Probing the EW Phase Transition with Exotic Higgs Decays at the CEPC

M.J. Ramsey-Musolf

- *T.D. Lee Institute/Shanghai Jiao Tong Univ.*
- *UMass Amherst*
- *Caltech*

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About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

CEPC Workshop, April 15, 2021

References

- *EWPT & Colliders General: MJRM 1912.07189*
- *EWPT & Exotic Higgs Decays:*
  - *Profumo, MJRM, Shaugnessy 0705.2425*
  - *Kozaczuk, MJRM Shelton 1911.10210*
  - *Carena, Liu, Wang 1911.10206*

This talk

Key Question

Was there an electroweak phase transition ?

Key Ideas for this Talk

- ***Determining the thermal history of EW symmetry breaking is a key challenge for particle physics***
- ***The "electroweak temperature" → a scale provided by nature that gives us a clear BSM target for colliders to address this challenge***
- ***Exotic Higgs decays provide a unique probe of light scalar-induced thermal history modifications***
- ***Interesting opportunities for the CEPC should be pursued → Snowmass study***

CEPC Snowmass Study @ SJTU/TDLI

- *Shu Li*
- *MJRM*
- *Yanda Wu*
- *Xuliang Zhu*

Incoming PhD students

Outline

I. Context & Questions

II. Model Illustrations

III. Exotic Higgs Decays

IV. Outlook

I. Context & Questions

Was there an electroweak phase transition ?

Electroweak Phase Transition

- *Higgs discovery $\rightarrow$ What was the thermal history of EWSB ?*
- *Baryogenesis $\rightarrow$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*
- *Gravitational waves $\rightarrow$ If a signal observed in next generation probes, could a cosmological phase transition be responsible ?*

Electroweak Phase Transition

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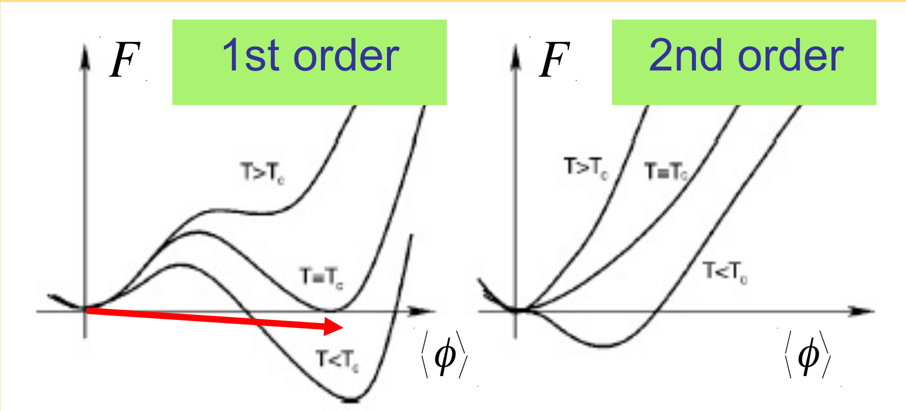
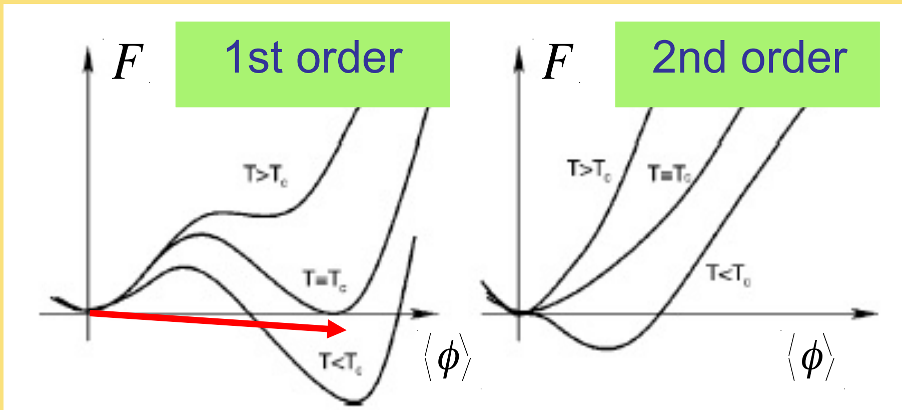
EWSB Transition: St'd Model



Increasing m_h →

EWSB Transition: St'd Model



Increasing m_h →

Lattice	Authors	M_h^C (GeV)
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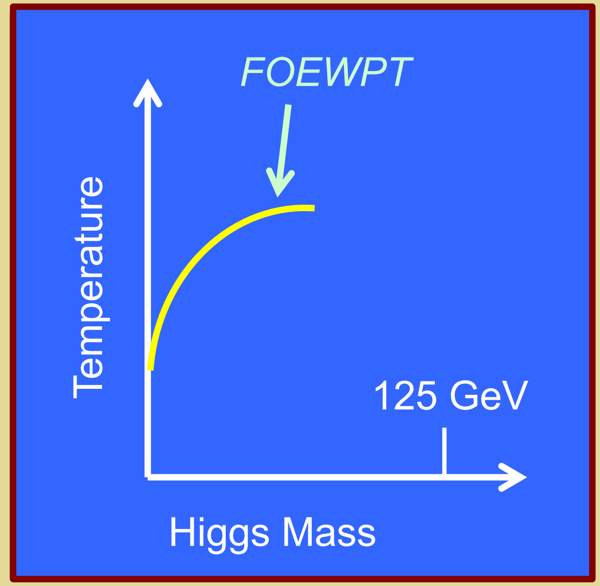
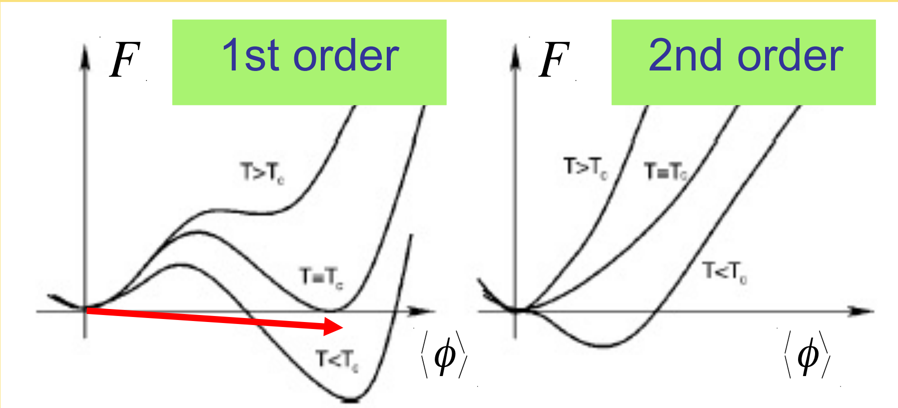
SM EW: Cross over transition



EW Phase Diagram

EWSB Transition: St'd Model



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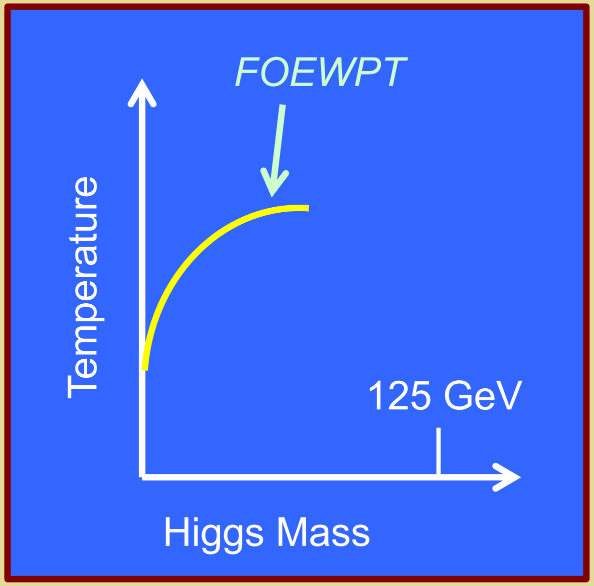
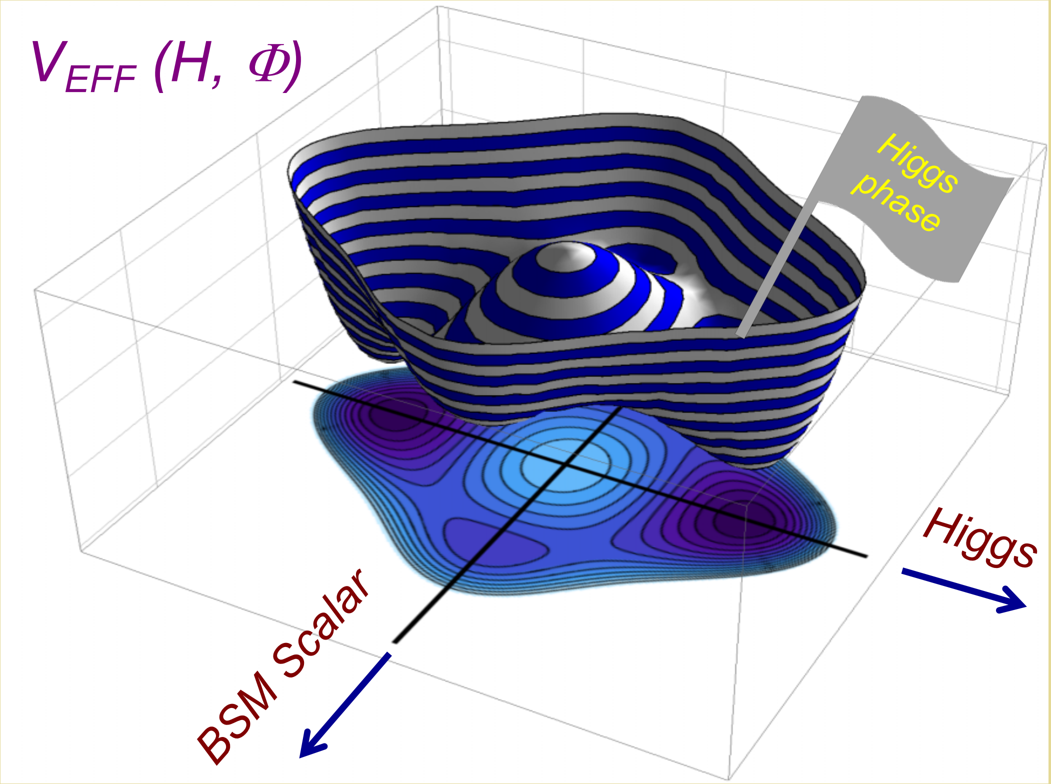


