

SUSY Higgs Inflation at Colliders

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+ work in progress

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work done in collaboration with

arXiv:1808.07371

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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]

- exclusion limits using CHECKMATE
- ILC cross sections neutralino/chargino production
- cross check with HiggsBounds and HiggsSignals
- distinguishing scenarios
- light singlet states (LEP/LHC hints? ... ~ 36 and 96 GeV?)



Work in Progress! with Cheng Li, Steven Paasch, Gudrid Moortgat-Pick (UHH).

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

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)

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

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

The cosmological μ -term

$$\mu \simeq \frac{3}{2} m_{3/2} 10^5 \lambda$$

Phenomenological interesting scenarios

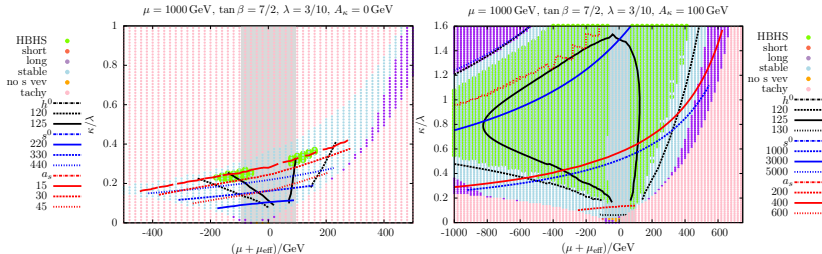
- small $\mu \simeq 1$ GeV: e. g. small $\lambda \sim 10^{-4}$, $m_{3/2} \lesssim 1$ GeV recovers MSSM-limit
- large $\mu \gtrsim 1$ TeV and $\mu_{\text{eff}} \simeq -\mu$: cancellation in $\mu + \mu_{\text{eff}}$ possible potentially interesting neutralino phenomenology
- $\mu \gtrsim 100$ GeV and $|\mu_{\text{eff}}| \lesssim 100$ GeV: phenomenology different from both the MSSM and the NMSSM

Theoretical constraints

- tachyonic states, i. e. $m_{h,s}^2 < 0$
- *alternative vevs*: $\langle h_u \rangle \neq v_u / \sqrt{2}$, $\langle h_d \rangle \neq v_d / \sqrt{2}$, $\langle s \rangle \neq \mu_{\text{eff}} / \lambda$

Boiling down the parameter space...

finding interesting scenarios



[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]

- additional constraints: HiggsBounds and HiggsSignals
green
- LEP chargino bound: grey
- A_κ influences singlet pseudoscalar mass:
light \rightarrow heavy with $A_\kappa = 0 \rightarrow 100 \text{ GeV}$

Using popular a popular tool

[NMSSMTools: Ellwanger, Gunion, Hugonie et al. 2006+]

μ NMSSM equivalent to \mathbb{Z}_3 -noninvariant NMSSM, “General” NMSSM (GNMSSM), implemented in NMSSMTools:

$$\mathcal{W}_{\text{Higgs}} = \lambda S H_u \cdot H_d + \frac{1}{3} \kappa S^3 + \mu H_u \cdot H_d + \frac{1}{2} \nu S^2 + \xi S$$

with $\nu = 0$ and $\xi = 0$ (preserved by superconformal symmetry)

However:

There is a freedom of choice: $\mu = 0$ in NMSSMTools.

Soft SUSY breaking terms:

$$-\mathcal{L}_{\text{soft}} = -\mathcal{L}_{\text{soft}}^{\text{NMSSM}} + \left[B_\mu \mu H_u \cdot H_d + \frac{1}{2} B_\nu \nu S^2 + C_\xi \xi S + \text{h. c.} \right]$$

Treat charged Higgs mass as input

[WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 2018]

$$A_\lambda = \frac{\sin 2\beta}{2\mu_{\text{eff}}} (m_{H^\pm}^2 - m_W^2 + v^2 \lambda^2) - \frac{1}{\mu_{\text{eff}}} (B_\mu \mu + \xi \lambda) - \left(\nu + \frac{\kappa}{\lambda} \mu_{\text{eff}} \right)$$

$$\stackrel{Z_3}{=} \frac{\sin 2\beta}{2\mu_{\text{eff}}} (m_{H^\pm}^2 - m_W^2 + v^2 \lambda^2) - \frac{\kappa}{\lambda} \mu_{\text{eff}}$$

Dictionary to use with NMSSMTools

 $\mu_{\text{eff}} \rightarrow \mu_{\text{eff}} + \mu$

$$B_\mu \mu \rightarrow -\mu \left(A_\lambda + \frac{\kappa}{\lambda} \mu_{\text{eff}} \right) \quad [\text{M3H}]$$

$$B_\nu \nu \rightarrow -2 \frac{\kappa \lambda \mu}{\mu_{\text{eff}} + \mu} \frac{v^2}{2} \sin 2\beta \quad [\text{M3S}]$$

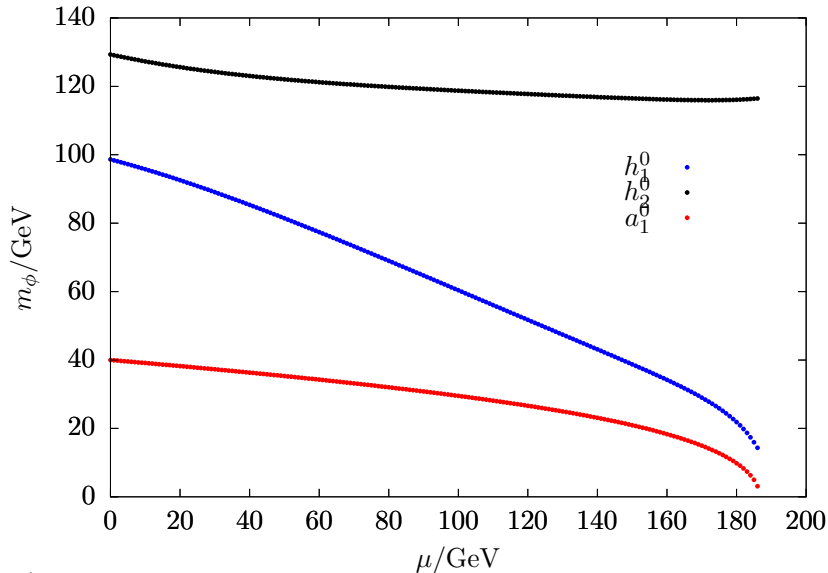
$$\kappa \rightarrow \kappa \frac{\mu_{\text{eff}}}{\mu_{\text{eff}} + \mu}$$

