Phenomenological consequences of Higgs inflation in the NMSSM at the electroweak scale

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Contents

Higgs inflation

- inflation required by cosmology
- instead of new field use Higgs boson as inflaton
- SM becomes unnatural [Barbon, Espinosa, arXiv:0903.0355]
- scale-free extension of the SM in canonical superconformal supergravity
  [Einhorn, Jones, arXiv:0912.2718] [Ferrera, Kallosh, Linde, Marrani, Van Proeyen, arXiv:1004.0712, arXiv:1008.2942]
  inflation triggered by non-minimal coupling to Einstein gravity:

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

  only possible choice: $X = \chi\, \hat{H}_u \cdot \hat{H}_d$
- MSSM no viable model for inflation [Einhorn, Jones, arXiv:0912.2718]
  additional scalar singlet + stabilisator term at high energy works
  [Ferrera, Kallosh, Linde, Marrani, Van Proeyen, arXiv:1008.2942] [Lee, arXiv:1005.2735]

The standard NMSSM

$\mathbb{Z}_3$ invariant NMSSM:

- two Higgs doublets, one Higgs singlet:

$$H_u = \begin{pmatrix} \eta_u^+ \\ v_u + \frac{1}{\sqrt{2}}\left(\sigma_u + i\,\phi_u\right) \end{pmatrix}, \quad H_d = \begin{pmatrix} v_d + \frac{1}{\sqrt{2}}\left(\sigma_d + i\,\phi_d\right) \\ \eta_d^- \end{pmatrix}, \quad S = v_s + \frac{1}{\sqrt{2}}\left(\sigma_s + i\,\phi_s\right)$$

- superpotential

$$\mathcal{W} = \lambda\, S\, H_u \cdot H_d + \frac{1}{3}\,\kappa\, S^3 + \text{Yukawa}$$

dynamically generated term $\mu_{\text{eff}} = \lambda\, v_s$ solves μ-problem of MSSM

The NMSSM with inflation

- term $X = \chi\, H_u \cdot H_d$ breaks $\mathbb{Z}_3$ symmetry, appears in Kähler potential

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

- superpotential changed: [Ferrera, Kallosh, Linde, Marrani, Van Proeyen, arXiv:1008.2942]

$$\mathcal{W} \to \mathcal{W} \exp \left(\frac{X}{M_\text{P}^2} \right) = \mathcal{W} + \frac{1}{M_\text{P}^2} \langle \mathcal{W}_\text{hidden} \rangle\, X \approx \mathcal{W} + m_{3/2}\, X$$

- can be accommodated by more general NMSSM with superpotential

$$\mathcal{W} = \lambda\, S\, H_u \cdot H_d + \frac{1}{3}\, \kappa\, S^3 + \frac{3}{2}\, m_{3/2}\, \chi\, H_u \cdot H_d + \text{Yukawa}$$

New parameters

- additional term appears as an MSSM-like μ term with $\mu = \frac{3}{2} m_{3/2} \chi$
- approximate value of $\chi \approx 10^5 \lambda$
  (last 60 e-folds of inflation, COBE normalization of scalar perturbations)
  [Ferrera, Kallosh, Linde, Marrani, Van Proeyen, arXiv:1008.2942] [Lee, arXiv:1005.2735]
- additional soft-breaking term

$$-\mathcal{L}_{\text{soft}} = \left[A_\lambda \lambda S H_u \cdot H_d + \frac{1}{3} A_\kappa \kappa S^3 + B_\mu \mu H_u \cdot H_d + \text{h.c.} \right] + m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_s^2 |S|^2$$

- additional $\mathbb{Z}_3$-breaking parameters possible,
  in the following: equal to zero at tree level
  $\to$ superpotential parameters zero at all orders
  $\to$ running of soft-breaking parameters in general small
  further studies in extended NMSSM or GNMSSM:
  [Ellwanger, Hugonie, Teixeira, arXiv:0910.1785] [Ross, Schmidt-Hoberg, arXiv:1108.1284]
  [Ross, Schmidt-Hoberg, Staub, arXiv:1205.1509] [Kaminska, Ross, Schmidt-Hoberg, arXiv:1308.4168] [Badziak, Wagner, arXiv:1611.02353]

