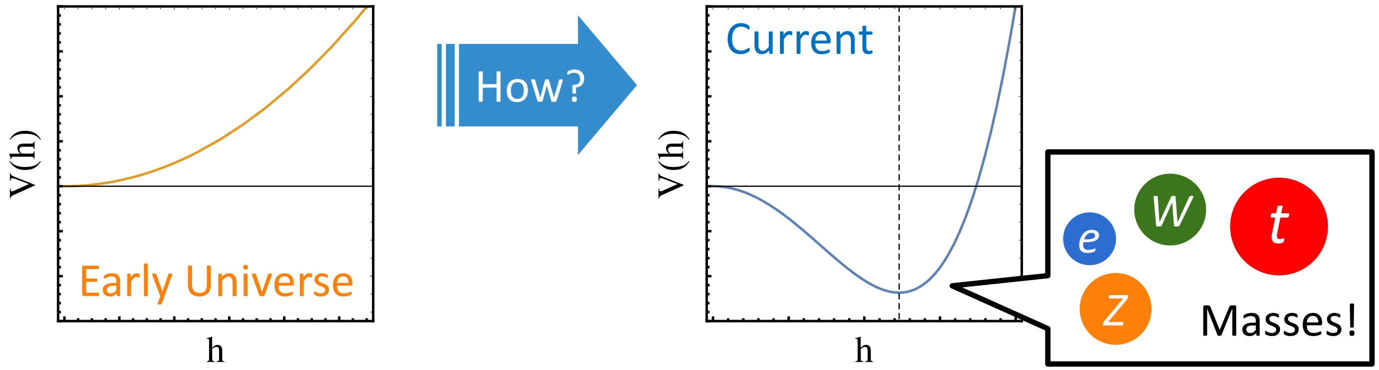
Probing the Electroweak Phase Transition with Exotic Higgs Decays

Ke-Pan Xie (谢柯盼)
University of Nebraska-Lincoln

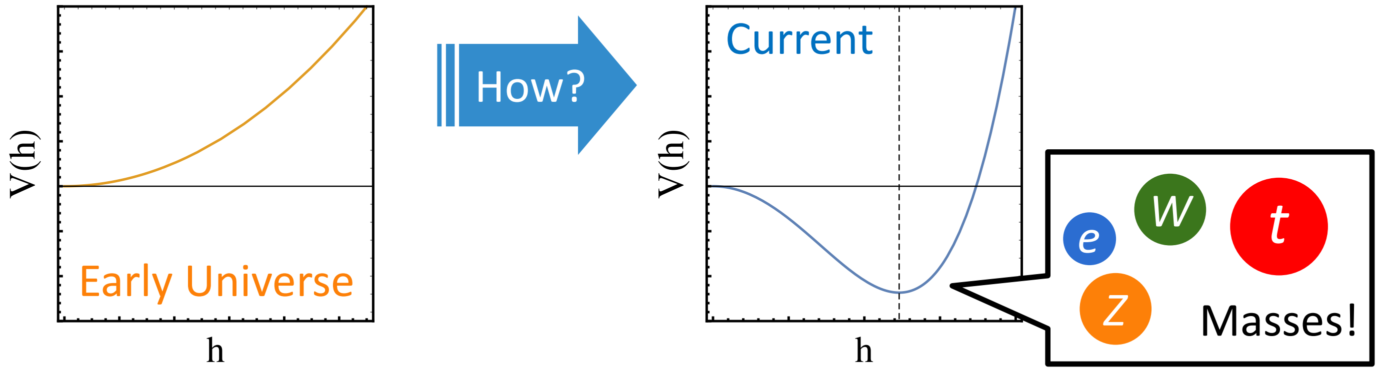
2022.5.25 @CEPC workshop 2022 (online)

Snowmass whitepaper 2203.08206 with Marcela Carena, Jonathan Kozaczuk, Zhen Liu, Tong Ou, Michael J. Ramsey-Musolf, Jessie Shelton and Yikun Wang

