SUSY Higgs Inflation at Colliders

Wolfgang Gregor Hollik, Cheng Li, Gudrid Moortgat-Pick,
Steven Paasch

Karlsruhe Institute of Technology

IKP & TTP @ KIT
KIT-Centrum für Elementarteilchen- und Astroteilchenphysik (KCETA)

27 November 2019 | 13th Terascale Alliance Meeting

Higgs inflation

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

$$\text{(SM) Higgs} = \text{inflaton}$$

- 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 → local SUSY
- modified SUGRA Lagrangian [Einhorn, Jones]

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

Higgs inflation

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

$$\text{(SM) Higgs} = \text{inflaton}$$

- 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 → local SUSY
- modified SUGRA Lagrangian [Einhorn, Jones]

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

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]

More collider pheno?

- distinguishing scenarios: light singlet states (LEP/LHC hints? … $\sim$ 36 and 96 GeV?)
- excl. limits using CheckMATE; LC XS (Whizard)
- cross check with HiggsBounds and HiggsSignals

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

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

The cosmological μ-term

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

Phenomenological interesting scenarios

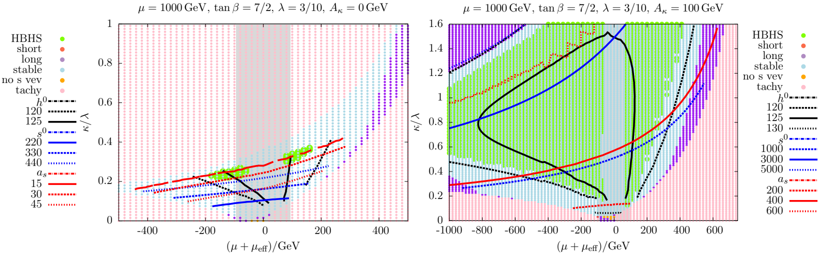
- small $\mu \simeq 1\,\text{GeV}$: e. g. small $\lambda \sim 10^{-4}$, $m_{3/2} \lesssim 1\,\text{GeV}$ recovers MSSM-limit of the NMSSM
- large $\mu \gtrsim 1\,\text{TeV}$ and $\mu_{\text{eff}} \simeq -\mu$: cancellation in $\mu + \mu_{\text{eff}}$ possible potentially interesting neutralino phenomenology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

Theoretical constraints

- tachyonic states, i. e. $m^2_{h,s} < 0$
- *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



[EPJC79(2019)75: WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein]

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

Using popular a popular tool

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

μNMSSM 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: $\boldsymbol{\mu = 0}$ in NMSSMTools.

Soft SUSY breaking terms:

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

Treat charged Higgs mass as input

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

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

$$\overset{\mathbb{Z}_3}{=} \frac{\sin 2\beta}{2\mu_{\text{eff}}}\left(m_{H^\pm}^2 - m_W^2 + v^2\lambda^2\right) - \frac{\kappa}{\lambda}\mu_{\text{eff}}$$

Dictionary to use with NMSSMTools $\mu_{\text{eff}} \to \mu_{\text{eff}} + \mu$

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

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

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

$$\nu, \xi \to 0 \quad \texttt{[MUP, XIF]}$$

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

- light singlet < 100 GeV
- small μ vs. large μ

Two scenarios $m_{H^\pm} = 800\,\text{GeV}$

Scen	λ	κ	$\tan\beta$	$\mu_{\text{eff}}/\text{GeV}$	μ/GeV	A_κ/GeV
1	0.035	0.085	12	−40	150	277
2	0.08	0.004	12	−1135	1020	50

Higgs and Neutralino mass spectrum

m/GeV	m_{s^0}	m_{h^0}	$m_{a_s^0}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_1^\pm}$
1	96.9	125.2	284.4	97.8	119.7	108.6
2	93.4	125.0	93.2	107.5	112.6	117.8

- gaugino masses: $M_1 = 239\,\text{GeV}$, $M_2 = 500\,\text{GeV}$, $M_3 = 2.5\,\text{TeV}$
- $A_{f_3} = 1200\,\text{GeV}$: adjusts m_{h^0}

