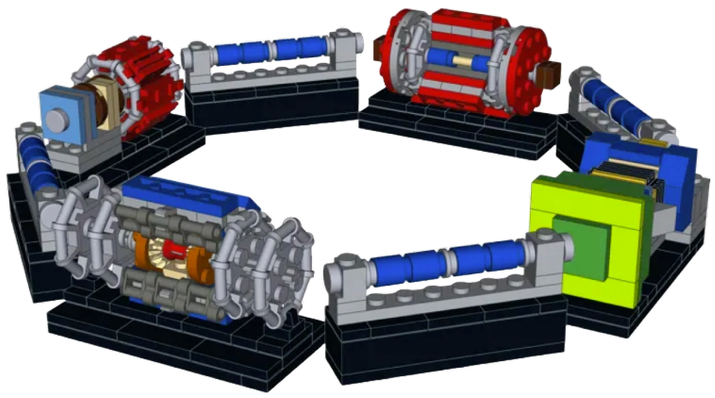
Higgs Probes of Beyond the Standard Model Physics



Yikun Wang

California Institute of Technology

The 12th edition of the LHCP Conference

June 6th, 2024, Boston

with Marcela Carena, Zhen Liu based on arXiv:1911.10206;
with Sebastian Baum, Marcela Carena, Nausheen Shah, Carlos Wagner, arXiv:2009.10743;
with Marcela Carena, Jonathan Kozaczuk, Zhen Liu, Tong Ou, Michael J. Ramsey-Musolf, Jessie Shelton, and Ke-Pan Xie based on arXiv:2203.08206.

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**

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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?**

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  - ➡ **Radiative generation of the EWSB**
  - ➡ **Solution to the Higgs hierarchy problem**

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Extended Higgs sectors
- ⇨ Multi-Higgs Doublet models
- ⇨ Additional singlet(s)
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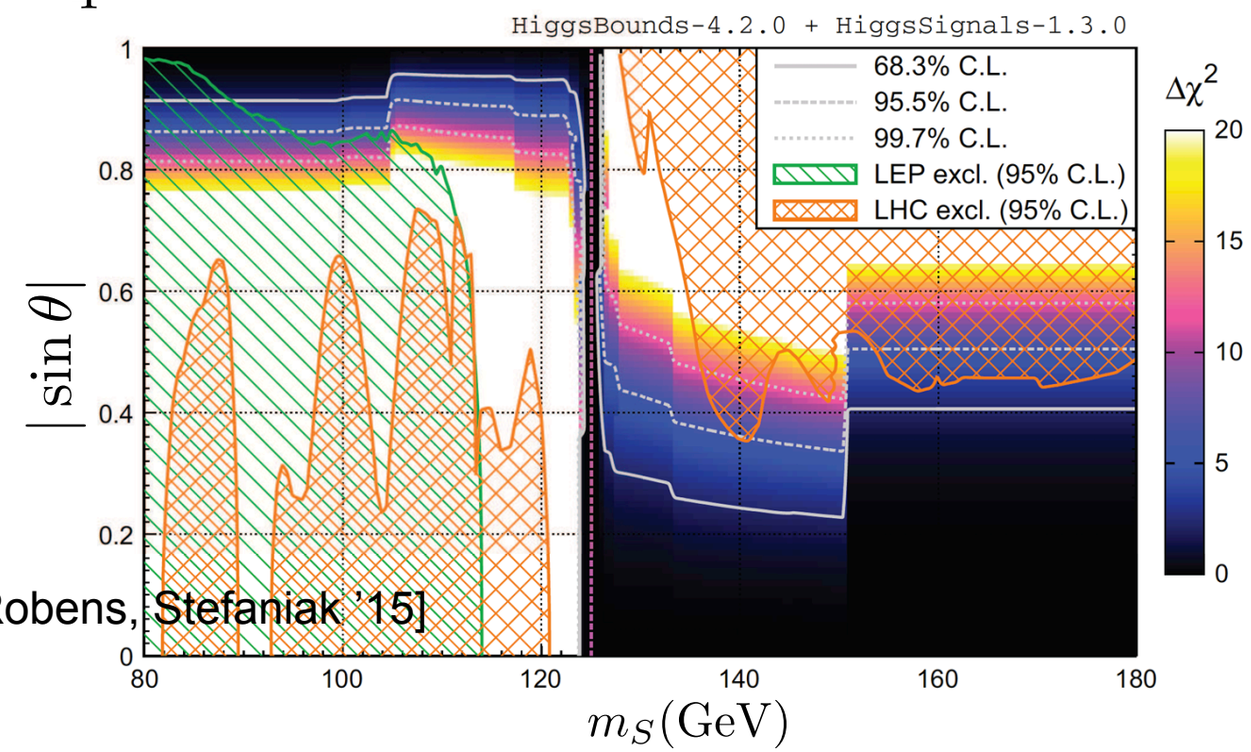
Example: adding a singlet

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

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

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



[Robens, Stefaniak '15]

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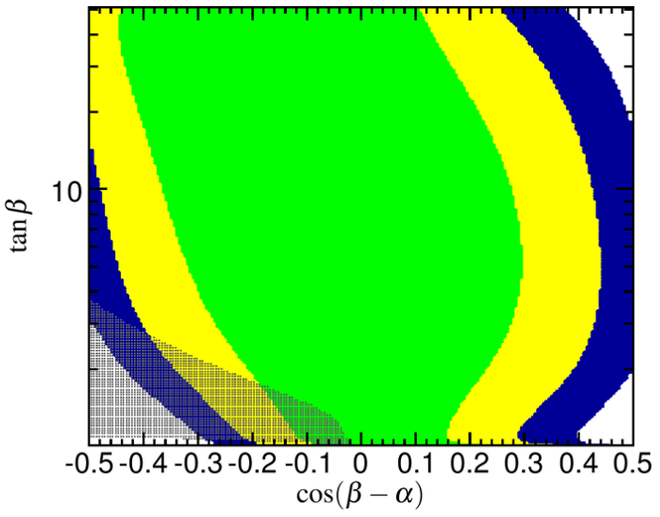
Example: Two Higgs Doublet Models (2HDM)

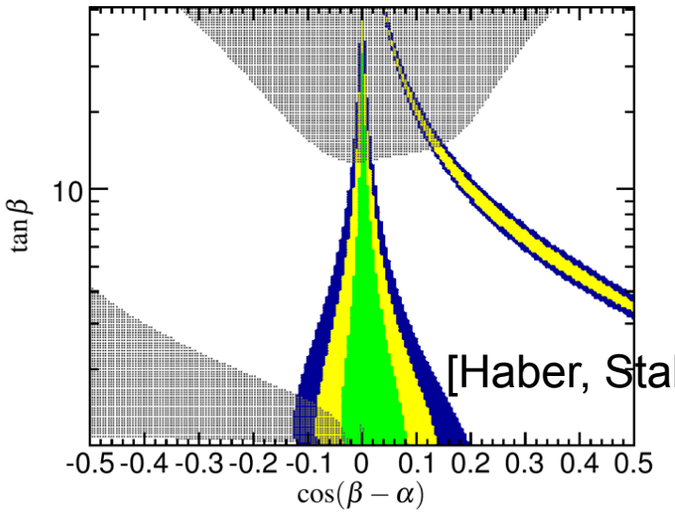
$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_3^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right)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

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

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]

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➡ **Facilitate the generation of BAU**

➡ **Provide Dark Matter candidates**

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

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➡ **Stabilize the Higgs vacuum**

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Baryon Asymmetry of the Universe and the Higgs

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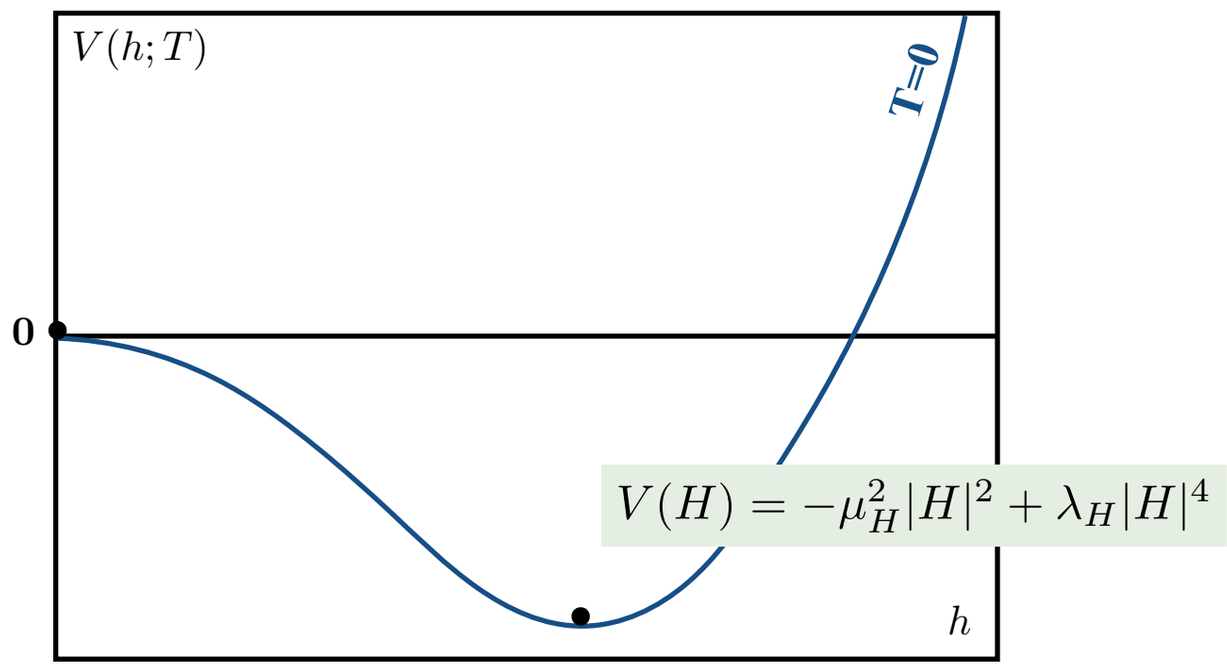

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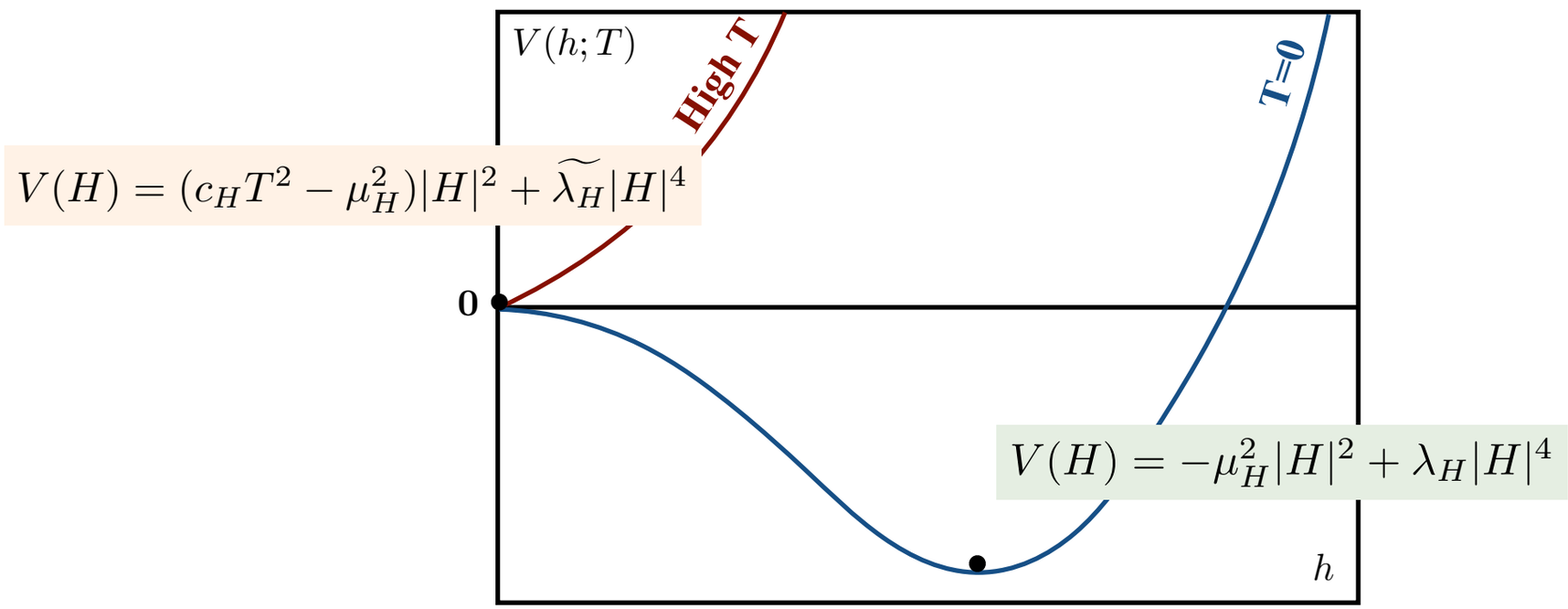
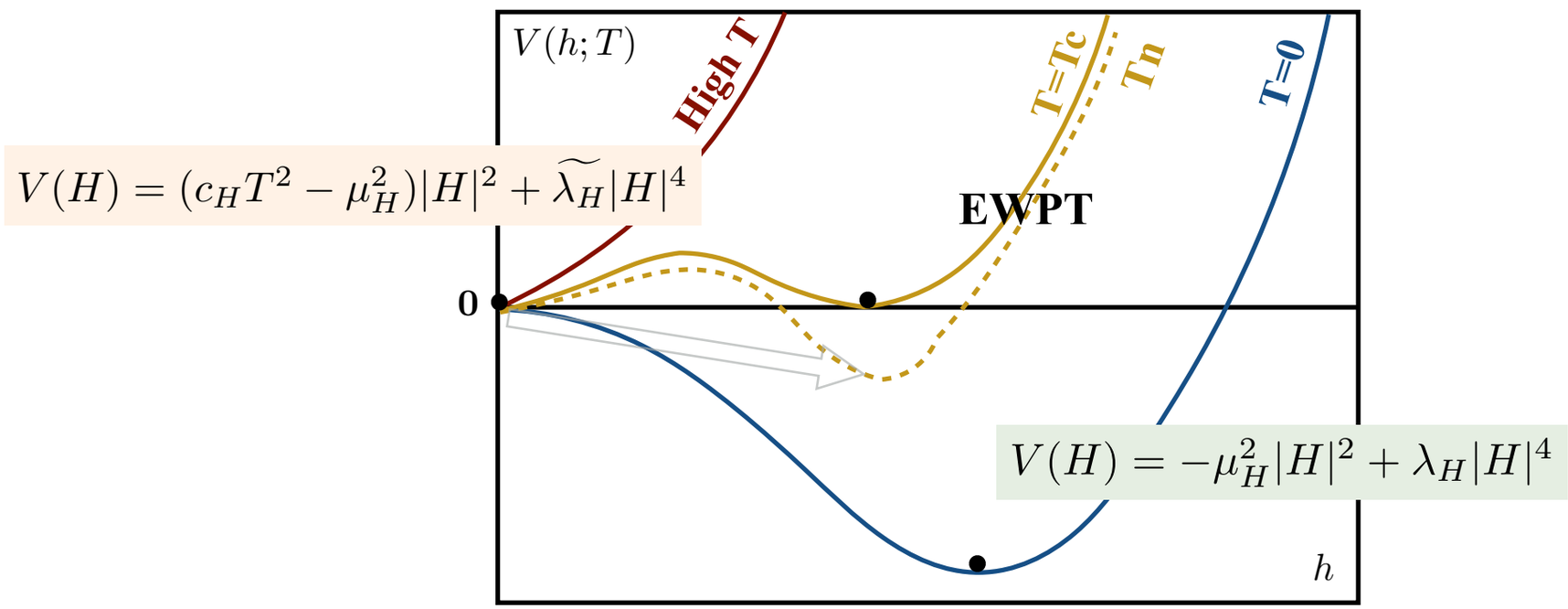
Baryon Asymmetry of the Universe and the Higgs



