FeynHiggs2.2:
A Precision Tool for the MSSM Higgs Sector

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based on collaboration with
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1. Motivation
2. The code FeynHiggs2.2
3. How to install FeynHiggs2.2
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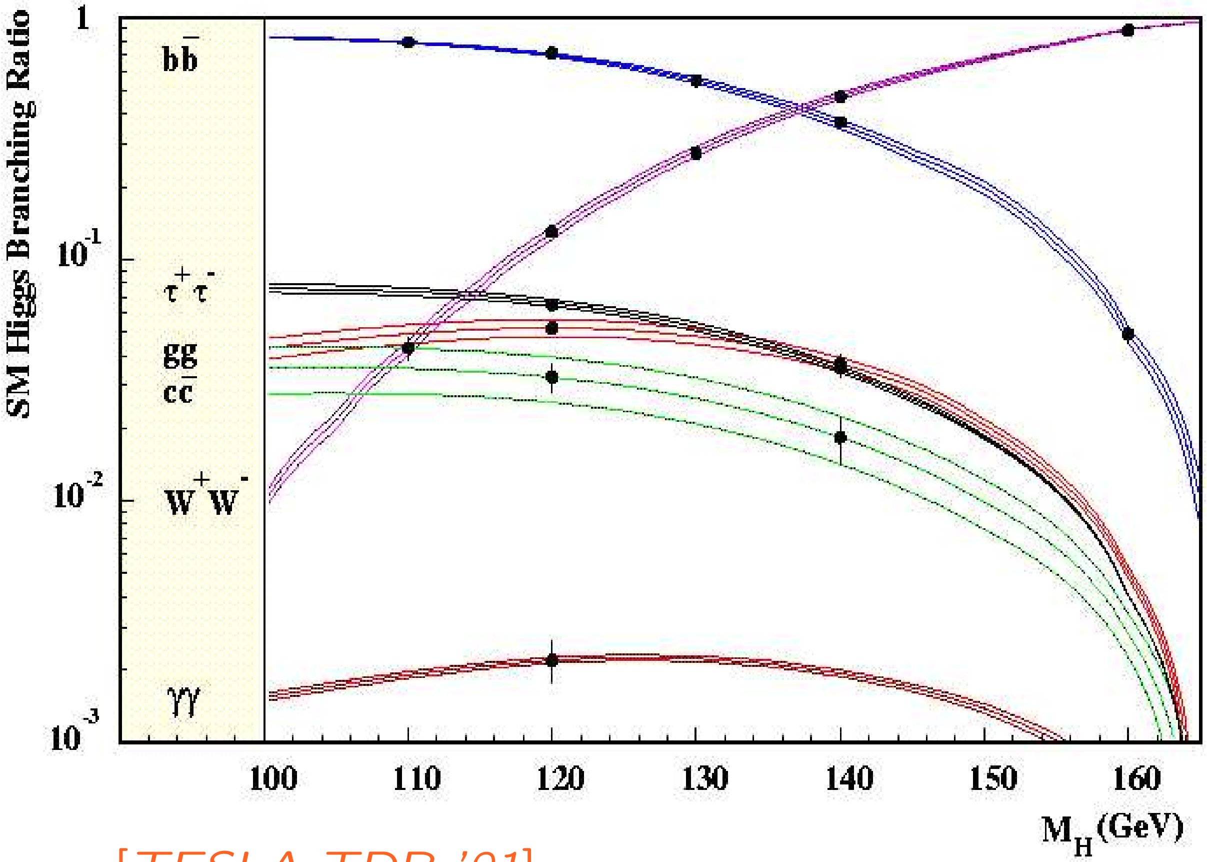
1. Motivation

SM Higgs @ LC:
Precise measurement of:

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



[*TESLA TDR '01*]

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

Q: Can this precision be utilized in the MSSM Higgs sector?