Cross section $(e^+e^- \to Z\, s^0)$

$\sqrt{s}$/GeV	Pol (e^+, e^-)	Scen 1 σ/fb	$\frac{dN}{N}$	Scen 2 σ/fb	$\frac{dN}{N}$
250	Unpol	96.51	0.45%	87.49	0.48%
250	(+30%, −90%)	148.0	0.37%	134.2	0.38%
250	(−30%, +90%)	97.14	0.45%	88.06	0.48%
250	(+60%, −90%)	180.4	0.33%	163.6	0.35%
250	(−60%, +90%)	116.8	0.41%	105.9	0.43%
350	Unpol	40.99	0.70%	36.43	0.74%
350	(+30%, −90%	62.86	0.56%	55.87	0.60%
350	(−30%, +90%)	41.26	0.70%	36.67	0.74%
350	(+60%, −90%)	76.63	0.51%	68.11	0.54%
350	(−60%. +90%)	49.62	0.63%	44.11	0.67%
500	Unpol	16.91	1.1%	14.92	1.2%
500	(+30%, −90%)	25.94	0.88%	22.88	0.93%
500	(−30%, +90%)	17.02	1.1%	15.02	1.2%
500	(+60%, −90%)	31.62	0.80%	27.90	0.85%
500	(−60%, +90%)	20.48	0.99%	18.06	1.1%

[Cheng Li, Masterthesis]

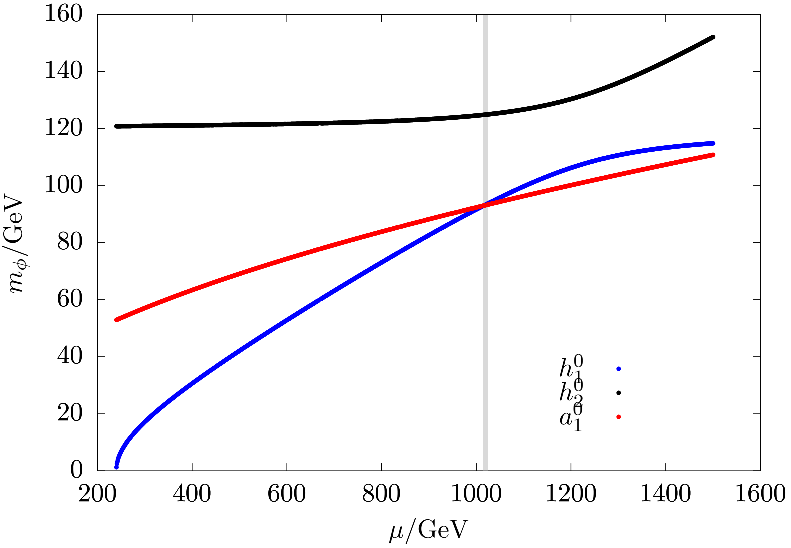
Cross sections at the LC (Whizard)

Cross section $(e^+e^- \to s^0 \{\nu_e \bar{\nu}_e, e^+e^-\})$

$\sqrt{s}$/GeV	Pol (e^+, e^-)	Scen 1 σ/fb	$\frac{dN}{N}$	Scen 2 σ/fb	$\frac{dN}{N}$
250	Unpol	5.035	2.0%	4.780	2.0%
250	(+30%, −90%)	11.93	1.3%	11.32	1.3%
250	(−30%, +90%)	0.6103	5.7%	0.5796	5.9%
250	(+60%, −90%)	14.56	1.2%	13.87	1.2%
250	(−60%, +90%)	0.4423	6.7%	0.4213	6.9%
350	Unpol	13.98	1.2%	12.94	1.2%
350	(+30%, −90%	33.55	0.77%	30.59	0.81%
350	(−30%, +90%)	1.644	3.5%	1.510	3.6%
350	(+60%, −90%)	41.44	0.70%	38.03	0.73%
350	(−60%. +90%)	1.204	4.1%	1.105	4.3%
500	Unpol	29.23	0.83%	26.36	0.87%
500	(+30%, −90%)	69.67	0.54%	62.93	0.56%
500	(−30%, +90%)	3.291	2.5%	2.963	2.6%
500	(+60%, −90%)	86.15	0.48%	77.85	0.51%
500	(−60%. +90%)	2.336	2.9%	2.113	3.1%