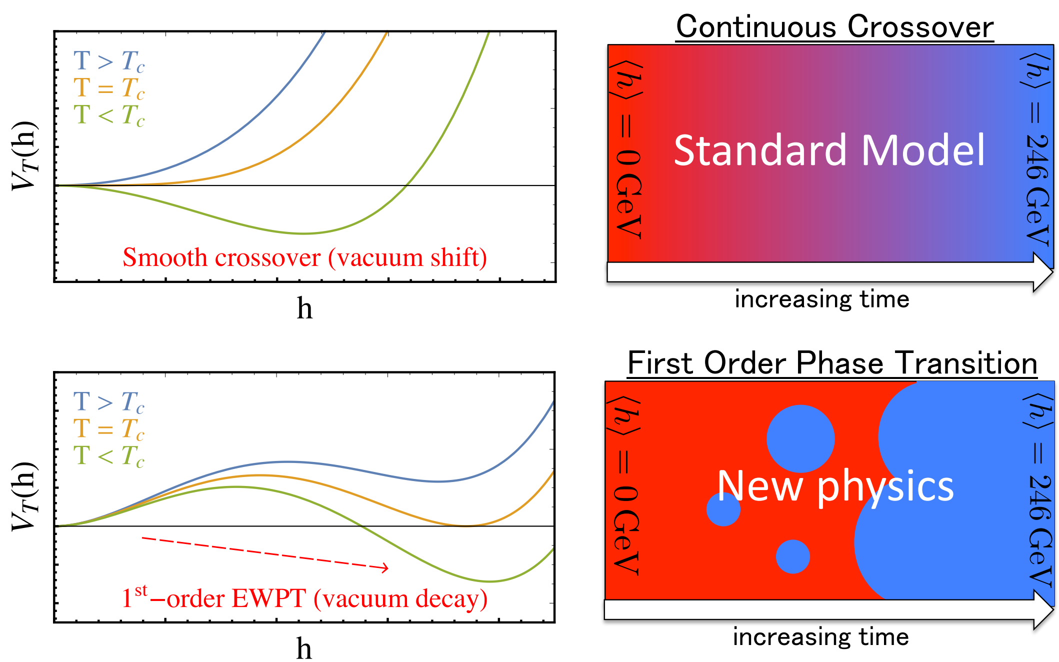
Electroweak phase transition



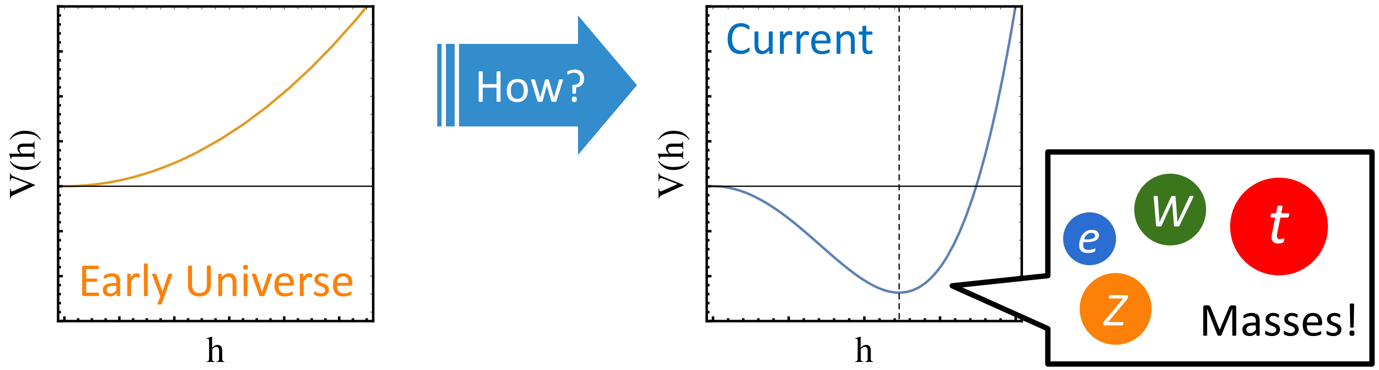
Electroweak phase transition



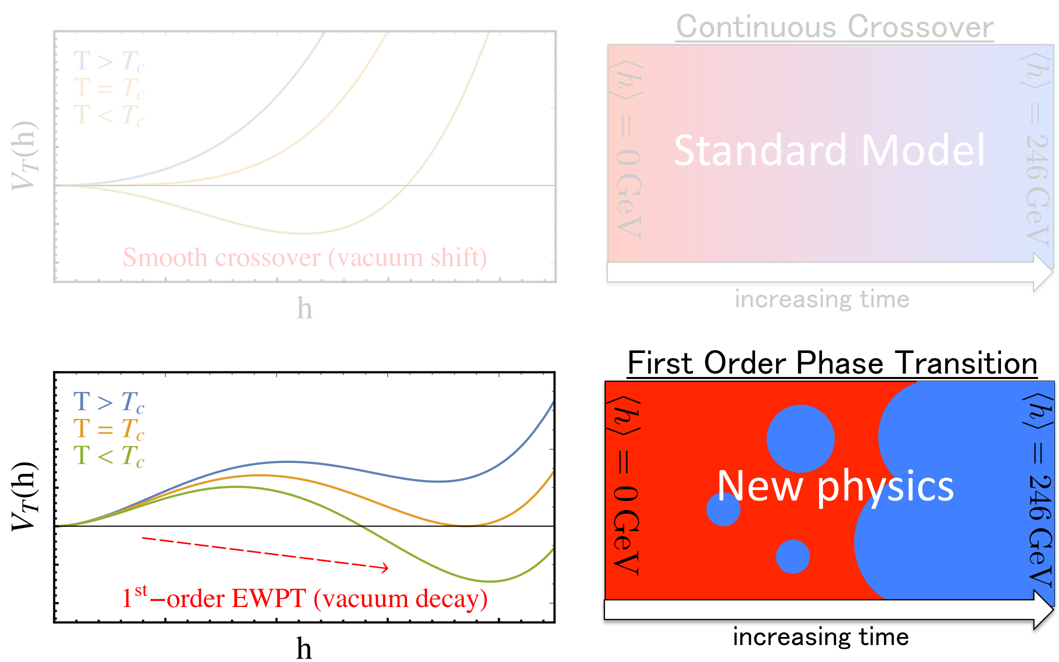
Two possibilities

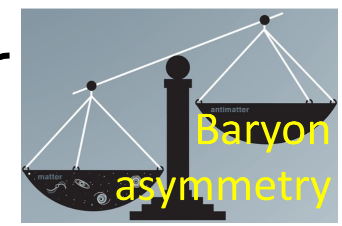


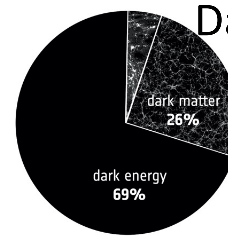
Electroweak phase transition



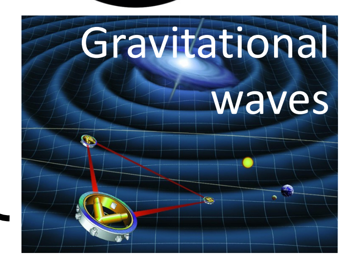
Two possibilities



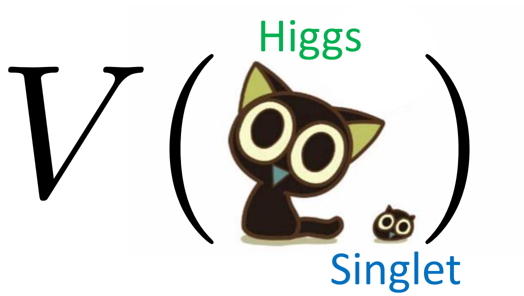




Dark matter or PBHs



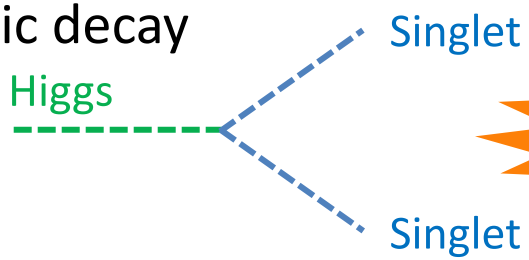
New physics from **Light** degrees of freedom

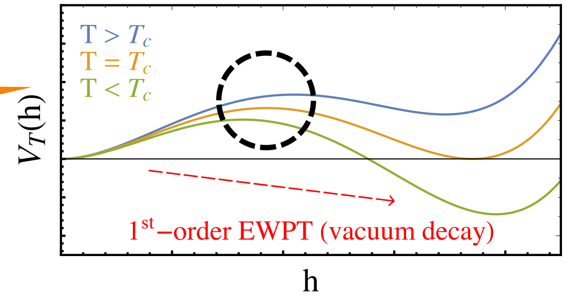


Higgs + singlet: scalar portal

Simple, but general

Exotic decay





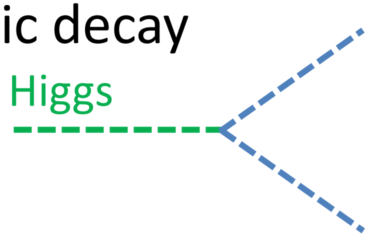
New physics from **Light** degrees of freedom

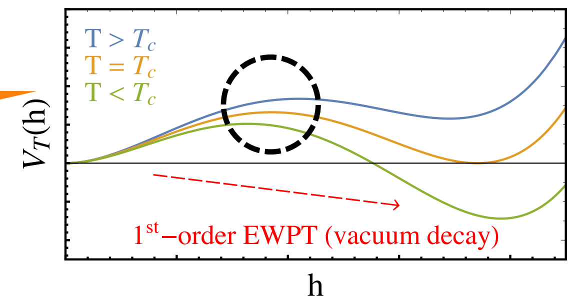
$V($  $)$

Higgs + singlet: scalar portal

Simple, but general

Exotic decay





Scenarios:

1. General Higgs + singlet [Kozaczuk *et al*, 1911.10210]

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \frac{a_1}{2}|H|^2S + \frac{a_2}{2}|H|^2S^2 + b_1S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

2. Singlet Z_2

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \frac{a_2}{2}|H|^2S^2 + \frac{b_2}{2}S^2 + \frac{b_4}{4}S^4 \begin{cases} Z_2 \text{ preserving} & \text{[Kozaczuk et al, 1911.10210]} \\ Z_2 \text{ spontaneous breaking} & \text{[Carena et al, 1911.10206]} \end{cases}$$

The Z_2 preserving scenario

Motivated by dark matter,[1407.0688] composite Higgs[1909.02014], etc

$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \boxed{\frac{a_2}{4}h^2 S^2} + \frac{b_2}{2}S^2 + \frac{b_4}{4}S^4$$