$$\nu, \xi \rightarrow 0 \quad [\text{MUP}, \text{XIF}]$$

$$C_\xi \xi \rightarrow \frac{\lambda}{\mu_{\text{eff}}} \left(v^2 \mu (\mu_{\text{eff}} + \mu) - \frac{v^2}{2} \sin 2\beta \mu A_\lambda \right) \quad [\text{XIS}]$$

From the NMSSM to the μ NMSSM — masses

$$\tan \beta = 12, \lambda = 0.0625, \kappa = 0.015, A_\kappa = -9 \text{ GeV}$$

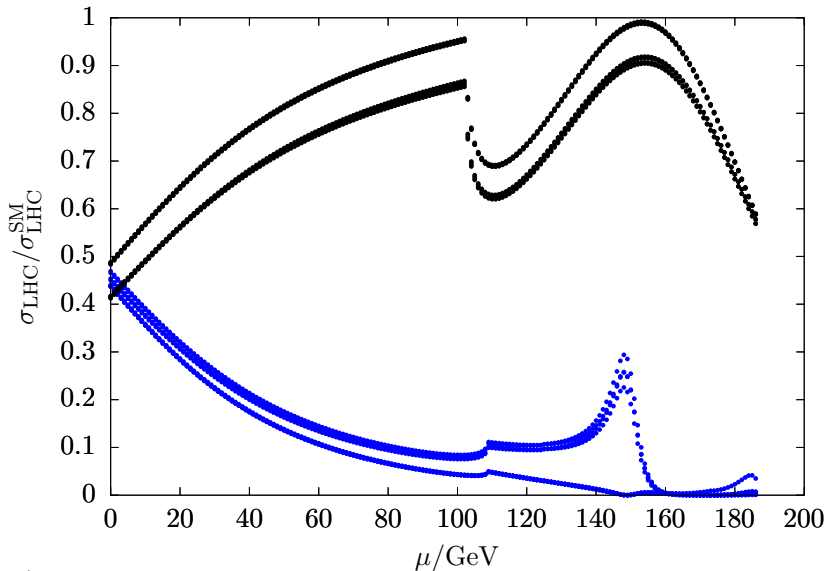


$$\mu'_{\text{eff}} = 242 \text{ GeV}$$

[preliminary, using NMSSMTools]

From the NMSSM to the μ NMSSM — cross sections

$$\tan\beta = 12, \lambda = 0.0625, \kappa = 0.015, A_\kappa = -9 \text{ GeV}$$

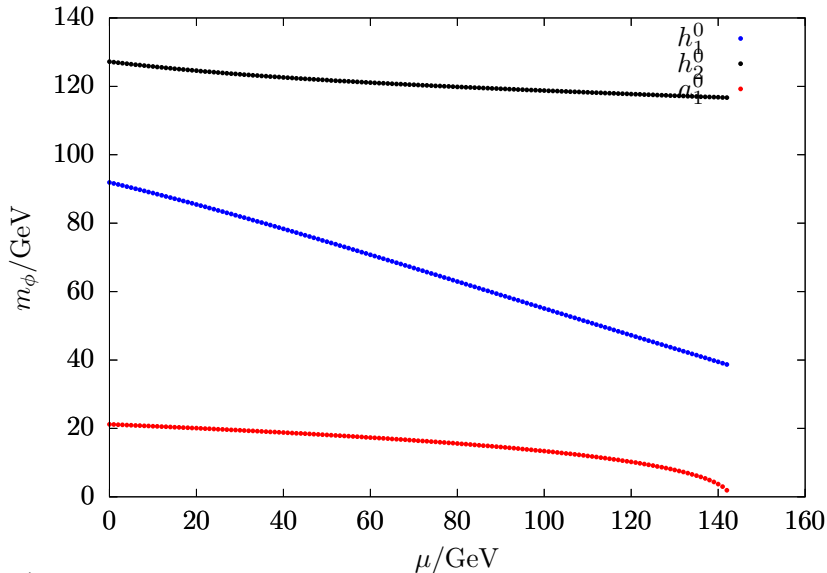


$$\mu'_{\text{eff}} = 242 \text{ GeV}$$

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From the NMSSM to the μ NMSSM — masses

$$\tan \beta = 12, \lambda = 0.0675, \kappa = 0.015, A_\kappa = -26 \text{ GeV}$$

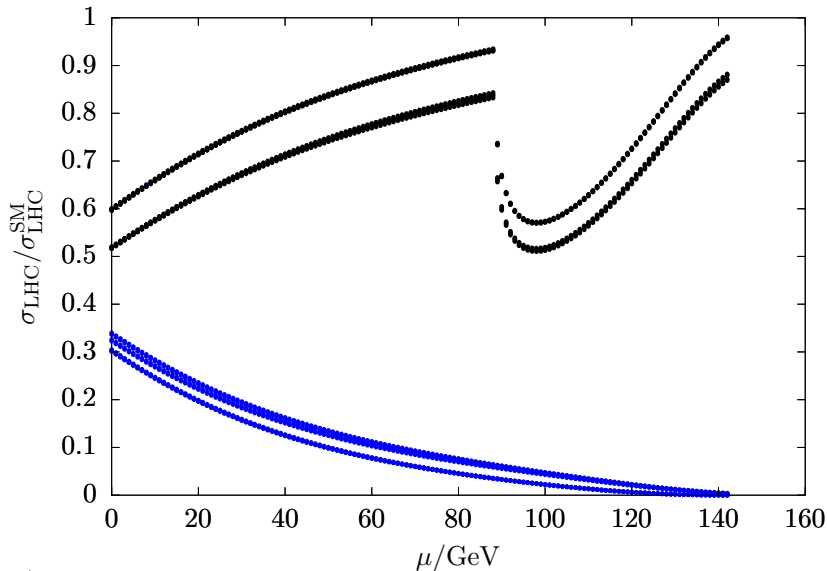


$$\mu'_{\text{eff}} = 239 \text{ GeV}$$

[preliminary, using NMSSMTools]

