

# Higgs Inflation at the LC

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work done in collaboration with

- Sebastian Passehr<sup>a,b</sup> Higgs mass @ 2loop
- Stefan Liebler<sup>a,c</sup> Higgs production & decays
- Gudrid Moortgat-Pick<sup>a,d</sup>
- Georg Weiglein<sup>a</sup>

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Inflationary model based on

- [1] M. B. Einhorn and D. R. T. Jones, “*Inflation with Non-minimal Gravitational Couplings in Supergravity*”, JHEP **1003**, 026 (2010) [arXiv:0912.2718]
- [2] S. Ferrara, R. Kallosh, A. Linde, A. Marrani and A. Van Proeyen, “*Jordan Frame Supergravity and Inflation in NMSSM*”, Phys. Rev. D **82**, 045003 (2010) [arXiv:1004.0712]
- [3] S. Ferrara, R. Kallosh, A. Linde, A. Marrani and A. Van Proeyen, “*Superconformal Symmetry, NMSSM, and Inflation*”, Phys. Rev. D **83**, 025008 (2011) [arXiv:1008.2942] [FKLMvP]

## Higgs inflation

- inflation is a cosmological necessity
- instead of introducing a new field:

(SM) Higgs = inflaton

- non-minimal couplings of the scalar field to gravity
- SM becomes “unnatural” [cf. Einhorn, Jones]
- a viable candidate might be the scale-free (Next-to) Minimal Supersymmetric Standard Model [FKLMvP]

## Canonical Superconformal Supergravity (CSS)

- scale invariance of global supersymmetry  $\rightarrow$  local SUSY
- modified SUGRA Lagrangian [Einhorn, Jones]

$$\mathcal{L} = -6 \int d^2 \theta \mathcal{E} \left[ R - \frac{1}{4} (\bar{\mathcal{D}}^2 - 8R) \Phi^\dagger \Phi + P(\Phi) \right] + \text{h. c.} + \dots$$

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- scale invariance of global supersymmetry  $\rightarrow$  local SUSY
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$$\mathcal{L} = -6 \int d^2 \theta \mathcal{E} \left[ R + X(\Phi)R - \frac{1}{4} (\bar{D}^2 - 8R) \Phi^\dagger \Phi + P(\Phi) \right] + \text{h. c.} + \dots$$

## Superconformal symmetry breaking

- $X(\Phi)$
- dimensionless coupling (!)
- only function of chiral superfields ( $\Phi$ , not  $\Phi^\dagger$ )

## Jordan frame $\rightarrow$ Einstein frame, $M_P = 1$

- frame function  $\Omega = \phi_i^* \phi_i - 3$
- Kähler potential  $K = -3 \log(-\Omega/3)$
- non-minimal coupling

$$\Omega_\chi = \Omega - \frac{3}{2} (X(\phi) + \text{h. c.})$$

## NMSSM superconformal symmetry breaking

$$\Omega = -3 + |S|^2 + |H_u|^2 + |H_d|^2 + \frac{3}{2} \chi (H_u \cdot H_d + \text{h. c.})$$

## Enlarged Higgs sector

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad S$$

Superpotential,  $\mathbb{Z}_3$ -invariant:

$$\mathcal{W}_{\text{Higgs}} = \lambda S H_u \cdot H_d + \frac{\kappa}{3} S^3,$$

where  $H_u \cdot H_d = H_u^+ H_d^- - H_u^0 H_d^0$

## The NMSSM solves the “ $\mu$ -problem”

$$\mathcal{W}_{\text{MSSM}} = \mu H_u \cdot H_d + \text{Yukawa}$$

only dimensionful parameter  $\mu$  has to be  $\sim$  electroweak scale

$$\mathcal{W}_{\text{NMSSM}} \supset \lambda S H_u \cdot H_d + \frac{\kappa}{3} S^3$$

dynamical  $\mu$ -term:  $\lambda \langle S \rangle = \mu_{\text{eff}}$

$\mathbb{Z}_3$  symmetry forbids dimensionful couplings (bilinear, tadpole terms)

## local U(1) $\mathcal{R}$ symmetry

- part of the superconformal SU(2, 2|1)
- $\chi$  term breaks continuous  $\mathcal{R}$  and discrete  $\mathbb{Z}_3$  symmetry
- breaking at dimension 6:  $\sim \chi \frac{\lambda^2 h^6}{M_p^2}$

## Corrected Superpotential

$$\begin{aligned}\mathcal{W}_{\text{eff}} &\rightarrow \mathcal{W} e^{X(\Phi)/M_p^2} = \mathcal{W} + \frac{\langle \mathcal{W}_{\text{hid}} \rangle}{M_p^2} X(\Phi) \\ &\simeq \mathcal{W} + m_{3/2} X(\Phi)\end{aligned}$$

## The iNMSSM

$$\mathcal{W}_{\text{eff}} = \lambda S H_u \cdot H_d + \frac{\kappa}{3} S^3 + \frac{3}{2} \chi m_{3/2} H_u \cdot H_d$$

Cosmo pheno requires  $|\chi/\lambda| \simeq 10^5$

like the NMSSM with an extended effective  $\mu$  term

$$\mu'_{\text{eff}} = \lambda \langle S \rangle + \frac{3}{2} \chi m_{3/2} = \mu_{\text{eff}} + \mu$$

Additional soft SUSY breaking term

$$V_{\text{soft}} = \lambda A_\lambda S H_u \cdot H_d + \frac{1}{3} \kappa A_\kappa S^3 \\ + \frac{3}{2} B_\mu \chi m_{3/2} (H_u \cdot H_d + \text{h. c.})$$

Higgs potential of the iNMSSM

$$V = \left[ m_{H_d}^2 + (\mu + \lambda S)^2 \right] |H_d|^2 + \left[ m_{H_u}^2 + (\mu + \lambda S)^2 \right] |H_u|^2 + m_S^2 S^2 \\ + \frac{2}{3} \kappa A_\kappa S^3 + \left[ \kappa S^2 + \lambda H_u \cdot H_d \right]^2 + 2 (B_\mu \mu + \lambda A_\lambda S) H_u \cdot H_d \\ + \frac{g_1^2 + g_2^2}{8} (|H_d|^2 - |H_u|^2)^2 + \frac{g_2^2}{2} |H_d^\dagger H_u|^2$$



