Precise determination of the neutral Higgs boson masses in the MSSM

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Based on:

B. Allanach, A. Djouadi, J.L. Kneur, W. Porod and P. S.,

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The Minimal Supersymmetric Standard Model

- Superfield Content: $\begin{cases} G^a\,,\ W^a\,,\ B & \text{(vector)} \\ L\,,\ Q\,,\ E^c\,,\ U^c\,,\ D^c\,,\ H_1\,,\ H_2 & \text{(chiral)} \end{cases}$

- MSSM superpotential [SU(3)×SU(2)×U(1) + R-parity]

$$W = \mu H_1 H_2 + h^E H_1 L E^c + h^D H_1 Q D^c + h^U H_2 Q U^c$$

- Supersymmetry must be broken without introducing quadratic divergences $\longrightarrow$ "soft" SUSY-breaking terms:

$$\begin{aligned} -\mathcal{L}_{\text{soft}} &= \frac{1}{2}\sum_A M_A \overline{\lambda}_A \lambda_A + \sum_i m_i^2 \, |\phi_i|^2 \\ &+ \ B H_1 H_2 + h^E A^E H_1 L E^c + h^D A^D H_1 Q D^c + h^U A^U H_2 Q U^c \end{aligned}$$

- $m_i^2\,,\ A^E\,,\ A^U\,,\ A^D$ are matrices in generation space

$\longrightarrow$ the MSSM contains 105 new parameters !!!

- The MSSM phenomenology becomes extremely complex unless we adopt some simplifying assumptions.

The Higgs sector of the MSSM at tree-level

- Two $SU(2) \times U(1)$ doublets: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$

$$H_i^0 = \frac{v_i + S_i + i\, P_i}{\sqrt{2}} \qquad \tan\beta = \frac{v_2}{v_1}$$

- The soft SUSY-breaking mass terms for H_1^0 and H_2^0 are responsible for electroweak symmetry breaking (EWSB):

$$\begin{aligned} V_{\text{tree}} &= (m_{H_1}^2 + \mu^2)\, |H_1^0|^2 + (m_{H_2}^2 + \mu^2)\, |H_2^0|^2 \\ &+ B\, \left(H_1^0 H_2^0 + \text{h.c.}\right) + \frac{1}{8}(g^2 + g'^2)\, \left(|H_1^0|^2 - |H_2^0|^2\right)^2 \end{aligned}$$

- Five physical states: $h\,,\ H\,,\ A^0\,,\ H^+\,,\ H^-$

- Tree–level mass matrix for the CP–even sector:

