Implications of R^2-Higgs inflation with two doblets for collider experiments

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Outline

- **Overview**
- **R^2-Higgs Inflation in 2HDM**
- **Implications at collider experiments**
- **Summary and outlook**

Overview

- Higgs inflation: One of the best-fit model to CMB data.
- Requires large non-minimal coupling: issue is perturbative unitarity.
- R^2-Higgs inflation: can restore perturbative unitarity. (see talk by Minxi He)
- Additional Higgs doublets may exist in nature.
- Focus of interest is Two Higgs doublet model (2HDM).

R^2-Higgs Inflation in 2HDM

Two Higgs doublet

Higgs sector:

$$V(\Phi,\Phi') = \mu_{11}^2|\Phi|^2 + \mu_{22}^2|\Phi'|^2 - (\mu_{12}^2\Phi^\dagger\Phi' + h.c.) + \frac{\eta_1}{2}|\Phi|^4 + \frac{\eta_2}{2}|\Phi'|^4 + \eta_3|\Phi|^2|\Phi'|^2 + \eta_4|\Phi^\dagger\Phi'|^2 + \left[\frac{\eta_5}{2}(\Phi^\dagger\Phi')^2 + \left(\eta_6|\Phi|^2 + \eta_7|\Phi'|^2\right)\Phi^\dagger\Phi' + h.c.\right]$$

(e.g. Davidson and Haber PRD'05, Hou and Kikuchi, EPL' 18)

- Additional-Higgs bosons:

$H,\ A,\ H^\pm$

$m_A,\ m_{H^\pm},\ m_H \sim 200\text{–}800\ \mathrm{GeV}$

$m_h = 125\ \mathrm{GeV}$

$c_\gamma \sim 0.2 - 0.1$

(W.-S. Hou, M. Kohda, TM PRD'19)

Yukawa sector:

$$\lambda^u \equiv \begin{pmatrix} \lambda_u & & \\ & \lambda_c & \\ & & \lambda_t \end{pmatrix}, \quad \lambda^d \equiv \begin{pmatrix} \lambda_d & & \\ & \lambda_s & \\ & & \lambda_b \end{pmatrix}, \quad \lambda^l \equiv \begin{pmatrix} \lambda_e & & \\ & \lambda_\mu & \\ & & \lambda_\tau \end{pmatrix} \quad \text{with, } \lambda^{\mathrm{f}} = \frac{\sqrt{2}\mathrm{m_f}}{\mathrm{v}}$$

$$\rho^u \equiv \begin{pmatrix} \rho_{uu} & \rho_{uc} & \rho_{ut} \\ \rho_{cu} & \rho_{cc} & \rho_{ct} \\ \rho_{tu} & \rho_{tc} & \rho_{tt} \end{pmatrix}, \ \rho^d \equiv \begin{pmatrix} \rho_{dd} & \rho_{ds} & \rho_{db} \\ \rho_{sd} & \rho_{ss} & \rho_{sb} \\ \rho_{bd} & \rho_{bs} & \rho_{bb} \end{pmatrix}, \ \rho^\ell \equiv \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

Higgs bosons couplings with fermions:

$h\bar{f}_i f_j$: $-\lambda_{ij} s_\gamma + \rho_{ij} c_\gamma$

$H\bar{f}_i f_j$: $\lambda_{ij} c_\gamma + \rho_{ij} s_\gamma$

$A\bar{f}_i f_j$: $-i\ \mathrm{sgn}(Q_f)\rho_{ij}$

$\bar{u}_i d_j H^+$: $(V\rho^D)_{ij} P_R - (\rho^{U\dagger} V)_{ij} P_L$

$c_\gamma \lesssim 0.2$ →

h couples to λ^f

$H, A, H^\pm$ couple to ρ^f

2HDM R^2 inflation

Inflationary dynamics:

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \rho_1\end{pmatrix} \qquad \text{and} \qquad \Phi' = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \rho_2 + i\rho_3\end{pmatrix}.$$

$$\phi^I(x^\mu) = \bar{\phi}^I(t) + \delta\phi^I(x^\mu); \text{with} \phi^I = \{\varphi, \rho_1, \rho_2, \rho_3\}$$

$$S_E = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}(\partial_\mu\varphi)^2 - \frac{1}{2}e^{-\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}}\left((\partial_\mu\rho_1)^2 + (\partial_\mu\rho_2)^2 + (\partial_\mu\rho_3)^2\right) - V_E\right]$$

$$V_E(\varphi, \rho_1, \rho_2, \rho_3) = \frac{1}{8}e^{-2\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}}\left[V(\rho_1, \rho_2, \rho_3) + 2\frac{M_P^4}{\xi_R}\left(e^{\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}} - 1 - \frac{\xi_{11}}{M_P^2}\rho_1^2\right)^2\right]$$

Background and perturbations:

$$\mathcal{D}_t\dot{\phi}^I + 3H\dot{\phi}^I + G^{IK}V_{E,K} = 0$$

$$\mathcal{D}_t^2 Q^I + 3H\mathcal{D}_t Q^I + \left(\frac{k^2}{a^2}\delta^I_J + \mathcal{M}^I_J - \frac{1}{{}^2a^3}D_t\left(\frac{a^3}{H}\dot{\phi}^I\dot{\phi}_J\right)\right)Q^J = 0$$

$$\mathcal{M}^I_J = G^{IM}\mathcal{D}_J\mathcal{D}_M V_E - R^I_{MNJ}\dot{\phi}^M\dot{\phi}^N; \qquad \delta\mathcal{M}^I_J = -\frac{1}{{}^2a^3}\mathcal{D}_t\left(\frac{a^3}{H}\dot{\phi}^I\dot{\phi}_J\right)$$

Adiabatic and isocurvature modes:

Spanned by unit vectors: $\hat{\sigma}_I,\ \hat{\omega}_I,\ \hat{\pi}_I,\ \hat{\tau}_I$

$$Q_\sigma = \hat{\sigma}_I Q^I, \qquad \mathcal{R} = \frac{H}{\dot{\sigma}}Q_\sigma, \qquad \mathcal{P}_\mathcal{R}(t;k) = \frac{k^3}{2\pi^2}P_\mathcal{R}(k)$$

$$Q_s = \hat{\omega}_I Q^I, \qquad \mathcal{S} = \frac{H}{\dot{\sigma}}Q_s, \qquad \mathcal{P}_\mathcal{S}(t;k) = \frac{k^3}{2\pi^2}|\mathcal{S}|$$

$$Q_u = \hat{\pi}_I Q^I, \qquad \mathcal{U} = \frac{H}{\dot{\sigma}}Q_u, \qquad \mathcal{P}_\mathcal{U}(t;k) = \frac{k^3}{2\pi^2}|\mathcal{U}|^2$$

$$Q_v = \hat{\tau}_I Q^I \qquad \mathcal{V} = \frac{H}{\dot{\sigma}}Q_v \qquad \mathcal{P}_\mathcal{V}(t;k) = \frac{k^3}{2\pi^2}|\mathcal{V}|^2$$

Numerical results

Low-scale:

$$\mu_{22} < 1 \text{ TeV}; |\eta_i| < 1.$$

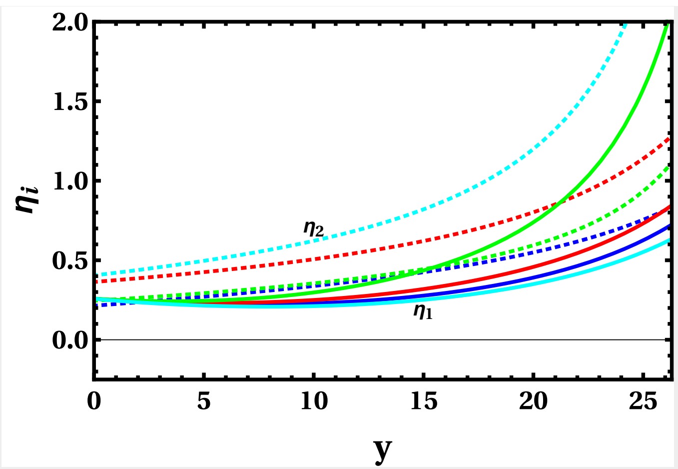
Perturbativity, Unitarity, Stability and EW precision observable.