After EW symmetry breaking, Higgs exotic decay

$$V \supset -\frac{a_2 v_{\rm EW}}{2} h S^2 \qquad \Gamma(h \to SS) = \frac{a_2^2 v_{\rm EW}^2}{32\pi m_h}\sqrt{1 - \frac{4m_S^2}{m_h^2}}$$

The Z_2 preserving scenario

Motivated by dark matter,[1407.0688] composite Higgs[1909.02014], etc

$$V=-\frac{\mu^2}{2}h^2+\frac{\lambda}{4}h^4+\boxed{\frac{a_2}{4}h^2S^2}+\frac{b_2}{2}S^2+\frac{b_4}{4}S^4$$

After EW symmetry breaking, Higgs exotic decay

$$V\supset-\frac{a_2v_{\rm EW}}{2}hS^2 \qquad\qquad \Gamma(h\to SS)=\frac{a_2^2v_{\rm EW}^2}{32\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}}$$

Thermal correction and phase transition

$$V=-\frac{\mu^2-c_hT^2}{2}h^2+\frac{\lambda}{4}h^4+\frac{a_2}{4}h^2S^2+\frac{b_2+c_ST^2}{2}S^2+\frac{b_4}{4}S^4$$

$$\boxed{\begin{aligned}c_h&=\frac{1}{48}\left(24a_2+9g^2+3g'^2+24\lambda+12y_t^2\right),\\ c_S&=\frac{1}{12}\left(2a_2+3b_4\right)\end{aligned}}$$

The Z_2 preserving scenario

Motivated by dark matter,[1407.0688] composite Higgs[1909.02014], etc

$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \boxed{\frac{a_2}{4}h^2S^2} + \frac{b_2}{2}S^2 + \frac{b_4}{4}S^4$$

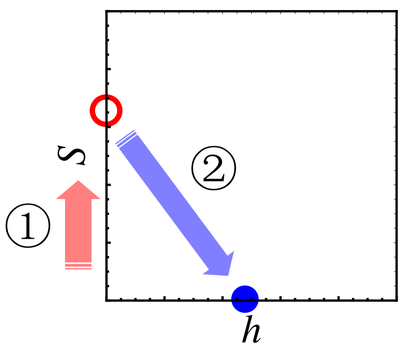
After EW symmetry breaking, Higgs exotic decay

$$V \supset -\frac{a_2 v_{\rm EW}}{2}hS^2 \qquad \Gamma(h\to SS) = \frac{a_2^2 v_{\rm EW}^2}{32\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}}$$

Thermal correction and phase transition

$$V = -\frac{\mu^2 - c_h T^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{a_2}{4}h^2S^2 + \frac{b_2 + c_S T^2}{2}S^2 + \frac{b_4}{4}S^4$$

$$\boxed{\begin{aligned} c_h &= \frac{1}{48}\left(24a_2 + 9g^2 + 3g'^2 + 24\lambda + 12y_t^2\right), \\ c_S &= \frac{1}{12}\left(2a_2 + 3b_4\right) \end{aligned}}$$



Two steps:

① $2^{\rm nd}$-order phase transition

② $1^{\rm st}$-order electroweak phase transition

The Z_2 preserving scenario

Motivated by dark matter,[1407.0688] composite Higgs[1909.02014], etc

$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \boxed{\frac{a_2}{4}h^2S^2} + \frac{b_2}{2}S^2 + \frac{b_4}{4}S^4$$

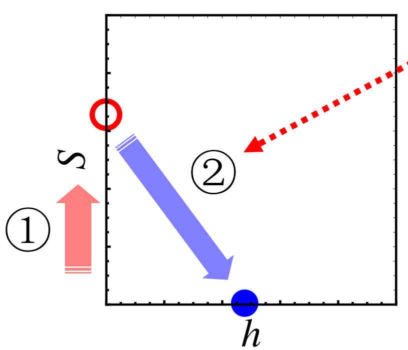
Higgs exotic decay

$$V \supset -\frac{a_2 v_{\rm EW}}{2}hS^2 \qquad \Gamma(h\to SS) = \frac{a_2^2 v_{\rm EW}^2}{32\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}}$$

Thermal correction and phase transition

$$V = -\frac{\mu^2 - c_h T^2}{2}h^2 + \frac{\lambda}{4}h^4 + \boxed{\frac{a_2}{4}h^2S^2} + \frac{b_2 + c_S T^2}{2}S^2 + \frac{b_4}{4}S^4$$

$$\boxed{\begin{aligned} c_h &= \frac{1}{48}\left(24a_2 + 9g^2 + 3g'^2 + 24\lambda + 12y_t^2\right), \\ c_S &= \frac{1}{12}\left(2a_2 + 3b_4\right) \end{aligned}}$$



Two steps:

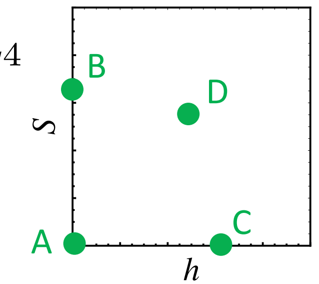
① 2nd-order phase transition

② 1st-order electroweak phase transition

Relation between a_2 and phase transition

Condition for two degenerate vacua

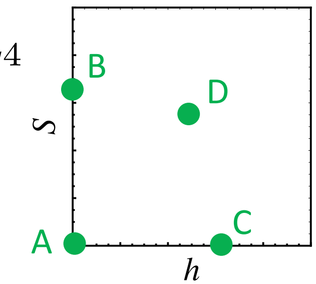
$$V = -\frac{\mu^2 - c_h T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \frac{a_2}{4} h^2 S^2 + \frac{b_2 + c_S T^2}{2} S^2 + \frac{b_4}{4} S^4$$



Relation between a_2 and phase transition

Condition for two degenerate vacua

$$V = -\frac{\mu^2 - c_h T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \frac{a_2}{4} h^2 S^2 + \frac{b_2 + c_S T^2}{2} S^2 + \frac{b_4}{4} S^4$$



Some facts:[1909.02014]

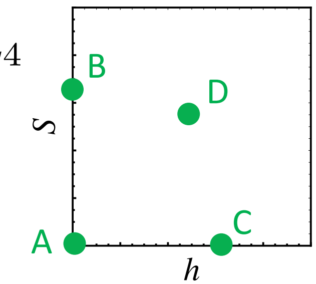
1. ABCD could be either local extrema or saddle points;
2. If D is a minimum then BC are saddle points;
3. If A is a minimum then BC are saddle points, while D is NOT a minimum.
4. The only case of two degenerate vacua is BC, which requires $b_2 < 0$.

$$\boxed{m_S = \sqrt{b_2 + \frac{a_2^2}{2} v_{\rm EW}^2}}$$

Relation between a_2 and phase transition

Condition for two degenerate vacua

$$V = -\frac{\mu^2 - c_h T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \frac{a_2}{4} h^2 S^2 + \frac{b_2 + c_S T^2}{2} S^2 + \frac{b_4}{4} S^4$$



Some facts:[1909.02014]

1. ABCD could be either local extrema or saddle points;
2. If D is a minimum then BC are saddle points;
3. If A is a minimum then BC are saddle points, while D is NOT a minimum.
4. The only case of two degenerate vacua is BC, which requires $b_2 < 0$.

