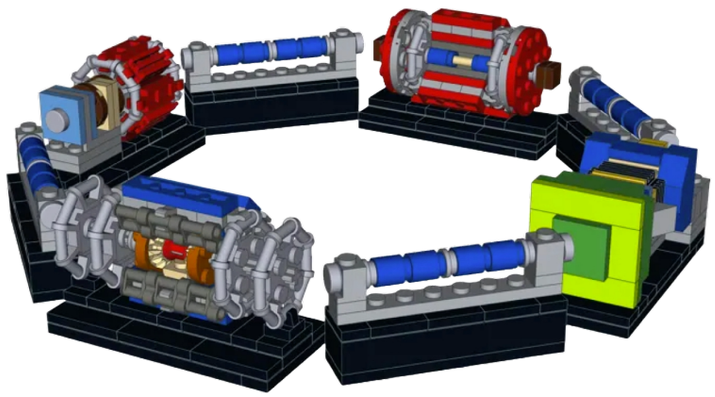
HIGGS POTENTIAL 2024

HIGGS POTENTIAL AND BSM OPPORTUNITIES

JOHNS HOPKINS UNIVERSITY

Electroweak Phase Transition from Modified Higgs Sectors



Yikun Wang

Johns Hopkins University

Higgs Potential 2024

Dec 22nd, 2024, Hefei

Collaborators: Sebastian Baum, Marcela Carena, Jonathan Kozaczuk, Zhen Liu, Tong Ou, Michael J. Ramsey-Musolf, Nausheen Shah, Jessie Shelton, Carlos Wagner, and Ke-Pan Xie

Open questions

- **Origin of the Electroweak Symmetry Breaking (EWSB)**
- **Hierarchy problem**
- **Flavor puzzle**
- **Dark Matter**
- **Origin of the Baryon Asymmetry of the Universe (BAU)**
- **Neutrino mass**
- **Dark Energy**
- **Inflation**
- **Quantum Gravity**

Open questions

- **Origin of the Electroweak Symmetry Breaking (EWSB)**
- **Hierarchy problem**
- **Flavor puzzle**
- **Dark Matter**
- **Origin of the Baryon Asymmetry of the Universe (BAU)**
- **Neutrino mass**
- **Dark Energy**
- **Inflation**
- **Quantum Gravity**

How can scrutinizing the **Higgs** help to answer these questions?

Let’s ask the Higgs about itself first

- **Is it elementary or composite?**
- **Is it supersymmetric?**

Let’s ask the Higgs about itself first

- **Is it elementary or composite?**
- **Is it supersymmetric?**

  ➡ **Radiative generation of the EWSB**

  ➡ **Solution to the Higgs hierarchy problem**

Let’s ask the Higgs about itself first

- **Is it a portal to the dark sector?**
- **Is the Higgs sector minimal?**
- **Does it have CP or flavor structures?**

Let's ask the Higgs about itself first

- **Is it a portal to the dark sector?**
- **Is the Higgs sector minimal?**
- **Does it have CP or flavor structures?**

Modified Higgs sectors ⇨ Multi-Higgs Doublet models

⇨ Additional singlet(s)

⇨ Additional triplet(s)

…

Let's ask the Higgs about itself first

- **Is it a portal to the dark sector?**
- **Is the Higgs sector minimal?**
- **Does it have CP or flavor structures?**

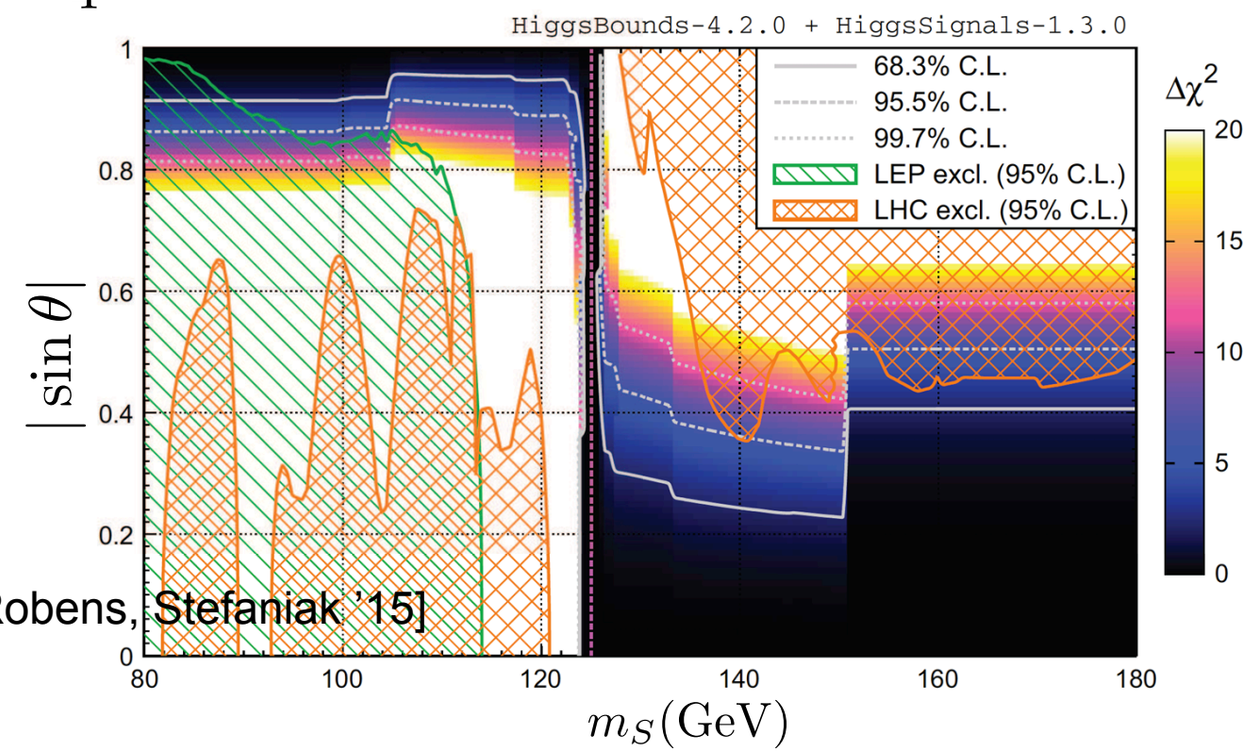
Modified Higgs sectors ⇨ Multi-Higgs Doublet models
⇨ Additional singlet(s)
⇨ Additional triplet(s)
⇨ …

Example: adding a singlet

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

$$M^2 = \begin{pmatrix} 3h^2\lambda_h - \mu_h^2 + \frac{1}{2}\lambda_m s^2 & \lambda_m h s \\ \lambda_m h s & \frac{1}{2}\lambda_m h^2 + \mu_s^2 + 3\lambda_s s^2 \end{pmatrix}$$

$$\sin\theta = \frac{\lambda_m v \langle s \rangle}{\sqrt{(m_S^2 - m_h^2)(m_S^2 - \lambda_h^2 v^2)}}$$



[Robens, Stefaniak '15]

Let's ask the Higgs about itself first

- **Is it a portal to the dark sector?**
- **Is the Higgs sector minimal?**
- **Does it have CP or flavor structures?**

Modified Higgs sectors ⇨ Multi-Higgs Doublet models
⇨ Additional singlet(s)
⇨ Additional triplet(s)
⇨ …

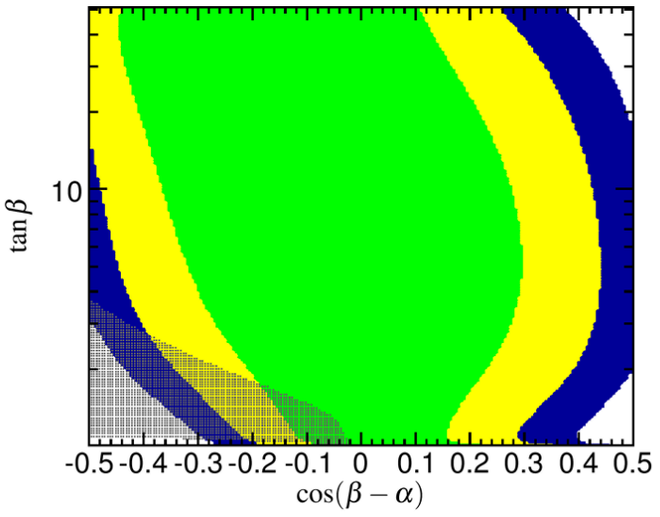
Example: Two Higgs Doublet Models (2HDM)

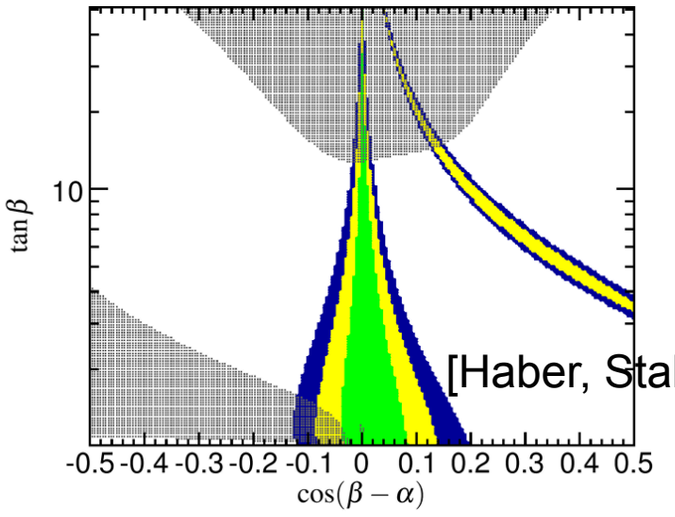
$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_3^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right]$$

$$\Phi_i \to \begin{pmatrix} H_i^+ \\ \frac{1}{\sqrt{2}}\left(v_i + H_i^0 + iA_i^0\right) \end{pmatrix}, \quad i = 1,2,$$

with $v = \sqrt{v_1^2 + v_2^2} = 246$ GeV

Five physical states: $H_1^0, H_2^0, A_0, H^\pm$





[Haber, Stal '15]

Let's ask the Higgs about itself first

- **Is it a portal to the dark sector?**
- **Is the Higgs sector minimal?**
- **Does it have CP or flavor structures?**

Modified Higgs sectors ⇨ Multi-Higgs Doublet models

⇨ Additional singlet(s)

⇨ Additional triplet(s)

…

Let's ask the Higgs about itself first

- **Is it a portal to the dark sector?**
- **Is the Higgs sector minimal?**
- **Does it have CP or flavor structures?**

Modified Higgs sectors ⇨ Multi-Higgs Doublet models

⇨ Additional singlet(s)

⇨ Additional triplet(s)

⇨ …

➡ **Stabilize the Higgs vacuum**

➡ **Facilitate the generation of BAU**

➡ **Provide Dark Matter candidates**

➡ **Additional CP source for BAU; Axion like particles**

➡ **Flavor textures**

Let's ask the Higgs about itself first

- **Is it a portal to the dark sector?**
- **Is the Higgs sector minimal?**
- **Does it have CP or flavor structures?**

Modified Higgs sectors ⇨ Multi-Higgs Doublet models
⇨ Additional singlet(s)
⇨ Additional triplet(s)
⇨ …

➡ **Stabilize the Higgs vacuum**

➡ **Facilitate the generation of BAU**

➡ **Provide Dark Matter candidates**

➡ **Additional CP source for BAU; Axion like particles**

➡ **Flavor textures**

Let's ask the Higgs about itself first

- **Is it a portal to the dark sector?**
- **Is the Higgs sector minimal?**
- **Does it have CP or flavor structures?**

Modified Higgs sectors ⇨ Multi-Higgs Doublet models

⇨ Additional singlet(s)

⇨ Additional triplet(s)

…

➡ **Stabilize the Higgs vacuum**

➡ **Facilitate the generation of BAU** **and how to probe experimentally?**

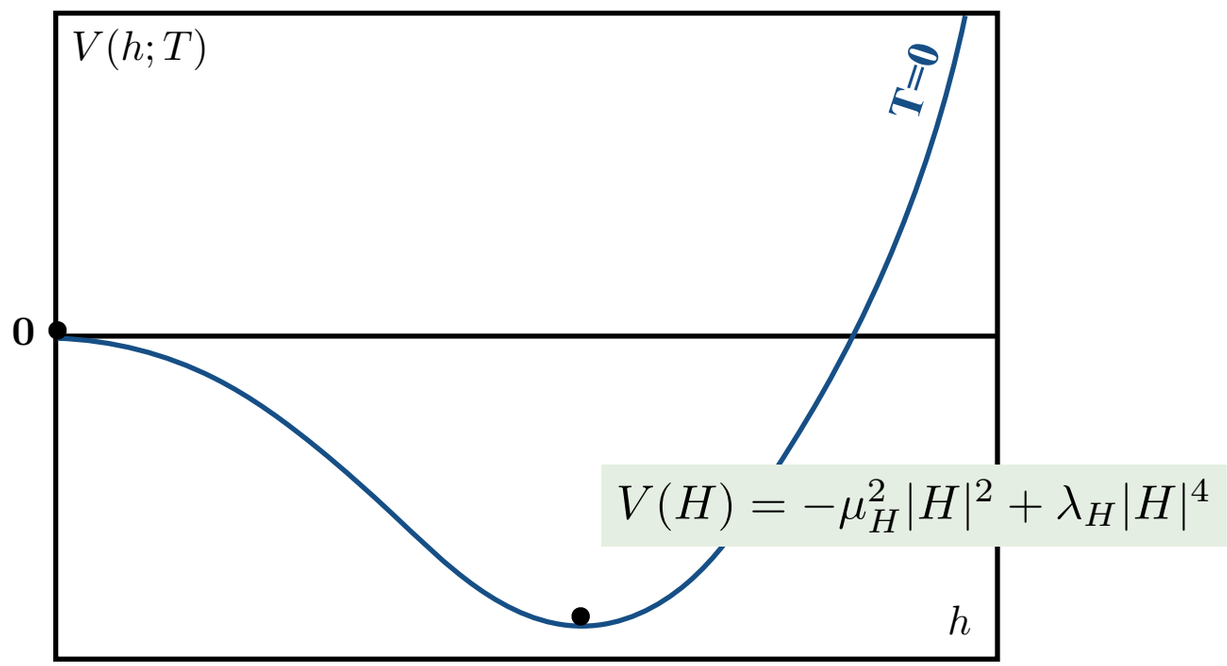
➡ **Provide Dark Matter candidates**

➡ **Additional CP source for BAU; Axion like particles**

➡ **Flavor textures**

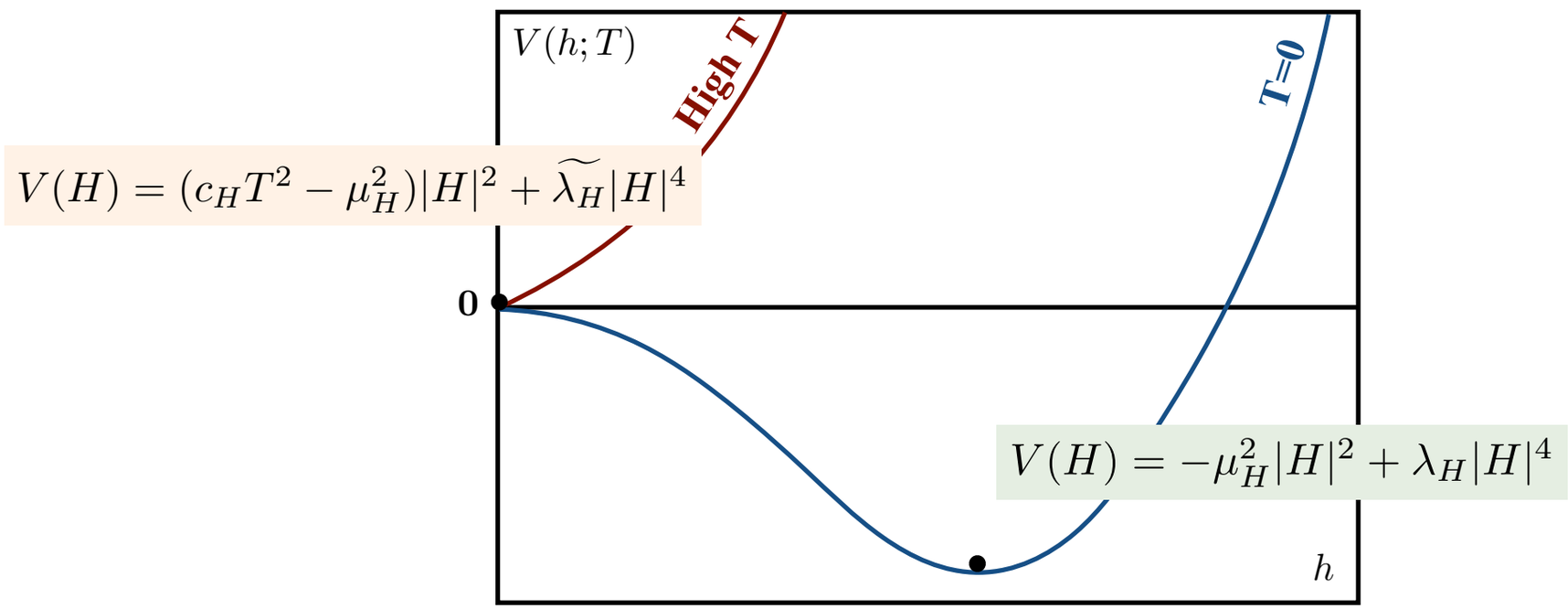
Baryon Asymmetry of the Universe and the Higgs