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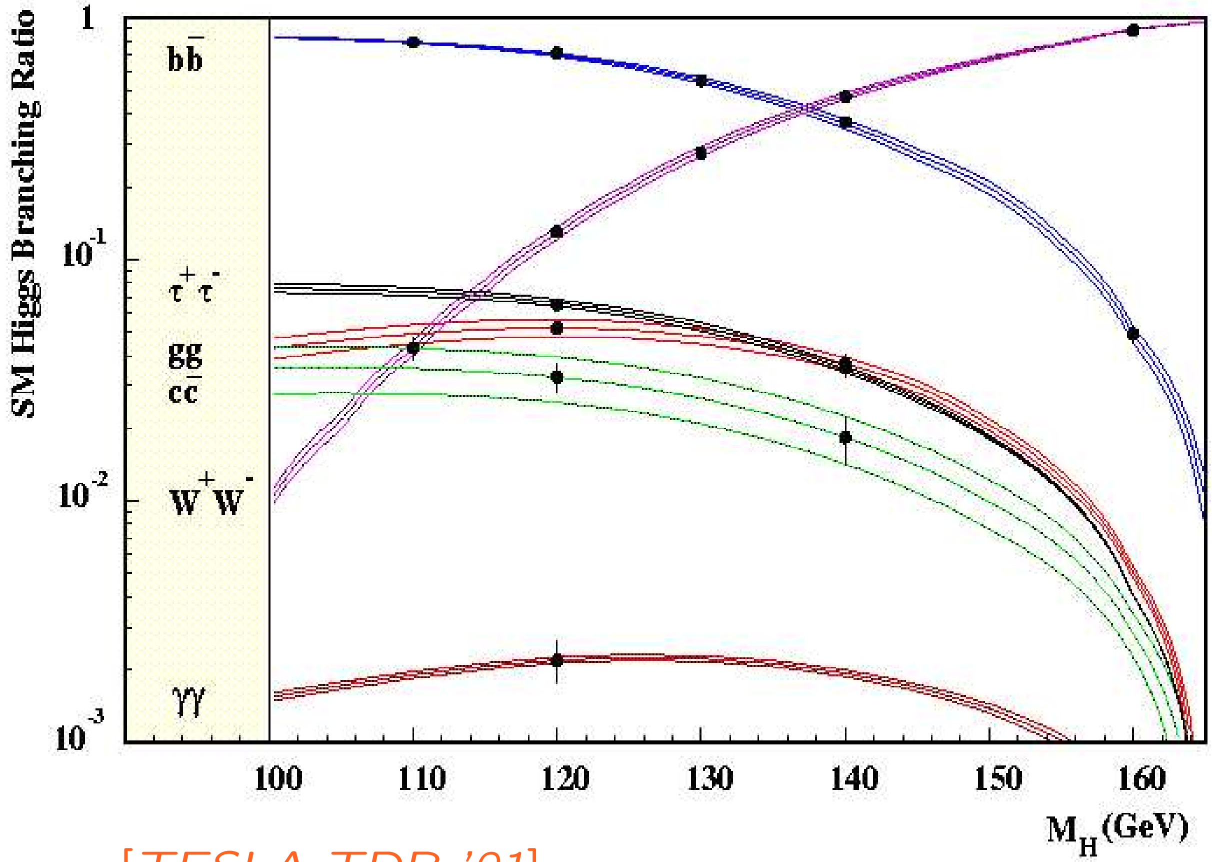


[*TESLA TDR '01*]

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

Q: Can this precision be utilized in the MSSM Higgs sector?

A: Yes! . . . if the theory predictions are as precise

Enlarged Higgs sector: Two Higgs doublets

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

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

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

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

gauge couplings, in contrast to SM

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

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

Input parameters:

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

Contrary to the SM:

m_h is not a free parameter

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

Large radiative corrections:

Dominant one-loop corrections:

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

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

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

LHC: $\Delta m_h \approx 0.2$ GeV, LC: $\Delta m_h \approx 0.05$ GeV

$\Rightarrow$ aim for theoretical precision!

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

The complex case:

Higgs potential of the cMSSM contains two Higgs doublets:

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

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

gauge couplings, in contrast to SM

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 compensate each other

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

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

Result:

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

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

2. The code FeynHiggs2.2

Latest version: FeynHiggs2.2.10 (07/05)

real MSSM:

($\rightarrow$ mostly relevant for CDM calculations)
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 working on the rest)

www.feynhiggs.de

Included in *FeynHiggs*2.2 (I):

Evaluation of all Higgs boson masses and mixing angles (rMSSM/cMSSM)

- $m_{h_1}, m_{h_2}, m_{h_3}, M_{H^\pm}$, $\alpha_{\rm eff}$, u_{ij}, . . .