Baryon Asymmetry of the Universe and the Higgs

- **Nature of the Electroweak Phase Transition**



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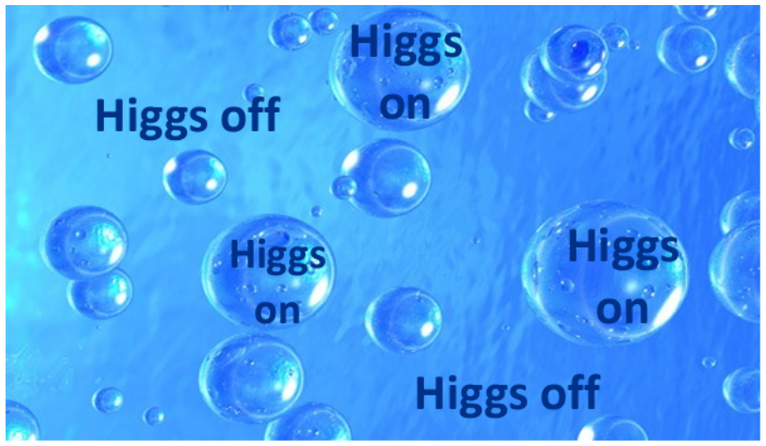

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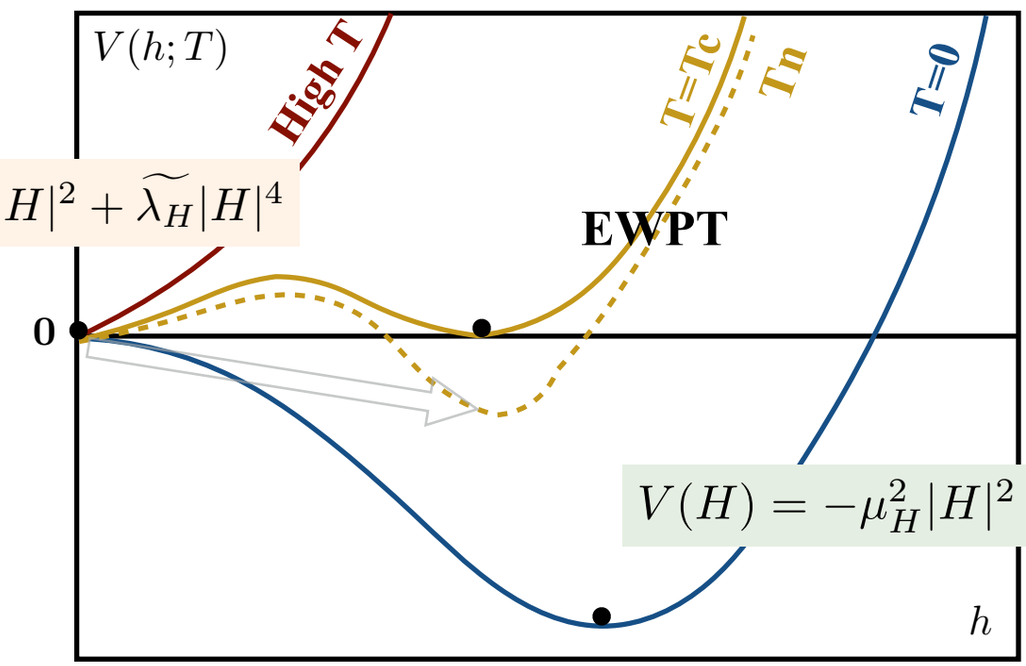

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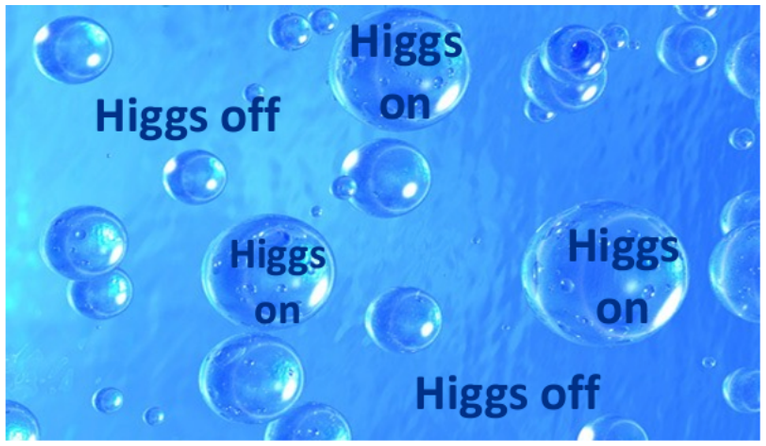

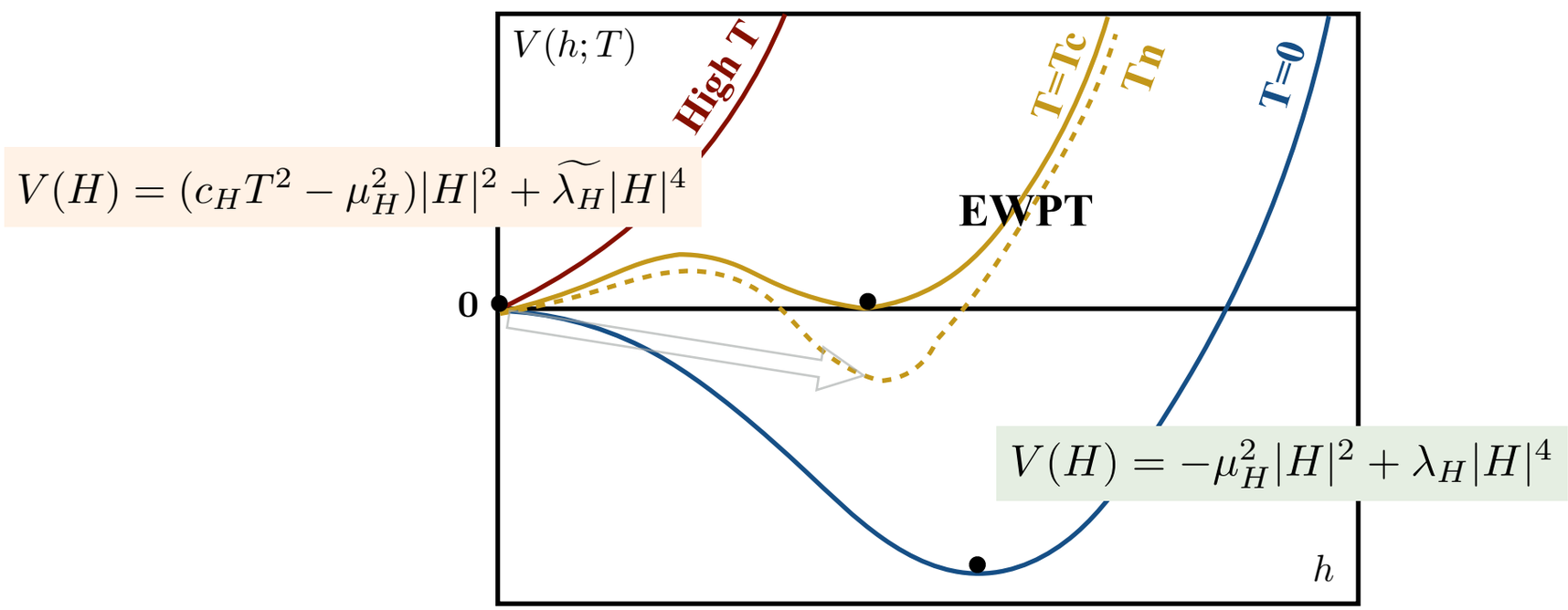

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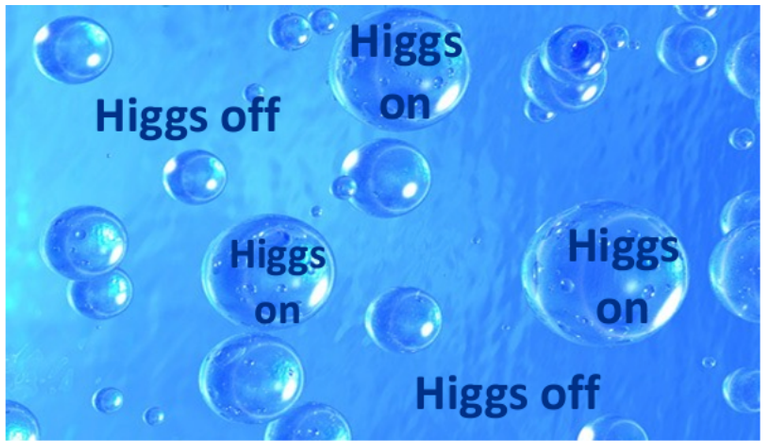
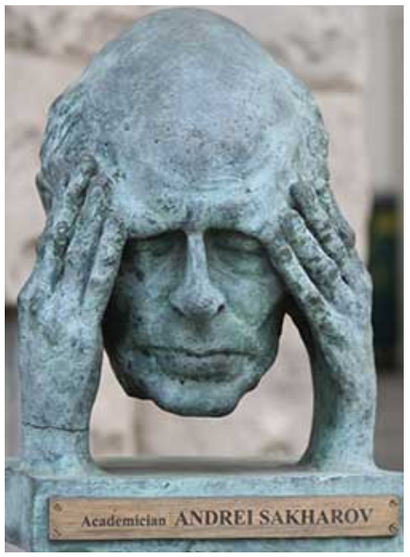
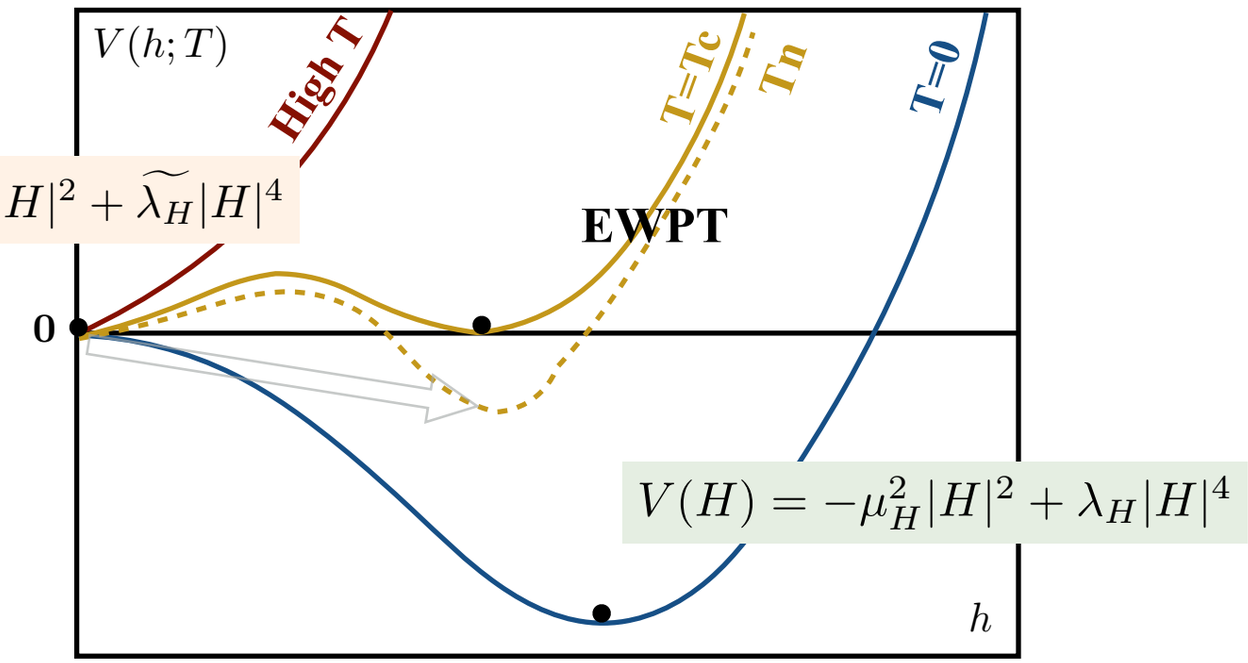


Sakharov's conditions for BAU creation



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



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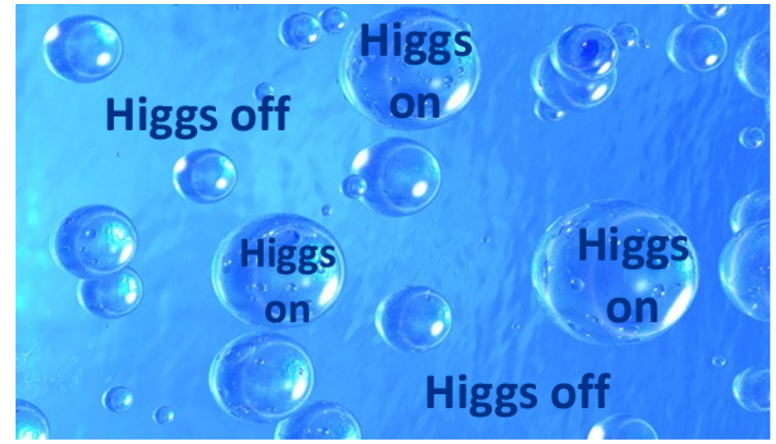

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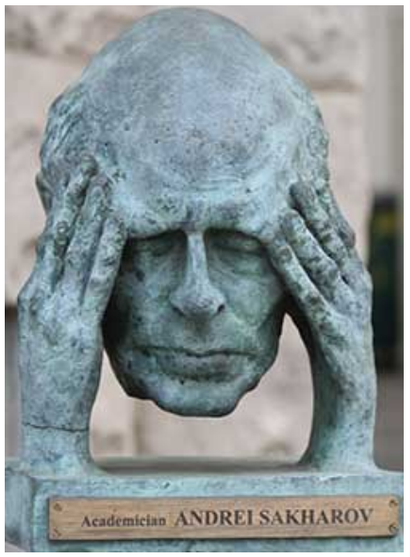

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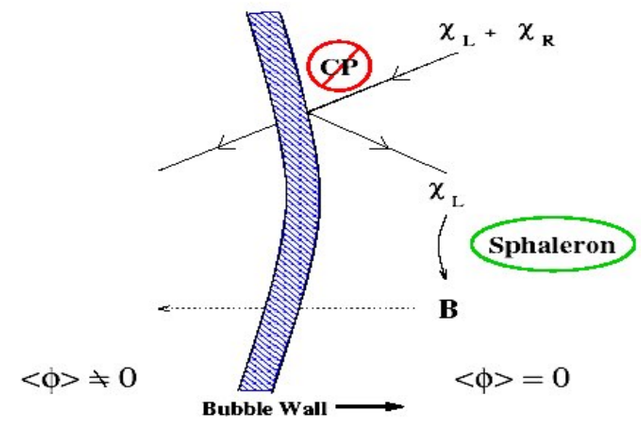