Baryon Asymmetry of the Universe and the Higgs



$$V(H) = -\mu_H^2 |H|^2 + \lambda_H |H|^4$$

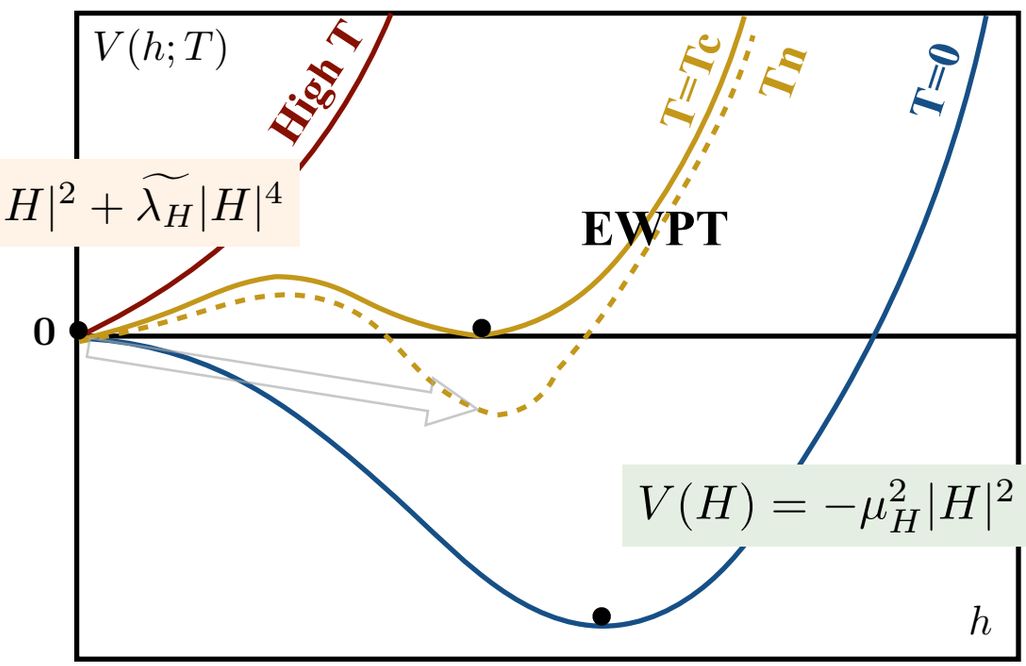
Baryon Asymmetry of the Universe and the Higgs



Baryon Asymmetry of the Universe and the Higgs

- **Nature of the Electroweak Phase Transition**

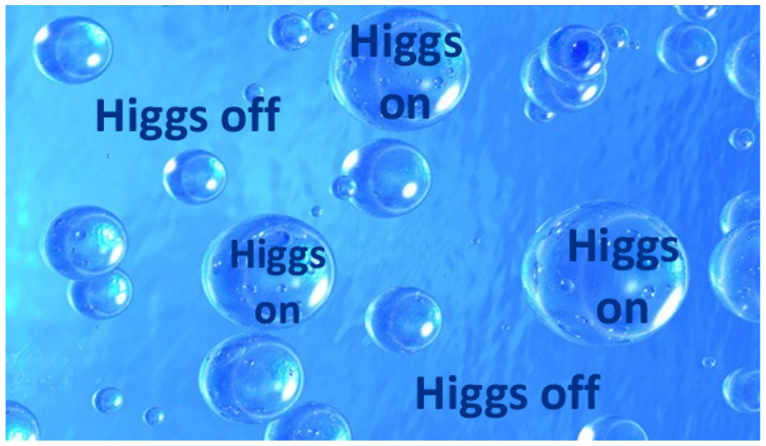
$$V(H) = (c_H T^2 - \mu_H^2)|H|^2 + \widetilde{\lambda_H}|H|^4$$



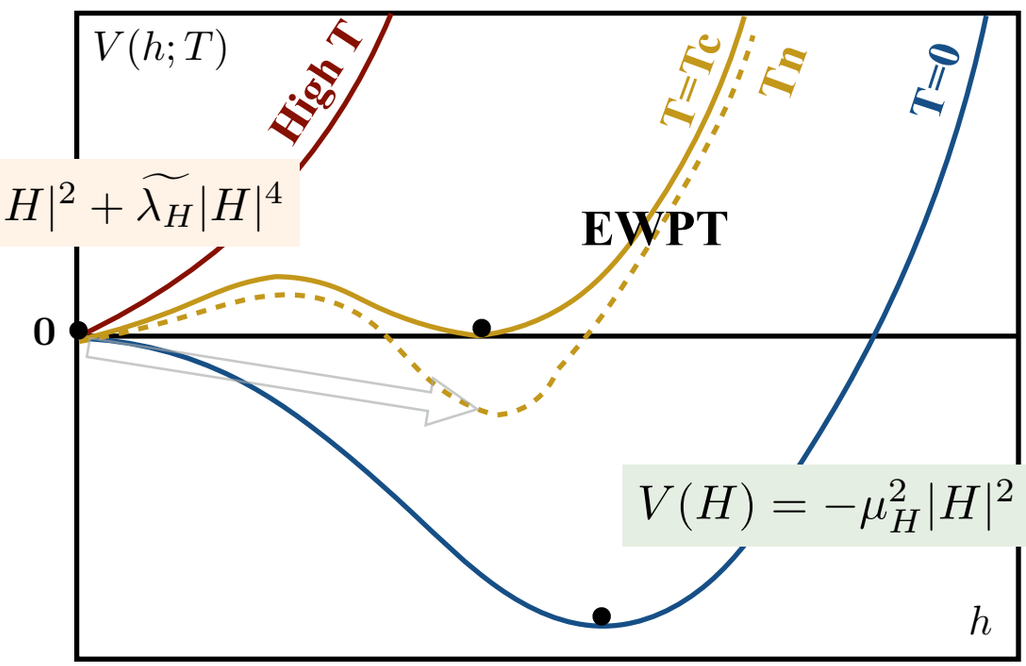
$$V(H) = -\mu_H^2|H|^2 + \lambda_H|H|^4$$

Baryon Asymmetry of the Universe and the Higgs

- **Nature of the Electroweak Phase Transition**



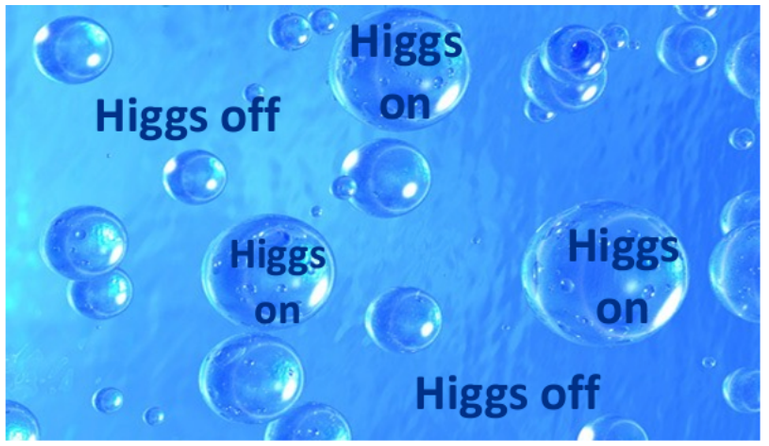
$V(H) = (c_H T^2 - \mu_H^2)|H|^2 + \widetilde{\lambda_H}|H|^4$

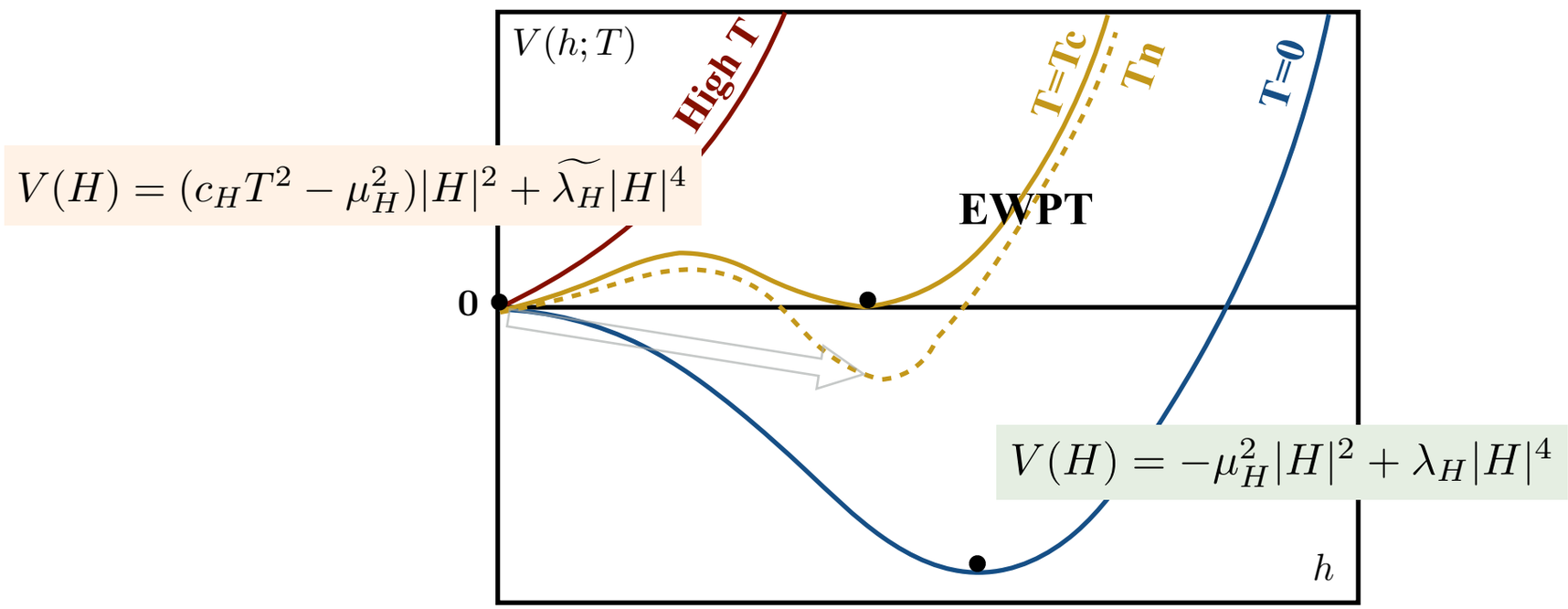


$V(H) = -\mu_H^2|H|^2 + \lambda_H|H|^4$

Baryon Asymmetry of the Universe and the Higgs

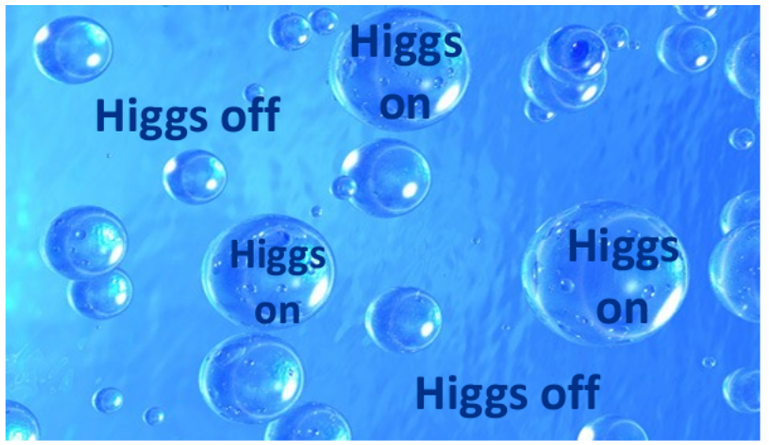
- **Nature of the Electroweak Phase Transition**
- **Origin of the Baryon Asymmetry of the Universe (BAU)**



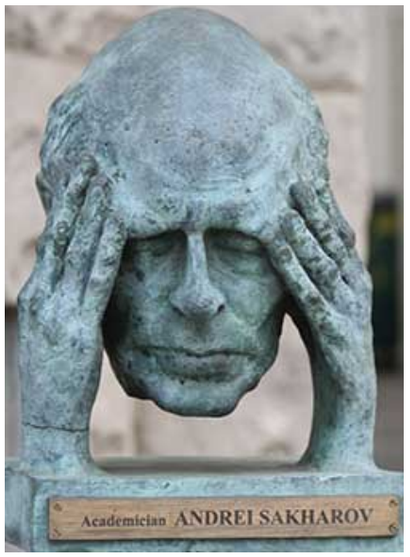


Baryon Asymmetry of the Universe and the Higgs

- **Nature of the Electroweak Phase Transition**
- **Origin of the Baryon Asymmetry of the Universe (BAU)**

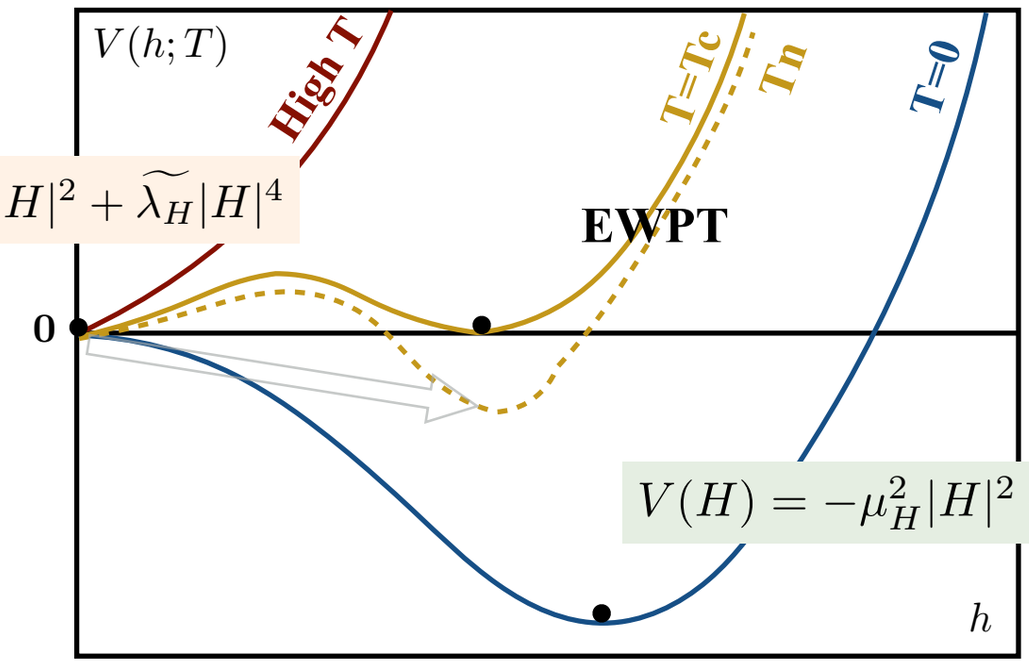


Sakharov's conditions for BAU creation



- **Baryon number violation**
- **C and CP violation**
- **Out-of-equilibrium**

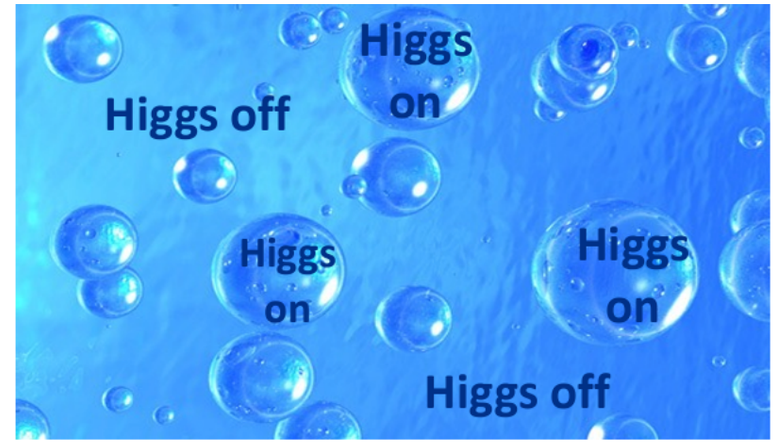
$$V(H) = (c_H T^2 - \mu_H^2)|H|^2 + \widetilde{\lambda_H}|H|^4$$



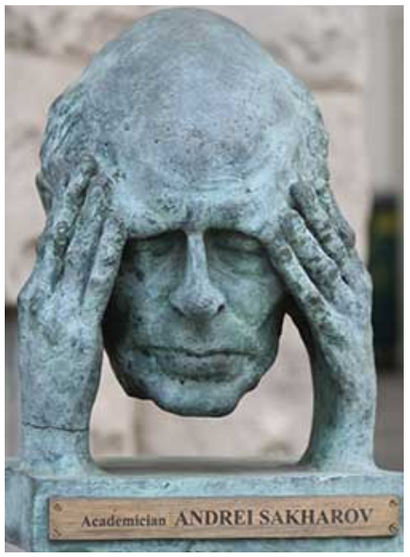
$$V(H) = -\mu_H^2|H|^2 + \lambda_H|H|^4$$

Baryon Asymmetry of the Universe and the Higgs

- **Nature of the Electroweak Phase Transition**
- **Origin of the Baryon Asymmetry of the Universe (BAU)**