BPs	η_1	η_2	η_3	η_4	η_5	η_6	η_7	m_{H^+}	m_A (GeV)	m_H (GeV)	$\frac{\mu_{22}^2}{v^2}$ (GeV)	c_γ
a	0.258353	0.214212	−0.104774	0.321234	−0.00339535	−0.0474321	0.132779	424	436	435	3.017	0.0165
b	0.257981	0.363637	−0.026754	0.194828	−0.225193	−0.0337426	0.0418302	429	443	428	3.043	0.0122
c	0.259349	0.245545	0.469357	−0.579992	−0.014849	−0.050576	0.061887	347	322	321	1.756	0.0352
d	0.258161	0.40482	0.134086	0.028604	0.059236	−0.066433	0.086559	681	681	683	7.581	0.0089

High-scale:

Perturbative Unitarity, Positivity

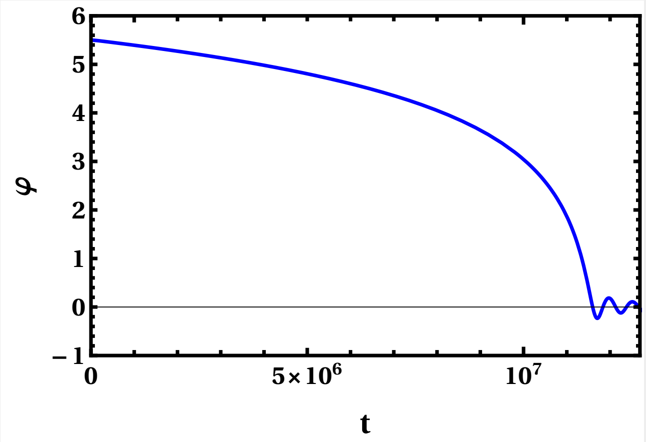
BPs	$\tilde{\eta}_1$	$\tilde{\eta}_2$	$\tilde{\eta}_3$	$\tilde{\eta}_4$	$\tilde{\eta}_5$	$\tilde{\eta}_6$	$\tilde{\eta}_7$	ξ_{11}	ξ_R
a	0.72459	0.834059	−0.287252	0.489654	−0.010900	−0.510739	0.333532	1	2.4×10^9
b	0.845674	1.281688	0.017365	0.611085	−0.776203	−0.361704	0.050345	1800	2.25×10^9
c	2.08746	1.11479	2.56305	−1.93179	−0.0412796	−0.521398	−0.0743505	10^{-3}	2.42×10^9
d	0.634249	2.98825	0.083228	0.087188	0.152301	−0.494063	0.679174	200	2.4×10^9