The setup

- NMSSM with $\mathbb{Z}_3$-breaking μ, B_μ terms,
  all parameters considered to be real
- compare phenomenology with $\mathbb{Z}_3$-preserving NMSSM
  $\rightarrow$ focus set on μ (and B_μ)
- take into account constraints from:
  - vacuum stability
  - SM-like Higgs at 125 GeV
  - observed Higgs data with `HiggsSignals`
  - limits on extended Higgs sector with `HiggsBounds`
  - neutralino and chargino masses (higgsinos)
  - sfermion mixing (charge-, color-breaking minima)

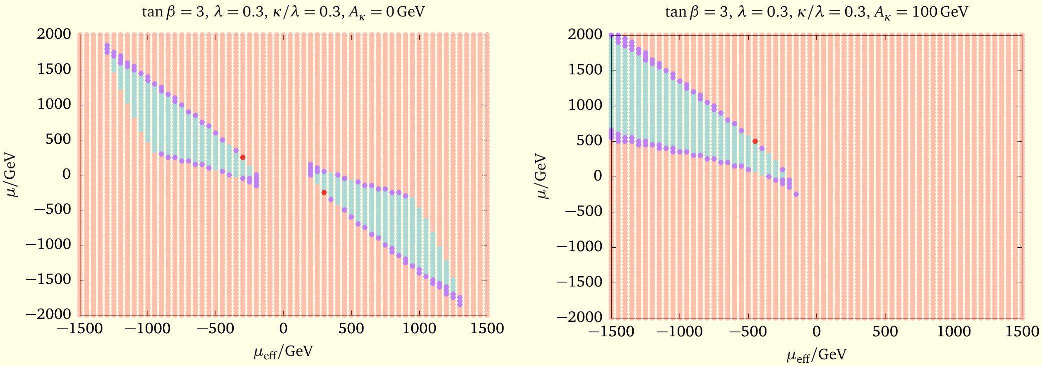
Vacuum stability

- minimization conditions of Higgs potential

$$\left.\frac{\partial V}{\partial h}\right|_{\text{vev}} \overset{!}{=} 0$$

  may be misleading
- scenarios with different minima at large field values possible
- check for global minimum = electroweak minimum
- other minima may be viable as well (meta-stable with long life time)
- minima typically hard to find analytically
  $\rightarrow$ numerical minimization of tree-level Higgs potential
- μ term in general increases allowed parameter region
- substitution of A_λ by charged Higgs mass $m_{H^\pm}$

Vacuum stability – example



light blue: stable vacuum,
purple: long-lived metastable vacuum,
red: short-lived metastable vacuum,
rose: instable vacuum (tachyons)

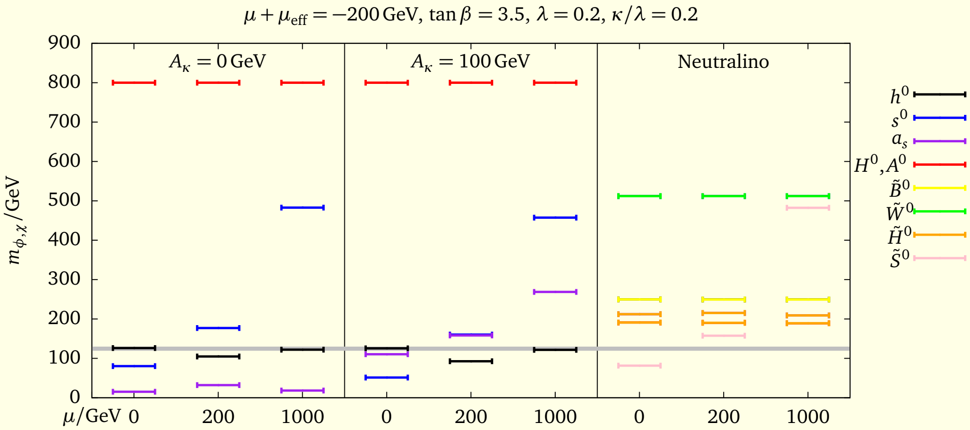
value of A_κ has severe impact (singlet states),
region around $\mu_{\mathrm{eff}} = 0$ not accessible,
in most scenarios: sign $A_\kappa = -$ sign μ_{eff},
non-zero μ: allow scenarios impossible in NMSSM