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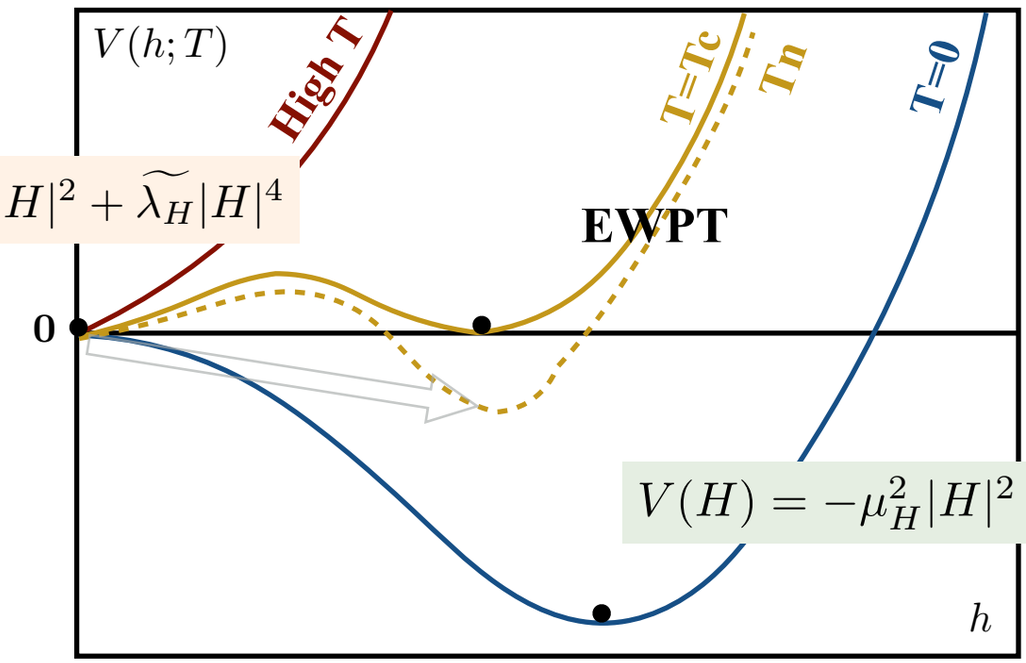

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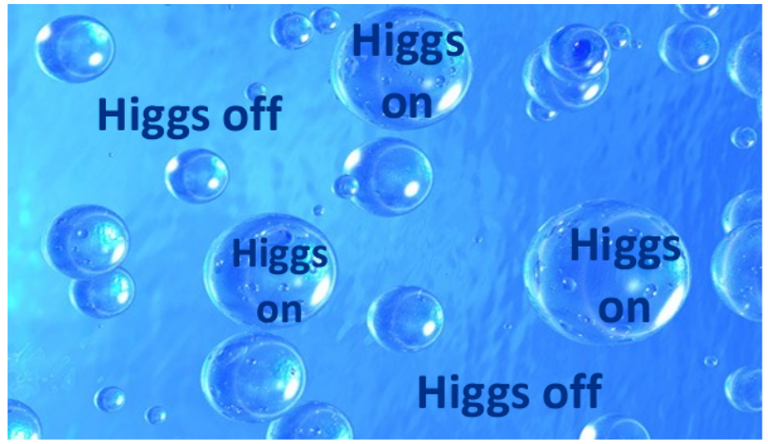

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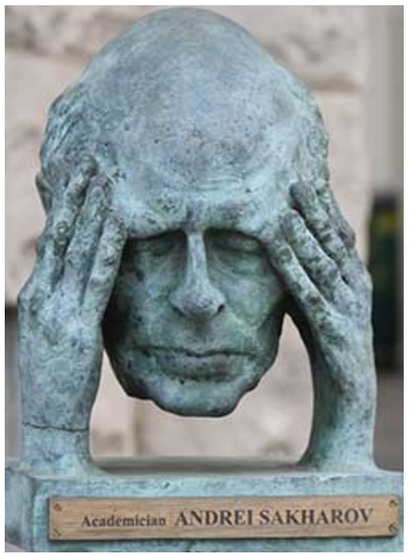

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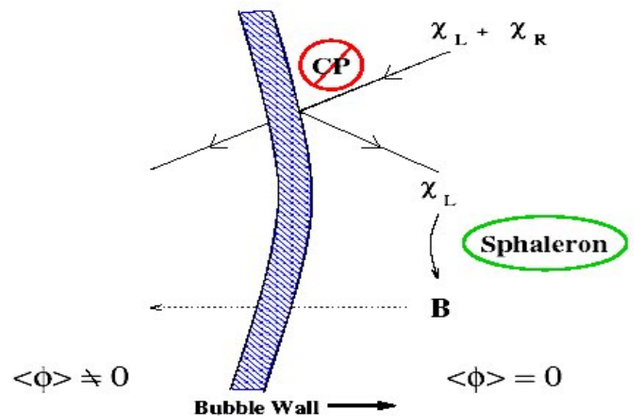

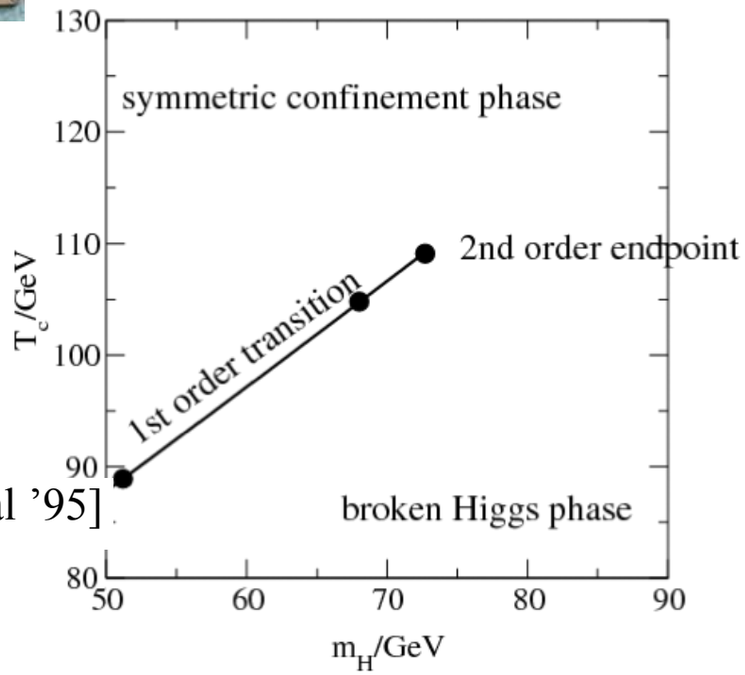

[Kajantie et al '95]

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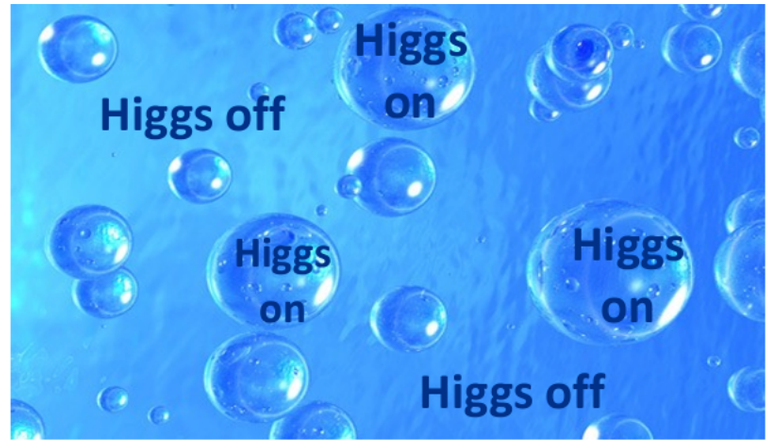

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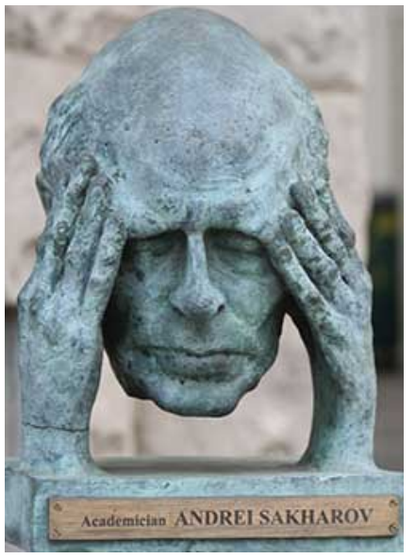

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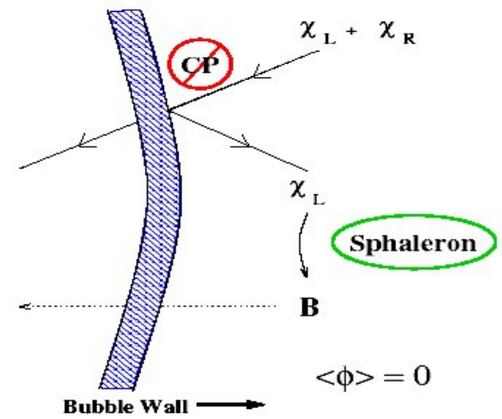

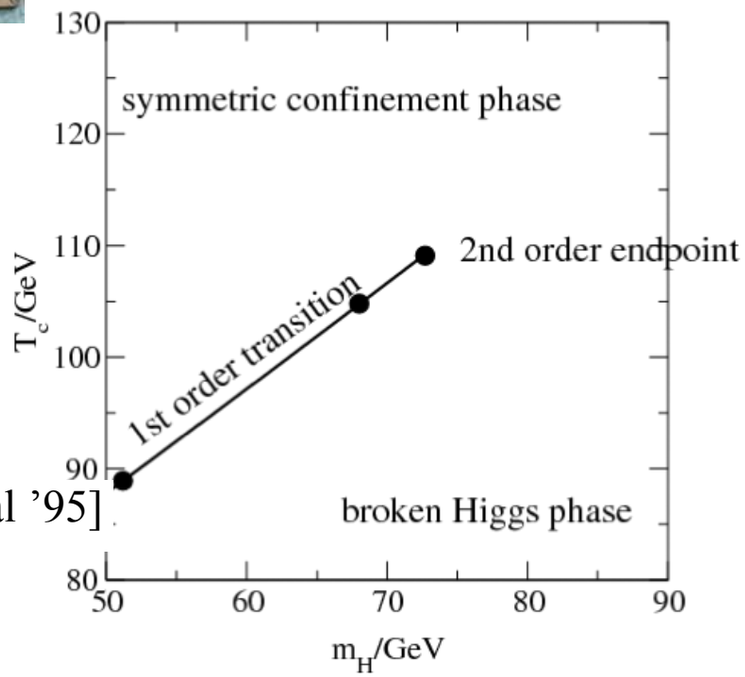

[Kajantie et al '95]

BSM is needed

⇨ Extended Higgs sectors

Electroweak phase transition and Higgs properties

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

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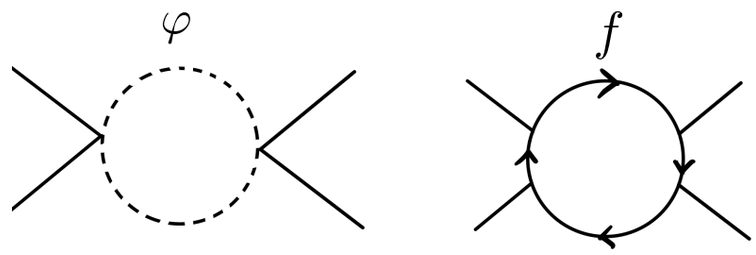

E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], …

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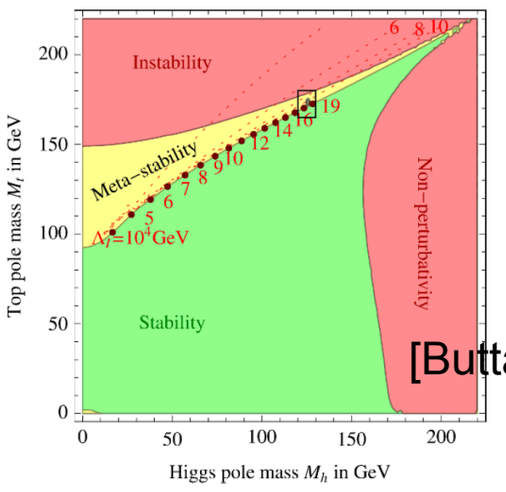

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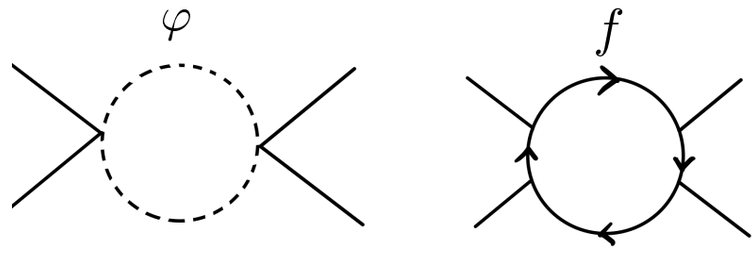

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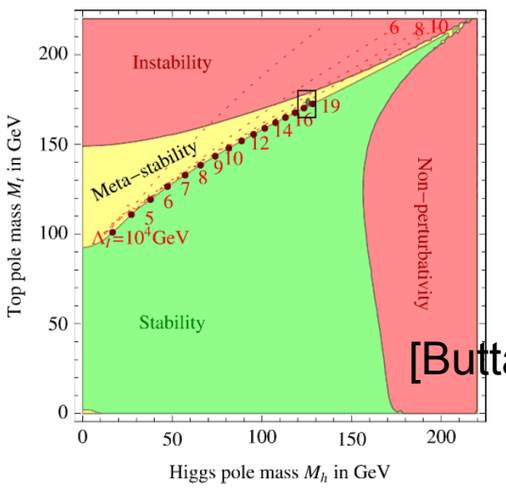

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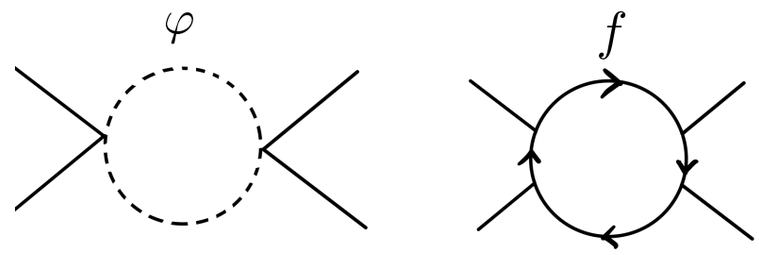

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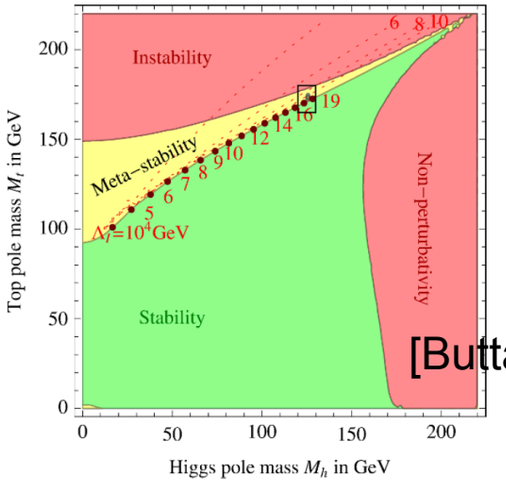

