Renormalisation of the NMSSM

Example of a theory with many Higgses, many parameters: meaning of parameters, mixings, schemes,..

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Work done with G. Bélanger, V. Bizouard, G. Chalons, PRD 2015 and in Progress

When asked about what to talk about?

Answer: 750 if confirmed (despite the fact I had nothing appealing) OR NMSSM (the "safe" bet)

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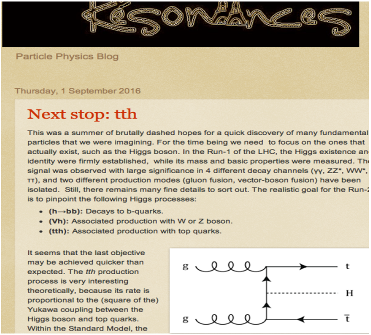
In the comments section you're welcome to lash out on the entire BSM community - we made a wrong call so we deserve it. Please, however, avoid personal attacks (unless on me). Alternatively, you can also give us a hug :)

When asked about what to talk about?

Could have looked up ResonAAnces...



ResonAAnces

Particle Physics Blog

Thursday, 1 September 2016

Next stop: tth

This was a summer of brutally dashed hopes for a quick discovery of many fundamental particles that we were imagining. For the time being we need to focus on the ones that actually exist, such as the Higgs boson. In the Run-1 of the LHC, the Higgs existence an identity were firmly established, while its mass and basic properties were measured. Th signal was observed with large significance in 4 different decay channels (γγ, ZZ*, WW*, ττ), and two different production modes (gluon fusion, vector-boson fusion) have been isolated. Still, there remains many fine details to sort out. The realistic goal for the Run- is to pinpoint the following Higgs processes:

- **(h→bb):** Decays to b-quarks.
- **(Vh):** Associated production with W or Z boson.
- **(tth):** Associated production with top quarks.

It seems that the last objective may be achieved quicker than expected. The *tth* production process is very interesting theoretically, because its rate is proportional to the (square of the) Yukawa coupling between the Higgs boson and top quarks. Within the Standard Model, the

But that was what I talked about, here, 2 years ago...

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- Renormalisation. But more about the definition/redefinition/reconstruction of parameters
- In particular when there are many of these parameters and when "things mix" and when nothing but the SM has been seen!
- Scheme/Scale dependence for a many-parameter set-up

NMSSM: The Higgs Sector

3 Higgs superfields : two $SU(2)_L$ doublets $\hat{H}_u$ and $\hat{H}_d$, as in the MSSM, and one additional gauge singlet $\hat{S}$

$$\hat{H}_u = \begin{pmatrix} \hat{H}_u^+ \\ \hat{H}_u^0 \end{pmatrix}, \quad \hat{H}_d = \begin{pmatrix} \hat{H}_d^0 \\ \hat{H}_d^- \end{pmatrix}, \quad \hat{S}.$$

NMSSM: The Higgs Sector

$\mathbb{Z}_3 \rightarrow$ Higgs superpotential involves 2 dimensionless couplings λ and κ,

$$W_{Higgs} = -\lambda \hat{S}\hat{H}_d \cdot \hat{H}_u + \frac{1}{3}\kappa \hat{S}^3, \quad \text{Higgs sector and neutralino (chargino) sector}$$

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$$\begin{aligned} -\mathcal{L}_{soft,scalar} \quad &= m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 \\ &\quad + \lambda A_\lambda H_u \cdot H_d S + \tfrac{1}{3}\kappa A_\kappa S^3 + h.c \end{aligned}$$

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$$\begin{aligned} V_{Higgs} =& |\lambda(H_u^+ H_d^- - H_u^0 H_d^0) + \kappa S^2|^2 + (m^2_{H_u} + |\lambda S|^2)\left(|H_u^0|^2 + |H_u^+|^2\right) \\ &+ (m^2_{H_d} + |\lambda S|^2)\left(|H_d^0|^2 + |H_d^+|^2\right) + \frac{g^2 + g'^2}{8}\left(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2\right)^2 \\ &+ \frac{g^2}{2}|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 + m_S^2|S|^2 + (\lambda A_\lambda (H_u^+ H_d^- - H_u^0 H_d^0)S + \frac{1}{3}\kappa A_\kappa S^3 + h.c). \end{aligned}$$

The Higgs fields

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = \begin{pmatrix} v_d + \frac{h_d^0 + i a_d^0}{\sqrt{2}} \\ h_d^- \end{pmatrix},$$

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} = \begin{pmatrix} h_u^+ \\ v_u + \frac{h_u^0 + i a_u^0}{\sqrt{2}} \end{pmatrix},$$

$$S = s + \frac{h_s^0 + i a_s^0}{\sqrt{2}}.$$

As in the MSSM $\tan\beta \equiv t_\beta = v_u/v_d$ and $v^2 = v_u^2 + v_d^2$, $(v_u = s_\beta v, c_\beta v)$ and $M_W^2 = g^2 v^2/2$. The non vanishing value of the vev of S also gives a solution to the so-called μ-problem of the MSSM, by generating this parameter dynamically:

