Precision calculations in the MSSM

H^+ decay to $t\bar{b}$

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Brief Intro to MSSM

MSSM:

- is the minimal supersymmetric extension of the SM
  - supersymmetry: relates bosons and fermions
  - minimal:
    1. minimal (=1) set of Susy generators $Q, \bar{Q}$
    2. minimal (=2) number of Higgs doublets
- has the following particle spectrum

SM with extended Higgs sector	Susy partners
fermions, higgses gauge bosons (g, γ, W, Z)	sfermions, higgsinos gauginos $(\tilde{g}, \tilde{\gamma}, \tilde{W}, \tilde{Z})$

neutral gauginos	+	neutral higgsinos	$\Rightarrow$	neutralinos
charged gauginos	+	charged higgsinos	$\Rightarrow$	charginos

- requires many new parameters: m_{A_0}, t_β, μ, M_1, M_2, M_3, A_l, A_u, A_d, M_E, M_L, M_D, M_Q, M_U (msugra: m_0, $m_{\frac{1}{2}}$, A_0, sign(μ), t_β)

plan and motivation

- plan
  - long term: to create a numerical program for calculating full one-loop total decay widths and branching ratios for Susy and Higgs particles within the SPA convention
- motivation
  - application to $1 \to 3$ and $2 \to 3$ processes with resonant propagators; total 1-loop widths are necessary for these one-loop calculations

work done so far

our work - brief overview :

- we use the packages FeynArts, FormCalc, LoopTools, SPheno
- we have been developing a fully automatized generator for the calculation of decay processes
  we have been developing an automatic calculation of particle decay widths at one-loop level
- we have implemented all the 1-loop counterterms in a mathematica .m file
- calculated processes are UV and IR convergent
- soft radiation is included, hard radiation is implemented in fortran code for SSS, SFF, SSV, SVV configurations; works generally - also with clashing arrows and one zero fermion mass
- we have calculated the $H^+ \to t\bar{b}$ process in the $\overline{DR}$ scheme and in the linear R_{ξ_W,ξ_Z} gauge ($R_{\xi_{\gamma,g}}$ gauge automatization is on the plan)
- our work is done within the SPA convetion

review of several works on H^+ decay to $t\bar{b}$

- Bartl, Eberl, Hidaka, Kon, Majeroto, Yamada: *QCD corrections to the decay $H^+ \to t\bar{b}$ in the Minimal Sypersymmetric Standard Model*, (1995)
  $\hookrightarrow$ complete QCD corrections, Susy-QCD comparable to SM-QCD in a large region of MSSM parameter space
- Jimenez, Sola: *Supersymmetric QCD corrections to the top quark decay of a heavy charged Higgs boson*, (1996)
  $\hookrightarrow$ comparison of Susy-QCD and SM-QCD
- Coarasa, Garcia, Guasch, Jimenez, Sola: *Quantum effects on $t \to H^+ b$ in the MSSM: A window to "virtual" supersymmetry?*, (1996)
  $\hookrightarrow$ analysis of strong and electroweak one-loop effects on top quark decay, OS scheme, Standard QCD and Susy-QCD corrections have opposite sign $\to$ regions where Susy-EW corr. are not negligible
- Coarasa, Garcia, Guasch, Jimenez, Sola: *Heavy charged Higgs boson decaying into top quark in the MSSM*, (1997)
  $\hookrightarrow$ inclusion of leading EW corrections originating from large yukawas, comparable to QCD corrections in relevant portions of MSSM par. space

review of several works on H^+ decay to $t\bar{b}$

- Eberl, Hidaka, Kraml, Majeroto, Yamada: *Improved Susy QCD corrections to Higgs boson decays into quarks and squarks*, (2000)
  $\hookrightarrow$ expansion of the Higgs decay width in terms of $m_b(m_{H^+}) \longrightarrow$ better convergence
- Carena, Garcia, Nierste, Wagner: *Effective lagrangian for the $\bar{t}bH^+$ interaction in the MSSM and charged Higgs phenomenology*, (2000)
  $\hookrightarrow$ resummation of the dominant supersymmetric corrections proportional to $\tan\beta$ to all orders for large $\tan\beta$