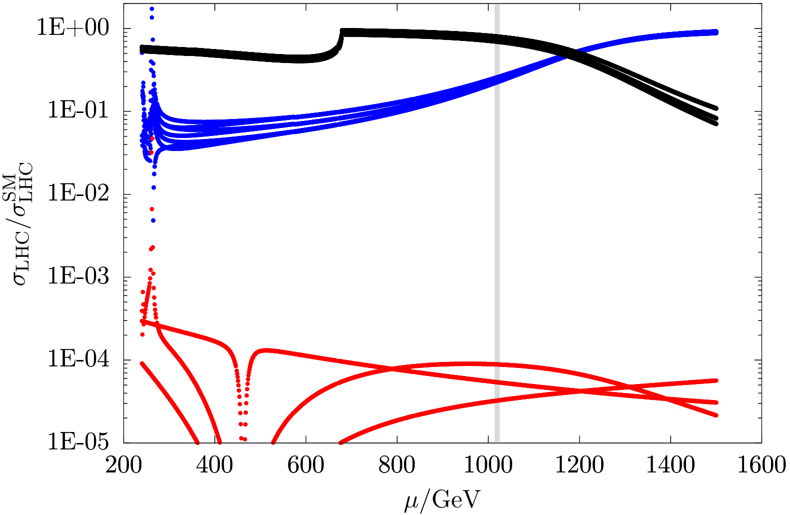
[Cheng Li, Masterthesis]

$\tan\beta = 12,\ \lambda = 0.08,\ \kappa = 0.004,\ A_\kappa = 10\,\text{GeV},\ \mu + \mu_{\text{eff}} = -115\,\text{GeV}$



using NMSSMTools [Ellwanger et al.]

$\tan\beta = 12,\ \lambda = 0.08,\ \kappa = 0.004,\ A_\kappa = 50\,\mathrm{GeV},\ \mu + \mu_{\mathrm{eff}} = -115\,\mathrm{GeV}$



various prod. cross sections x branching ratios @ LHC [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 Higgses; vacuum stability; singlet-doublet mixing
- 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 $\Phi^\dagger$): $H_u \cdot H_d$, not $|H_u|^2$

Jordan frame → 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

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

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

Corrected Superpotential: Kähler transformation

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

The iNMSSM (same field content as the NMSSM)

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

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

Stabilization of the inflationary trajectory

- only neutral components ("truncation")

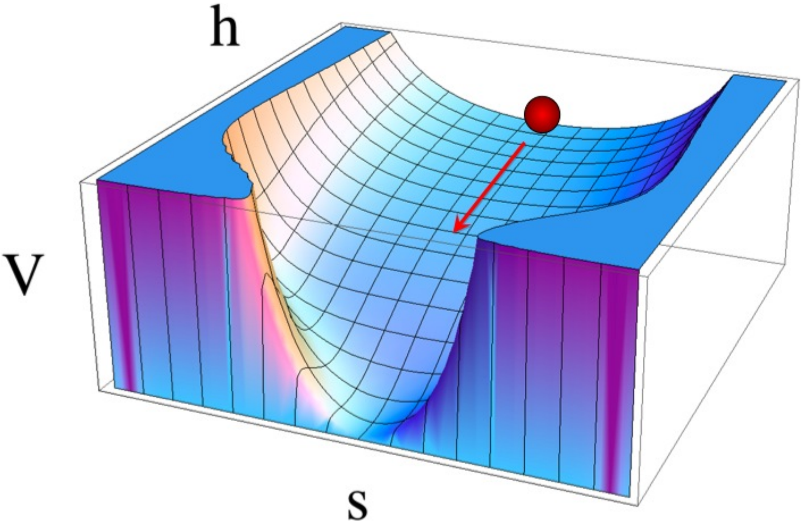
$$S = s e^{i\alpha}/\sqrt{2}, \quad H_u^0 = h_2 e^{i\alpha_1}/\sqrt{2}, \quad H_d^0 = h_1 e^{i\alpha_2}/\sqrt{2},$$

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

- D-flat direction:

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

- "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 $V(\phi, \ldots)$

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]

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

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

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

in Planck units!

Flat potential $V(\phi, \ldots)$

slow roll parameters $\epsilon, \eta \gg 1$:

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

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

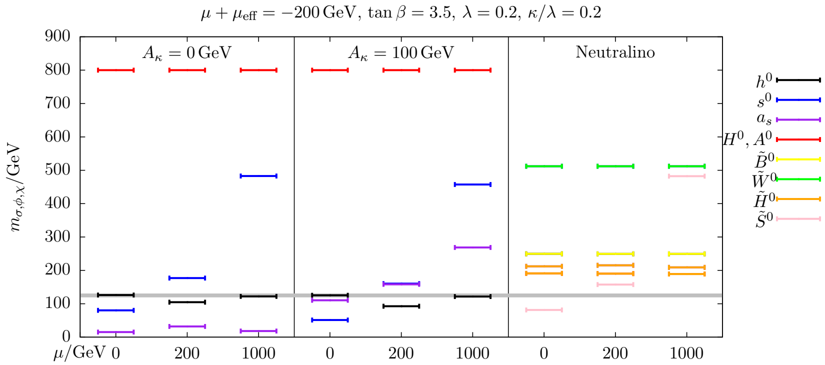
inflationary NMSSM [FLKMvP]

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

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

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

in Planck units!