## Stabilization of the inflationary trajectory

- only neutral components (“truncation”)

$$S = se^{i\alpha}/\sqrt{2}, \quad H_u^0 = h_2 e^{i\alpha_1}/\sqrt{2}, \quad H_d^0 = h_1 e^{i\alpha_2}/\sqrt{2},$$

with  $h_1 = h \cos \beta$  and  $h_2 = h \sin \beta$ ;  $\tan \beta = h_2/h_1$

- $D$ -flat direction:

$$\beta = \pi/4 \quad h_1^2 = h_2^2 = h^2$$

- “simplest” direction:  $s = 0$ ,  $\alpha_{1,2} = 0$

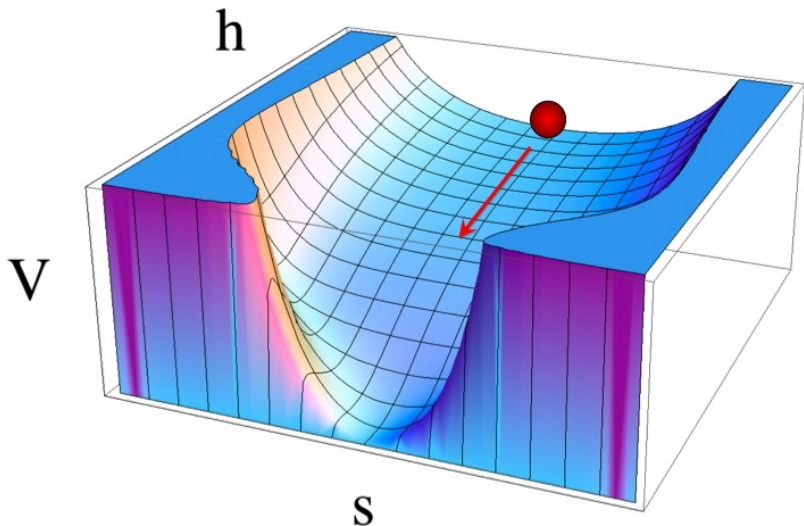
[FLKMvP]

- ⚡ tachyonic singlet directions

[Einhorn, Jones]

- add  $-\zeta(S\bar{S})^2$  to the frame function

# Stabilization mechanism



stabilization for  $\zeta > \frac{2|\lambda\kappa|}{\lambda^2 h^2} + 0.0327$

[FLKMvP]

Flat potential  $V(\phi, \dots)$ slow roll parameters  $\epsilon, \eta \gg 1$ :

$$\epsilon = \frac{1}{2} \left( \frac{1}{V} \frac{\partial V}{\partial \phi} \right)^2$$

$$\eta = \frac{1}{V} \frac{\partial^2 V}{\partial \phi^2}$$

## inflationary NMSSM

[FLKMvP]

$$\epsilon \simeq -\frac{64}{3\chi^2 h^4}, \quad \eta \simeq -\frac{16}{3\chi h^2}$$

slow roll ends when  $\epsilon, \eta \simeq 1$ , thus

$$h_{\text{end}} \simeq 2.2/\sqrt{\chi} \approx 0.007$$

in Planck units!

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**007**

## A SUSY electroweak model

$$V = \left[ m_{H_d}^2 + (\mu + \lambda S)^2 \right] |H_d|^2 + \left[ m_{H_u}^2 + (\mu + \lambda S)^2 \right] |H_u|^2 + m_S^2 S^2 \\ + \frac{2}{3} \kappa A_\kappa S^3 + \left[ \kappa S^2 + \lambda H_u \cdot H_d \right]^2 + 2(B_\mu \mu + \lambda A_\lambda S) H_u \cdot H_d \\ + \frac{g_1^2 + g_2^2}{8} (|H_d|^2 - |H_u|^2)^2 + \frac{g_2^2}{2} |H_d^\dagger H_u|^2$$

$$m_{H_d}^2 = -(\mu + \mu_{\text{eff}})^2 - v^2 \lambda^2 s_\beta^2 - \frac{1}{2} M_Z^2 c_{2\beta} + a_1 t_\beta,$$

$$m_{H_u}^2 = -(\mu + \mu_{\text{eff}})^2 - v^2 \lambda^2 c_\beta^2 + \frac{1}{2} M_Z^2 c_{2\beta} + a_1/t_\beta,$$

$$m_S^2 = a_4 - a_5 - a_7 - v^2 \lambda^2 - \left( v + 2\mu_{\text{eff}} \frac{\kappa}{\lambda} \right),$$

with  $\langle h_u^0 \rangle_{\text{ew}} = v_u/\sqrt{2}$ ,  $\langle h_d^0 \rangle_{\text{eq}} = v_d/\sqrt{2}$ ,  $\langle s^0 \rangle_{\text{ew}} = \mu_{\text{eff}}/\lambda$ .

## Minimisation conditions are in general misleading!

$$\left. \frac{\partial V}{\partial h_u} \right|_{\text{vev}} = 2m_{H_u}^2 v_u + \dots$$

$$\left. \frac{\partial V}{\partial h_d} \right|_{\text{vev}} = 2m_{H_d}^2 v_d + \dots$$

$$\left. \frac{\partial V}{\partial h_s} \right|_{\text{vev}} = 2m_S^2 v_s + \dots$$

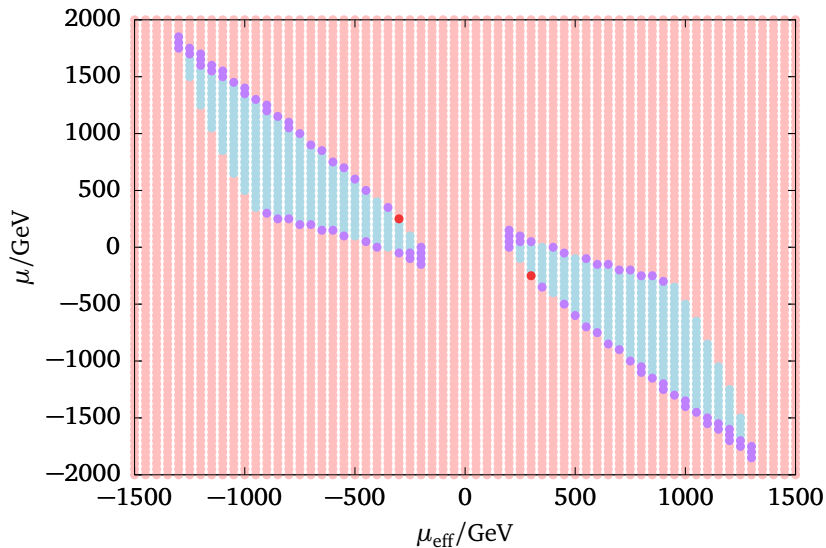
linear equations for soft SUSY breaking masses  $m_{H_u}^2$ ,  $m_{H_d}^2$ ,  $m_S^2$ , can be solved uniquely; determine numerical values for those