Tree level

lagrangian:

$$\mathcal{L}_{H^+\bar{t}b} = H^{-\dagger}\bar{t}\,(y_t P_L + y_b P_R)\, b = H^{-\dagger}\bar{t}\,(h_t c_\beta P_L + h_b s_\beta P_R)\, b$$

where h_t, h_b are yukawa couplings. The CKM matrix is assumed to be diagonal.

$$y_t = \frac{e}{\sqrt{2} m_W s_w} m_t \cot\beta, \qquad y_b = \frac{e}{\sqrt{2} m_W s_w} m_b \tan\beta$$

tree-level width:

$$\Gamma_0 = \frac{\kappa}{16\pi m_{H^+}^3} C_F[-2m_t m_b(y_t^* y_b + y_t y_b^*) + (m_{H^+}^2 - m_t^2 - m_b^2)(|y_t|^2 + |y_b|^2)]$$

where $\kappa = \sqrt{(m_{H^+}^2 - m_t^2 - m_b^2)^2 - 4m_t^2 m_b^2}$

note: $\tan\beta \sim 20 \rightarrow y_t^2 \sim 0.01 y_b^2$

One-loop level

corrected width

$$\Gamma_1 = \frac{\kappa}{16\pi m_{H^+}^3} C_F[-2m_t m_b(y_t^* Y_b + Y_t y_b^*) + (m_{H^+}^2 - m_t^2 - m_b^2)(y_t^* Y_t + y_b^* Y_b)] + \Gamma_{rad}$$

where

$$Y_{b,t} = y_{b,t} + y_{b,t}^{(v)} + y_{b,t}^{(w)} + y_{b,t}^{(c)}$$

$\overline{DR}$ scheme: $y_{b,t}^{(c)} \rightarrow$ only UV divergent part

$y_{b,t}^{(w)} \rightarrow$ UV part + part due to LSZ formula

$(y_{b,t}^{(v)} + y_{b,t}^{(w)} + y_{b,t}^{(c)})_{UV} = 0$

IR divergence present in: $y_{b,t}^{(v)}, y_{b,t}^{(w),LSZ}, \Gamma_{rad}$

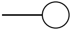
charged Higgs sector

The relevant parts of the tree level lagrangian read:

$$\begin{aligned}\mathcal{L} &= \partial_\mu G^{-\dagger}\partial^\mu G^- + \partial_\mu H^{-\dagger}\partial^\mu H^- - (m^2_{H^\pm} + t_{H^\pm H^\pm})|H^-|^2 \\ &- (m^2_{G^\pm} + t_{G^\pm G^\pm})|G^-|^2 - (t_{G^\pm H^\pm})G^{-\dagger}H^- - t_{H^\pm G^\pm}H^{-\dagger}G^-\end{aligned}$$

where:

$$\begin{aligned} m^2_{H^\pm} &= m^2_{A^0} + m^2_{W^\pm} \\ m^2_{G^\pm} &= \xi^\pm_W m^2_{W^\pm} \\ t_{H^\pm H^\pm} &= \frac{e}{2m_W s_w}\left[T_{h^0}\left(-s^2_\beta s_\alpha/c_\beta + c^2_\beta c_\alpha/s_\beta\right) + T_{H^0}\left(s^2_\beta s_\alpha/c_\beta + c^2_\beta s_\alpha/s_\beta\right)\right] \\ t_{G^\pm H^\pm} &= \frac{e}{2m_W s_w}\left[T_{h^0}\left(s_\alpha s_\beta + c_\beta c_\alpha\right) + T_{H^0}\left(-s_\beta c_\alpha + c_\beta s_\alpha\right)\right]\end{aligned}$$ [1]

tree-level: $T_{H^0} = T_{h^0} = 0,$ one-loop level: $T_{H^0} \to \tau_{H^0}$  $i\tau_{H^0}$

renormalization conditions:

$$\hat{\Gamma}_{H^-H^-}(m^2_{H^\pm})|^\Delta = \hat{\Gamma}_{G^-H^-}(m^2_{H^\pm})|^\Delta = 0, \qquad \left.\frac{\partial\hat{\Gamma}_{H^-H^-}(p^2)}{\partial p^2}\right|^\Delta_{p^2=m^2_{H^\pm}} = 1$$ [2]