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we can also define:

$$\Lambda_v = \lambda v \qquad m_\kappa = \kappa s = (\kappa/\lambda)\mu$$

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$$V_{mass} = \frac{1}{2}\begin{pmatrix} h^0_d & h^0_u & h^0_s \end{pmatrix} M_S^2 \begin{pmatrix} h^0_d \\ h^0_u \\ h^0_s \end{pmatrix} + \frac{1}{2}\begin{pmatrix} a^0_d & a^0_u & a^0_s \end{pmatrix} M_P^2 \begin{pmatrix} a^0_d \\ a^0_u \\ a^0_s \end{pmatrix} + \begin{pmatrix} h^-_d & h^-_u \end{pmatrix} M^2_\pm \begin{pmatrix} h^+_d \\ h^+_u \end{pmatrix},$$

Charged Higgs, as in the MSSM, almost

$$M_{\pm}^2 = \frac{1}{2}\begin{pmatrix} \frac{\mathcal{T}_{h_u^0}}{v_u} & 0 \\ 0 & \frac{\mathcal{T}_{h_d^0}}{v_d} \end{pmatrix} + \frac{s_{2\beta}}{2}\left(\underbrace{\frac{2\mu}{s_{2\beta}}(A_\lambda + m_\kappa)}_{M_A^2 = M_{A,\mathrm{MSSM}}^2} + \left(M_W^2 - \Lambda_v^2\right)\right)\begin{pmatrix} 1/t_\beta & 1 \\ 1 & t_\beta \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = U_\beta \begin{pmatrix} h_d^\pm \\ h_u^\pm \end{pmatrix},$$

with (here quite simple)

$$U_\beta = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix}.$$

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Issues with definition of β. **Here it is just a rotation matrix, change of basis.**

Observables are basis independent.

Mass mixing in the CP-even Higgs system

$$\begin{cases} M^2_{S_{11}} = \frac{\mathcal{T}_{h^0_d}}{2v_d} + M_Z^2 c_\beta^2 + M_A^2 s_\beta^2, \\ M^2_{S_{22}} = \frac{\mathcal{T}_{h^0_u}}{2v_u} + M_Z^2 s_\beta^2 + M_A^2 c_\beta^2, \\ M^2_{S_{33}} = \frac{\mathcal{T}_{h^0_s}}{2s} + \Lambda_v^2 A_\lambda \frac{c_\beta s_\beta}{\mu} + m_\kappa(A_\kappa + 4m_\kappa), \\ M^2_{S_{12}} = M^2_{S_{21}} = (\Lambda_v^2 - \frac{M_Z^2}{2})s_{2\beta} - M_A^2 s_\beta c_\beta, \\ M^2_{S_{13}} = M^2_{S_{31}} = \Lambda_v(2\mu c_\beta - (A_\lambda + 2m_\kappa)s_\beta), \\ M^2_{S_{23}} = M^2_{S_{32}} = \Lambda_v(2\mu s_\beta - (A_\lambda + 2m_\kappa)c_\beta), \end{cases}$$

$$\begin{pmatrix} h_1^0 \\ h_2^0 \\ h_3^0 \end{pmatrix} = S_h \begin{pmatrix} h_d^0 \\ h_u^0 \\ h_s^0 \end{pmatrix},$$

$$M_Z^2\left(c_{2\beta}^2 + \frac{\Lambda_v^2}{M_Z^2} s_{2\beta}^2\right) \equiv M_Z^2\left(1 + \left(\frac{\Lambda_v^2}{M_Z^2} - 1\right) s_{2\beta}^2\right)$$

The underlying parameters

$$\underbrace{t_\beta, \lambda, \kappa, \mu}_{\text{in } \tilde{\chi} \text{ sector also}}, A_\lambda, A_\kappa, (t_{H_d}, t_{H_u}, t_S) \quad \text{and} \quad \underbrace{g, g', v \to e, M_W, M_Z}_{\text{SM}}$$

Charginos and Neutralinos, the link with the Higgs sector

• The mass matrix for the charginos reads, in the basis $(\tilde{W}^-, \tilde{H}_d^-)$

$$X = \begin{pmatrix} M_2 & \sqrt{2} M_W s_\beta \\ \sqrt{2} M_W c_\beta & \mu \end{pmatrix},$$

t_β dep. very weak:

Measurement of the charginos masses reconstruct M_2 and μ although assignment ambiguous unless one has an idea about "higgsino"/wino content

Charginos and Neutralinos, the link with the Higgs sector

The 5×5 neutralino matrix in the basis

$$\psi_n^{RT} = \psi_n^{LT} = \psi^{0T} = \left(-i\tilde{B}^0, -i\tilde{W}_3^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}^0\right)$$

$$Y = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta & 0 \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta & 0 \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu & -\Lambda_v s_\beta \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 & -\Lambda_v c_\beta \\ 0 & 0 & -\Lambda_v s_\beta & -\Lambda_v c_\beta & 2m_\kappa \end{pmatrix},$$

t_β and λ intertwined. If λ small t_β extraction difficult.

Renormalisation: Parameters and counterterms. See my talk here in ...2009

- From $\mathcal{G}_p = \underbrace{t_\beta\,, \lambda, \kappa, \mu}_{\text{in } \tilde{\chi} \text{ sector also}}, A_\lambda\,, A_\kappa\,, \left(M^2_{H_u}\,, M^2_{H_d}\,, M^2_S \to t_{H_d}\,, t_{H_u}\,, t_S\right), M_1\,, M_2$ and $\underbrace{g, g'\,, v \to e, M_W\,, M_Z}_{\text{SM}}$

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- shift all (independent basic Lagrangian) parameters: $\mathcal{G}_p \to \mathcal{G}_p + \delta\mathcal{G}_p$

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- shift all (independent basic Lagrangian) parameters: $\mathcal{G}_p \to \mathcal{G}_p + \delta\mathcal{G}_p$
- this means that mass mixing will appear: non diagonal transition $A^0_i Z^0\,, A^0_i G^0\,, h_1 h_2\,, \ldots\ (\delta m_{h_i h_j}\,, \delta m^2_{H^\pm G^\pm})$ and diagonal masses shifted $(\delta m^2_{h_i})$.