- different phenomenology than pure  $\mathbb{Z}_3$ -invariant NMSSM
- tachyonic directions in both
- additional  $\mu$ -term allows for *more* allowed (i. e physical) parameter space
- selection for sign  $\mu_{\text{eff}}$  ( $\mu > 0$  by construction)
- scenarios with *alternative vevs* possible
  - $\langle h_u \rangle \neq v_u/\sqrt{2}$ ,  $\langle h_d \rangle \neq v_d/\sqrt{2}$ ,  $\langle s \rangle \neq \mu_{\text{eff}}/\lambda$
  - in general:  $h_u \simeq h_d \gg v$  or 0 and/or  $s \gg \mu_{\text{eff}}/\lambda$
  - vacuum tunneling: mostly long lifetimes
- SM-like Higgs mass @ 125 GeV!
- no (too) light singlets (can be shifted with  $A_\kappa$ )
- not much viable space left

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# One example

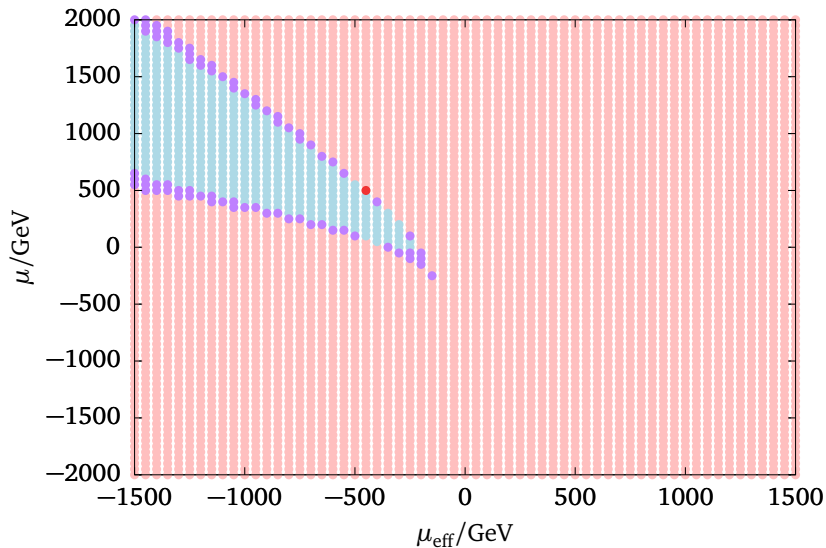
$$\tan \beta = 3, \lambda = 0.3, \kappa/\lambda = 0.3, A_\kappa = 0 \text{ GeV}$$





# One example

$$\tan\beta = 3, \lambda = 0.3, \kappa/\lambda = 0.3, A_\kappa = 100 \text{ GeV}$$



# Main features can be seen from tree-level

$$\mathcal{M}_S^2 = \begin{pmatrix} M_Z^2 c_\beta^2 + a_1 t_\beta & (2v^2 \lambda^2 - M_Z^2) c_\beta s_\beta - a_1 & a_2 c_\beta - a_3 s_\beta \\ \cdot & M_Z^2 s_\beta^2 + a_1/t_\beta & a_2 s_\beta - a_3 c_\beta \\ \cdot & \cdot & a_4 + a_5 \end{pmatrix}$$

$$\mathcal{M}_P^2 = \begin{pmatrix} a_1 t_\beta & a_1 & -a_6 s_\beta \\ \cdot & a_1/t_\beta & -a_6 c_\beta \\ \cdot & \cdot & a_4 - 3a_5 - 2a_7 \end{pmatrix}$$

with

$$a_1 = B_\mu \mu + \mu_{\text{eff}} \left( \frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right) \quad a_2 = 2v\lambda(\mu + \mu_{\text{eff}})$$

$$a_3 = v\lambda \left( 2 \frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right)$$

$$a_4 = \frac{1}{\mu_{\text{eff}}} \left[ v^2 \lambda^2 c_\beta s_\beta \left( \frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right) - v^2 \lambda^2 \mu \right]$$

$$a_5 = 4 \left( \frac{\kappa}{\lambda} \right)^2 \mu_{\text{eff}}^2 + \frac{\kappa}{\lambda} \left[ \mu_{\text{eff}} A_\kappa - v^2 \lambda^2 c_\beta s_\beta \right]$$

$$a_6 = v\lambda \left( 2 \frac{\kappa}{\lambda} \mu_{\text{eff}} - A_\lambda \right) \quad a_7 = -6 \left( \frac{\kappa}{\lambda} \right)^2 \mu_{\text{eff}}^2$$

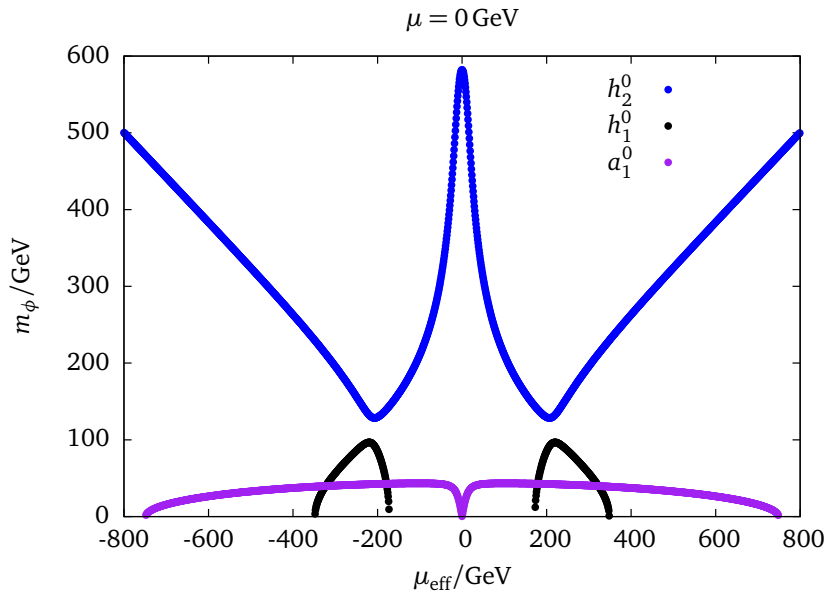
## Avoid tachyonic charged Higgs by definition