$$\boxed{m_S = \sqrt{b_2 + \frac{a_2^2}{2} v_{\rm EW}^2}}$$

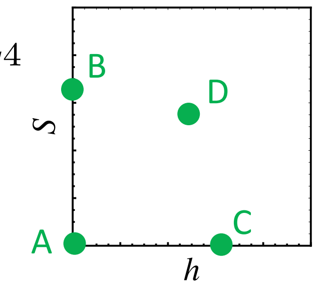
Therefore we get

$$\boxed{a_2 > \frac{2m_S^2}{v_{\rm EW}^2}}$$

Relation between a_2 and phase transition

Condition for two degenerate vacua

$$V = -\frac{\mu^2 - c_h T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \frac{a_2}{4} h^2 S^2 + \frac{b_2 + c_S T^2}{2} S^2 + \frac{b_4}{4} S^4$$



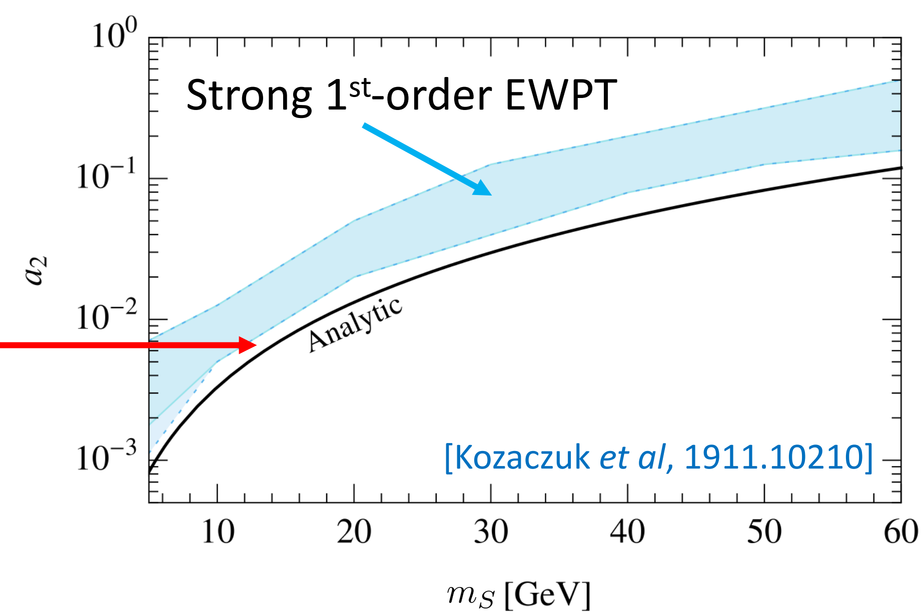
Some facts:[1909.02014]

1. ABCD could be either local extrema or saddle points;
2. If D is a minimum then BC are saddle points;
3. If A is a minimum then BC are saddle points, while D is NOT a minimum.
4. The only case of two degenerate vacua is BC, which requires $b_2 < 0$.

$$\boxed{m_S = \sqrt{b_2 + \frac{a_2^2}{2} v_{\rm EW}^2}}$$

Therefore we get

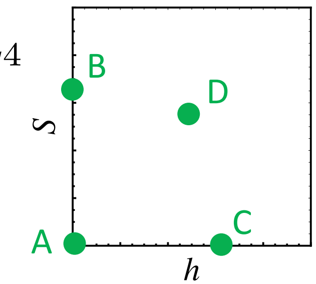
$$\boxed{a_2 > \frac{2m_S^2}{v_{\rm EW}^2}}$$



Relation between a_2 and phase transition

Condition for two degenerate vacua

$$V = -\frac{\mu^2 - c_h T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \frac{a_2}{4} h^2 S^2 + \frac{b_2 + c_S T^2}{2} S^2 + \frac{b_4}{4} S^4$$



Some facts:[1909.02014]

1. ABCD could be either local extrema or saddle points;
2. If D is a minimum then BC are saddle points;
3. If A is a minimum then BC are saddle points, while D is NOT a minimum.
4. The only case of two degenerate vacua is BC, which requires $b_2 < 0$.

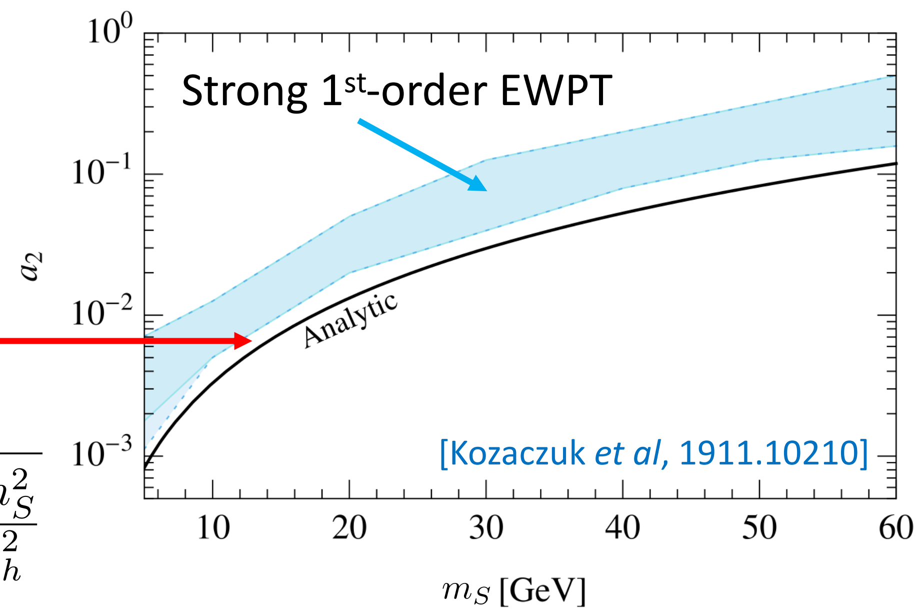
$$\boxed{m_S = \sqrt{b_2 + \frac{a_2^2}{2} v_{\rm EW}^2}}$$

Therefore we get

$$\boxed{a_2 > \frac{2m_S^2}{v_{\rm EW}^2}}$$

Which is a lower limit on

$$\Gamma(h \to SS) = \frac{a_2^2 v_{\rm EW}^2}{32\pi m_h} \sqrt{1 - \frac{4m_S^2}{m_h^2}}$$



The general Higgs + singlet case

The potential in unitary gauge

$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{a_1}{4}h^2 S + \frac{a_2}{4}h^2 S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

$$\boxed{h \to v_{\rm EW} + h, \quad S \to v_s + S}$$

Shift *S* such that v_s = 0; expand around vacuum

$$\begin{array}{r} \text{Singlet-like} \\ \text{Higgs-like} \end{array} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S \\ h \end{pmatrix}$$

Exotic decay

$$V \supset \frac{1}{2}\lambda_{211} h_2 h_1^2 \qquad \Gamma(h_2 \to h_1 h_1) = \frac{1}{32\pi m_2}\lambda_{211}^2 \sqrt{1 - \frac{4m_1^2}{m_2^2}}$$

Light *S*: LEP & LHC-- $|\sin\theta| \lesssim 0.07$; future colliders $|\sin\theta| \sim 0.01$

$$\boxed{\begin{aligned} &\lambda = \frac{m_2^2}{2v_{\rm EW}^2} + \mathcal{O}(\theta^2), \quad b_2 = -\frac{1}{2}a_2 v_{\rm EW}^2 + m_1^2 + \mathcal{O}(\theta^2) \times m_2^2, \\ &a_1 = \mathcal{O}(\theta) \times \frac{m_2^2}{v_{\rm EW}}, \quad b_1 = \mathcal{O}(\theta) \times m_2^2 v_{\rm EW} \end{aligned}}$$

