

The EW Phase Transition @ CLIC

(Based on [1807.04284](#))

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CLICdp Meeting 28/08/18



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Teórica
UAM-CSIC



The EW Phase Transition:

Understanding the EW Epoch

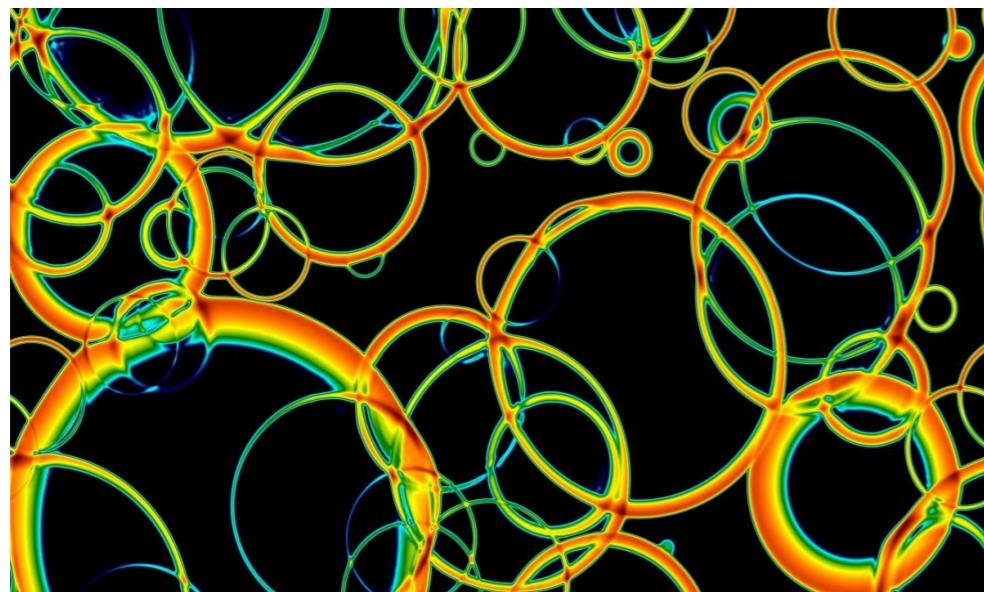
WHY?

- Yield Precise Understanding of EWSB in Early Universe
- (Possible) Cosmological Relics from the EW Epoch

The EW Phase Transition: *Understanding the EW Epoch*

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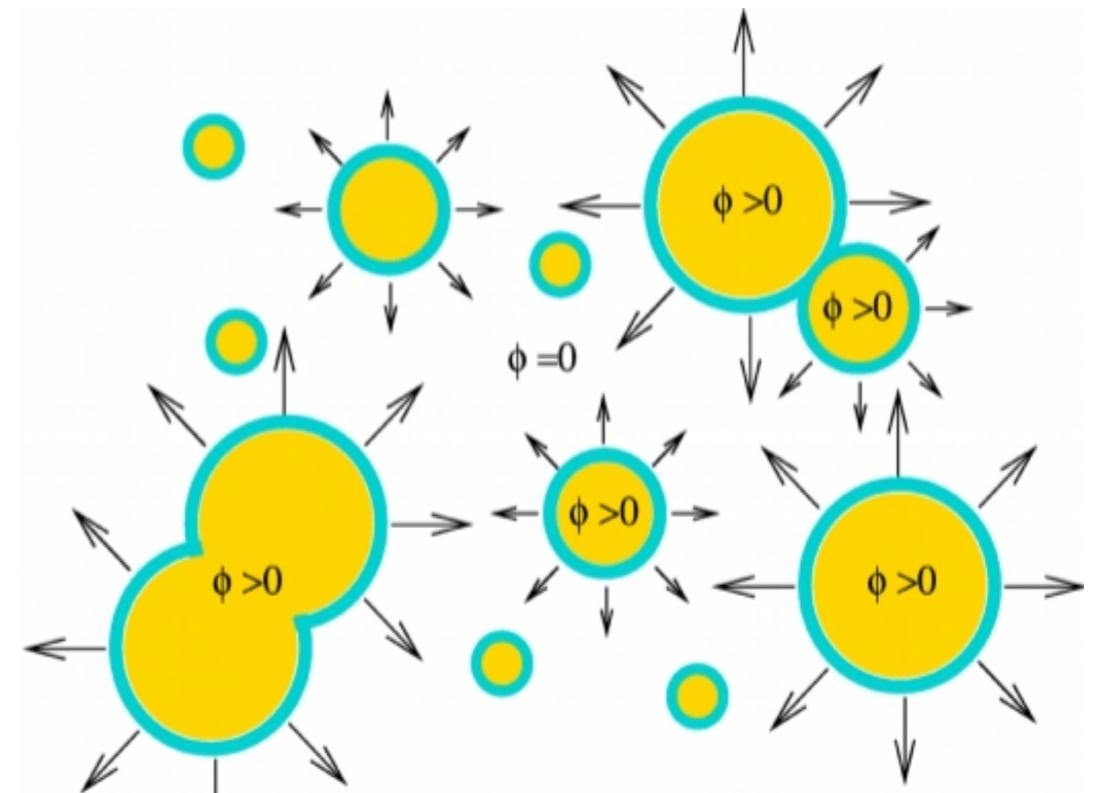


Courtesy of D. Weir

Hindmarsh, Huber, Rummukainen, Weir, PRD **92** (2015) 123009

Gravitational Wave Signal

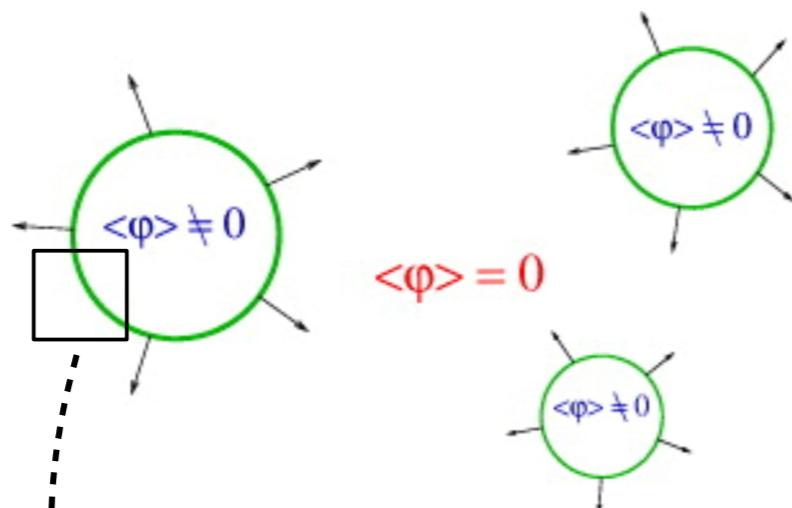
Sourced by bubble Collisions &
subsequent plasma motions



The EW Phase Transition: *Understanding the EW Epoch*

WHY?