From the NMSSM to the μ NMSSM — cross sections

$$\tan \beta = 12, \lambda = 0.0675, \kappa = 0.015, A_\kappa = -26 \text{ GeV}$$



$$\mu'_{\text{eff}} = 239 \text{ GeV}$$

[preliminary, using NMSSMTools]

Higgs Inflation in the NMSSM

- the MSSM is not enough (though $\chi H_u \cdot H_d$)
- Singlet direction to stabilize inflationary trajectory $\sim (S\bar{S})^2$
[without a stabilizer term: Ben-Dayan and Einhorn 2010]
- inflaton formed out of doublet Higgses

A μ term from gravity, breaks (accidental) \mathbb{Z}_3 symmetry

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

Caveats and features

- tachyonic Higgs directions; vacuum stability
- Higgs-to-Higgs decays phenomenologically interesting!
- Neutralino sector different from pure NMSSM (DM pheno!)
- interesting phenomenology with light singlets (LHC hints?)

Backup

Slides

Superconformal symmetry breaking

- $X(\Phi)$ either $\chi H_u \cdot H_d$ or χS^2
- dimensionless (!) coupling χ ; $\chi = 0$: minimal grav. coupling
- function of chiral superfields (Φ , not Φ^\dagger): $H_u \cdot H_d$, not $|H_u|^2$

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 modifies Kähler potential

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

NMSSM superconformal symmetry breaking

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

local U(1) \mathcal{R} symmetry: Supergravity magic

- χ term breaks continuous \mathcal{R} and discrete \mathbb{Z}_3 symmetry

apparent in the Kähler potential (following from frame function Ω)

$$\mathcal{K}_\chi = -3 \log \left[1 - \frac{1}{3} (|S|^2 + |H_u|^2 + |H_d|^2) - \frac{1}{2} \chi (H_u \cdot H_d + \text{h.c.}) \right]$$

Corrected Superpotential: Kähler transformation

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

The iNMSSM (same field content as the NMSSM)

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

Cosmo pheno requires $|\chi/\lambda| \simeq 10^5$ and constraints on $m_{3/2}$.

A SUSY electroweak model

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

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

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

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

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

Minimisation conditions are in general misleading!

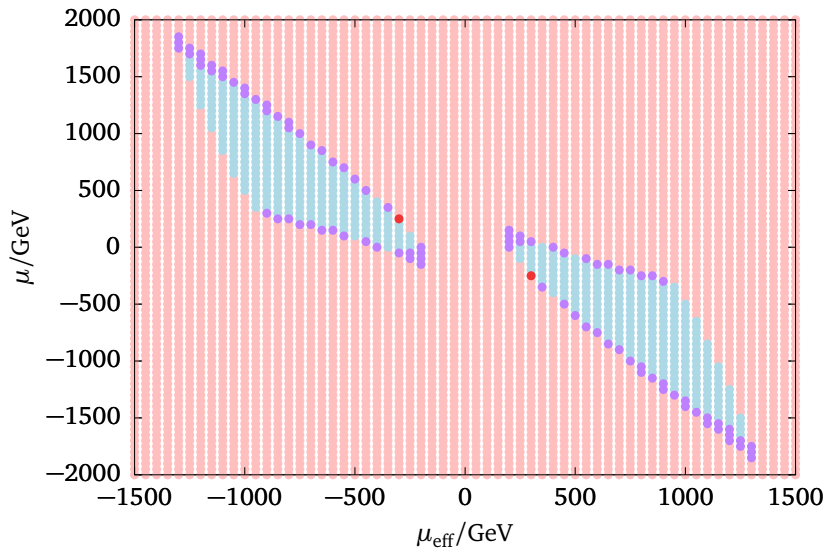
$$\left. \frac{\partial V}{\partial h_u} \right|_{\text{vev}} = 2m_{H_u}^2 v_u + \dots$$

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

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

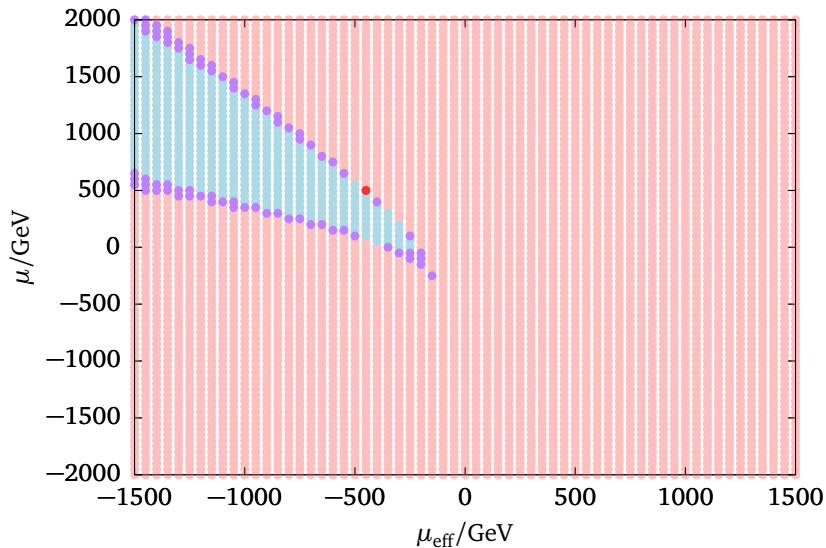
linear equations for soft SUSY breaking masses $m_{H_u}^2$, $m_{H_d}^2$, m_S^2 , can be solved uniquely; determine numerical values for those