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

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

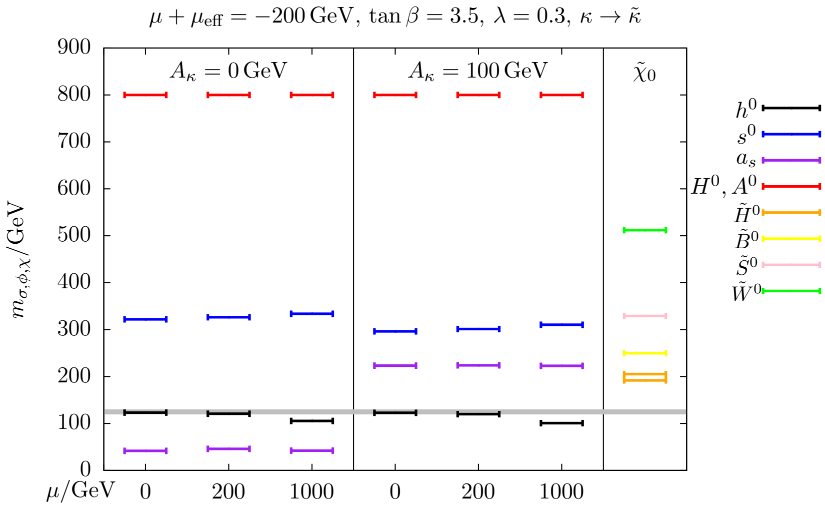
$$\mathcal{M}_\chi = \begin{pmatrix} M_1 & 0 & -M_Z\, s_\mathrm{w}\, c_\beta & M_Z\, s_\mathrm{w}\, s_\beta & 0 \\ \cdot & M_2 & M_Z\, c_\mathrm{w}\, c_\beta & -M_Z\, c_\mathrm{w}\, s_\beta & 0 \\ \cdot & \cdot & 0 & -(\mu_\mathrm{eff} + \mu) & -\lambda\, v\, s_\beta \\ \cdot & \cdot & \cdot & 0 & -\lambda\,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

"Liebler" rescaling [G. Weiglein]

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

$$\kappa \to \tilde{\kappa} = \kappa\,\frac{\mu + \mu_\mathrm{eff}}{\mu_\mathrm{eff}}$$

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



$\mu + \mu_{\text{eff}} = -200\,\text{GeV},\ \tan\beta = 3.5,\ \lambda = 0.3,\ \kappa \to \tilde{\kappa}$
$A_\kappa = 0\,\text{GeV}$
$A_\kappa = 100\,\text{GeV}$
$\tilde{\chi}_0$
900
800
700
600
500
400
300
200
100
0
$m_{\sigma,\phi,\chi}/\text{GeV}$
μ/GeV
0
200
1000
0
200
1000
h^0
s^0
a_s
H^0, A^0
$\tilde{H}^0$
$\tilde{B}^0$
$\tilde{S}^0$
$\tilde{W}^0$

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
$m_{H^\pm}/\text{GeV}$	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^s}/GeV	168.2	277.0	257.2	75.6
$\frac{\sigma(e^+e^- \to Zs^0) \cdot \text{BR}(s^0 \to b\bar{b})}{\sigma^{\text{SM}}(e^+e^- \to ZH) \cdot \text{BR}^{\text{SM}}(H \to b\bar{b})}$	0.28	0.31	0.14	0.35
$\sigma(gg \to s^0)/\text{pb}$	25.3	28.1	14.4	31.5
$\text{BR}(s^0 \to \gamma\gamma)$	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	
$\sigma(e^+e^- \to \tilde{\chi}_i\tilde{\chi}_j)$/fb for $\sqrt{s} = 350$/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
$\mathrm{Pol}(e^+, e^-) = (+30\%, -80\%)$	208	287	0.12	0.28	1620
$\mathrm{Pol}(e^+, e^-) = (-30\%, +80\%)$	142	196	0.08	0.19	352
$\sigma(e^+e^- \to \tilde{\chi}_i\tilde{\chi}_j)$/fb for $\sqrt{s} = 500$/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
$\mathrm{Pol}(e^+, e^-) = (+30\%, -80\%)$	110	161	0.19	0.32	926
$\mathrm{Pol}(e^+, e^-) = (-30\%, +80\%)$	75	110	0.13	0.22	212

Gravitino dark matter

typical gravitino mass $\mathcal{O}(10\,\text{MeV})$

Long-lived NLSP

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

lifetime

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

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

How to distinguish from the NMSSM?