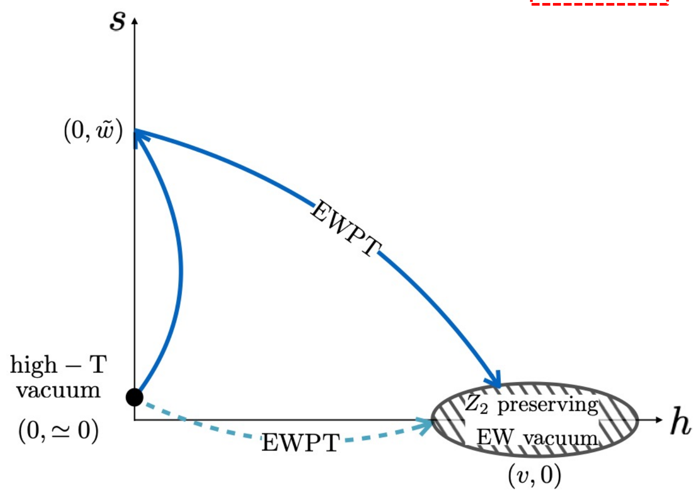
[Kozaczuk *et al*, 1911.10210]

$$\boxed{\frac{\lambda_{211}}{v_{\rm EW}} = -a_2 + \mathcal{O}(\theta^2)}$$

The general Higgs + singlet case

The potential at finite temperature

$$V = -\frac{\mu^2 - c_h T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \boxed{\frac{a_1}{4} h^2 S} + \boxed{\frac{a_2}{4} h^2 S^2} + b_1 S + \frac{b_2 + c_S T^2}{2} S^2 + \boxed{\frac{b_3}{3} S^3} + \frac{b_4}{4} S^4$$

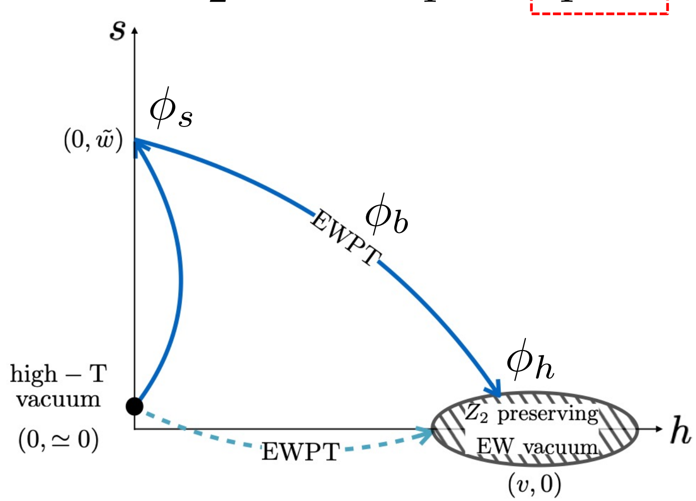


$$\boxed{\begin{aligned} c_h &= \frac{1}{48}\left(24 a_2 + 9 g^2 + 3 g'^2 + 24\lambda + 12 y_t^2\right), \\ c_S &= \frac{1}{12}\left(2 a_2 + 3 b_4\right) \end{aligned}}$$

The general Higgs + singlet case

The potential at finite temperature

$$V = -\frac{\mu^2 - c_h T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \boxed{\frac{a_1}{4} h^2 S} + \boxed{\frac{a_2}{4} h^2 S^2} + b_1 S + \frac{b_2 + c_S T^2}{2} S^2 + \boxed{\frac{b_3}{3} S^3} + \frac{b_4}{4} S^4$$

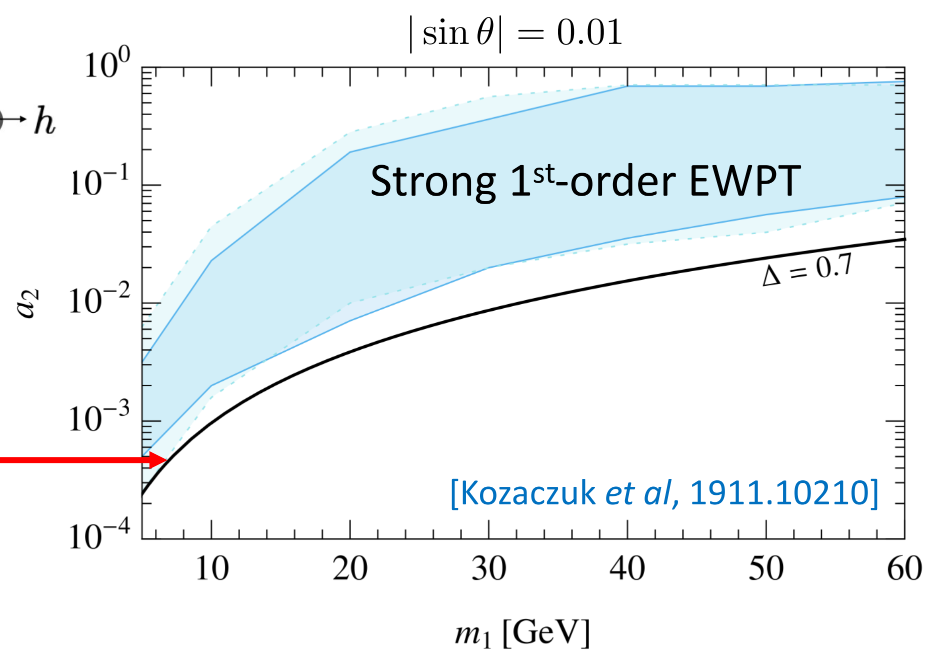


$$\boxed{\begin{aligned} c_h &= \frac{1}{48}\left(24 a_2 + 9 g^2 + 3 g'^2 + 24\lambda + 12 y_t^2\right), \\ c_S &= \frac{1}{12}\left(2 a_2 + 3 b_4\right) \end{aligned}}$$

Analytical estimation

$$\frac{V(\phi_s, T_*) - V(\phi_h, T_*)}{V(\phi_b, T_*) - V(\phi_h, T_*)} > \Delta$$

$$\boxed{a_2 \gtrsim \frac{m_1^2}{4 v_{\rm EW}^2} \frac{\Delta}{1 - \Delta}}$$



The Z_2 spontaneous breaking scenario

Motivated by dark symmetry breaking models[Carena *et al*, 1911.10206]

$$V=-\frac{\mu^2}{2}h^2+\frac{\lambda}{4}h^4+\frac{a_2}{4}h^2S^2+\frac{b_2}{2}S^2+\frac{b_4}{4}S^4$$

A complete one-loop level analysis

$$V_{\rm CW}=\frac{1}{64\pi^2}\left(\sum_B n_B m_B^4(h,S)\left[\ln\frac{m_B^2(h,S)}{Q^2}-c_B\right]-\sum_F n_F m_F^4(h,S)\left[\ln\frac{m_F^2(h,S)}{Q^2}-\frac{3}{2}\right]\right)$$

$$V^T(h,s,T)=\frac{T^4}{2\pi^2}\left[\sum_B n_B J_B\left(\frac{m_B^2(h,S)}{T^2}\right)+\sum_F n_F J_F\left(\frac{m_F^2(h,S)}{T^2}\right)\right]+\text{Daisy resummation}$$