- Yield Precise Understanding of EWSB in Early Universe
- (Possible) Cosmological Relics from the EW Epoch
- (Possible) Answer to Open Mysteries at Interface Particle Physics
Cosmology



Matter-Antimatter Asymmetry
► Baryogenesis

SAKHAROV CONDITIONS (for dynamical generation
of baryon asymmetry)

B Violation

C/CP Violation

Departure from Thermal Equilibrium
EW Phase Transition

Higgs Evolution
in Early Universe



FINITE-TEMPERATURE EFFECTIVE POTENTIAL

$$V_{\text{eff}}(h, T) = V_0(h) + V_0^{\text{loop}}(h) + V_T(h, T)$$

Tree-level
potential

Loop
corrections

Thermal
corrections

(Perturbative) Nature of EWPT

Higgs Evolution in Early Universe



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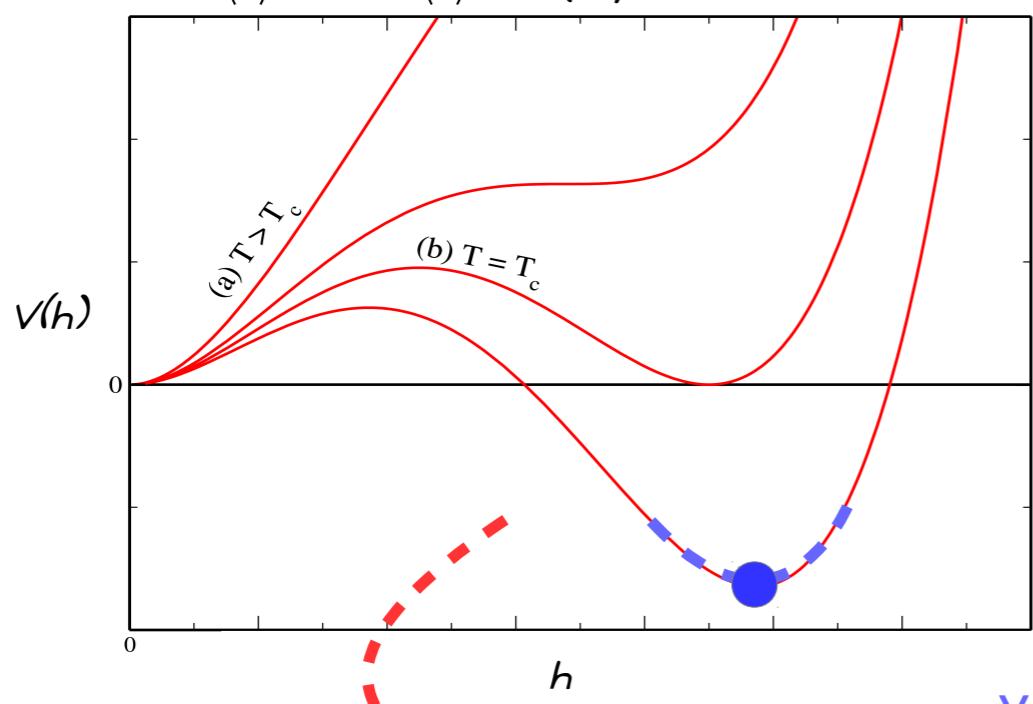
Loop
corrections

Thermal
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(Perturbative) Nature of EWPT

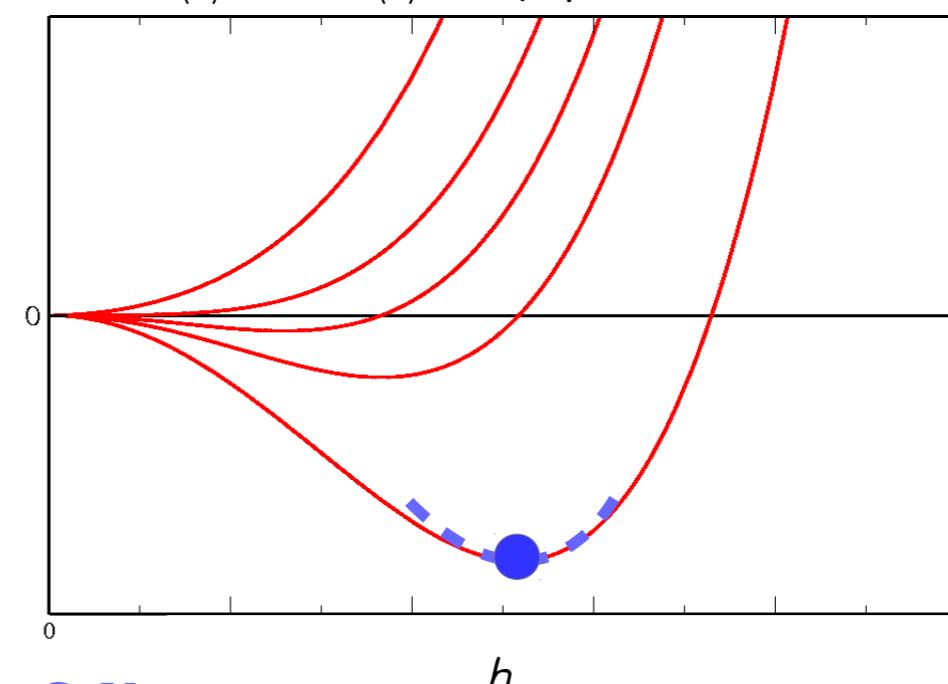
1st Order:

$$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T) \text{ Discontinuous}$$



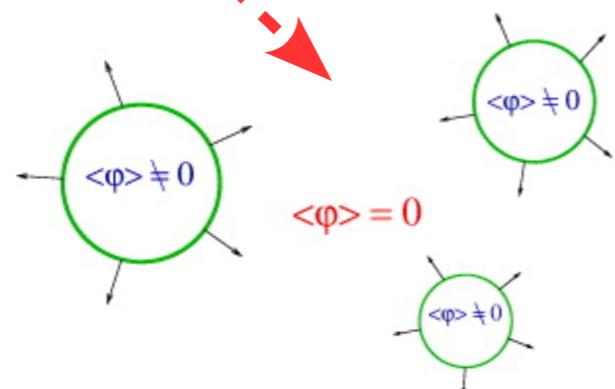
2nd Order:

$$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T) \text{ Continuous}$$



$$v = 246 \text{ GeV}$$

$$m_h = 125 \text{ GeV}$$



Higgs Evolution in Early Universe



FINITE-TEMPERATURE EFFECTIVE POTENTIAL

$$V_{\text{eff}}(h, T) = V_0(h) + V_0^{\text{loop}}(h) + V_T(h, T)$$

Tree-level
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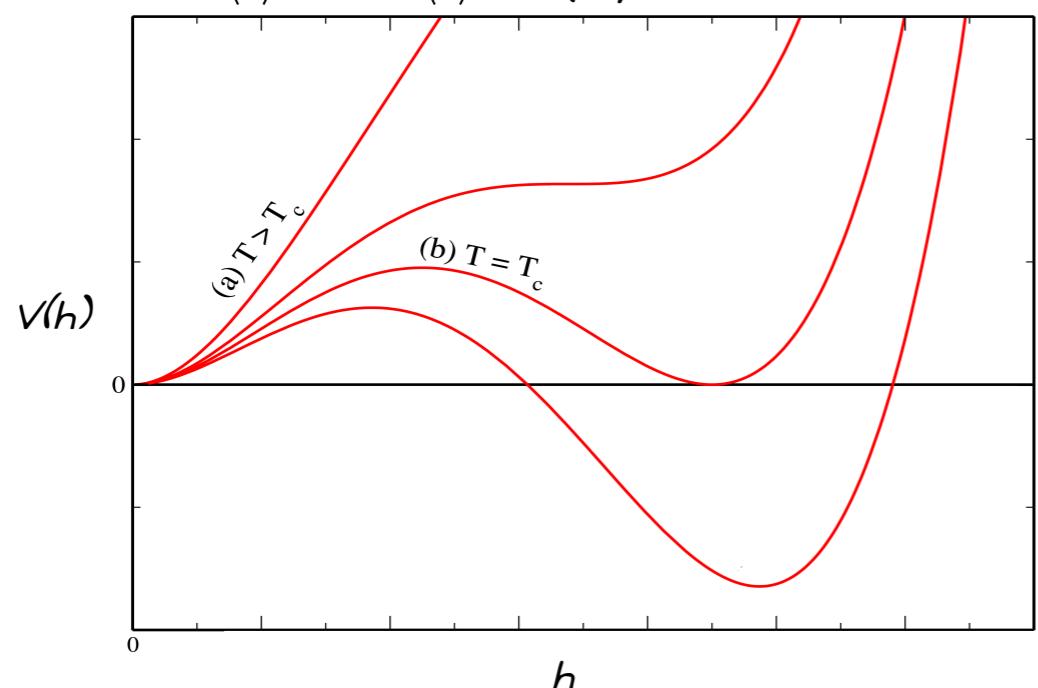
Loop
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(Perturbative) Nature of EWPT

