravitino
next-to-lightest SUSY particle (NLSP): $\tilde{\chi}_1^0$ or $\tilde{\tau}_1$

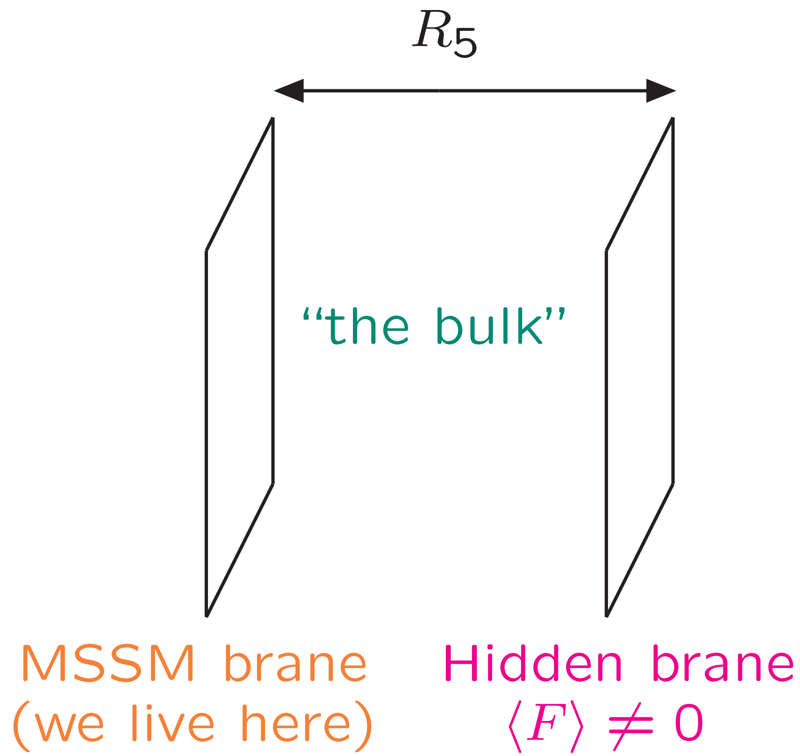
can decay into LSP inside or outside the detector

GMSB scenario with $\tilde{\tau}$ NLSP

(SPS 7 benchmark scenario):



1C. (minimal) anomaly mediated SUSY breaking: mAMSB



No MSSM in the "bulk"

Anomaly: $\langle F \rangle$ enters RGEs

$$m^2_{\tilde{f}_k} \sim \frac{|\langle F \rangle|^2}{(16\pi^2)^2} g_k^4 \, , \qquad M_i \sim \frac{\langle F \rangle}{16\pi^2} g_i^2$$

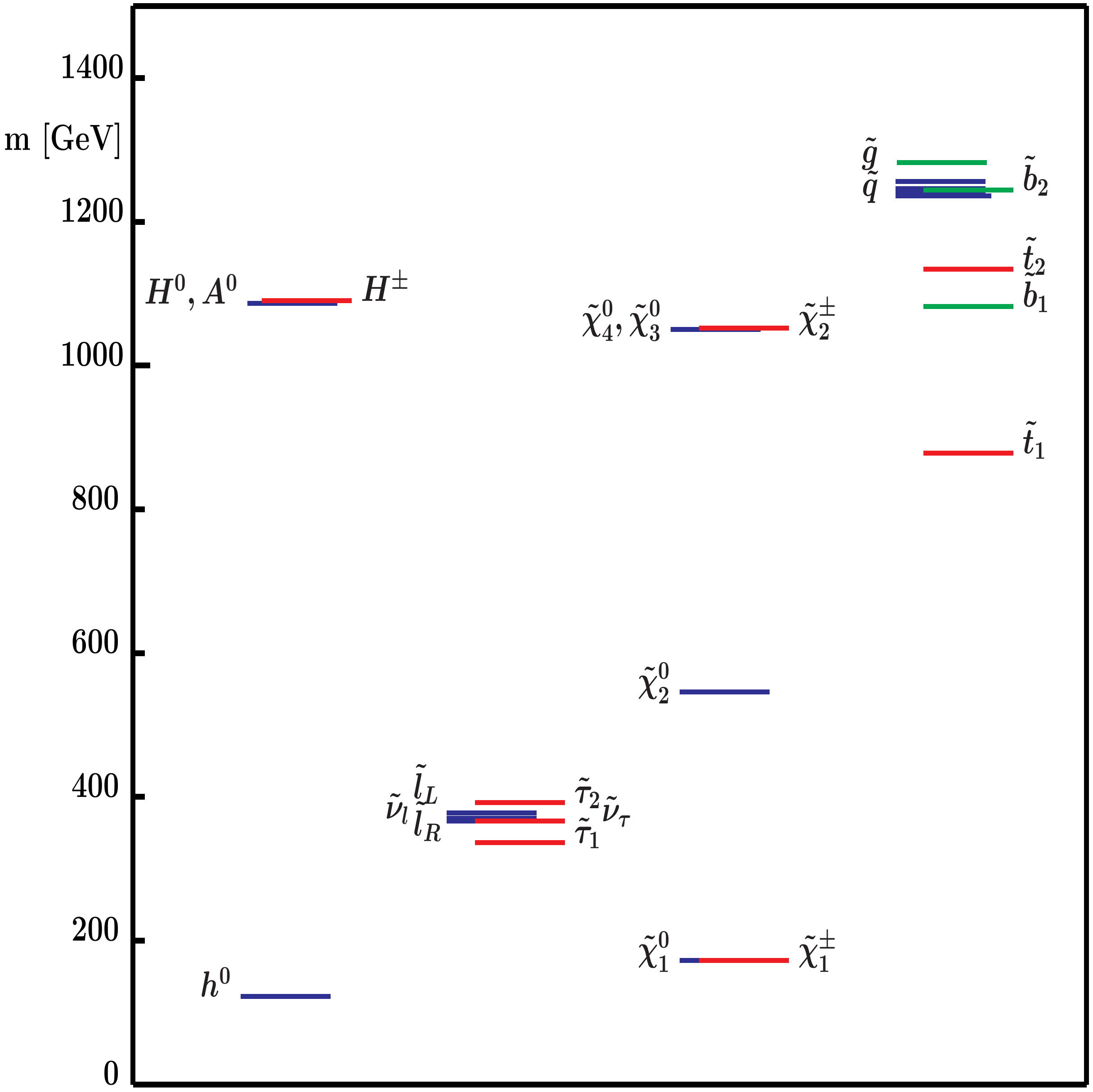
mAMSB scenario characterized by

$$m_{3/2}, m_0, \tan\beta, \mathrm{sign}(\mu)$$

$m_{3/2} = \langle F \rangle / M_{\text{Planck}}$: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term introduced in order to keep squares of slepton masses positive

AMSB scenario (SPS 9):