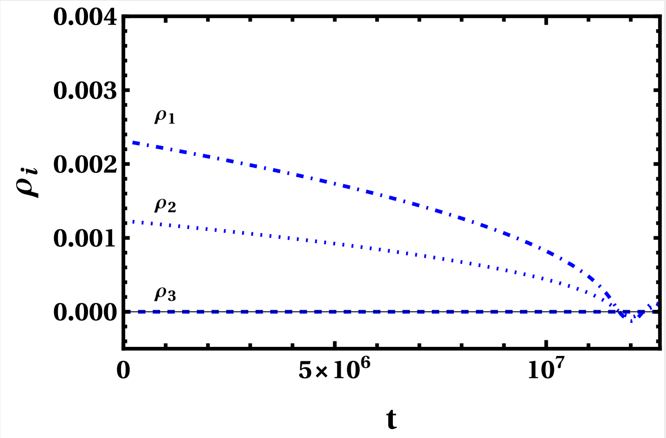


$$y = \ln(\mu/m_W)$$

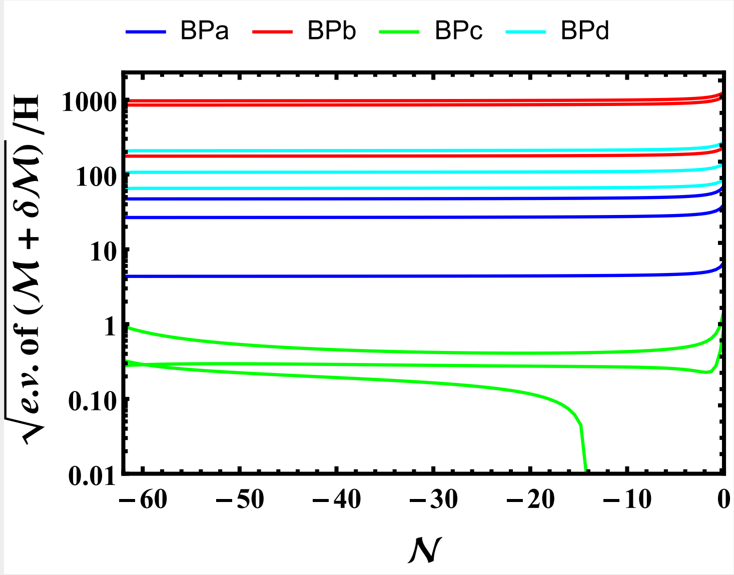
Background evolution:

φ plays the role of inflaton





Mass eigen values of isocurvature modes:

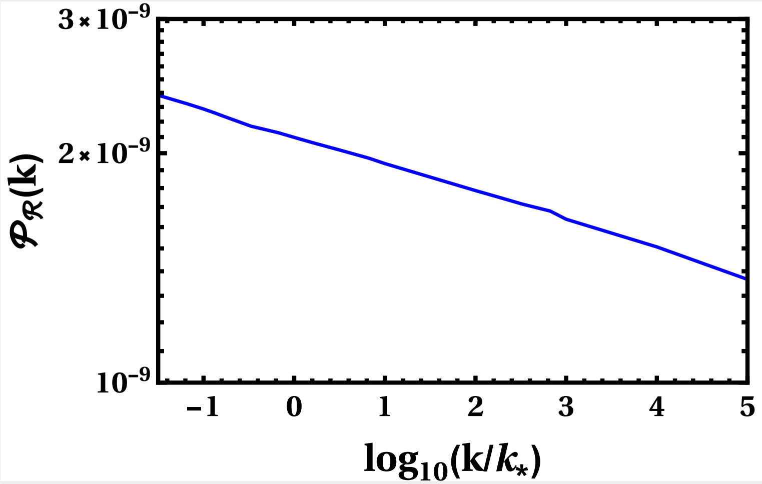


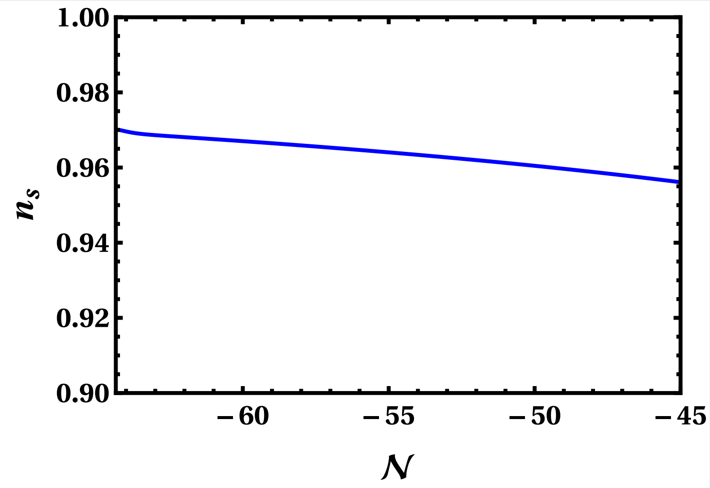
(Planck 2018)