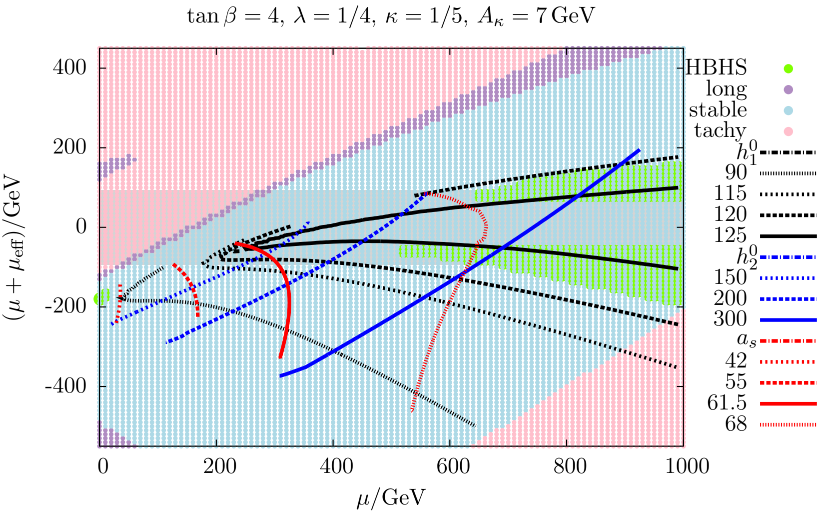
- contributions $(\mu + \mu_{\text{eff}})$ vs. μ_{eff}
- singlet sector mostly affected
- sizeable mixing effects possible, even with $\lambda \ll 1$
- look for NMSSM-like scenarios: $\mu = 0$
- identify the effect of $\mu \neq 0$

Relevant phenomenology

decays:

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

Deviating from the NMSSM



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

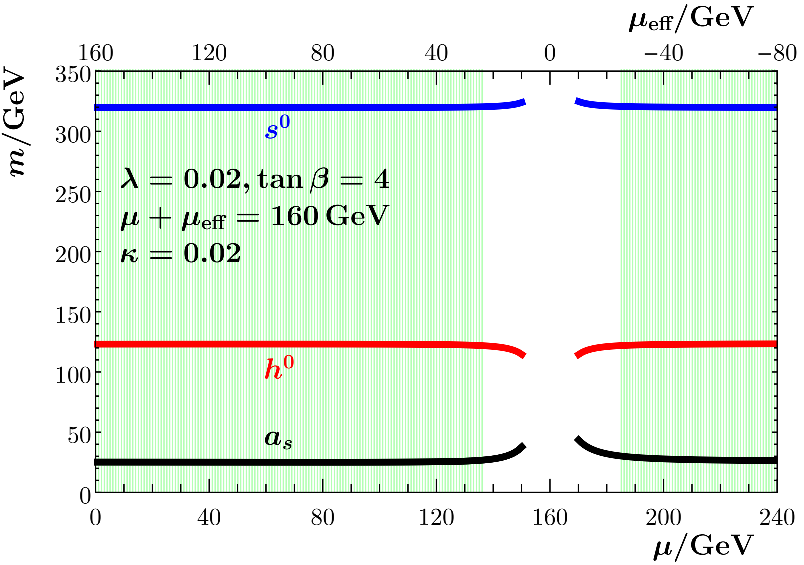
Mock MSSM-limit

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

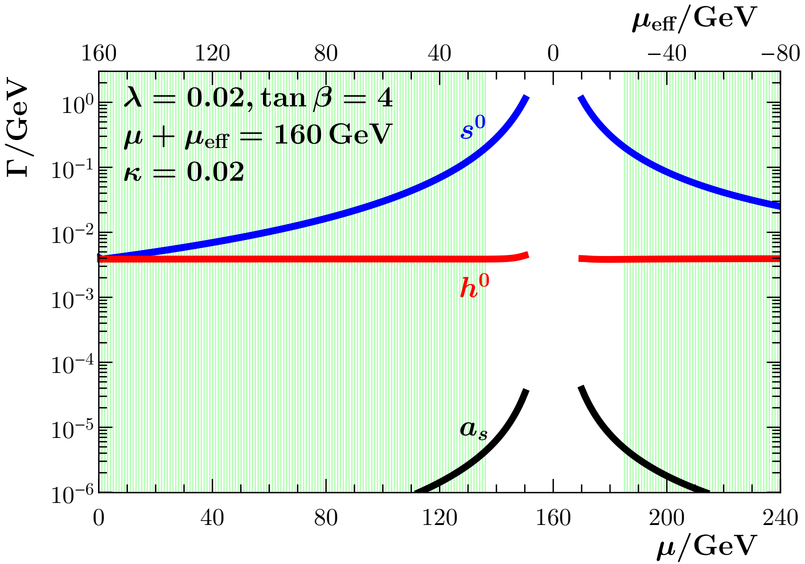
Crucial A_κ behaviour

- controls singlet mass
- small A_κ ~ 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!

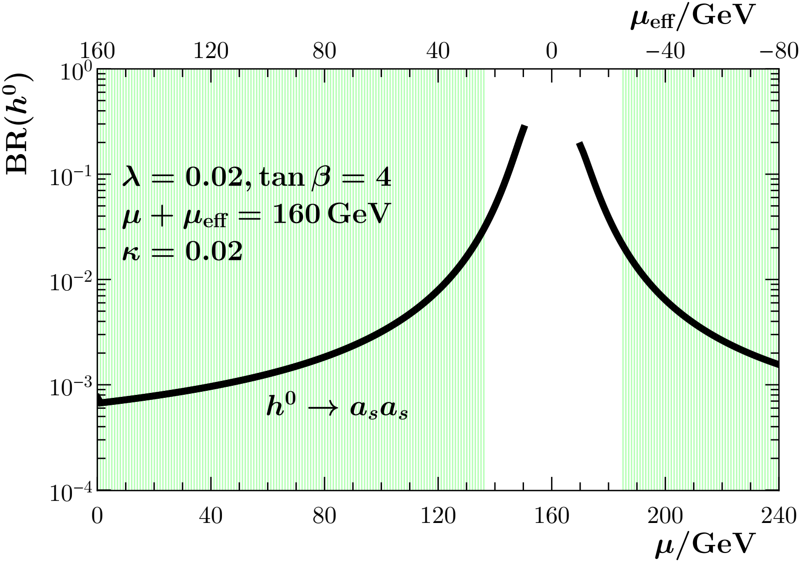
$$A_\kappa = -\,\text{sign}(\mu_{\text{eff}}\tilde{\kappa})\,1.3\,\text{GeV}$$



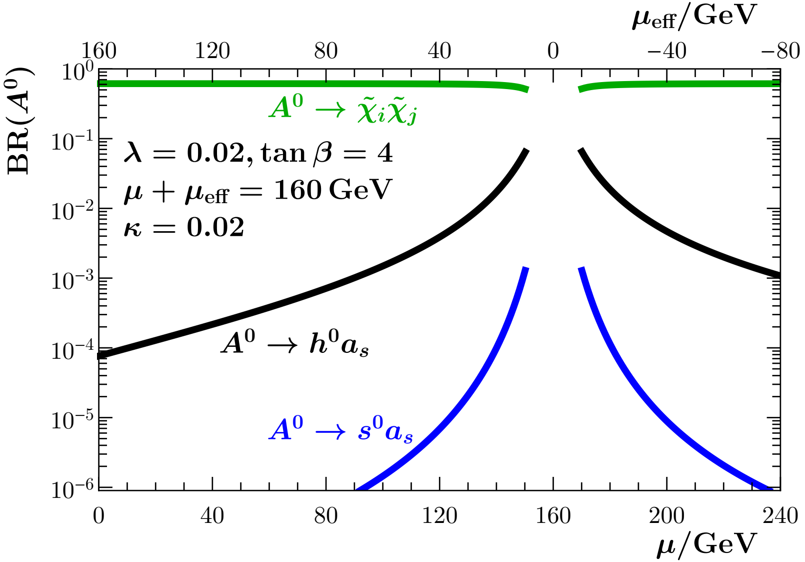
[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]