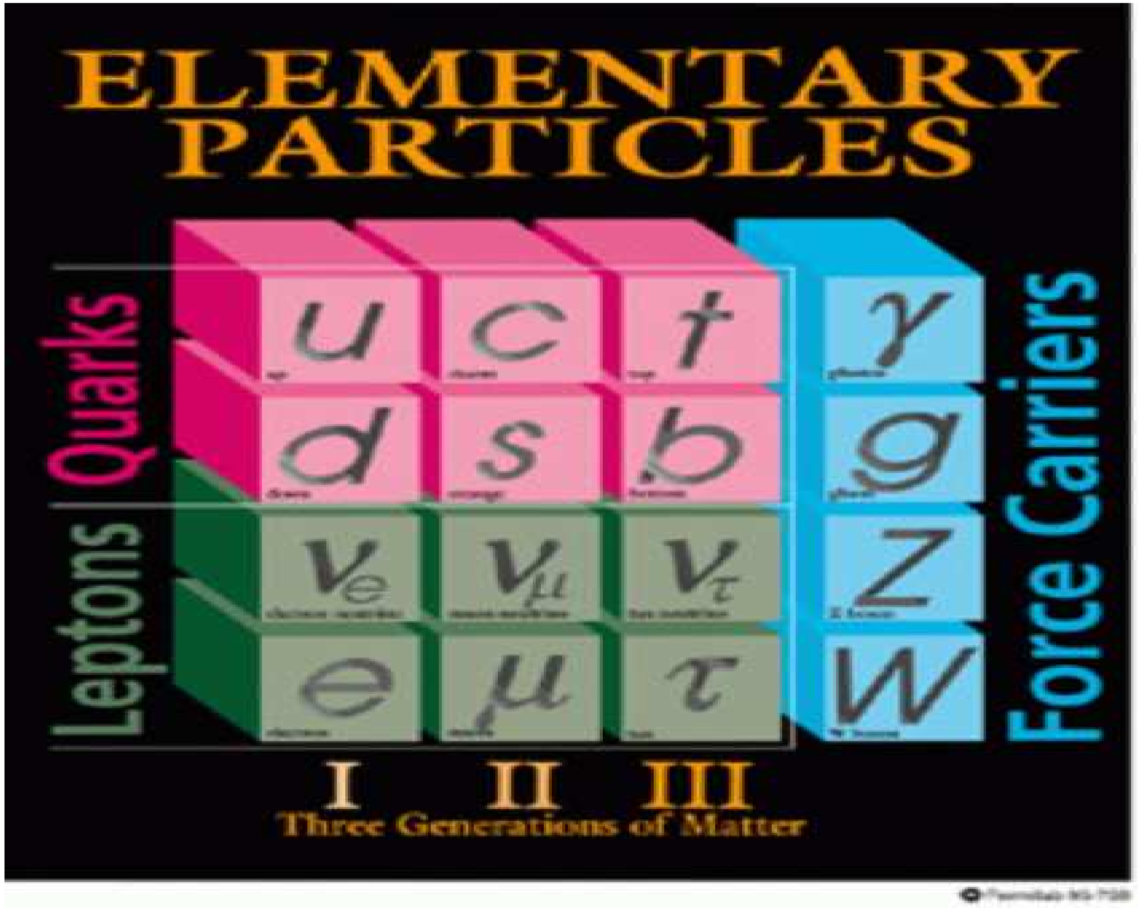
typical feature: very small neutralino–chargino mass difference

$\Rightarrow \tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm$

with very soft pions

1.5 The Standard Model Higgs Sector

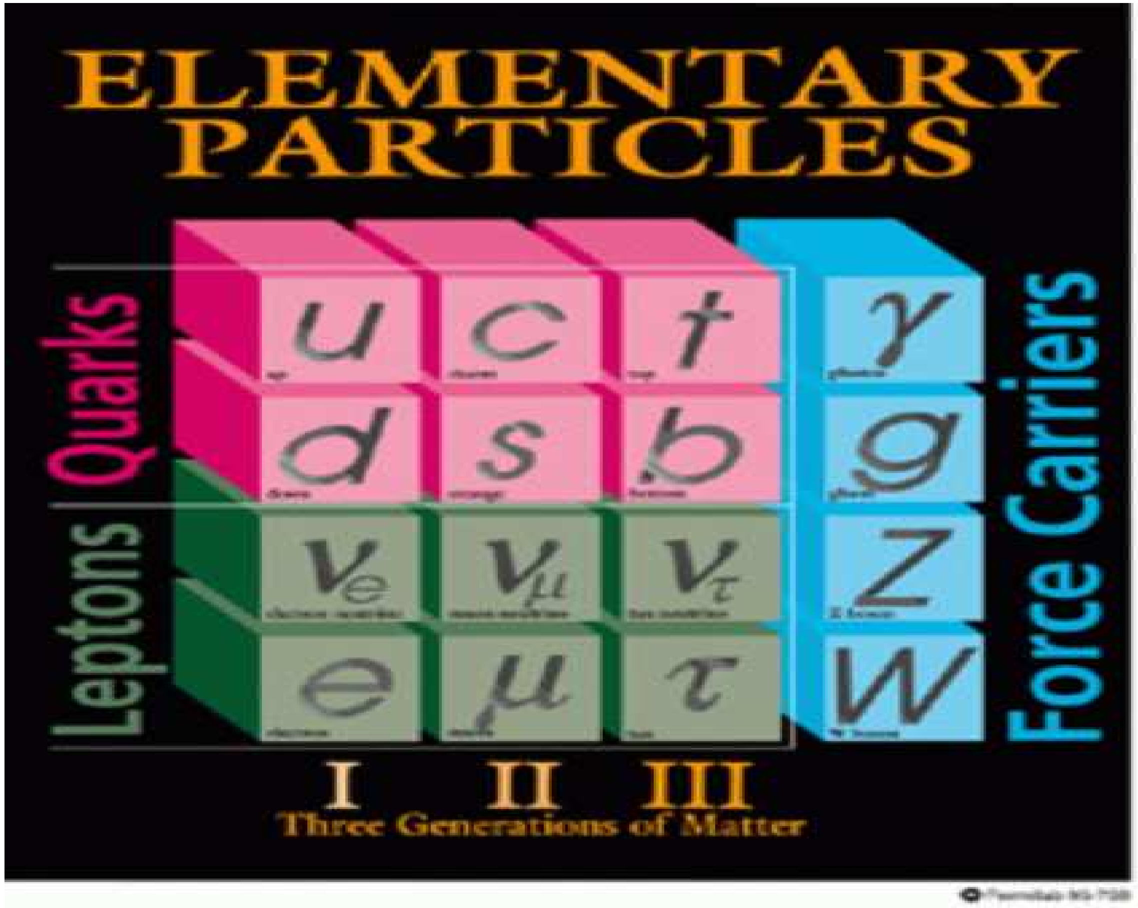
Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

1.5 The Standard Model Higgs Sector

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

⇒ but one particle is missing . . .

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:

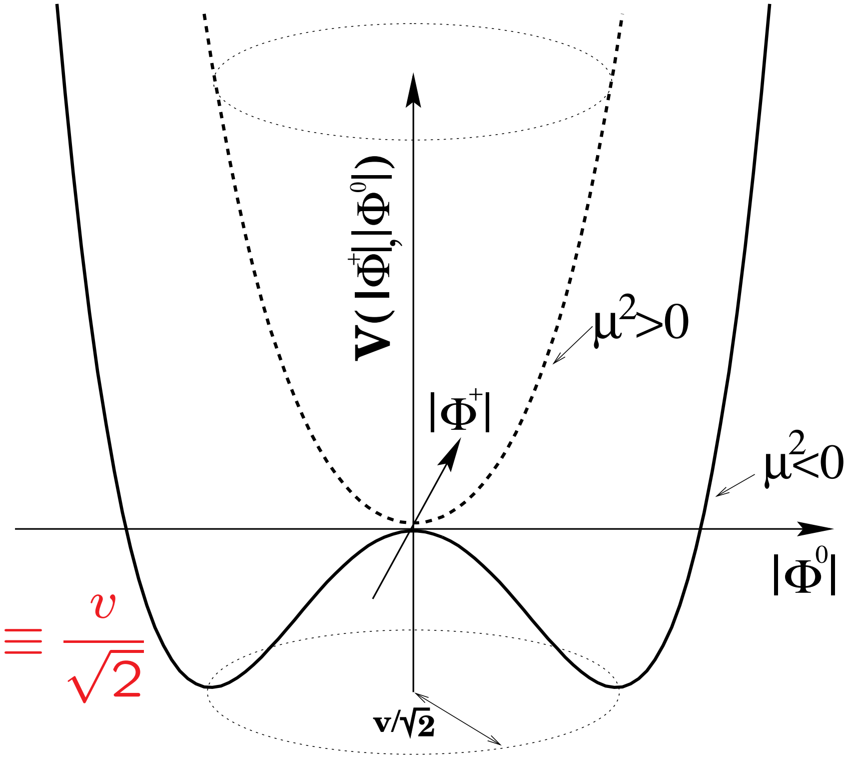
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

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

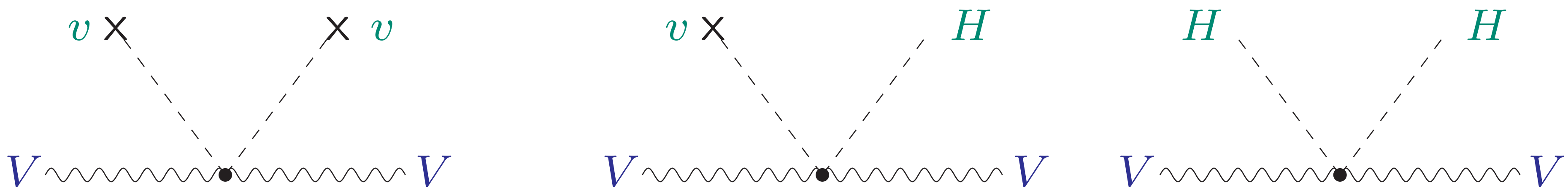
Lagrange density:

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

Gauge invariant coupling to gauge fields

$\Rightarrow$ mass terms for gauge bosons and fermions

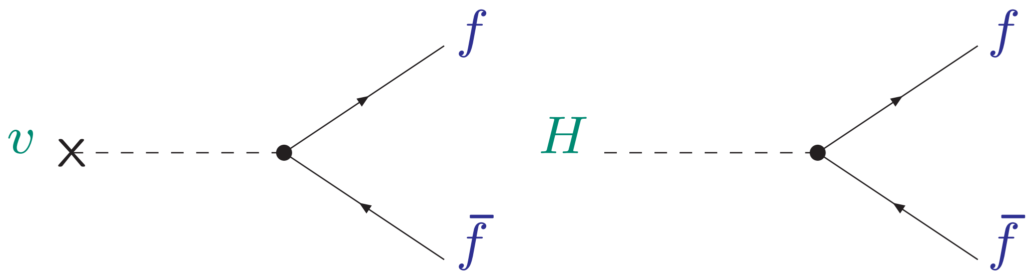
1.) $VV\Phi\Phi$ coupling:



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

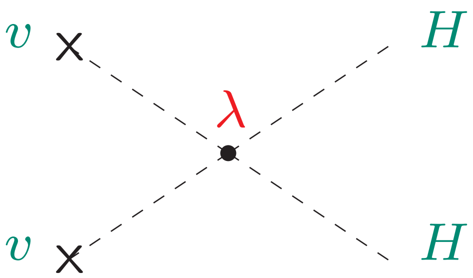
$g_2^2 v^2/2 \equiv M_W^2$, $(g_1^2 + g_2^2) v^2/2 \equiv M_Z^2$ $\Rightarrow$ coupling $\propto$ masses

2.) fermion mass terms: Yukawa couplings



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

3.) mass of the Higgs boson: self coupling



. . .

$\lambda = M_H^2/v$

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

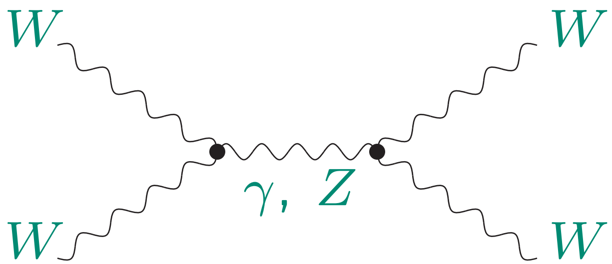
$\longrightarrow$ last unknown parameter of the SM

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

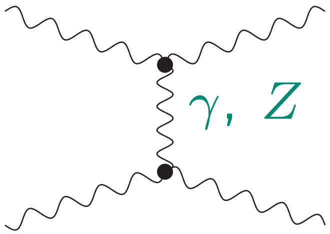
Another effect of the Higgs field:

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

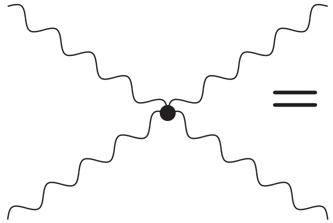
$\mathcal{M}_V =$



$+$



$+$



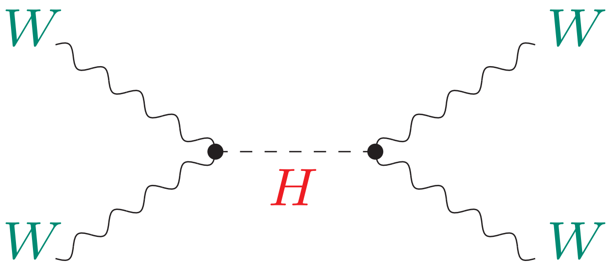
$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$

for $E \to \infty$

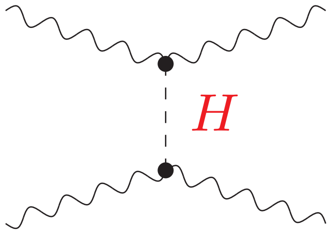
$\Rightarrow$ violation of unitarity

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 $E \to \infty$

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

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

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

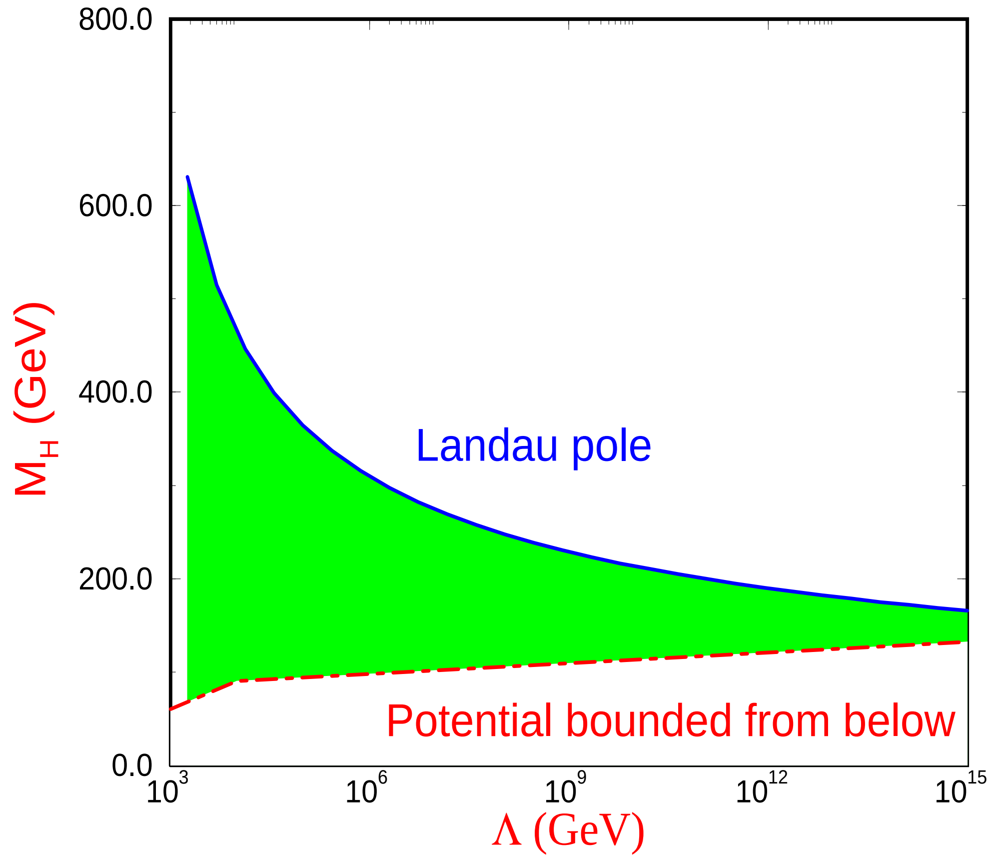
What else do we know about the Higgs boson?

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

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

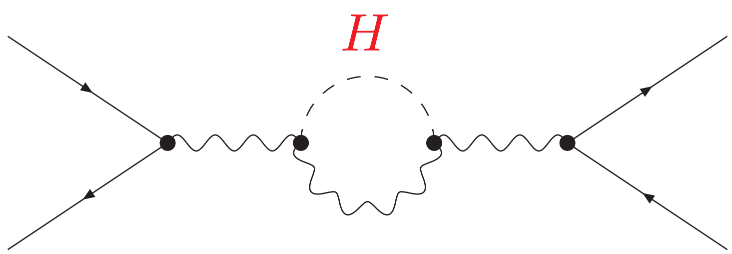
Indirect measurements via precision observables (POs):

