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

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Higgs inflation

- inflation required by cosmology
- instead of new field use Higgs boson as inflaton
- scale-free extension of the SM in canonical superconformal supergravity
  inflation triggered by non-minimal coupling to Einstein gravity:

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

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
The standard NMSSM

$Z_3$ invariant NMSSM:

- two Higgs doublets, one Higgs singlet:

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

- 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 $\mu$-problem of MSSM
The NMSSM with inflation

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

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


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

- 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 $\mu$ 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)


- additional soft-breaking term

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

- additional $Z_3$-breaking parameters possible,
  in the following: equal to zero at tree level
  $\rightarrow$ superpotential parameters zero at all orders
  $\rightarrow$ running of soft-breaking parameters in general small

further studies in extended NMSSM or GNMSSM:

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Conclusions and outlook
The setup

- NMSSM with $Z_3$-breaking $\mu$, $B_\mu$ terms, all parameters considered to be real
- compare phenomenology with $Z_3$-preserving NMSSM $\rightarrow$ focus set on $\mu$ (and $B_\mu$)
- 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

\[ \left. \frac{\partial V}{\partial h} \right|_{\text{vev}} = 0 \]

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
  → numerical minimization of tree-level Higgs potential

• \( \mu \) term in general increases allowed parameter region

• substitution of \( A_\lambda \) 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)

The value of $A_\kappa$ has severe impact (singlet states). Region around $\mu_{\text{eff}} = 0$ is not accessible. In most scenarios: $\text{sign } A_\kappa = -\text{sign } \mu_{\text{eff}}$. Non-zero $\mu$: 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,
  $\mu/\mu_{\text{eff}}$ appears in diagonal elements of singlets

- full one-loop corrections:
  $\overline{\text{DR}}$ scheme for $\mu$, $B_\mu$ (and also $\lambda$, $\kappa$, $A_\kappa$, $\mu_{\text{eff}}$)

- 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

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

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

\[ \begin{align*}
A_\kappa &= 0 \text{ GeV} \\
A_\kappa &= 100 \text{ GeV} \\
\text{Neutralino} &
\end{align*} \]

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

fixed sum \[ \mu + \mu_{\text{eff}}: \text{ large positive } \mu \rightarrow \text{ large negative } \mu_{\text{eff}}, \]
singlets and singlinos sensitive to \[ \mu_{\text{eff}} \]
Neutralino masses

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

sum \( \mu + \mu_{\text{eff}} \) in MSSM-like higgsino mass terms (analogous for charged),

term \( \frac{\kappa}{\lambda} \mu_{\text{eff}} \) in singlino mass term,

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

\[
\mu_{\text{eff}} \rightarrow \mu'_{\text{eff}} - \mu,
\]

\[
\frac{\kappa}{\lambda} \rightarrow \frac{\kappa'}{\lambda} \frac{\mu'_{\text{eff}}}{\mu_{\text{eff}} - \mu}
\]
Higgs production and decays

- **production:**
  in general: SM-normalized effective couplings of a Higgs boson to gluons,

- **decays:** SM-normalized effective couplings

- **mixing:** employ $Z$ matrix in the algorithm of Ref. [Domingo, Drechsel, SP, arXiv:1706.00437]

- relevant couplings $\lambda_{ijk}$ of $\phi_{i,j,k} \in (\sigma_d, \sigma_u, \sigma_s, A, \phi_s)$ containing $\mu$ and/or $\mu_{\text{eff}}$:

  \[
  \begin{align*}
  \lambda_{113} &= \lambda_{223} = \lambda_{344} = \lambda_{355} = -2\lambda(\mu + \mu_{\text{eff}}) \\
  \lambda_{123} &= -\lambda_{345} = \lambda A_\lambda + 2\kappa \mu_{\text{eff}}
  \end{align*}
  \]

  (in addition: couplings to charged Higgs)

- **sensitive decays:** $s^0 \rightarrow h^0 h^0, H^0 \rightarrow s^0 h^0, A^0 \rightarrow s^0 a_s$

  ($h^0, H^0, s^0, A^0, a_s$ denote states with most contribution of this type, mixing matrices appear and are relevant)
masses nearly constant via rescaling

scenario with large $\kappa$ and very small $\lambda$ and $\mu_{\text{eff}}$, but large mixing of $h^0$ and $s^0$ (not possible in NMSSM due to constraints on higgsino mass)
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grey bar: LEP-limit for chargino masses, 
green background: allowed by HiggsSignals and HiggsBounds 

singlet masses very sensitive to $A_\kappa$ (like NMSSM), 
SM-like Higgs with 125 GeV only in region with stable vacuum (light blue)
Dependence on $B_\mu$ over $\mu + \mu_{\text{eff}}$

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

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

non-zero $B_\mu$ may cause instable vacua,
differences between tachyons at tree level and loop level can be large
→ large loop corrections,
for some scenarios: more two-loop (or higher-order) corrections necessary
Conclusions and outlook

- Higgs inflation in extension of NMSSM by $Z_3$-breaking $\mu$ term
- vacuum stability and SM-like Higgs at 125 GeV significantly constrain parameter space
- parameter rescaling to keep impact of $\mu$ 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