EW Phase Diagram

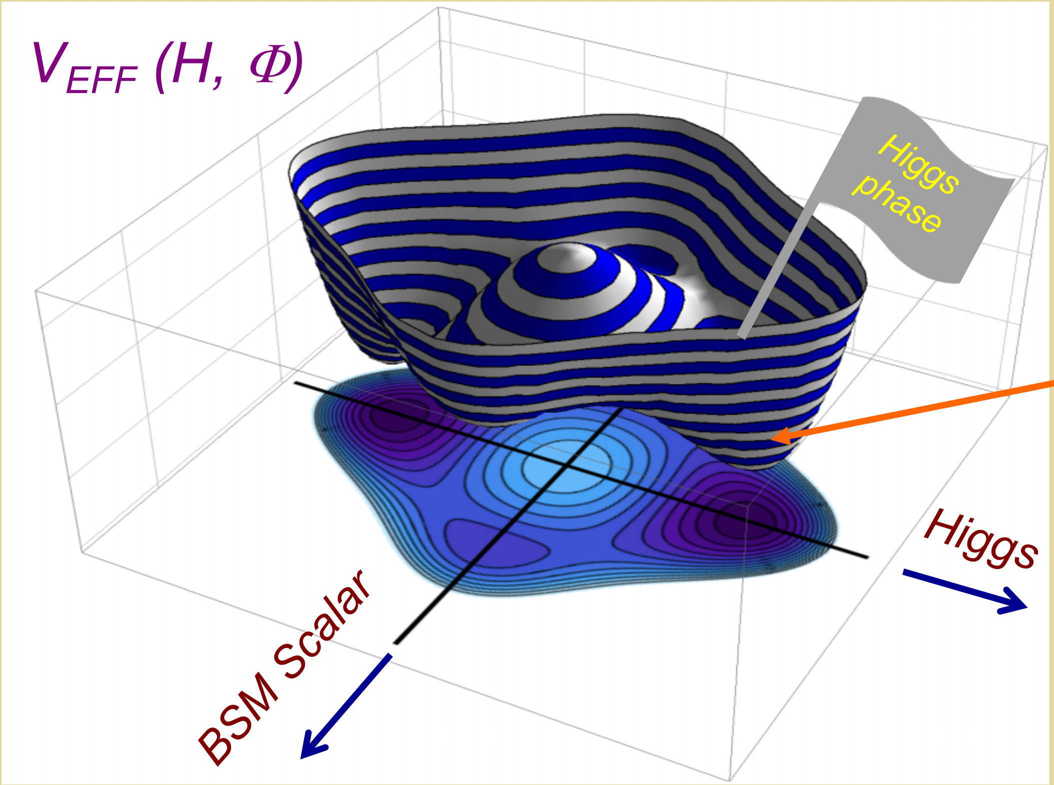
How does new TeV scale physics change this picture ? What is the phase diagram ? EWPT ? If so, what kind ?

Patterns of Symmetry Breaking



Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

Patterns of Symmetry Breaking



How did we end up here ?

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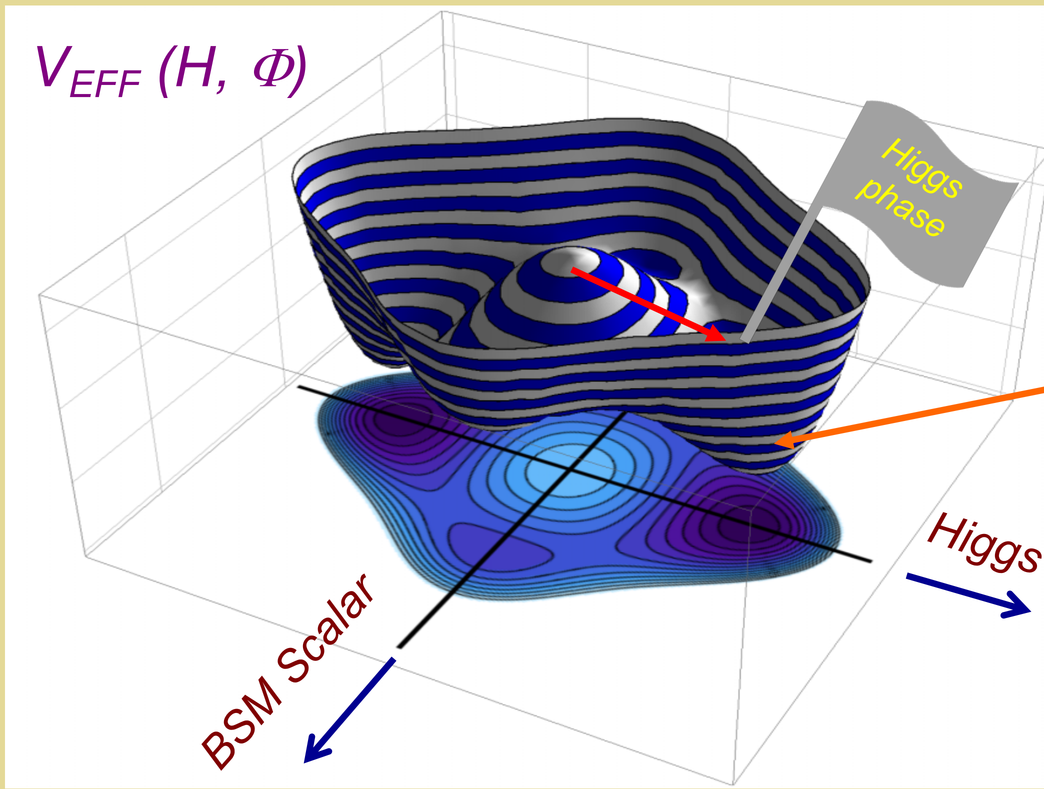

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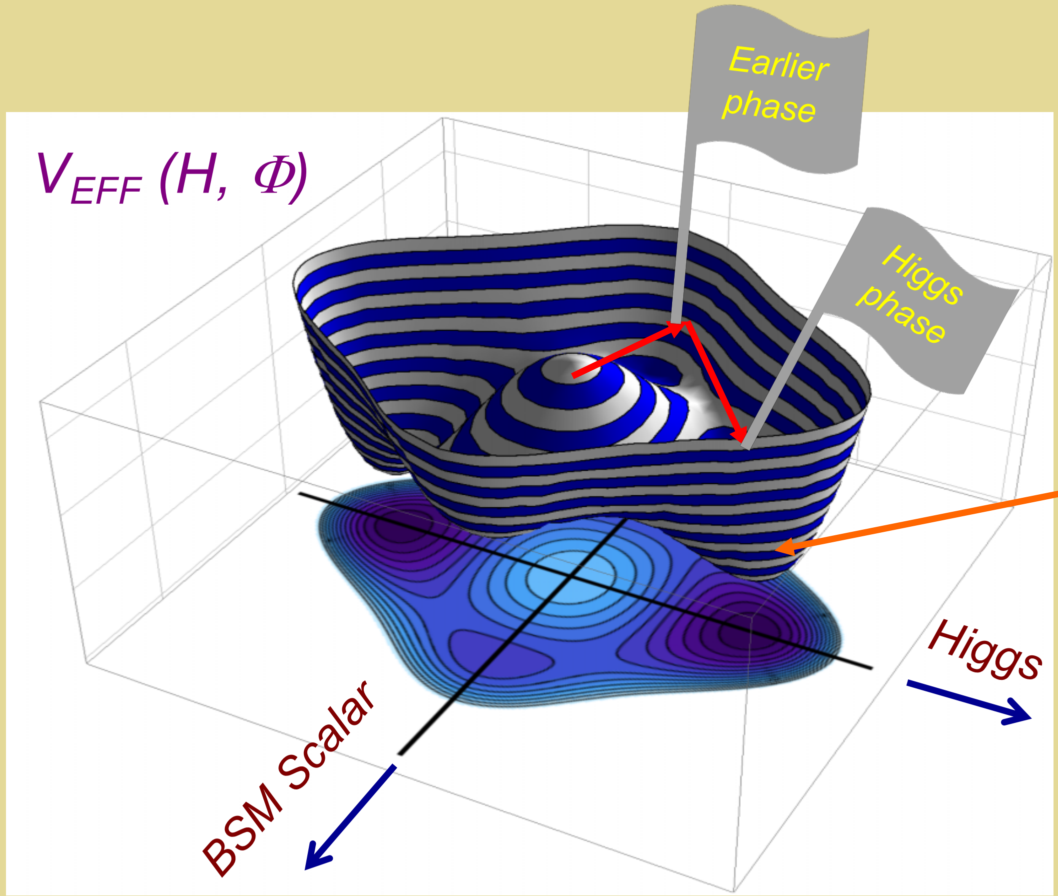

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Electroweak Phase Transition

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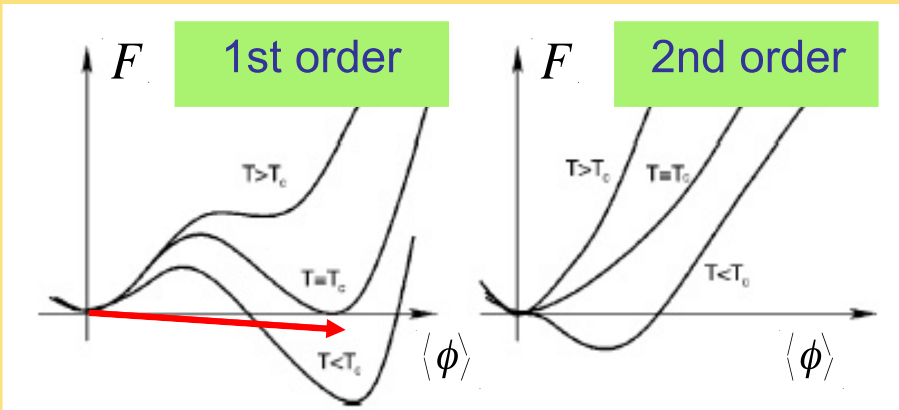
EW Phase Transition: Baryogen & GW