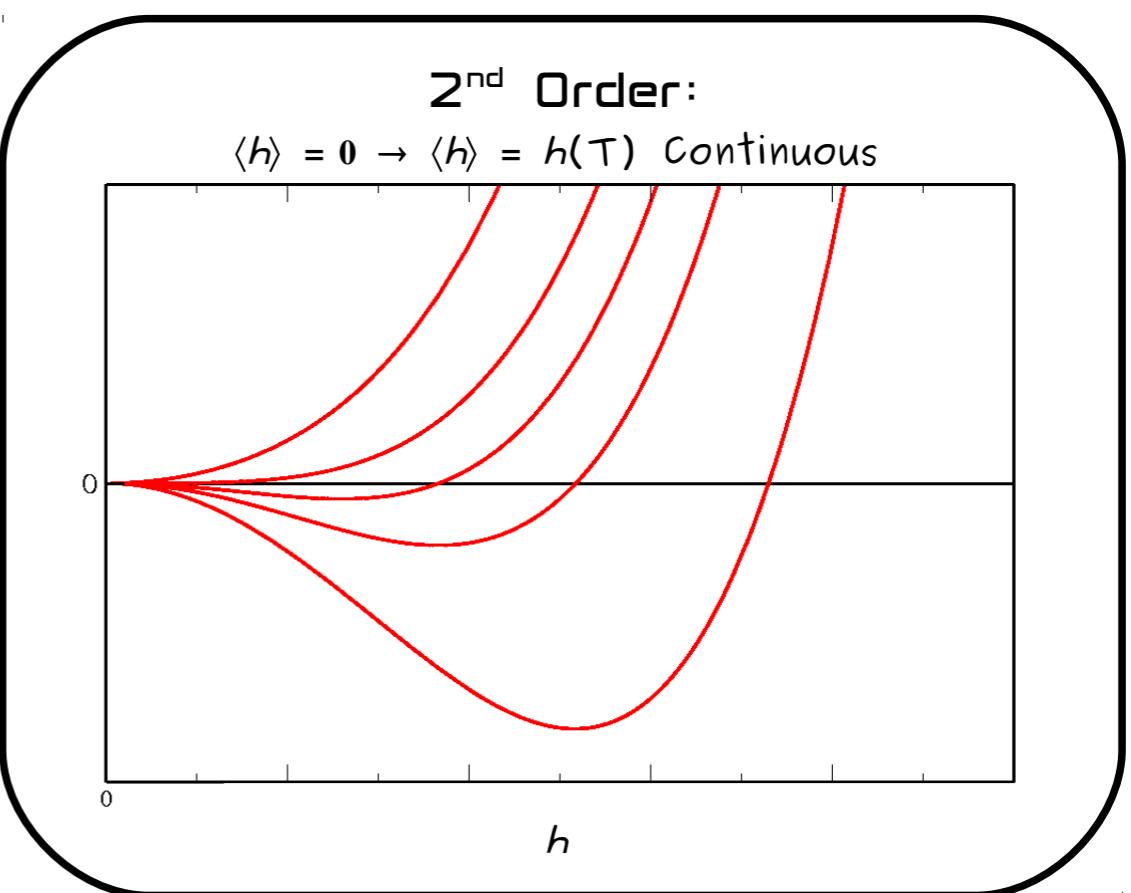
1st Order:

$$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T) \text{ Discontinuous}$$



2nd Order:

$$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T) \text{ Continuous}$$



SM : EWPT (non-perturbatively) is Smooth Cross-Over

*K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887*

Higgs Evolution in Early Universe



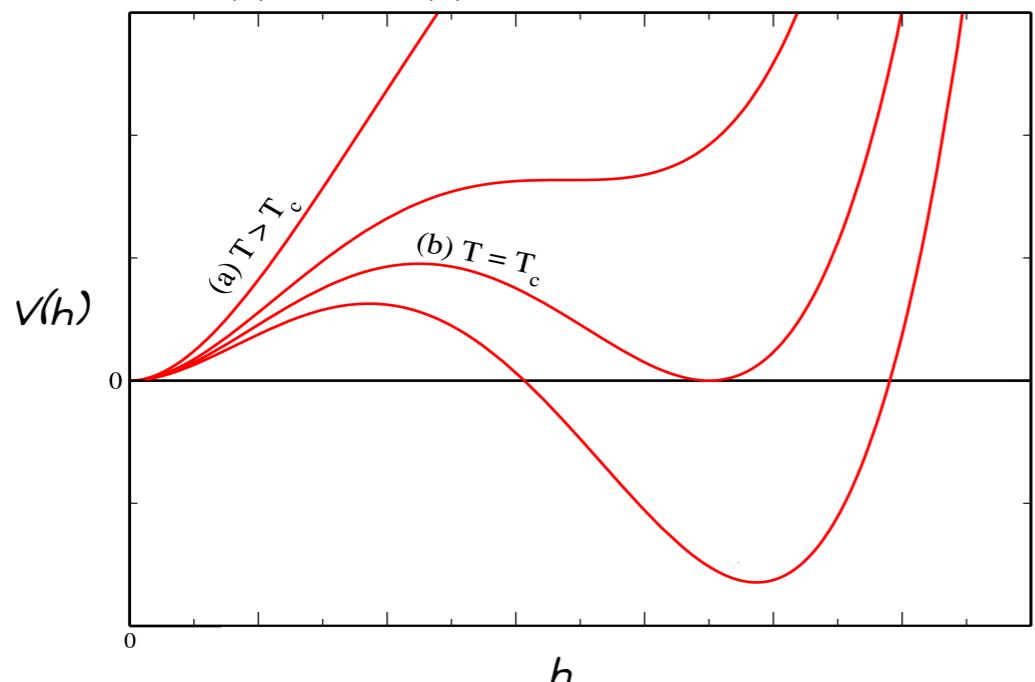
FINITE-TEMPERATURE EFFECTIVE POTENTIAL

$$V_{\text{eff}}(h, T) = V_0(h) + V_0^{\text{loop}}(h) + V_T(h, T)$$

(Perturbative) Nature of EWPT

1st Order:

$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Discontinuous



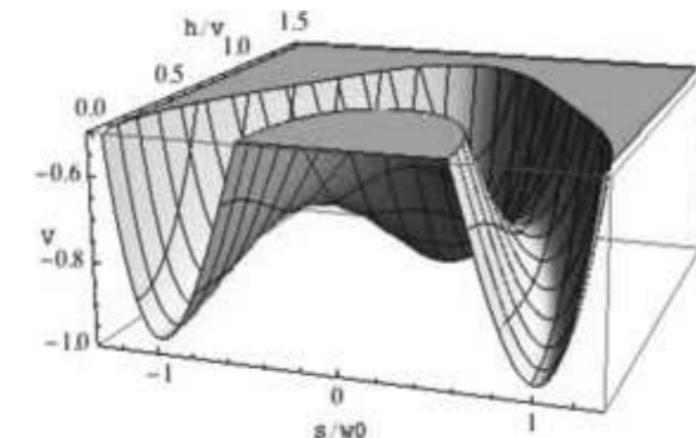
Tree-level
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Loop
corrections

Thermal
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Non-analytic term $(m^2)^{3/2}$ in $V(h, T)$
from Matsubara Zero-modes
(only present for bosons)

Multiple fields involved in the EWPT
may allow for tree-level potential barrier



BSM: New Physics sizeably coupled to Higgs can drastically change the EWPT nature

First Order EW Phase Transition (EWPT)

New Physics

- ▶ Induce deviations in Higgs couplings
- ▶ Needed close to EW scale

within Collider reach !