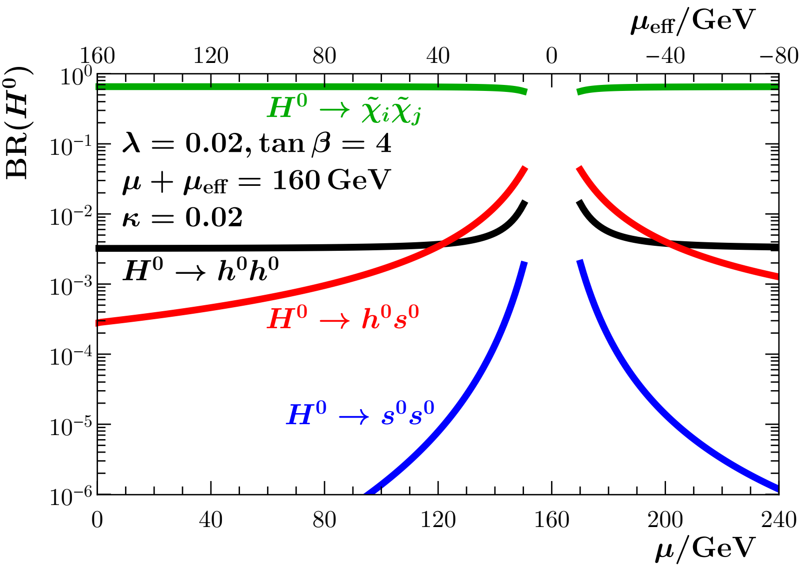
[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]



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

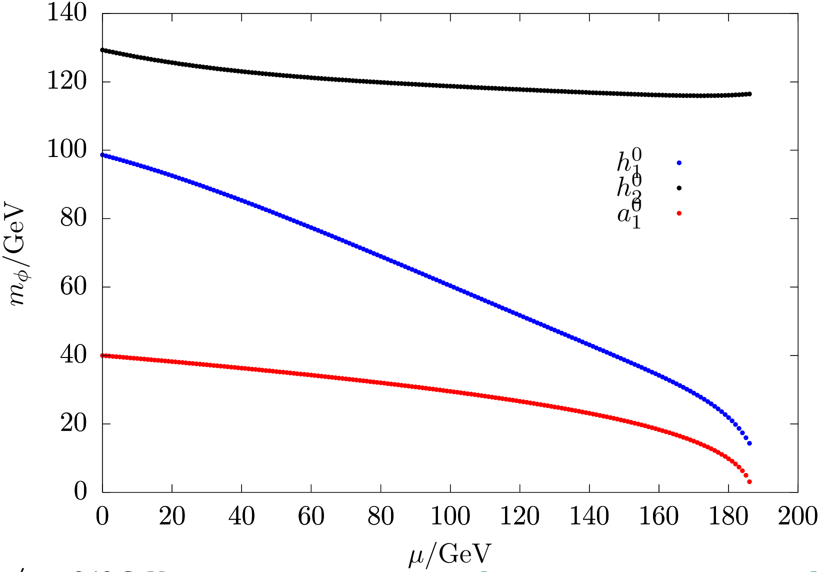


[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]



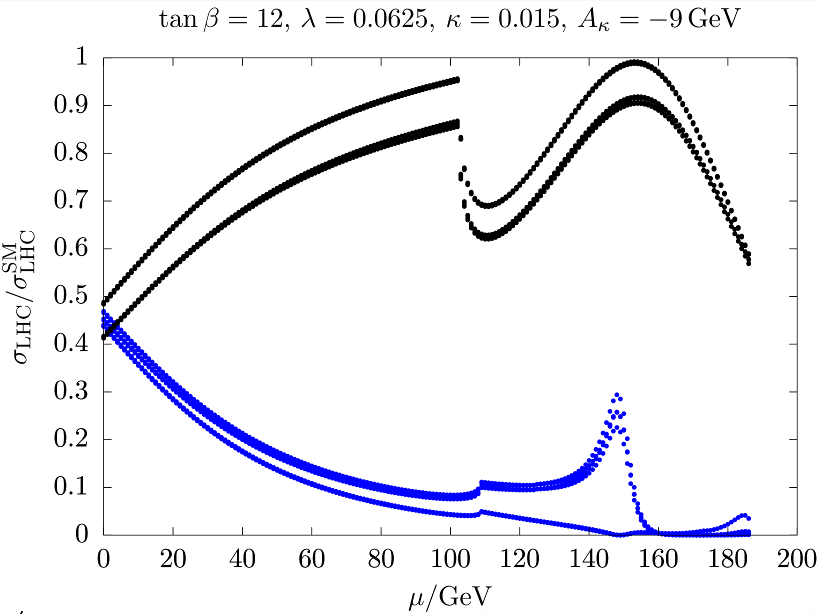
[arXiv:1808.07371—WGH, Liebler, Moortgat-Pick, Paßehr, Weiglein 18]