$$n_s^* = 0.9649 \pm 0.0042$$

$$A_s^* = (2.099 \pm 0.014) \times 10^{-9}$$

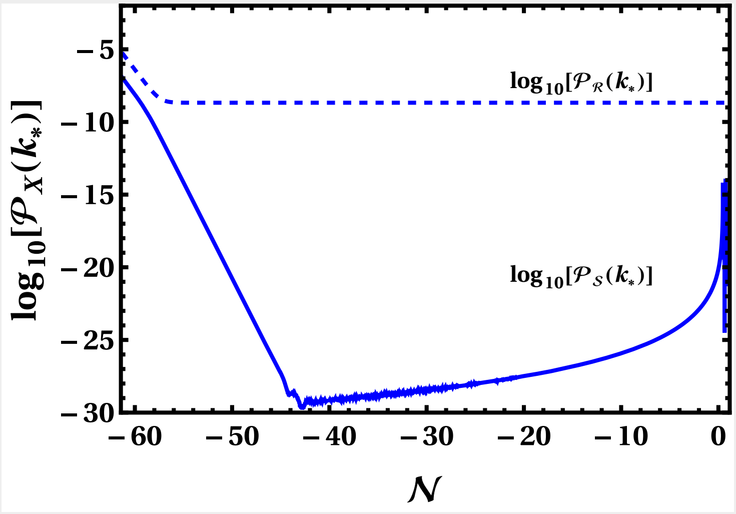
$$r_{\varphi^*} < 0.056$$



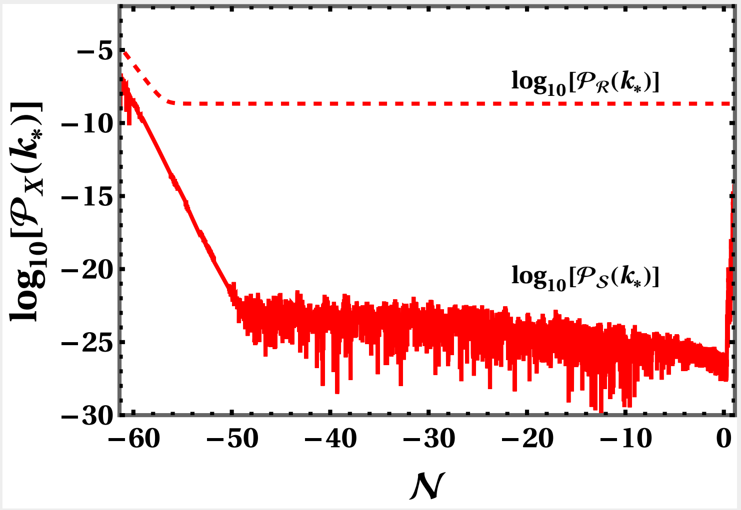


$$r_{\varphi *} \approx 3.3 \times 10^{-3}, \; n_{s^*} = 0.965$$

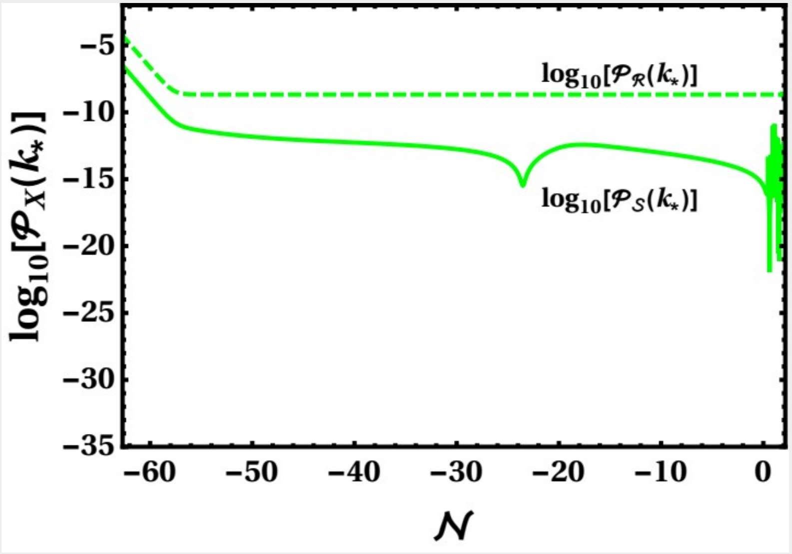
BPa



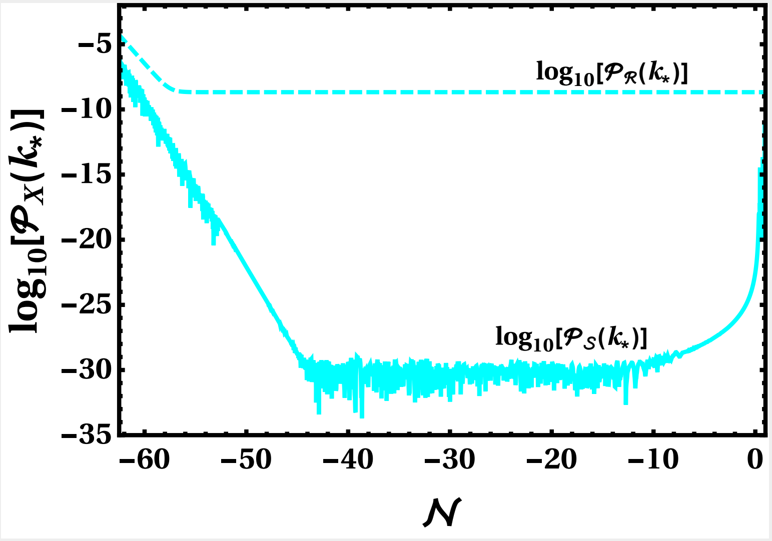
BPb



BPc



BPd



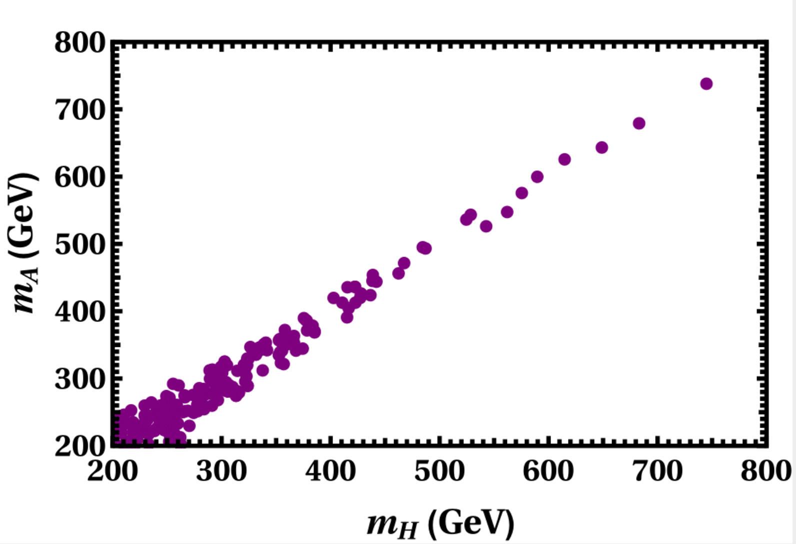