[1] see for example Pierce and Papadopoulos, arXiv:hep-ph/9206257

[2] Δ - parts of t_{GH}, t_{HH} and $\Pi(p^2)$ are taken

charged Higgs sector

The above RCs lead to:

$$\begin{aligned}
m^2_{H^\pm} &= m^2_{A^0} + m^2_{W^0} + \delta m^2_{A^0} + \delta m^2_W + t^\Delta_{H^\pm H^\pm} - \Pi^\Delta_{H^- H^-}(m^2_{H^\pm}) \\
\delta Z_{H^- H^-} &= -\dot{\Pi}^\Delta_{H^- H^-}(m^2_{H^\pm}) \\
\delta Z_{G^- H^-} &= \frac{2}{m^2_{G^\pm} - m^2_{H^\pm}}(\Pi^\Delta_{G^- H^-}(m^2_{H^\pm}) - t^\Delta_{G-H-})
\end{aligned}$$

LSZ formula: $S(p_1, \ldots, p_n) \sim G_0^{tr}(p_1, \ldots, p_n) R_0^{\frac{n}{2}}$ [3]

after field renormalization $f \to \sqrt{Z} f$:

$$S(p_1, \ldots, p_n) \sim G_R^{tr}(p_1, \ldots, p_n) R_R^{\frac{n}{2}}, \quad \text{where } R_R = R_0/Z$$

in the $\overline{DR}$ scheme:

$$R_R = 1 - \dot{\Pi}^{fin}_{H^- H^-}(m^2_{H^\pm}) \Rightarrow \delta Z_{H^- H^-} \to -\dot{\Pi}^\Delta_{H^- H^-}(m^2_{H^\pm}) - \dot{\Pi}^{fin}_{H^- H^-}(m^2_{H^\pm})$$

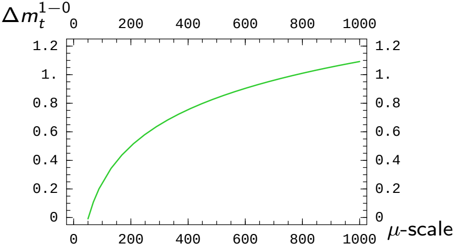
[3] written for n fields of the same type

linear R_ξ gauge

By a proper modification of the packages FeynArts and FormCalc, we are now able to get a working numerical code in the general R_ξ gauge (except photon/gluon gauge - on the plan). We have checked the gauge independence of the calculated result.

notice:

$$\Delta m_t^{\xi=1} - \Delta m_t^{\xi} = \frac{\alpha m_t}{32\pi m_w^2 s_w^2}\left[A_0(m_Z^2) - A_0(\xi m_Z^2) + 2A_0(m_W^2) - 2A_0(\xi m_W^2)\right]$$



PDG: $m_t = 171.2 \pm 2.1$ GeV

SPheno: RGEs in Landau gauge

SEs in Feynman gauge

running of the couplings

The running of the couplings y_t, y_b is ξ-independent and is given by

$$\begin{aligned}
\frac{\partial y_t}{\partial \ln Q} &= -\frac{64\pi}{3}\alpha_s - \frac{13}{9}g_1^2 - 3g_2^2 + 3h_t^2 + h_b^2 \\
&+ (1+s_\beta^2)\sum_{f=u,c,t} N_C^f h_f^2 - s_\beta^2 \sum_{f=e,\mu,\tau,d,s,b} N_C^f h_f^2 \\
\frac{\partial y_b}{\partial \ln Q} &= -\frac{64\pi}{3}\alpha_s - \frac{7}{9}g_1^2 - 3g_2^2 + 3h_b^2 + h_t^2 \\
&+ (1+c_\beta^2)\sum_{f=e,\mu,\tau,d,s,b} N_C^f h_f^2 - c_\beta^2 \sum_{f=u,c,t} N_C^f h_f^2
\end{aligned}$$

where $N_C^f = \left[\begin{array}{ll} 1 & \text{for leptons} \\ 3 & \text{for quarks} \end{array} \right.$

note: running of $\tan\beta$ at one-loop level is ξ-independent [4]