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- No need to apply shifts to the diagonalising matrices (S_h, $U(\beta), \cdots$), these are renormalised (no shift), same with gauge-fixing (not physical)

$$\begin{pmatrix} G^+ \\ H^+ \end{pmatrix}_0 = U(\beta) \begin{pmatrix} h_d^+ \\ h_u^+ \end{pmatrix}_0 \quad \text{implies also} \quad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = U(\beta) \begin{pmatrix} h_d^+ \\ h_u^+ \end{pmatrix}.$$

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- In any case field renormalisation (before or after rotation) still needed

$$\begin{pmatrix} h_1^0 \\ h_2^0 \\ h_3^0 \end{pmatrix}_0 = Z_S \begin{pmatrix} h_1^0 \\ h_2^0 \\ h_3^0 \end{pmatrix}, \quad \begin{pmatrix} A_1^0 \\ A_2^0 \\ G^0 \end{pmatrix}_0 = Z_P \begin{pmatrix} A_1^0 \\ A_2^0 \\ G^0 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}_0 = Z_C \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} \left(\quad (Z_S)_{ij} = 1_{ij} + \delta Z_{h_i h_j}/2\right)$$

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- In any case field renormalisation (before or after rotation) still needed

$$\begin{pmatrix} h^0_1 \\ h^0_2 \\ h^0_3 \end{pmatrix}_0 = Z_S \begin{pmatrix} h^0_1 \\ h^0_2 \\ h^0_3 \end{pmatrix}, \quad \begin{pmatrix} A^0_1 \\ A^0_2 \\ G^0 \end{pmatrix}_0 = Z_P \begin{pmatrix} A^0_1 \\ A^0_2 \\ G^0 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}_0 = Z_C \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} \left(\quad (Z_S)_{ij} = 1_{ij} + \delta Z_{h_i h_j}/2 \right)$$

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$$\left\{ \begin{array}{lcl} \hat{\Sigma}_{h^0_i h^0_i}(p^2) & = & \Sigma_{h^0_i h^0_i}(p^2) - \delta m^2_{h^0_i} + (p^2 - m^2_{h^0_i})\delta Z_{h^0_i} \\ \hat{\Sigma}_{h^0_i h^0_j}(p^2) & = & \Sigma_{h^0_i h^0_j}(p^2) - \delta m^2_{h^0_i h^0_j} + \frac{1}{2}(p^2 - m^2_{h^0_i})\delta Z_{h^0_i h^0_j} + \frac{1}{2}(p^2 - m^2_{h^0_j})\delta Z_{h^0_j h^0_i} \end{array} \right.$$

Conditions: To define wave function renormalisation constants and the counterterms for the underlying parameters

- Mixing vanishes between physical states when these are on-shell, *essentially* (to solve for δZ_{ij}'s
- Residue at the pole (mass) of the propagator is 1
- The other conditions are set by using/choosing a (minimum/sufficient) set of physical masses as input parameters except α_{em}. Only two point-functions are needed (in the present implementation of the NMSSM).
- which minimum set?

Solving for a coupled system of counterterms

$$\begin{pmatrix} \delta\texttt{input}_1 \\ \cdots \\ \cdots \\ \delta\texttt{input}_8 \end{pmatrix}_{\chi^\pm,\chi_i^0,h_i^0,A_i^0,H^\pm} = \mathcal{P}_{8,\text{param.}} \begin{pmatrix} \delta M_1 \\ \delta M_2 \\ \delta\kappa \; \bullet \\ \delta\mu \; \bullet \\ \delta\lambda \\ \delta t_\beta \\ \delta A_\lambda \\ \delta A_\kappa \end{pmatrix} + \mathcal{R}_{n,\text{residual}},$$

$\mathcal{R}_{8,\text{residual}}$ counterterms such as gauge couplings, etc (SM)

Finding the counterterms. Inverting the system

Best to break up the system. $\mathcal{P}_{n,\text{param.}} = \mathcal{P}_{m,\text{param.}} \oplus \mathcal{P}_{p,\text{param.}} \oplus \cdots , \quad m + p + \cdots = n$

At each step, if possible, avoid a choice such that $\text{Det}(\mathcal{P}_{m,\text{param.}}) \to 0$ (like picking up a wino-like neutralino to reconstruct M_1).