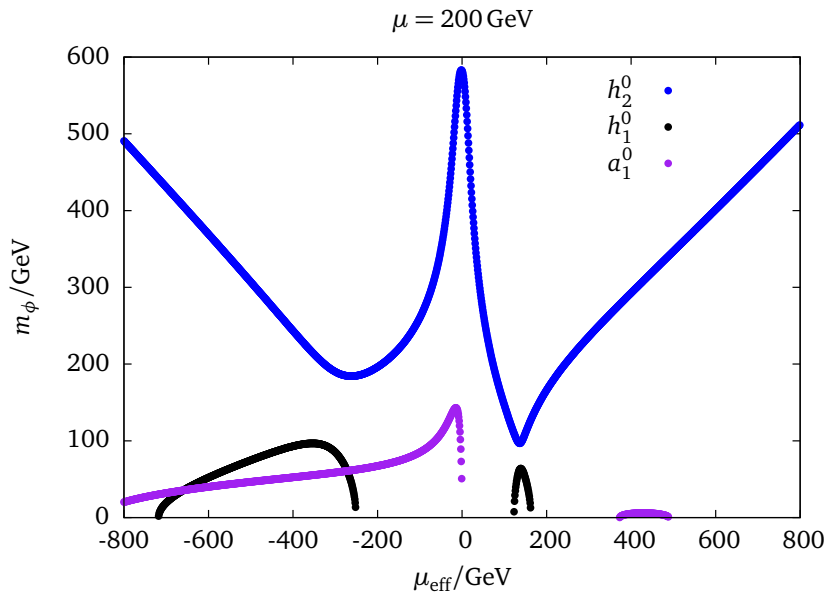
$$m_{H^\pm}^2 = M_W^2 - v^2 \lambda^2 + \frac{a_1}{c_\beta s_\beta}$$

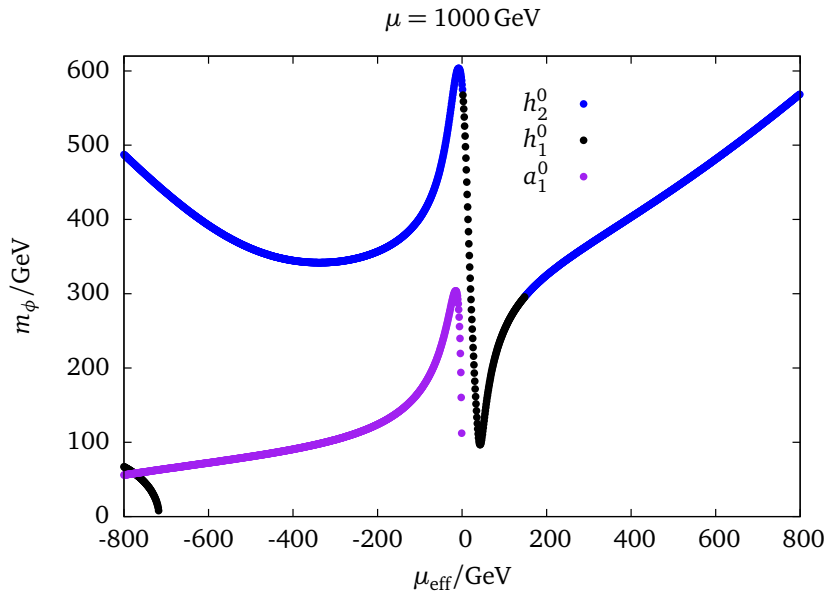
$$a_1 = B_\mu \mu + \mu_{\text{eff}} \left( \frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right)$$

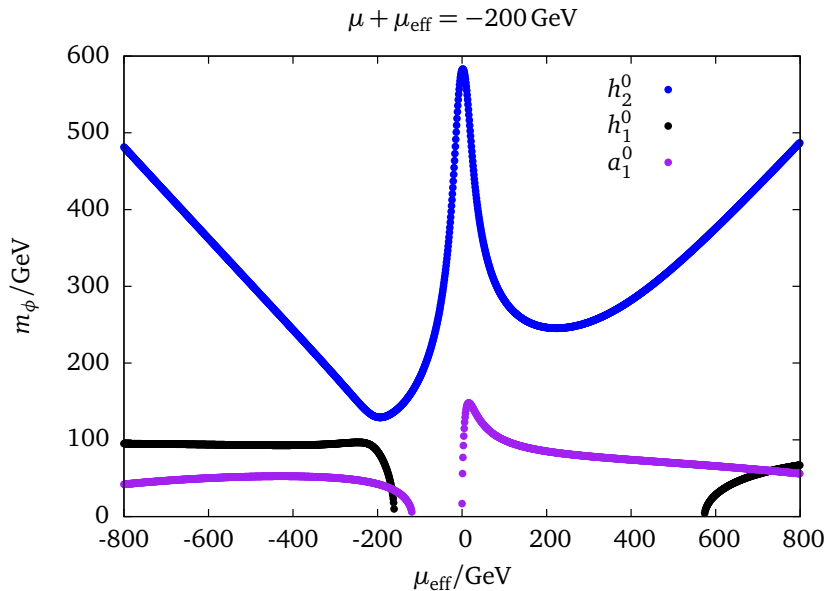
$$A_\lambda = \frac{c_\beta s_\beta}{\mu_{\text{eff}}} \left( m_{H^\pm}^2 - M_W^2 + v^2 \lambda^2 \right) - \frac{B_\mu \mu}{\mu_{\text{eff}}} - \mu_{\text{eff}} \frac{\kappa}{\lambda}$$