Implications at collider experiments

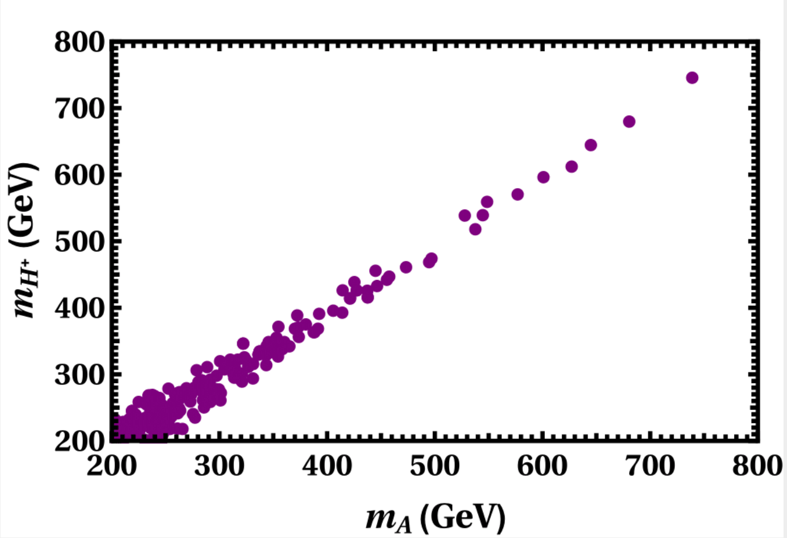
$$m_{H^\pm}^2 = \frac{1}{2}\eta_3 v^2 + \mu_{22}^2,$$

$$m_A^2 = \frac{1}{2}(\eta_3 + \eta_4 - \eta_5)v^2 + \mu_{22}^2,$$

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + (\eta_1 + \eta_5)v^2 \mp \sqrt{\left(m_A^2 + (\eta_5 - \eta_1)v^2\right)^2 + 4\eta_6^2 v^4}\right].$$

- Quasi-degenerate mass spectra favored by 2HDM inflation.





