

Hunting Higgs Inflation in the NMSSM

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work done in collaboration with

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Higgs mass @ 2loop

Higgs production & decays

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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 (Φ , 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 “ μ -problem”

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

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

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

dynamical μ -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)
- χ 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 μ 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

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

A SUSY electroweak model

$$V = \left[m_{H_d}^2 + (\mu + \lambda S)^2 \right] |H_d|^2 + \left[m_{H_u}^2 + (\mu + \lambda S)^2 \right] |H_u|^2 + m_S^2 S^2 \\ + \frac{2}{3} \kappa A_\kappa S^3 + \left[\kappa S^2 + \lambda H_u \cdot H_d \right]^2 + 2 (B_\mu \mu + \lambda A_\lambda S) H_u \cdot H_d \\ + \frac{s_1^2 + s_2^2}{8} (|H_d|^2 - |H_u|^2)^2 + \frac{s_2^2}{2} |H_d^\dagger H_u|^2$$

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

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

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

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

Minimisation conditions are in general misleading!

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

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

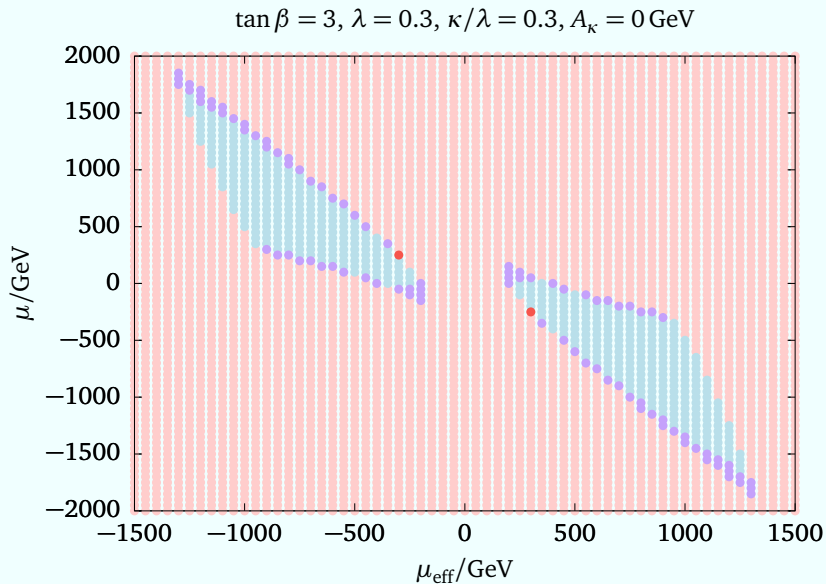
$$\left. \frac{\partial V}{\partial h_s} \right|_{\text{vev}} = 2m_S^2 v_s + \dots$$

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

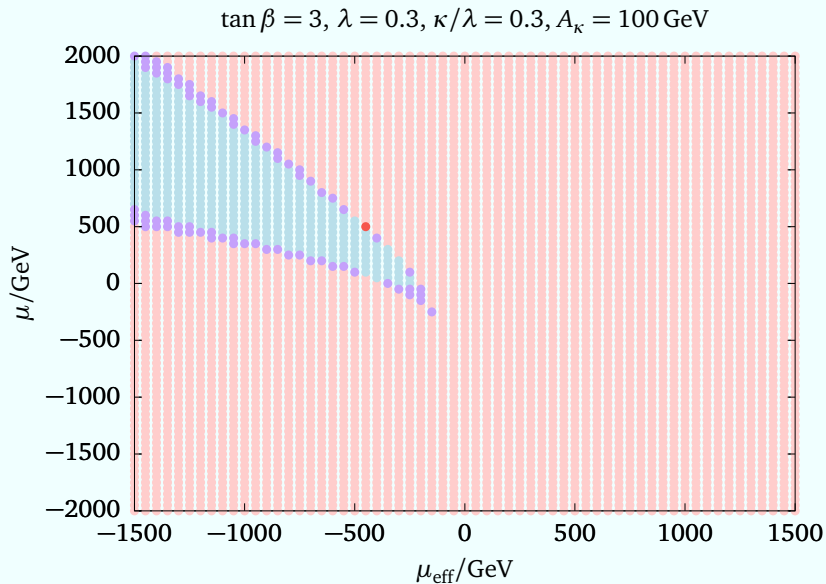
- different phenomenology than pure $\mathbb{Z}_3$ -invariant NMSSM
- tachyonic directions in both
- additional μ -term allows for *more* allowed (i. e physical) parameter space
- selection for sign μ_{eff} ($\mu > 0$ by construction)
- scenarios with *alternative vevs* possible
 - $\langle h_u \rangle \neq v_u/\sqrt{2}$, $\langle h_d \rangle \neq v_d/\sqrt{2}$, $\langle s \rangle \neq \mu_{\text{eff}}/\lambda$
 - 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_κ)
- not much viable space left