- small  $\tan \beta$ : large NMSSM-effect on light Higgs mass ( $\Delta m_{h^0}^2 \sim \lambda^2 v^2 \sin^2 2\beta$ )
- large  $m_{H^\pm} = 800 \text{ GeV}$  (although not needed for small  $\tan \beta$ )
- $\text{sign} A_\kappa$  selects  $\text{sign} \mu_{\text{eff}}$
- $\mu + \mu_{\text{eff}}$  as effective  $\mu$ -term
- single  $\mu_{\text{eff}}$  contributions



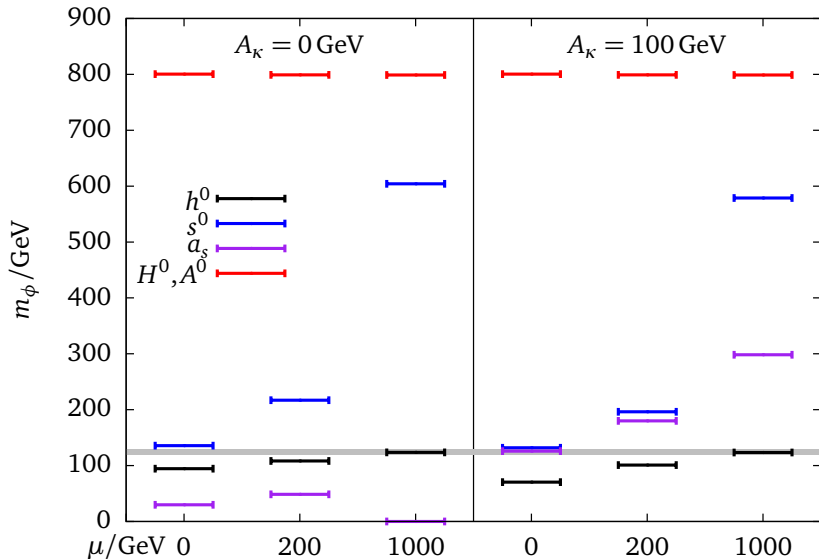






# A Higgs spectrum

$$\mu + \mu_{\text{eff}} = -200 \text{ GeV}, \tan \beta = 3.5, \lambda = 0.3, \kappa/\lambda = 0.3$$





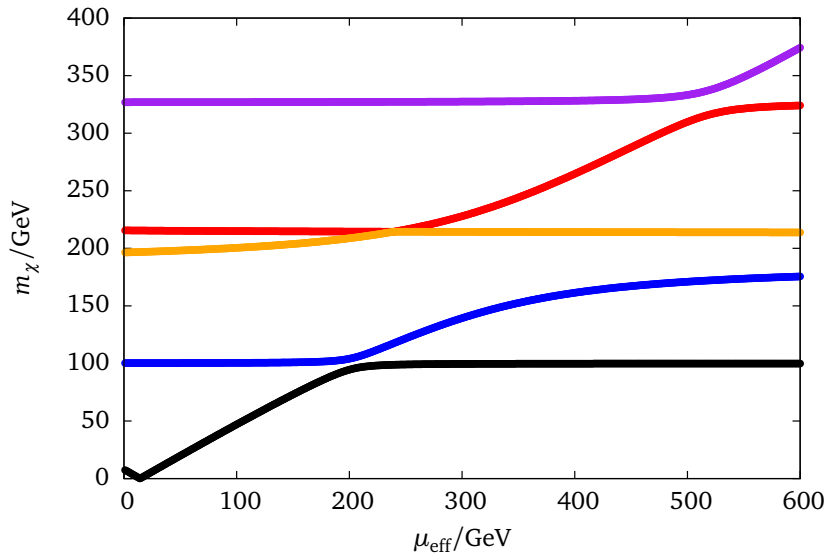
- as in NMSSM: 5 Neutralino states
- different scaling behaviour with  $\mu$ ,  $\mu_{\text{eff}}$
- lightest state probably dark matter candidate
- generically heavy Singlino!

$$\mathcal{M}_\chi = \begin{pmatrix} M_1 & 0 & -M_Z s_w c_\beta & M_Z s_w s_\beta & 0 \\ \cdot & M_2 & M_Z c_w c_\beta & -M_Z c_w s_\beta & 0 \\ \cdot & \cdot & 0 & -(\mu_{\text{eff}} + \mu) & -\lambda v s_\beta \\ \cdot & \cdot & \cdot & 0 & -\lambda v c_\beta \\ \cdot & \cdot & \cdot & \cdot & 2 \frac{\kappa}{\lambda} \mu_{\text{eff}} \end{pmatrix}$$

### Possible distinct scenarios

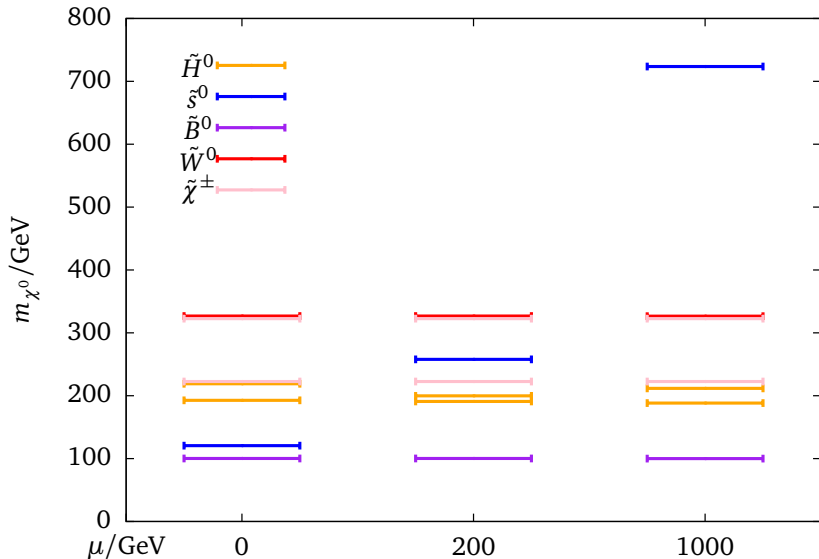
- physical Higgsino mass  $\sim (\mu_{\text{eff}} + \mu)$
- small  $\mu_{\text{eff}} + \mu$
- large cancellation possible: Singlino mass  $\nearrow!$

$$\mu + \mu_{\text{eff}} = -200 \text{ GeV}$$



# A Neutralino spectrum

$$\mu + \mu_{\text{eff}} = -200 \text{ GeV}, \tan \beta = 3.5, \lambda = 0.3, \kappa/\lambda = 0.3$$