First Order EW Phase Transition (EWPT)

New Physics

- ▶ Induce deviations in Higgs couplings
- ▶ Needed close to EW scale

Indirect Probes: Higgs signal strengths + Higgs self-coupling

&

Direct Searches: New states

Required to “Establish” 1st Order EWPT

First Order EW Phase Transition (EWPT)

New Physics

- ▶ Induce deviations in Higgs couplings
- ▶ Needed close to EW scale

Indirect Probes: Higgs signal strengths + Higgs self-coupling

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Direct Searches: New states

Required to “Establish” 1st Order EWPT

We concentrate on SM + Singlet Scalar

Simple

Well-motivated

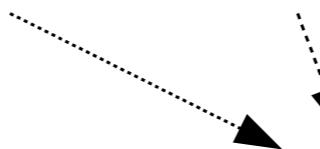
“Poster-child” of EWPT

- ▶ Neutral Naturalness
- ▶ Higgs Portal (Dark Sectors)
- ▶ Non-minimal SUSY (NMSSM), Composite Higgs ($SO(6)/SO(5)$)
- ▶ ...



Singlet Driven EW Phase Transition

$$V(H, S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{a_1}{2} |H|^2 S + \frac{a_2}{2} |H|^2 S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$



Higgs Portal (Higgs - Singlet Mixing)

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

h_1 is SM-like Higgs

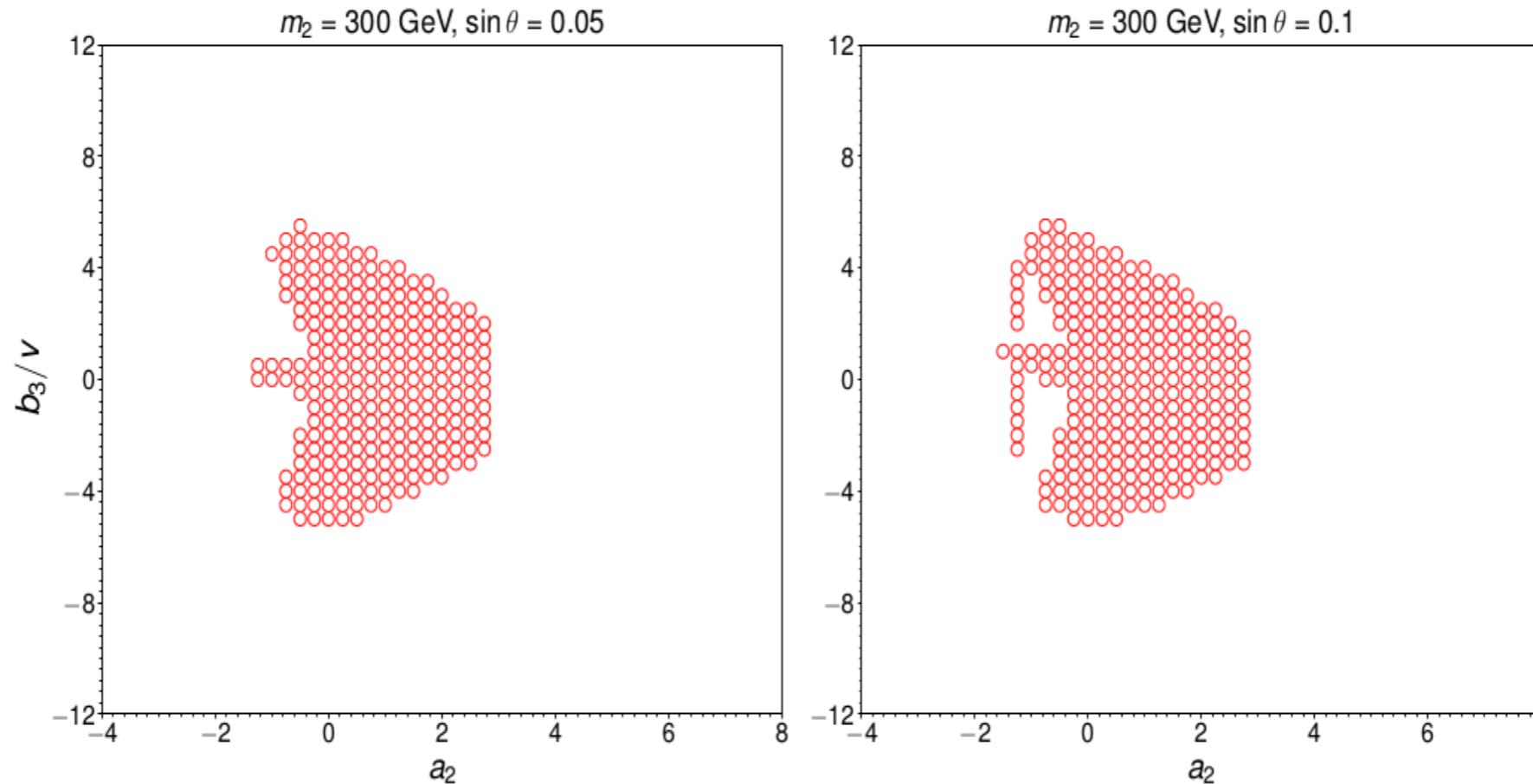
h_2 inherits its couplings to
SM particles via Mixing

Singlet Driven EW Phase Transition

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- ⇒ Use tadpole $b_1 S$ to set $v_s = 0$
- ⇒ Parameters: $\{v, m_1, m_2, \theta, a_2, b_3, b_4\}$ (5 BSM param.)

Unitarity + Absolutely stable EW vacuum



Singlet Driven EW Phase Transition

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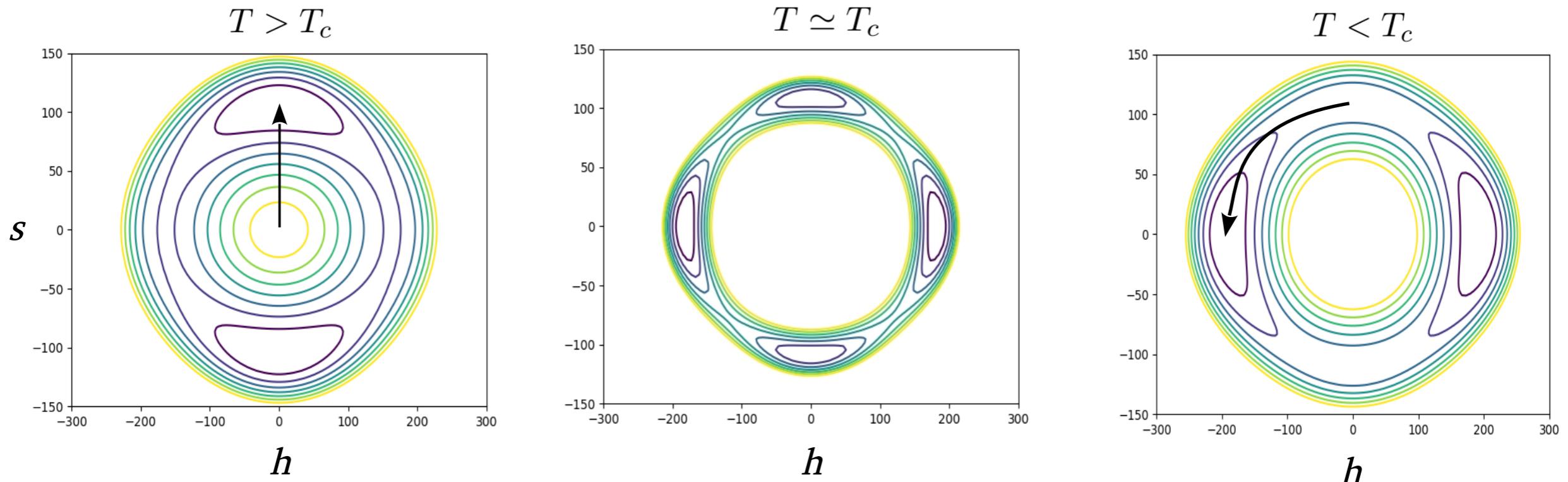
$$V_{T^2} = \left(\frac{c_h}{2} h^2 + \frac{c_s}{2} S^2 + c_t S \right) T^2$$