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

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

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

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

Included in *FeynHiggs*2.2 (II):

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:

- $g(V \to V h_i, h_i h_j)$: 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*2.2 (III):

Evaluation of theory error on masses and mixing

$\rightarrow$ estimate of uncertainty in m_h from unknown higher-order corrections

Evaluation of masses, mixing and decay in the NMFV MSSM

NMFV: Non Minimal Flavor Violation

$\Rightarrow$ Connection to Flavor physics

[*S.H., W. Hollik, F. Merz, S.P. '04*]

Evaluation of additional constraints (rMSSM/cMSSM)

- ρ-parameter: $\Delta\rho$ at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_s)$, ...

  $\Delta\rho \gtrsim 2 \times 10^{-3}$ indicates experimentally disfavored $\tilde{t}/\tilde{b}$ masses
- anomalous magnetic moment of the μ: $(g_\mu - 2)_{\text{SUSY}}$

Planned:

- $\text{BR}(b \rightarrow s\gamma)$ and similar observables
- EDMs of electron, neutron, Hg, ...

3. How to install FeynHiggs2.2

1. Go to www.feynhiggs.de
2. Download the latest version
3. type `./configure`, `make`, `make install`
   $\Rightarrow$ library `libFH.a` is created
4. 3 possible ways to use *FeynHiggs*:

   A) as a stand alone program

   B) called from a Fortran/C++ code

   C) called within Mathematica

   processing of Les Houches Accord data possible
5. Detailed instructions and help are provided in the man pages

Alternative: On-line version

1. Go to 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

$\Rightarrow$ online presentation

Also man pages are available on-line

4. How to run FeynHiggs2.2

A) Stand alone program

- Prepare input file:

```
MSusy        500
MA0          1000
TB           5
Abs(At)      800
Qt           0
...
```

  loops possible for one or two parameters (→ scan)

- call *FeynHiggs*:

  `./FeynHiggs var.in 40030231`

  `var.in` : input file (any name possible)
  `40020211` : options (precision, real/complex MSSM, . . .)
  `Qt 0` : input parameters $\overline{\mathrm{DR}}$ or on-shell

- output to screen (human readable)
  output to file (machine readable) (→ see man pages)

Possible screen output:

```
...
| TB          =      5.000000
| MA0         =    200.000000                              input parameter
| MHp         =     -1.000000
| MSusy       =    500.000000
...
| MStop       =   441.2194   601.6737                      derived parameters
...
| mssmpart    = 4                                          options
| tanbren     = 0
...
| Mh1         =    117.186672                              Higgs masses
...
| UHiggs      =    0.99589960    0.09046538    0.00000000
|                 -0.09046538    0.99589960    0.00000000
|                  0.00000000    0.00000000    1.00000000
...
| DeltaMh0    =      0.919435                              Uncertainties
...
```

B) Called from a Fortran/C++ code

Link *FeynHiggs* as a subroutine ⇒ link `libFH.a`

`call FHSetFlags(...)` :
→ specification of accuracy etc.

`call FHSetPara(...)` :
→ specify input parameters

`call FHGetPara(...)` :
→ obtain derived parameters

`call FHHiggsCorr(...)` :
→ obtain Higgs boson masses and mixings

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

`call FHCouplings(...)` :
→ obtain decay widths, BRs 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.

Processing SUSY Les Houches Accord data

(SLHA: [*P. Skands et al. '03*])
(I/O routine: [*T. Hahn '04*])

- call *FeynHiggs* with input file (from spectrum generator, . . .)
  `./FeynHiggs Isajet.spc 40020211`

  FeynHiggs checks whether input file is in SLHA format

  `Isajet.spc` : input file
  `40020211` : options (as before)

- *FeynHiggs* reads all necessary data

- *FeynHiggs* evaluates the Higgs boson masses, couplings, BRs, etc.

- `Isajet.spc.fh` is created

  all input data remains

  Higgs masses and mixing angles are overwritten

  Higgs BRs etc. are added

5. Conclusinos

- Very precise MSSM Higgs sector evaluation necessary for
  - reliable bounds on e.g. $m_{1/2}$
  - reliable calculations e.g. in the funnel region

- *FeynHiggs*2.2 provides Higgs boson masses, mixing angles, couplings, branching ratios, etc.
  in the MSSM with/without complex parameters (and for NMFV)

- *FeynHiggs*2.2 is available at `www.feynhiggs.de`

- On-line version is available at `www.feynhiggs.de/fhucc`

- Possible:
  Stand alone vers. - call within Fortran/C++ - call within Mathematica