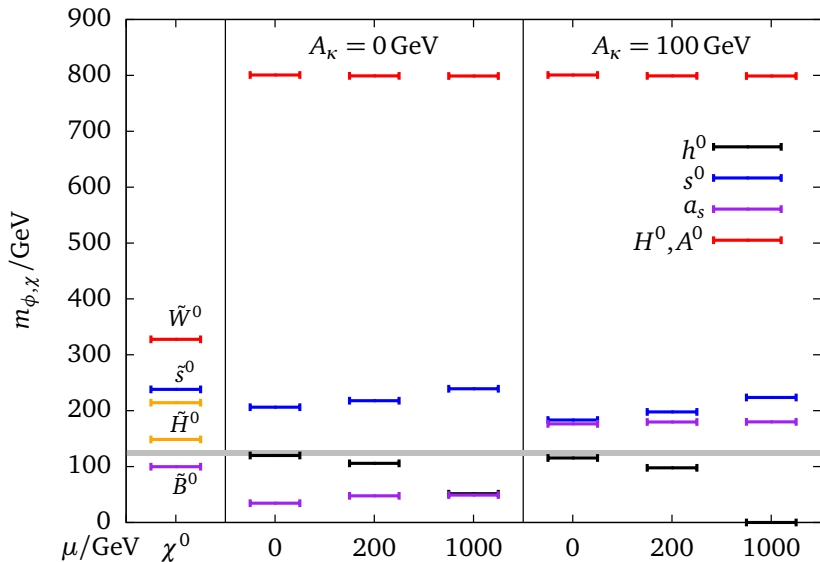
$$\mathcal{M}_\chi = \begin{pmatrix} M_1 & 0 & -M_Z s_w c_\beta & M_Z s_w s_\beta & 0 \\ \cdot & M_2 & M_Z c_w c_\beta & -M_Z c_w s_\beta & 0 \\ \cdot & \cdot & 0 & -(\mu_{\text{eff}} + \mu) & -\lambda v s_\beta \\ \cdot & \cdot & \cdot & 0 & -\lambda v c_\beta \\ \cdot & \cdot & \cdot & \cdot & 2 \frac{\kappa}{\lambda} \mu_{\text{eff}} \end{pmatrix}$$

### “Liebler” rescaling

[G. Weiglein]

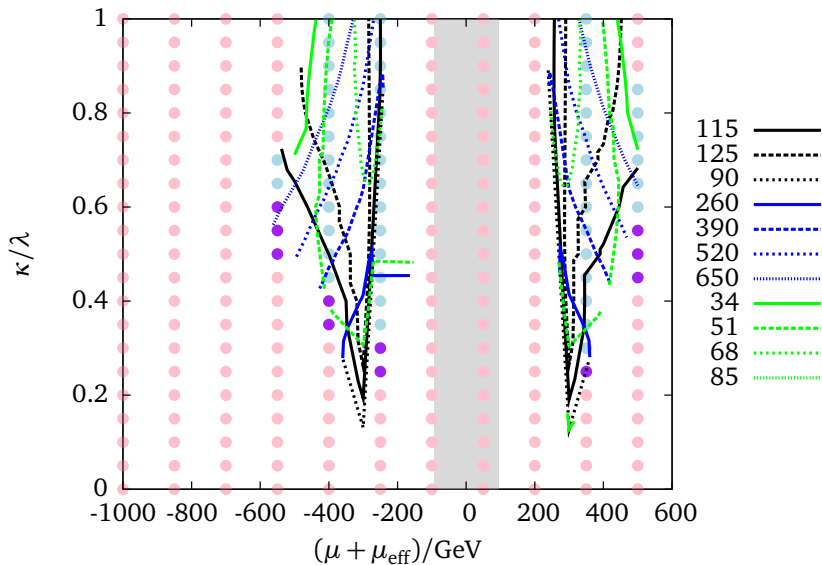
- only 5-5 elements depends on  $\kappa$
- keep  $\mu_{\text{eff}} + \mu$  fixed
- rescale  $\frac{\kappa}{\lambda}$  such that  $(\mathcal{M}_\chi)_{55}$  stays the same

$$\mu + \mu_{\text{eff}} = -200 \text{ GeV}, \tan \beta = 3.5, \lambda = 0.3, \kappa/\lambda = \text{rescaled}$$

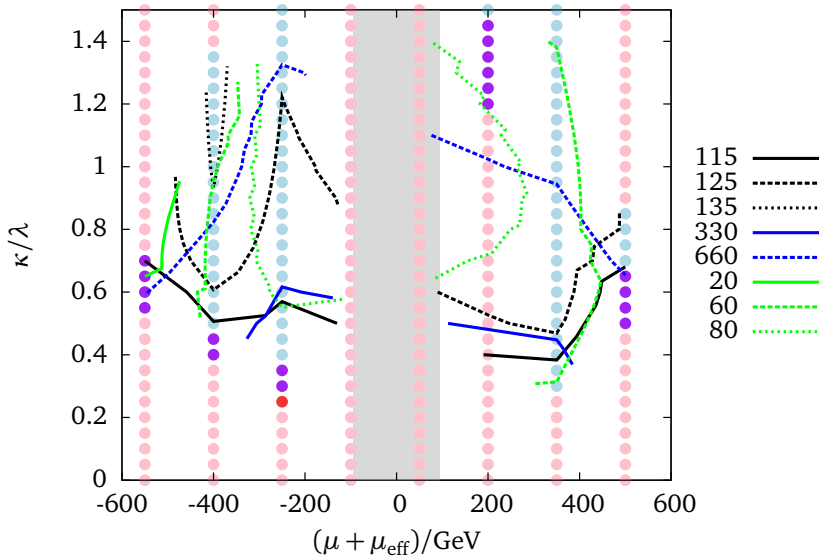


Boiling down the parameter space...