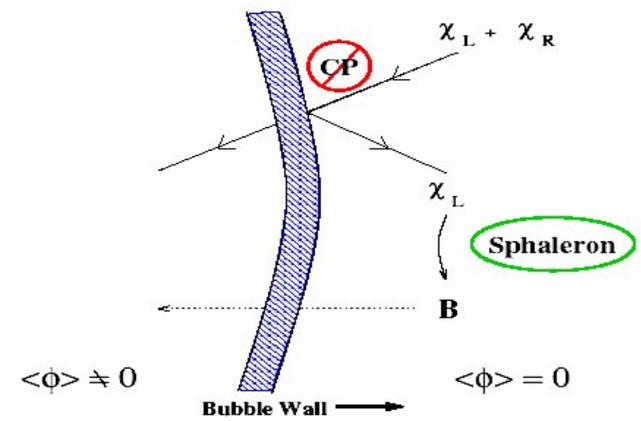


Sakharov's conditions for BAU creation

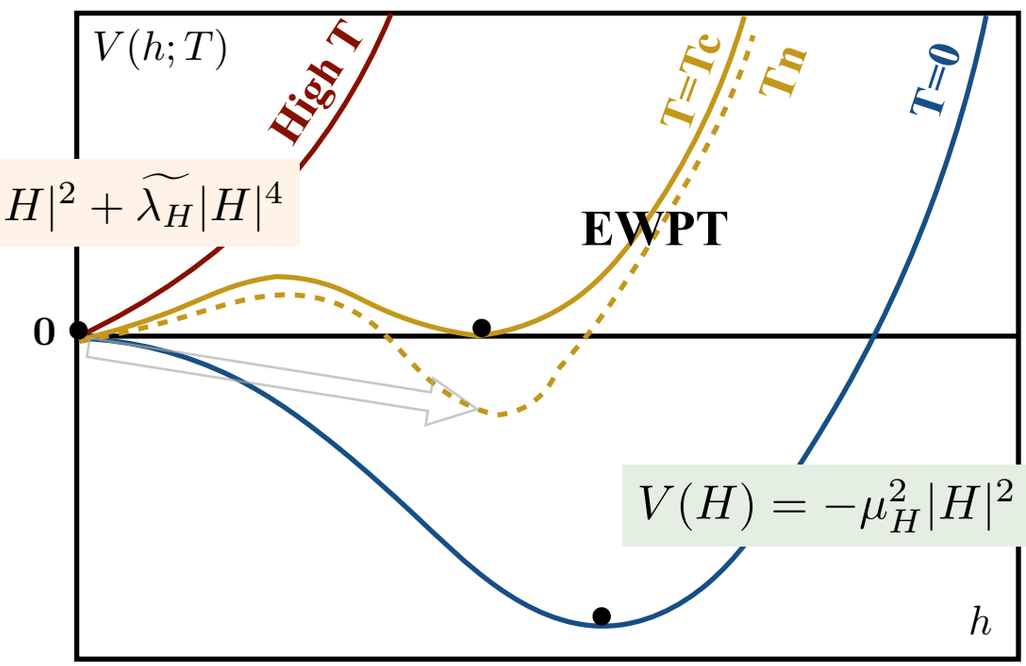


- **Baryon number violation**
- **C and CP violation**
- **Out-of-equilibrium**

Electroweak Baryogenesis



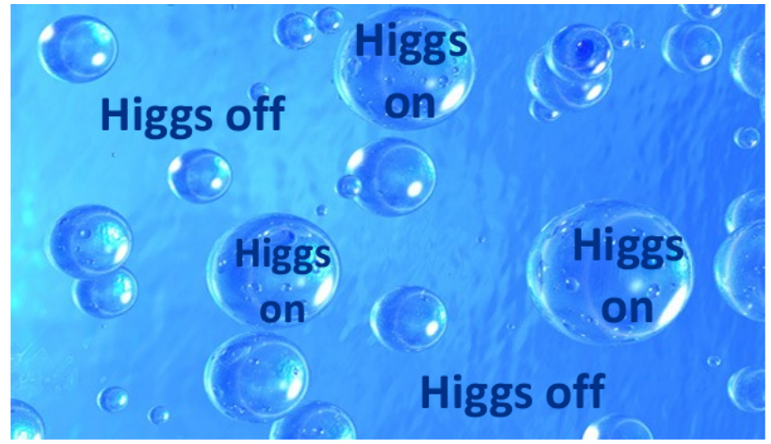
$$V(H) = (c_H T^2 - \mu_H^2)|H|^2 + \widetilde{\lambda_H}|H|^4$$



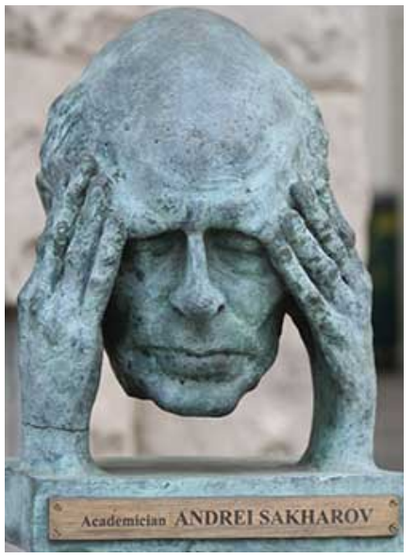
$$V(H) = -\mu_H^2|H|^2 + \lambda_H|H|^4$$

Baryon Asymmetry of the Universe and the Higgs

- Nature of the Electroweak Phase Transition
- Origin of the Baryon Asymmetry of the Universe (BAU)

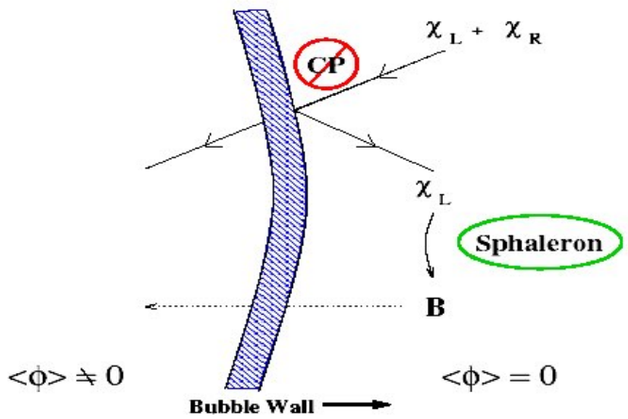


Sakharov's conditions for BAU creation

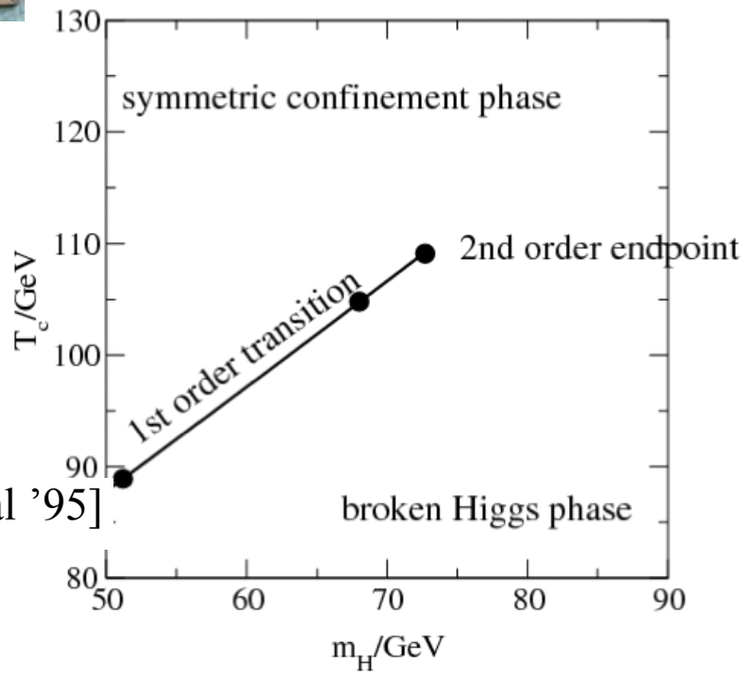


- Baryon number violation
- C and CP violation
- Out-of-equilibrium

Electroweak Baryogenesis

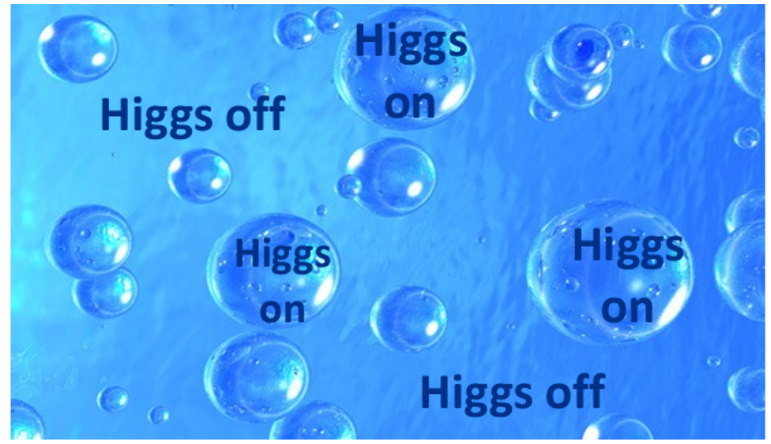


[Kajantie et al '95]

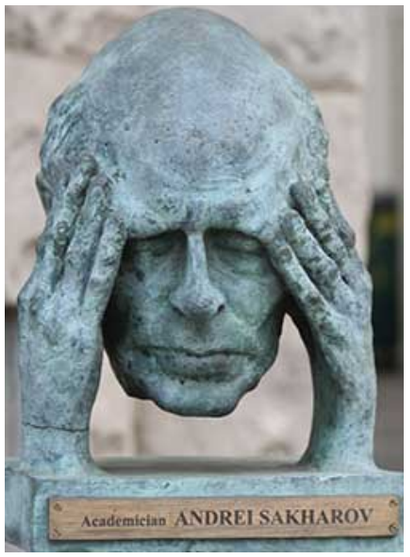


Baryon Asymmetry of the Universe and the Higgs

- Nature of the Electroweak Phase Transition
- Origin of the Baryon Asymmetry of the Universe (BAU)

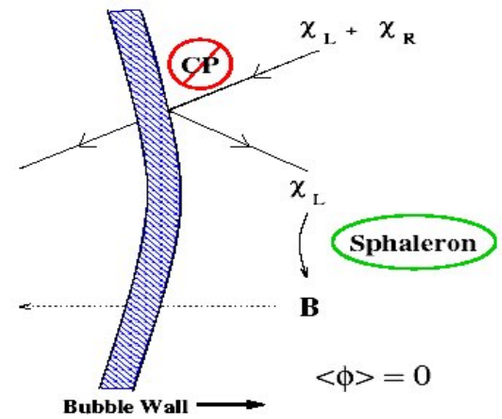


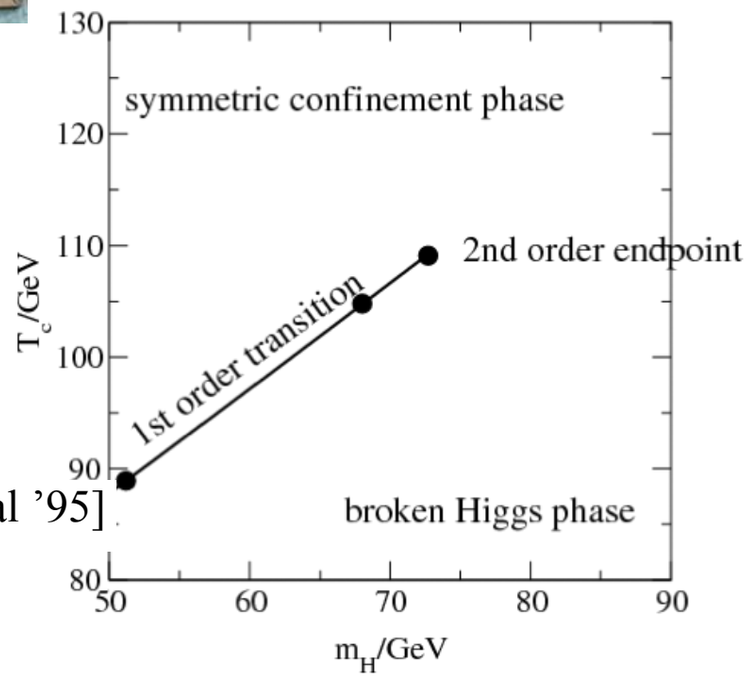
Sakharov's conditions for BAU creation



- Baryon number violation
- C and CP violation
- Out-of-equilibrium

Electroweak Baryogenesis





[Kajantie et al '95]

BSM is needed

⇨ Extended Higgs sectors

Electroweak phase transition and Higgs properties

$$V_{\mathrm{EFF}}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$

Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$

$$\widetilde{\lambda_H} \sim \lambda_H \left(1 + \alpha \log \frac{h^2}{M^2}\right)$$

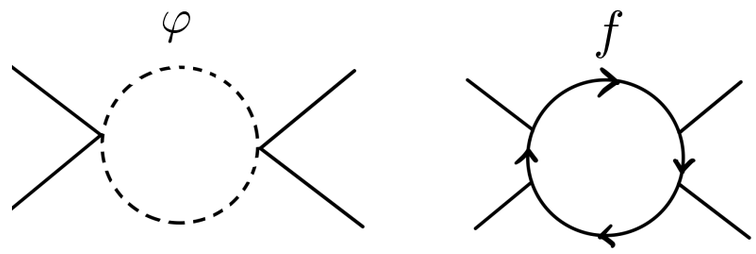
Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

$$\text{Order of the Phase Transition } \propto \frac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$$

- **Zero Temperature loop effects**

$$\widetilde{\lambda_H} \sim \lambda_H \left(1 + \alpha \log \frac{h^2}{M^2}\right)$$

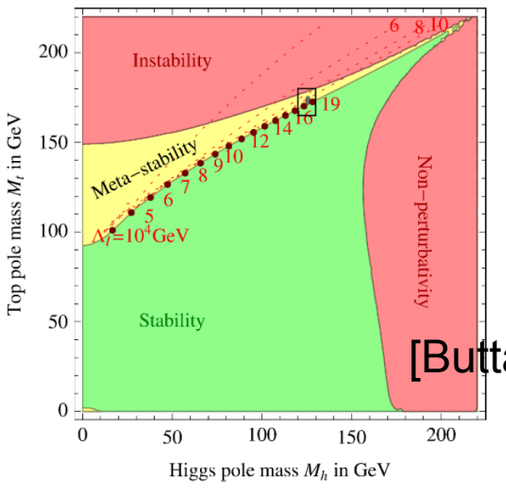


E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], …

Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

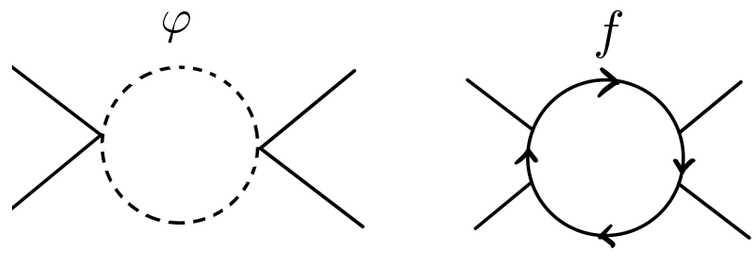
Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$



[Buttazzo et al '13],

- **Zero Temperature loop effects**

$$\widetilde{\lambda_H} \sim \lambda_H \left(1 + \alpha \log \frac{h^2}{M^2}\right)$$

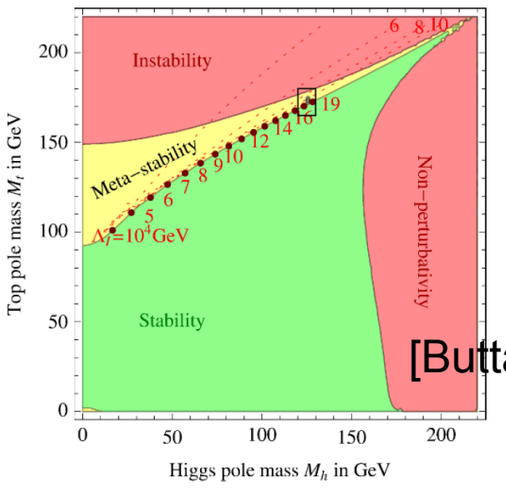


E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], …

Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

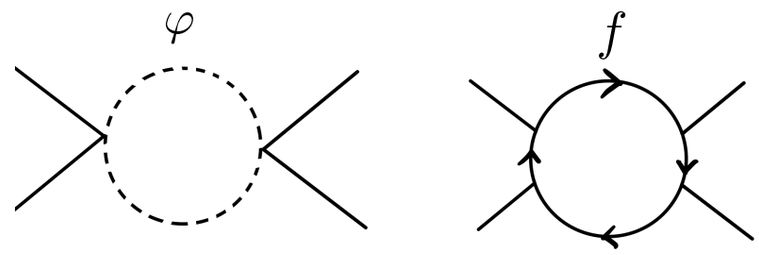
Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$



[Buttazzo et al '13],

- **Zero Temperature loop effects**

$$\widetilde{\lambda_H} \sim \lambda_H \left(1 + \alpha \log \frac{h^2}{M^2}\right)$$



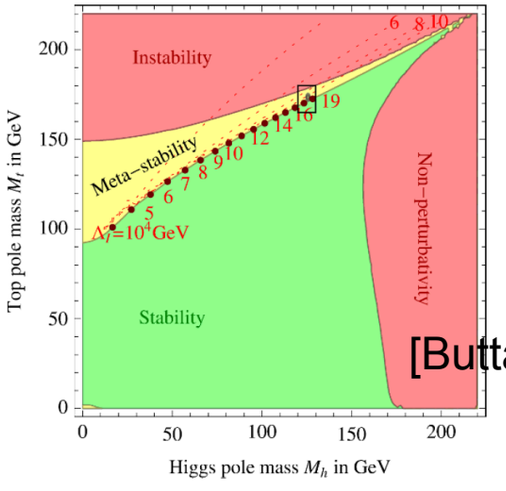
E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], …

$$Eh^3 \sim \left(m_{\rm eff}(h, T_c)\right)^{3/2} \sim \lambda^{3/2} h^3$$

Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

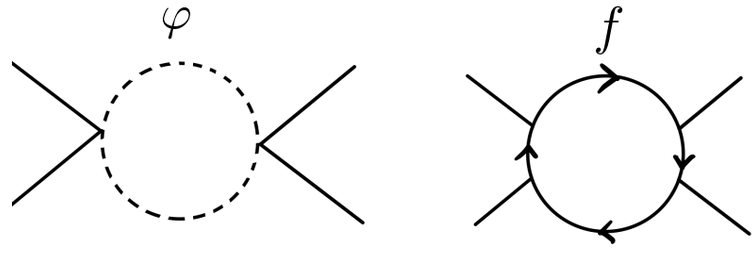
Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$