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

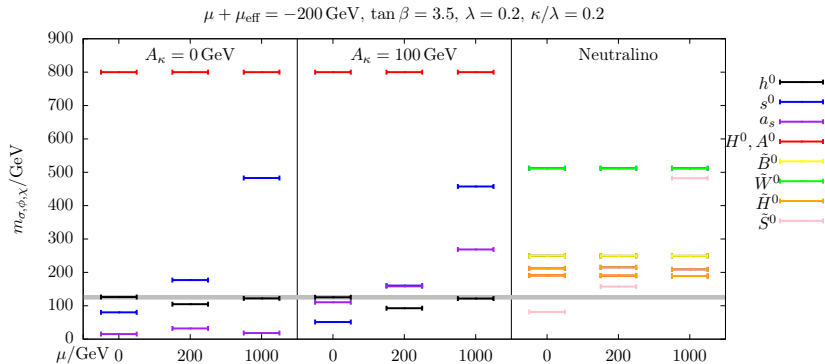


One example

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



A Higgs spectrum



$$\mu_{\text{eff}} = \{-200, -400, -1200\} \text{ GeV}; m_{H^{\pm}} = 800 \text{ GeV}$$

[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]

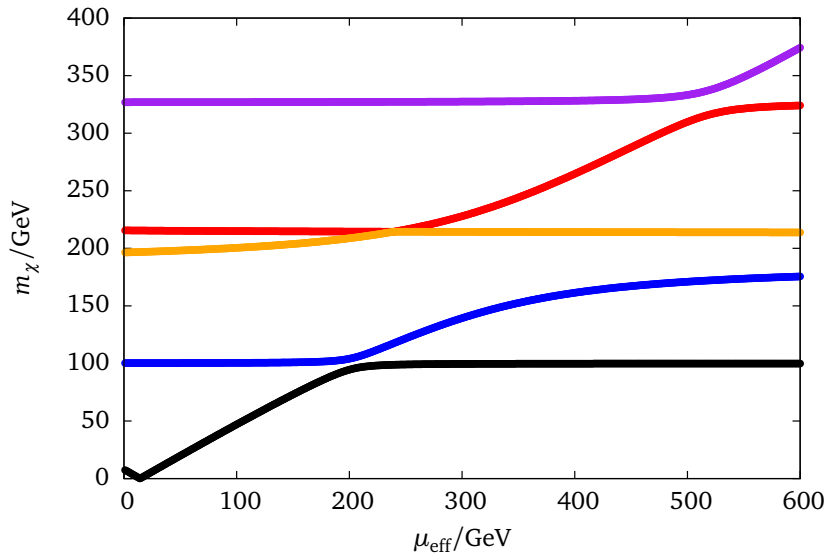
- as in NMSSM: 5 Neutralino states
- different scaling behaviour with μ , μ_{eff}
- lightest state probably dark matter candidate
- generically heavy Singlino!

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

Possible distinct scenarios

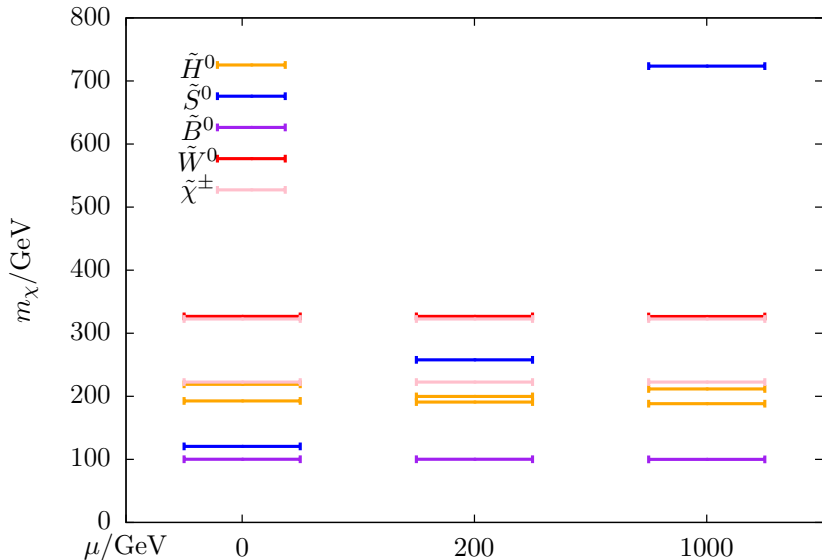
- physical Higgsino mass $\sim (\mu_{\text{eff}} + \mu)$; Singlino mass $\frac{\kappa}{\lambda} \mu_{\text{eff}}$
- small $\mu_{\text{eff}} + \mu$ with large individual contributions
- large cancellation possible: Singlino mass $\nearrow!$

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



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

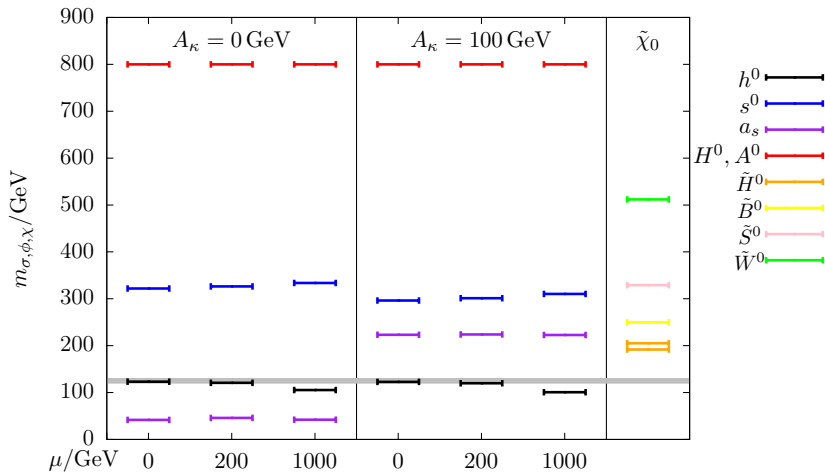
[G. Weiglein]

