FeynHiggs for the CMS PTDR: A Precision Tool for the MSSM Higgs Sector

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The FeynHiggs Team also includes:
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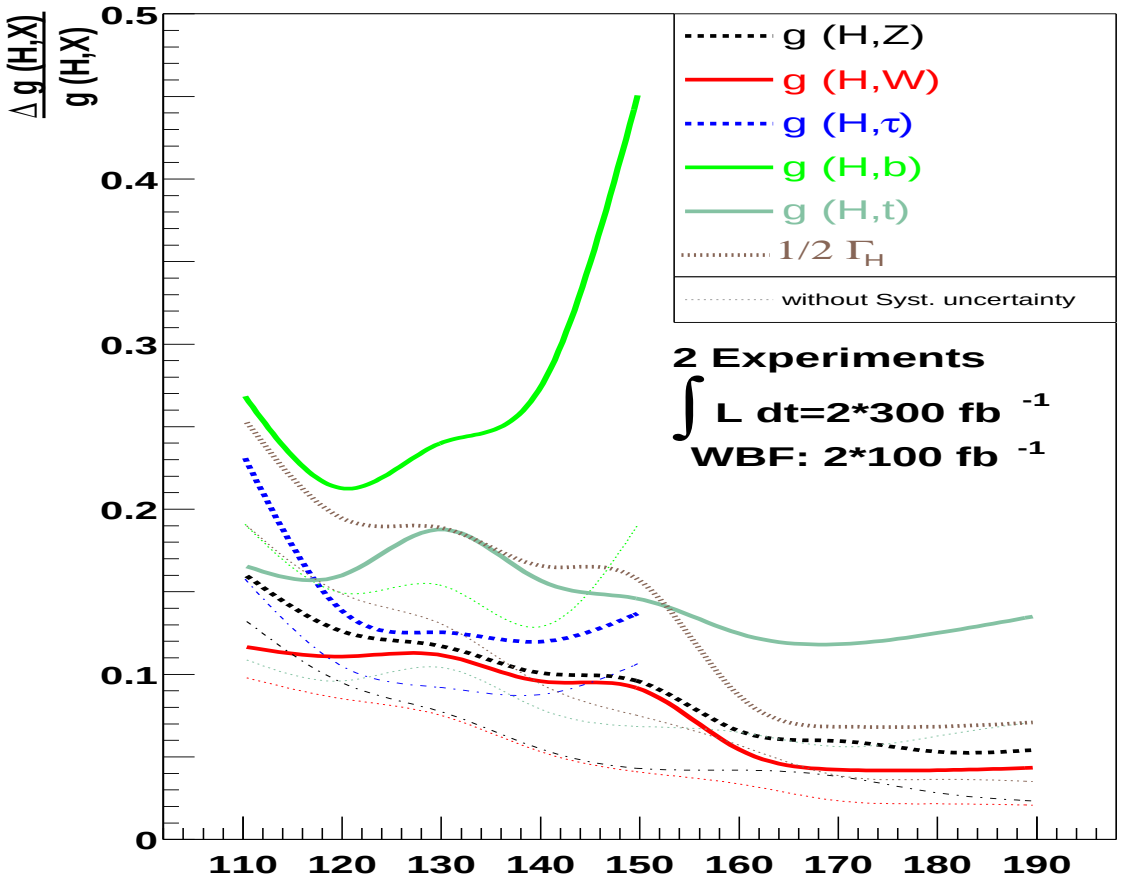
1. Motivation
2. The code FeynHiggs2.2.6 (CMS PTDR version)
3. How to install and run FeynHiggs
4. Special FeynHiggs CMS PTDR features
5. Conclusions

1. Motivation

SM Higgs @ LHC:
Measurements of:

1. Higgs boson mass, $\delta M_H \approx 200$ MeV
2. Higgs boson width
3. Higgs boson couplings, $\mathcal{O}(10\%)$ $\Rightarrow$
4. Higgs boson quantum numbers: spin, ... ?