Increasing m_h →

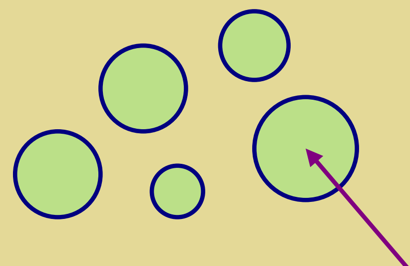
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

- *Baryogen**
- *GW*

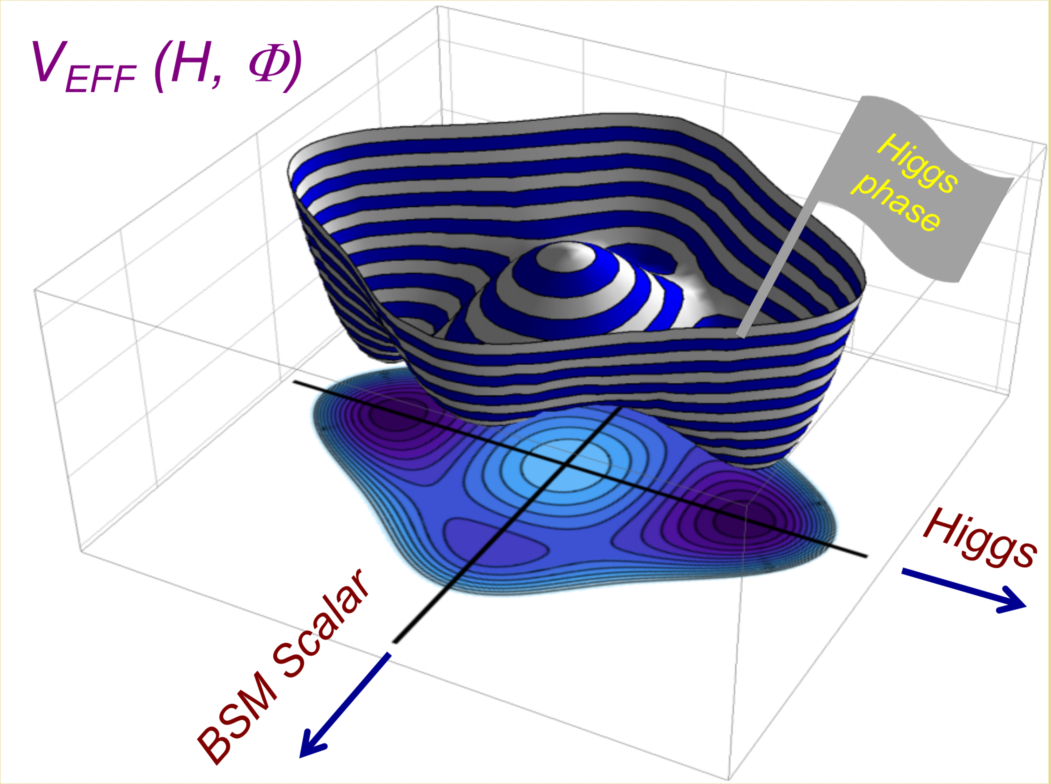
Bubble nucleation



EWSB

* *Need BSM CPV*

Experimental Probes



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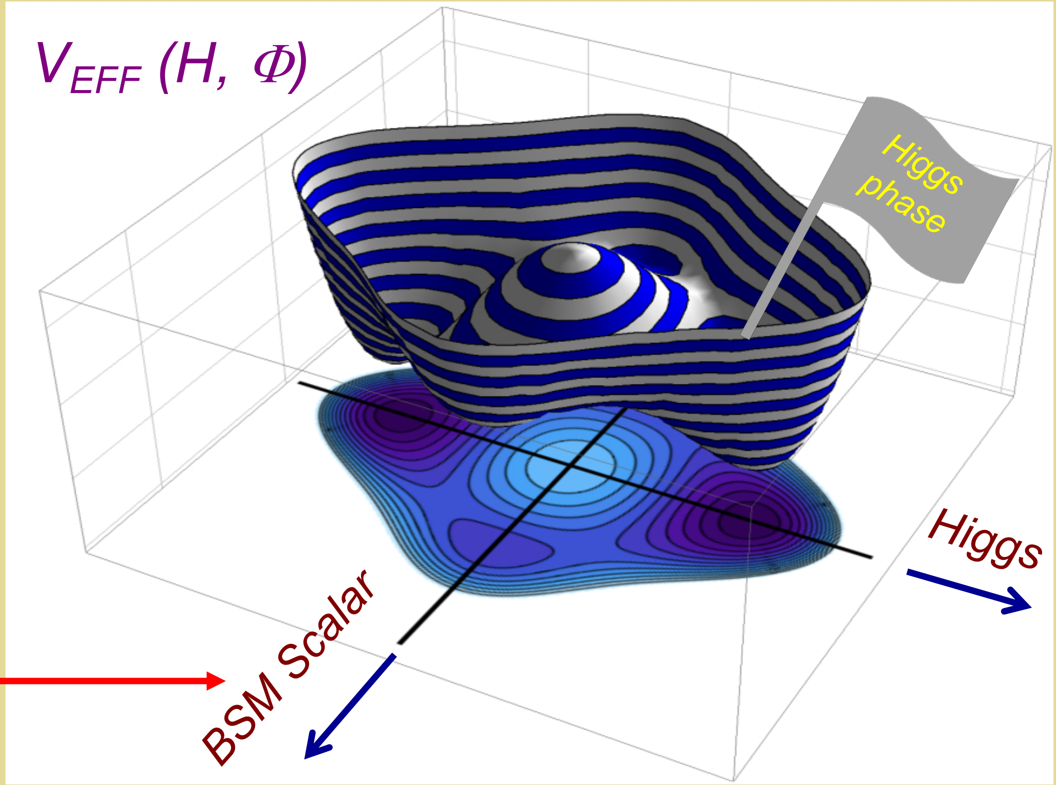
Experimental Probes

Direct Production

BSM Higgs



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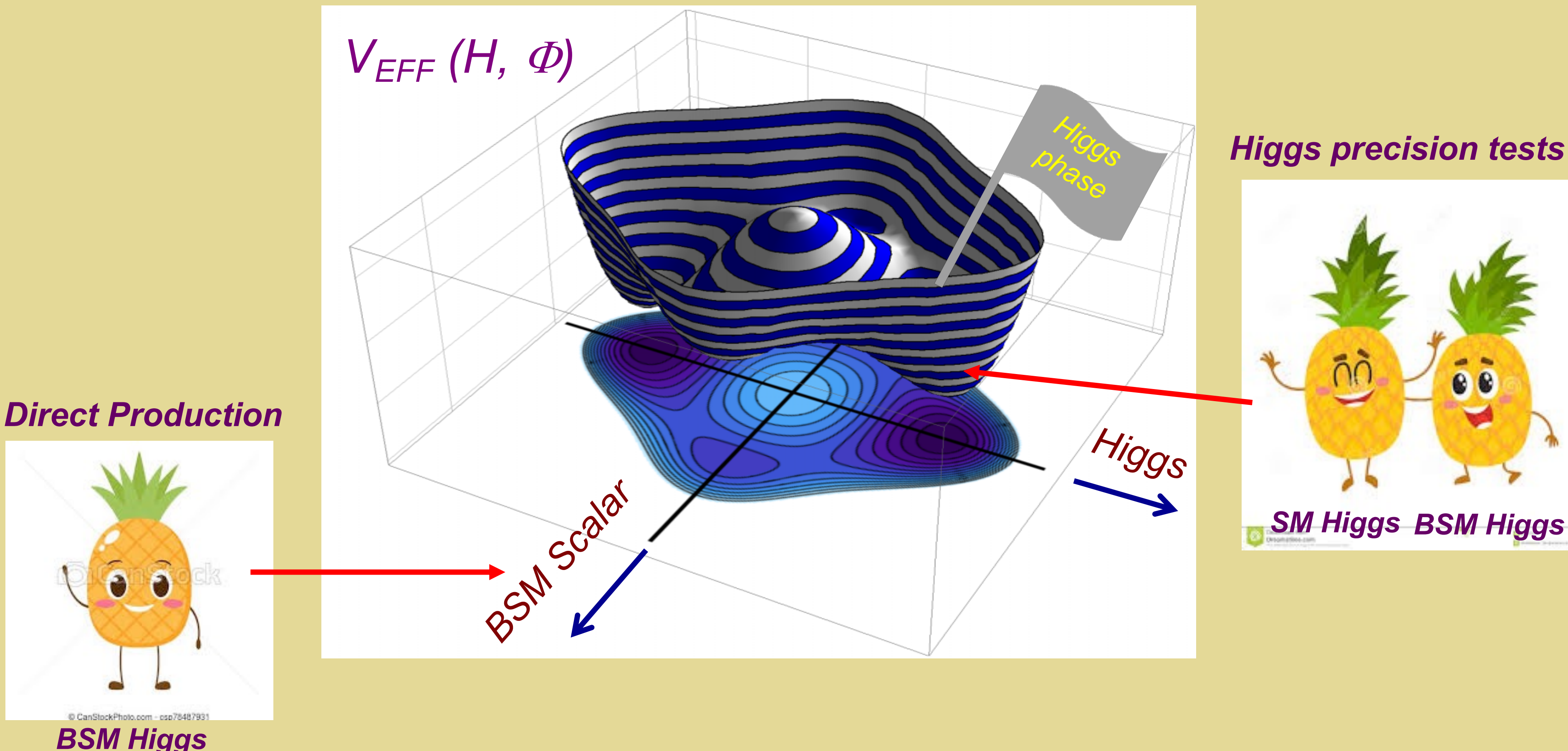