[Buttazzo et al '13],

Zero Temperature loop effects

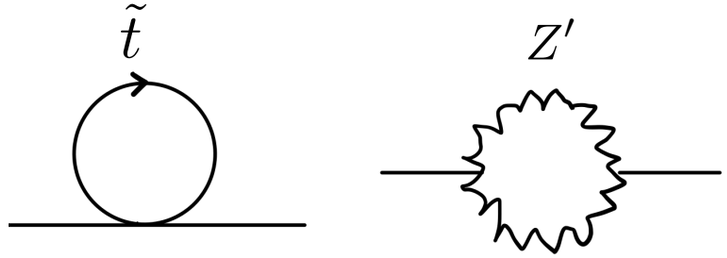
$$\widetilde{\lambda_H} \sim \lambda_H\left(1 + \alpha \log\frac{h^2}{M^2}\right)$$



E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], …

Thermal effects

$$Eh^3 \sim \left(m_{\rm eff}(h,T_c)\right)^{3/2} \sim \lambda^{3/2}h^3$$



E.g. [Anderson, Hall '92], [Cohen, Morrissey, Pierce '12], [Chowdhury et al '12]
[Carena, Quiros, Wagner, '96], [Delepine, et al '96]

Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$

- **Tree-level Effects**

Example: **heavy scalars** $e \propto \langle s \rangle \neq 0$

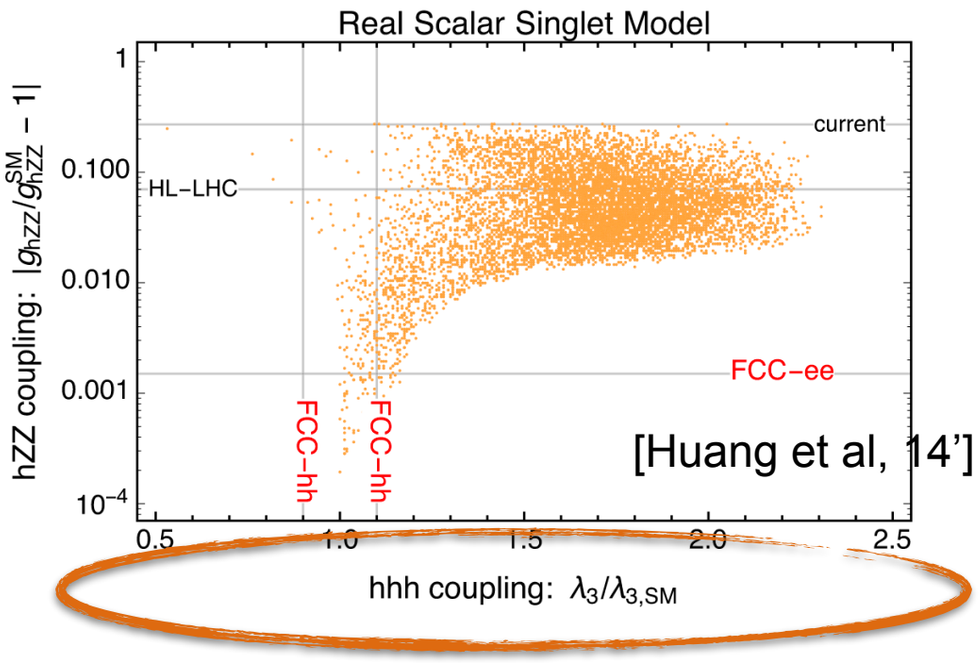
Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

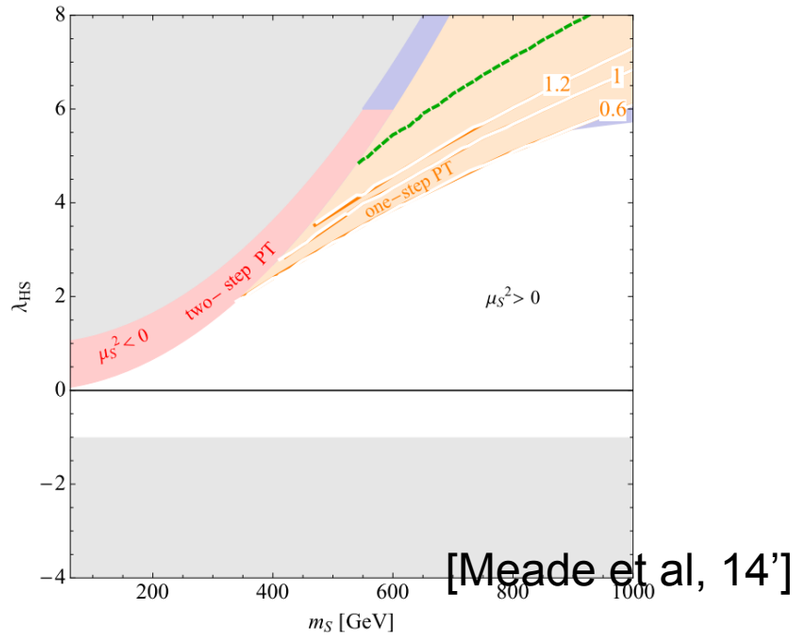
Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$

- **Tree-level Effects**

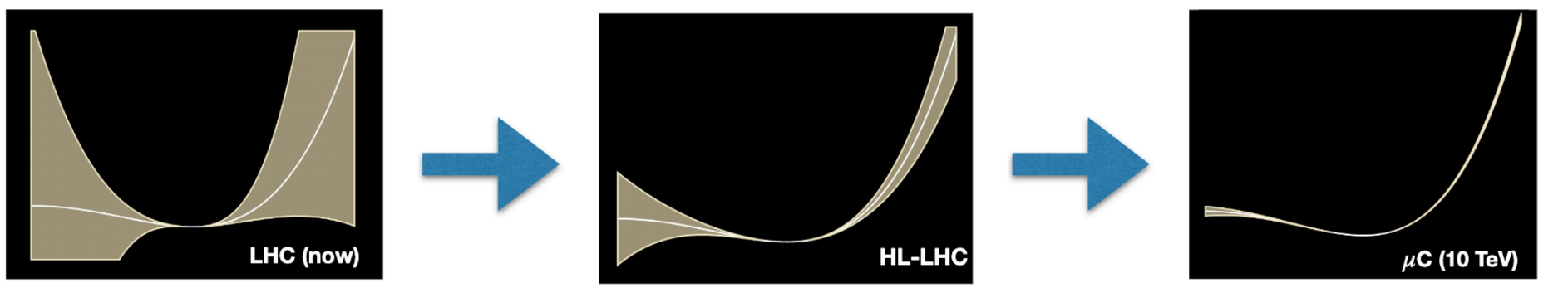
Example: **heavy scalars** $e \propto \langle s \rangle \neq 0$



[Huang et al, 14']



[Meade et al, 14']



Courtesy of N. Craig

Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

$$\text{Order of the Phase Transition } \propto \frac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$$

- **Tree-level Effects**

A more complicated example: **NMSSM** [Baum, Carena, Shah, Wagner, Y.W. '20]

$$V_0 = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + \lambda^2 |S|^2 \left(|H_d|^2 + |H_u|^2\right) + \left|\lambda H_u \cdot H_d + \kappa S^2\right|^2$$
$$+ \left(\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}\right) + \frac{g_1^2 + g_2^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{g_2^2}{2}\left|H_d^\dagger H_u\right|^2$$

Scalar contents: CP even interaction states $\{H^{\rm SM}, H^{\rm NSM}, H^S\}$ $\rightarrow$ CP even mass states $\{h_{125}, H, h_S\}$

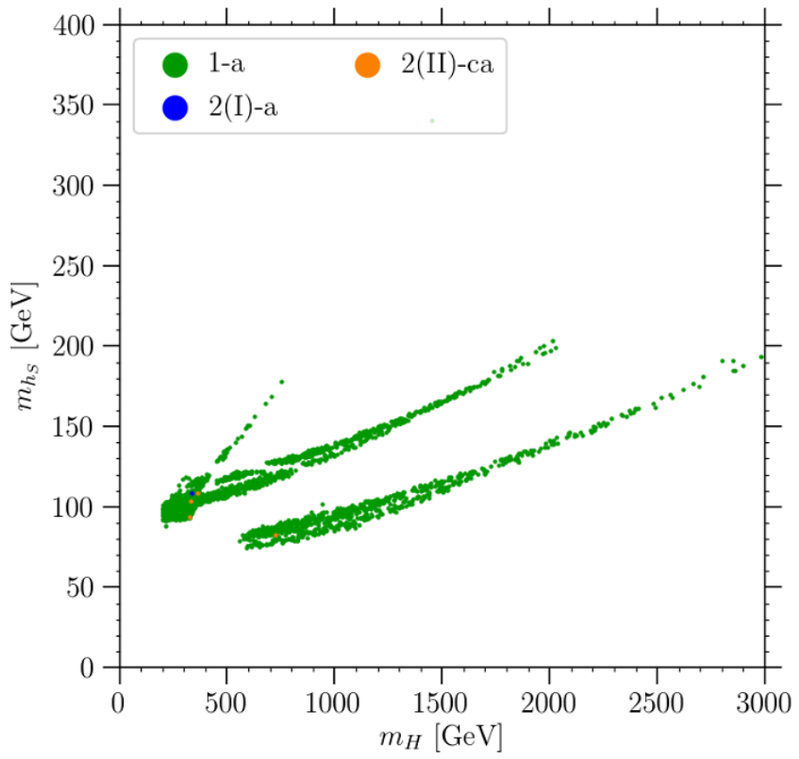
Three CP odd states; Two charged states.

Alignment (without decoupling) limits

$$|\mathcal{M}^2_{S,12}| \ll |\mathcal{M}^2_{S,22} - \mathcal{M}^2_{S,11}|\,,$$

$$|\mathcal{M}^2_{S,13}| \ll |\mathcal{M}^2_{S,33} - \mathcal{M}^2_{S,11}|$$

The mass eigenstate h_{125} dominantly composed of $H^{\rm SM}$.



An open question: **can the CP odd scalar play a role?**

Electroweak phase transition and Higgs properties

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

$$\text{Order of the Phase Transition } \propto \frac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$$

- **Tree-level Effects**

A more complicated example: **NMSSM** [Baum, Carena, Shah, Wagner, Y.W. '20]

$$V_0 = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + \lambda^2 |S|^2 \left(|H_d|^2 + |H_u|^2\right) + \left|\lambda H_u \cdot H_d + \kappa S^2\right|^2$$
$$+ \left(\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}\right) + \frac{g_1^2 + g_2^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{g_2^2}{2}\left|H_d^\dagger H_u\right|^2$$

Scalar contents: CP even interaction states $\{H^{\rm SM}, H^{\rm NSM}, H^S\}$ $\rightarrow$ CP even mass states $\{h_{125}, H, h_S\}$

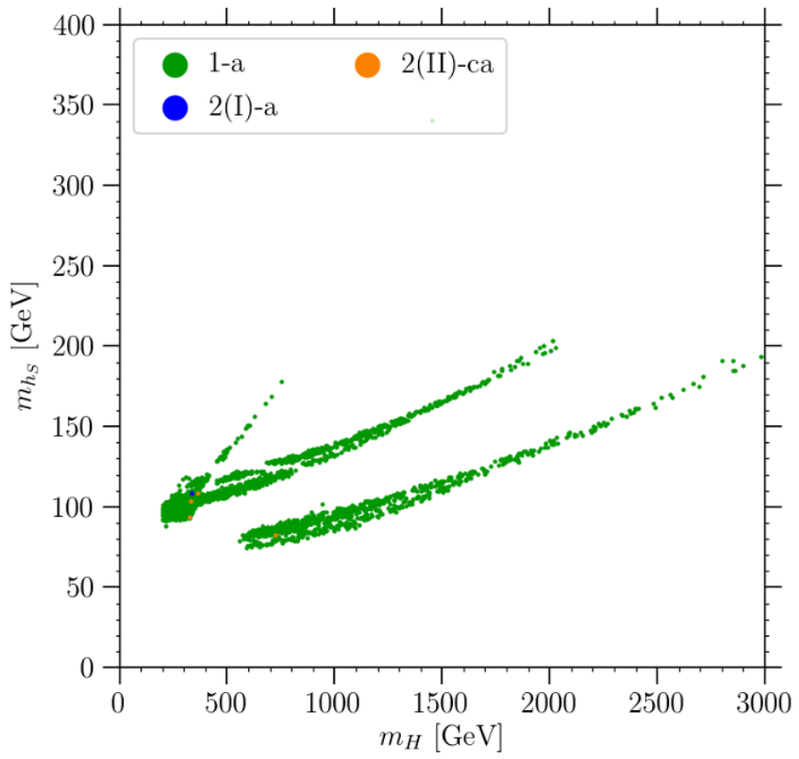
Three CP odd states; Two charged states.

Alignment (without decoupling) limits

$$|\mathcal{M}^2_{S,12}| \ll |\mathcal{M}^2_{S,22} - \mathcal{M}^2_{S,11}|\,,$$

$$|\mathcal{M}^2_{S,13}| \ll |\mathcal{M}^2_{S,33} - \mathcal{M}^2_{S,11}|$$

The mass eigenstate h_{125} dominantly composed of $H^{\rm SM}$.



An open question: **can the CP odd scalar play a role?**

Electroweak phase transition and Higgs properties

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

$$\rightarrow V_{\text{EFF}}(h,s,T)$$

Electroweak phase transition and Higgs properties

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

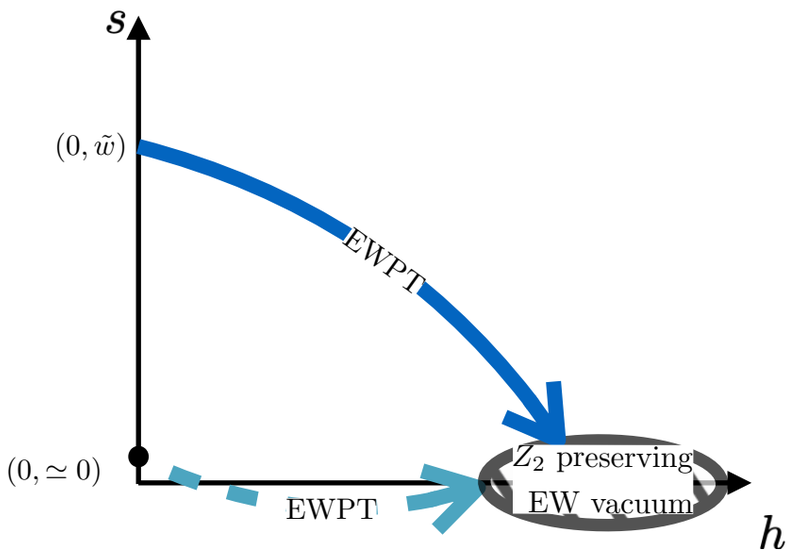
$$\rightarrow V_{\text{EFF}}(h,s,T)$$

Electroweak phase transition and Higgs properties

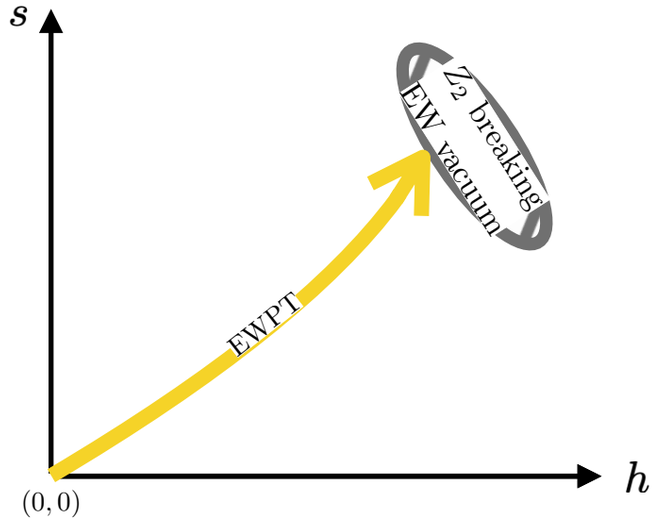
$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

$$\rightarrow V_{\text{EFF}}(h,s,T)$$

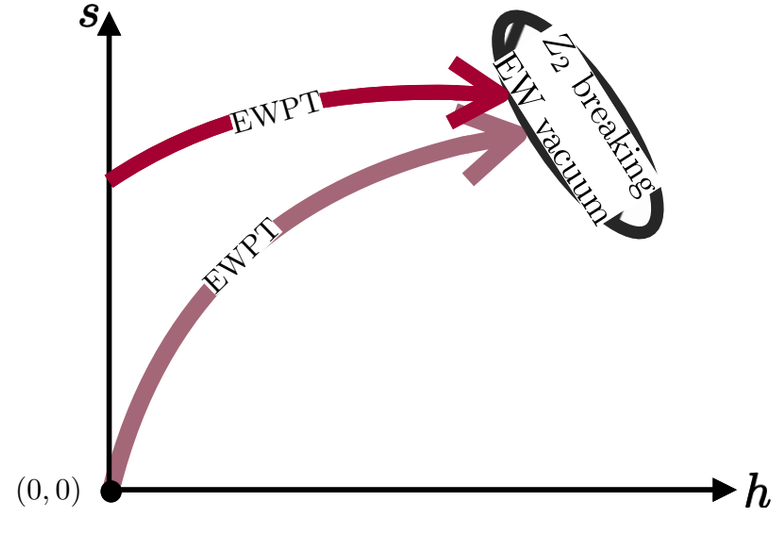
Tree-level Effects



Z_2 preserving



Z_2 breaking (explicit)