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Easiest set up:

- a mixed $\overline{\mathrm{DR}}$, with t_β extracted independently from the Higgs sector (through wave function renormalisation condition) $\delta t_\beta / t_\beta = \left[\frac{1}{2}(\delta Z_{H_u} - \delta Z_{H_d})\right]_\infty$,

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- $A_\lambda, A_\kappa(\lambda)$ from Higgs (A, h, H^+)

$$\mathcal{P}_8 = \mathcal{P}_{1,t_\beta} \oplus \mathcal{P}_{2,\chi^\pm_{1,2}} \oplus \mathcal{P}_{3,\chi^0} \oplus \mathcal{P}_{2,A^0_1,A^0_2} \quad OR$$

$$\mathcal{P}_8 = \mathcal{P}_{1,t_\beta} \oplus \mathcal{P}_{2,\chi^\pm_{1,2}} \oplus \mathcal{P}_{2,\chi^0} \oplus \mathcal{P}_{3,H^\pm,A^0_1,A^0_2(h^0)}$$

Finding the counterterms. Inverting the system

Best to break up the system. $\mathcal{P}_{n,\text{param.}} = \mathcal{P}_{m,\text{param.}} \oplus \mathcal{P}_{p,\text{param.}} \oplus \cdots, \quad m + p + \cdots = n$

Or,

Go all On-Shell, 8×8, *identified*?: $\mathcal{P}_{8;\chi^{\pm}_{1,2},\chi^0_{1,2,3},H^{\pm},A^0_1,h^0}$ 8 Masses

$H^{\pm} \to A_\lambda$ only

$A^0, h^0_i \to A_\lambda$ and A_κ, A_κ sensitive to singlet

λ, t_β weak from $\chi^{\pm}, \chi^0$ better from Higgs masses.

Variants (that all take the chargino masses as input):

$OS_{ijkA_1A_2H^+}$ with the masses of 3 χ^0 preferably $\tilde{b}, \tilde{h}, \tilde{s}$-dominated

$OS_{ijh_\alpha A_1A_2H^+}$ (only 2 neutralinos)

$OS_{ih_\alpha h_\beta A_1A_2H^+}$ (only one neutralino,$\tilde{b}$)

Finding the counterterms. Inverting the system

Best to break up the system. $\mathcal{P}_{n,\mathrm{param.}} = \mathcal{P}_{m,\mathrm{param.}} \oplus \mathcal{P}_{p,\mathrm{param.}} \oplus \cdots, \quad m + p + \cdots = n$

Or,

Go all $\overline{\mathrm{DR}}$

Schemes. Scales. OS *vs* $\overline{\text{DR}}$ *vs* mixed schemes

Renormalisation: a definition of the underlying parameters to get rid of infinities.

- The infinities: Most loop calculations (1, 2, 3-point functions), regularization introduces $\widetilde{C}_{UV} = 2/\epsilon - \gamma_E + \ln(4\pi/\bar{\mu}^2) = 2/\epsilon - \gamma_E + \ln(4\pi) + \ln(1/\bar{\mu}^2)$

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  $\delta p_i/p_i = \beta_{p_i}(C_{UV} + \ln(Q_{p_i}/\bar{\mu})) \quad (\beta_{p_i} = \partial p_i/\partial \ln 1/\bar{\mu})$
  Note $ln(Q_{p_i}) = ln(\tilde{Q}_{p_i}) + F(Q'_{p_i})$, Q_{p_i} is **scheme dependent** but β_{p_i} universal

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- Full one-loop correction: $\delta\mathcal{O}/\mathcal{O} = \Delta(C_{UV} + \ln(Q_\Delta/\bar{\mu})) + \sum_i \kappa_i \delta p_i/p_i$

Schemes. Scales. OS *vs* $\overline{\mathrm{DR}}$ *vs* mixed schemes

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good choice of Q_{p_i}, $\bar{\mu}$ especially if large β, κ. In full $\overline{\mathrm{DR}}$ μ dep. trackable.

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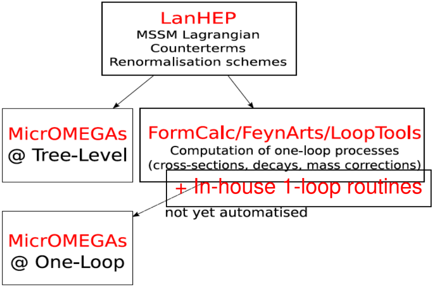
  good choice of Q_{p_i}, $\bar{\mu}$ especially if large β, κ. In full $\overline{\rm DR}$ μ dep. trackable.
- mixed scheme, say p_0 $\overline{\rm DR}$ (the rest of p_i is OS). In the inversion of OS scheme, p_0 may enter as residual (good choice?)

$$\frac{\delta O^{\rm mixed}}{O} = \frac{\delta O^S}{O} + \beta_{p_0}\left(-\kappa_0 \ln(Q_0/\bar{\mu}) + \sum_{i\neq 0} \kappa_{i0} \ln(\tilde{Q}_i/\bar{\mu})\right)$$



SLOOPS

An automatic code for calculation of loops diagrams for $\mathcal{SM}$ and $\mathcal{BSM}$ processes with application to colliders, astrophysics and cosmology.

- Automatic derivation of the CT Feynman rules and computation of the CT's
- Models renormalized: SM, MSSM, NMSSM, **xSM** (w/ & w/o singlet vev)
- Modularity between different renormalisation schemes.
- Non-linear gauge fixing.
- Checks: results UV,IR finite and gauge independent.