- Processing of Les Houches Accord data

Back-up slides

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

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

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

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

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

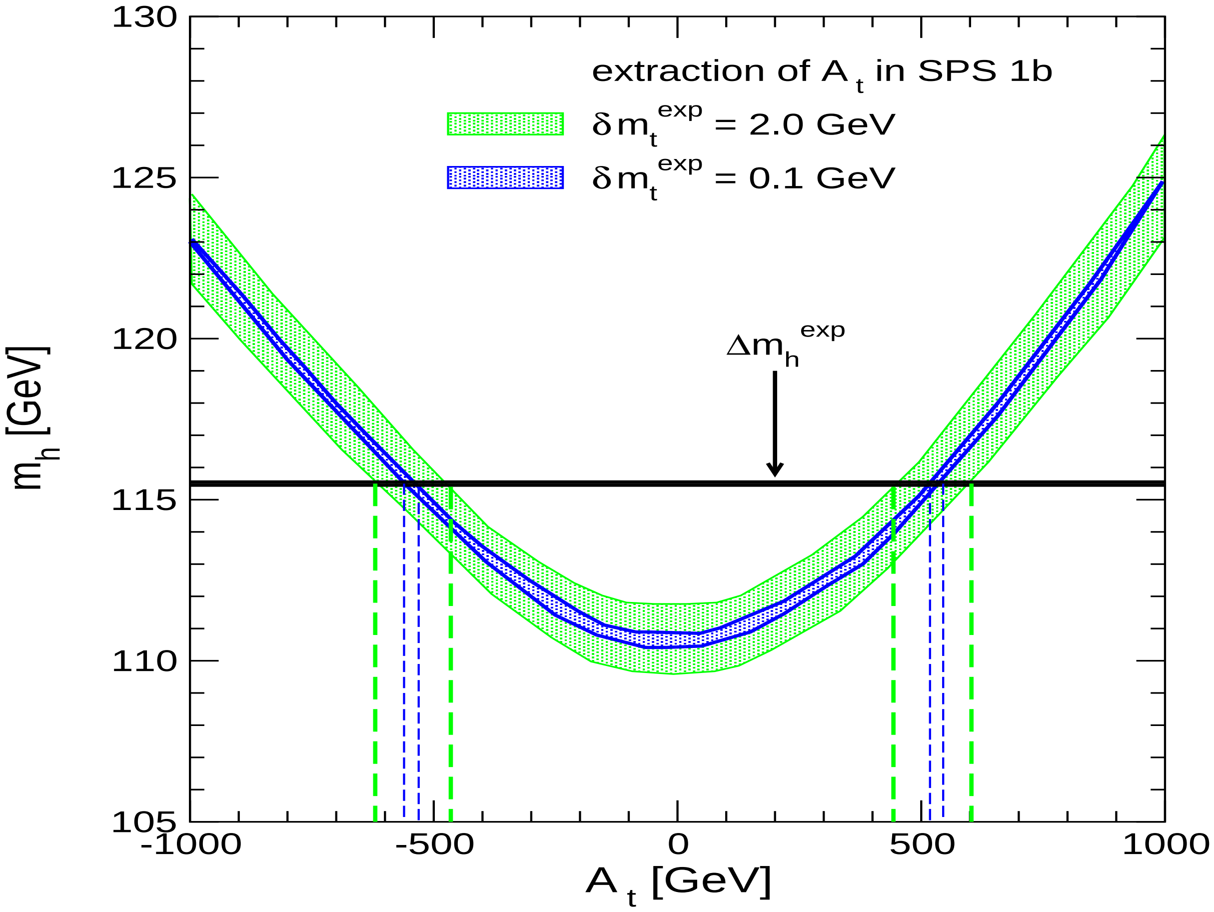
mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

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

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

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

Example of application: m_h prediction as a function of A_t



SPS1b:

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$ known,

A_t unknown

tan β, M_A known,

realistic parametric errors assumed (from SUSY exp. errors)

$\Rightarrow$ extraction of A_t possible
Theory error neglected

$\Rightarrow$ m_h is crucial input for SUSY fit programs (Fittino, Sfitter)