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One example



One example



Avoid tachyonic charged Higgs by definition

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

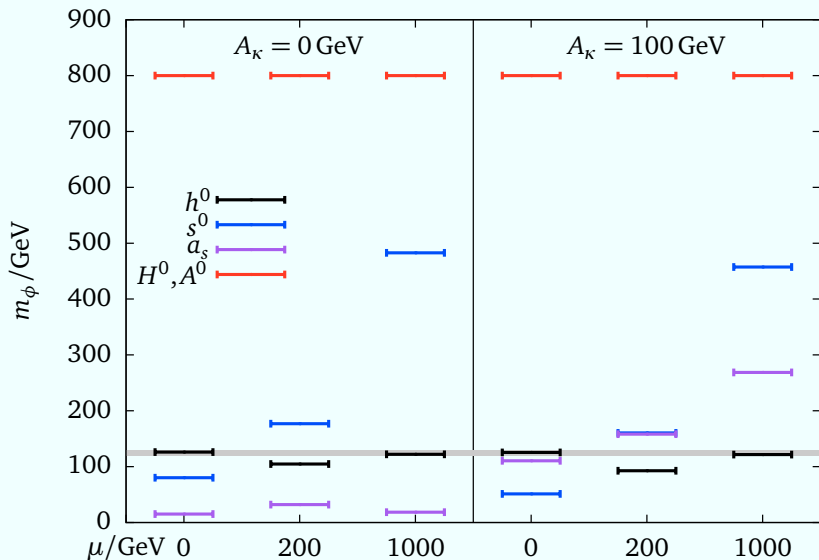
$$a_1 = B_\mu \mu + \mu_{\text{eff}} \left(\frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right)$$

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

- 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 μ -term
- single μ_{eff} contributions

A Higgs spectrum

$$\mu + \mu_{\text{eff}} = -200 \text{ GeV}, \tan \beta = 3.5, \lambda = 0.2, \kappa/\lambda = 0.2$$



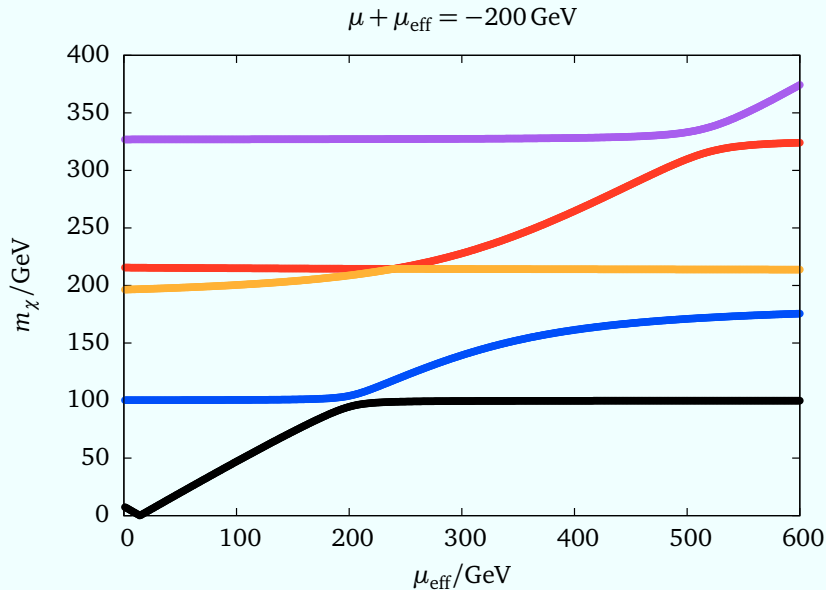
A different sector: Neutralinos!