Application to Higgs decays in the NMSSM

Point A($\mathrm{Q_{susy}} = 1117.25$GeV, $m_t = 173$GeV, $m_{h_1^0} = 125.45$GeV(1-loop OS))

M_1	700	λ	0.1	A_κ	0	$m_{\tilde{Q}_3}$	1740	$m_{\tilde{D},\tilde{U}_{1,2}}$	1000
M_2	1000	κ	0.1	A_t	4000	$m_{\tilde{U}_3}$	800	$m_{\tilde{L}_3}$	1000
M_3	1000	μ	120	A_b	1000	$m_{\tilde{D}_3}$	1000	$m_{\tilde{l}_3}$	1000
t_β	10	A_λ	150	A_l	1000	$m_{\tilde{Q}_{1,2}}$	1000	$m_{\tilde{L},\tilde{l}_{1,2}}$	1000

$\lambda A_\lambda = 15$GeV, $A_t/A_\lambda \sim 27$

Point B($\mathrm{Q_{susy}} = 753.55$GeV, $m_t = 146.94$GeV, $m_{h_1^0} = 124.44$GeV(1-loop OS))

M_1	120	λ	0.67	A_κ	0	$m_{\tilde{Q}_3}$	750	$m_{\tilde{D},\tilde{U}_{1,2}}$	1500
M_2	300	κ	0.2	A_t	1000	$m_{\tilde{U}_3}$	750	$m_{\tilde{L}_3}$	1500
M_3	1500	μ	200	A_b	1000	$m_{\tilde{D}_3}$	1500	$m_{\tilde{l}_3}$	1500
t_β	1.92	A_λ	405	A_l	1000	$m_{\tilde{Q}_{1,2}}$	1500	$m_{\tilde{L},\tilde{l}_{1,2}}$	1500

$\lambda A_\lambda = 271$GeV, $A_t/A_\lambda \sim 2.5$

Applications. Two scenarios

		Point A	Point B
h_1^0	h_d^0	1.1%	22.5%
	h_u^0	**98.6%**	**67.4%**
	h_s^0	0.3%	10.1%
h_2^0	h_d^0	0.1%	0.%
	h_u^0	0.3%	12.5%
	h_s^0	**99.6%**	**87.5%**
h_3^0	h_d^0	**98.8%**	**77.5%**
	h_u^0	1.1%	19.7%
	h_s^0	0.1%	2.8%
A_1^0	a_d^0	0%	1.8%
	a_u^0	0%	0.5%
	a_s^0	**100%**	**97.7%**
A_2^0	a_d^0	**99.0%**	**76.9%**
	a_u^0	1.0%	20.8%
	a_s^0	0.0%	2.3%

Point A: h_u, h_s, h_d, a_s, a_d

Point B: h_u, h_s, h_d, a_s, a_d

		Point A	Point B
$\tilde{\chi}_1^0$	$\tilde{B}^0$	-	**56.6%**
	$\tilde{W}^0$	-	32.3%
	$\tilde{h}^0$	**98.4%**	10.3%
	$\tilde{S}^0$	0.77%	0.8%
$\tilde{\chi}_2^0$	$\tilde{B}^0$	-	4.0%
	$\tilde{W}^0$	-	2.6%
	$\tilde{h}^0$	**99.5%**	19.3%
	$\tilde{S}^0$	-	**74.0%**
$\tilde{\chi}_3^0$	$\tilde{B}^0$	-	10.1%
	$\tilde{W}^0$	-	-
	$\tilde{h}^0$	0.9%	**78.9%**
	$\tilde{S}^0$	**99.1%**	11.0%
$\tilde{\chi}_4^0$	$\tilde{B}^0$	**99.6%**	18.1%
	$\tilde{W}^0$	-	12.3%
	$\tilde{h}^0$	-	**55.8%**
	$\tilde{S}^0$	-	13.7%
$\tilde{\chi}_5^0$	$\tilde{B}^0$	-	11.2%
	$\tilde{W}^0$	**99.3%**	**52.8%**
	$\tilde{h}^0$	0.69%	35.7%
	$\tilde{S}^0$	-	0.4%

Point A: $\tilde{h}$, $\tilde{h}$, $\tilde{s}$, $\tilde{b}$, $\tilde{w}$

Point B: $\tilde{b}$, $\tilde{s}$, $\tilde{h}$, $\tilde{h}$, $\tilde{w}$

Beware. B much more mixing, A quite pure

Point A. β's and counterterms

(β in units of 10^{-3}) $\beta_\mu = -11.4, \beta_{t_\beta} = 16.9, \beta_\lambda = -11.7, \beta_\kappa = -0.76,$ $\beta_{\mathbf{A}_\lambda} = -\mathbf{1097}.\mathbf{4}$

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$$
\begin{aligned}
16\pi^2 \frac{1}{h_t^2}\frac{\mathrm{d}h_t^2}{\mathrm{d}t} &= 6h_t^2, \qquad 16\pi^2 \frac{1}{\lambda^2}\frac{\mathrm{d}\lambda^2}{\mathrm{d}t} = 3h_t^2, \\
16\pi^2 \frac{1}{\mu^2}\frac{\mathrm{d}\mu^2}{\mathrm{d}t} &= 3h_t^2, \qquad 16\pi^2 \frac{1}{A_t}\frac{\mathrm{d}A_t}{\mathrm{d}t} = 6h_t^2, \\
16\pi^2 \frac{1}{A_\lambda}\frac{\mathrm{d}A_\lambda}{\mathrm{d}t} &= 3h_t^2 \frac{A_t}{A_\lambda} \qquad (+\,4\lambda^2), \\
\frac{1}{2}6\pi^2 \frac{1}{A_t}\frac{\mathrm{d}A_t}{\mathrm{d}t} &= 6h_t^2, \qquad (16\pi^2 \frac{1}{A_\kappa}\frac{\mathrm{d}A_\kappa}{\mathrm{d}t} = 6\kappa + 6\lambda^2 \frac{A_\lambda}{A_\kappa}).
\end{aligned}
$$