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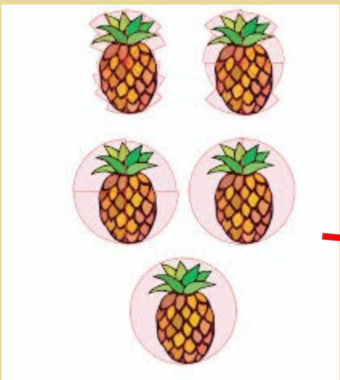
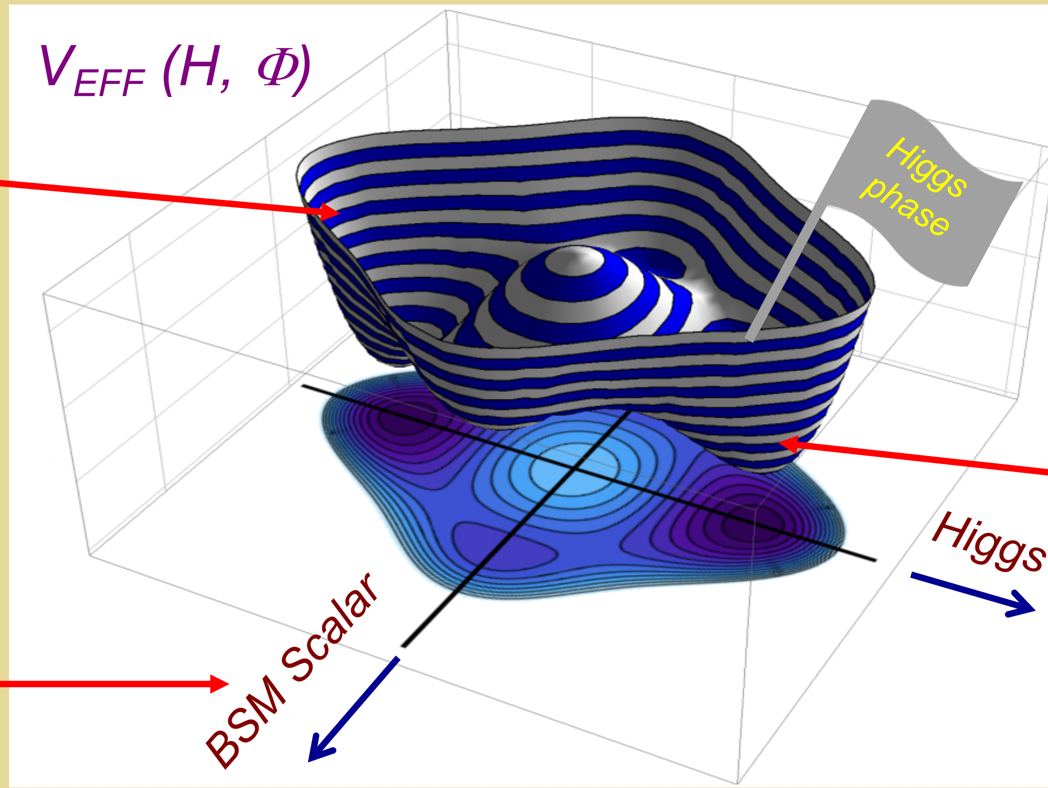
Experimental Probes

Bubble Collisions

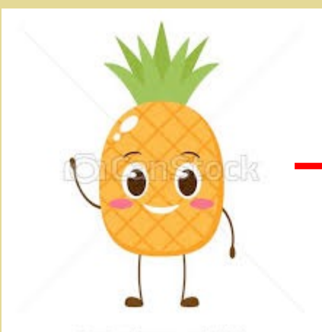


Grav Radiation



Higgs precision tests

Direct Production



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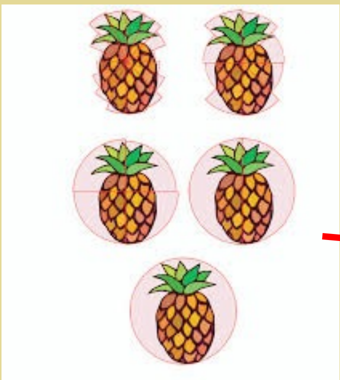

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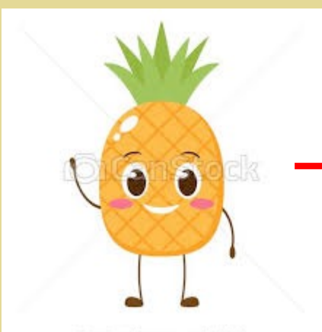

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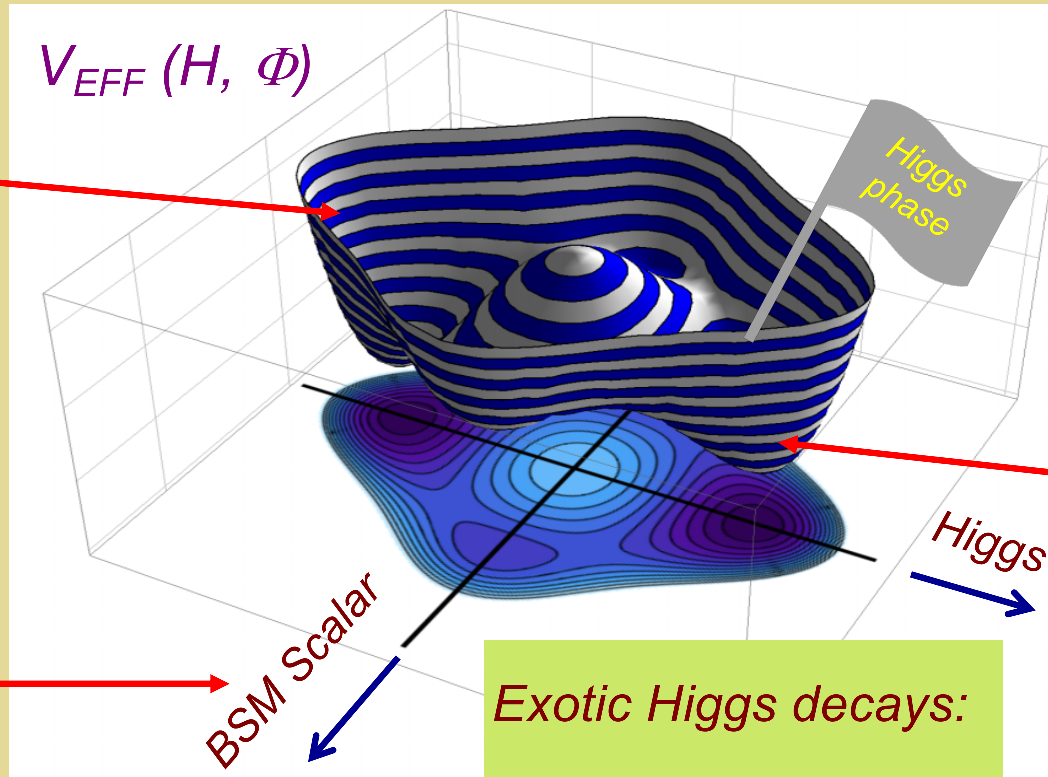


Higgs precision tests

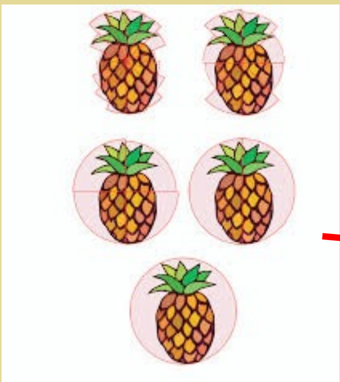
Exotic Higgs decays:

$h \rightarrow \Phi\Phi \rightarrow ??$

Extrema can evolve differently as T evolves → rich possibilities for symmetry breaking

Experimental Probes

Bubble Collisions



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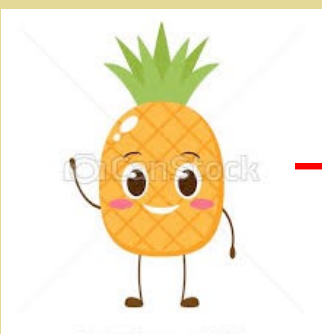
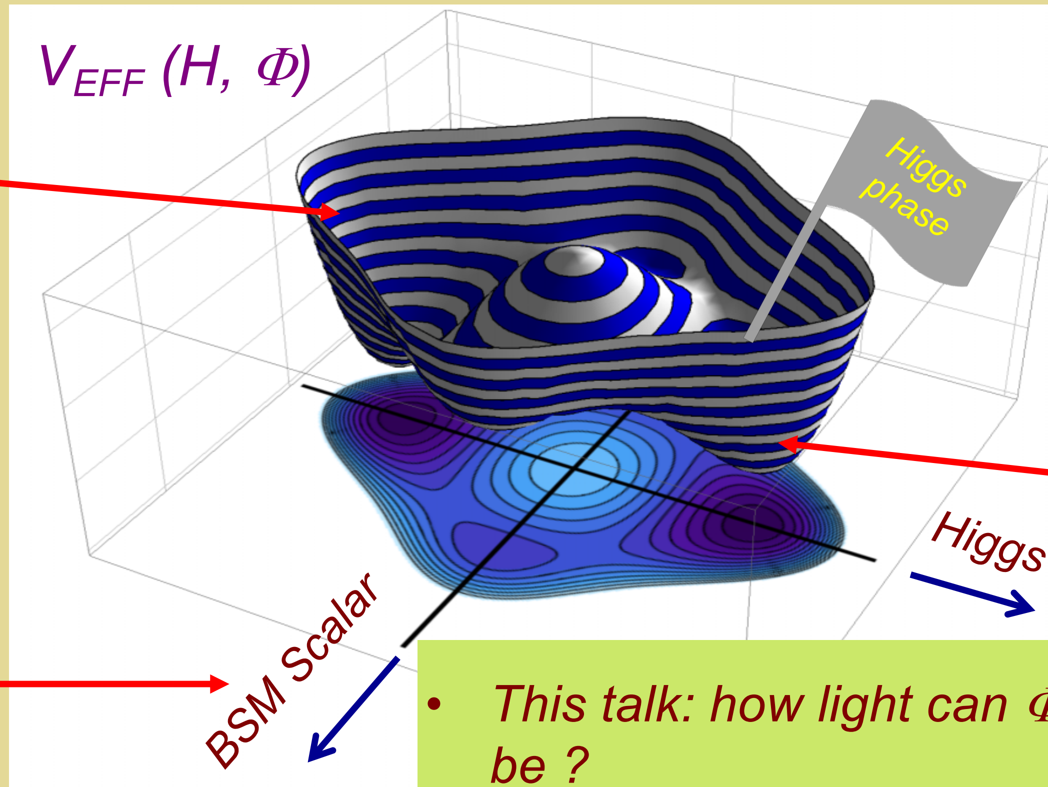