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

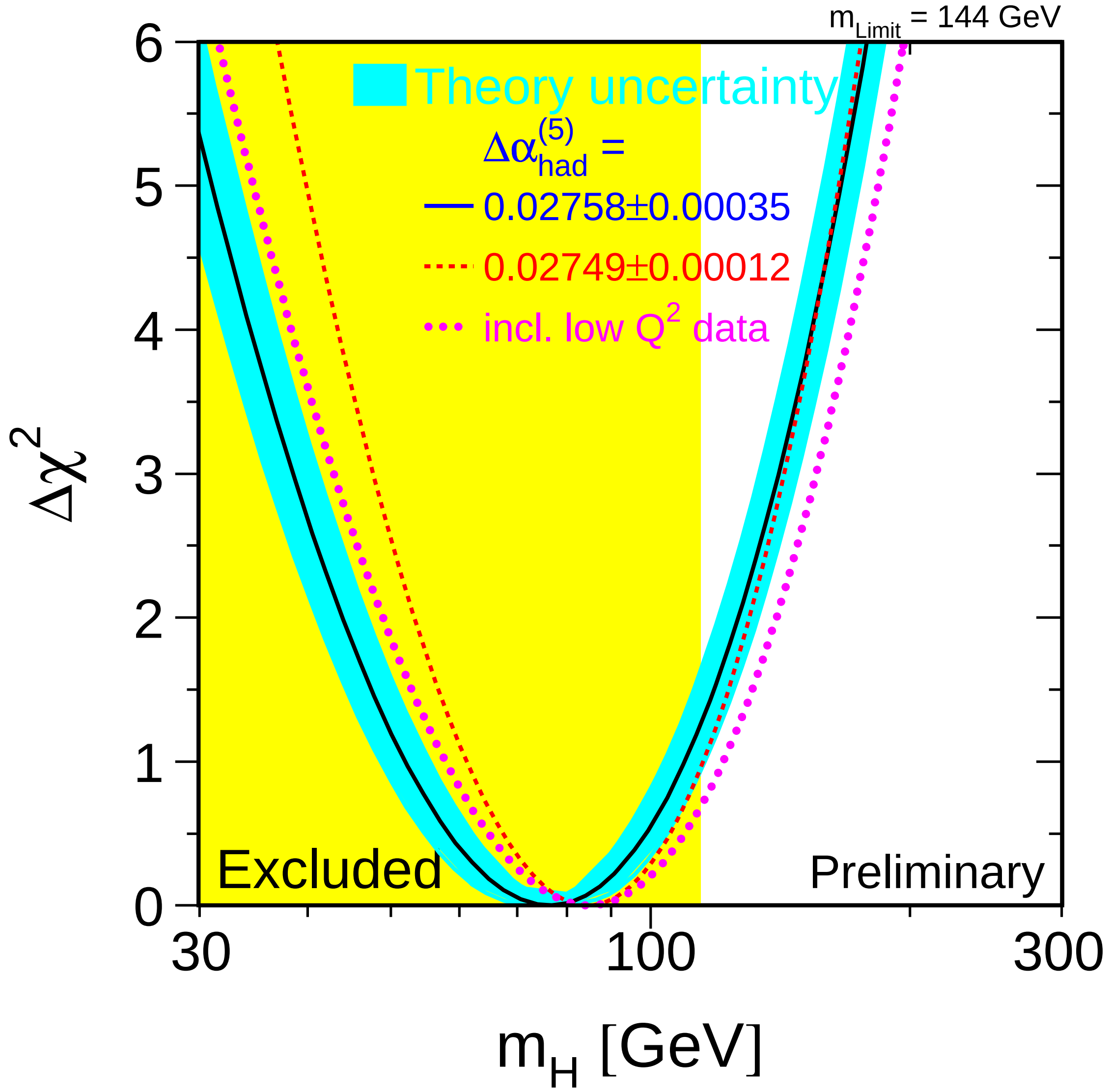
limits on M_H

Global fit to all SM data:

[*LEPEWWG '07*]

$\Rightarrow M_H = 76^{+33}_{-24}$ GeV

$M_H < 144$ 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, $M_H \lesssim 150$ GeV

2. The MSSM Higgs Sector with real parameters

Two Higgs doublets:

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1^0 - i\chi_1^0)/\sqrt{2} \\ -\phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + i\chi_2^0)/\sqrt{2} \end{pmatrix}
\end{aligned}
$$

$\rightarrow$ Higgs potential (for the neutral Higgs bosons)

2. The MSSM Higgs Sector with real parameters

Two Higgs doublets:

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

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

Higgs potential:

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

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

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

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

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

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

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

h, H: neutral, $\mathcal{CP}$-even, A^0: neutral, $\mathcal{CP}$-odd, $H^\pm$: charged

Gauge-boson masses:

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

Problem:

MSSM contains term $\mu H_1 H_2$ in superpotential

μ: dimensionful parameter

For ew symmetry breaking required: $\mu \sim$ electroweak scale

But: no a priori reason for $\mu \neq 0$, $\mu \ll M_\mathrm{P}$

(problem mainly in GMSB scenario, easier to overcome in mSUGRA)

Possible solution:

μ related to v.e.v. of additional field

$\Rightarrow$ Introduction of extra singlet field S, v.e.v. s $\Rightarrow$ "NMSSM"

Superpotential: $\mathcal{V} = \lambda H_1 H_2 S + \frac{1}{3}\kappa S^3 + \ldots$

Physical states in NMSSM Higgs-sector:

S_1, S_2, S_3 (CP-even), P_1, P_2 (CP-odd), $H^\pm$

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:

$$M^{2,\text{tree}}_{\text{Higgs}} = \begin{pmatrix} m^2_{\phi_1} & m^2_{\phi_1\phi_2} \\ m^2_{\phi_1\phi_2} & m^2_{\phi_2} \end{pmatrix} =$$

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

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

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

Tree-level result for m_h, m_H:

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

$\Rightarrow$ $m_h \leq M_Z$ 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)

Higgs couplings, tree level:

$$
\begin{aligned}
g_{hVV} &= \sin(\beta-\alpha)\, g_{HVV}^{\text{SM}}, \qquad V = W^\pm, Z \\
g_{HVV} &= \cos(\beta-\alpha)\, g_{HVV}^{\text{SM}} \\
g_{hAZ} &= \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_W}
\end{aligned}
$$

$$
\begin{aligned}
g_{hb\bar{b}}, g_{h\tau^+\tau^-} &= -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{\text{SM}} \\
g_{ht\bar{t}} &= \frac{\cos\alpha}{\sin\beta}\, g_{Ht\bar{t}}^{\text{SM}} \\
g_{Ab\bar{b}}, g_{A\tau^+\tau^-} &= \gamma_5 \tan\beta\, g_{Hb\bar{b}}^{\text{SM}}
\end{aligned}
$$

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

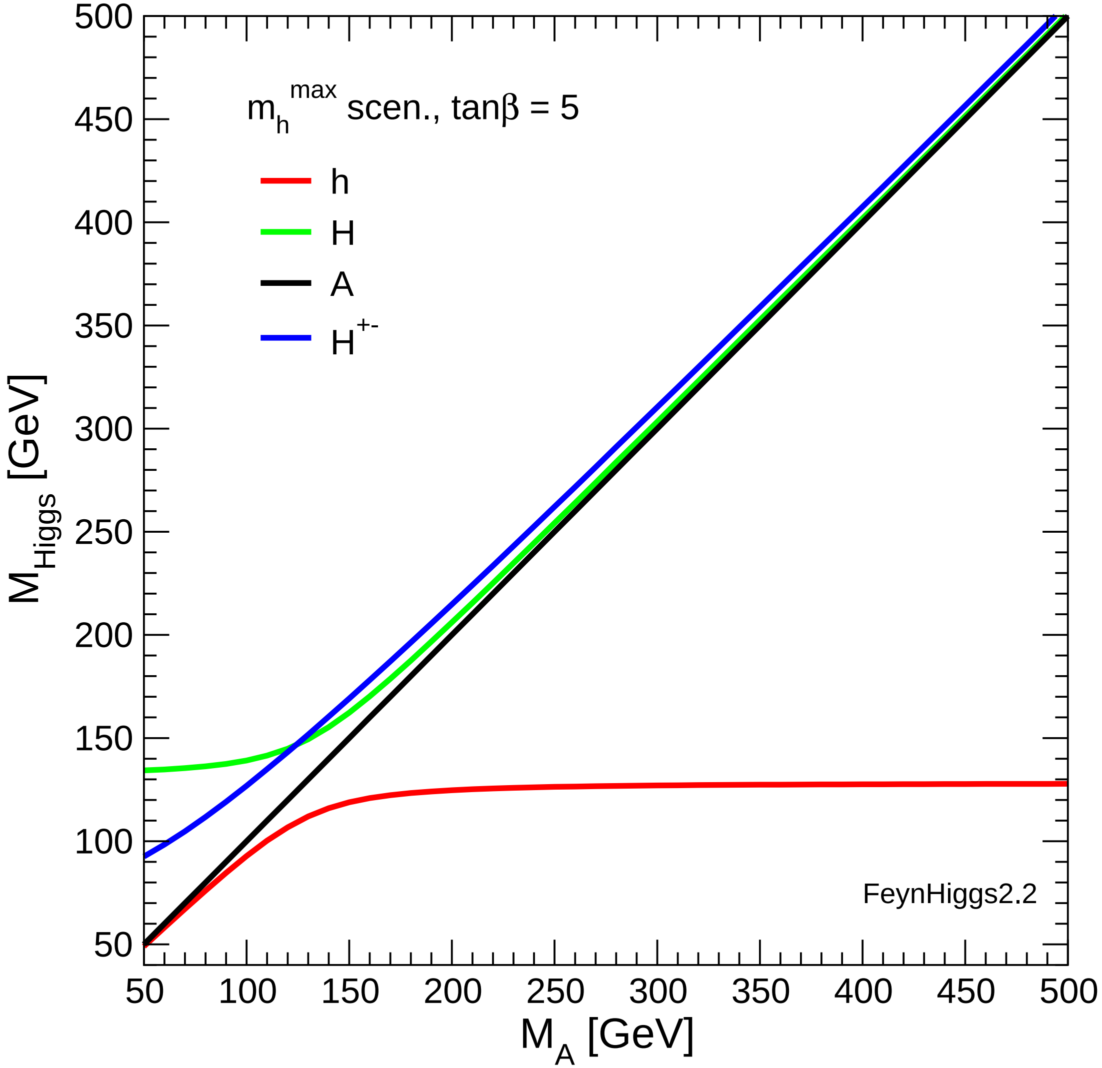
$g_{hb\bar{b}}, g_{h\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