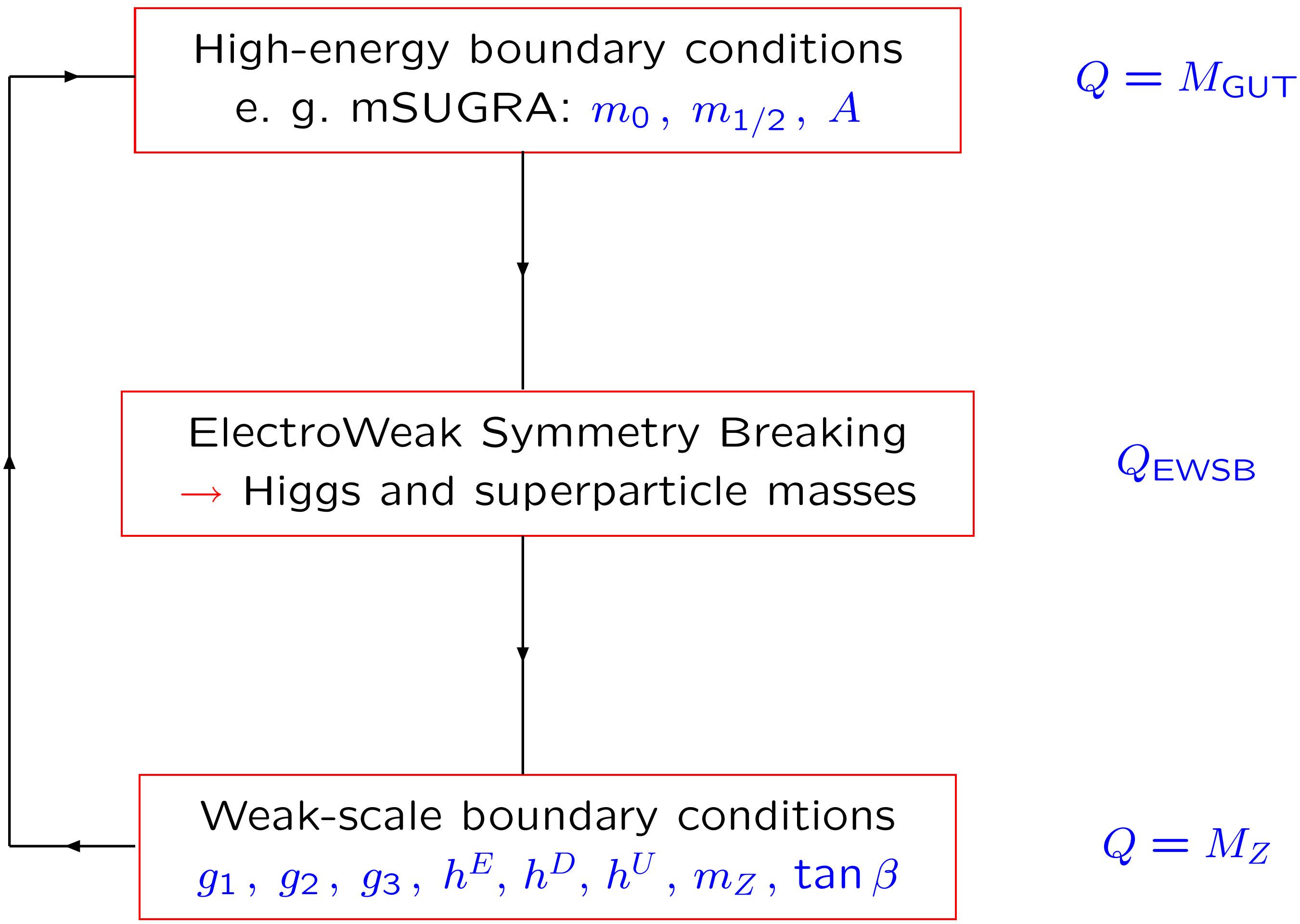
$$\left(\mathcal{M}_S^2\right)^{\text{tree}} = \begin{pmatrix} m_Z^2\, c_\beta^2 + m_A^2\, s_\beta^2 & -\left(m_Z^2 + m_A^2\right) s_\beta\, c_\beta \\ -\left(m_Z^2 + m_A^2\right) s_\beta\, c_\beta & m_Z^2\, s_\beta^2 + m_A^2\, c_\beta^2 \end{pmatrix}$$

$\rightarrow$ m_h and m_H are predicted in terms of m_Z, m_A and $\tan\beta$

- Tree–level mass relation: $m_h^2 \leq \cos^2 2\beta\, m_Z^2$ **!!!**

- Radiative corrections can push m_h well above the tree–level bound (e.g. $m_h \leq 135$ GeV for typical parameter choices) and introduce a dependence on many MSSM parameters.

High-energy boundary conditions and RG evolution



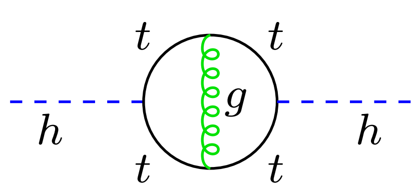
- Other models for the mechanism of SUSY–breaking: GMSB $(\Lambda\,,\ M_{\rm mess}\,,\ N_{\rm mess})$, AMSB $(m_{3/2}\,,\ m_0)$.

- RGEs provide the $\overline{\rm DR}$–renormalized parameters at $Q_{\rm EWSB}$, where we compute the masses for all the MSSM particles.

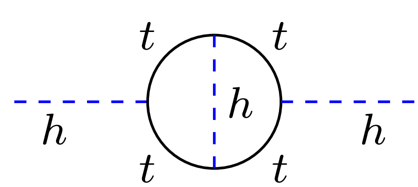
- The physical masses should not depend on the choice of $Q_{\rm EWSB}$, which can be anywhere between M_Z and the TeV scale.