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

$$\kappa \rightarrow \tilde{\kappa} = \kappa \frac{\mu + \mu_{\text{eff}}}{\mu_{\text{eff}}}$$

- $\tilde{\kappa} \gg \lambda$ possible (if $\mu + \mu_{\text{eff}} \gg \mu_{\text{eff}}$)
- $\tilde{\kappa} < 0$ if $\text{sign}(\mu + \mu_{\text{eff}}) \neq \text{sign} \mu_{\text{eff}}$

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



motivated by certain CMS and ATLAS analyses

Scenario	1	2	3	4
λ	0.08	0.08	0.28	0.08
κ	0.04	0.023	0.08	0.0085
$\tan\beta$	12	12	2.5	2
$(\mu + \mu_{\text{eff}})/\text{GeV}$	-140	-140	-300	-400
μ/GeV	5	195	5	150
B_μ/GeV	0	0	0	-300
m_{H^\pm}/GeV	800	800	800	1000
A_κ/GeV	130	265	250	32
A_f/GeV	400	450	3200	4000
m_{s^0}/GeV	97.6	95.7	97.2	97.1
m_{h^0}/GeV	124.7	126.8	124.6	125.0
m_{a^0}/GeV	168.2	277.0	257.2	75.6
$\frac{\sigma(e^+e^- \rightarrow Zs^0) \cdot \text{BR}(s^0 \rightarrow bb)}{\sigma^{\text{SM}}(e^+e^- \rightarrow ZH) \cdot \text{BR}^{\text{SM}}(H \rightarrow b\bar{b})}$	0.28	0.31	0.14	0.35
$\sigma(gg \rightarrow s^0)/\text{pb}$	25.3	28.1	14.4	31.5
$\text{BR}(s^0 \rightarrow \gamma\gamma)$	0.0020	0.0016	0.0024	0.0005
$\chi^2(\text{HS})$	97	96	82	101

Scenario 1 Masses / GeV	$\tilde{\chi}_1^0$ 127.3	$\tilde{\chi}_2^0$ 138.3	$\tilde{\chi}_3^0$ 155.9	$\tilde{\chi}_1^\pm$ 138.4	
$\sigma(e^+e^- \rightarrow \tilde{\chi}_i\tilde{\chi}_j)/\text{fb}$ for $\sqrt{s} = 350/\text{GeV}$	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\chi}_1^0\tilde{\chi}_3^0$	$\tilde{\chi}_2^0\tilde{\chi}_3^0$	$\tilde{\chi}_2^0\tilde{\chi}_2^0$	$\tilde{\chi}_1^+\tilde{\chi}_1^-$
Unpolarized	141	195	0.08	0.19	795
Pol(e^+, e^-) = (+30%, -80%)	208	287	0.12	0.28	1620
Pol(e^+, e^-) = (-30%, +80%)	142	196	0.08	0.19	352
$\sigma(e^+e^- \rightarrow \tilde{\chi}_i\tilde{\chi}_j)/\text{fb}$ for $\sqrt{s} = 500/\text{GeV}$	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\chi}_1^0\tilde{\chi}_3^0$	$\tilde{\chi}_2^0\tilde{\chi}_3^0$	$\tilde{\chi}_2^0\tilde{\chi}_2^0$	$\tilde{\chi}_1^+\tilde{\chi}_1^-$
Unpolarized	74	109	0.12	0.22	459
Pol(e^+, e^-) = (+30%, -80%)	110	161	0.19	0.32	926
Pol(e^+, e^-) = (-30%, +80%)	75	110	0.13	0.22	212

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:

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

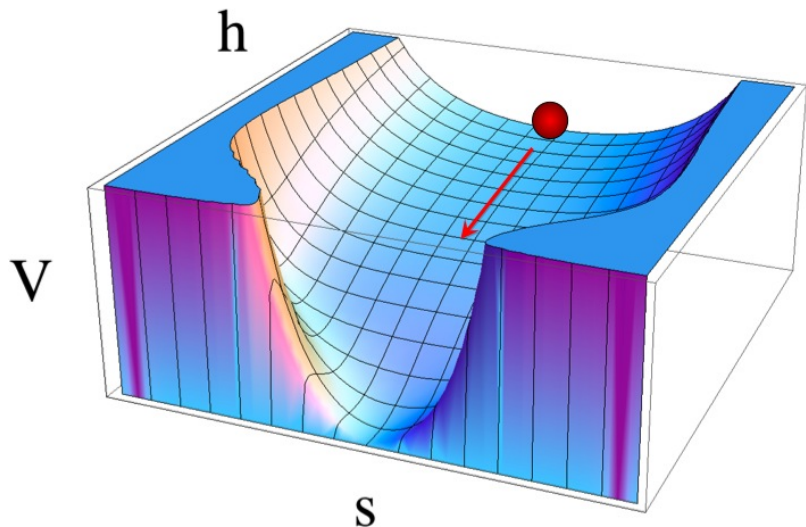
- “simplest” direction: $s = 0$, $\alpha_{1,2} = 0$

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

inflationary NMSSM

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in Planck units!