- as in NMSSM: 5 Neutralino states
- different scaling behaviour with μ , μ_{eff}
- lightest state probably dark matter candidate
- generically heavy Singlino!

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

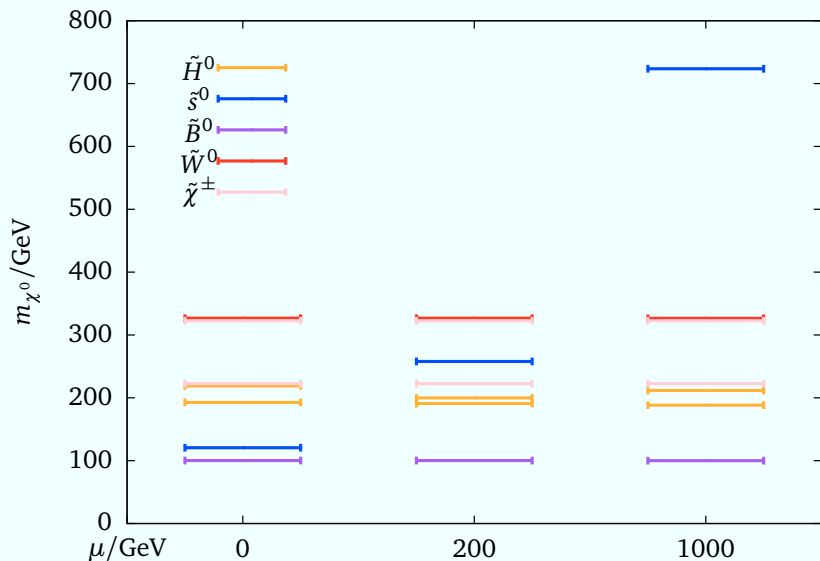
Possible distinct scenarios

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



A Neutralino spectrum

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



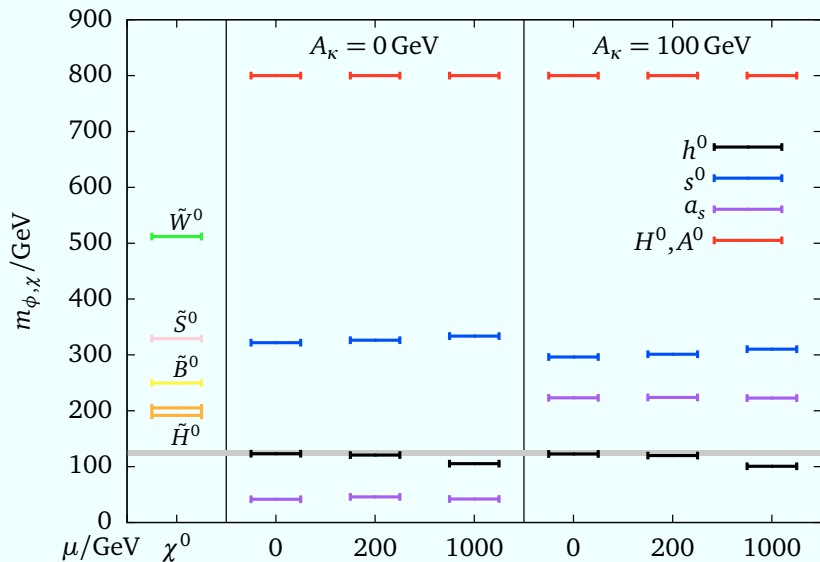
$$\mathcal{M}_\chi = \begin{pmatrix} M_1 & 0 & -M_Z s_w c_\beta & M_Z s_w s_\beta & 0 \\ \cdot & M_2 & M_Z c_w c_\beta & -M_Z c_w s_\beta & 0 \\ \cdot & \cdot & 0 & -(\mu_{\text{eff}} + \mu) & -\lambda v s_\beta \\ \cdot & \cdot & \cdot & 0 & -\lambda v c_\beta \\ \cdot & \cdot & \cdot & \cdot & 2 \frac{\kappa}{\lambda}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