Z_2 breaking (spontaneous)

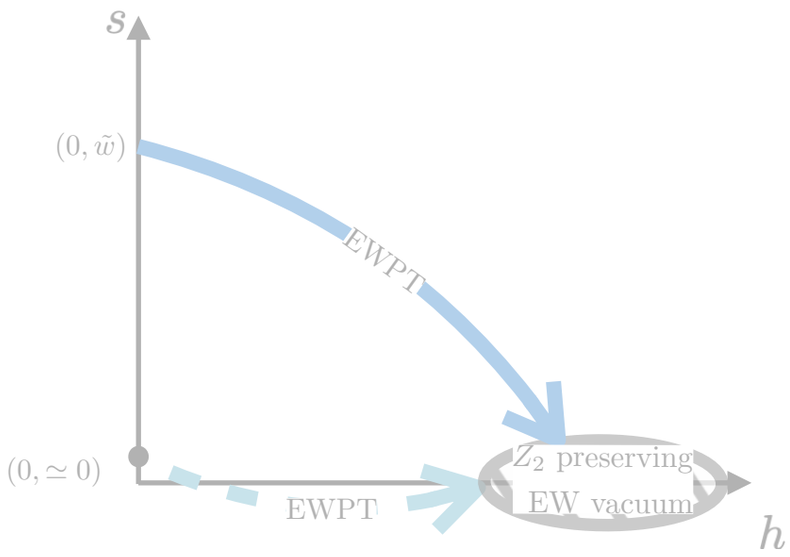
Electroweak phase transition and Higgs properties

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

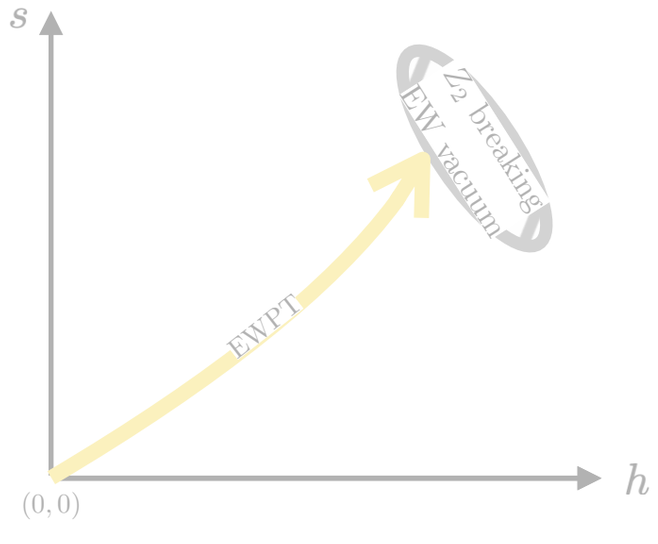
$$\rightarrow V_{\rm EFF}(h,s,T)$$

[Carena, Liu, Y.W. '19]

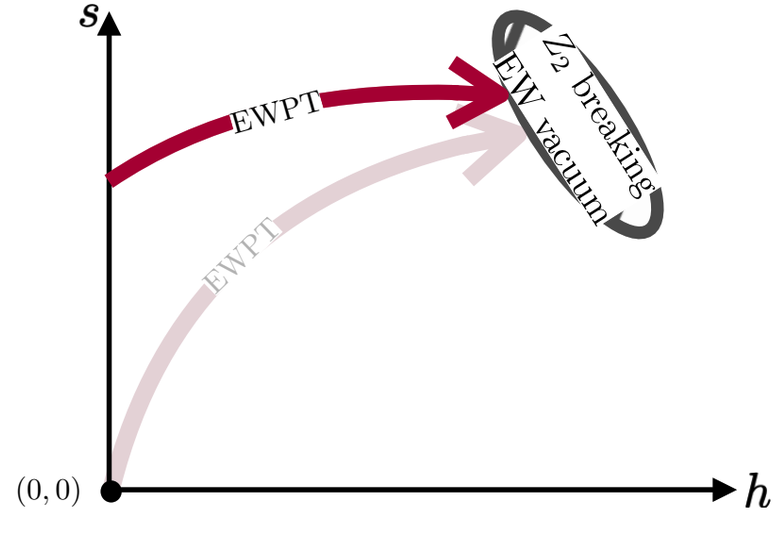
Tree-level Effects



Z_2 preserving



Z_2 breaking (explicit)



Z_2 breaking (spontaneous)

Example: Order of the Phase Transition $\propto \left(\lambda_h - \frac{\lambda_m^2}{4\lambda_s}\right)^{-1}$

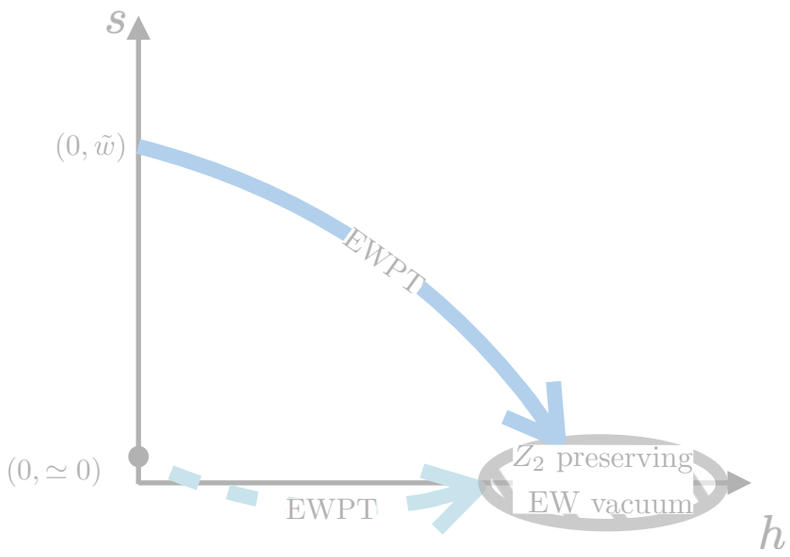
Electroweak phase transition and Higgs properties

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

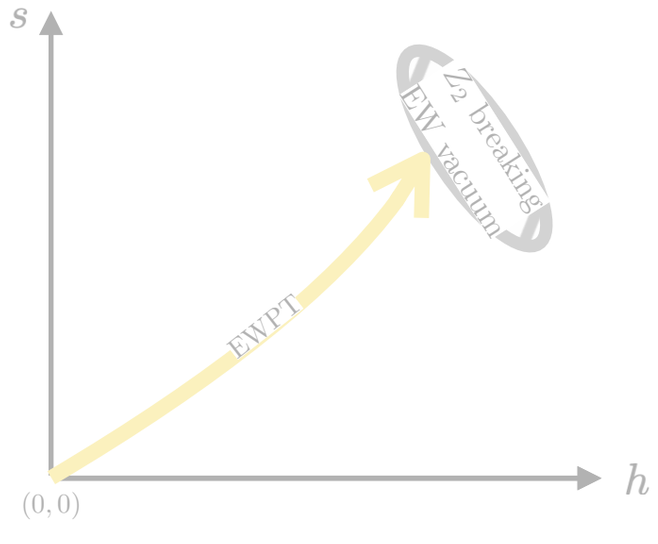
$$\rightarrow V_{\rm EFF}(h,s,T)$$

[Carena, Liu, Y.W. '19]

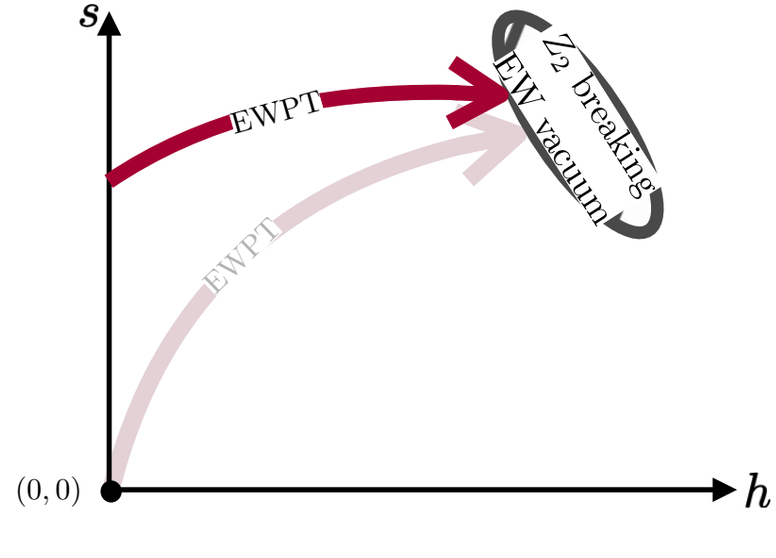
Tree-level Effects



Z_2 preserving



Z_2 breaking (explicit)



Z_2 breaking (spontaneous)

Example: Order of the Phase Transition $\propto \left(\lambda_h - \frac{\lambda_m^2}{4\lambda_s}\right)^{-1}$

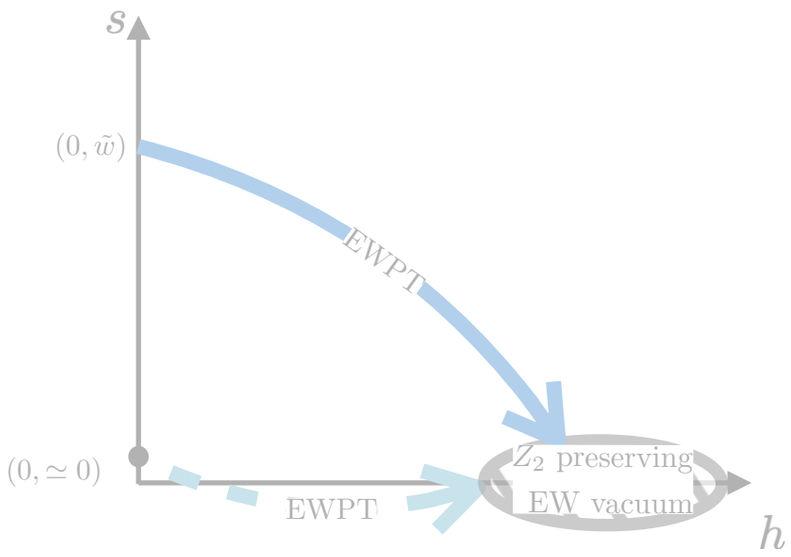
Electroweak phase transition and Higgs properties

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

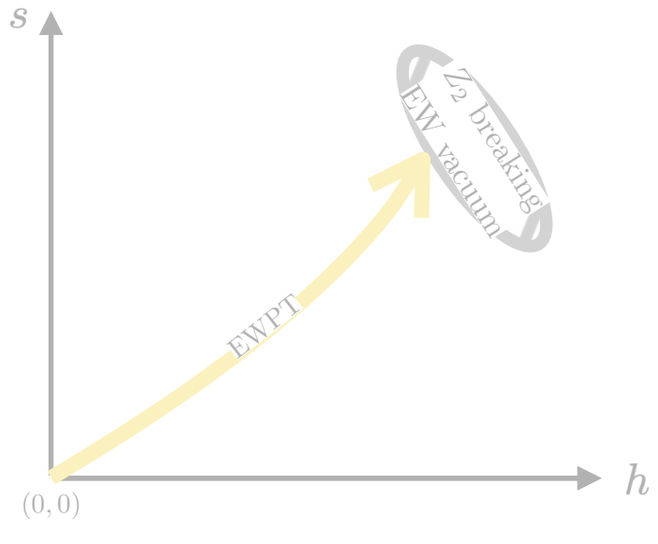
$$\rightarrow V_{\rm EFF}(h,s,T)$$

[Carena, Liu, Y.W. '19]

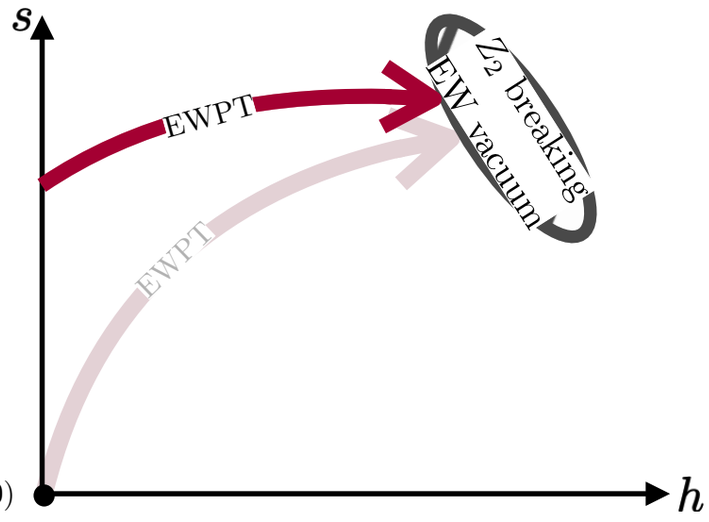
Tree-level Effects



Z_2 preserving



Z_2 breaking (explicit)



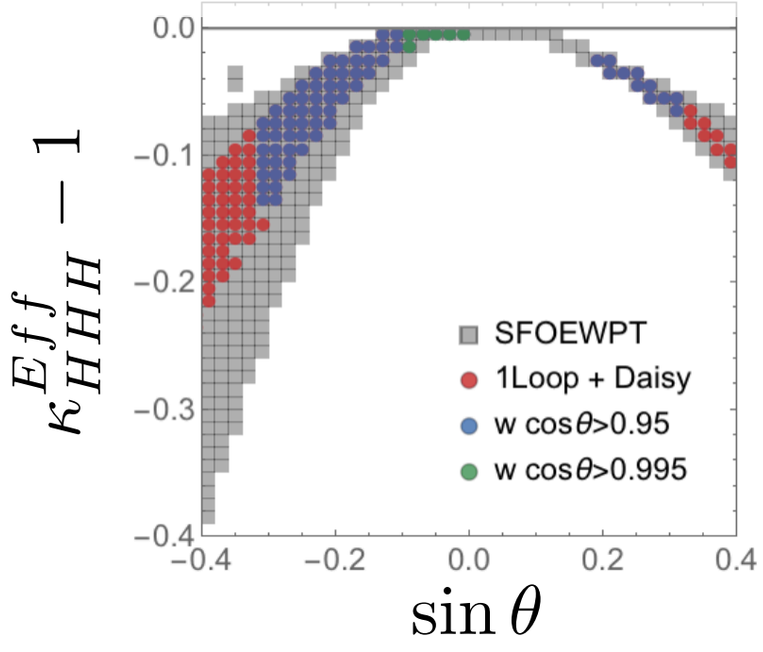
Z_2 breaking (spontaneous)

Example: Order of the Phase Transition $\propto \left(\lambda_h - \frac{\lambda_m^2}{4\lambda_s}\right)^{-1}$

$$\Lambda_{HHH} = \frac{m_H^2\left(-\sin^3\theta + \tan\beta\cos^3\theta\right)}{2\tan\beta\ v}$$

$$\Lambda_{SHH} = \frac{(2m_H^2 + m_S^2)(\sin\theta + \tan\beta\cos\theta)\sin 2\theta}{4\tan\beta\ v}.$$

$$\kappa_{HHH}^{Eff} \equiv \frac{\Lambda_{HHH}^{Eff}}{\Lambda_{HHH}^{SM}}$$



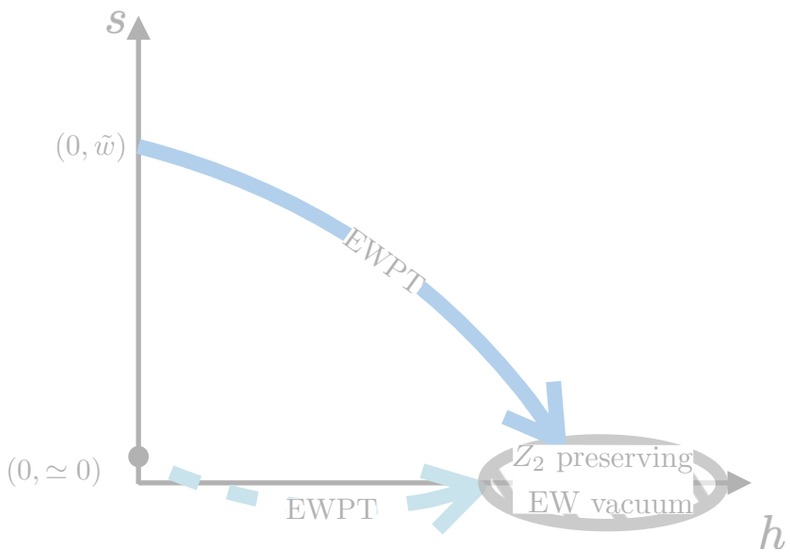
Electroweak phase transition and Higgs properties