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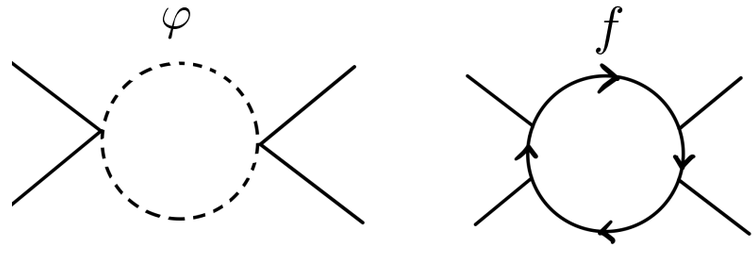

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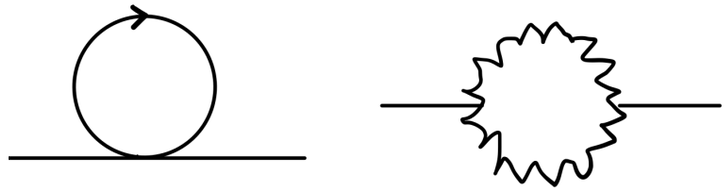

E.g. [Anderson, Hall '92], [Cohen, Morrissey, Pierce '12], [Chowdhury et al '12]
[Carena, Quiros, Wagner, '96], [Delepine, et al '96]

Electroweak phase transition and Higgs properties

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

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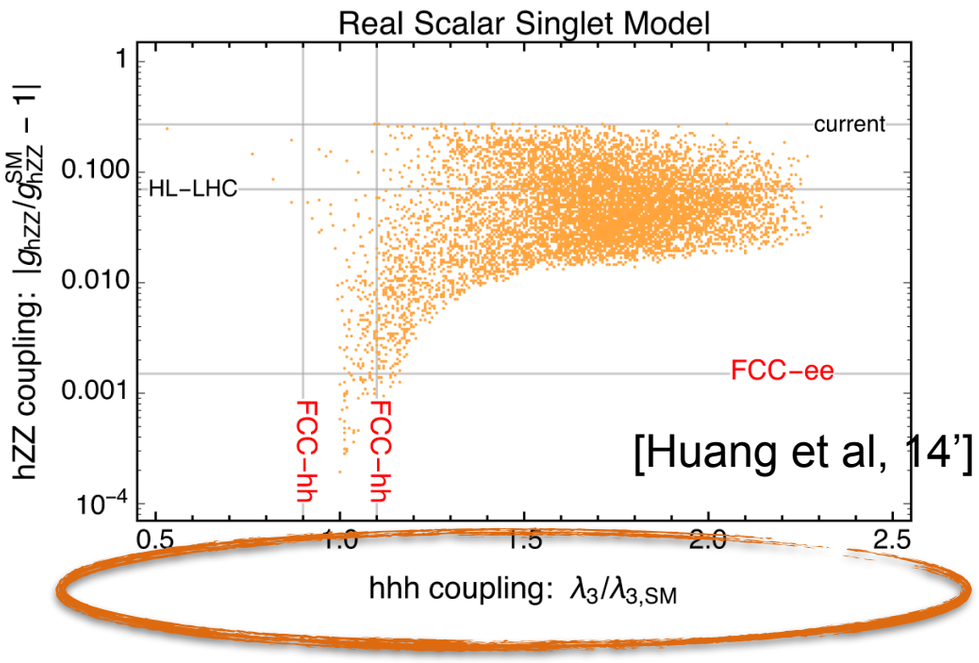
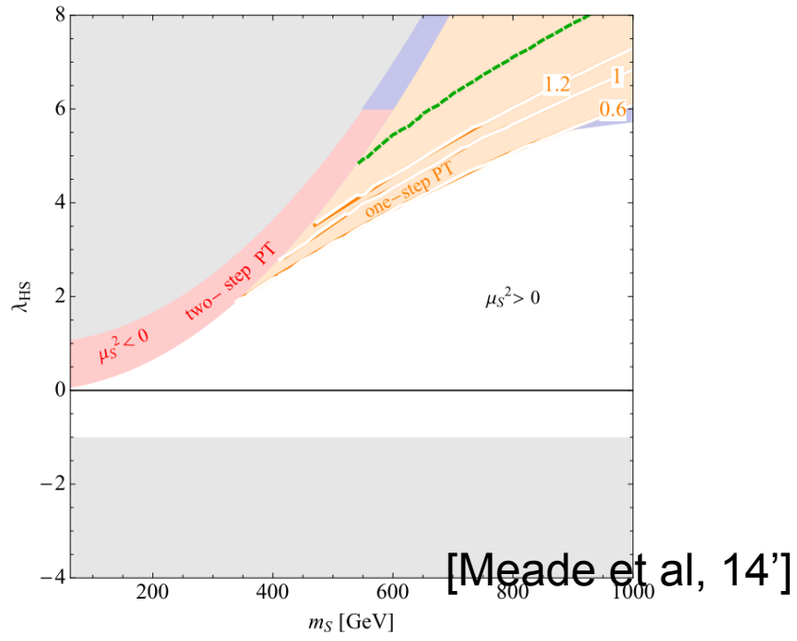


[Huang et al, 14']



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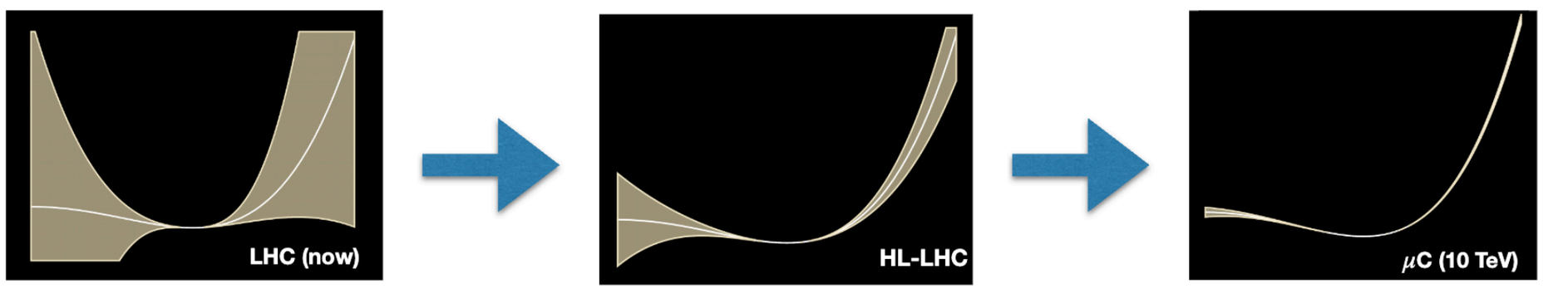

Courtesy of N. Craig

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

$$V_0 = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + \lambda^2 |S|^2 \left(|H_d|^2 + |H_u|^2\right) + \left|\lambda H_u \cdot H_d + \kappa S^2\right|^2$$
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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

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

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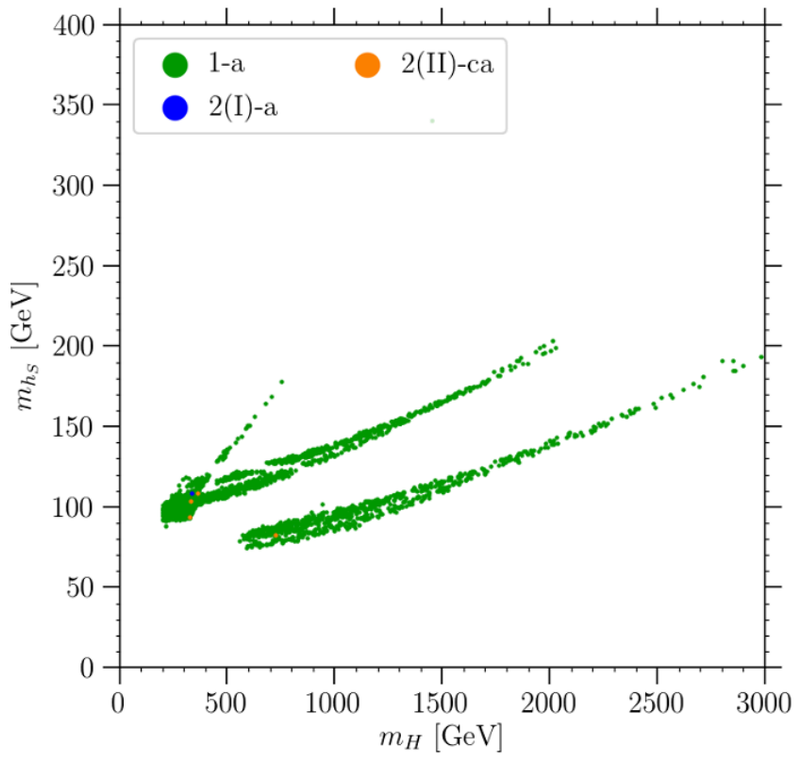
The mass eigenstate h_{125} dominantly composed of $H^{\rm SM}$.



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

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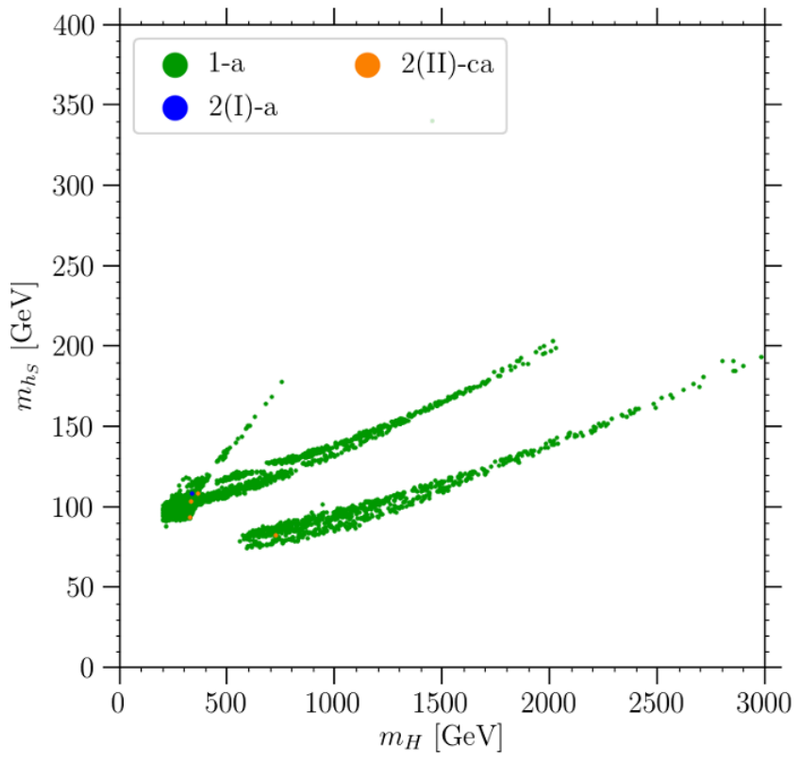

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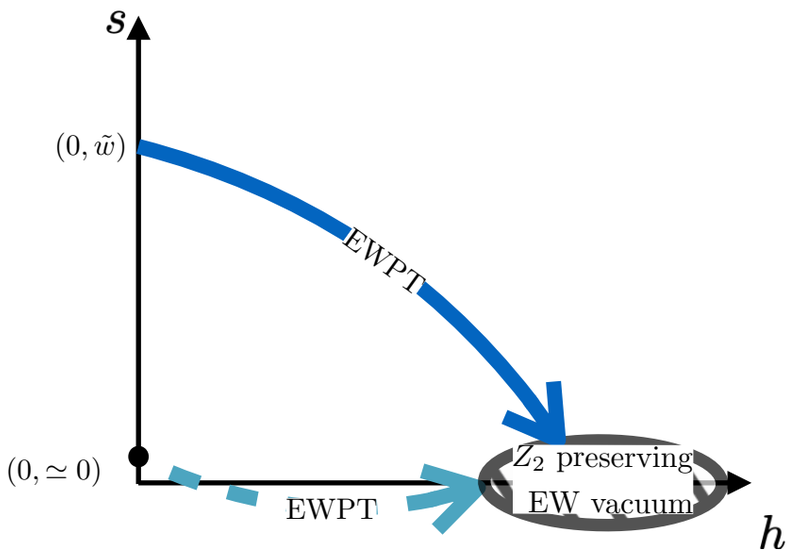

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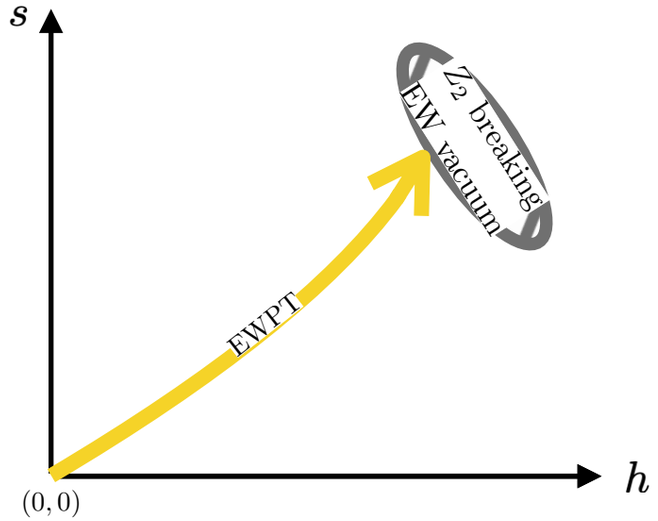

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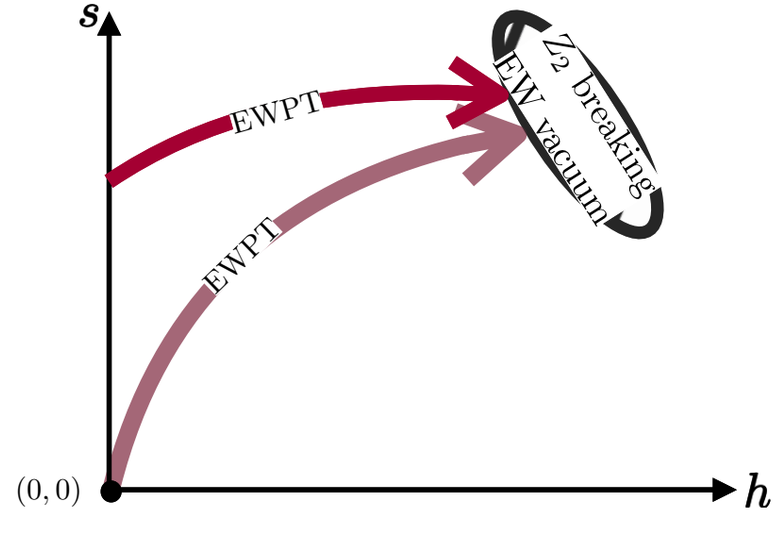