The decoupling limit:

For $M_A \gtrsim 150$ GeV:

The lightest MSSM Higgs is SM-like

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



of course there are exceptions . . .

Higgs mass bounds in SUSY theories

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

$$\boxed{M_h \lesssim 135 \text{ GeV}}$$

for $m_t = 170.9 \pm 1.8\,\text{GeV}$

(including theoretical uncertainties from unknown higher orders)
$\Rightarrow$ observable at the LHC

Obtained with:

FeynHiggs

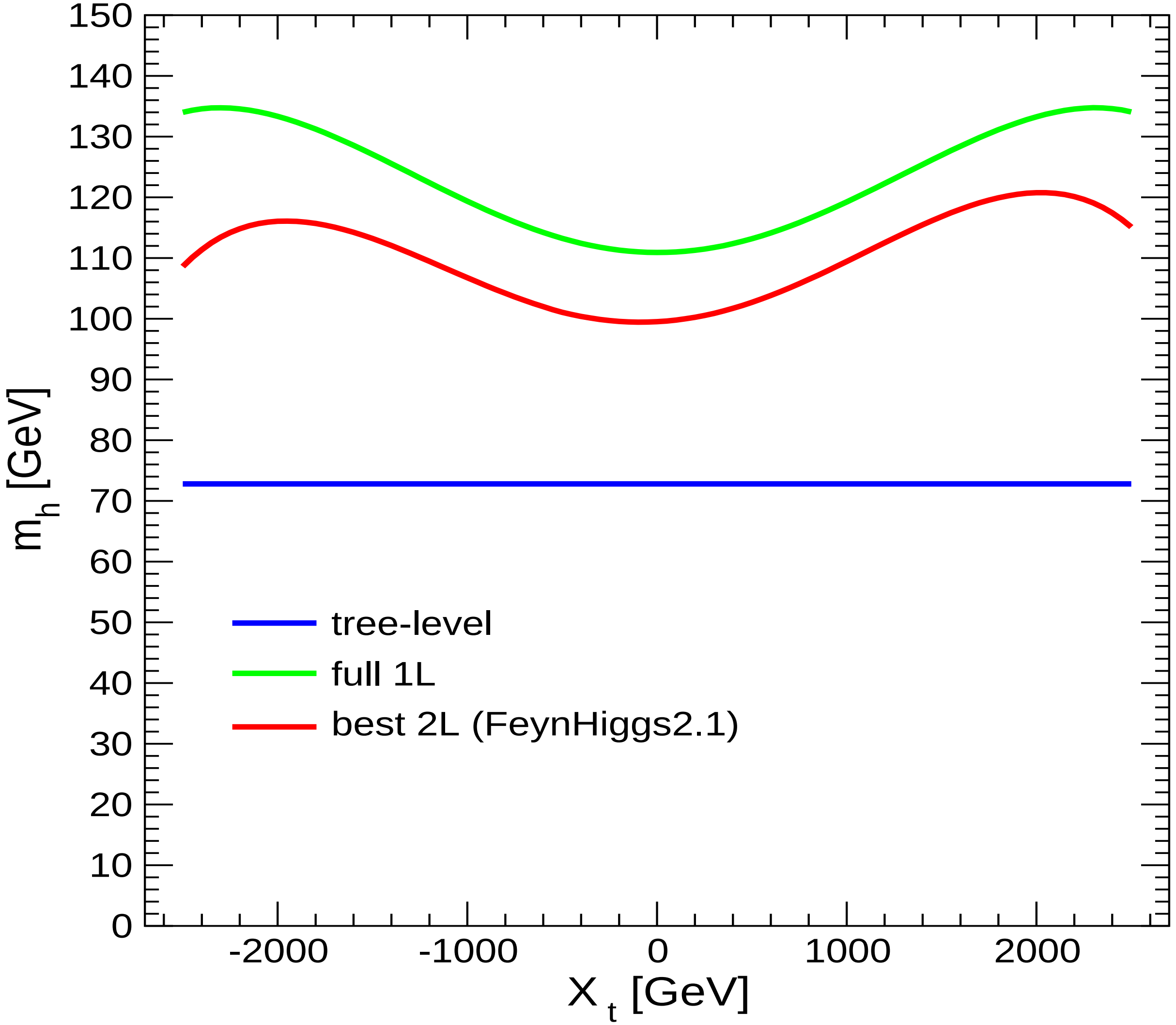
[*S.H., W. Hollik, G. Weiglein '98, '00, '02*]
[*T. Hahn, S.H., W. Hollik, G. Weiglein '03 – '07*]

`www.feynhiggs.de`

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

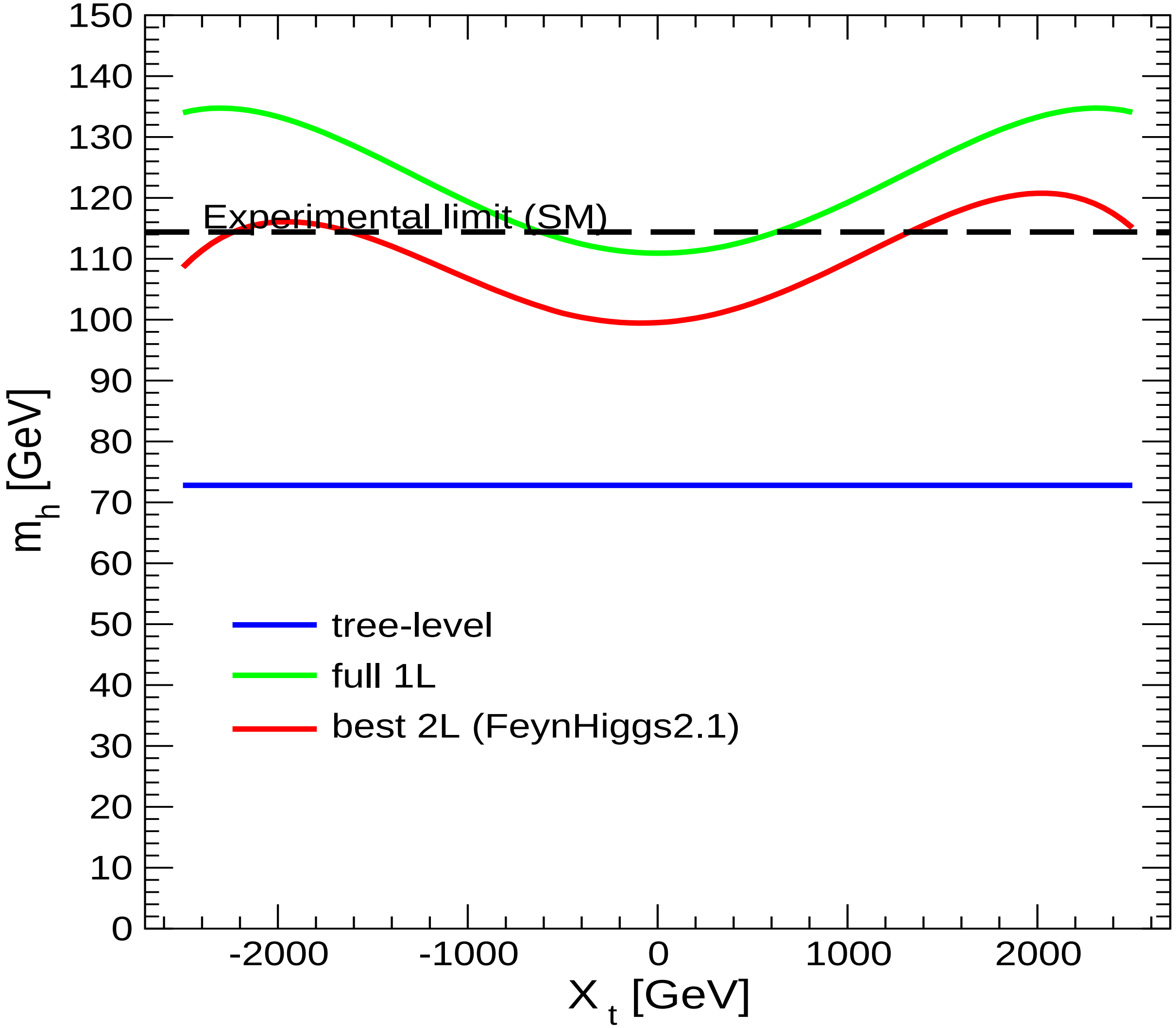
Effects of the two-loop corrections to the lightest Higgs mass:

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

Upper bound $M_h \lesssim 135$ GeV reduced by

$\approx 7, 12, 11$ GeV in mSUGRA , GMSB , AMSB scenarios

[S. Ambrosanio, A. Dedes, S.H., S. Su, G. Weiglein'01]

Upper bound on M_h in extensions of MSSM: $M_h \lesssim 200$ GeV
(no new gauge groups!)

[G. Kane, C. Kolda, J. Wells '93] [J. Espinosa, M. Quirós '93, '98]

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

definite and robust prediction of SUSY models

testable at next generation of colliders

Remaining theoretical uncertainties in prediction for M_h in the MSSM:

[*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

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

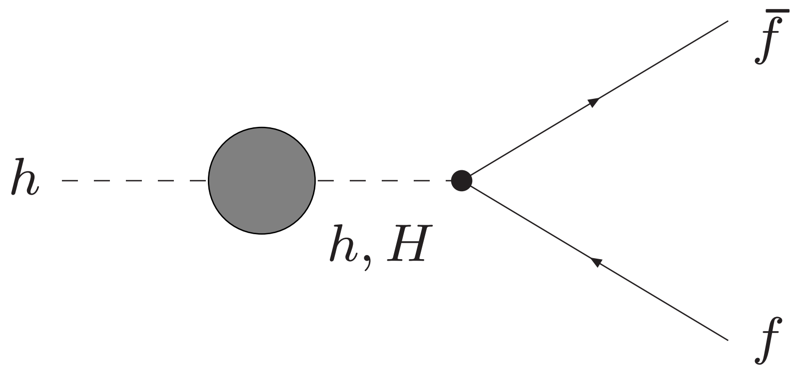
  $\Delta m_t \approx 2$ GeV $\;\Rightarrow\; \Delta M_h \approx 2$ GeV

Higgs couplings, production cross sections

Also affected by large SUSY loop corrections

FD two-loop corrections implemented in results for $h \to f\bar{f}$, $e^+e^- \to hZ, hA$
[*S.H., W. Hollik, G. Weiglein '00*]
[*S.H., W. Hollik, J. Rosiek, G. Weiglein'01*]

$hf\bar{f}$ coupling:



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

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

Gluino vertex corrections to $h \to q\bar{q}$:

$\Rightarrow$ ratio $\Gamma(h \to \tau^+\tau^-)/\Gamma(h \to b\bar{b})$ can significantly differ from SM value for large $\tan\beta$

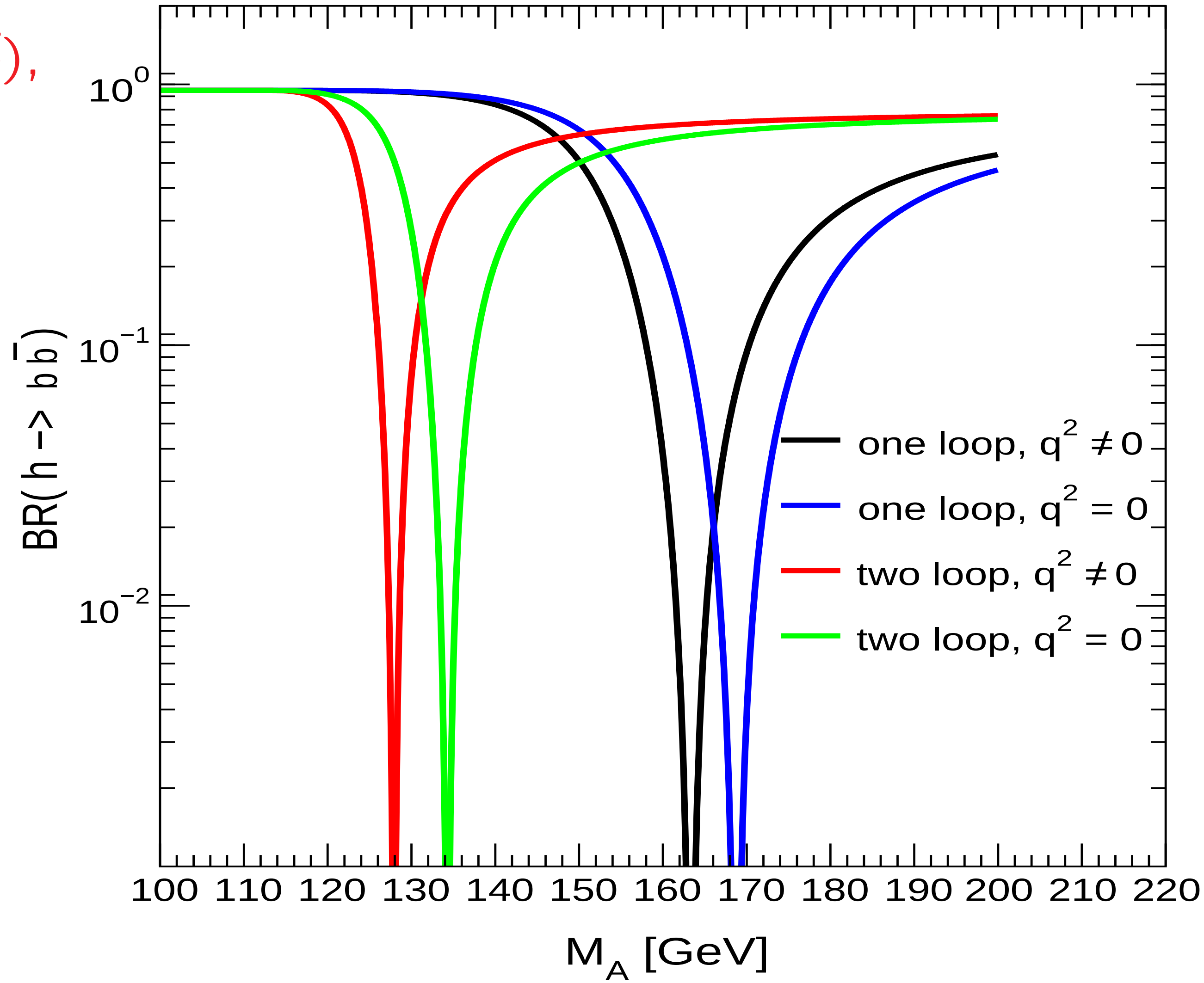
Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{\rm hH}$

$\Rightarrow$ "Pathological regions"

[*W. Loinaz, J. Wells '98*] [*M. Carena, S. Mrenna, C. Wagner '99*]

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

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



3. The Higgs sector in the MSSM with complex parameters (cMSSM)

Higgs potential of the cMSSM contains two Higgs doublets:

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

Five physical states: $h^0, H^0, A^0, H^\pm$ (no $\mathcal{CP}$V at tree-level)

2 $\mathcal{CP}$-violating phases: ξ, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