Presence of singlet field direction allows for tree-level potential barriers (at finite T)

Espinosa, Konstandin, Riva, Nucl. Phys. **B854** (2012) 592

→ 1st Order EWPT

$v_T/T_c > 1$

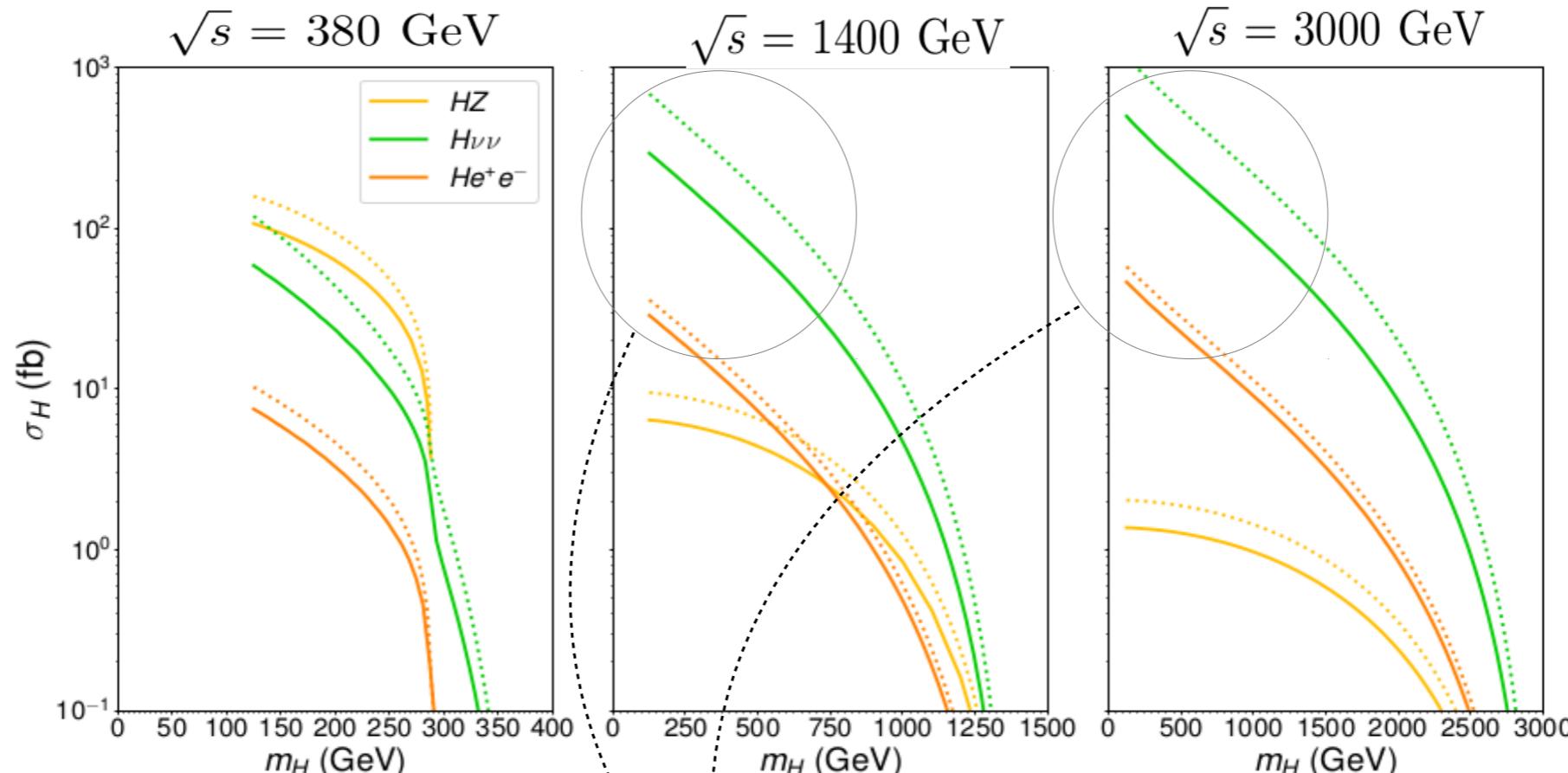


EWPT w. perturbative couplings requires $m_2 < 1 \text{ TeV}$

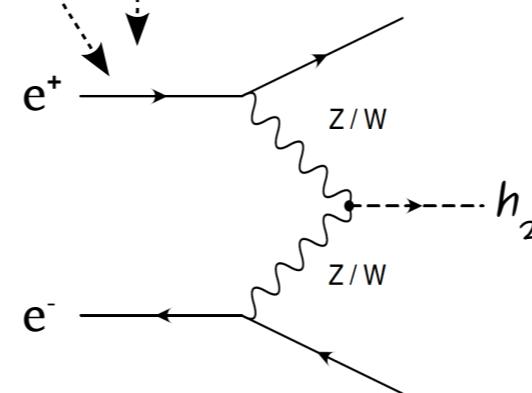
Singlet Driven EW Phase Transition

@ 

Heavy Higgs production @ CLIC:



Solid: Unpolarized
Dashed: Polarization
 $e^- \rightarrow -80\%$
 $e^+ \rightarrow +30\%$



Heavy Higgs XS (VBF)
 $\sim 100 \text{ fb} - 1 \text{ pb}$ for $m_H < 1 \text{ TeV}$

Singlet Driven EW Phase Transition

@ 

$m_2 > 250 \text{ GeV} \rightarrow \text{Resonant Higgs Pair Production}$ (w. MadGraph5_aMC@NLO)
 $e^+e^- \rightarrow H\nu\nu (H \rightarrow hh \rightarrow 4b)$

CLIC $\rightarrow 1.4 \text{ TeV } (1500 \text{ fb}^{-1})$
 $\rightarrow 3 \text{ TeV } (2000 \text{ fb}^{-1})$