The Z_2 spontaneous breaking scenario

Motivated by dark symmetry breaking models[Carena *et al*, 1911.10206]

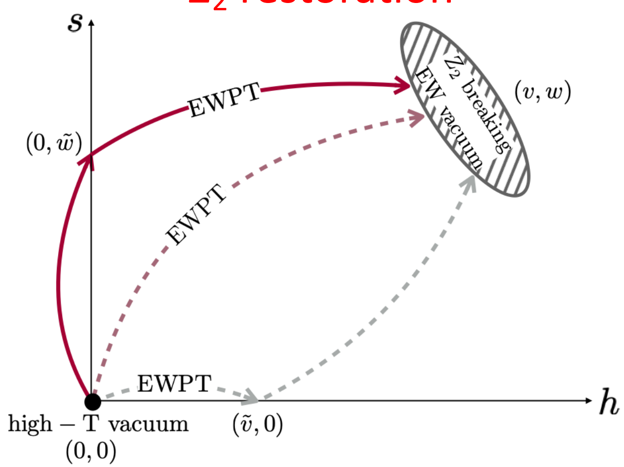
$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{a_2}{4}h^2S^2 + \frac{b_2}{2}S^2 + \frac{b_4}{4}S^4$$

A complete one-loop level analysis

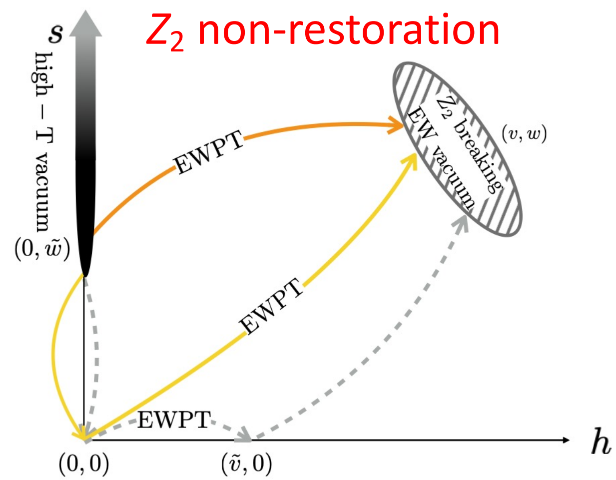
$$V_{\rm CW} = \frac{1}{64\pi^2}\left(\sum_B n_B m_B^4(h,S)\left[\ln\frac{m_B^2(h,S)}{Q^2} - c_B\right] - \sum_F n_F m_F^4(h,S)\left[\ln\frac{m_F^2(h,S)}{Q^2} - \frac{3}{2}\right]\right)$$

$$V^T(h,s,T) = \frac{T^4}{2\pi^2}\left[\sum_B n_B J_B\left(\frac{m_B^2(h,S)}{T^2}\right) + \sum_F n_F J_F\left(\frac{m_F^2(h,S)}{T^2}\right)\right] + \text{Daisy resummation}$$

Z_2 restoration

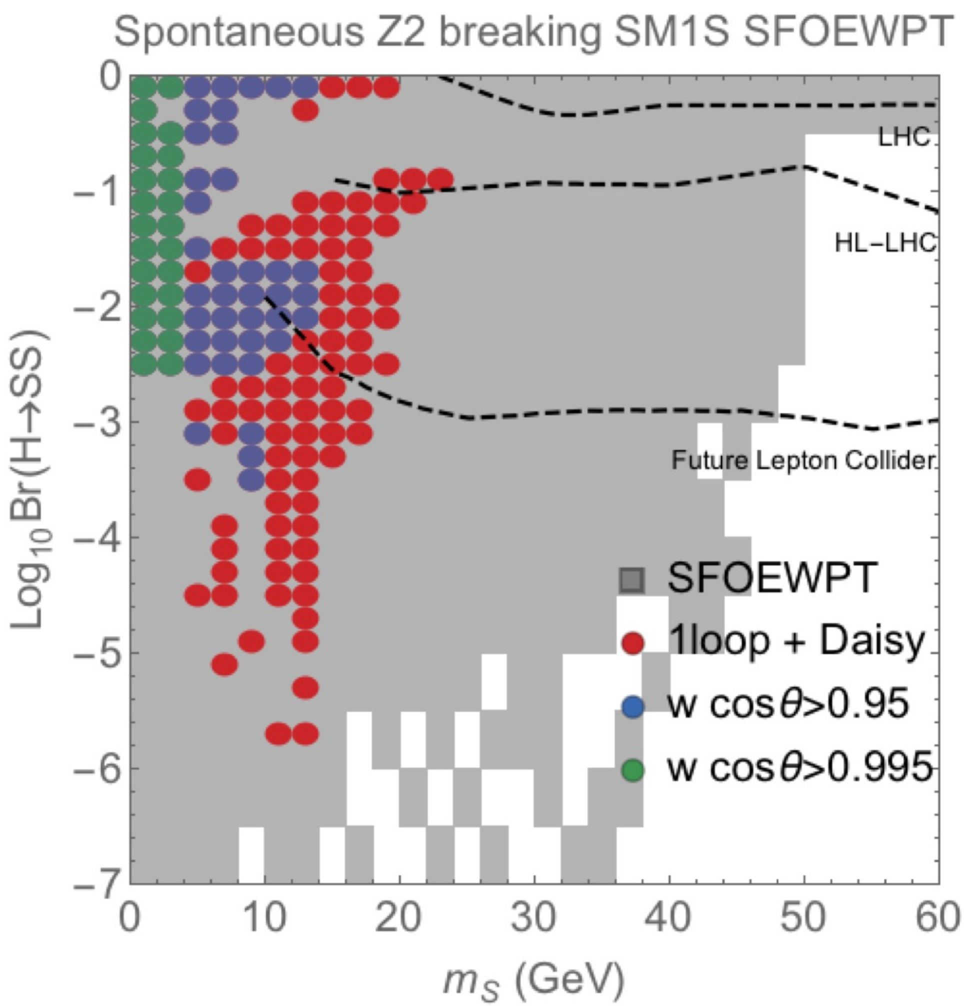


Z_2 non-restoration



The Z_2 spontaneous breaking scenario

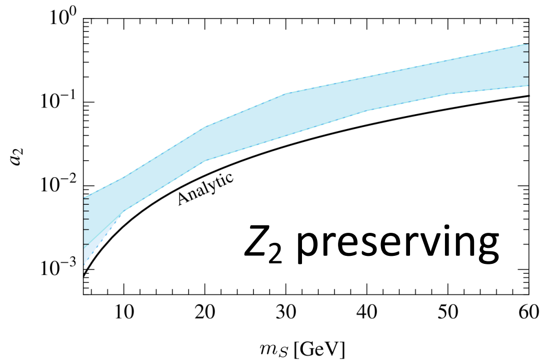
Correlation between exotic decay and EWPT [Carena *et al*, 1911.10206]