[M. Dührssen, S.H. et al. '04]

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

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

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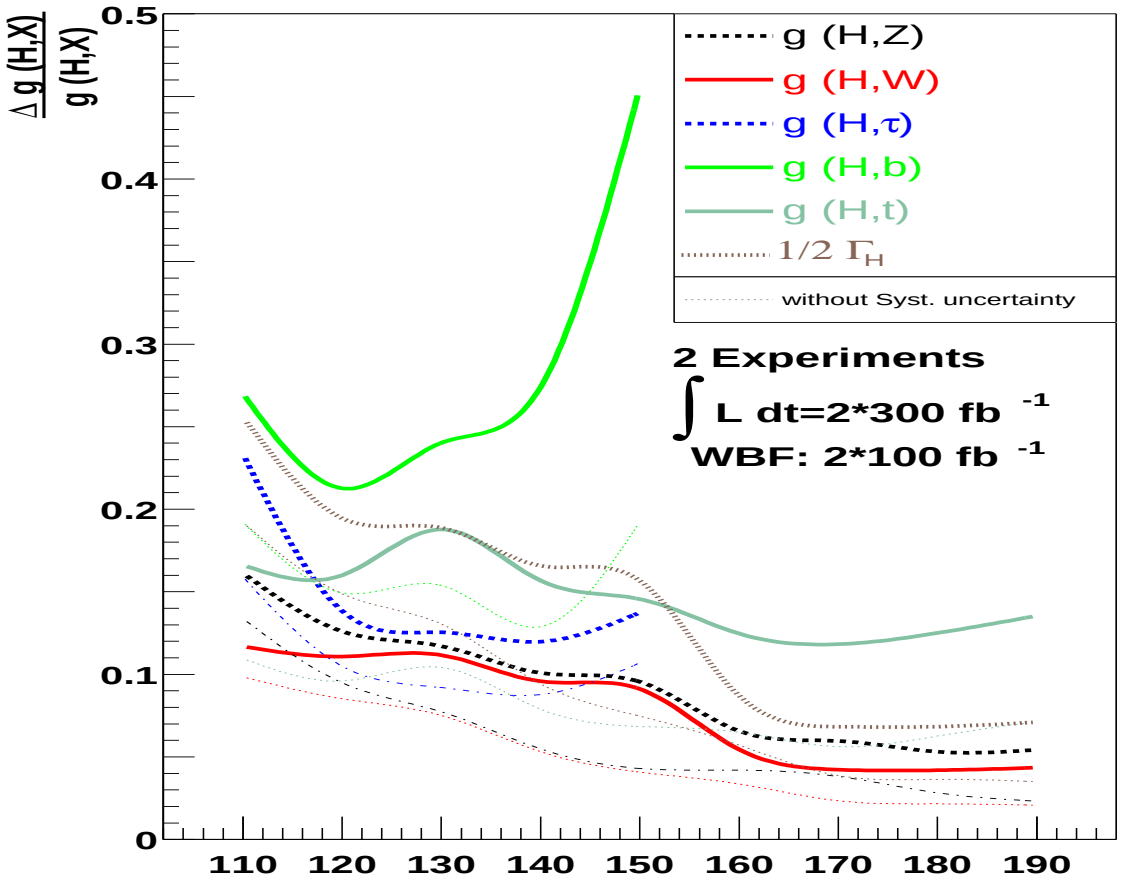

[M. Dührssen, S.H. et al. '04]

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, ILC: $\Delta m_h \approx 0.05$ GeV

$\Rightarrow$ aim for theoretical precision!

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

The complex case:

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:

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

with

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

2. The code FeynHiggs2.2.6 (CMS PTDR version)

Latest version: FeynHiggs2.2.9 (05/05) $\Rightarrow$ no changes important for LHC

www.feynhiggs.de/CMSPTDR

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 working on the rest)

Included in *FeynHiggs*2.2 (I):

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

- $m_{h_1}, m_{h_2}, m_{h_3}, M_{H^\pm}$, α_{eff}, u_{ij}, $\ldots$

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

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

Included in *FeynHiggs*2.2 (II):

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

- total decay width Γ_{tot}
- BR($H^+ \to f\bar{f}'$): decay to SM fermions
- BR($H^+ \to h_i W^+$): decay to gauge and Higgs bosons
- BR($H^+ \to \tilde{f}_i \tilde{f}'_j$): decay to sfermions
- 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: $(g_\mu - 2)_{\text{SUSY}}$

Currently included:

- inclusive Higgs production cross sections at the LHC/Tevatron
- EDMs of electron, neutron, Hg, ...

3. How to install and run FeynHiggs2.2

1. Go to www.feynhiggs.de

2. Download the latest version

3. type `./configure`, `make`, `make install`
   ⇒ 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

FeynHiggs Called from a Fortran/C++ code

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

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

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

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

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

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

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

Alternative: On-line version (FeynHiggs User Control Center)

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

⇒ for single points and checks of your downloaded version of FeynHiggs
⇒ always the latest version

⇒ online presentation

Also man pages are available on-line

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 (precision, approximations, ...)