Point A. β's and counterterms

(β in units of 10^{-3}) $\beta_\mu = -11.4, \beta_{t_\beta} = 16.9, \beta_\lambda = -11.7, \beta_\kappa = -0.76,$ $\beta_{\mathbf{A}_\lambda} = -\mathbf{1097.4}$

Finite parts computed at $\bar{\mu} = \mathrm{Q_{susy}} = 1117.25 GeV$.

$$(\delta\mu/\mu, \delta t_\beta/t_\beta, \delta\lambda/\lambda)_{\text{finite}} = \overbrace{(-2.42\%, 0, 62.26\%)}^{t_{134A_1A_2}}; \overbrace{(-1.57\%, -80.69\%, -7.88\%)}^{OS_{34h_2A_1A_2H^+}}$$

$$(\delta\kappa/\kappa, \delta A_\lambda/A_\lambda, \delta A_\kappa)_{\text{finite}} = \overbrace{(\mathbf{64.01}\%, -5.49\%, 0.65)}^{t_{134A_1A_2}}; \overbrace{(-6.01\%, 134\%, 0.66)}^{OS_{34h_2A_1A_2H^+})}.$$

β's and counterterms

(β in units of 10^{-3})

Point A

$\beta_\mu = -11.40, \beta_{t_\beta} = 16.9, \beta_\lambda = -11.65, \beta_\kappa = -0.76, \beta_{\mathbf{A}_\lambda} = -\mathbf{1097.4}$

Point B

$\beta_\mu = -14.25, \beta_{t_\beta} = 17.63, \beta_\lambda = -20.45, \beta_\kappa = -18.57, \beta_{\mathbf{A}_\lambda} = -\mathbf{122.7}$

β's and counterterms

(β in units of 10^{-3})

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$\beta_\mu = -11.40, \beta_{t_\beta} = 16.9, \beta_\lambda = -11.65, \beta_\kappa = -0.76, \beta_{A_\lambda} = \mathbf{-1097.4}$

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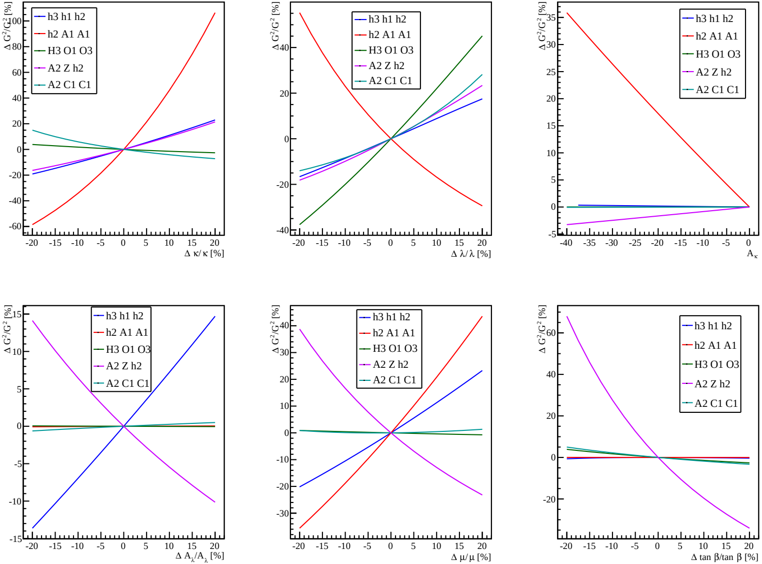
$\beta_\mu = -14.25, \beta_{t_\beta} = 17.63, \beta_\lambda = -20.45, \beta_\kappa = -18.57, \beta_{A_\lambda} = \mathbf{-122.7}$

"Finite parts" computed at $\bar{\mu} = \mathrm{Q_{susy}} = 753.55 GeV$

$$(\delta\mu/\mu, \delta t_\beta/t_\beta, \delta\lambda/\lambda)_{\rm finite} = \overbrace{(-1.04\%, 0, 3.71\%)}^{t_{123A_1A_2}}; \overbrace{(-1.63\%, 6.49\%, 5.94\%)}^{OS_{34h_2A_1A_2H^+}}$$

$$(\delta\kappa/\kappa, \delta A_\lambda/A_\lambda, \delta A_\kappa)_{\rm finite} = \overbrace{(3.25\%, 6.85\%, 10.84)}^{t_{123A_1A_2}}; \overbrace{(6.05\%, 3.40\%, 11.54)}^{OS_{34h_2A_1A_2H^+}}.$$

Point A, parametric dependence



Point A, singlet-like: h_2^0, A_1^0, χ_3^0, $Q_{\rm SUSY} = 1117$, $m_{h_2^0} = 240$, $m_{h_3^0, A_2^0, H\pm} \sim 570$, $\tilde{\chi}_i^0 = (\tilde{h}, \tilde{h}, \tilde{s}, \tilde{b}, \tilde{w})$

units width=GeV/100	$t_{134 A_1 A_2, \mu = m_{h_i} \to}$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\rm DR}, \mu = m_{h_i} \to$	$\overline{\rm DR}\ Q_{\rm SUSY}$