Programs computing the MSSM mass spectrum

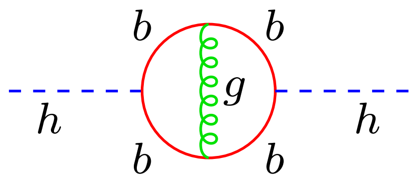
- We present the new versions of three public programs for the computation of the MSSM mass spectrum:
  - *SuSpect* 2.3 (A.Djouadi, J.L.Kneur and G.Moultaka)
  - *SoftSusy* 1.8.7 (B.Allanach)
  - *SPheno* 2.2.1 (W.Porod)
- In the latest versions, all the codes include a two–loop computation of the Higgs masses and EWSB conditions performed in the $\overline{\rm DR}$ renormalization scheme.
- The full one–loop corrections are taken from Pierce-Bagger-Matchev-Zhang (PBMZ) 1996.
- The leading two–loop corrections in the limit of zero external momentum in the self–energies are taken from Brignole-Dedes-Degrassi-Slavich-Zwirner (BDDSZ) 2001-2003.



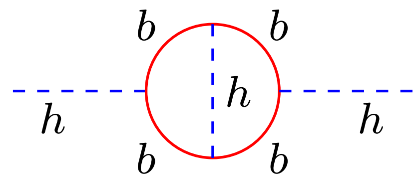
$\mathcal{O}(\alpha_t\alpha_s)$



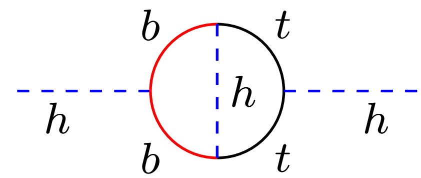
$\mathcal{O}(\alpha_t^2)$



$\mathcal{O}(\alpha_b\alpha_s)$



$\mathcal{O}(\alpha_b^2)$



$\mathcal{O}(\alpha_t\alpha_b)$

- We also computed and included the (small) two–loop corrections controlled by the tau Yukawa coupling.

Benchmark scenarios

- *Snowmass* points: six (out of ten) representative choices for the input parameters (see hep-ph/0202233)

mSUGRA:	m_0 (GeV)	$m_{1/2}$ (GeV)	A (GeV)	$\tan\beta$	sign(μ)
SPS1a	100	250	-100	10	$+$
SPS2	1450	300	0	10	$+$
SPS4	400	300	0	50	$+$
SPS5	150	300	-1000	5	$+$

GMSB:	Λ (TeV)	M_{mess} (TeV)	N_{mess}	$\tan\beta$	sign(μ)
SPS8	100	200	1	15	$+$

AMSB:	$m_{3/2}$ (TeV)	m_0 (GeV)		$\tan\beta$	sign(μ)
SPS9	60	450		10	$+$

- The SM input parameters: $M_t = 178.0 \pm 4.3$ GeV,

$$m_b(m_b)^{\overline{\text{MS}}} = 4.25 \pm 0.25 \text{ GeV}, \qquad M_\tau = 1.777 \text{ GeV},$$

$$M_Z = 91.1876 \text{ GeV}, \qquad G_F = 1.1663910^{-5} \text{ GeV}^{-2},$$

$$\alpha_{\text{em}}^{-1}(M_Z)^{\overline{\text{MS}}} = 127.934 \pm 0.027, \qquad \alpha_s(M_Z)^{\overline{\text{MS}}} = 0.1172 \pm 0.002.$$

Results for the Higgs masses

- Light CP-even Higgs boson mass m_h:

	SPS1a	SPS2	SPS4	SPS5	SPS8	SPS9
SoftSusy	112.1	116.8	114.1	116.3	115.4	117.4
SPheno	112.2	117.1	114.3	116.5	115.8	117.8
SuSpect	112.1	116.8	114.1	116.1	115.5	117.5

- Heavy CP-even Higgs boson mass m_H:

	SPS1a	SPS2	SPS4	SPS5	SPS8	SPS9
SoftSusy	406.5	1553.0	335.8	686.8	550.4	1056.9
SPheno	406.0	1554.6	360.5	686.5	552.4	1051.1
SuSpect	406.5	1552.1	355.3	686.9	550.6	1056.6