- *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

4. Special FeynHiggs CMS PTDR features

1. Go to www.feynhiggs.de/CMSPTDR

2. Download the frozen version: FeynHiggs2.2.6
   We will keep it there till the end of the LHC ...

3. type `./configure`, `make`, `make install`
   ⇒ library `libFH.a` is created

4. 3 possible ways to use *FeynHiggs*:

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   processing of Les Houches Accord data possible

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Frozen benchmark scenarios:

Scenarios: $m_h^{\max}$, no-mixing, gluophobic Higgs, small α_{eff}, CPX

On www.feynhiggs.de/CMSPTDR you find permanently:

- FeynHiggs2.2.6 input files
- the corresponding output files
- the corresponding on-line evaluation from
  www.feynhiggs.de/CMSPTDR/fhucc

$\Rightarrow$ easy checks of your code permanently possible

In addition:

- frozen on-line version: `www.feynhiggs.de/CMSPTDR/fhucc`

  $\Rightarrow$ any point can be checked against our version

- man pages for frozen version available permanently

- statically linked version for Linux permanently available

possible: addition of Higgs production cross sections ...

$\Rightarrow$ obvious errors will be corrected, but original version will always stay there

5. Conclusinos

- Very precise MSSM Higgs sector evaluation necessary for
  - precise m_h prediction
  - precise BR and coupling predictions

  $\Rightarrow$ to match the LHC precision

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

- *FeynHiggs*2.2.6 (CMS PTDR version) at `www.feynhiggs.de/CMSPTDR`

  $\Rightarrow$ frozen version till the end of the LHC ...

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

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

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

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

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

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

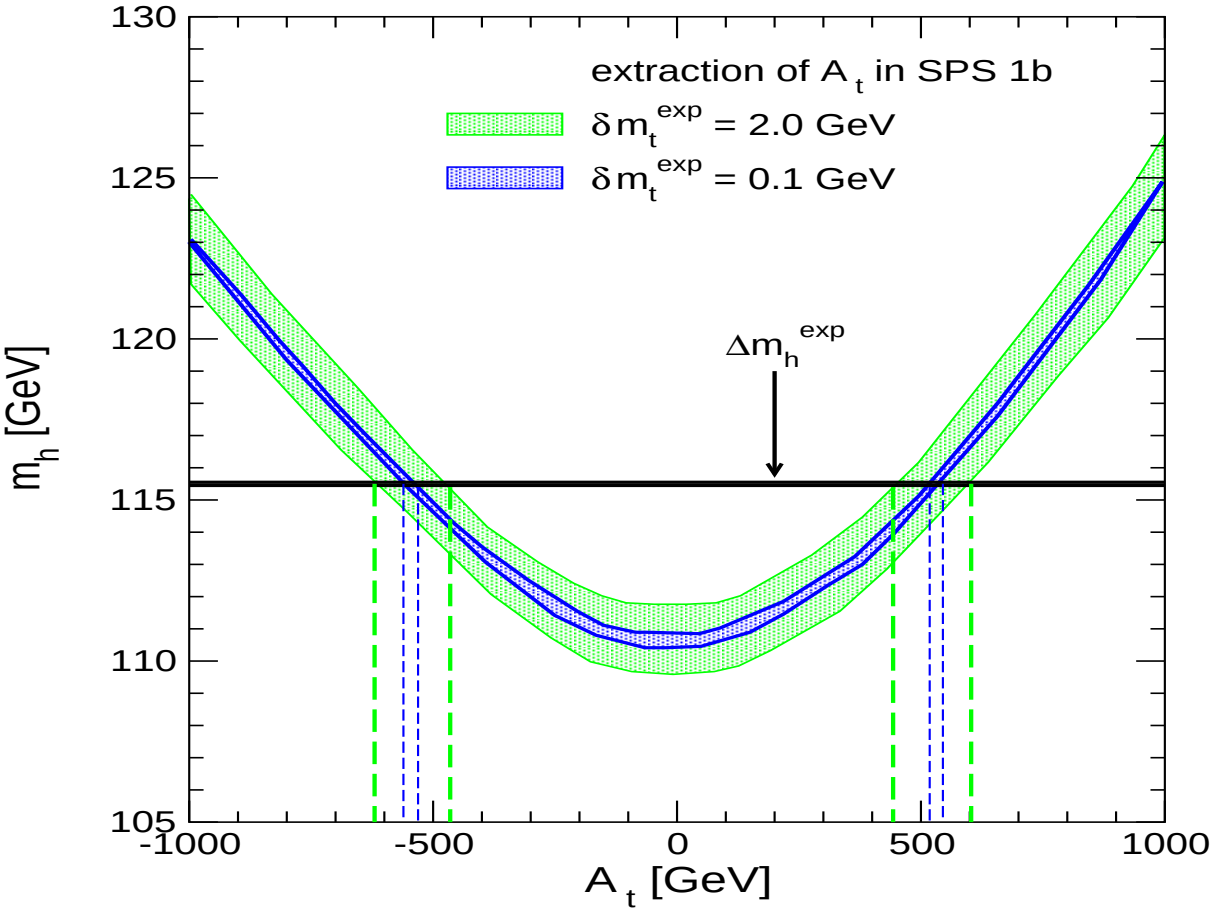
mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