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units width=GeV/100	$t_{134 A_1 A_2, \mu=m_{h_i \to}}$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\rm DR}, \mu = m_{h_i \to}$	$\overline{\rm DR}\ Q_{\rm SUSY}$
$h_3^0 \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$	4.61 (1%)	4.03 (-11%)	4.13 (-9%)	4.21 (-7.4%)
$A_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$	4.22 (28%)	3.72 (13%)	3.30 (0.3%)	3.24 (-1.6%)
$A_2^0 \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$	4.96 (-10%)	5.43 (-1.5%)	5.15 (-6%)	5.06 (-8%)

Point A, singlet-like: h_2^0, A_1^0, χ_3^0, $Q_{\rm SUSY}=1117$, $m_{h_2^0}=240$, $m_{h_3^0,A_2^0,H^\pm}\sim 570$, $\tilde{\chi}_i^0=(\tilde{h},\tilde{h},\tilde{s},\tilde{b},\tilde{w})$

units width=GeV/100	$t_{134A_1A_2,\mu=m_{h_j\to}}$	$OS_{34h_2A_1A_2H^+}$	$\overline{\rm DR}, \mu=m_{h_i\to}$	$\overline{\rm DR}\ Q_{\rm SUSY}$
$h_2^0\to A_1^0A_1^0$	10.9 (128%)	4.21 (-12%)	4.80 (0.4%)	4.77 (-0.4%)

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units width=GeV/100	$t_{134A_1A_2,\mu=m_{h_i\to}}$	$OS_{34h_2A_1A_2H^+}$	$\overline{\rm DR}, \mu=m_{h_i\to}$	$\overline{\rm DR}\ Q_{\rm SUSY}$
$h_3^0\to\tilde{\chi}_1^0\tilde{\chi}_3^0$	7.80 (122%)	3.41 (-3%)	3.58 (2%)	3.52 (0.3%)
$h_3^0\to\tilde{\chi}_2^0\tilde{\chi}_3^0$	7.64 (126%)	2.19 (-35%)	3.47 (3%)	3.42 (1.1%)
$A_2^0\to\tilde{\chi}_1^0\tilde{\chi}_3^0$	5.62 (130%)	1.69 (-31%)	2.63 (8%)	2.59 (6.2%)
$A_2^0\to\tilde{\chi}_2^0\tilde{\chi}_3^0$	6.71 (122%)	2.87 (-5%)	3.01 (-0.4%)	2.96 (-1.9%)
$H^+\to\tilde{\chi}_1^+\tilde{\chi}_3^0$	14.4 (125%)	5.24 (-18%)	6.57 (3%)	6.47 (1.1%)

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units width=GeV/100	$t_{134 A_1 A_2, \mu=m_{h_i\to}}$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\rm DR}, \mu = m_{h_i\to}$	$\overline{\rm DR}\ Q_{\rm SUSY}$
$h_3^0 \to h_1^0 h_2^0$	4.76 (116%)	3.95 (79%)	3.35 (52%)	2.17 (-1.7%)

Point A, singlet-like: h_2^0, A_1^0, χ_3^0, $Q_{\rm SUSY} = 1117$, $m_{h_2^0} = 240$, $m_{h_3^0, A_2^0, H^\pm} \sim 570$, $\tilde{\chi}_i^0 = (\tilde{h}, \tilde{h}, \tilde{s}, \tilde{b}, \tilde{w})$

units width=GeV/100	$t_{134A_1A_2,\mu=m_{h_i\to}}$	$OS_{34h_2A_1A_2H^+}$	$\overline{\rm DR}$, $\mu = m_{h_i\to}$	$\overline{\rm DR}$ $Q_{\rm SUSY}$
$h_2^0 \to A_1^0 A_1^0$	10.9 (128%)	4.21 (-12%)	4.80 (0.4%)	4.77 (-0.4%)

With $A_\kappa = 0$ (at tree-level), this interaction stems solely from the term $\kappa^2 S^4$. The trilinear $\kappa^2 s \propto (\kappa s)^2/s \propto \lambda/\mu\ (\kappa s)^2$. $2\kappa s$ sets the mass of the singlino. The percentage correction 128% in the t scheme and -12% in the OS scheme extremely well approximated by the λ dependence ($\sim 2\delta\lambda/\lambda$) of the counterterm.

$$\beta_\mu = -11.40,\ \beta_{t_\beta} = 16.9,\ \beta_\lambda = -11.65,\ \beta_\kappa = -0.76,\ \beta_{\mathbf{A}_\lambda} = \mathbf{-1097.4}$$

Finite parts computed at $\bar{\mu} = {\rm Q_{susy}} = 1117.25 GeV$.

$$(\delta\mu/\mu, \delta t_\beta/t_\beta, \delta\lambda/\lambda)_{\rm finite} = \overbrace{(-2.42\%, 0, 62.26\%)}^{t_{134A_1A_2}}; \overbrace{(-1.57\%, -80.69\%, -7.88\%)}^{OS_{34h_2A_1A_2H^+}}$$

$$(\delta\kappa/\kappa, \delta A_\lambda/A_\lambda, \delta A_\kappa)_{\rm finite} = \overbrace{(\mathbf{64.01}\%, -5.49\%, 0.65)}^{t_{134A_1A_2}}; \overbrace{(-6.01\%, 134\%, 0.66)}^{OS_{34h_2A_1A_2H^+})}.$$

Point A, singlet-like: h_2^0, A_1^0, χ_3^0, $Q_{\rm SUSY}=1117$, $m_{h_2^0}=240$, $m_{h_3^0, A_2^0, H^\pm}\sim 570$, $\tilde{\chi}_i^0=(\tilde{h},\tilde{h},\tilde{s},\tilde{b},\tilde{w})$

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- The other decays of the Higgses (CP-even, CP-odd or charged) into neutralinos/charginos involving the mostly singlet χ_3^0 require mixing (through λ for these processes to proceed. Once this is identified, the results ($\sim 2\delta\lambda/\lambda$)are very similar to the one obtained for $h_2\to A_1^0A_1^0$.