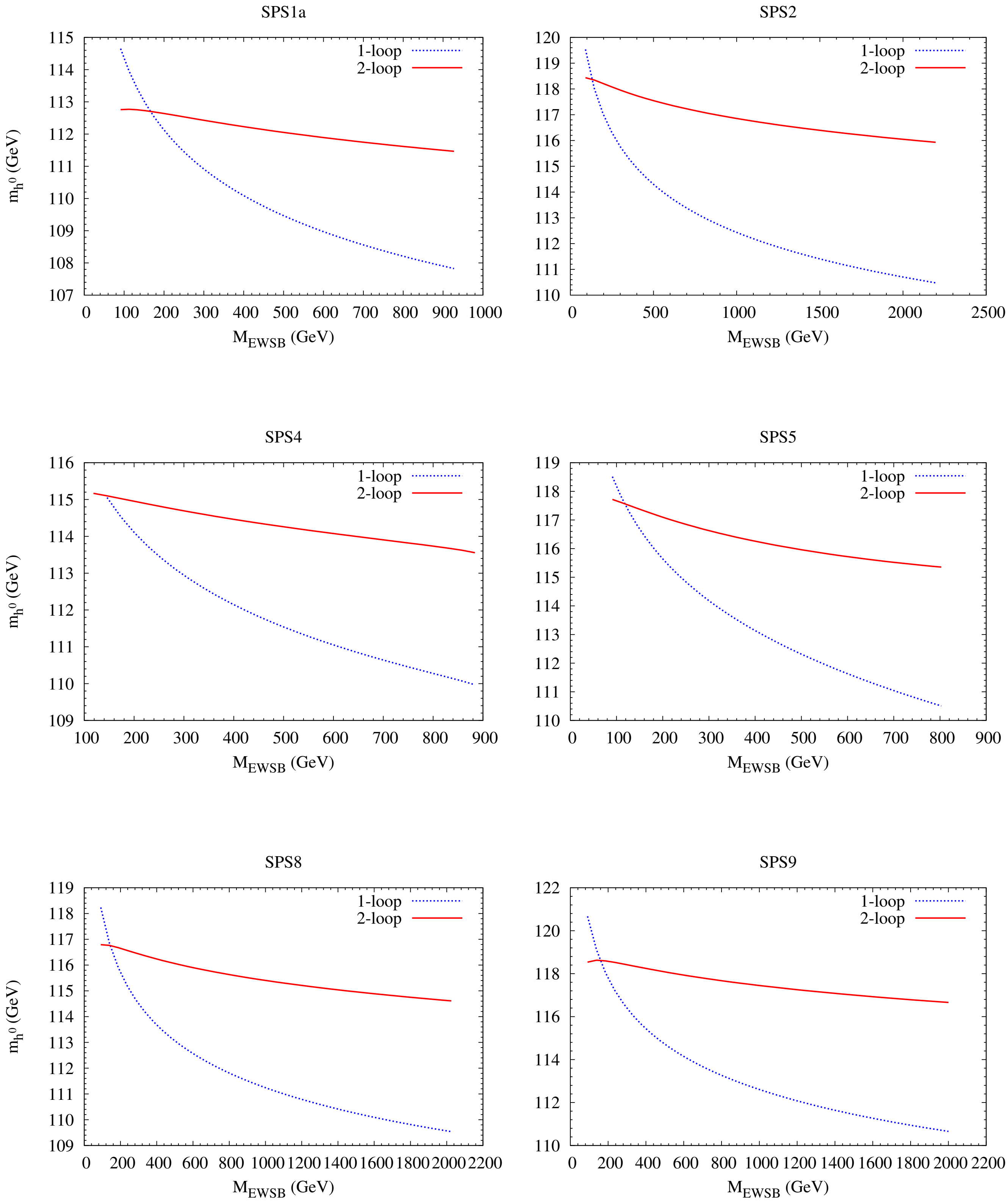
- CP–odd Higgs boson mass m_A:

	SPS1a	SPS2	SPS4	SPS5	SPS8	SPS9
SoftSusy	406.2	1552.9	355.8	687.0	550.1	1056.8
SPheno	405.7	1554.5	360.5	686.9	552.1	1051.0
SuSpect	406.1	1552.0	355.3	687.2	550.3	1056.5

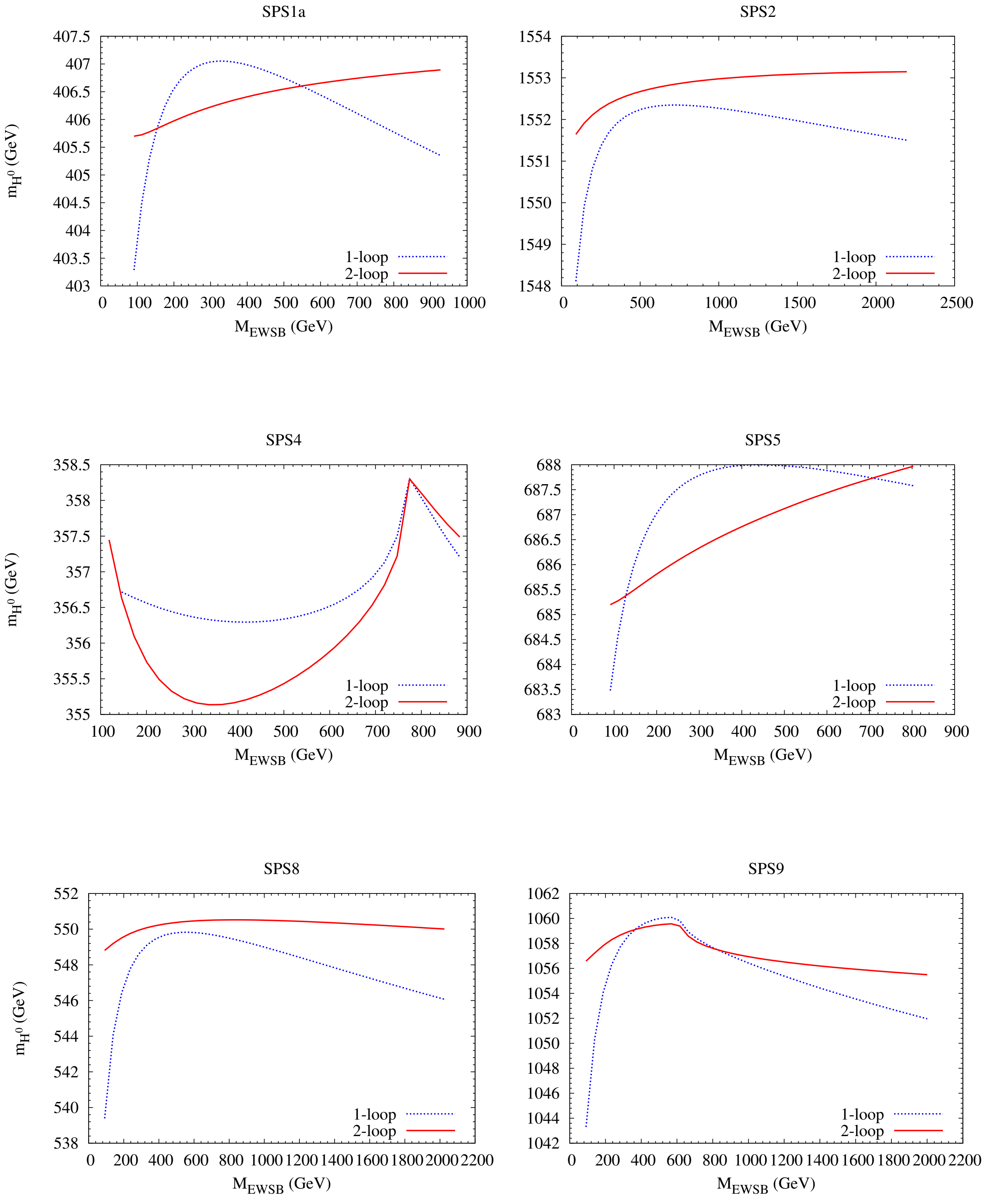
- Superpotential Higgs mass parameter μ:

	SPS1a	SPS2	SPS4	SPS5	SPS8	SPS9
SoftSusy	364.8	586.5	413.8	631.2	440.1	1011.8
SPheno	364.3	588.2	414.7	631.2	442.2	1005.9
SuSpect	364.7	583.6	413.6	631.3	440.3	1011.1

Renormalization scale dependence of m_h



Renormalization scale dependence of m_H



Comparing the $\overline{\text{DR}}$ and OS calculations

- In the two–loop results implemented in *SoftSusy, SPheno* and *SuSpect* the MSSM parameters are expressed in the $\overline{\text{DR}}$ scheme (as they come naturally from the RG evolution).

- In alternative, we might express the MSSM input parameters in terms of physical (On–Shell) masses and mixing angles.

- The code *FeynHiggs* (S.Heinemeyer *et al.*) includes all the leading two–loop corrections in the OS renormalization scheme.

- The differences between the $\overline{\text{DR}}$ and OS calculations measure the uncertainty coming from higher–order corrections.

- Comparing the light CP-even Higgs boson mass m_h:

	SPS1a	SPS2	SPS4	SPS5	SPS8	SPS9
SuSpect	112.1	116.8	114.1	116.1	115.5	117.5
FeynHiggs *	113.8	118.3	116.1	118.5	117.3	118.3

- Comparing the heavy CP-even Higgs boson mass m_H:

	SPS1a	SPS2	SPS4	SPS5	SPS8	SPS9
SuSpect	406.5	1552.1	355.3	686.9	550.6	1056.6
FeynHiggs *	406.5	1552.0	354.8	686.5	550.6	1056.7

$*$ The MSSM input parameters for *FeynHiggs*, including m_A, are taken from the output of *SuSpect*.

Some phenomenology: bounds on m_h and $\tan\beta$

- We searched for the maximal values of m_h by varying the parameters in the various SUSY–breaking models:

	$M_t = 173.7$	178.0	182.3	conservative bound
mSUGRA	126.2	129.0	131.7	136
AMSB	122.0	124.6	127.1	131
GMSB	120.8	123.7	126.7	131

- We searched for the minimal values of $\tan\beta$ compatible with the LEP2 exclusion bounds on the Higgs mass:

	$M_t = 173.7$	178.0	182.3	conservative bound
mSUGRA	2.8	2.4	2.1	1.9
AMSB	3.7	3.1	2.7	2.3
GMSB	4.2	3.3	2.7	2.2

- The conservative bounds are obtained by including a theoretical uncertainty $\Delta m_h \simeq 4$ GeV in the results corresponding to the 1σ upper bound on M_t.

- All the bounds also depend on the selected ranges for the parameters. For example, in mSUGRA we imposed

$$m_0,\, m_{1/2} < 1\,\text{TeV}, \qquad |A_0| < 3\,\text{TeV}, \qquad \sqrt{m_{\tilde{t}_1}\, m_{\tilde{t}_2}} < 2\,\text{TeV}$$

Results in the general MSSM

- The codes have options allowing to set the $\overline{\text{DR}}$ parameters directly at the weak scale (instead of evolving them from M_{GUT}).