“Liebler” rescaling

[G. Weiglein]

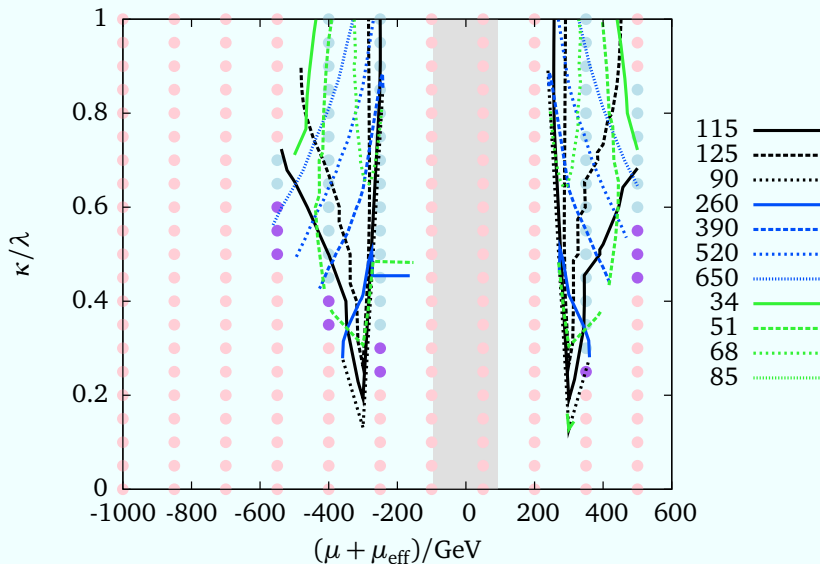
- only 5-5 elements depends on κ
- keep $\mu_{\text{eff}} + \mu$ fixed
- rescale $\frac{\kappa}{\lambda}$ such that $(\mathcal{M}_\chi)_{55}$ stays the same

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

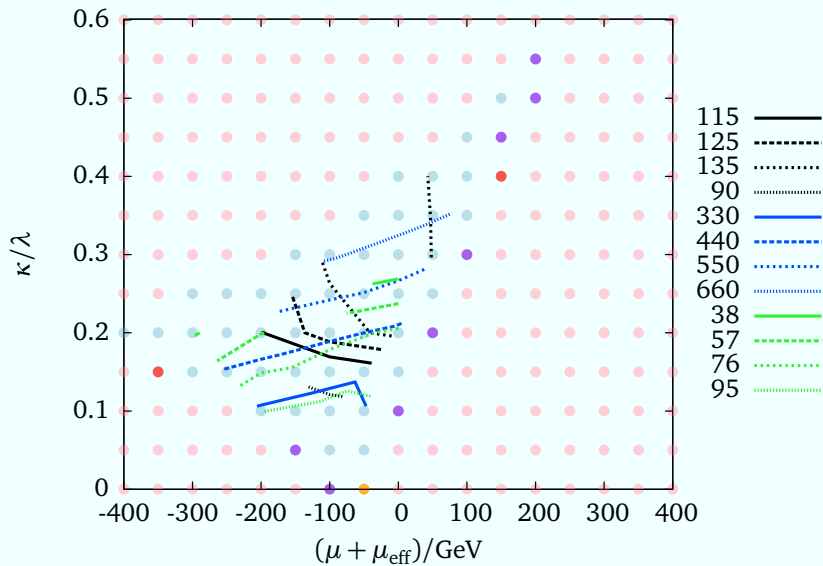


Boiling down the parameter space...