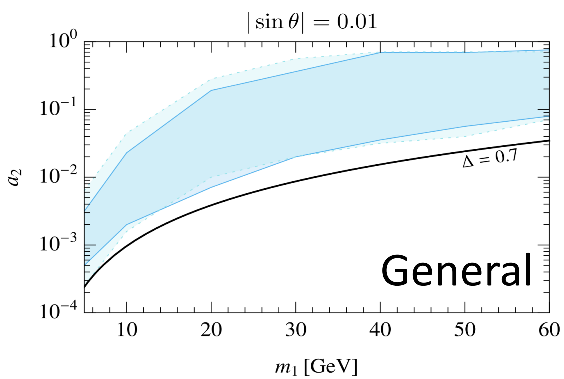


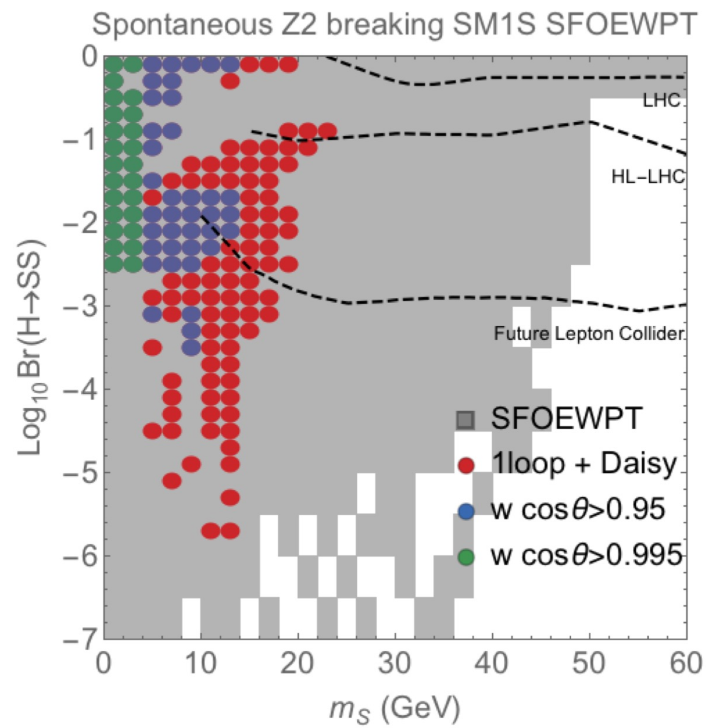
A short summary

Three strong 1st-order electroweak phase transition scenarios:

1. General Higgs + singlet; [Kozaczuk *et al*, 1911.10210]
2. Singlet Z_2-preserving [Kozaczuk *et al*, 1911.10210] & spontaneous breaking[Carena *et al*, 1911.10206]





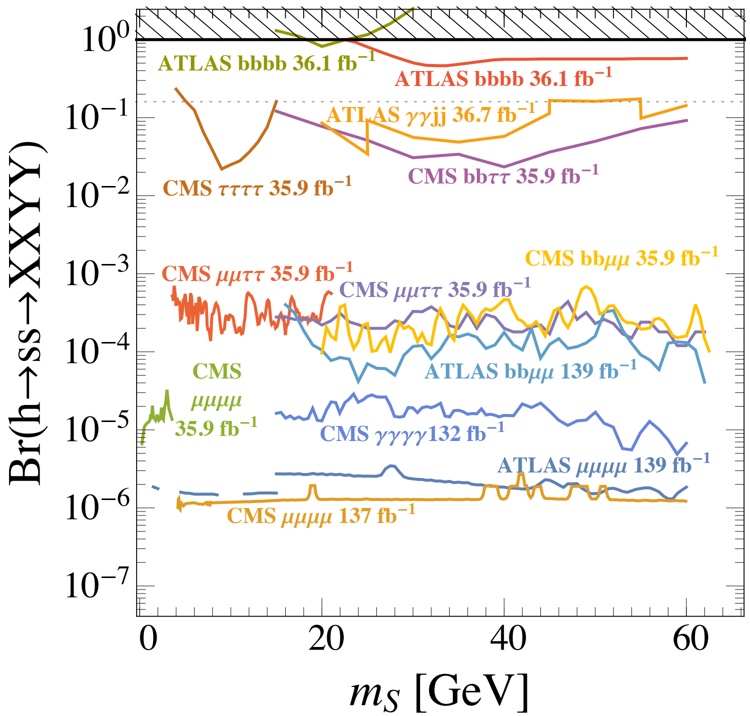


All show the correlation between EWPT and Higgs exotic decay!!

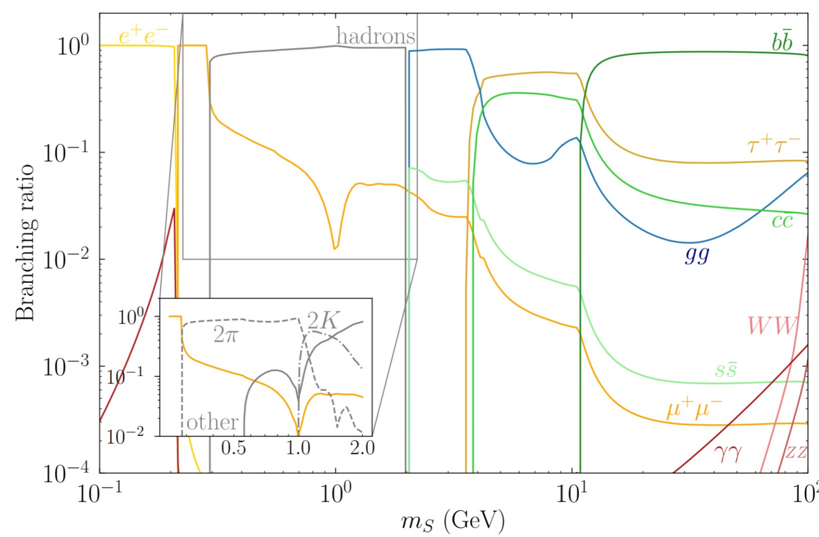
Searching for Higgs to double-singlet exotic decay

If S decays invisibly: Br(h > invisible)
Current LHC bound < 14.5%;[2202.07953] future HL-LHC 2.5%;[1902.00134]
CEPC 0.27%.[1905.03764]

If S decays visibly: Br(h > SS > $XXYY$)



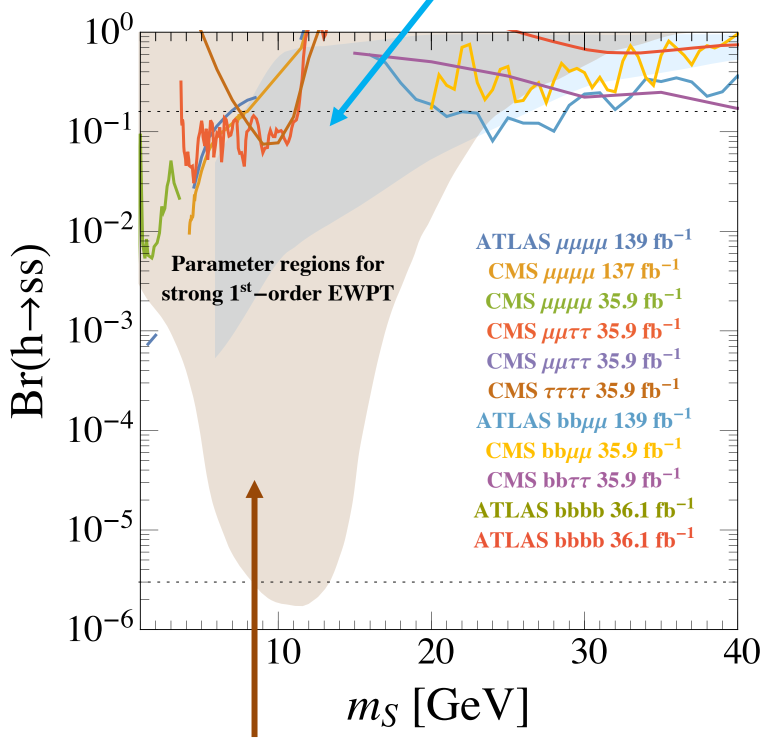
[Gershtein *et al*, 2012.07864]