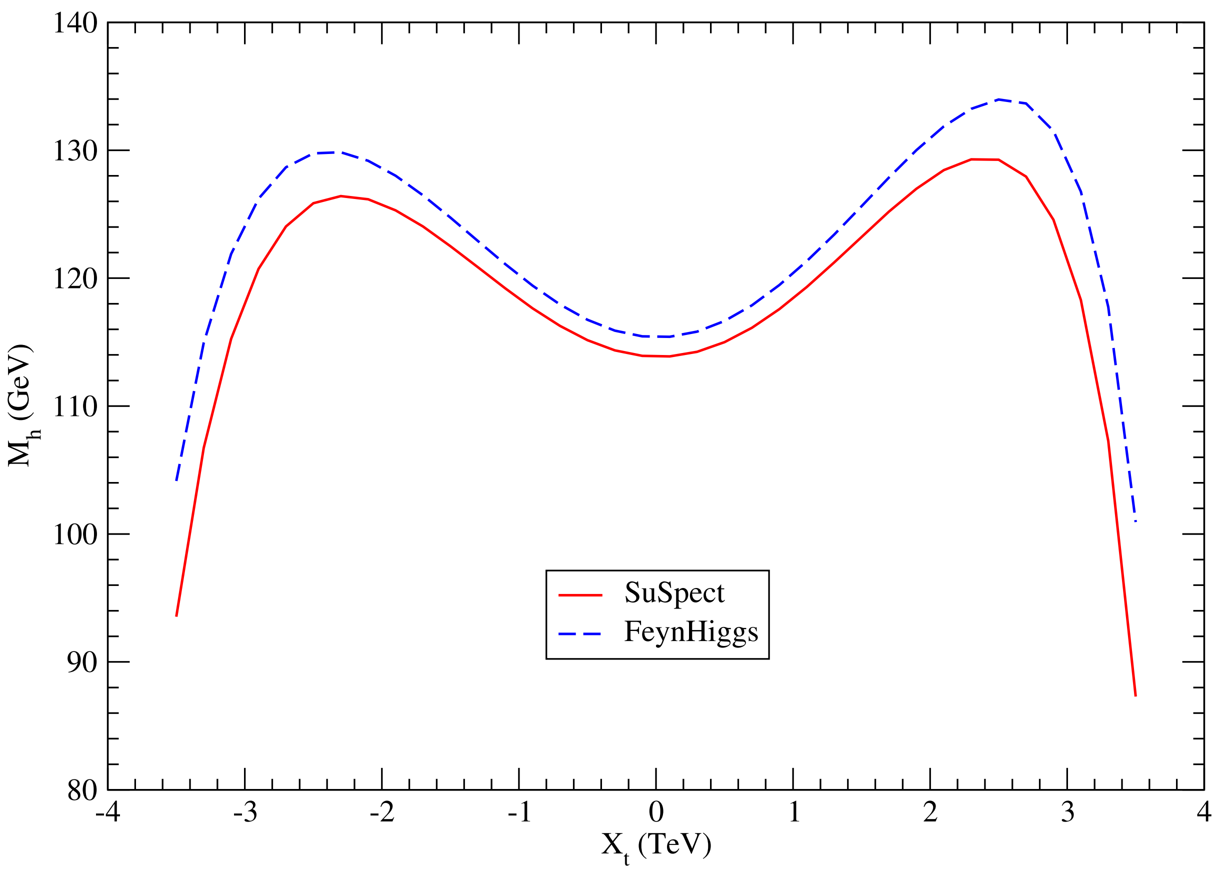
- For a representative choice of the MSSM parameters

$$M_S = m_{\tilde{g}} = \mu = m_A = 1 \text{ TeV}, \qquad \tan\beta = 10$$

- *SPheno* and *SuSpect* agree well on m_h:

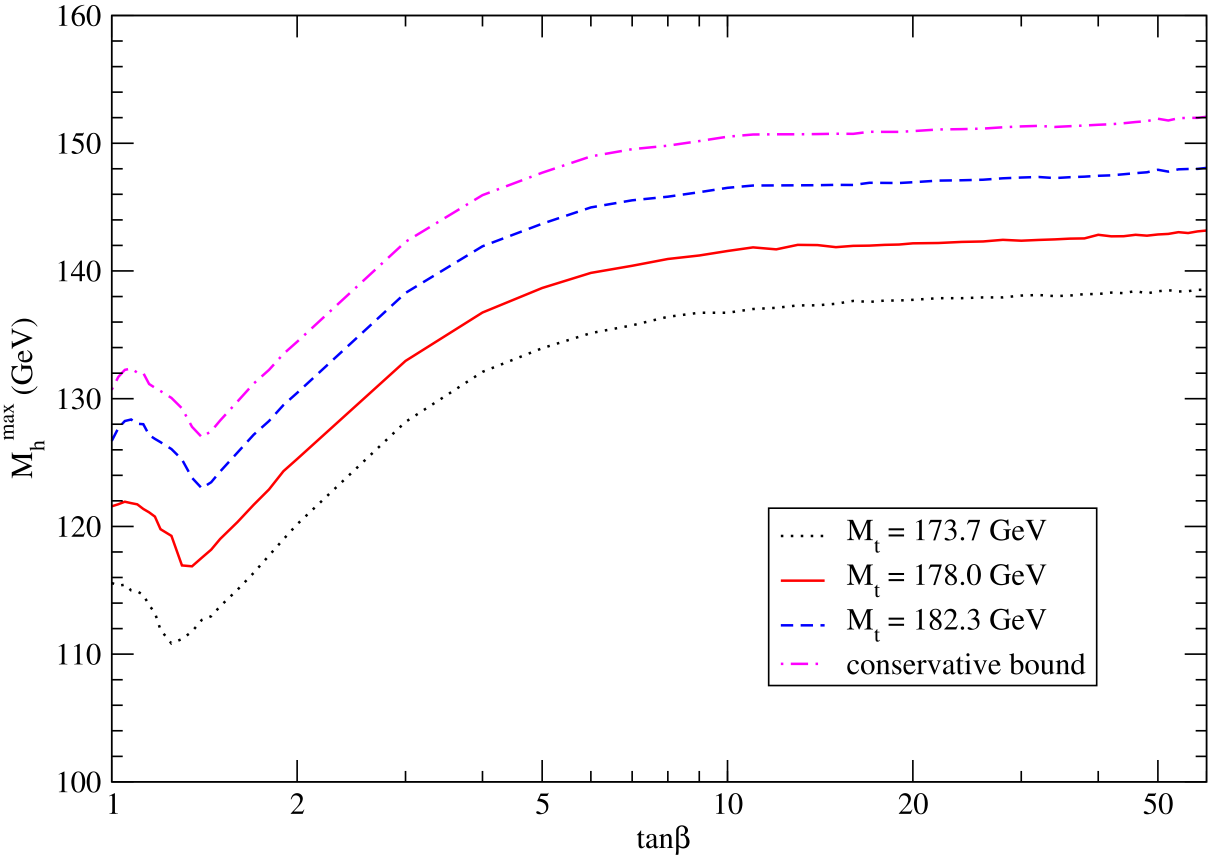
	$X_t = 0$	$X_t = 1$ TeV	$X_t = \sqrt{6} M_S$
SPheno	114.3	118.8	130.0
SuSpect	113.8	118.4	129.4

- Comparing with the OS calculation of *FeynHiggs*:



Bounds on m_h and $\tan\beta$ in the general MSSM

- We performed a general scan on the MSSM parameters, looking for the maximal m_h as a function of $\tan\beta$:



- Again, the bounds depend on the input value for M_t:

	$M_t = 173.7$	178.0	182.3	conservative bound
$m_h^{\max}$	138	143	148	152
$\tan\beta^{\min}$	1.6	–	–	–

- Very interesting phenomenology if the bounds are saturated (e.g. the light Higgs would decay dominantly in two W bosons).

Summary

- *SuSpect* 2.3, *SoftSusy* 1.8.7 and *SPheno* 2.2.1 now include a fully consistent two-loop $\overline{\text{DR}}$ computation of the Higgs tadpoles and masses, and agree well for several choices of the MSSM boundary conditions at the GUT scale.
  The small residual differences are due to higher–order effects and they are understood.

- The inclusion of the two-loop corrections clearly improves the renormalization scale dependence of the Higgs masses.
  The residual $\sim$ 2–3 GeV variation in m_h is a measure of the unknown higher–order effects.

- The 2–5 GeV difference in m_h w.r.t. the two-loop On-Shell computation of *FeynHiggs* 1.5.1 is another measure of the higher–order effects (compare with $\Delta m_h^{\text{theory}} \simeq 3$ GeV).

- In the constrained MSSM models we derived upper bounds of 120–130 GeV on m_h and lower bounds of 2–4 on $\tan\beta$ (sensitive to the chosen ranges for the high–energy params).

- In the unconstrained MSSM, we found the upper bound $m_h < 143$ GeV, which becomes $m_h < 152$ GeV when theoretical and experimental uncertainties are included.
  No lower bound can be derived on $\tan\beta$.

- All the codes are public: `DOWNLOAD AND ENJOY!`