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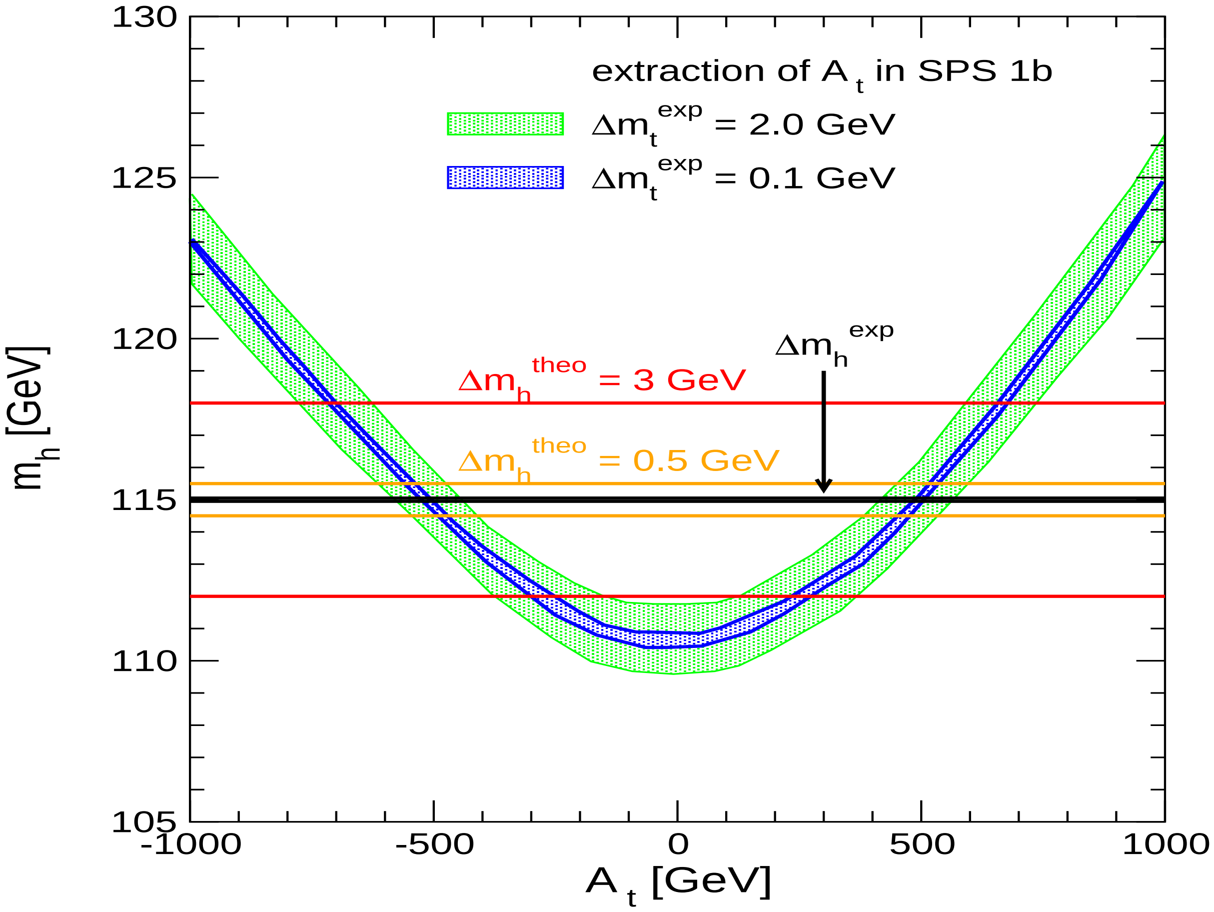

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Inclusion of higher-order corrections:

($\to$ 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

Our result 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)

Result: $(A, H, h) \to (h_3, h_2, h_1)$ with $m_{\mathrm{h}_3} > m_{\mathrm{h}_2} > m_{\mathrm{h}_1}$

Higgs boson couplings:

(in $q^2 = 0$ approximation)

$$\begin{pmatrix} h_3 \\ h_2 \\ h_1 \end{pmatrix} = \begin{pmatrix} u_{11} & u_{12} & u_{13} \\ u_{21} & u_{22} & u_{23} \\ u_{31} & u_{32} & u_{33} \end{pmatrix} \cdot \begin{pmatrix} A \\ H \\ h \end{pmatrix}$$

– h_1, h_2, h_3 : neutral Higgs boson with $\mathcal{CP}$V couplings

– $u_{12}, u_{13}, u_{21}, u_{31}$: $\mathcal{CP}$V mixings

– u_{ij} determine Higgs-fermion and Higgs-gauge boson couplings