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



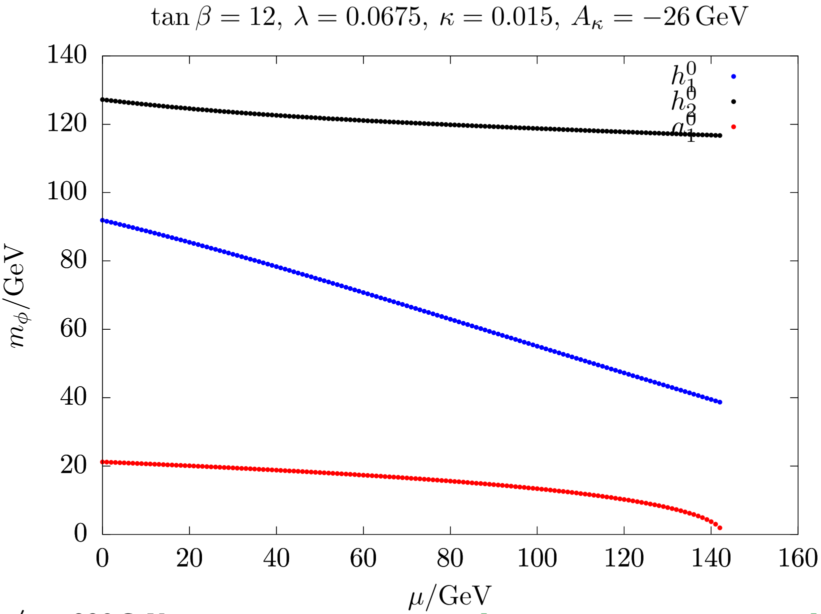
$\mu'_{\mathrm{eff}} = 242\,\mathrm{GeV}$

[*preliminary*, using NMSSMTools]



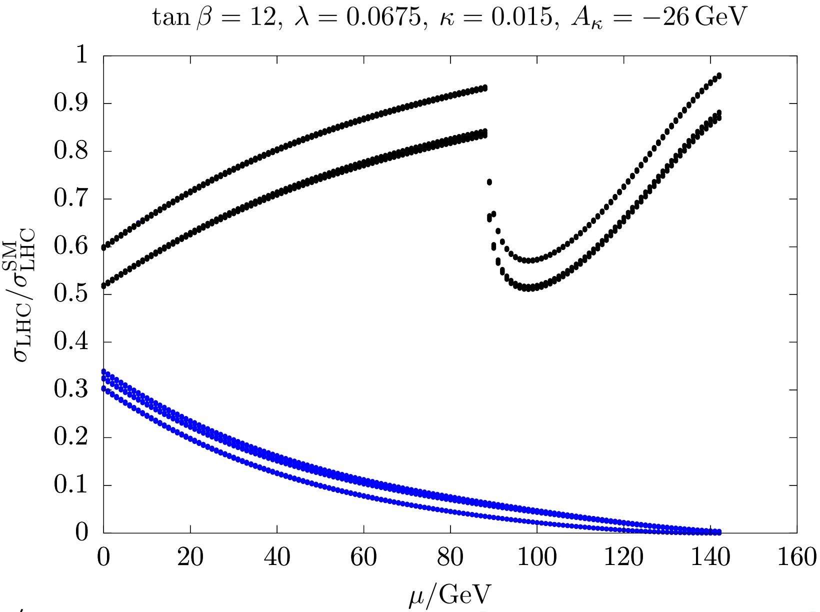
$\mu'_{\mathrm{eff}} = 242\,\mathrm{GeV}$

[*preliminary*, using NMSSMTools]



$\mu'_{\mathrm{eff}} = 239\,\mathrm{GeV}$

[*preliminary*, using NMSSMTools]



$\mu'_{\mathrm{eff}} = 239\,\mathrm{GeV}$

[*preliminary*, using NMSSMTools]