BSM Higgs



Higgs precision tests

- *This talk: how light can Φ be ?*
- *Is there a lower bound on the exotic decay BR ?*

Extrema can evolv ***→***
rich possibilities for symmetry breaking

T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

$$V(h,T)_{\rm SM} = D(T^2 - T_0^2)\, h^2 + \lambda\, h^4 \;\; + \cdots$$

$$T_0^2 = (8\lambda + \text{ loops}) \left(4\lambda + \frac{3}{2}g^2 + \frac{1}{2}g'^{\,2} + 2y_t^2 + \cdots\right)^{-1} \; v^2$$

$T_0 \sim$ 140 GeV

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$$V(h,T)_{\rm SM} = D(T^2 - T_0^2)\,h^2 + \lambda\,h^4 + \cdots$$

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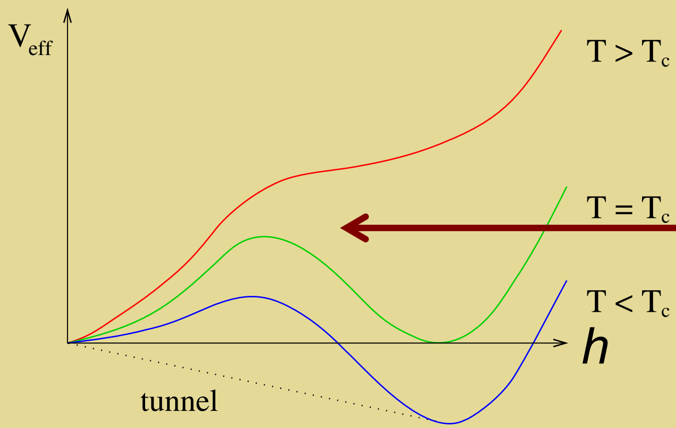
$T_0 \sim$ 140 GeV

$\equiv \quad T_{EW}$

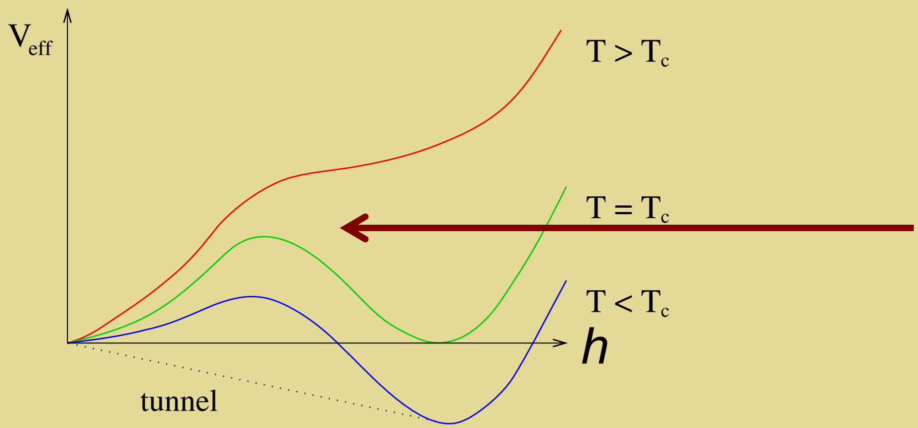
First Order EWPT from BSM Physics



Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

First Order EWPT from BSM Physics



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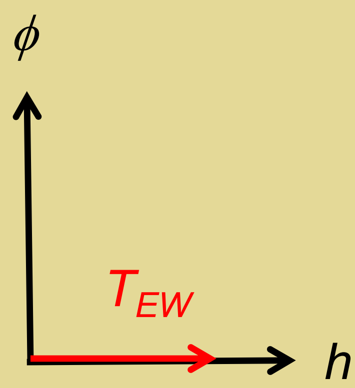
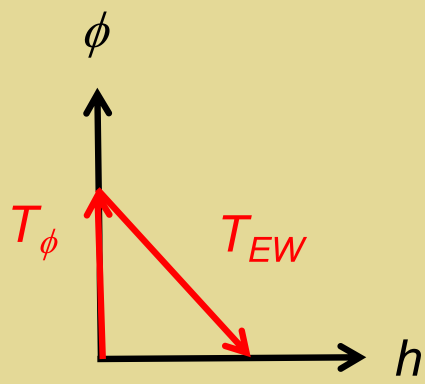


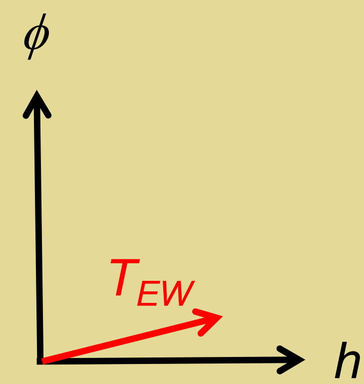
$a_2\, H^2\phi^2$: $T > 0$

loop effect



$a_2\, H^2\phi^2$: $T = 0$

tree-level effect



$a_1\, H^2\phi$: $T = 0$

tree-level effect

II. Model Illustrations

Simple Higgs portal models:

- ***Real gauge singlet (SM + 1)***
- ***Real EW triplet (SM + 3)***

Model Illustrations

Simple Higgs portal models:

- *Real gauge singlet (SM + 1)*
- *Real EW triplet (SM + 3)*

Real Singlet

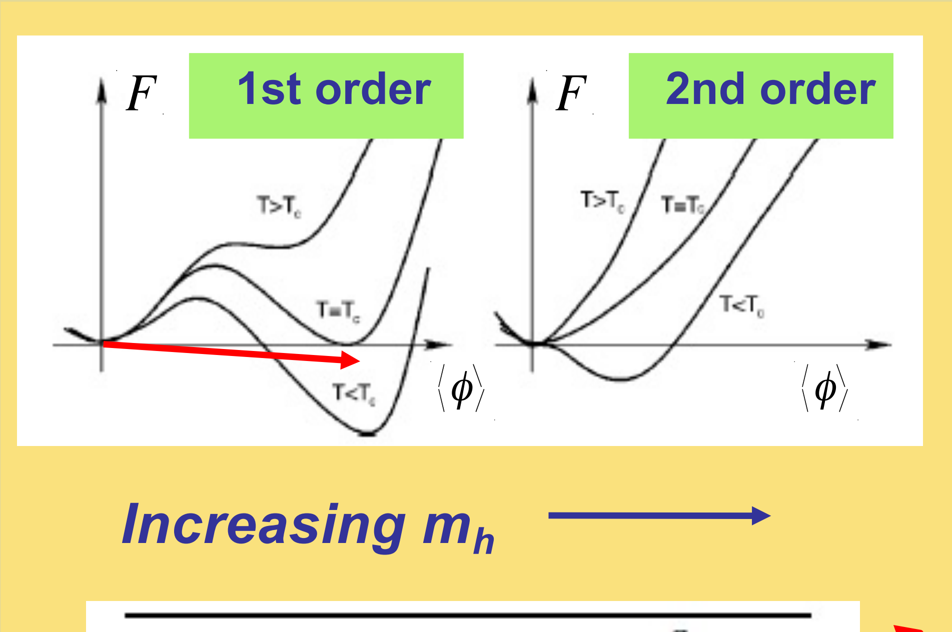
Potential & conventions

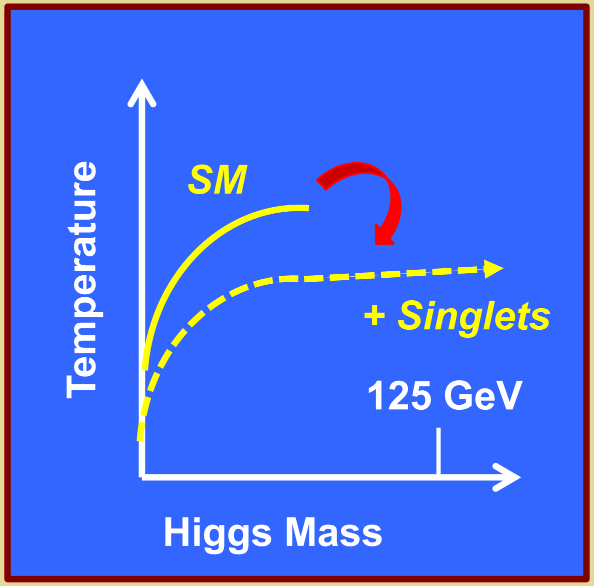
$$V = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4,$$

$$h_1 = h\cos\theta + s\sin\theta$$
$$h_2 = -h\sin\theta + s\cos\theta,$$

- *Profumo, RM, Shaugnessy: h_1 = SM-like*
- *Kozaczuk, RM, Shelton: h_1 = lightest*

EW Phase Transition: Singlet Scalars





EW Phase Diagram

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SM EW: Cross over transition

How does this picture change in presence of new TeV scale physics ? What is the phase diagram ?