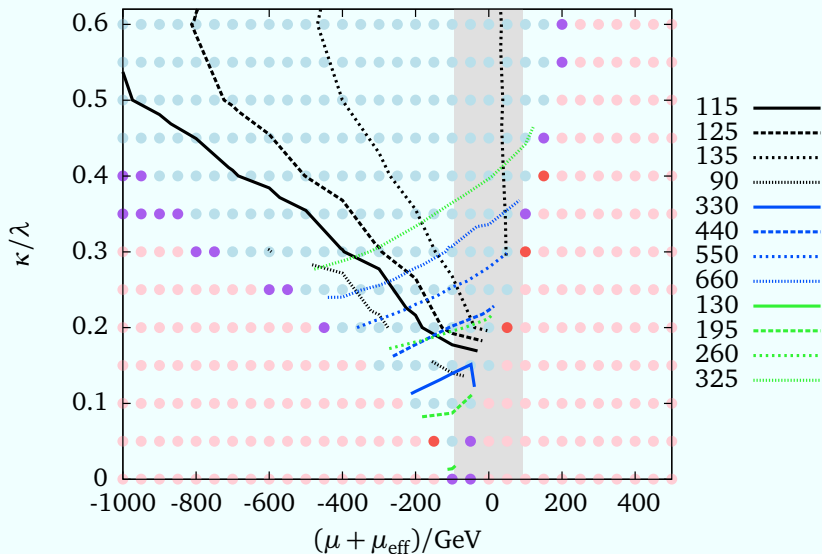
$$\mu = 0 \text{ GeV}, \tan \beta = 5/2, \lambda = 1/2, A_\kappa = 0 \text{ GeV}$$



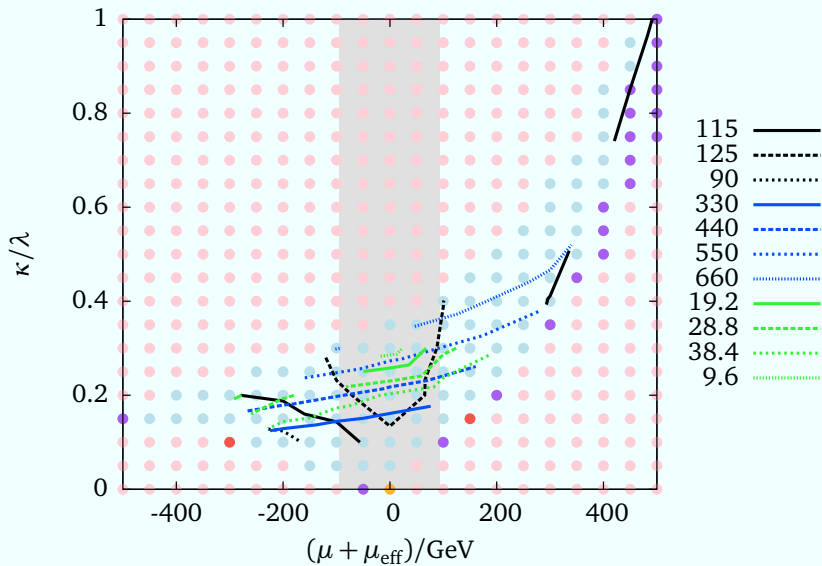
$$\mu = 1000 \text{ GeV}, \tan \beta = 5/2, \lambda = 3/5, A_\kappa = 0 \text{ GeV}$$



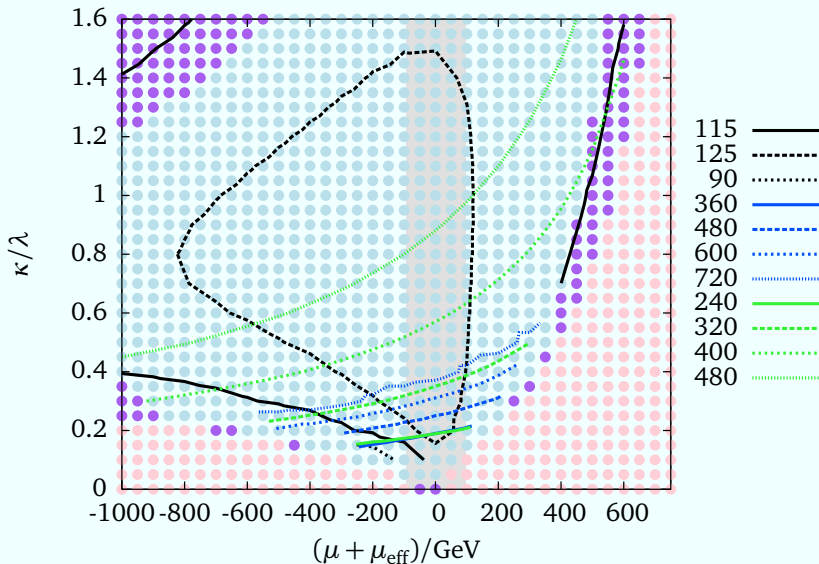
$$\mu = 1000 \text{ GeV}, \tan \beta = 5/2, \lambda = 3/5, A_\kappa = 100 \text{ GeV}$$