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

$\tan\beta, M_A$ known,

realistic parametric errors assumed

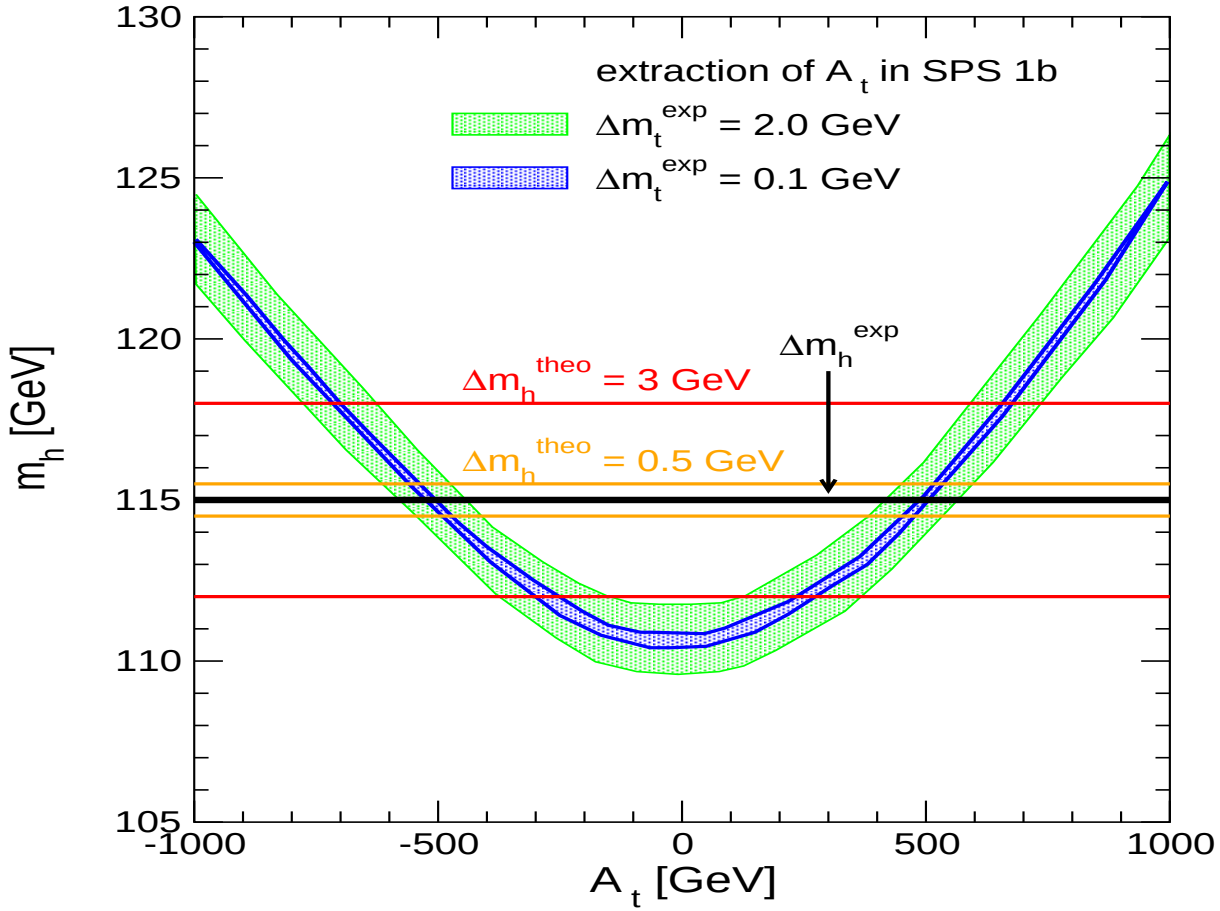
(from SUSY exp. errors)

$\Rightarrow$ extraction of A_t possible

Theory error neglected

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

Example of application: m_h prediction as a function of A_t



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$\Rightarrow$ extraction of A_t possible

Theory error neglected

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The complex case:

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 compensate each other

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