Real Singlet: Z_2 or Not to Z_2 ?

Potential & conventions

Z_2 symmetry: S → -S

$$V = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

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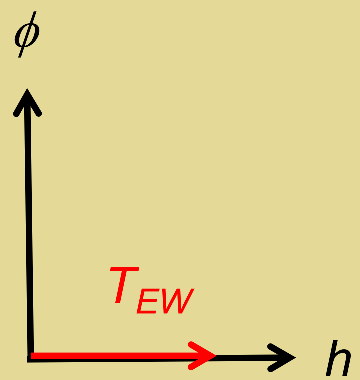
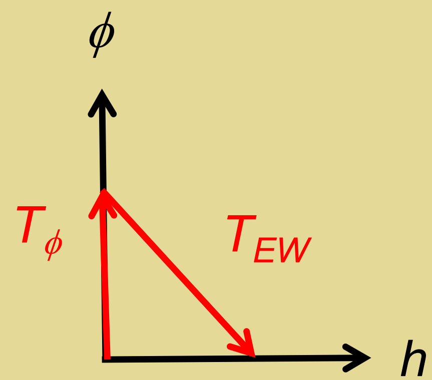
Z_2 symmetry: θ → 0

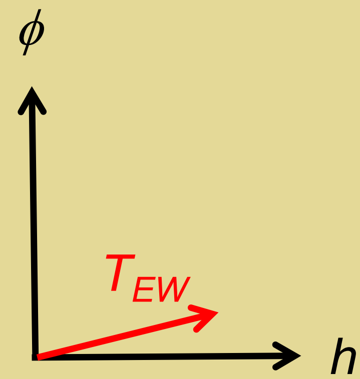
Real Singlet



$a_2\, H^2\phi^2$: $T > 0$
loop effect



$a_2\, H^2\phi^2$: $T = 0$
tree-level effect



$a_1\, H^2\phi$: $T = 0$
tree-level effect

No Z_2 breaking at $T = 0$ required

Z_2 breaking at $T = 0$ (explicit or spontaneous)

First Order EWPT from BSM Physics

- $\Gamma(h \rightarrow \gamma\gamma)$
- ***Higgs signal strengths***
- ***Higgs self-coupling***
- ***Exotic Decays***

First Order EWPT from BSM Physics

- $\Gamma(h \rightarrow \gamma\gamma)$
- *Higgs signal strengths*
- *Higgs self-coupling*
- *Exotic Decays*

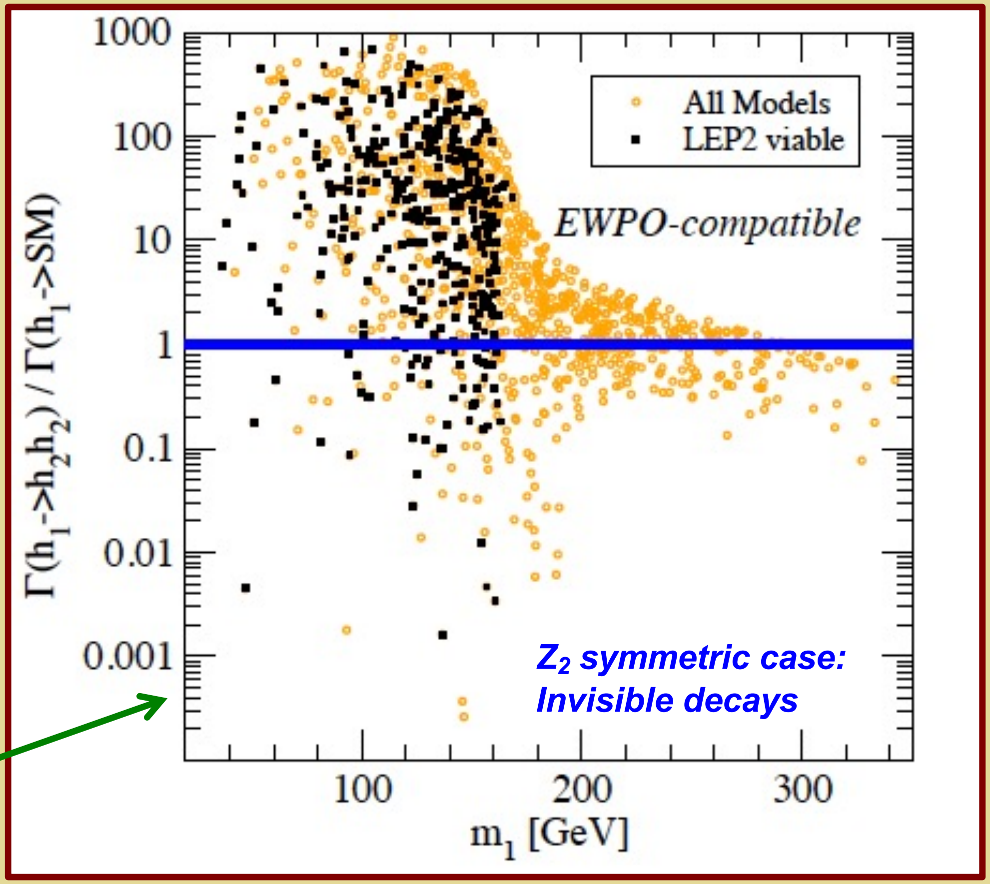
Can a light BSM scalar catalyze a first order EWPT ?

III. Exotic Higgs Decays

Simple Higgs portal models:

- ***Real gauge singlet (SM + 1)***
- ***Real EW triplet (SM + 3)***

Light Singlets: Exotic Higgs Decays



Is there a lower bound ?

Profumo, MJRM, Shaugnessy 0705.2425

Exotic Decay BR: Lower Bound

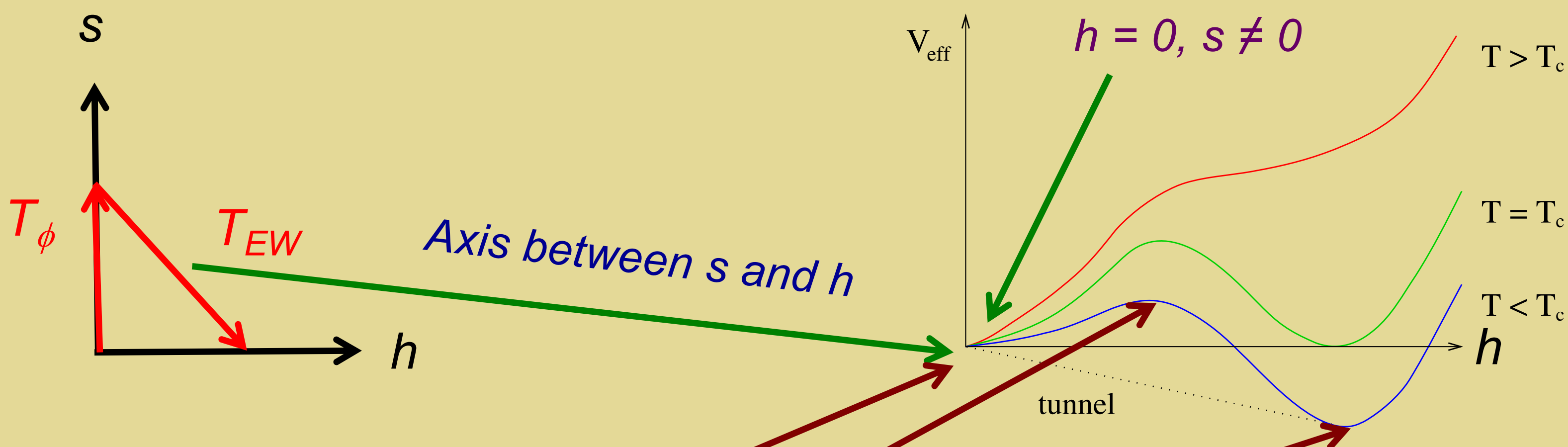
- ***Numerical scan indicates a lower bound as a function of singlet-like scalar mass***

- ***Can we understand it analytically ?***

Exotic Decay BR: Semi-Analytic Lower Bound

- Two-step transition
- SFOEWPT to Higgs phase
- A minimum exists along singlet direction at $T > 0$
- EW vac as absolute min at $T = 0$
- Singlet min is absolute min for some $T > T_{EW}$
- Tunneling is rate sufficiently large that the transition completes (numerical input required)

Exotic Decay BR: Semi-Analytic Lower Bound



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

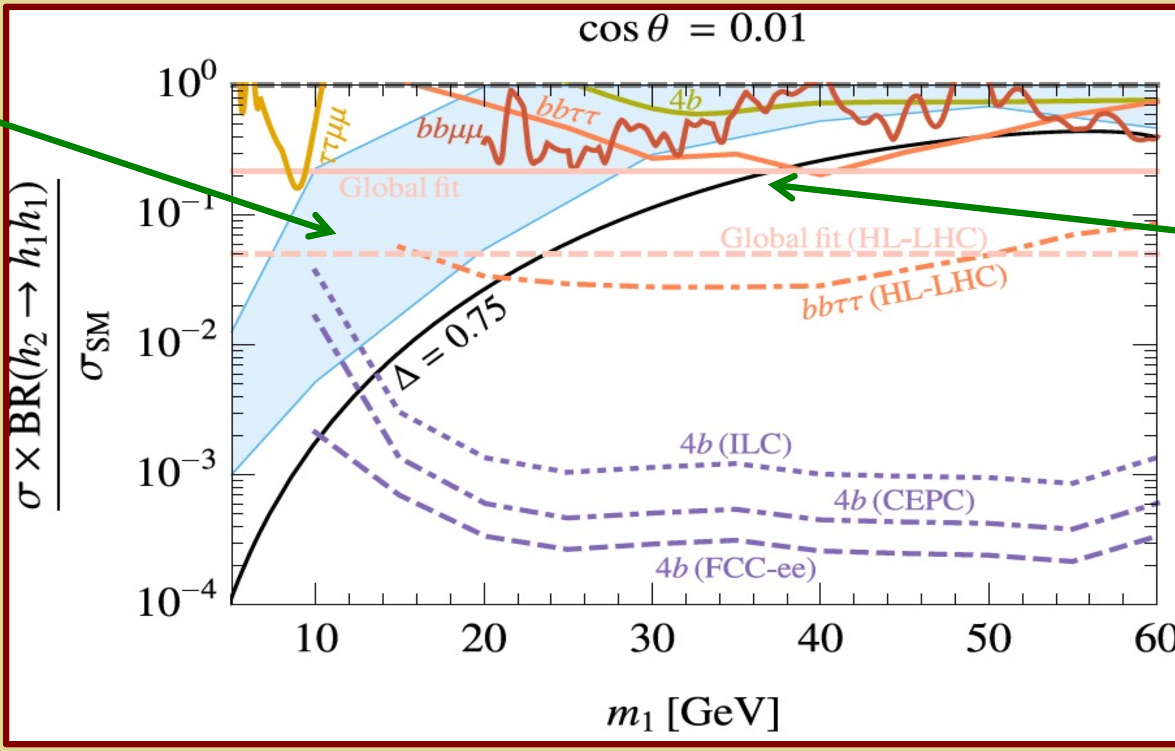
Δ Must be sufficiently large for tunneling to occur