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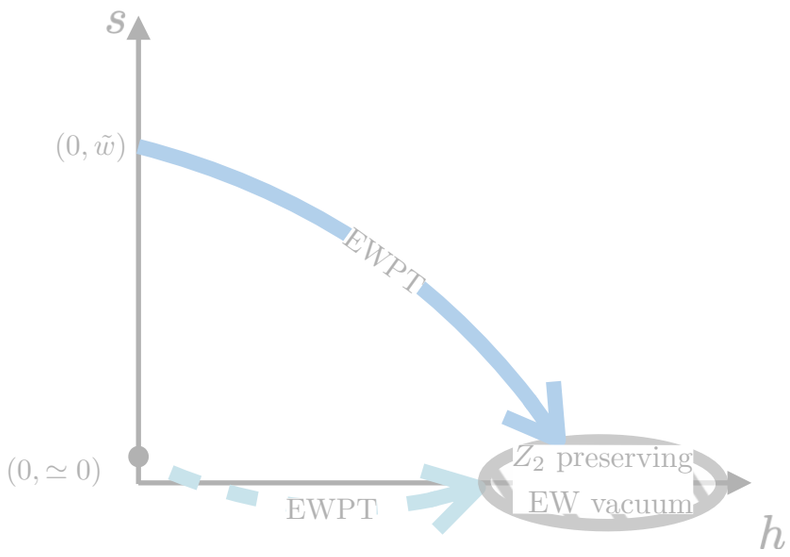

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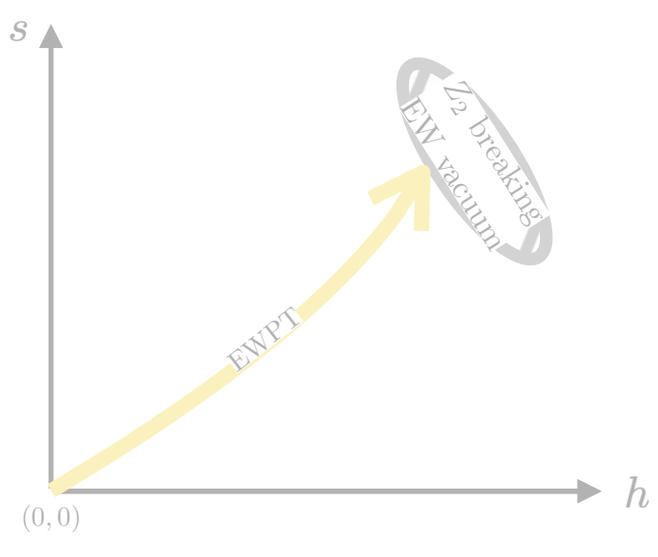

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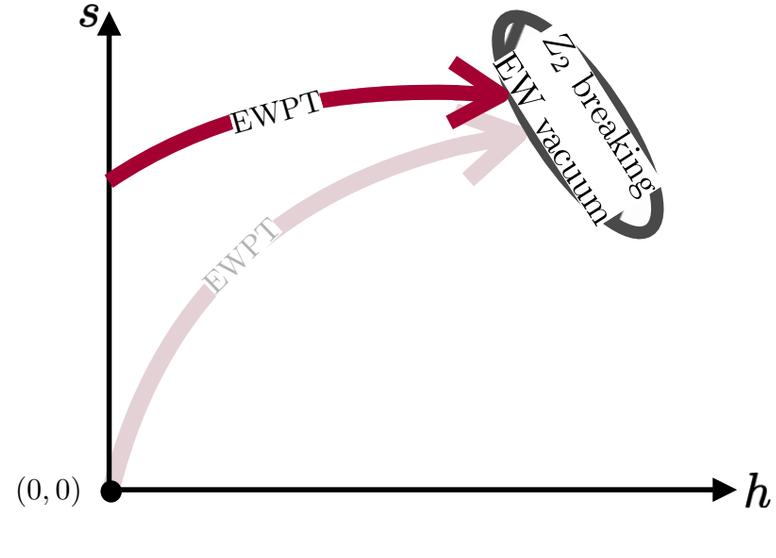

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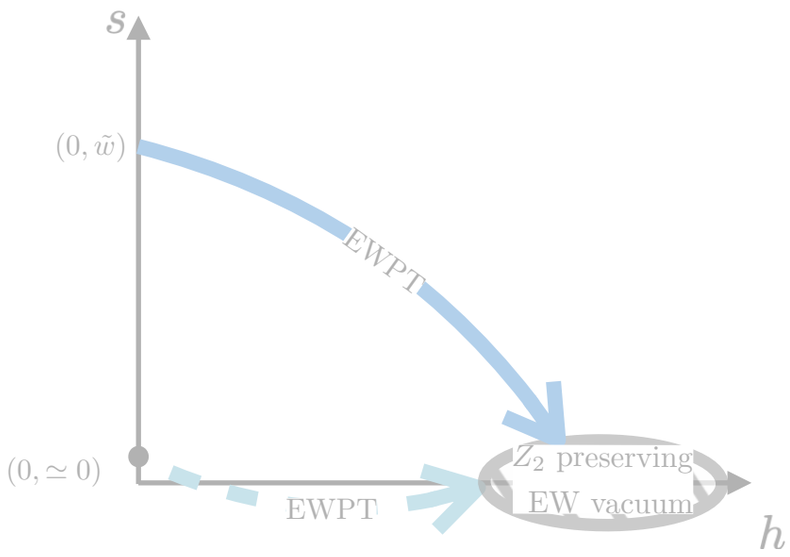

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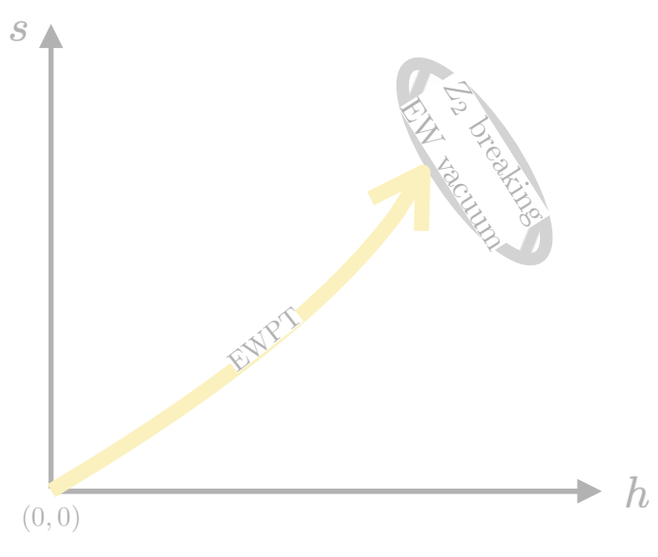

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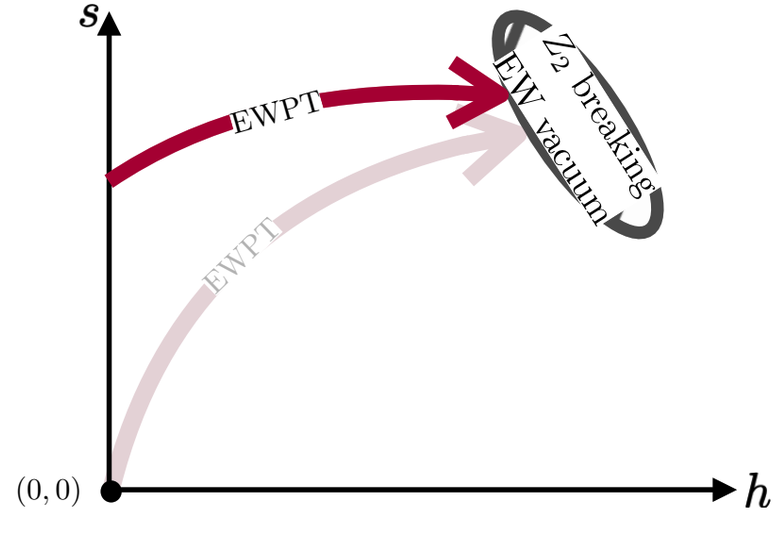

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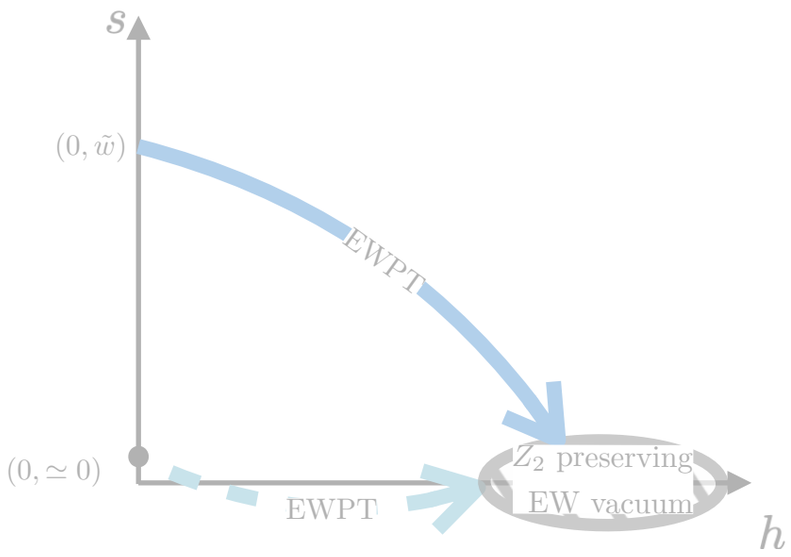

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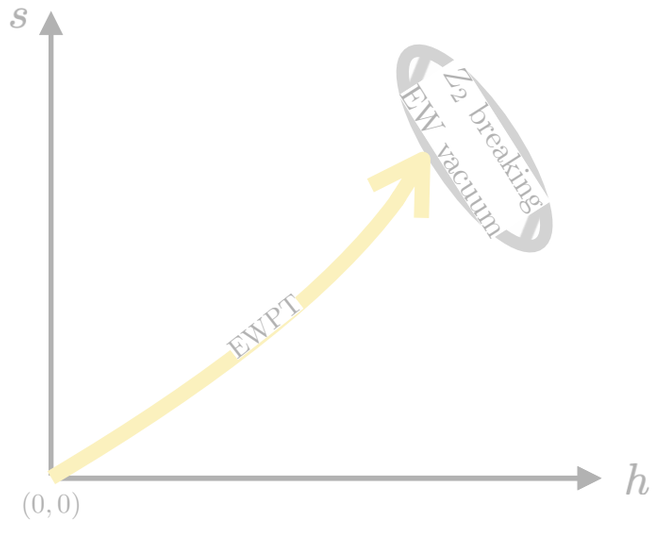

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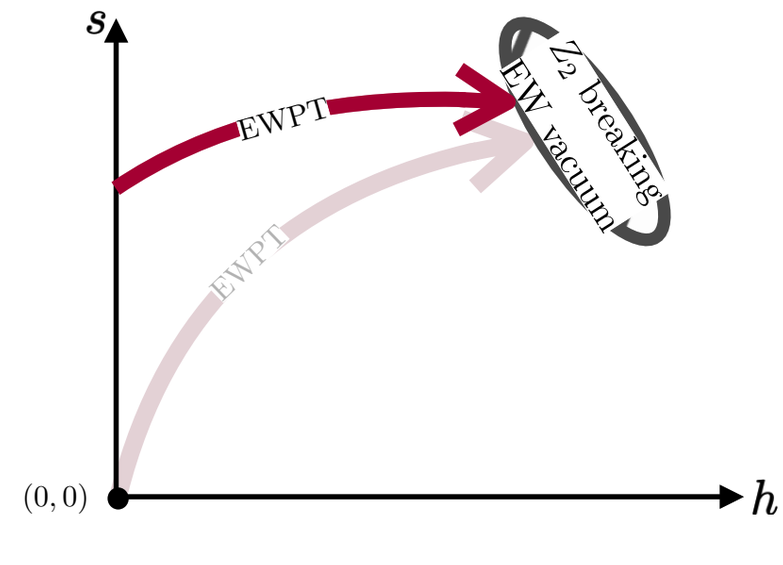

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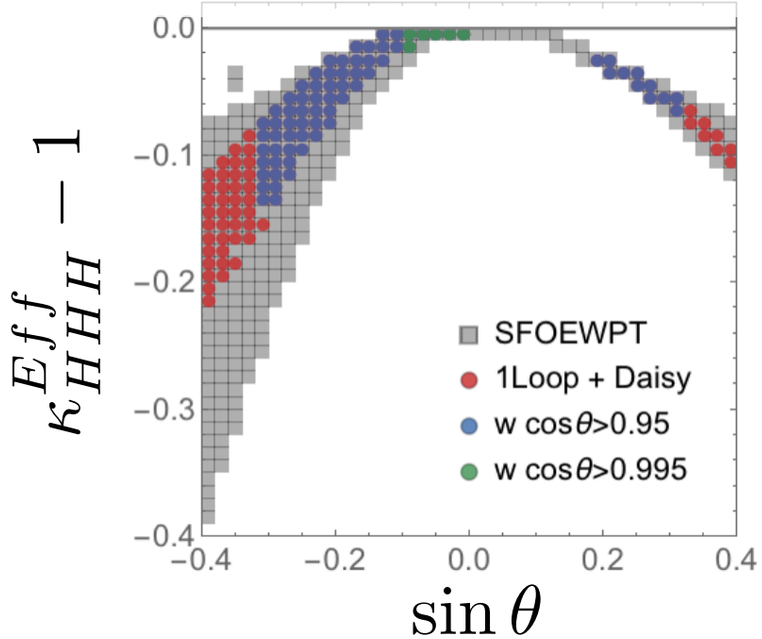
$$\Lambda_{SHH} = \frac{(2m_H^2 + m_S^2)(\sin\theta + \tan\beta\cos\theta)\sin 2\theta}{4\tan\beta\ v}.$$

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



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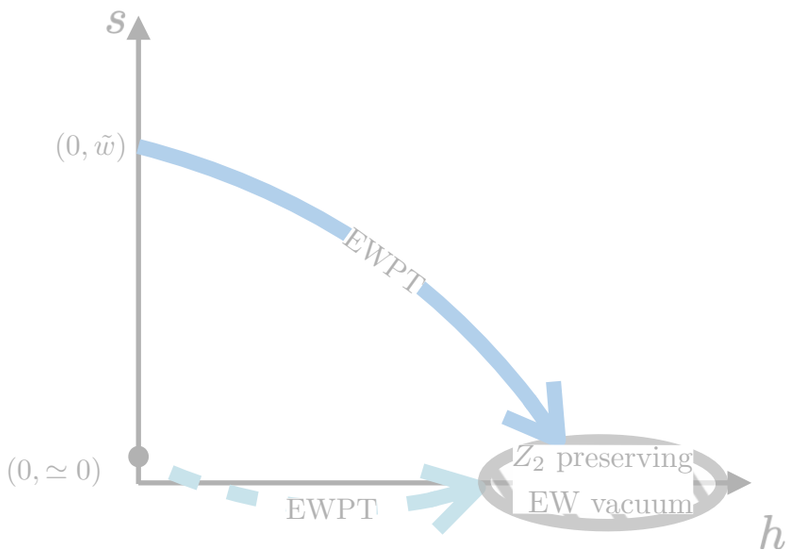