Higgs masses

- at tree level:
  SM-like Higgs mass shifted upwards compared to MSSM (same as in NMSSM),
  $\mu + \mu_{\text{eff}}$ appears in singlet–doublet mixing,
  μ/μ_{eff} appears in diagonal elements of singlets
- full one-loop corrections:
  $\overline{\text{DR}}$ scheme for μ, B_μ (and also λ, κ, A_κ, μ_{eff})
- additional two-loop corrections in the MSSM-limit with `FeynHiggs`:
  important mass shifts of $\mathcal{O}(\alpha_t \alpha_s, \alpha_t^2)$ to SM-like state
- masses determined from poles of

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

Higgs masses – example



grey bar: mass of $125 \pm 3\,\text{GeV}$

fixed sum $\mu + \mu_{\text{eff}}$: large positive $\mu \rightarrow$ large negative μ_{eff},
singlets and singlinos sensitive to μ_{eff}

Neutralino masses

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

sum $\mu + \mu_\mathrm{eff}$ in MSSM-like higgsino mass terms (analogous for charged),
term $\frac{\kappa}{\lambda}\,\mu_\mathrm{eff}$ in singlino mass term,

for $\mu \neq 0$ all neutralino/chargino masses constant by shifting and rescaling

$$\mu_\mathrm{eff} \to \mu'_\mathrm{eff} - \mu,$$
$$\frac{\kappa}{\lambda} \to \frac{\kappa'}{\lambda}\,\frac{\mu'_\mathrm{eff}}{\mu'_\mathrm{eff} - \mu}$$

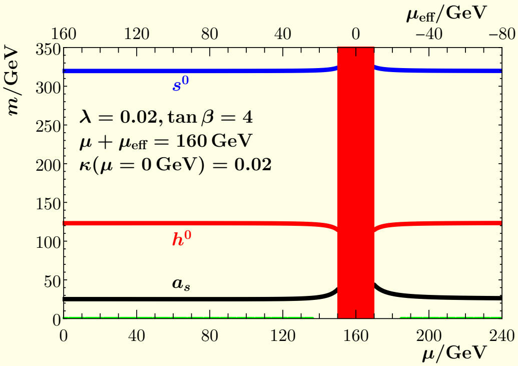
Higgs production and decays

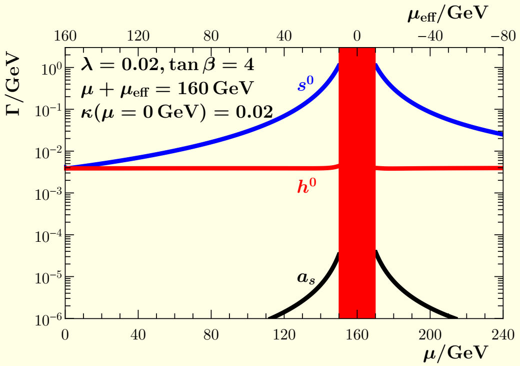
- production:
  in general: SM-normalized effective couplings of a Higgs boson to gluons,
  light-singlet scenario: NMSSM version of `SusHi` [Liebler, arXiv:1502.07972]
- decays: SM-normalized effective couplings
- mixing: employ Z matrix in the algorithm of Ref. [Domingo, Drechsel, SP, arXiv:1706.00437]
- relevant couplings λ_{ijk} of $\phi_{i,j,k} \in (\sigma_d, \sigma_u, \sigma_s, A, \phi_s)$ containing μ and/or μ_{eff}:

$$\lambda_{113} = \lambda_{223} = \lambda_{344} = \lambda_{355} = -2\,\lambda\,(\mu + \mu_{\text{eff}})$$
$$\lambda_{123} = -\lambda_{345} = \lambda\,A_\lambda + 2\,\kappa\,\mu_{\text{eff}}$$

  (in addition: couplings to charged Higgs)
- sensitive decays: $s^0 \to h^0 h^0$, $H^0 \to s^0 h^0$, $A^0 \to s^0 a_s$
  (h^0, H^0, s^0, A^0, a_s denote states with most contribution of this type, mixing matrices appear and are relevant)