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



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



Higgs Inflation in the NMSSM

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

A μ 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

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

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

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

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

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

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

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

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

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

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

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

with

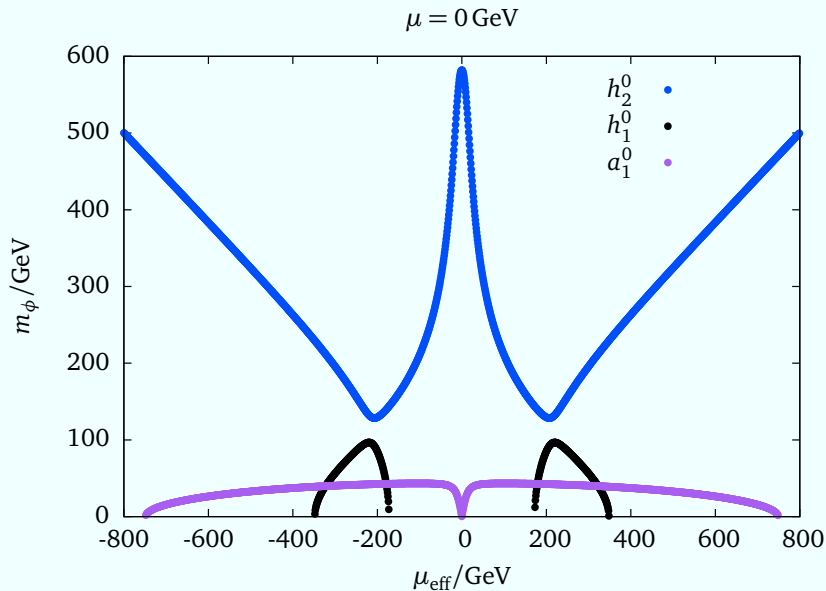
$$a_1 = B_\mu \mu + \mu_{\text{eff}} \left(\frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right) \quad a_2 = 2v\lambda(\mu + \mu_{\text{eff}})$$

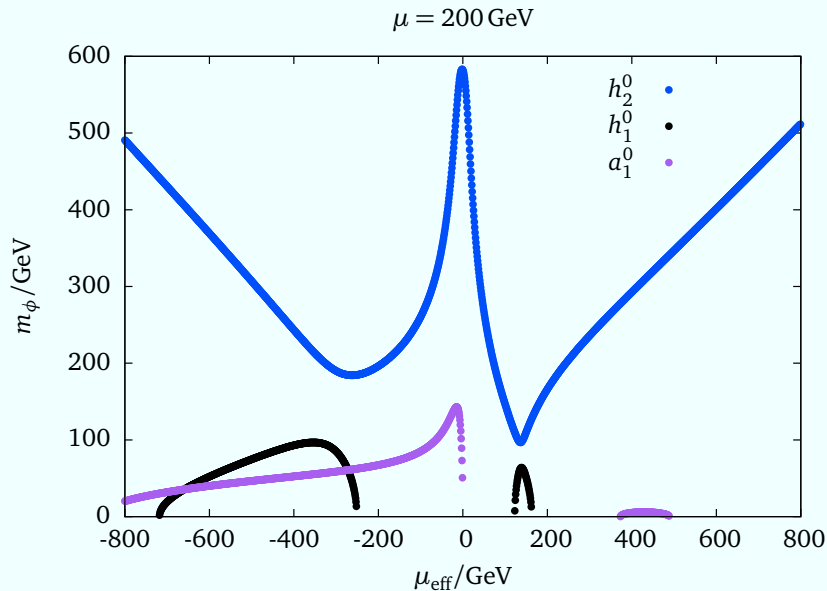
$$a_3 = v\lambda \left(2 \frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right)$$