Input parameters: $\tan\beta = \frac{v_2}{v_1}$, M_A or $M_{H^\pm}$

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

- μ : Higgsino mass parameter
- $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^* \{\cot\beta, \tan\beta\}$ complex
- $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)
- M_3 : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \to (h_3, h_2, h_1)$$

with

$$M_{h_3} > M_{h_2} > M_{h_1}$$

Inclusion of higher-order corrections:

($\rightarrow$ Feynman-diagrammatic approach)

Propagator / mass matrix with higher-order corrections:

$$\begin{pmatrix} q^2 - M_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H, A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow \mathcal{CP}$V, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

Results available for $\hat{\Sigma}_{ij}$:

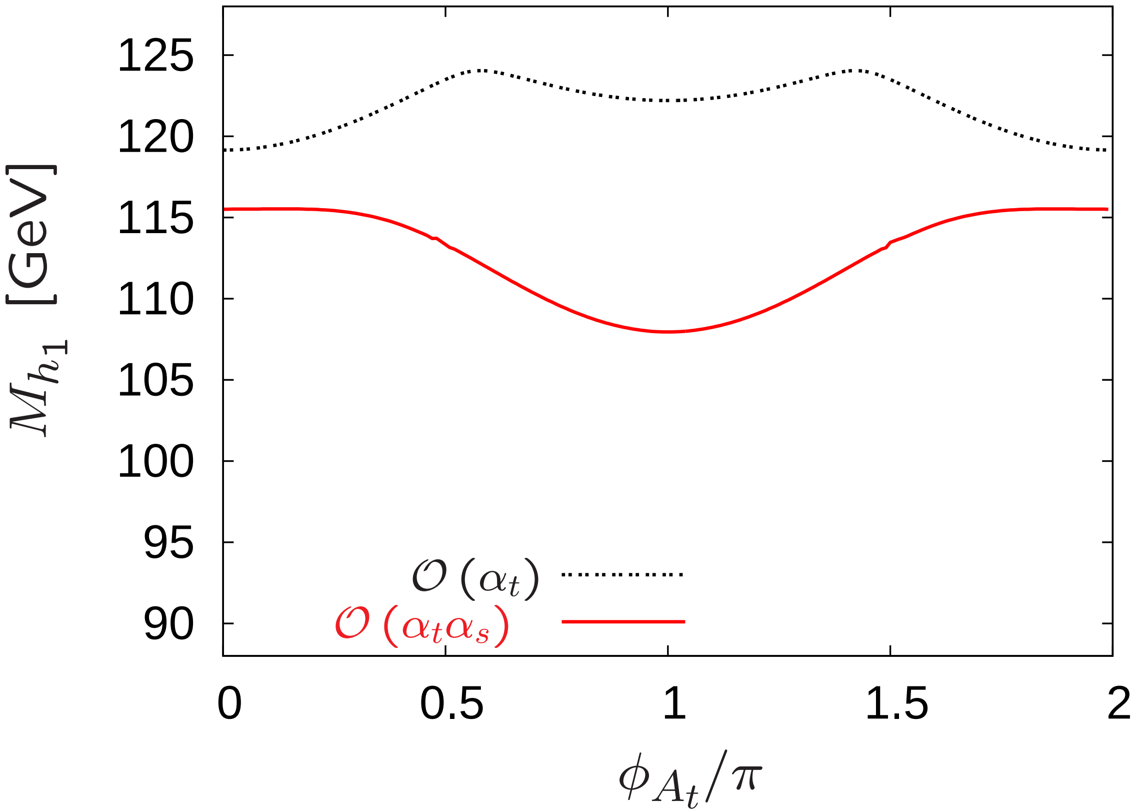
– full 1-loop evaluation: dependence on all possible phases included

– New: $\mathcal{O}(\alpha_t\alpha_s)$ corrections in the FD approach

(rMSSM: difference between FD and RGiEP approach $\mathcal{O}$(few GeV))

M_{h_1} as a function of ϕ_{A_t}:

[S.H., W. Hollik, H. Rzehak, G. Weigelin '05]



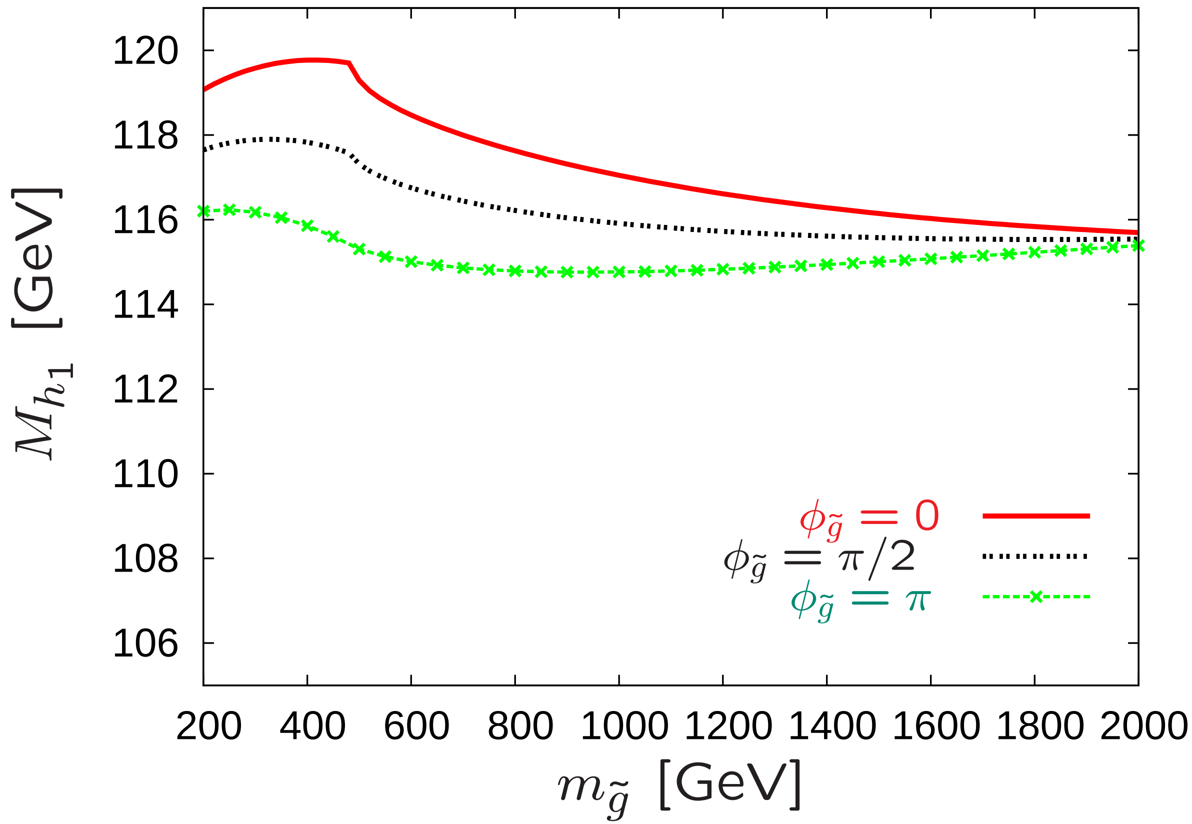
$M_{\mathrm{SUSY}} = 1000$ GeV
$|A_t| = 2000$ GeV
$\tan\beta = 10$
$M_{H^\pm} = 150$ GeV

OS renormalization

$\Rightarrow$ modified dependence on ϕ_{A_t} at the 2-loop level

M_{h_1} as a function of $\phi_{\tilde{g}}$:

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



$M_{\text{SUSY}} = 500$ GeV
$A_t = 1000$ GeV
$\tan\beta = 10$
$M_{H^\pm} = 500$ GeV

OS renormalization

$\Rightarrow$ threshold at $m_{\tilde{g}} = m_{\tilde{t}} + m_t$

$\Rightarrow$ large effects around threshold

$\Rightarrow$ phase dependence has to be taken into account

4. The code FeynHiggs 2.5

Latest version: FeynHiggs 2.5 (11/06)

real MSSM:

contains all available higher-order corrections
to Higgs boson masses and couplings

FeynHiggs contains
– full 1 loop calculations
– all available 2 loop calculations (leading and subleading)
– very leading 3 loop contributions

complex MSSM:

contains nearly all available results
(we are (even currently) working on the rest)

`www.feynhiggs.de`

Included in FeynHiggs 2.5 (I):

Evaluation of all Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}$, α_{eff}, $\mathbf{Z}_{ij}$, $\mathbf{U}_{ij}$, . . .