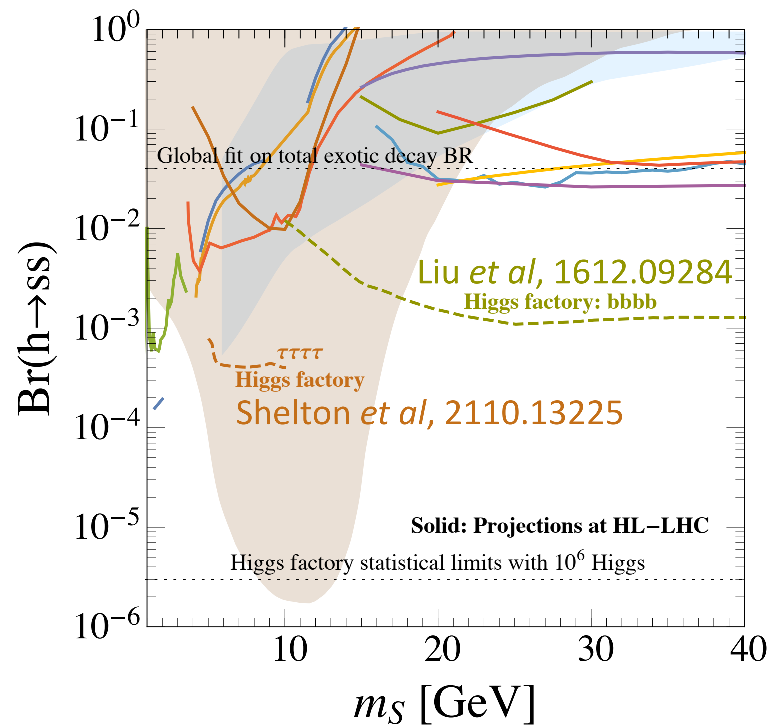


Probing EWPT with Higgs exotic decay

h > *SS* > *XXYY* as a probe [assuming *S* decays via *h*-*S* mixing]

General Higgs + singlet $|\sin\theta| = 0.01$ [Kozaczuk *et al*, 1911.10210]





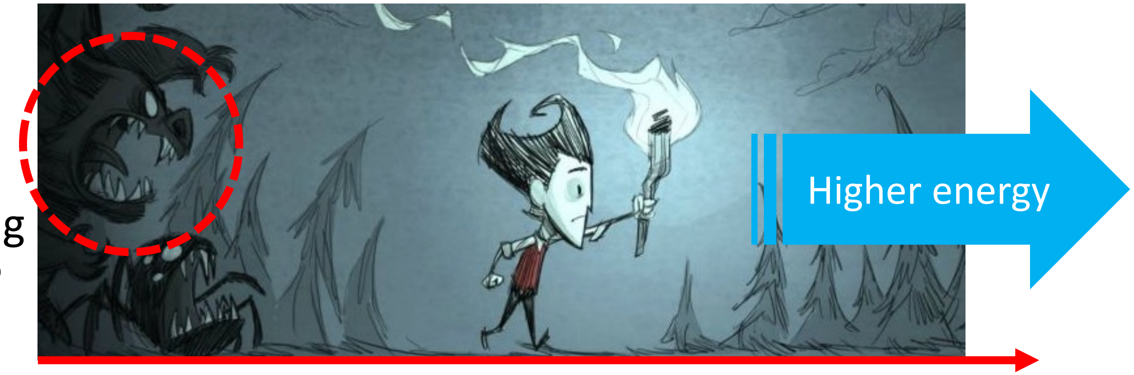
Z_2 spontaneous breaking [Carena *et al*, 1911.10206]

Recently: probing 1st-order EWPT via long-lived particle searches for *h* > *SS* > *jjjj* at CMS, MAPP [Liu *et al*, 2205.08205]

Conclusion

New physics might be hidden at lower energy scale…

Origin of a strong
1^{st}-order EWPT?



Highly correlated with Higgs exotic decay, especially h > SS > $XXYY$

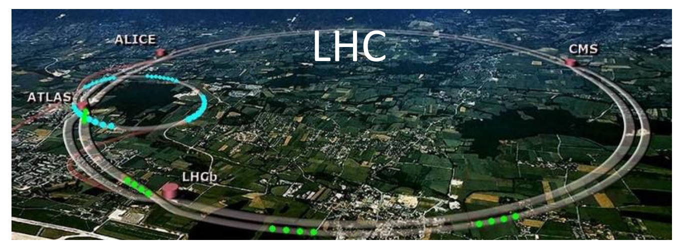
Conclusion

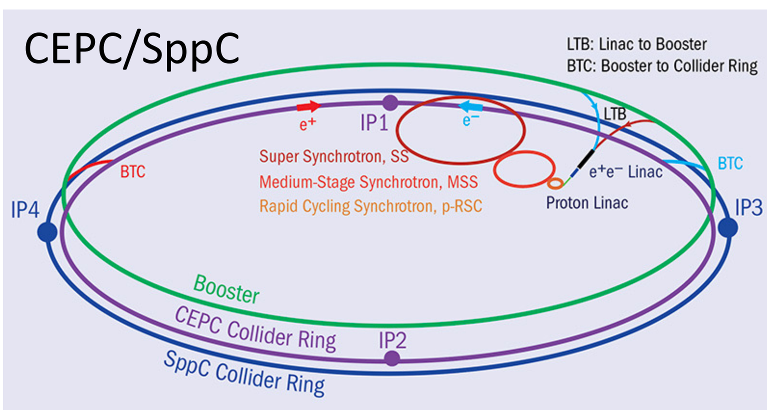
New physics might be hidden at lower energy scale…

Origin of a strong 1^{st}-order EWPT?

Highly correlated with Higgs exotic decay, especially $h > SS > XXYY$

Might be revealed at …



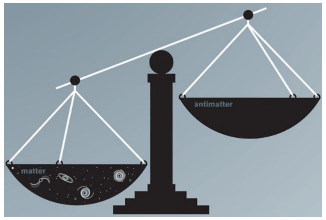


Other hopeful channels

- $\mu\mu jj$, $\tau\tau jj$, $\mu\mu\tau\tau$…

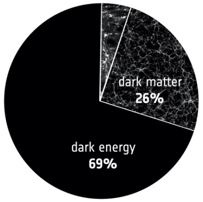
Thank you!

Backup: implications of first-order phase transitions



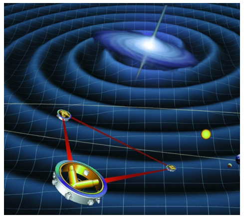
Matter-antimatter asymmetry

2011.04821, 2005.13552, 1206.2942, hep-ph/9410282, 9408339, etc



Dark matter/primordial black holes

2201.07243, 2106.05637, 2106.00111, 2105.07481, 2008.04430, 1912.02830, etc



Gravitational wave signals

2204.05434, 2008.10332, 1807.09495, 1512.02076, 1512.06239, 1910.13125, etc