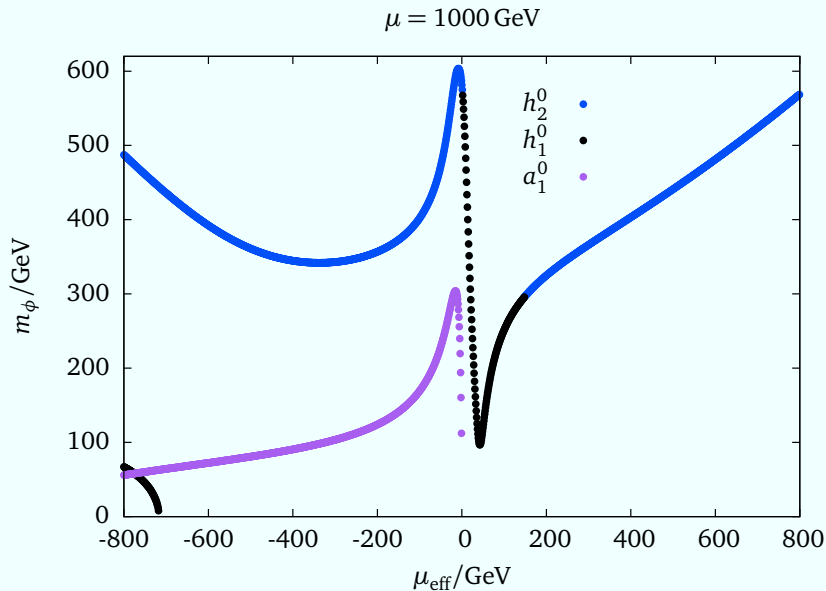
$$a_4 = \frac{1}{\mu_{\text{eff}}} \left[v^2 \lambda^2 c_\beta s_\beta \left(\frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right) - v^2 \lambda^2 \mu \right]$$

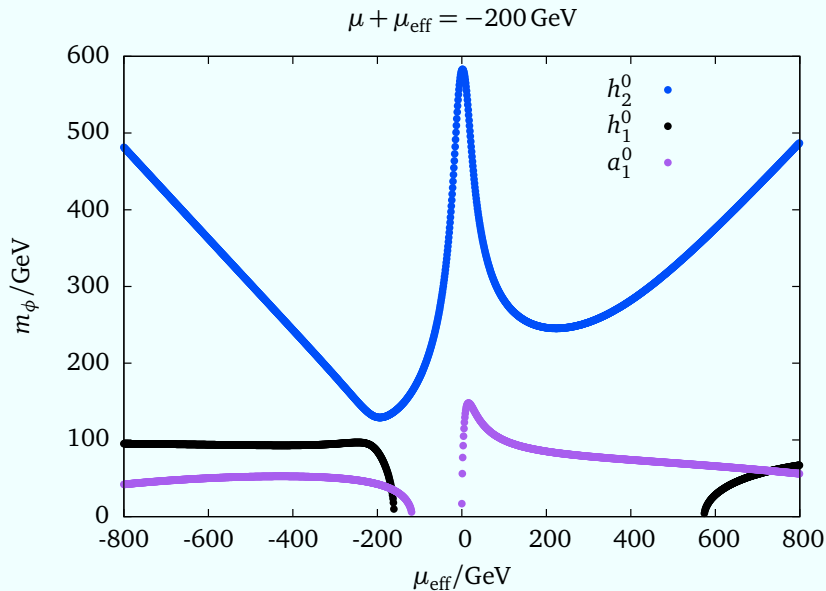
$$a_5 = 4 \left(\frac{\kappa}{\lambda} \right)^2 \mu_{\text{eff}}^2 + \frac{\kappa}{\lambda} [\mu_{\text{eff}} A_\kappa - v^2 \lambda^2 c_\beta s_\beta]$$