007

Gravitino dark mattertypical gravitino mass $\mathcal{O}(10 \text{ MeV})$ **Long-lived NLSP**

$$\Gamma_{\tilde{\chi}_1^0 \rightarrow \gamma/Z\psi_{3/2}} \simeq \frac{1}{48\pi M_P^2} \frac{M^5}{m_{3/2}^2} \tilde{\chi}_1^0$$

lifetime

$$\tau = 1/\Gamma \simeq \mathcal{O}(\text{s})$$

bino-like NLSP: decay to photon + gravitino

singlino-like NLSP: singlet Higgs + gravitino

Typical neutralino LSP signature

missing energy: decay either outside the detector or decay into invisible

Higher order Higgs masses

- full one-loop $\overline{\text{DR}}$ corrections
- include MSSM two-loop effects $\mathcal{O}(\alpha_t \alpha_s, \alpha_t^2)$ with FeynHiggs
- masses from poles of the propagator

$$\hat{\Delta}(k^2) = -i \left[k^2 \mathbf{1} - M_{\text{tree}}^2 + \hat{\Sigma}^{(1L)}(k^2) + \hat{\Sigma}_{\text{MSSM}}^{(\alpha_t \alpha_s, \alpha_t^2)}(0) \right]^{-1}$$

Tree-level effects

- NMSSM-like shift to SM-like Higgs mass $\sim \lambda^2 v^2 \sin^2 2\beta$
- $\mu + \mu_{\text{eff}}$ in singlet-doublet mixing
- singlet mass $\sim \mu/\mu_{\text{eff}}$ and $\mu_{\text{eff}} \kappa/\lambda$

(Doublet-like) Higgsino mass: $\sim \mu + \mu_{\text{eff}}$

singlino mass $\sim \mu_{\text{eff}} \kappa/\lambda$

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 $\tan \beta$)
- typically: $\text{sign} A_\kappa = -\text{sign} \mu_{\text{eff}}$
- $\mu + \mu_{\text{eff}}$ as effective higgsino mass-term
- (ignore neutralino pheno in the following)
- single μ_{eff} contributions: $\sim \frac{\kappa}{\lambda}$

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

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

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

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

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

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

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

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

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

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

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

with

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

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

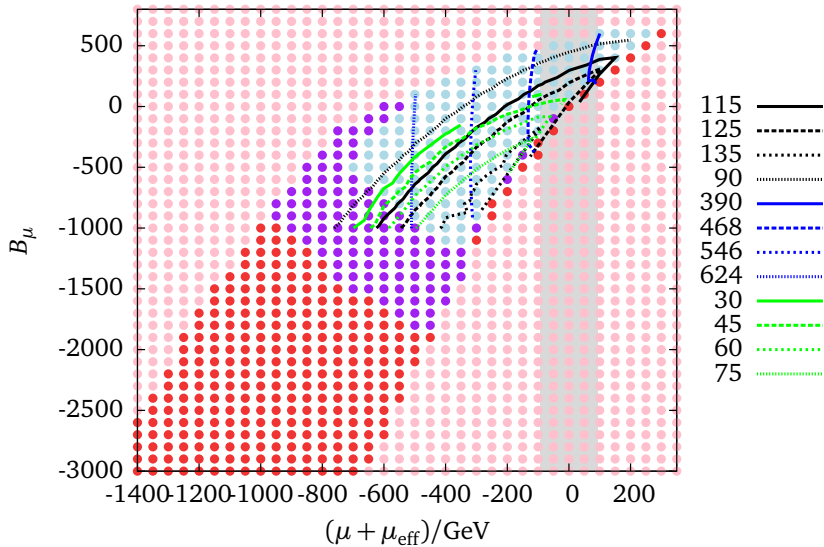
$$a_4 = \frac{1}{\mu_{\text{eff}}} \left[v^2 \lambda^2 c_\beta s_\beta \left(\frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda \right) - v^2 \lambda^2 \mu \right]$$

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

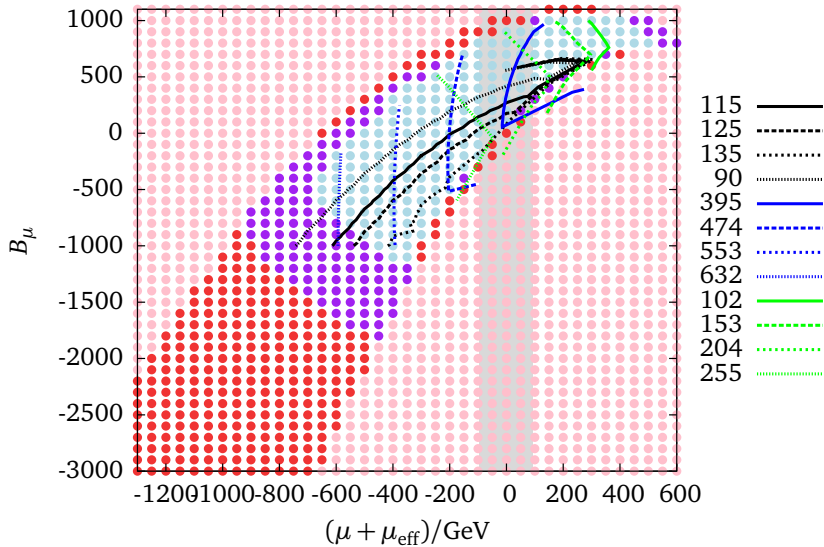
$$a_6 = v\lambda \left(2 \frac{\kappa}{\lambda} \mu_{\text{eff}} - A_\lambda \right) \quad a_7 = -6 \left(\frac{\kappa}{\lambda} \right)^2 \mu_{\text{eff}}^2$$

Additional soft Z_3 breaking leads to severe instabilities.

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



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



How to distinguish from the NMSSM?