Δ Taken from numerical studies

Light Singlets: Exotic Higgs Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical



EWPT viable: Semi analytic

J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206

Future Projections

CEPC: 5 ab^{-1} *FCC-ee: 5 ab^{-1}* *ILC: 2 ab^{-1}*

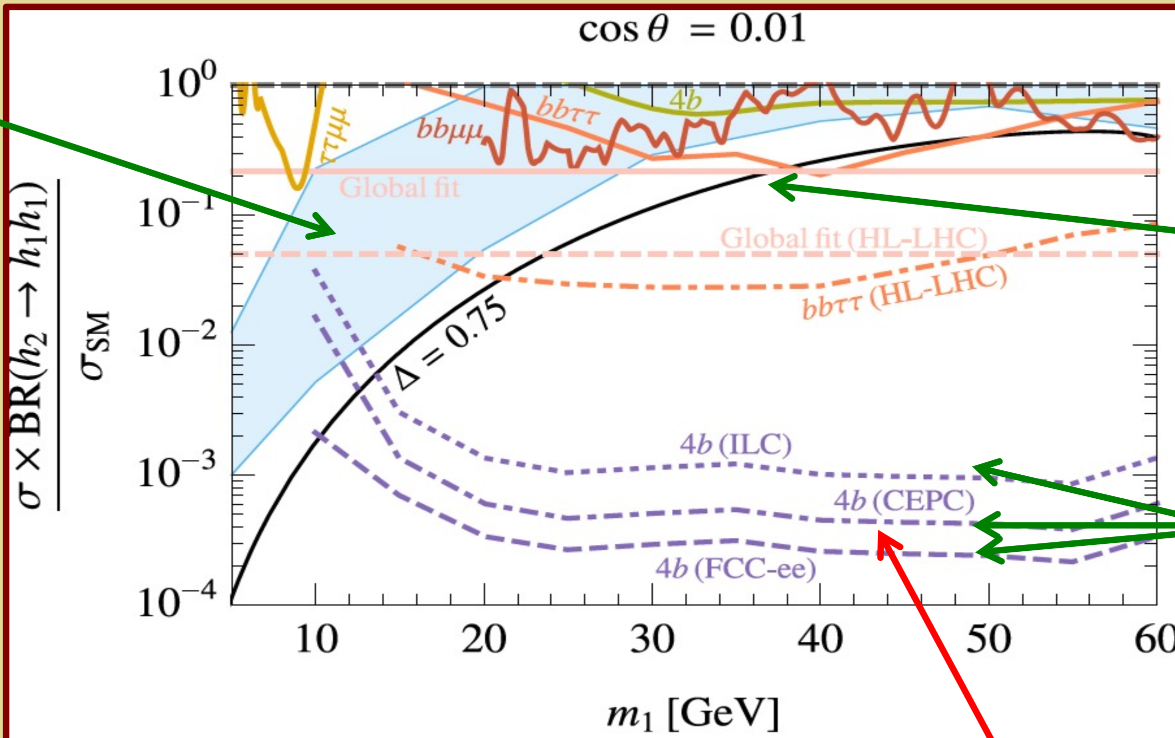
Decay Mode	95% C.L. limit on Br				
	LHC	HL-LHC	CEPC	ILC	FCC-*ee*
$\not{E}_T$	0.23 [49, 50]	0.056 [12–14]	0.0028 [16]	0.0025 [17]	0.005 [18]
$(b\bar{b})+\not{E}_T$	–	[0.2]	1×10^{-4}	2×10^{-4}	5×10^{-5}
$(jj)+\not{E}_T$	–	–	5×10^{-4}	5×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)+\not{E}_T$	–	[1]	$8\times10^{-4}*$	1×10^{-3}	3×10^{-4}
$b\bar{b}+\not{E}_T$	–	[0.2] [39]	3×10^{-4}	4×10^{-4}	1×10^{-4}
$jj+\not{E}_T$	–	–	5×10^{-4}	7×10^{-4}	2×10^{-4}
$\tau^+\tau^-+\not{E}_T$	–	–	$8\times10^{-4}*$	1×10^{-3}	3×10^{-4}
$(b\bar{b})(b\bar{b})$	1.7 [51]	(0.2)	4×10^{-4}	9×10^{-4}	3×10^{-4}
$(c\bar{c})(c\bar{c})$	–	(0.2)	8×10^{-4}	1×10^{-3}	3×10^{-4}
$(jj)(jj)$	–	[0.1]	1×10^{-3}	2×10^{-3}	7×10^{-4}
$(b\bar{b})(\tau^+\tau^-)$	[0.1]* [52]	[0.15]	$4\times10^{-4}*$	6×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)(\tau^+\tau^-)$	[1.2]* [53]	[0.2∼0.4]	$1\times10^{-4}*$	2×10^{-4}	5×10^{-5}
$(jj)(\gamma\gamma)$	–	[0.01]	1×10^{-4}	2×10^{-4}	3×10^{-5}
$(\gamma\gamma)(\gamma\gamma)$	[7×10^{-3}] [54]	$4\times10^{-4}*$	1×10^{-4}	1×10^{-4}	3×10^{-5}

Z. Liu, L-T Wang, H. Zhang 1612.09284

Light Singlets: Exotic Higgs Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical



EWPT viable: Semi analytic

Future e^+e^-

Our Snowmass study:

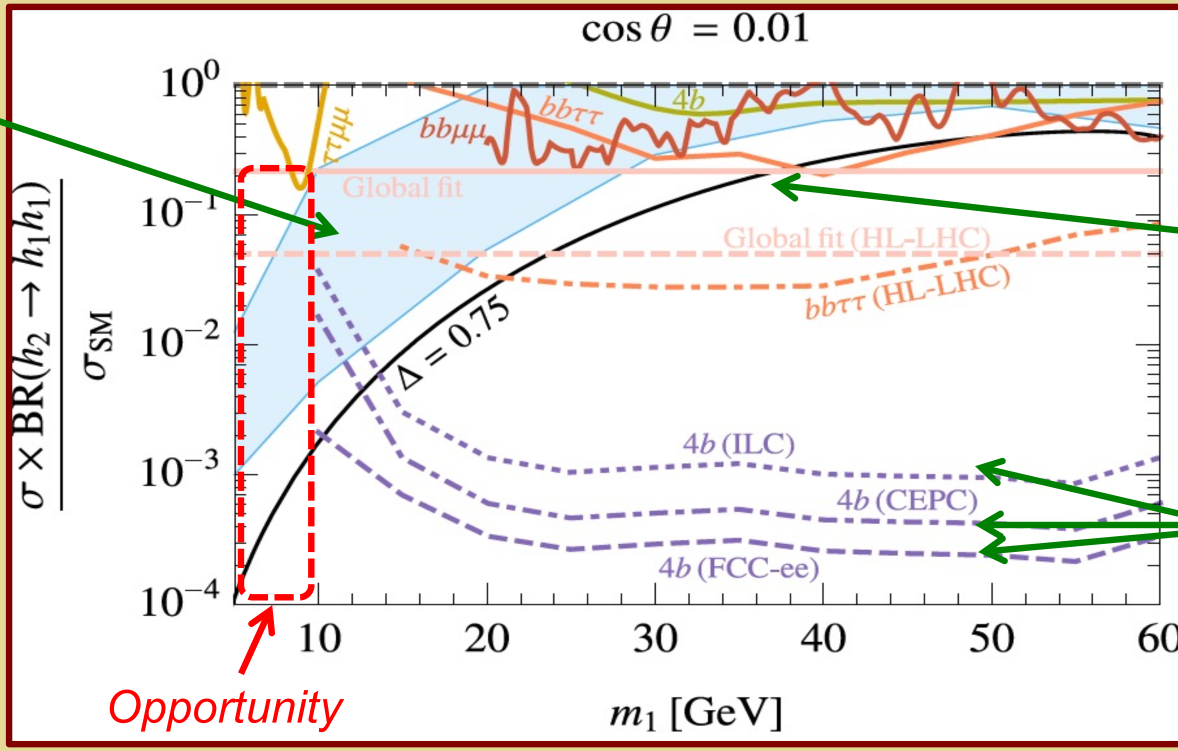
- Where is CEPC sensitivity?
- Opportunities w/ other channels ?