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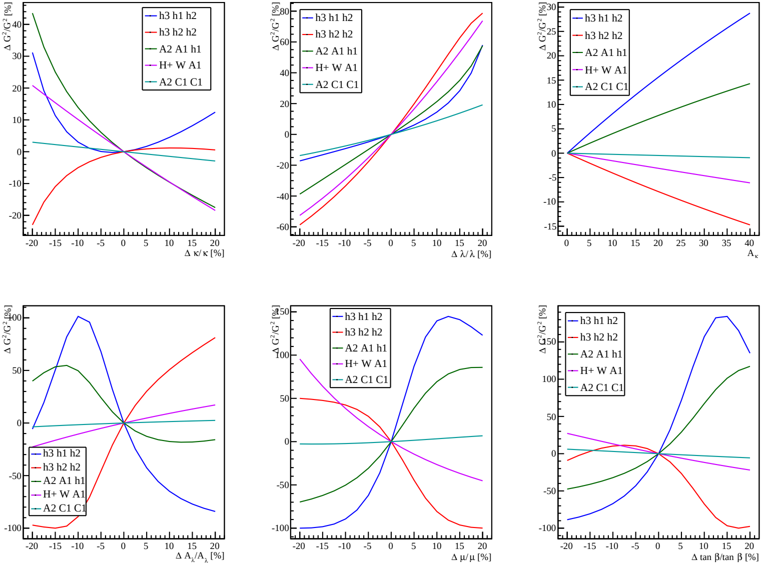
units width=GeV/100	$t_{134A_1A_2,\mu=m_{h_i\to}}$	$OS_{34h_2A_1A_2H^+}$	$\overline{\rm DR}, \mu=m_{h_i\to}$	$\overline{\rm DR}\ Q_{\rm SUSY}$
$h_3^0\to h_1^0h_2^0$	4.76 (116%)	3.95 (79%)	3.35 (52%)	2.17 (-1.7%)

with λ small $h_1h_2h_3\sim h_u^0h_d^0h_s^0$, the coupling can be read off directly from the potential (before diagonalisation):

$$\lambda A_\lambda + 2\kappa\mu$$

the differences between the schemes explained by the values of the counterterms. Here $Q_{\rm SUSY}$ is a good scale in $\overline{\rm DR}$. but the scale dependence is very large.

Point B: Strong parametric dependence



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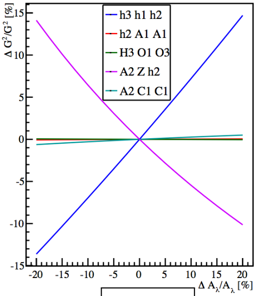
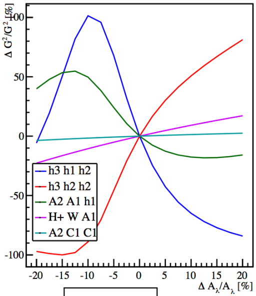


Point A



Point B

Point B. Mixing large, difficult to discuss in terms of the (almost) "pure" states

	$OS_{12h_2A_1A_2H^+}$	$\overline{\rm DR}$	$\overline{\rm DR}\ Q_{\rm SUSY}$
$h_3^0 \to \tilde{\chi}_1^0\tilde{\chi}_2^0$	(14%)	(5%)	(3%)
$h_3^0 \to A_1^0 Z$	(3%)	(-3%)	(-8 %)
$h_3^0 \to h_2^0 h_1^0$	(-25%)	(-106%)	(-50%)
$h_3^0 \to h_2^0 h_2^0$	(6%)	(13%)	(-28%)
$A_2^0 \to \tilde{\chi}_1^+\tilde{\chi}_1^-$	(7%)	(2%)	(1%)
$A_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$	(32%)	(2%)	(2%)
$A_2^0 \to Z h_2^0$	(12%)	(-16%)	(-9%)
$A_2^0 \to A_1^0 h_1^0$	(-0.3%)	(-32%)	(-17%)
$H^+ \to \tilde{\chi}_1^+\tilde{\chi}_2^0$	(6%)	(10%)	(8%)
$H^+ \to W^+ h_2^0$	(11%)	(-18%)	(-10%)
$H^+ \to W^+ A_1^0$	(2%)	(-3%)	(-9%)
$H^+ \to \tilde{\chi}_1^+\tilde{\chi}_1^0$	(21%)	(9%)	(9%)

- OS does a good job.
- Again $h_3 h_2 h_1$ large scheme dependence. The coupling is not totally controlled by A_λ which runs less, however the parametric dependence on A_λ is quite large

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- This is technically much more challenging, but it is possible (at least in some manifestations). In the MSSM $A^0 \to \tau\bar{\tau}$ was shown to be an **excellent** input for t_β, *see my 2009 talk.*