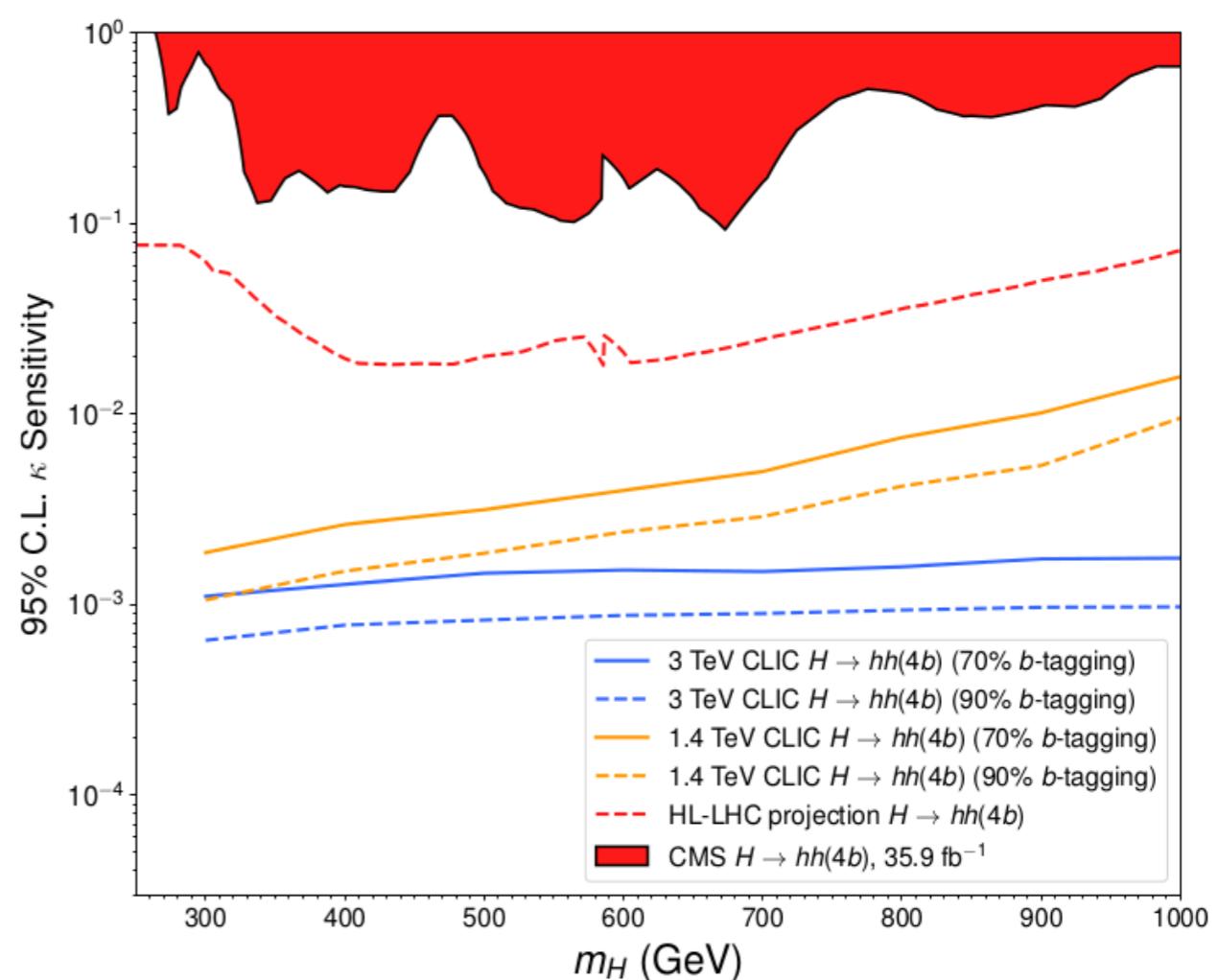
Polarization:
 $e^- = -80\%$, $e^+ = +30\%$

CLICdet Delphes Simulation
(CLICdp-Note-2017-001)

Ultimate CLIC sensitivity

$$\kappa \sim 10^{-3} - 5 \times 10^{-4}$$

(no systematics)



$$(\kappa = \sigma_S / \sigma_S^{\text{SM}} \times \text{BR}(H \rightarrow hh))$$

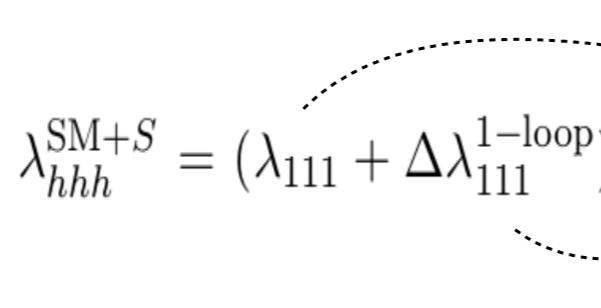
Singlet Driven EW Phase Transition

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$m_2 > 250 \text{ GeV} \rightarrow \text{Resonant Higgs Pair Production}$
 $e^+e^- \rightarrow H\nu\nu (H \rightarrow hh \rightarrow 4b)$

Complementary (indirect) probes @ CLIC:

Higgs self-coupling $\delta\lambda_{hhh} \equiv |\lambda_{hhh}^{\text{SM}+S} - \lambda_{hhh}^{\text{SM}}| / \lambda_{hhh}^{\text{SM}} = 0.10 \quad (68\% \text{ C.L.})$

$$\lambda_{hhh}^{\text{SM}+S} = (\lambda_{111} + \Delta\lambda_{111}^{\text{1-loop}})$$


$$\lambda_{111} = \lambda v c_\theta^3 + \frac{1}{4} a_1 c_\theta^2 s_\theta + \frac{1}{2} a_2 v c_\theta s_\theta^2 + \frac{b_3}{3} s_\theta^3$$

$$\Delta\lambda_{111}^{\text{1-loop}} = \frac{1}{16\pi^2} \left(\frac{a_2^3 v^3}{12 m_2^2} + \frac{a_2^2 b_3 v^2}{2 m_2^2} s_\theta \right)$$

Higgs signal strengths Higgs + Singlet fit (h -couplings universally reduced by mixing)