[4] see Yamada, arXiv:hep-ph/0112251

resummation of leading tan β terms

the leading tan β terms in the one-loop level relation:

$$m_b^0 = (m_b^R + \delta m_b^R) = m_b(1 - \Delta_b)$$

can be resummed to all orders [5]:

$$m_b^0 = (m_b^R + \delta m_b^R) = \frac{m_b}{1 + \Delta_b}$$

with [6]

$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan\beta \; I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}}) + \frac{h_t^2}{16\pi^2} \mu A_t \tan\beta \; I(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2) + \ldots$$

thus

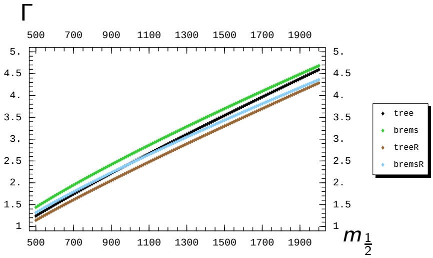
$$m_b^{\overline{DR}}(Q) = \frac{m_{b,SM}^{\overline{DR}}}{1 + \Delta_b(Q)} + Re\Sigma_b^{'}(Q)$$

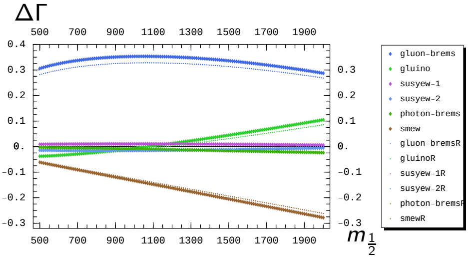
[5] Carena, Garcia, Nierste, Wagner (arXiv:hep-ph/9912516)
[6] for full Δ_b see note 4 or SPA paper (arXiv:hep-ph/0511344)

Preliminary results

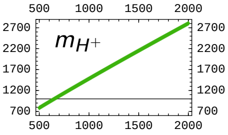
constraints (not all): $b \to s\gamma$, vacuum conditions, $\Delta\rho$

SPS 1a slope: $m_0 = 0.4 m_{\frac{1}{2}}, A_0 = -0.4 m_{\frac{1}{2}}, \tan\beta = 10, \mu > 0$ [7]





susy-EW1: $\chi \wedge \tilde{f}$	gluon: g	gluino: $\tilde{g}$	UV-finite
susy-EW2: $\chi \vee \tilde{f}$	photon: γ	smew: rest	
	IR finite		



[7] for constraints and $\overline{DR}$ parameters SPheno was used

Preliminary results

MSSM $\overline{DR}$ parameter set:
$M_1 = 100, M_2 = 200, M_3 = 600, A_{tril} = -500, \mu = 400,$
$m_{A^0} = 400, MSL = MSE = MSQ = 900, MSU = MSD = 1000$

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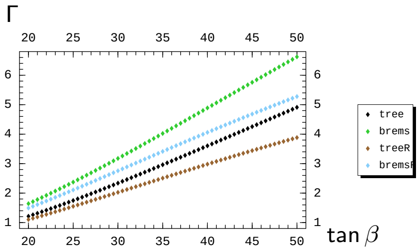

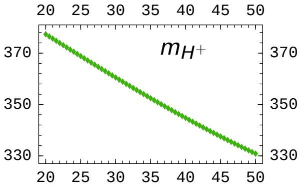

future work and conclusion

- finish the decay $H^+ \to t\bar{b}$ and put the package to the web
- finish the programming of the generator
- use the generator to calculate total widths of all sfermions at one-loop level

Thank you for the attention!