Higgs decays – example





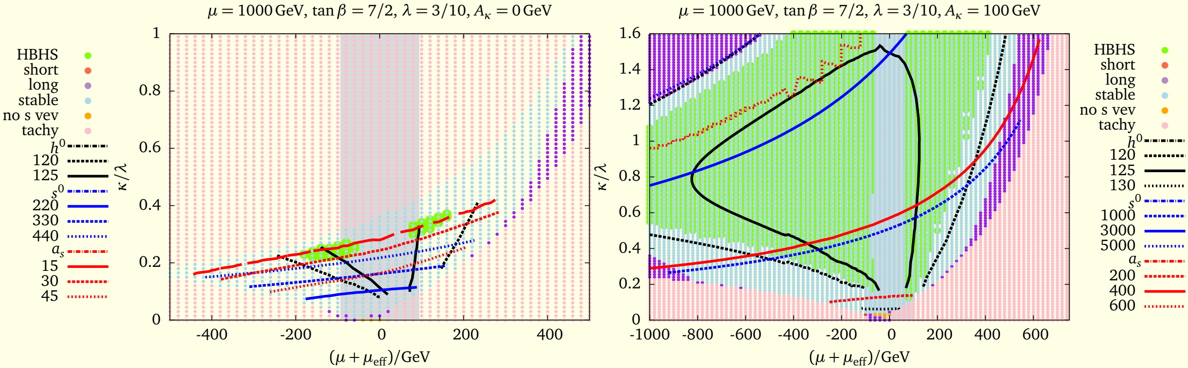
masses nearly constant via rescaling

total width

red bar: $\kappa > 0.5$

scenario with large κ and very small λ and μ_{eff}, but large mixing of h^0 and s^0
(not possible in NMSSM due to constraints on higgsino mass)

Dependence on κ/λ over $\mu + \mu_{\text{eff}}$



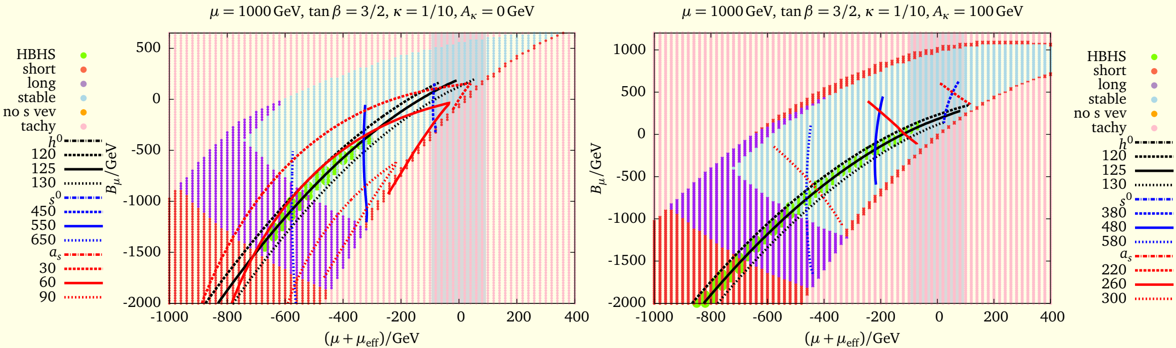
grey bar: LEP-limit for chargino masses,

green background: allowed by `HiggsSignals` and `HiggsBounds`

singlet masses very sensitive to A_κ (like NMSSM),

SM-like Higgs with 125 GeV only in region with stable vacuum (light blue)

Dependence on B_μ over $\mu + \mu_{\text{eff}}$



non-zero B_μ may cause instable vacua,

differences between tachyons at tree level and loop level can be large

$\rightarrow$ large loop corrections,

for some scenarios: more two-loop (or higher-order) corrections necessary

Conclusions and outlook

- Higgs inflation in extension of NMSSM by $\mathbb{Z}_3$-breaking μ term
- vacuum stability and SM-like Higgs at 125 GeV significantly constrain parameter space
- parameter rescaling to keep impact of μ on Higgs masses small, but: decay widths of singlets strongly affected
- attributes of singlet-like Higgs bosons required to distinguish inflation-inspired model from standard NMSSM
- light singlet scenarios which do not exist in standard NMSSM