Stage 1 (350 GeV): $\delta\kappa = 0.2\%$

Stage 1 + Stage 2 (1.4 TeV): $\delta\kappa = 0.09\%$

Stage 1 + Stage 2 + Stage 3 (3 TeV): $\delta\kappa = 0.06\%$

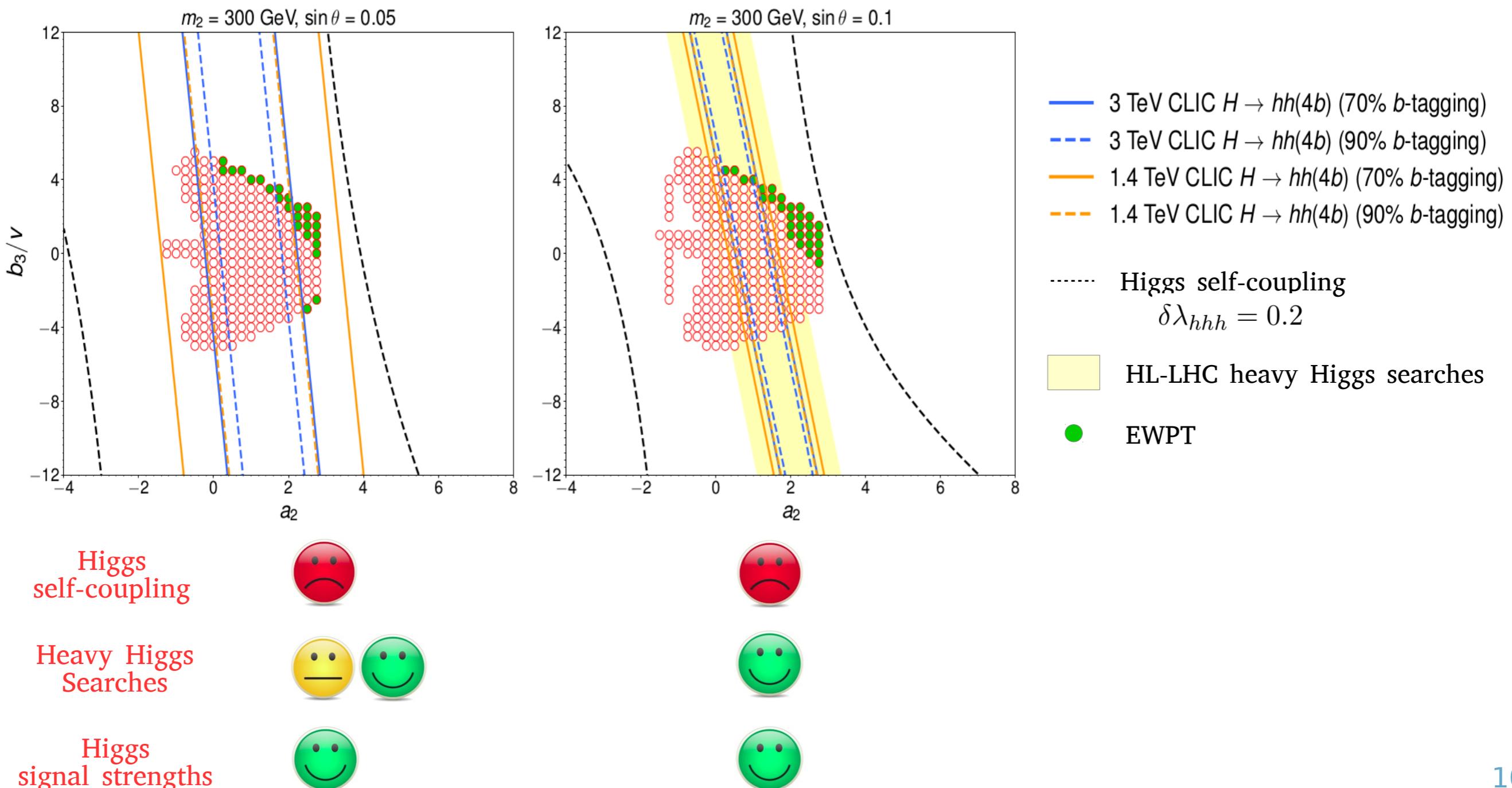
$$|\sin\theta| < 0.049 \quad (95\% \text{ C.L.})$$

$$\kappa = \cos\theta$$

Singlet Driven EW Phase Transition

@ 

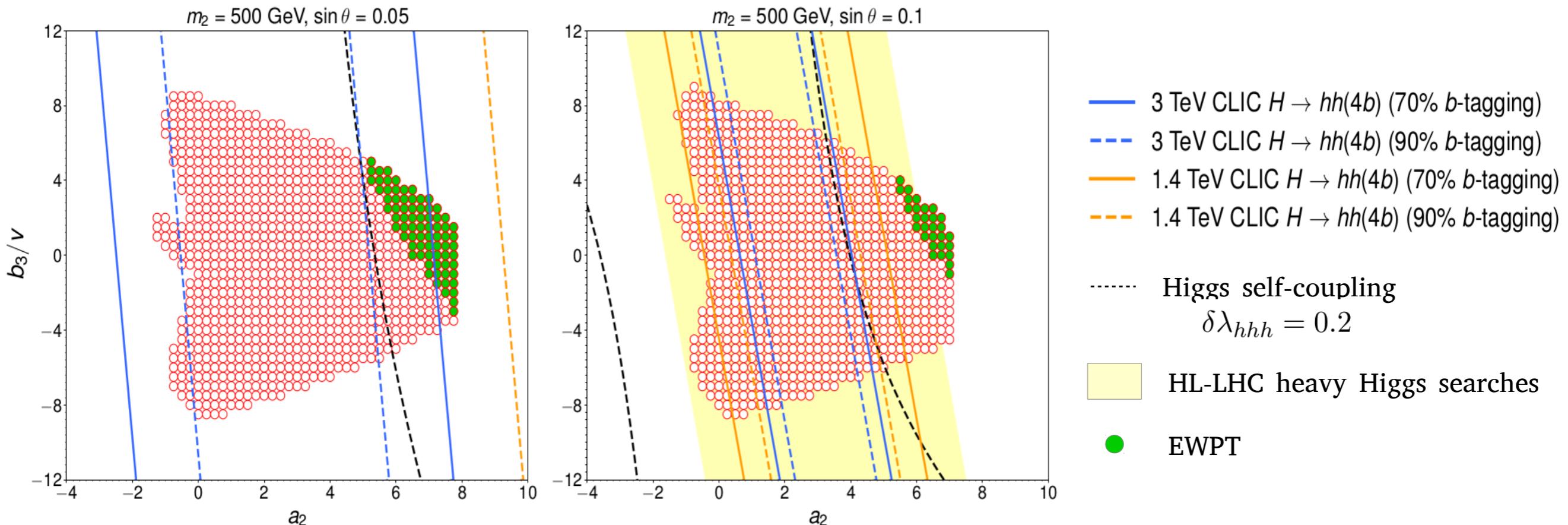
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Singlet Driven EW Phase Transition

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Higgs
self-coupling



Heavy Higgs
Searches



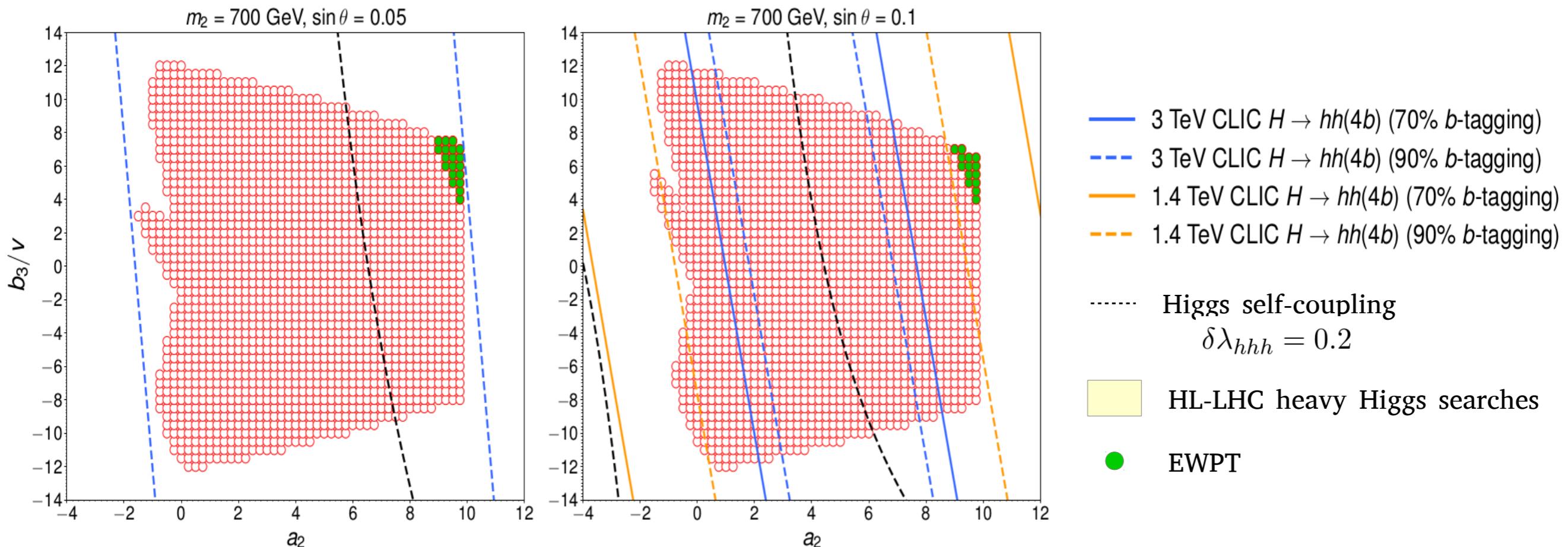
Higgs
signal strengths



Singlet Driven EW Phase Transition

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Thank you!