J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206

Light Singlets: Exotic Higgs Decays

$h_2 \rightarrow h_1\, h_1 \rightarrow 4b$

EWPT viable: numerical



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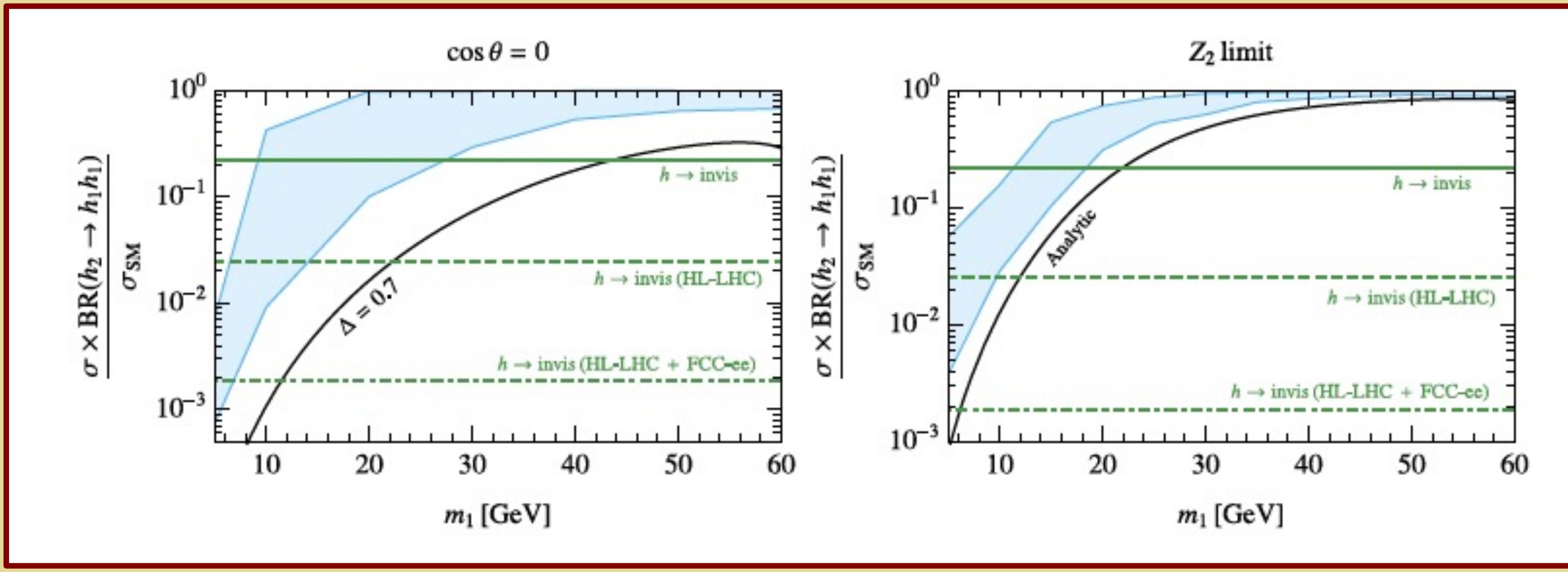
Light Singlets: Exotic Higgs Decays

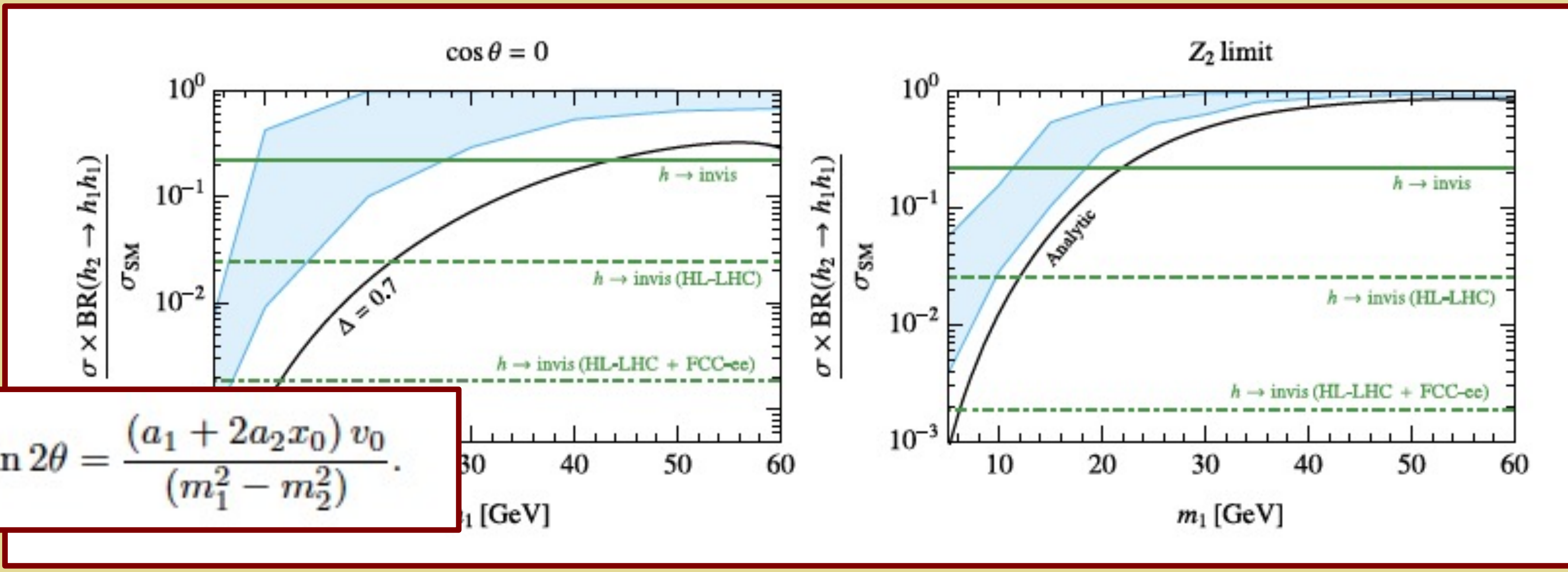
Invisible decays



J. Kozaczuk, MR-M, J. Shelton 1911.10210

Light Singlets: Exotic Higgs Decays

Invisible decays



$$\sin 2\theta = \frac{(a_1 + 2a_2 x_0)\, v_0}{(m_1^2 - m_2^2)}.$$

Cancellation –> Fine tuning

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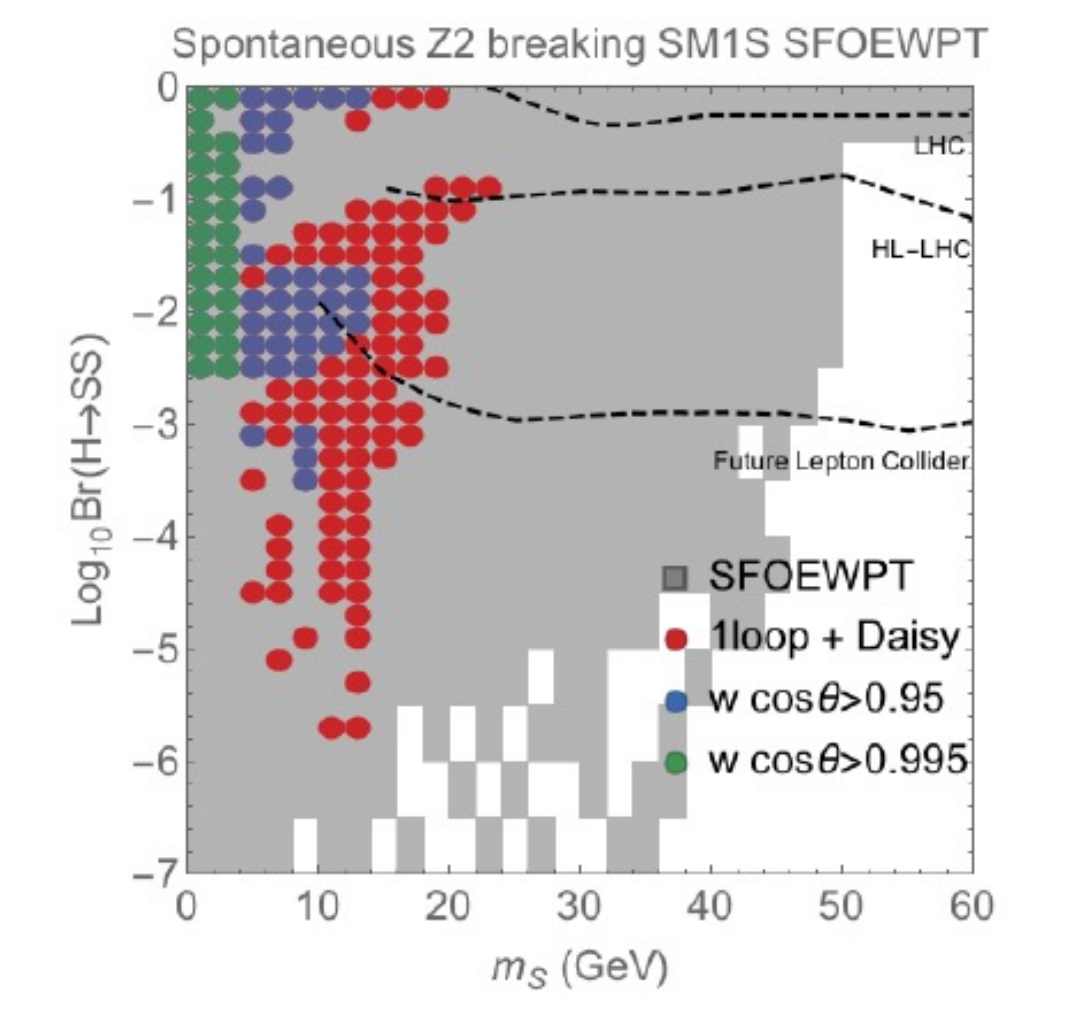
Spontaneous Z_2 Breaking



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IV. Outlook

Was there an electroweak phase transition ?

Key Ideas for this Talk

- ***Determining the thermal history of EW symmetry breaking is a key challenge for particle physics***

- ***The "electroweak temperature" → a scale provided by nature that gives us a clear BSM target for colliders to address this challenge***

- ***Exotic Higgs decays provide a unique probe of light scalar-induced thermal history modifications***

- ***Interesting opportunities for the CEPC should be pursued → Snowmass study***