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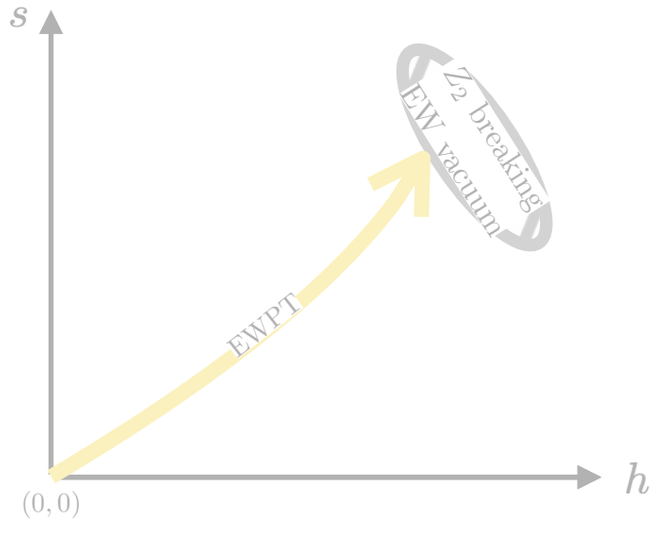

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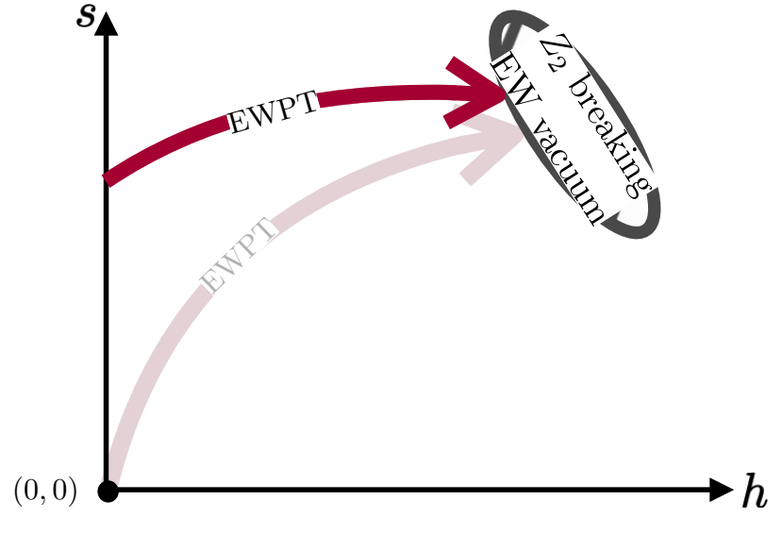

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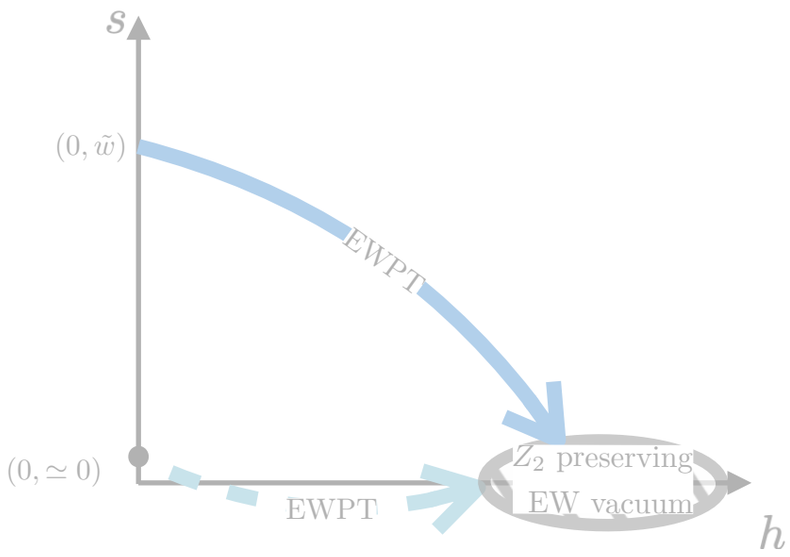

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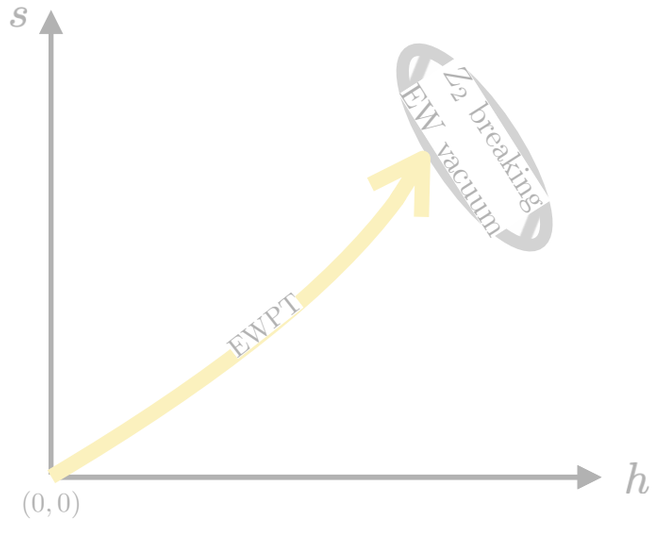

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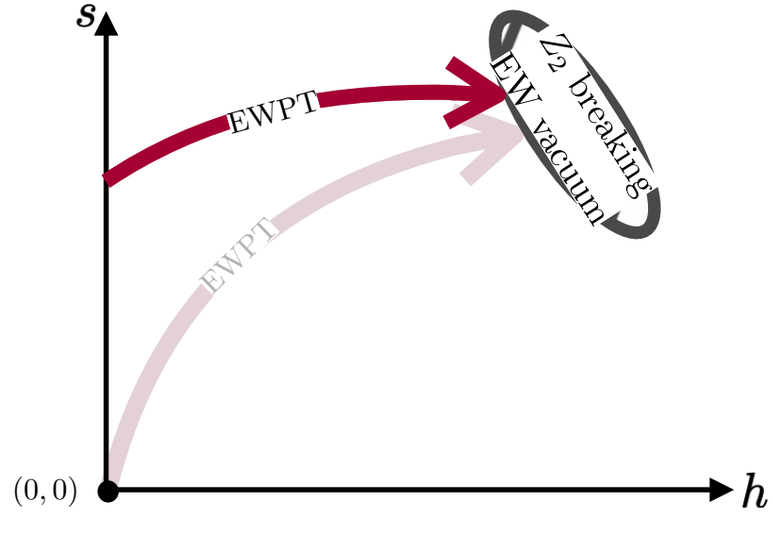

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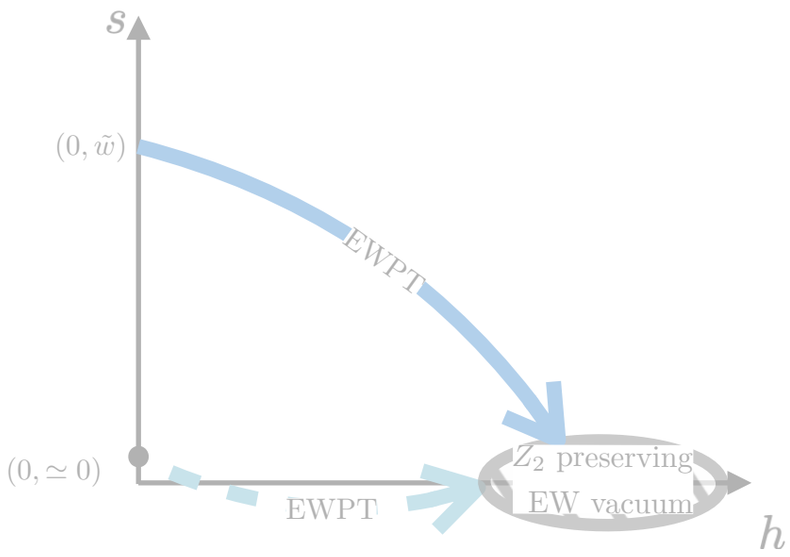

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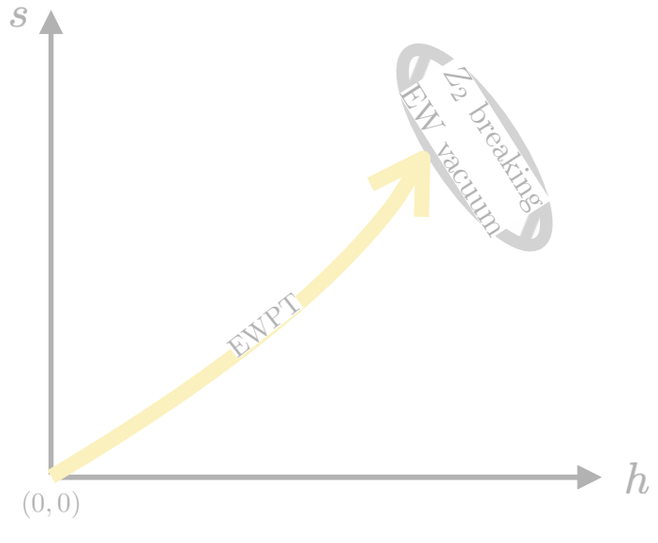

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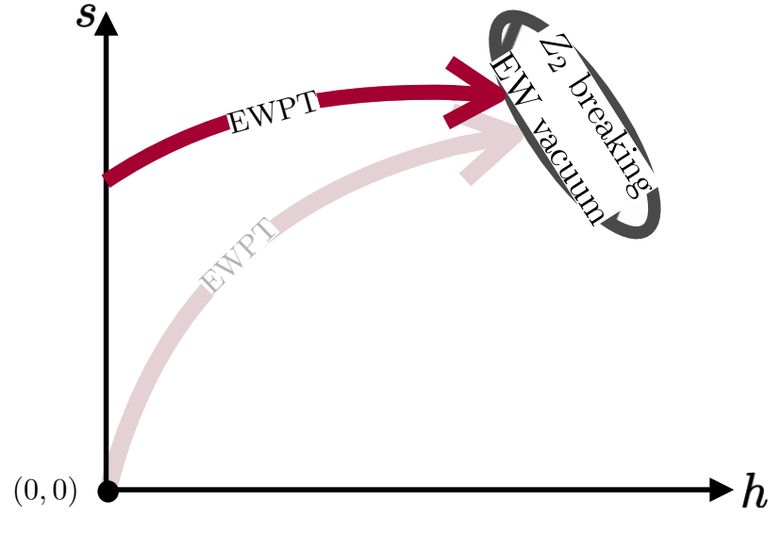

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Observation window: Higgs exotic decay

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.

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Topologies and final states

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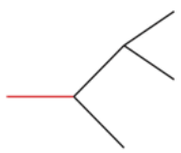
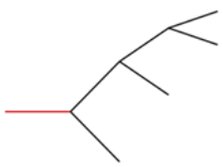
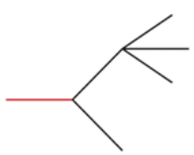
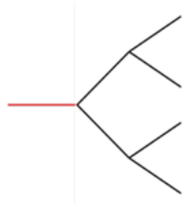
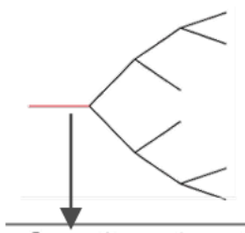
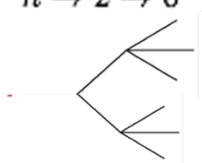
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_{\rm T}$ $h \to (b\bar{b}) + \not{E}_{\rm T}$ $h \to (jj) + \not{E}_{\rm T}$ $h \to (\tau^+\tau^-) + \not{E}_{\rm T}$ $h \to (\gamma\gamma) + \not{E}_{\rm T}$ $h \to (\ell^+\ell^-) + \not{E}_{\rm T}$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_{\rm T}$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

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

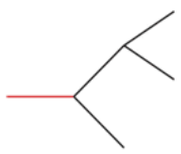
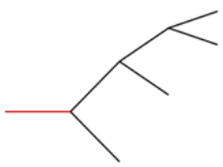
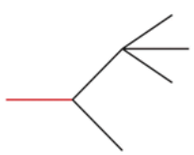
[Zhen Liu et al '13, 16']

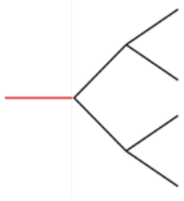
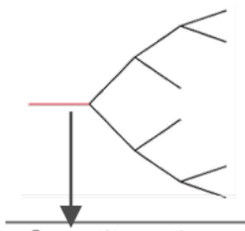
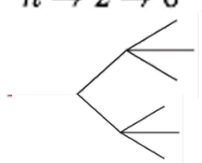
Higgs Exotic Decays: a rich variety of phenomenological interests

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

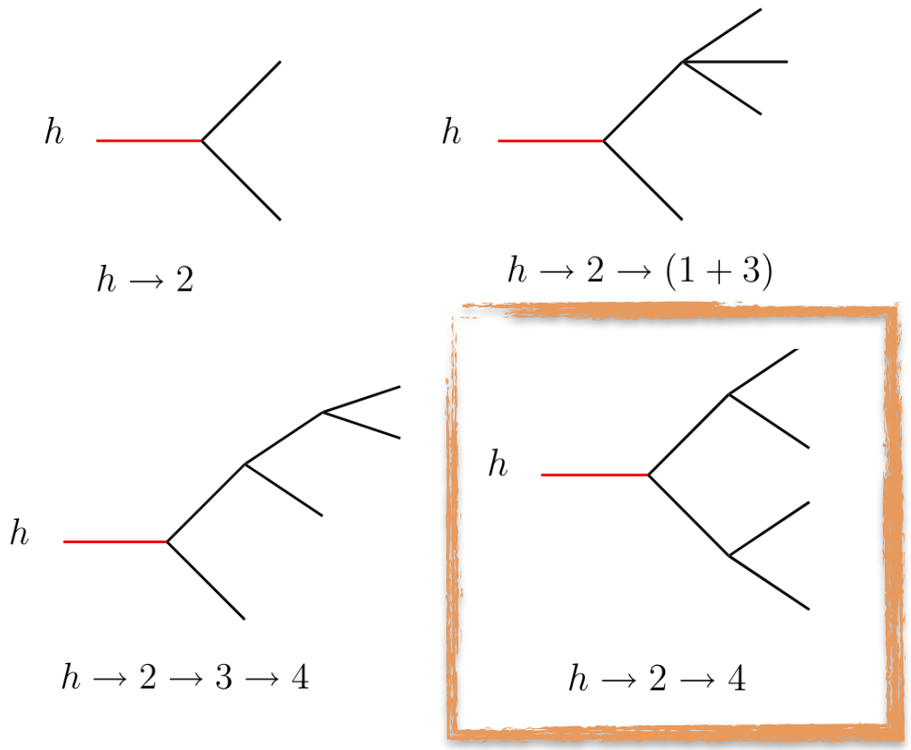
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to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