EWPT: What BSM Scenarios?

Chung, Long, Wang, PRD **87** (2013) 023509

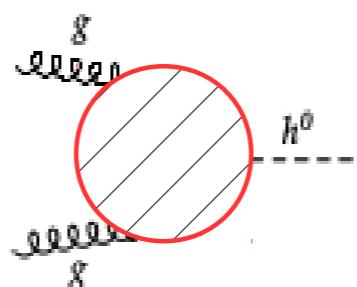
NO Systematic approach for BSM
yielding 1st Order EW Phase Transition



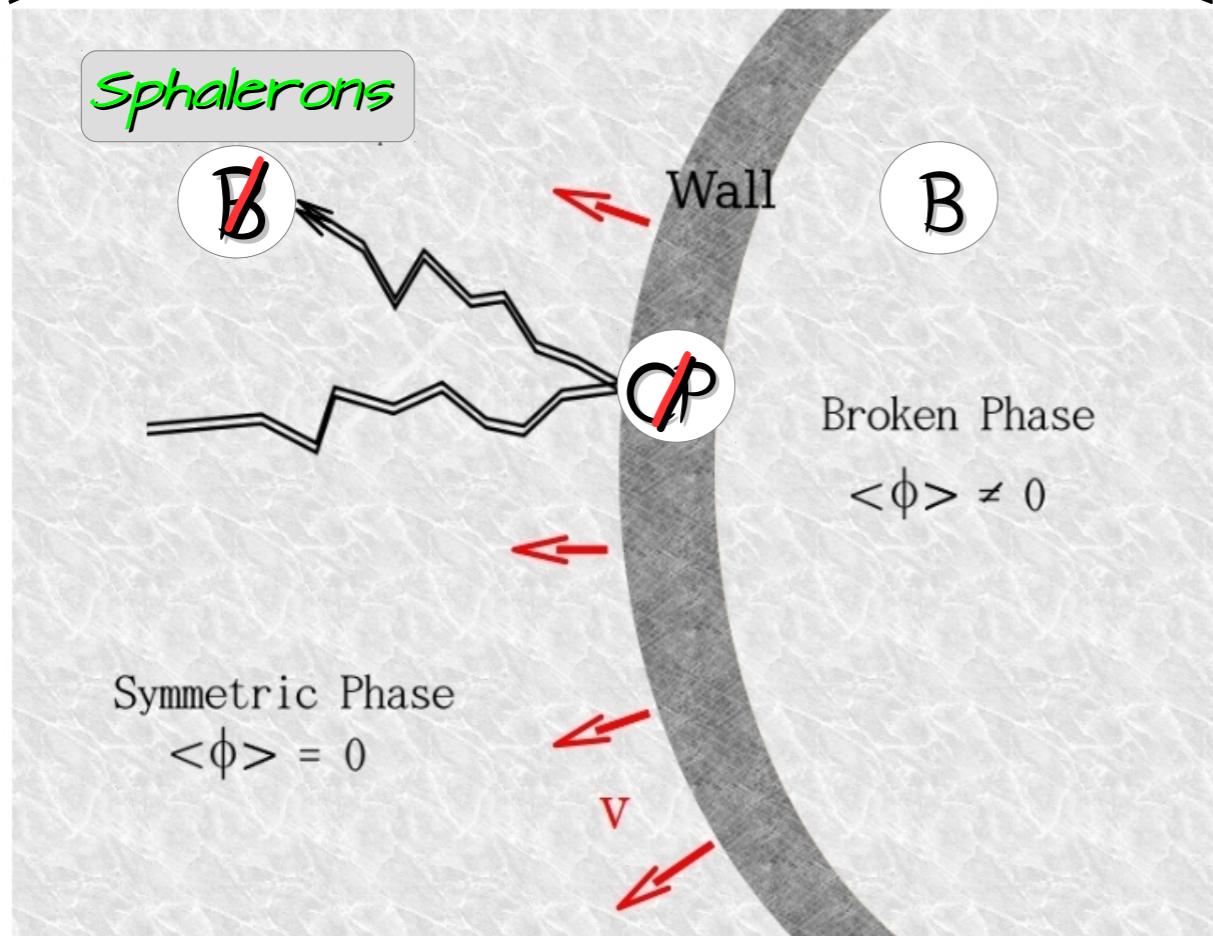
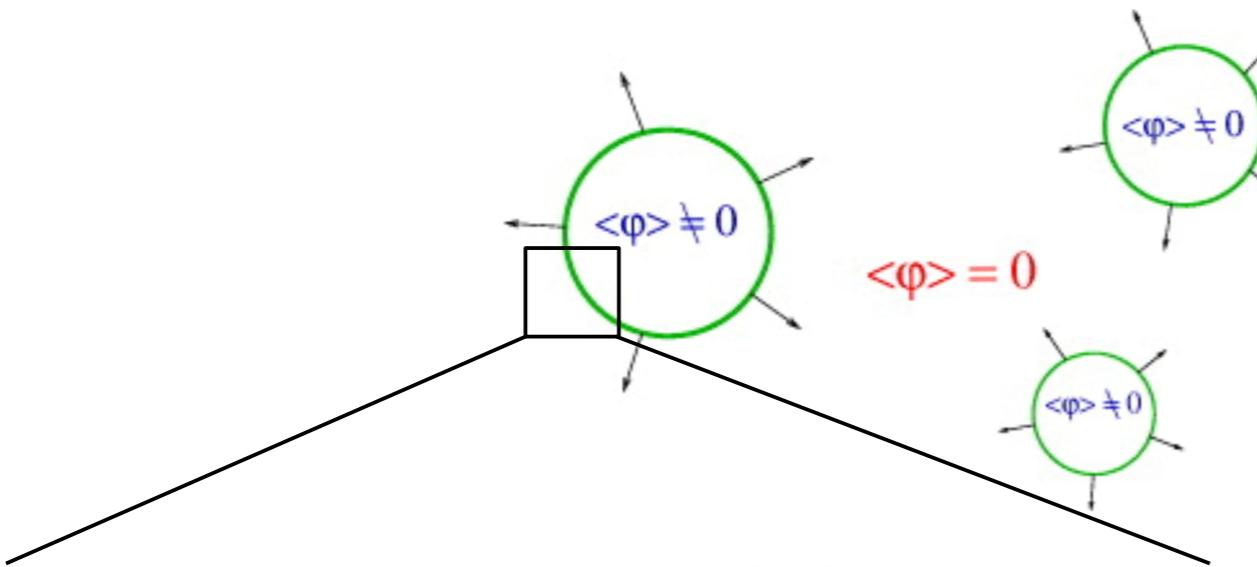
Collider Phenomenology

- ① EFT not possible in general
 - New Particles Present in Thermal plasma → EW Scale
 - New Particles get mass from EWSB
- ② Models with same EWPT Dynamics & Very Different Collider Phenomenology

e.g. Colored vs Uncolored BSM



EW Baryogenesis



SAKHAROV CONDITIONS

B Violation *Sphalerons*

C/CP Violation

Departure from Thermal Equilibrium

EW Phase Transition

Singlet Driven EW Phase Transition

@ 

Very small mixing angles...

Butazzo, Redigolo, Sala, Tesi, arXiv:1807.04743