$\mu = 0 \text{ GeV}, \tan \beta = 5/2, \lambda = 1/2, A_\kappa = 0 \text{ GeV}$

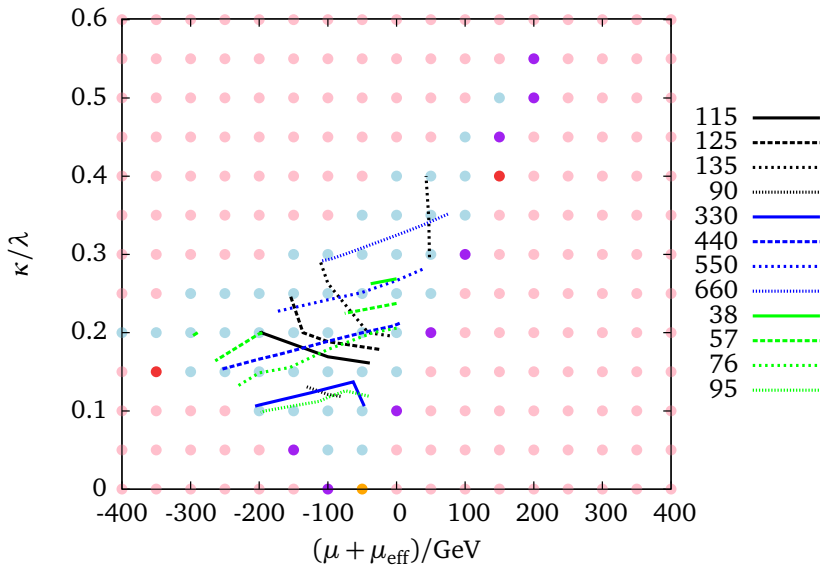


$\tan\beta = 5/2, \lambda = 3/5, A_\kappa = 0 \text{ GeV}$

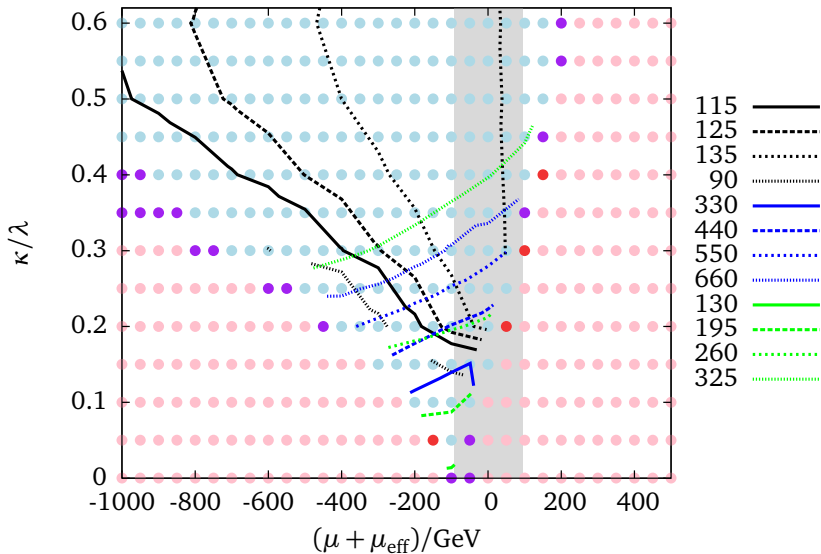




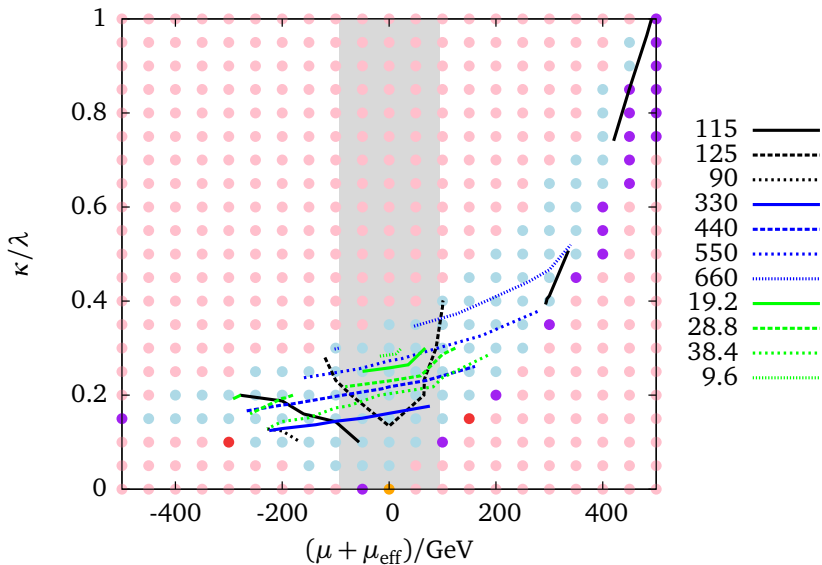
$\mu = 1000 \text{ GeV}, \tan \beta = 5/2, \lambda = 3/5, A_\kappa = 0 \text{ GeV}$



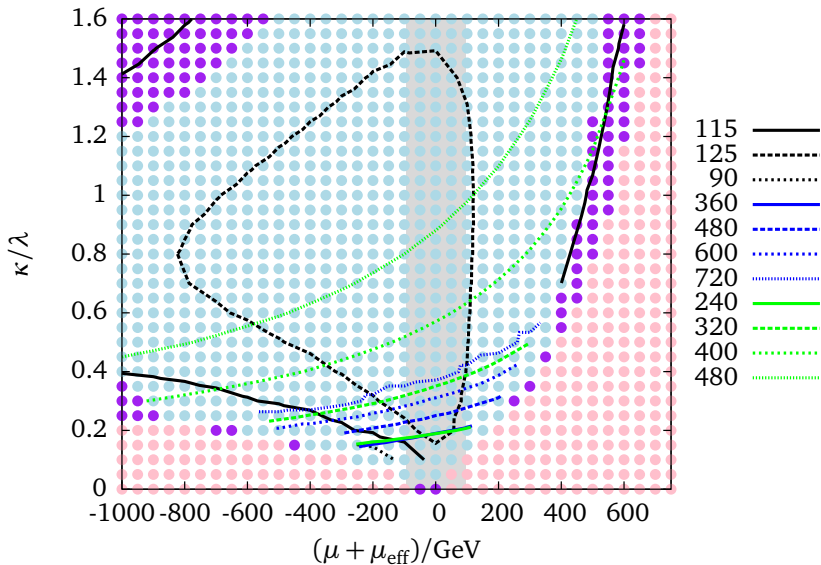
$\mu = 1000 \text{ GeV}, \tan \beta = 5/2, \lambda = 3/5, A_\kappa = 100 \text{ GeV}$