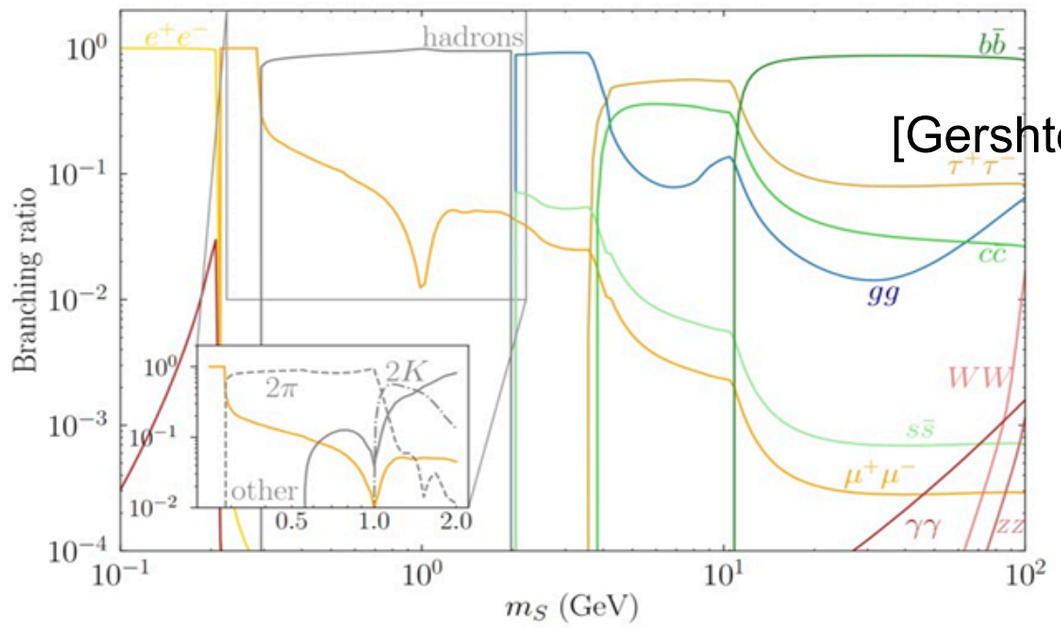
[Zhen Liu et al '13, 16']

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

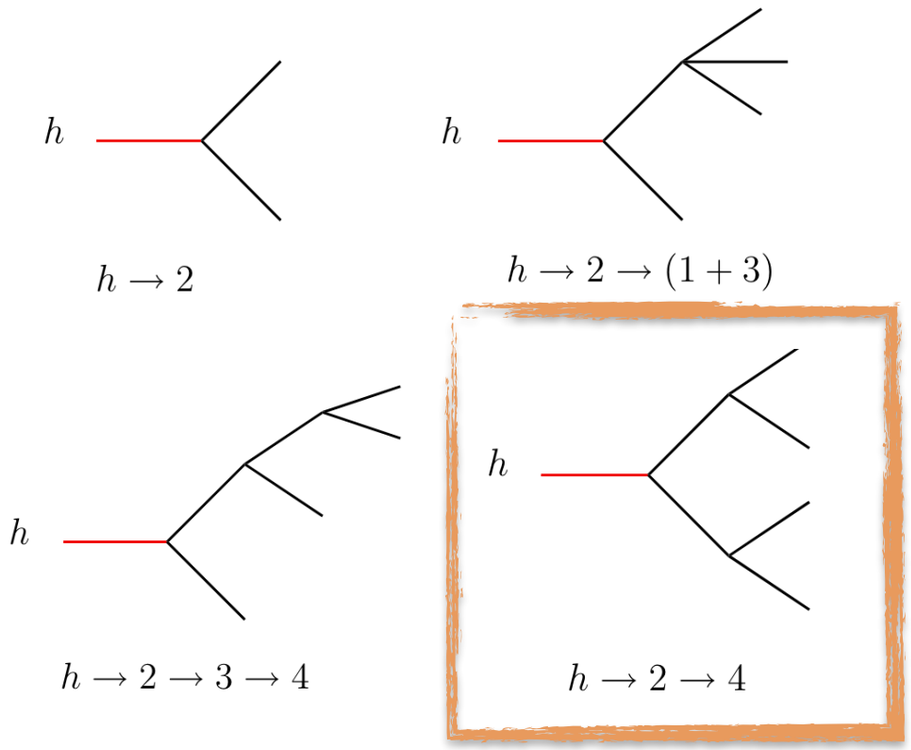
Electroweak phase transition and Higgs Exotic Decays

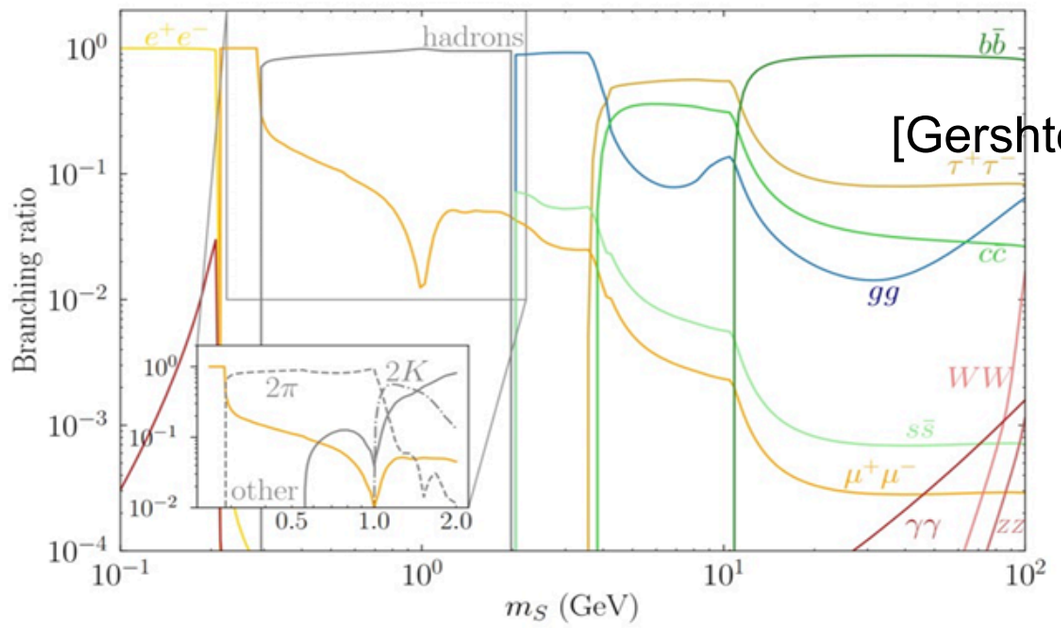




Higgs exotic decay $H \to SS$ and S branching fraction into $XXYY$ final states mediated through mixing.

Electroweak phase transition and Higgs Exotic Decays





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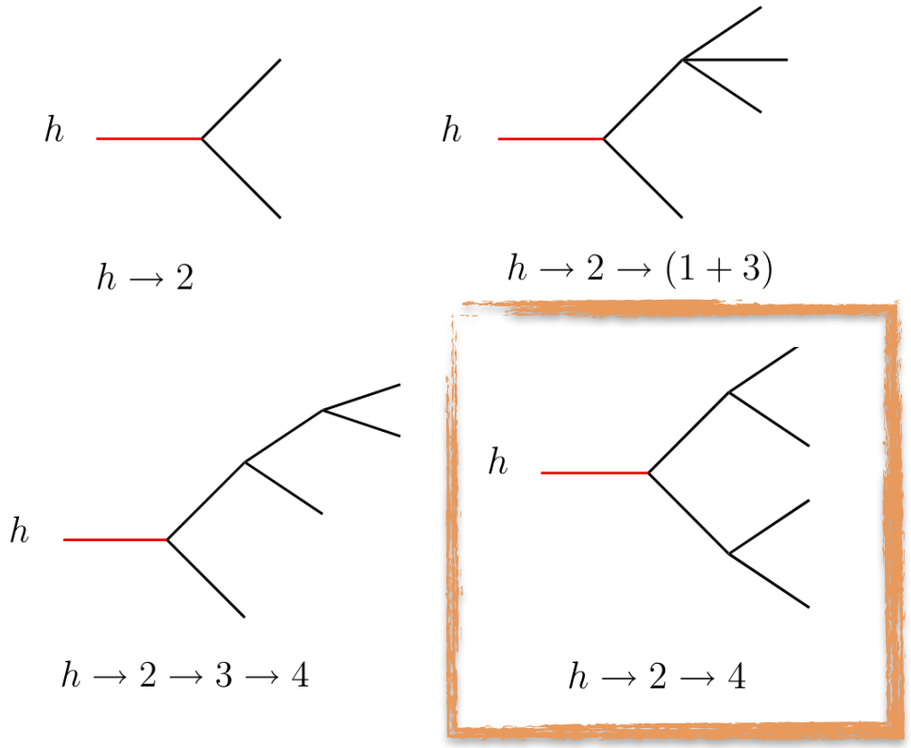
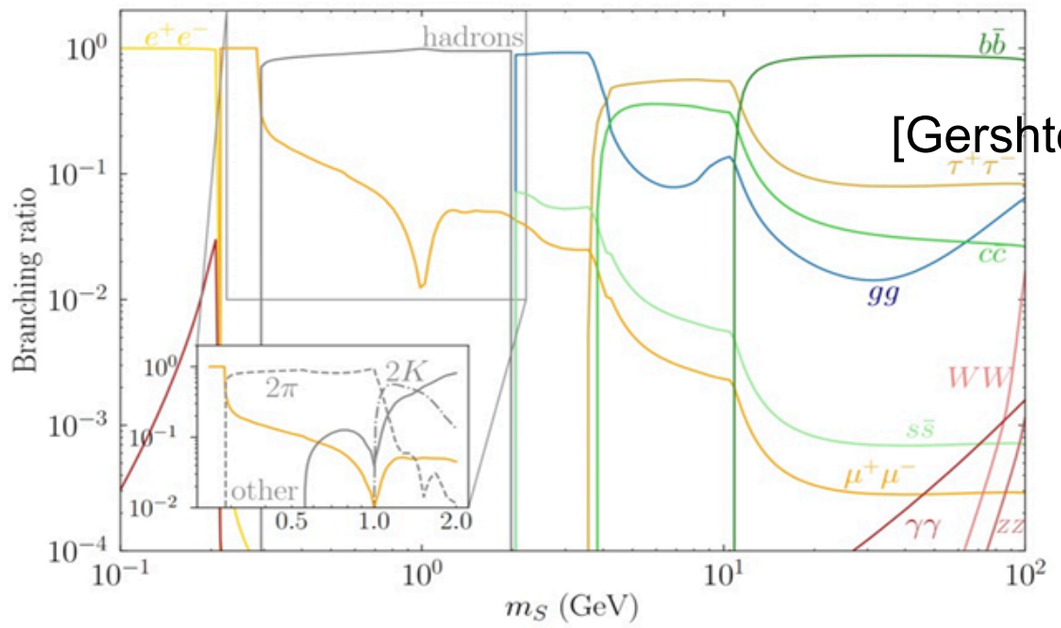
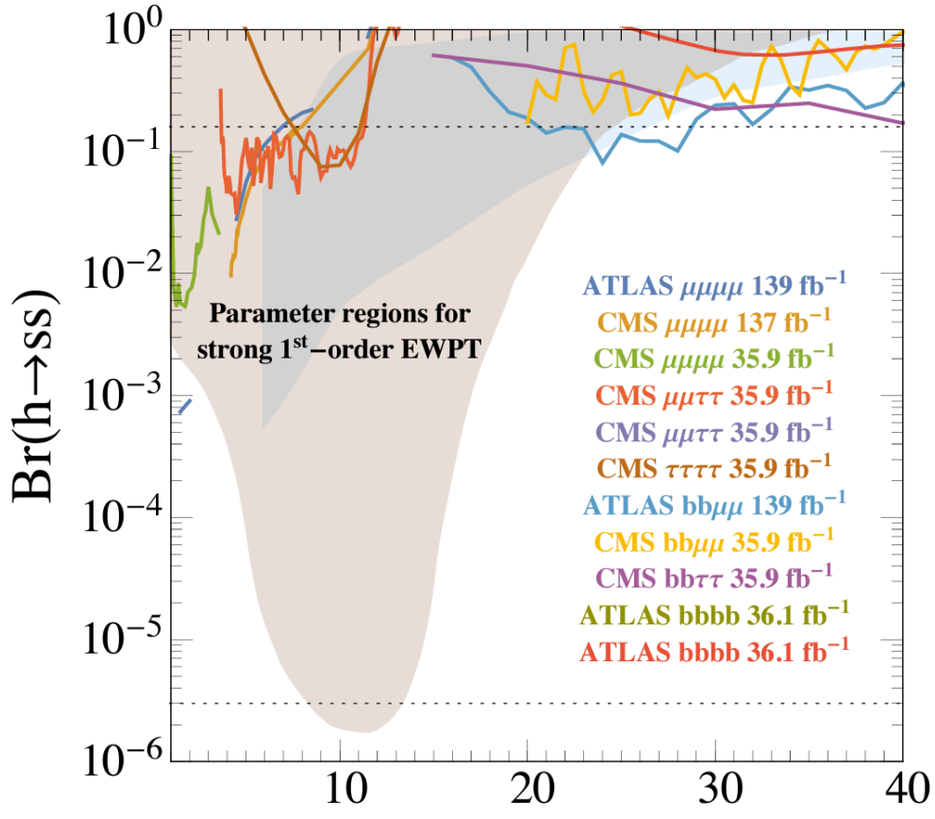
Electroweak phase transition and Higgs Exotic Decays





[Gershtein, et al, 21']

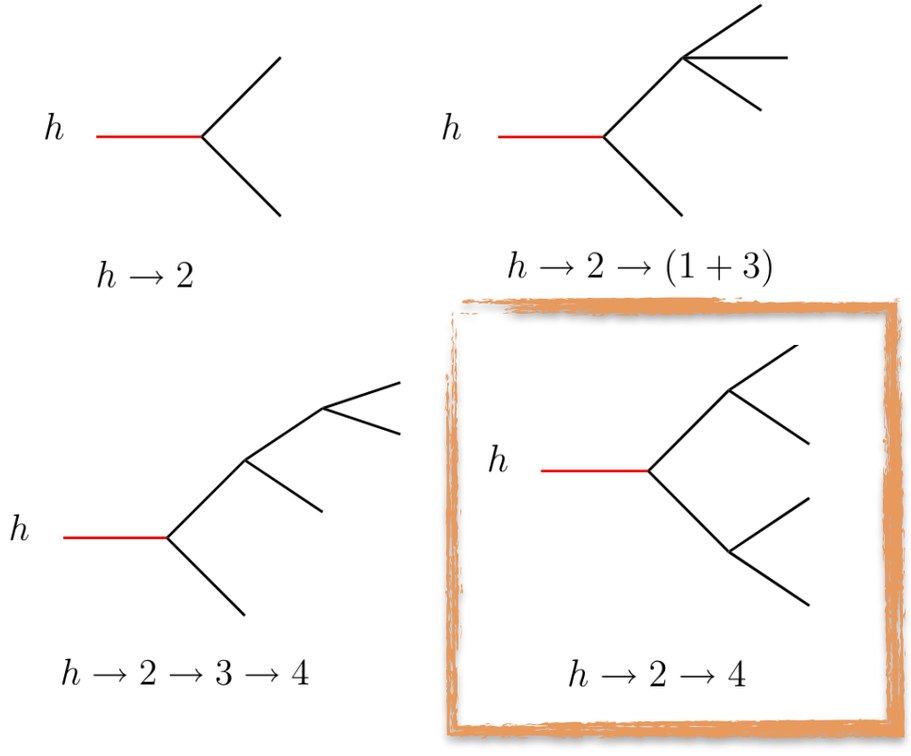
Higgs exotic decay $H \to SS$ and S branching fraction into $XXYY$ final states mediated through mixing.