- contributions $(\mu + \mu_{\text{eff}})$ vs. μ_{eff}
- singlet sector mostly affected
- sizeable mixing effects possible, even with $\lambda \ll 1$
- look for NMSSM-like scenarios: $\mu = 0$
- identify the effect of $\mu \neq 0$

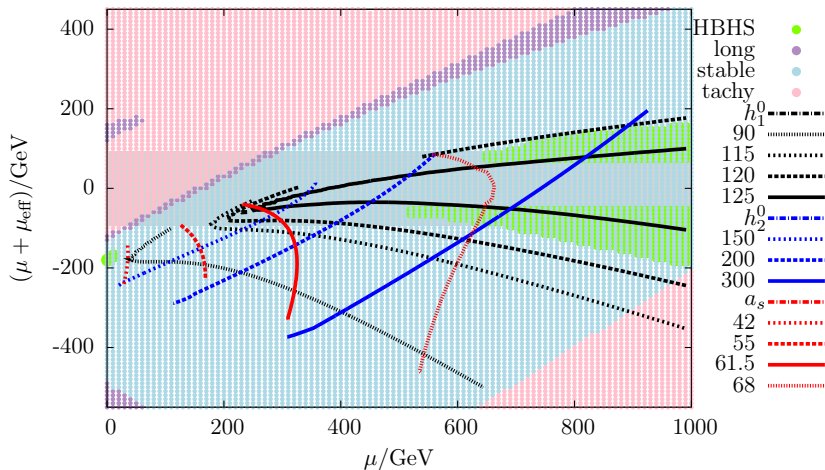
Relevant phenomenology

decays:

- $h^0 \rightarrow a_s a_s$: Higgs to invisible
- $s^0 \rightarrow h^0 h^0$: affects Higgs pair production
- $A \rightarrow h^0 a_s$: non-standard heavy Higgs decays
- ...

Deviating from the NMSSM

$$\tan\beta = 4, \lambda = 1/4, \kappa = 1/5, A_\kappa = 7 \text{ GeV}$$



[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]

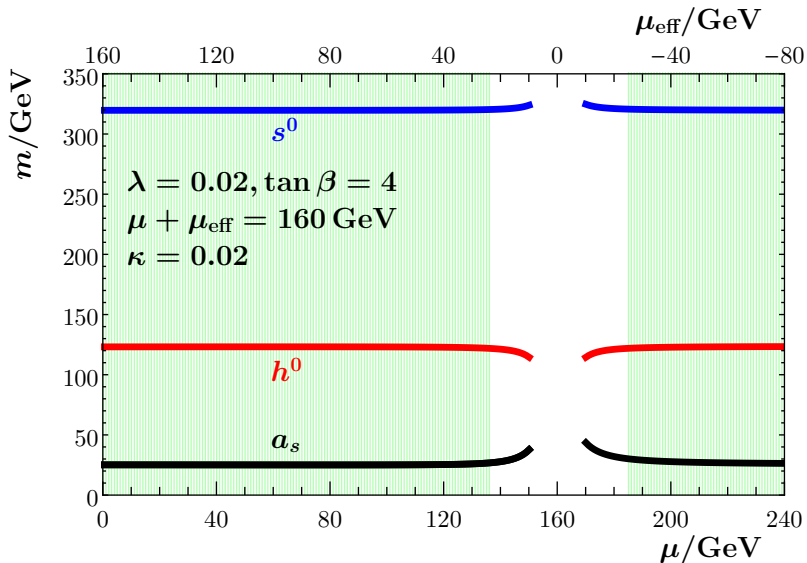
Mock MSSM-limit

- small $\lambda = 0.02$, ratio $\frac{\kappa}{\lambda} = 1$ fixed
- rescale $\kappa \rightarrow \tilde{\kappa}$
- fix $\mu + \mu_{\text{eff}} = 160 \text{ GeV}$
- scan $\mu \in [0, 240] \text{ GeV}$
- feature light singlets
- possibly large Singlet-Doublet mixing

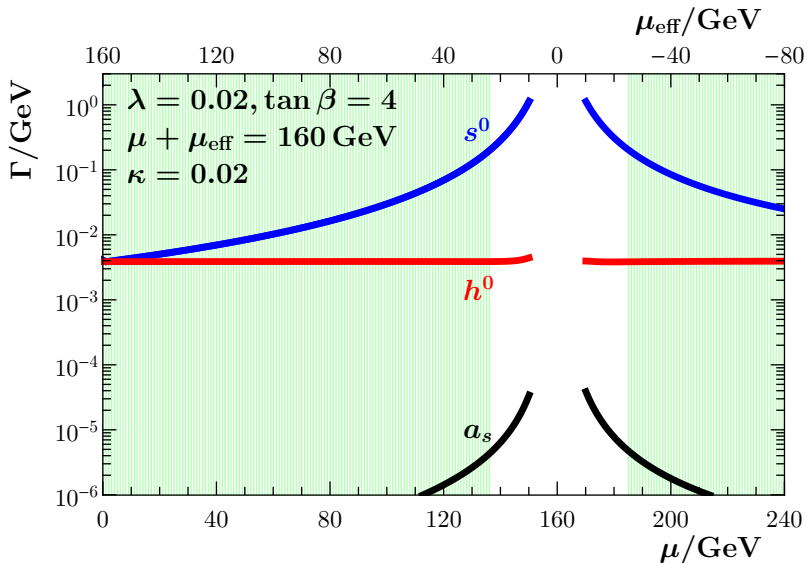
Crucial A_κ behaviour

- controls singlet mass
- small $A_\kappa \sim$ light singlets (together with small $|\mu_{\text{eff}}| \simeq 200 \text{ GeV}$)
- opposite sign from μ_{eff} to avoid tachyonic singlets
- rescaling changes sign of κ !