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

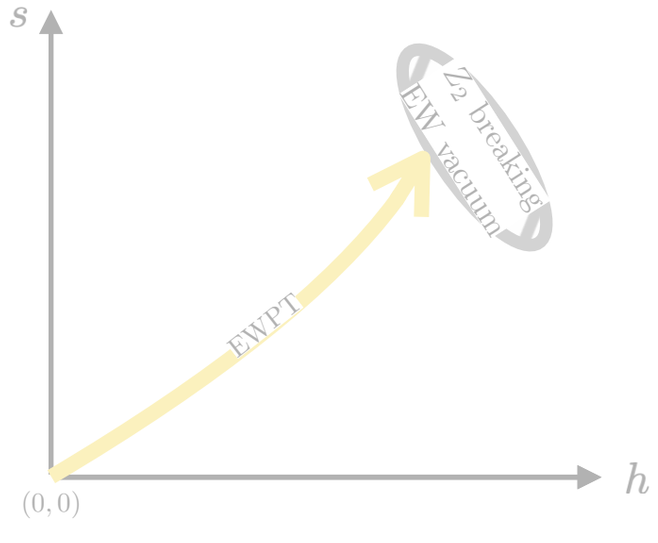
$$\rightarrow V_{\rm EFF}(h,s,T)$$

[Carena, Liu, Y.W. '19]

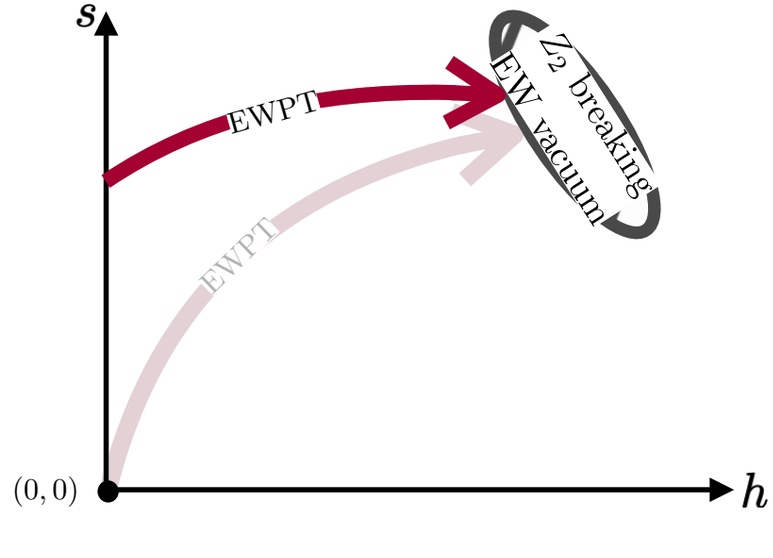
Tree-level Effects



Z_2 preserving



Z_2 breaking (explicit)



Z_2 breaking (spontaneous)

Example: Order of the Phase Transition $\propto \left(\lambda_h - \frac{\lambda_m^2}{4\lambda_s}\right)^{-1} \propto 1 + \sin^2\theta \left(\frac{(125\text{GeV})^2}{m_S^2} - 1\right)$

- $\sin\theta \lesssim 0.4$ bounded by **Higgs precision measurements**
- A firm prediction of a **light scalar**
- $\text{BR}(H \rightarrow SS)$ **bounded from below**

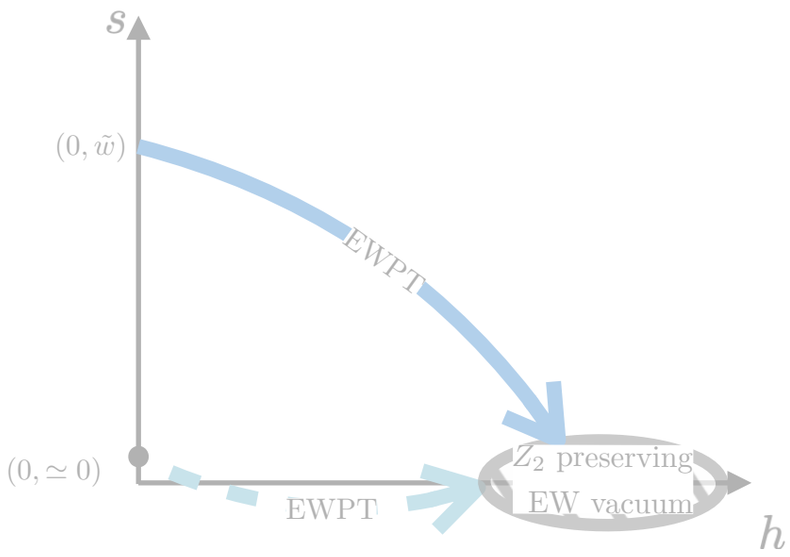
Electroweak phase transition and Higgs properties

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

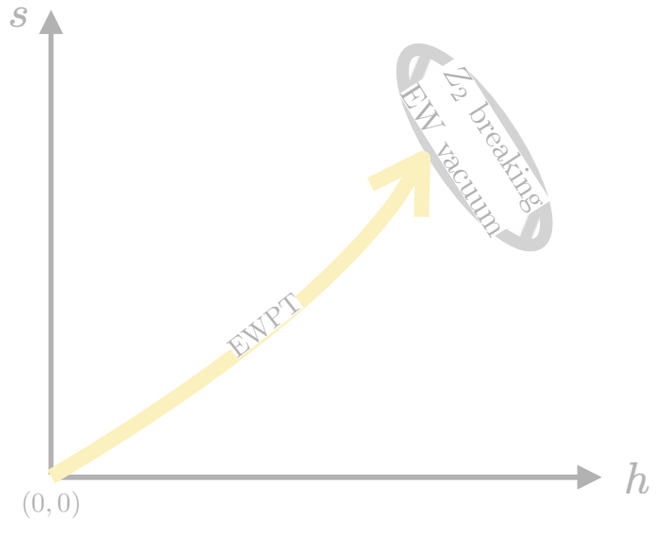
$$\rightarrow V_{\rm EFF}(h,s,T)$$

[Carena, Liu, Y.W. '19]

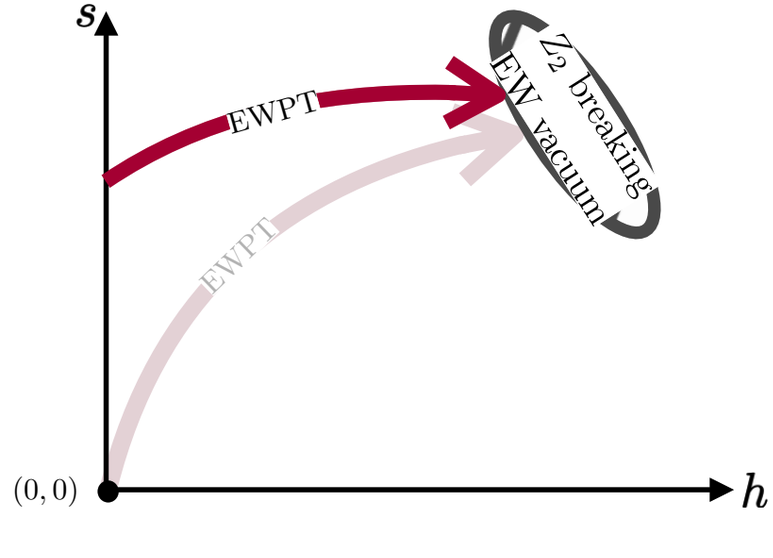
Tree-level Effects



Z_2 preserving



Z_2 breaking (explicit)



Z_2 breaking (spontaneous)

Example: Order of the Phase Transition $\propto \left(\lambda_h - \frac{\lambda_m^2}{4\lambda_s}\right)^{-1} \propto 1 + \sin^2\theta \left(\frac{(125\text{GeV})^2}{m_S^2} - 1\right)$

- $\sin\theta \lesssim 0.4$ bounded by **Higgs precision measurements**
- A firm prediction of a **light scalar**
- $\text{BR}(H \rightarrow SS)$ **bounded from below**

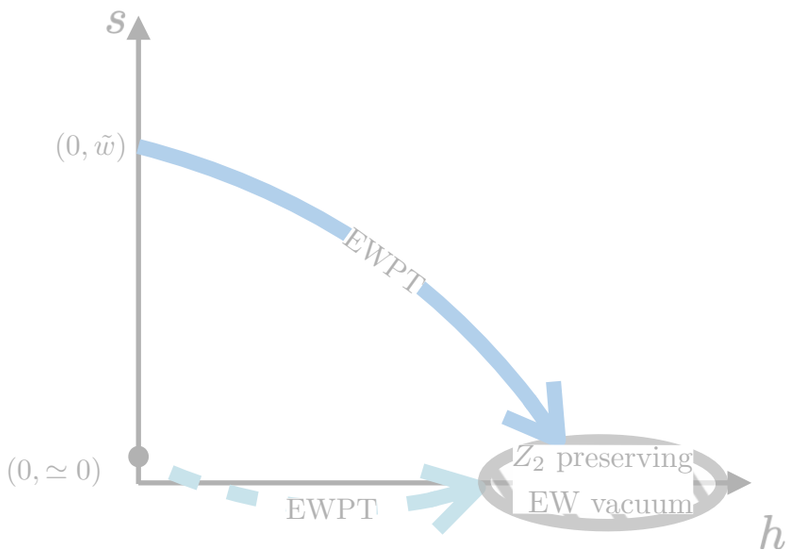
Electroweak phase transition and Higgs properties

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + (\text{explicit Z2} - \text{breaking terms})$$

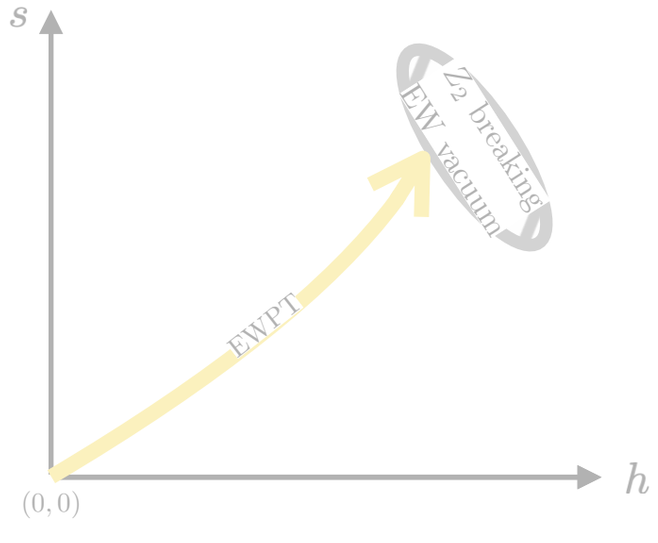
$$\rightarrow V_{\text{EFF}}(h,s,T)$$

[Carena, Liu, Y.W. '19]

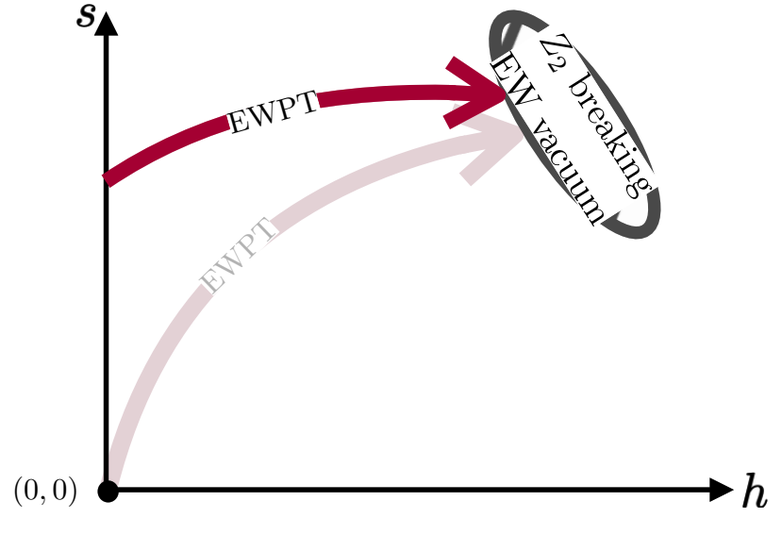
Tree-level Effects



Z_2 preserving



Z_2 breaking (explicit)



Z_2 breaking (spontaneous)

Example: Order of the Phase Transition $\propto \left(\lambda_h - \frac{\lambda_m^2}{4\lambda_s}\right)^{-1} \propto 1 + \sin^2\theta \left(\frac{(125\text{GeV})^2}{m_S^2} - 1\right)$

- $\sin\theta \lesssim 0.4$ bounded by **Higgs precision measurements**
- A firm prediction of a **light scalar**
- $\text{BR}(H \rightarrow SS)$ **bounded from below**

Observation window: Higgs exotic decay

Higgs Exotic Decays: a rich variety of phenomenological interests

- The SM decay width of the Higgs is tiny
- Small couplings to BSM can lead to sizable BRs

$\Delta L = \frac{\zeta}{2} s^2 |H|^2$ BR $\sim \mathcal{O}(0.1)$ for $\zeta \sim 0.01$; $\Delta L = \frac{\mu}{\Lambda} |H|^2 \bar{\psi}\psi$ BR $\sim \mathcal{O}(0.01)$ for $\Lambda \gtrsim 1$ TeV.

Higgs Exotic Decays: a rich variety of phenomenological interests

- The SM decay width of the Higgs is tiny
- Small couplings to BSM can lead to sizable BRs

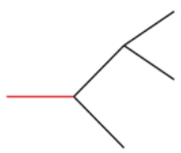
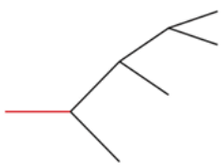
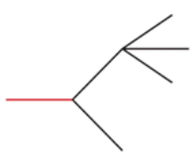
$\Delta L = \frac{\zeta}{2} s^2 |H|^2$ BR $\sim \mathcal{O}(0.1)$ for $\zeta \sim 0.01$; $\Delta L = \frac{\mu}{\Lambda} |H|^2 \bar{\psi}\psi$ BR $\sim \mathcal{O}(0.01)$ for $\Lambda \gtrsim 1$ TeV.

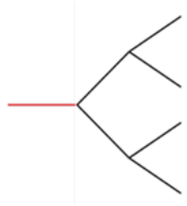
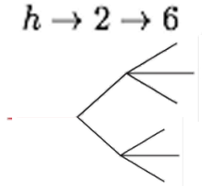
Higgs Exotic Decays: a rich variety of phenomenological interests

- The SM decay width of the Higgs is tiny
- Small couplings to BSM can lead to sizable BRs

$\Delta L = \frac{\zeta}{2} s^2 |H|^2$ BR $\sim \mathcal{O}(0.1)$ for $\zeta \sim 0.01$; $\Delta L = \frac{\mu}{\Lambda} |H|^2 \bar{\psi}\psi$ BR $\sim \mathcal{O}(0.01)$ for $\Lambda \gtrsim 1$ TeV.

Topologies and final states

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_{\rm T}$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_{\rm T}$ $h \to (b\bar{b}) + \not{E}_{\rm T}$ $h \to (jj) + \not{E}_{\rm T}$ $h \to (\tau^+\tau^-) + \not{E}_{\rm T}$ $h \to (\gamma\gamma) + \not{E}_{\rm T}$ $h \to (\ell^+\ell^-) + \not{E}_{\rm T}$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_{\rm T}$ $h \to (jj) + \not{E}_{\rm T}$ $h \to (\tau^+\tau^-) + \not{E}_{\rm T}$ $h \to (\gamma\gamma) + \not{E}_{\rm T}$ $h \to (\ell^+\ell^-) + \not{E}_{\rm T}$ $h \to (\mu^+\mu^-) + \not{E}_{\rm T}$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_{\rm T}$ $h \to jj + \not{E}_{\rm T}$ $h \to \tau^+\tau^- + \not{E}_{\rm T}$ $h \to \gamma\gamma + \not{E}_{\rm T}$ $h \to \ell^+\ell^- + \not{E}_{\rm T}$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_{\rm T}$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_{\rm T}$ $h \to (\ell^+\ell^-) + \not{E}_{\rm T} + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_{\rm T}$ $h \to \ell^+\ell^- + \not{E}_{\rm T} + X$

[Zhen Liu et al '13, 16']

Higgs Exotic Decays: a rich variety of phenomenological interests

- The SM decay width of the Higgs is tiny
- Small couplings to BSM can lead to sizable BRs

$\Delta L = \frac{\zeta}{2} s^2 |H|^2$ BR $\sim \mathcal{O}(0.1)$ for $\zeta \sim 0.01$; $\Delta L = \frac{\mu}{\Lambda} |H|^2 \bar{\psi}\psi$ BR $\sim \mathcal{O}(0.01)$ for $\Lambda \gtrsim 1$ TeV.