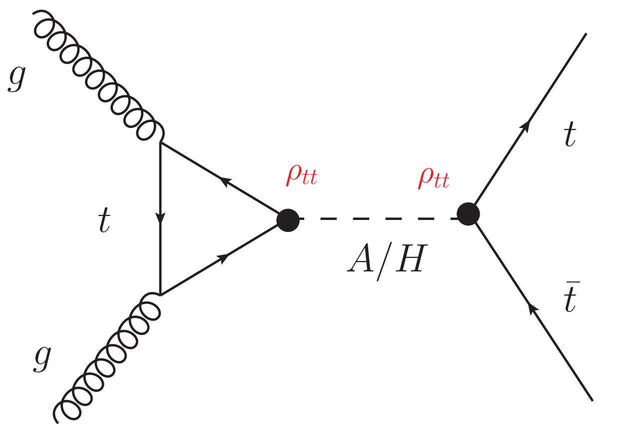
Discovery and mass reconstruction

ρ_{tt} driven discovery:

$$gg \to A/H \to t\bar{t}$$

$$gg \to Z^* \to A/H$$

$$gg \to A \to Zh$$

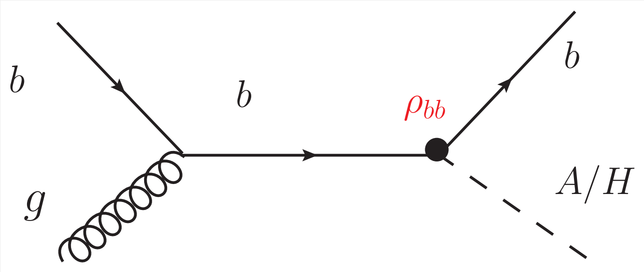


ρ_{bb} driven discovery:

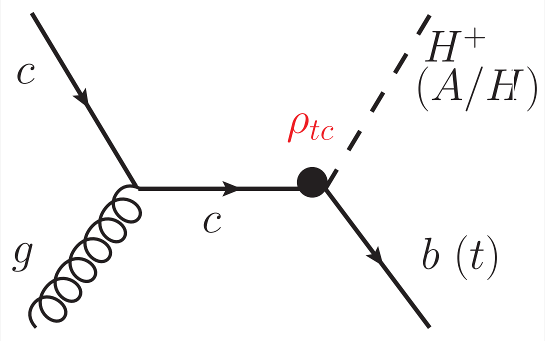
$$bg \to bA \to bZH$$

$$bg \to bA \to bZh$$

$$e^+e^- \to AH \to 4b/6b$$



Indirect signature of quasi-degeneracy



$pp \to tA/tH \to tt\bar{c}$ (Same-sign top)

$pp \to tA/tH \to tt\bar{t}$ (Triple-top)

$pp \to bH^+ \to bt\bar{b}$ (single-top)

For non-degenerate masses:

In terms of discovery: Same-sign top >> triple-top, single-top.

For quasi-degenerate masses:

Same-sign top ~ triple-top, single-top

EWBG + Inflation? Perhaps not

- $10^{-2} \lesssim |\rho_{tt}| \lesssim 1$ or $|\rho_{tc}| \gtrsim 0.5$ (K. Fuyuto,W.-S Hou, E. Senaha; PLB '18)
- $|\mathrm{Im}(\rho_{bb})| \gtrsim 0.1$ (TM, E. Senaha; PRD '19, PLB'21)

EWBG

Supports strongly 1st order EWPT

BP	η_1	η_2	η_3	η_4	η_5	η_6	η_7	$m_{H^\pm}$ (GeV)	m_A (GeV)	m_H (GeV)	$\frac{\mu_{22}^2}{v^2}$
a	0.282	2.034	4.053	−1.039	1.343	−0.243	1.231	391	285	405	0.5
b	0.289	1.959	4.064	−0.418	1.56	−0.316	−1.216	414	334	456	0.8
c	0.303	0.413	5.129	−0.477	1.534	−0.455	0.457	508	444	541	1.7

Summary and outlook

- 2HDM-R^2 inflation: Four field dynamics.
- Quasi-degenerate mass spectra.
- Discovery and mass reconstruction: LHC and future collider experiments.
- Inflation+ EWBG ???

Thank You