$\mu = 1000 \text{ GeV}, \tan \beta = 7/2, \lambda = 3/10, A_\kappa = 0 \text{ GeV}$

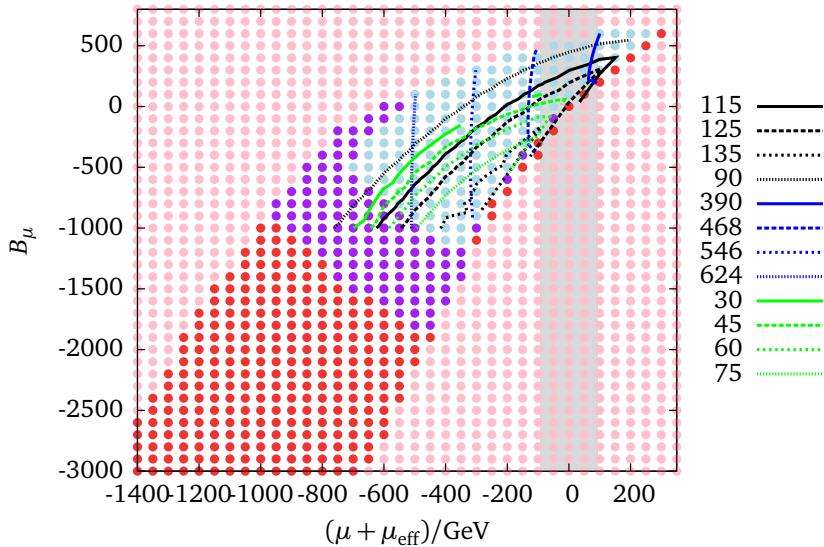


$\mu = 1000 \text{ GeV}, \tan \beta = 7/2, \lambda = 3/10, A_\kappa = 100 \text{ GeV}$

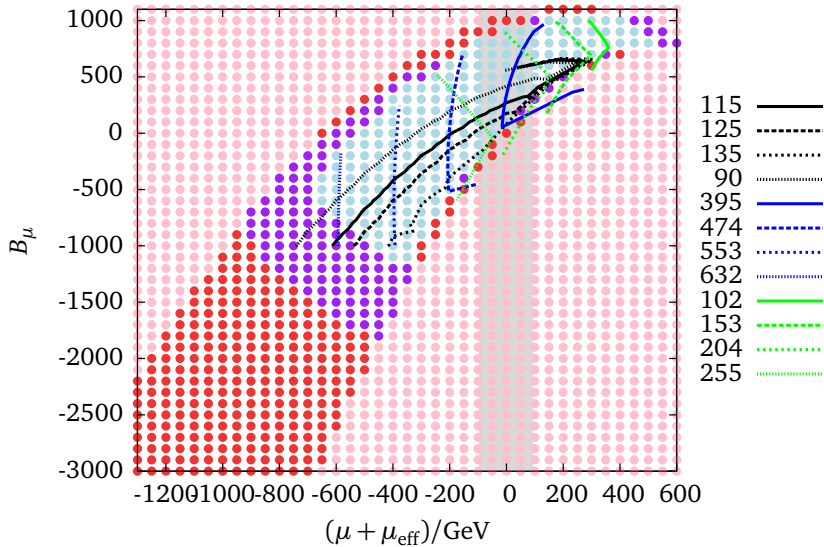


Additional soft  $Z_3$  breaking leads to severe instabilities.

$\mu = 1000, \tan \beta = 3/2, \kappa = 1/10, A_\kappa = 0$



$\mu = 1000, \tan \beta = 3/2, \kappa = 1/10, A_\kappa = 100$



## Higgs Inflation in the NMSSM

- the MSSM is not enough
- Singlet direction to stabilize inflationary trajectory
- inflaton formed out of doublet Higgses

## A $\mu$ term from gravity

$$\mathcal{W}_{\text{iNMSSM}} = \mathcal{W}_{\text{NMSSM}} + \mu H_u \cdot H_d$$

## Caveats and features

- tachyonic Higgs directions
- alternative vevs
- Neutralino sector different from NMSSM
- Higgs-to-Higgs decays! (not talked about)
- parameter region of light Higgsinos favoured!



Backup

Slides

$$\lambda_{111} = -\frac{3}{2}(g_1^2 + g_2^2)c_\beta v \quad \lambda_{112} = \frac{1}{2}(g_1^2 + g_2^2)s_\beta v - 2\lambda^2 s_\beta v \quad (1)$$

$$\lambda_{113} = -2\lambda(\mu_{\text{eff}} + \mu) \quad \lambda_{122} = \frac{1}{2}(g_1^2 + g_2^2)c_\beta v - 2\lambda^2 c_\beta v \quad (2)$$

$$\lambda_{123} = A_\lambda \lambda + 2\kappa \mu_{\text{eff}} \quad \lambda_{133} = -2\lambda^2 c_\beta v + 2\kappa \lambda s_\beta v \quad (3)$$

$$\lambda_{222} = -\frac{3}{2}(g_1^2 + g_2^2)s_\beta v \quad \lambda_{223} = -2\lambda(\mu_{\text{eff}} + \mu) \quad (4)$$

$$\lambda_{233} = -2\lambda^2 s_\beta v + 2\kappa \lambda c_\beta v \quad \lambda_{333} = -2A_\kappa \kappa - 12\frac{\kappa}{\lambda} \mu_{\text{eff}} \quad (5)$$

$$\lambda_{144} = -\frac{1}{2}(g_1^2 + g_2^2)c_\beta v \quad \lambda_{244} = \frac{1}{2}(g_1^2 + g_2^2)s_\beta v - 2\lambda^2 s_\beta v \quad (6)$$

$$\lambda_{344} = -2\lambda(\mu_{\text{eff}} + \mu) \quad \lambda_{345} = -\lambda A_\lambda - 2\kappa \mu_{\text{eff}} \quad (7)$$

$$\lambda_{155} = \frac{1}{2}(g_1^2 + g_2^2)c_\beta v - 2\lambda c_\beta v \quad \lambda_{255} = -\frac{1}{2}(g_1^2 + g_2^2)s_\beta v \quad (8)$$

$$\lambda_{355} = -2\lambda(\mu_{\text{eff}} + \mu) \quad (9)$$