Topologies and final states

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_{\rm T}$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_{\rm T}$
	$h \to (b\bar{b}) + \not{E}_{\rm T}$
	$h \to (jj) + \not{E}_{\rm T}$
	$h \to (\tau^+\tau^-) + \not{E}_{\rm T}$
	$h \to (\gamma\gamma) + \not{E}_{\rm T}$
	$h \to (\ell^+\ell^-) + \not{E}_{\rm T}$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_{\rm T}$
	$h \to (jj) + \not{E}_{\rm T}$
	$h \to (\tau^+\tau^-) + \not{E}_{\rm T}$
	$h \to (\gamma\gamma) + \not{E}_{\rm T}$
	$h \to (\ell^+\ell^-) + \not{E}_{\rm T}$
	$h \to (\mu^+\mu^-) + \not{E}_{\rm T}$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_{\rm T}$
	$h \to jj + \not{E}_{\rm T}$
	$h \to \tau^+\tau^- + \not{E}_{\rm T}$
	$h \to \gamma\gamma + \not{E}_{\rm T}$
	$h \to \ell^+\ell^- + \not{E}_{\rm T}$

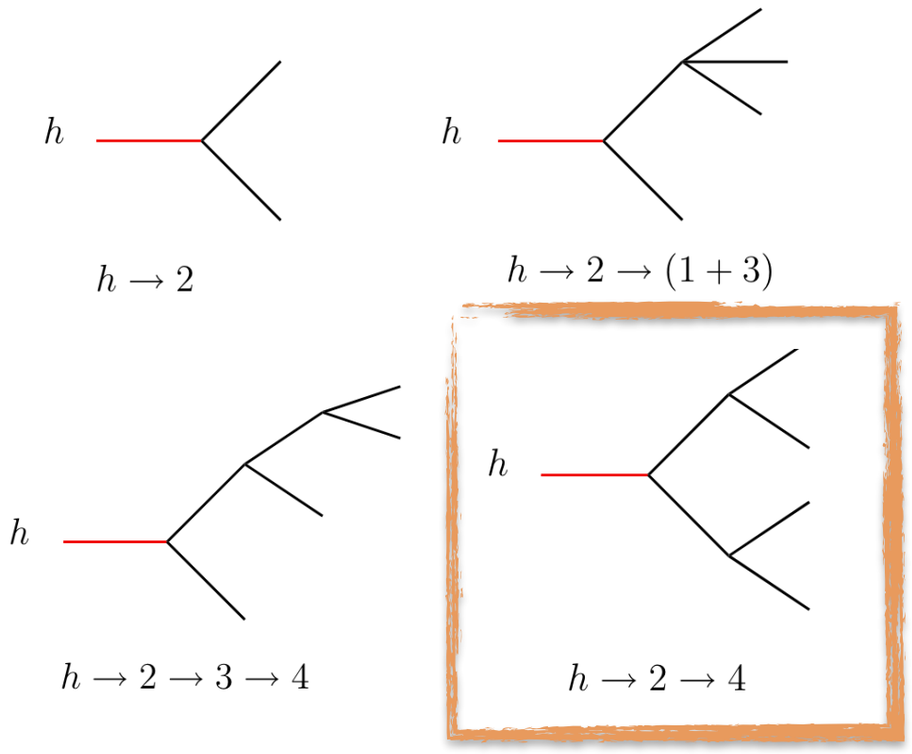
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_{\rm T}$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_{\rm T}$
	$h \to (\ell^+\ell^-) + \not{E}_{\rm T} + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_{\rm T}$
	$h \to \ell^+\ell^- + \not{E}_{\rm T} + X$

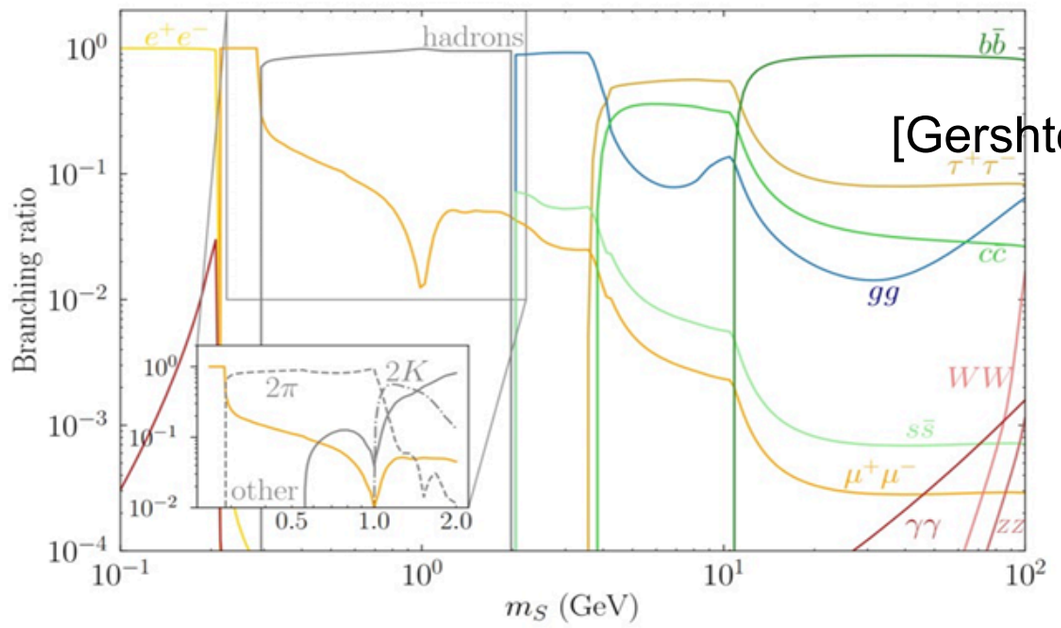
[Zhen Liu et al '13, 16']

Model motivations ('simplified')

- **Extended Higgs sectors**
  - SM + scalars
  - 2HDM
  - etc
- **SM + fermion(s)**
  - Neutrino portal
  - Higgs portal
- **SM gauge extensions**
  - Dark photon, dark Z
  - Dark Higgs portal

Electroweak phase transition and Higgs Exotic Decays

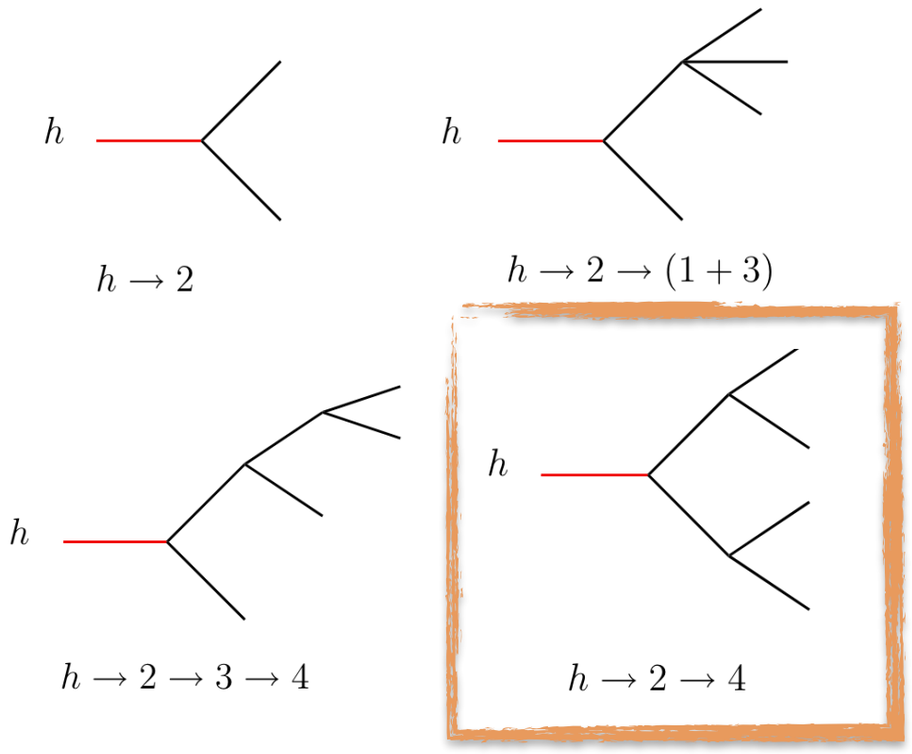


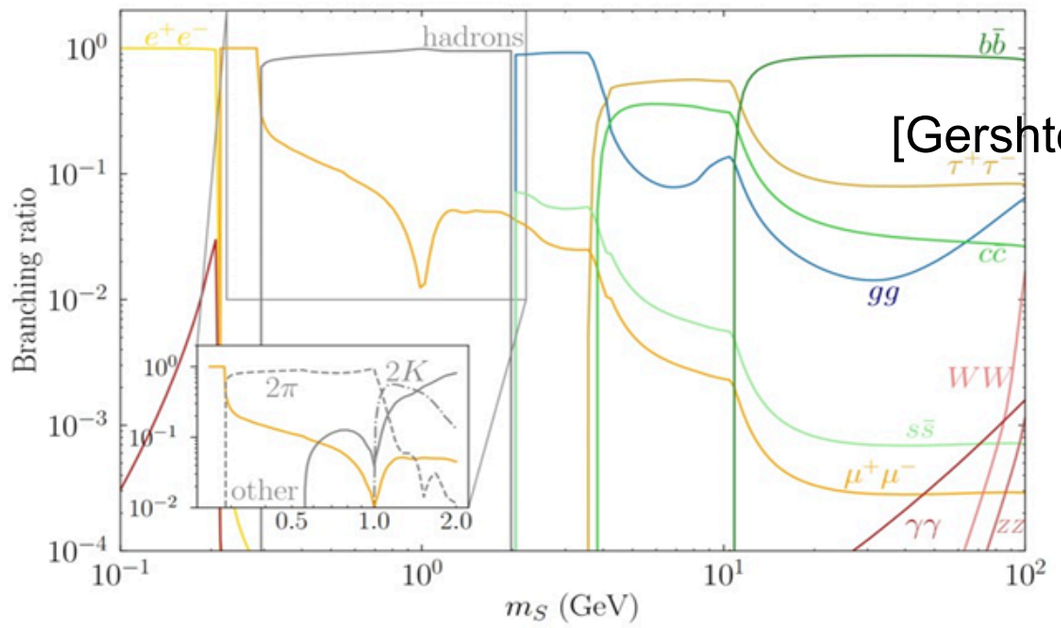


[Gershtein, et al, 21']

Higgs exotic decay $H \to SS$ and S branching fraction into $XXYY$ final states mediated through mixing.

Electroweak phase transition and Higgs Exotic Decays

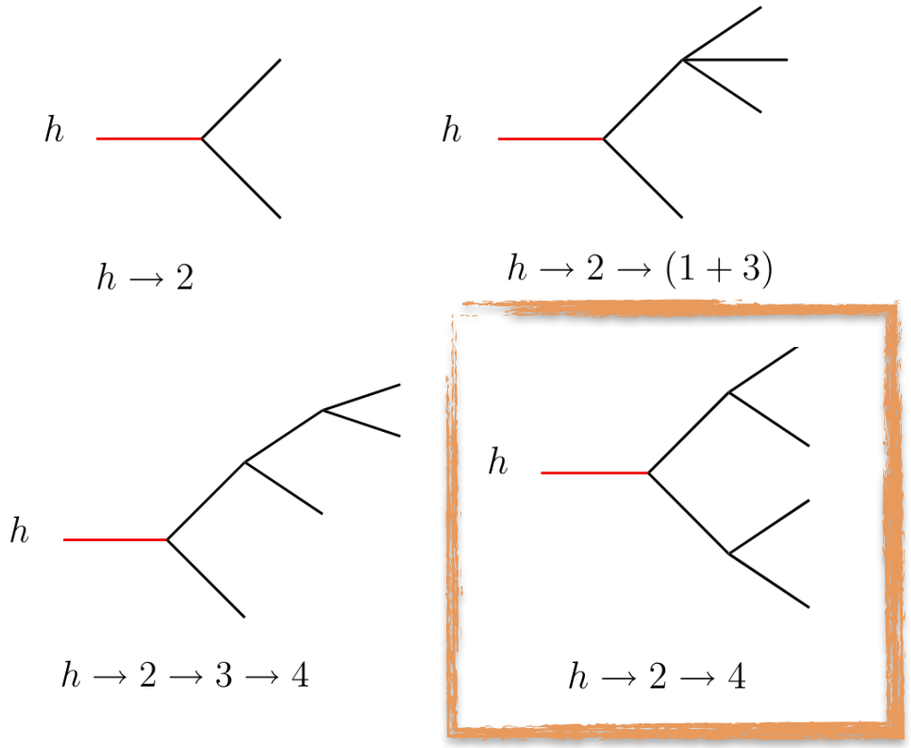


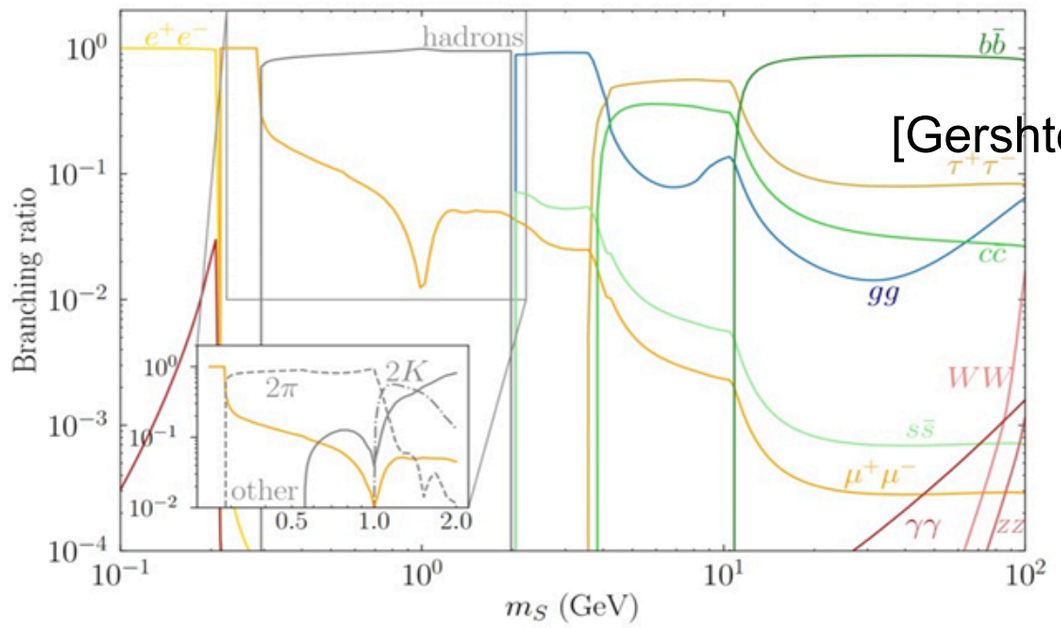


[Gershtein, et al, 21']

Higgs exotic decay $H \to SS$ and S branching fraction into $XXYY$ final states mediated through mixing.

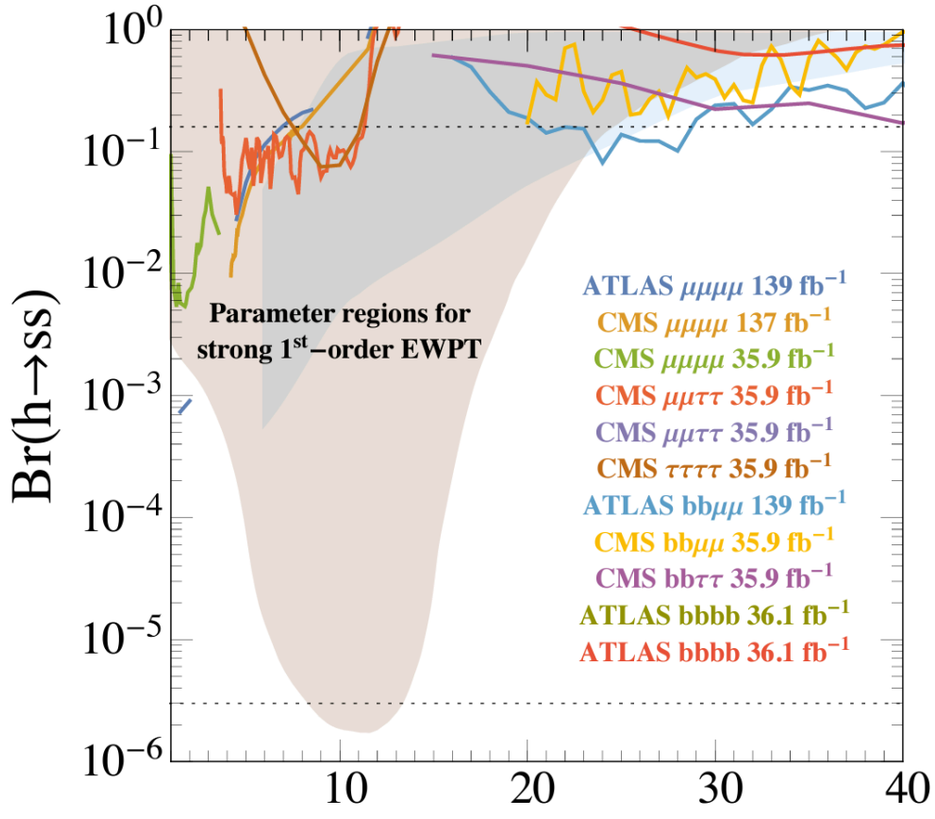
Electroweak phase transition and Higgs Exotic Decays





[Gershtein, et al, 21']

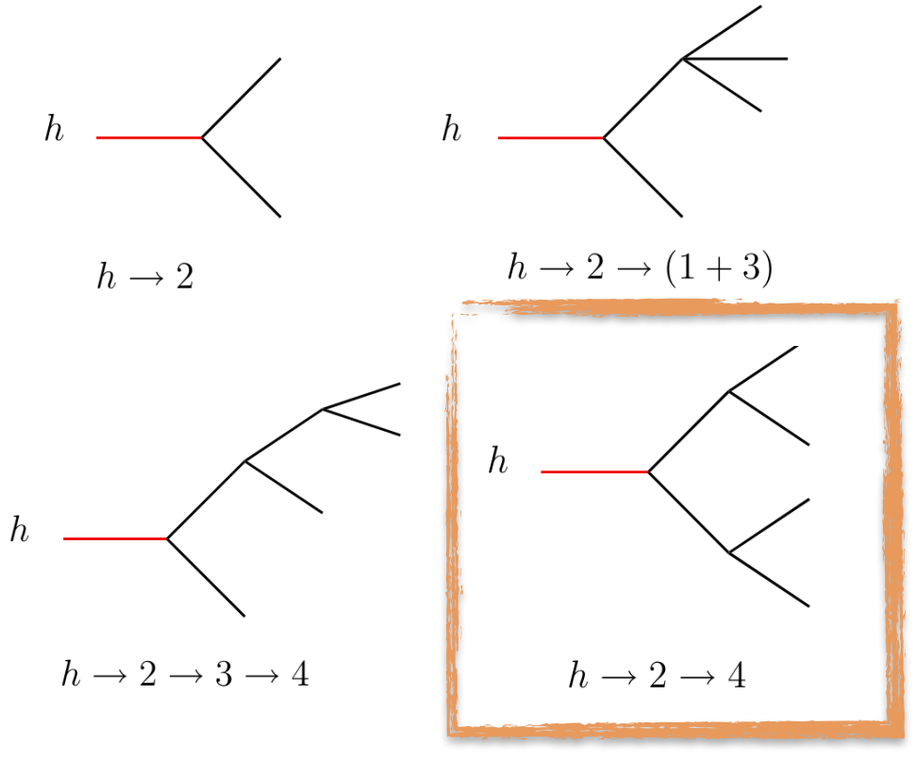
Higgs exotic decay $H \to SS$ and S branching fraction into $XXYY$ final states mediated through mixing.