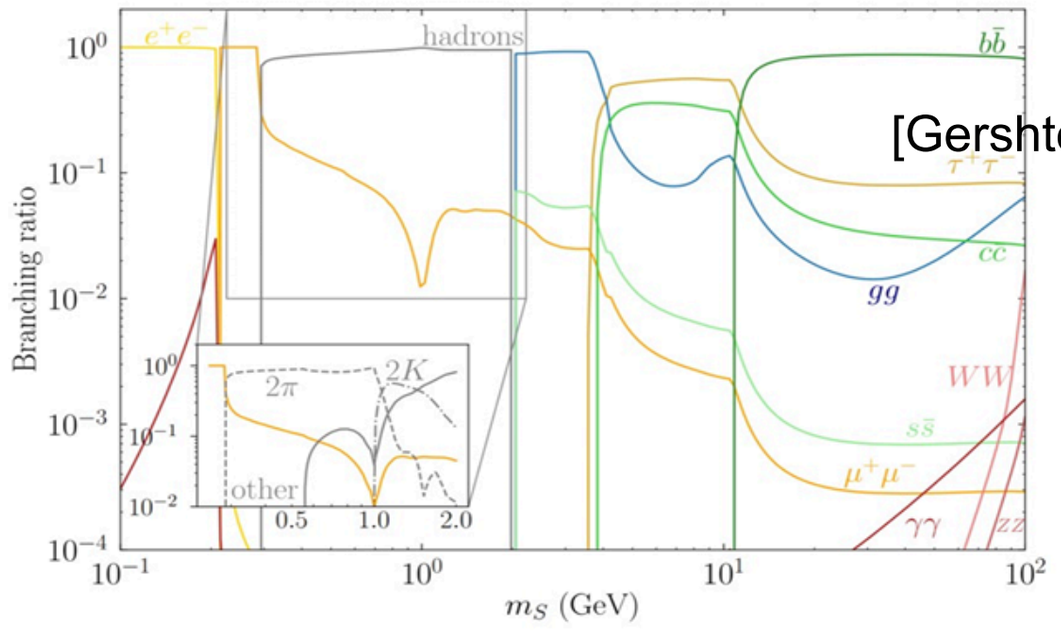


[Kozaczuk, et al, 19']

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

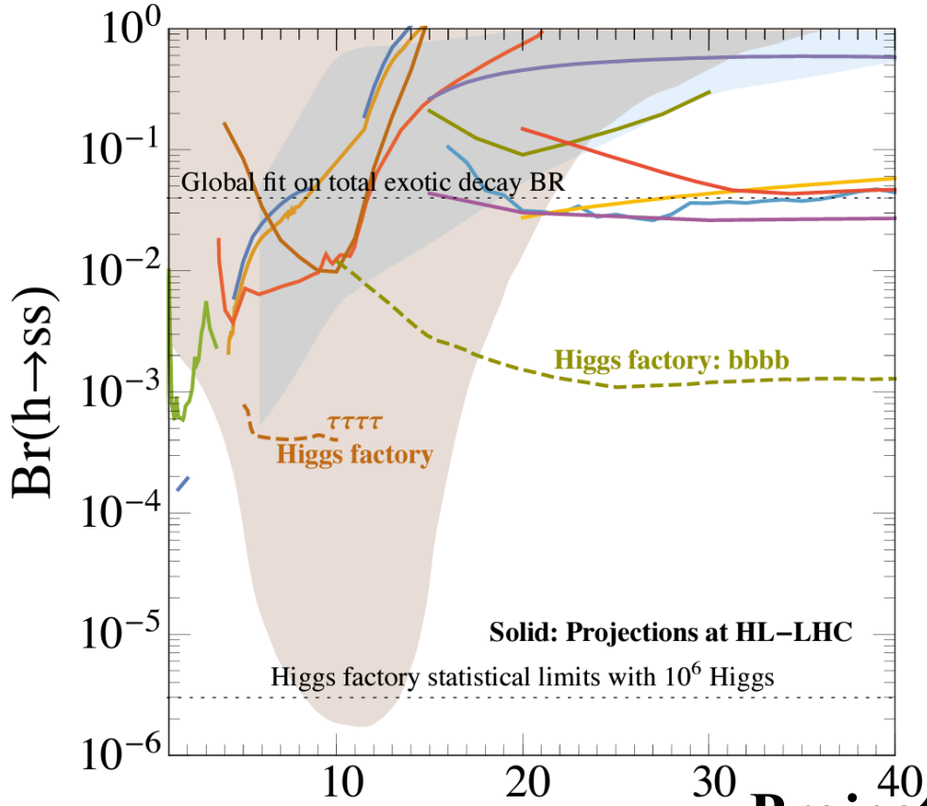
Electroweak phase transition and Higgs Exotic Decays





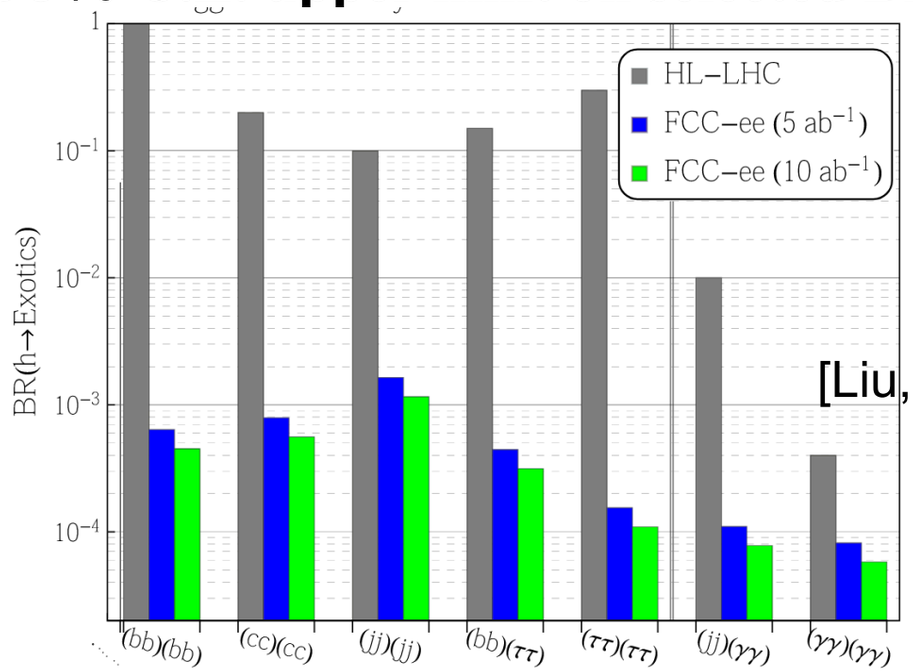
[Gershtein, et al, 21']

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



[Kozaczuk, et al, 19']

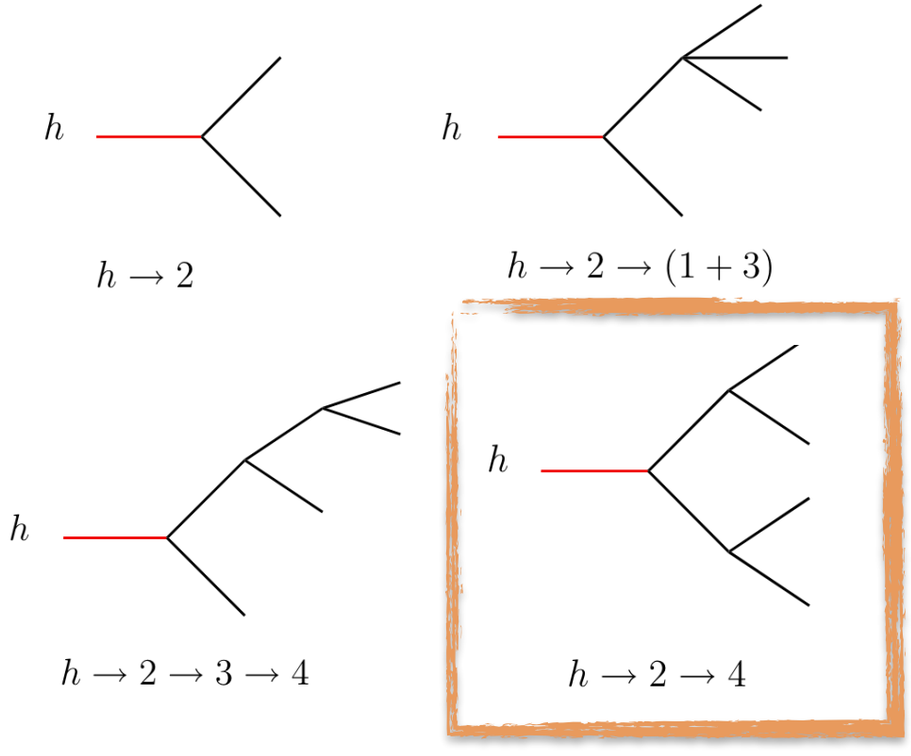
95% C.L. upper limit on selected BRs

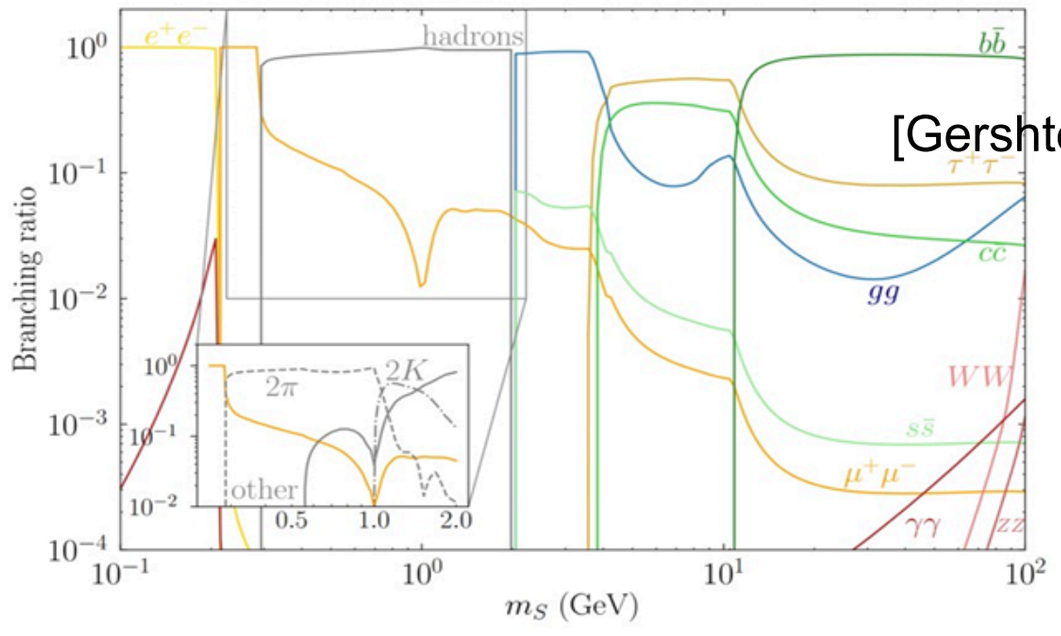


[Liu, et al, 16']

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

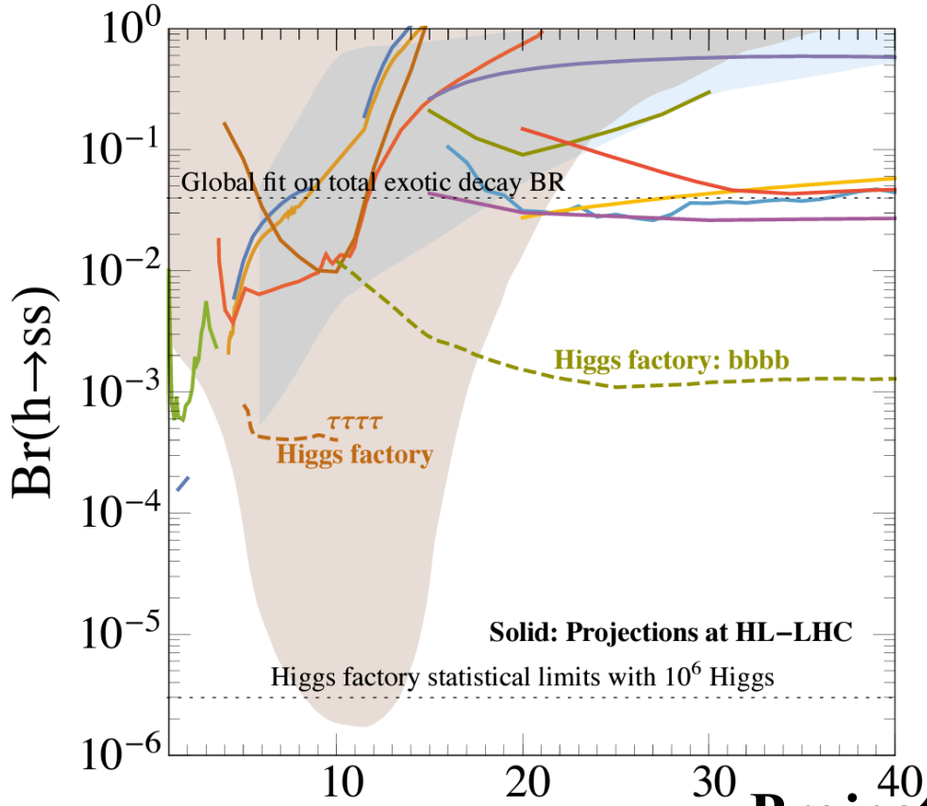
Electroweak phase transition and Higgs Exotic Decays





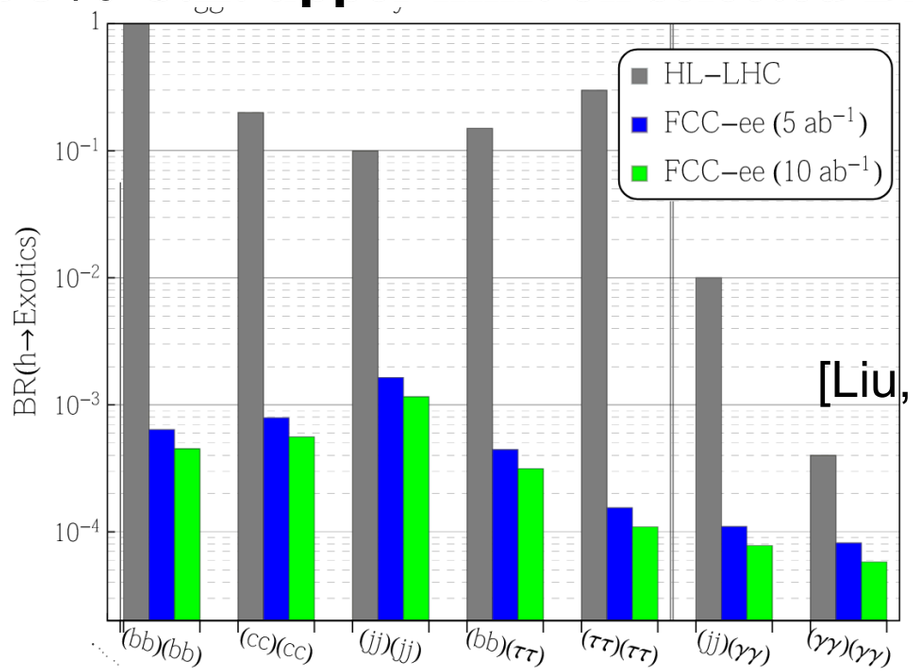
[Gershtein, et al, 21']

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

- The Higgs is tightly connected to many open questions that need introduction of beyond the Standard Model physics;
- The extended Higgs sector contains ample opportunities to answer such questions;
- 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 electroweak phase transition, and additional CP violation sources;
- Some interesting channels to look: trilinear Higgs coupling, Higgs exotic decays, and more!