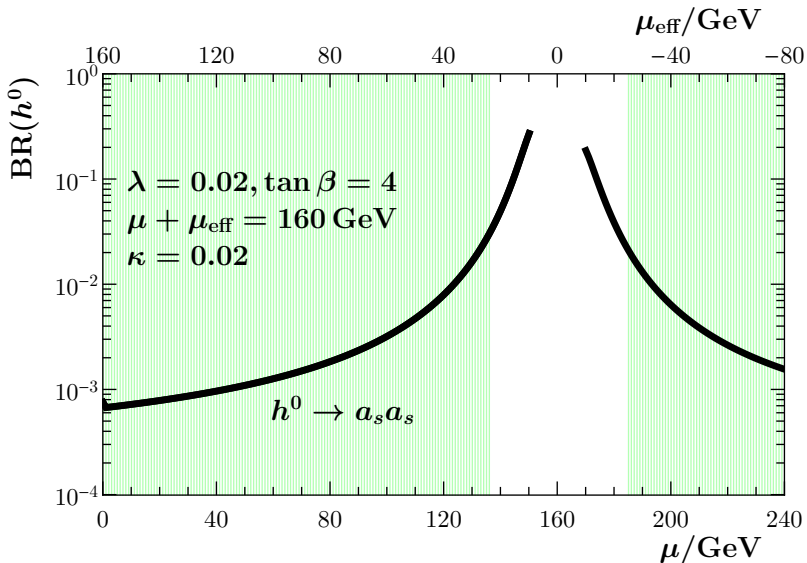
$$A_\kappa = -\text{sign}(\mu_{\text{eff}}\tilde{\kappa}) 1.3 \text{ GeV}$$



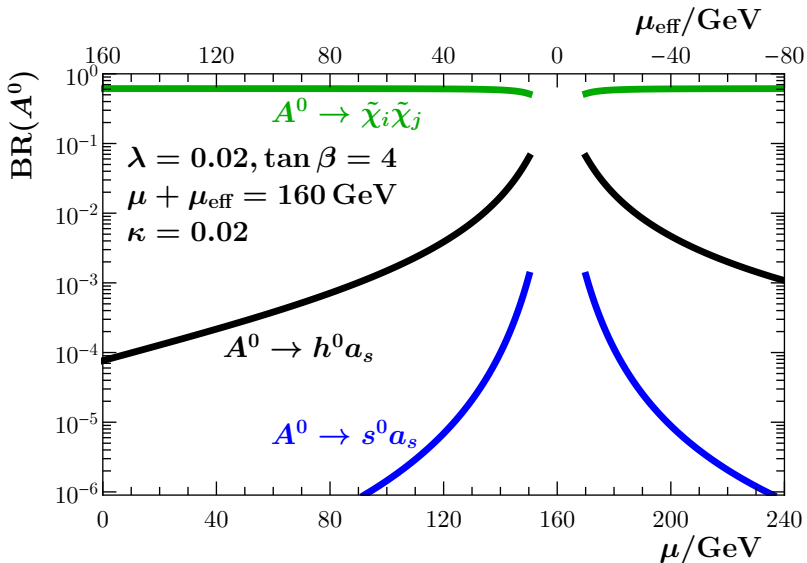
[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]



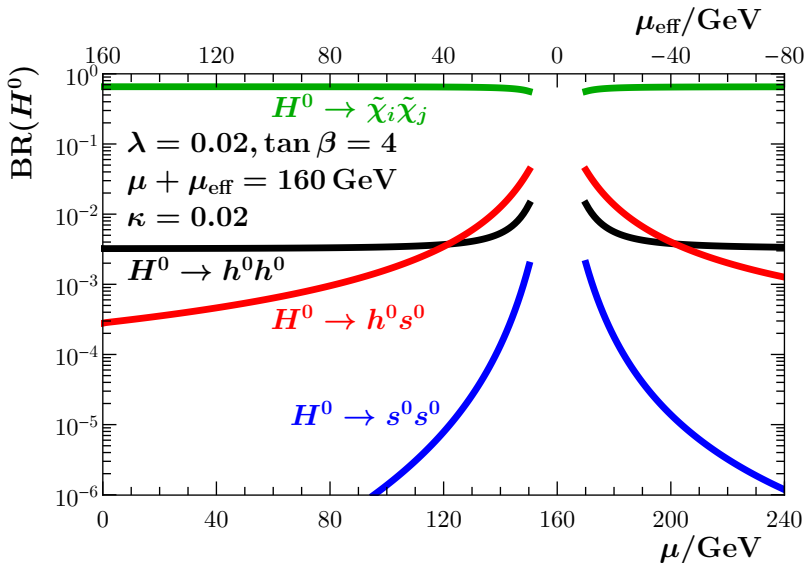
[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]



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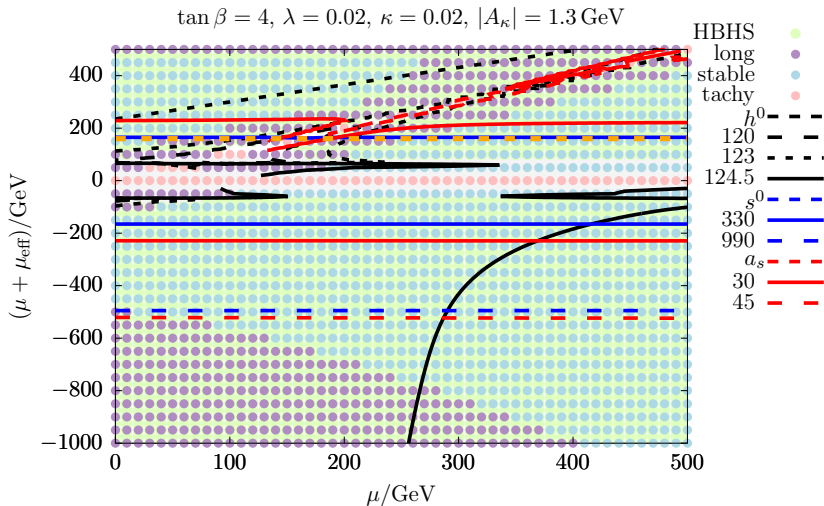


[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]



[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]

A Broader view, preliminary



[arXiv:1808.07371v2—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]