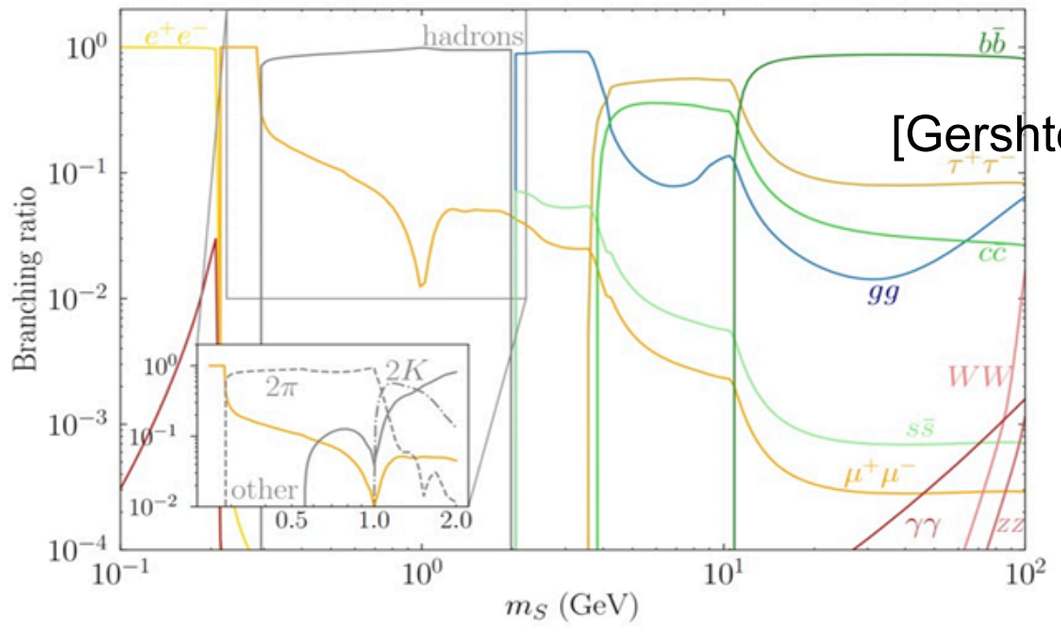


[Kozaczuk, et al, 19']

Current bounds on Higgs exotic decay $H \to SS$

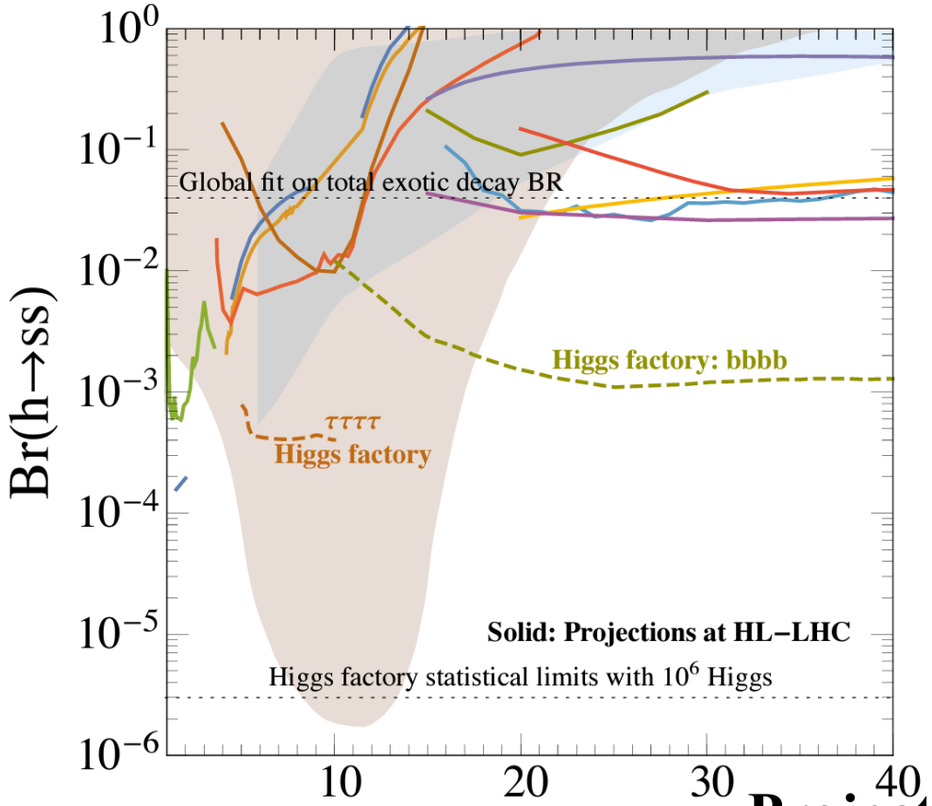
Electroweak phase transition and Higgs Exotic Decays





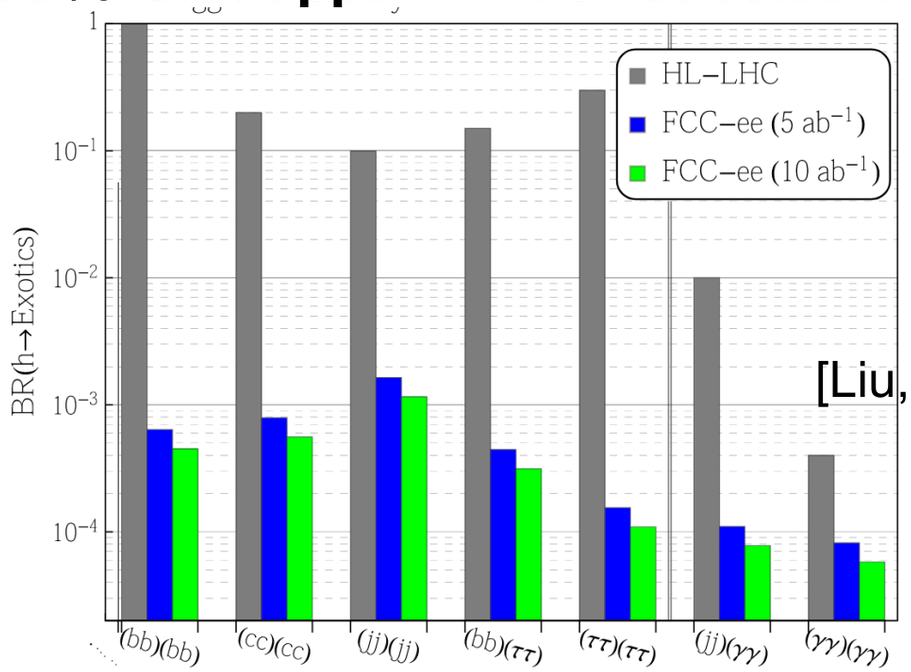
[Gershtein, et al, 21']

Higgs exotic decay $H \to SS$ and S branching fraction into $XXYY$ final states mediated through mixing.



[Kozaczuk, et al, 19']

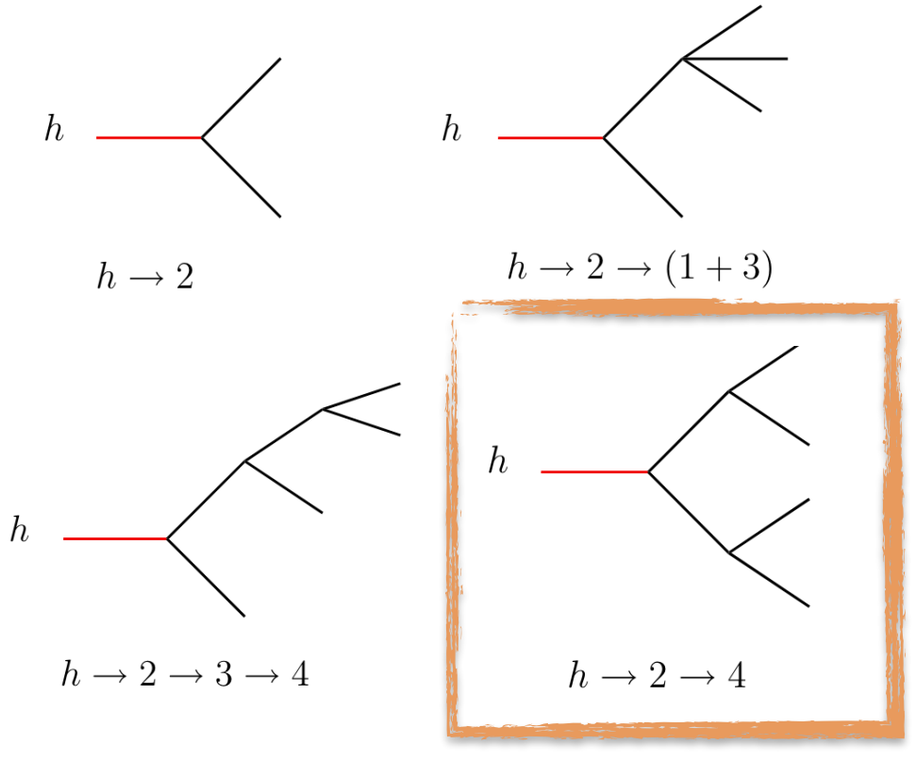
95% C.L. upper limit on selected BRs

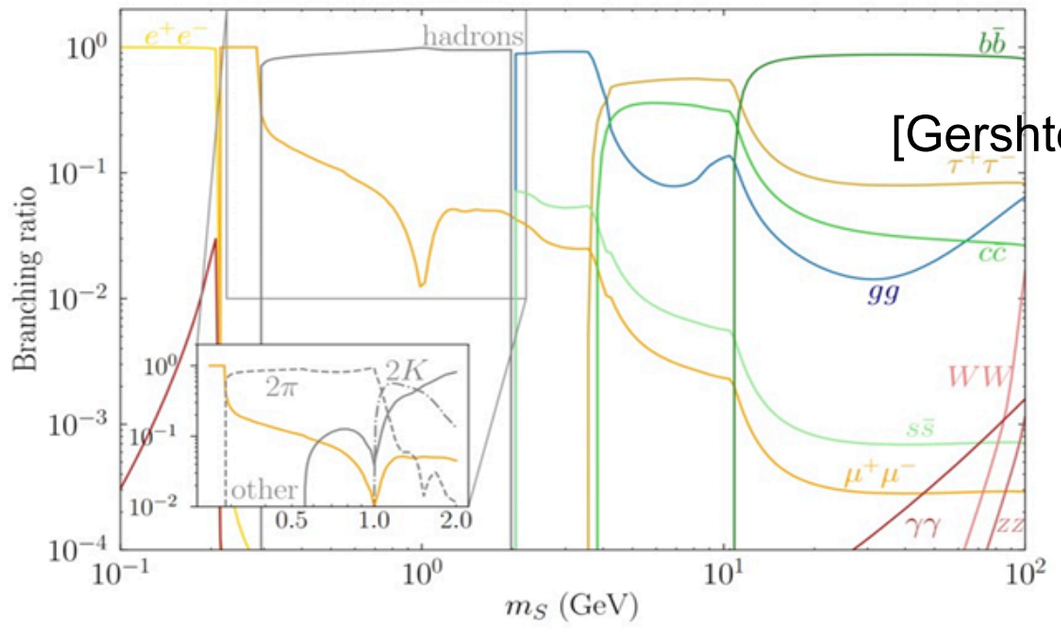


[Liu, et al, 16']

Projections at HL-LHC and Higgs factories on Higgs exotic decay $H \to SS$

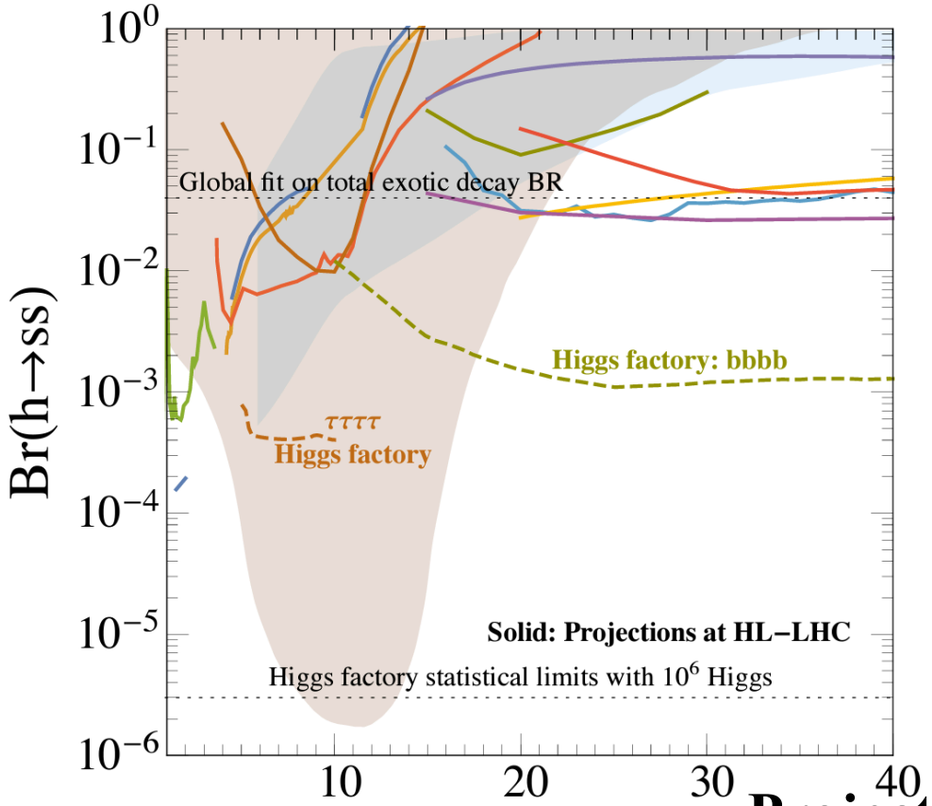
Electroweak phase transition and Higgs Exotic Decays





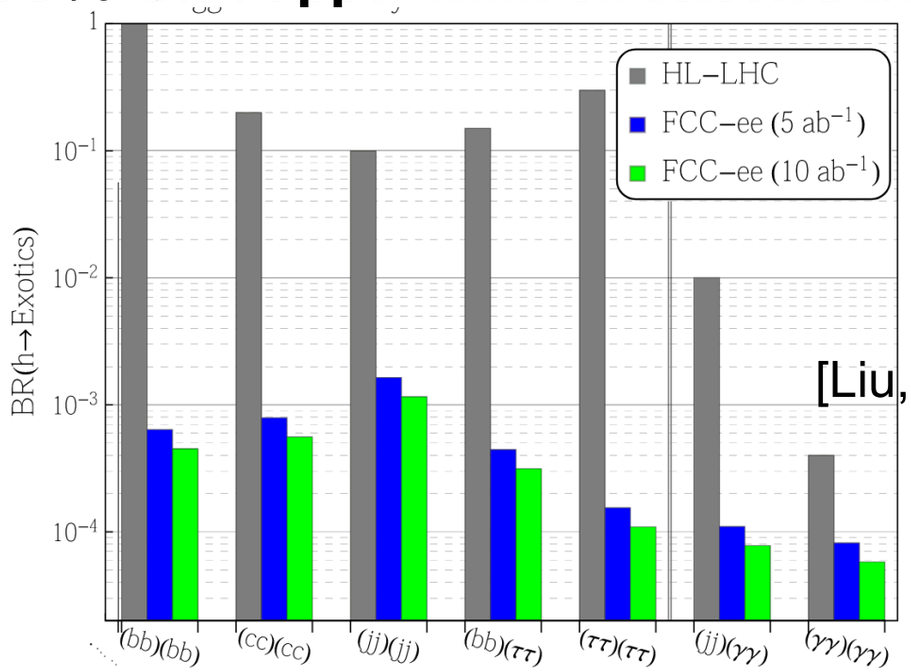
[Gershtein, et al, 21']

Higgs exotic decay $H \to SS$ and S branching fraction into $XXYY$ final states mediated through mixing.



[Kozaczuk, et al, 19']

95% C.L. upper limit on selected BRs



[Liu, et al, 16']

Projections at HL-LHC and Higgs factories on Higgs exotic decay $H \to SS$

Summary and Outlook

- Modified Higgs sector provides opportunities to answer many open questions that need introduction of beyond the Standard Model physics;
- Connected to the origin of the Baryon Asymmetry of the Universe, an extended Higgs sector can provide both the necessary out-of-equilibrium condition via the EWPT, and additional CP violation sources;
- EWPT is tightly connected to Higgs properties;
- Lots of parameter space open in modified Higgs sectors that leads to a strongly first order EWPT;
- Some interesting channels to look: trilinear Higgs coupling, Higgs exotic decays, and more!