Evaluation of all neutral Higgs boson decay channels $\Leftarrow$ with $\mathbf{Z}$

- total decay width Γ_{tot}
- $\text{BR}(h_i \to f\bar{f})$: decay to SM fermions
- $\text{BR}(h_i \to \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$: decay to SM gauge bosons
- $\text{BR}(h_i \to h_1 Z^{(*)}, h_1 h_1)$: decay to gauge and Higgs bosons
- $\text{BR}(h_i \to \tilde{f}_i \tilde{f}_j)$: decay to sfermions
- $\text{BR}(h_i \to \tilde{\chi}_i^\pm \tilde{\chi}_j^\pm, \tilde{\chi}_i^0 \tilde{\chi}_j^0)$: decay to charginos, neutralinos

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- total decay width $\Gamma_{\text{tot}}^{\text{SM}}$
- $\text{BR}(h_i^{\text{SM}} \to f\bar{f})$: decay to SM fermions
- $\text{BR}(h_i^{\text{SM}} \to \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$: decay to SM gauge bosons

Included in FeynHiggs 2.5 (II):

Evaluation of all neutral Higgs boson production cross sections at Tevatron/LHC $\Leftarrow$ with $\mathbf{Z}$

SM: most up-to-date, MSSM: additional effective couplings

- $gg \to h_i$: gluon fusion
- $WW \to h_i$, $ZZ \to h_i$: gauge boson fusion
- $W \to Wh_i$, $Z \to Zh_i$: Higgs strahlung
- $b\bar{b} \to b\bar{b}h_i$: Yukawa process
- $b\bar{b} \to b\bar{b}h_i$, $h_i \to b\bar{b}$, one b tagged
- $t\bar{t} \to t\bar{t}h_i$: Yukawa process
- $\tilde{t}_1\tilde{t}_1 \to \tilde{t}_1\tilde{t}_1 h_i$: SUSY-Yukawa process

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- all SM-like channels as above

Included in FeynHiggs 2.5 (III):

Evaluation of all charged Higgs boson decay channels (rMSSM/cMSSM)

- total decay width $\Gamma_{\rm tot}$
- $\mathrm{BR}(H^+ \to f \bar{f}')$: decay to SM fermions
- $\mathrm{BR}(H^+ \to h_i W^+)$: decay to gauge and Higgs bosons
- $\mathrm{BR}(H^+ \to \tilde{f}_i \tilde{f}'_j)$: decay to sfermions
- $\mathrm{BR}(H^+ \to \tilde{\chi}^0_i \tilde{\chi}^+_j)$: decay to charginos and neutralinos

Evaluation of additional couplings: $\Leftarrow$ with $\mathbf{U}$

- $g(V \to V h_i, h_i h_j)$: coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$: all Higgs self couplings (including charged Higgs)
- $\sigma(\gamma\gamma \to h_i)$: Higgs production XS at a γC

Included in FeynHiggs 2.5 (IV):

Evaluation of theory error on masses and mixing

$\rightarrow$ estimate of uncertainty in $M_{h_i}, \mathbf{U}_{ij}, \mathbf{Z}_{ij}$ from unknown higher-order corr.

Evaluation of masses, mixing and decay in the NMFV MSSM

NMFV: Non Minimal Flavor Violation *[Hahn, S.H., Hollik, Merz, Peñaranda '04-'06]*
$\Rightarrow$ Connection to Flavor physics

Evaluation of additional constraints (rMSSM/cMSSM)

- ρ-parameter: $\Delta\rho^{\text{SUSY}}$ at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_s)$, ..., including NMFV effects
  $\Rightarrow M_W$, $\sin^2\theta_{\text{eff}}$ via SM formula + $\Delta\rho^{\text{SUSY}}$, including NMFV effects
- anomalous magnetic moment of the μ: $(g-2)_\mu$
- BR$(b \rightarrow s\gamma)$, including NMFV effects *[T. Hahn, W. Hollik, J. Illana, S. Peñaranda '06]*
- LEP Higgs constraints *[LEP Higgs WG '06]*
- EDMs of electron, neutron, Hg, ...

Planned:

- ILC production cross sections

How to install FeynHiggs 2.5

1. Go to www.feynhiggs.de

2. Download the latest version

3. type `./configure`, `make`, `make install`
   $\Rightarrow$ library `libFH.a` is created

4. 4 possible ways to use *FeynHiggs*:

   A) Command-line mode

   B) called from a Fortran/C++ code

   C) called within Mathematica
   D) WWW mode

   processing of Les Houches Accord data possible

5. Detailed instructions and help are provided in the man pages

How to run FeynHiggs 2.5

A) Command-line mode

Input File

```
MT          172.7
MB          4.7
MW          80.4
MZ          91.1
MSusy       975
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Command

FeynHiggs *file flags* →

Screen Output

```
------------------- HIGGS MASSES -------------------
| Mh0     =   116.022817
| MHH     =   199.943497
| MA0     =   200.000000
| MHp     =   216.973920
| SAeff   =  -0.02685112
| UHiggs =   0.99999346  -0.00361740   0.00000000 \
|            0.00361740   0.99999346   0.00000000 \
|            0.00000000   0.00000000   1.00000000

-------------- ESTIMATED UNCERTAINTIES -------------
| DeltaMh0   =  1.591957
| DeltaMHH   =  0.004428
| DeltaMA0   =  0.000000
| DeltaMHp   =  0.152519
  ...
```

- Loops over parameter values possible (parameter scans).
- Mask off details with `FeynHiggs` *file flags* `| grep -v %`
- `table` utility converts to machine-readable format, e.g.
  `FeynHiggs` *file flags* `| table TB Mh0 > outfile`

SUSY Les Houches Accord Format

Input File

```
BLOCK MODSEL
    1     1
BLOCK MINPAR
    1    0.10000E+03  # m0
    2    0.25000E+03  # m12
    3    0.10000E+02  # tanb
    4    0.10000E+01  # sgn mu
    5   -0.10000E+03  # A
BLOCK SMINPUTS
    4    0.91187E+02  # MZ
    5    0.42500E+01  # mb(mb)
    6    0.17500E+03  # t
  ...
```

Command

FeynHiggs *file flags* $\longrightarrow$

file.fh

```
BLOCK MASS
   25    1.12697840E+02    # Mh0
   35    4.00145460E+02    # MHH
   36    3.99769788E+02    # MA0
   37    4.08050556E+02    # MHp
  ...
BLOCK ALPHA
        -1.10658125E-01    # Alpha
  ...
```

- { Uses / was developed into } the SLHA I/O Library. [*T. Hahn '04*]
- SLHA can also be used in Library Mode with `FHSetSLHA`.
- *FeynHiggs* tries to read each file in SLHA format first.
  If that fails, fallback to native format.

B) Called from a Fortran/C++ code

Link *FeynHiggs* as a subroutine $\Rightarrow$ link `libFH.a`

`call FHSetFlags(...)` :
$\longrightarrow$ specification of accuracy etc.

`call FHSetPara(...)` :
$\longrightarrow$ specify input parameters

`call FHGetPara(...)` :
$\longrightarrow$ obtain derived parameters

`call FHHiggsCorr(...)` :
$\longrightarrow$ obtain Higgs boson masses and mixings

`call FHUncertainties(...)` :
$\longrightarrow$ obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

`call FHCouplings(...)` :
$\longrightarrow$ obtain decay widths, BRs, XSs, etc.

C) Called within Mathematica

- install the math link to *MFeynHiggs* , e.g.:

  `Install[''MFeynHiggs'']`

- `FHSetFlags[...]` :
  → specification of accuracy etc.

  `FHSetPara[...]` :
  → specify input parameters

  `FHGetPara[]` :
  → obtain derived parameters

  `FHHiggsCorr[]` :
  → obtain Higgs boson masses and mixings

  `FHUncertainties[]` :
  → obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

  `FHCouplings[]` :
  → obtain decay widths, BRs etc.

D) WWW mode

1. The FeynHiggs User Control Center is available at

   www.feynhiggs.de/fhucc

2. Enter you parameters on-line in the web page

3. Obtain your results with a mouse click

$\Rightarrow$ for single points and checks of your downloaded version of FeynHiggs
$\Rightarrow$ always the latest version

$\boxed{\Rightarrow \text{online presentation}}$

Also man pages are available on-line

D) WWW mode

1. The FeynHiggs User Control Center is available at /fhucc
2.
3.

⇒ Higgs

⇒

Also man pages are available on-line