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



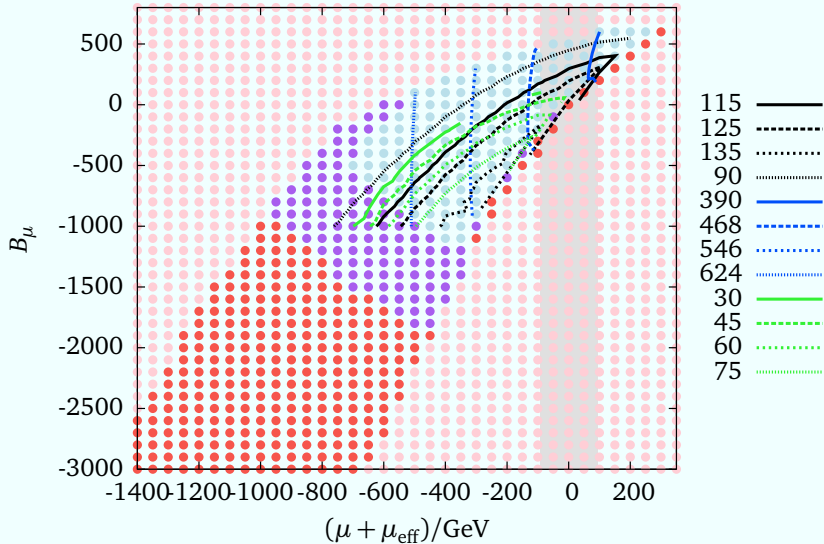




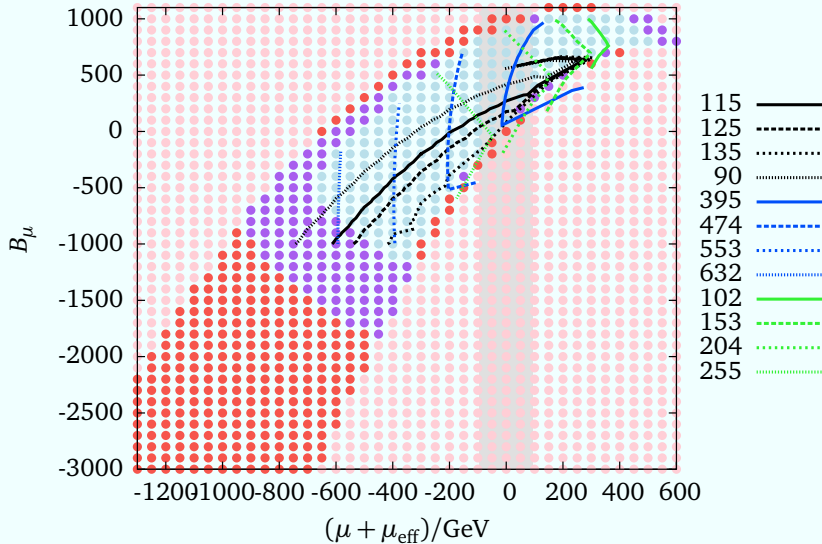


Additional soft $\mathbb{Z}_3$ breaking leads to severe instabilities.

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



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



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:

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

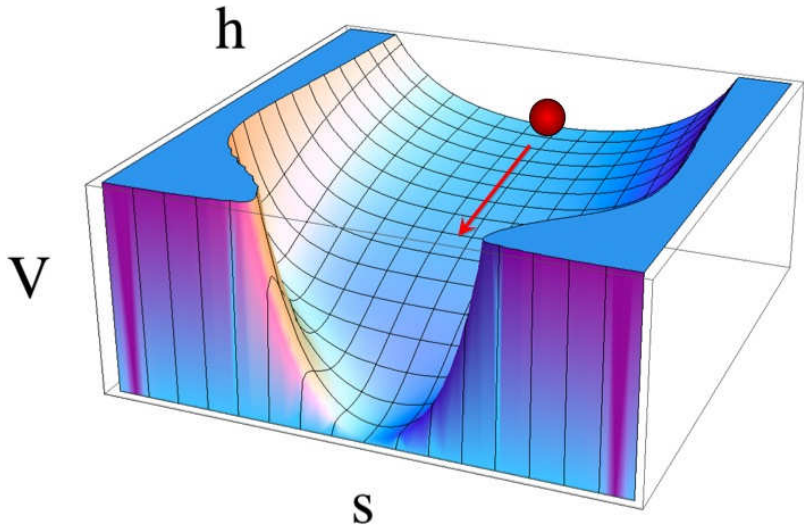
- “simplest” direction: $s = 0$, $\alpha_{1,2} = 0$

[FLKMvP]

- ⚡ tachyonic singlet directions

[Einhorn, Jones]

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



stabilization 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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