Di-Higgs Searches: Connections to Cosmology

M.J. Ramsey-Musolf

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

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

Muon Collider Workshop, June 4 2021

Key Ideas for this Talk

- ***Extensions of the Standard Model scalar sector can address key open questions in cosmology***
- ***Di-Higgs searches provide one important window on the cosmological implications of extended scalar sectors***
- ***This talk: focus on delineating the thermal history of EWSB and consequences for baryogenesis and gravitation wave searches***
- ***There are exciting opportunities and synergies involving the LHC and prospective future colliders***
  → how might a muon collider fit into this picture?

Outline

I. *Cosmological Implications*

II. *Was There an EW Phase Transition?*

III. *Model Illustration: Real Singlet*

IV. *Di-Higgs: Opportunities*

V. *Outlook*

Di-Higgs & Triscalar Interactions

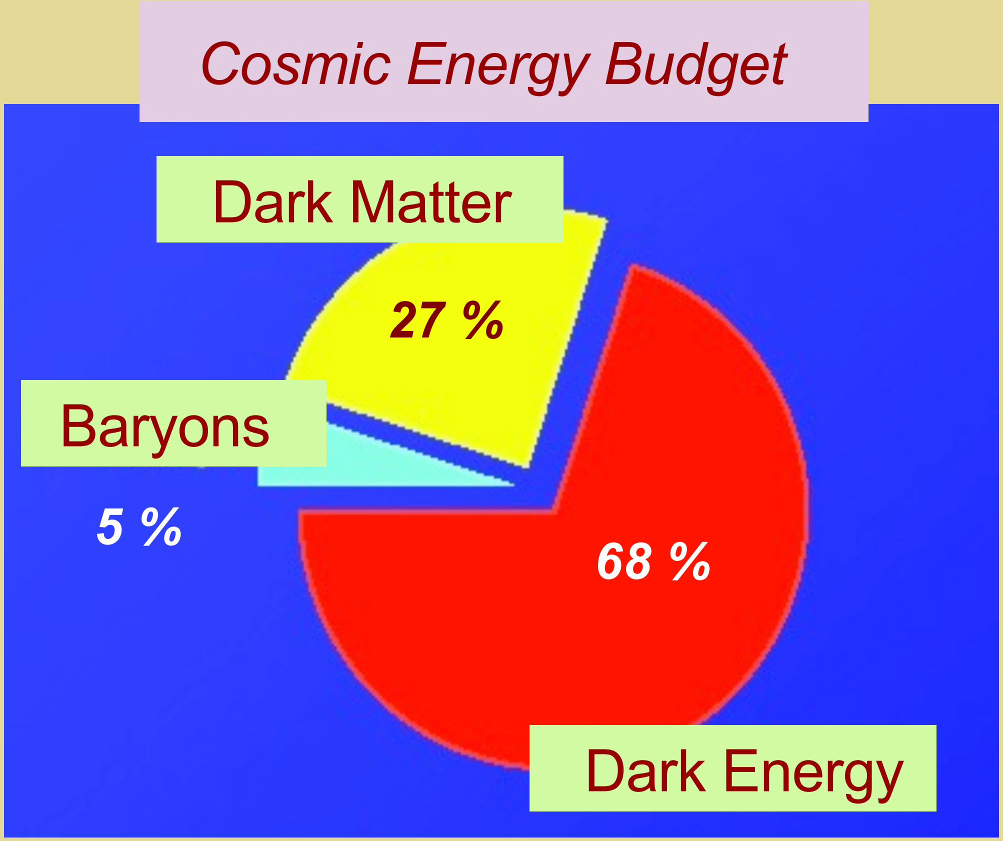
h_1 SM-like
h_2 SM-like

$$\lambda_{ijk}\, h_i\, h_j\, h_k$$

λ_{111}	Non-resonant
λ_{211}	Resonant
λ_{122}	Resonant – exotic decays & non-resonant

I. Cosmological Implications

The Origin of Matter



How can extended scalar sectors address this puzzle ?

Connections with Cosmology

- ***Dark Matter: stable h_2***

- ***Thermal history of EWSB: Was there an electroweak phase transition ?***

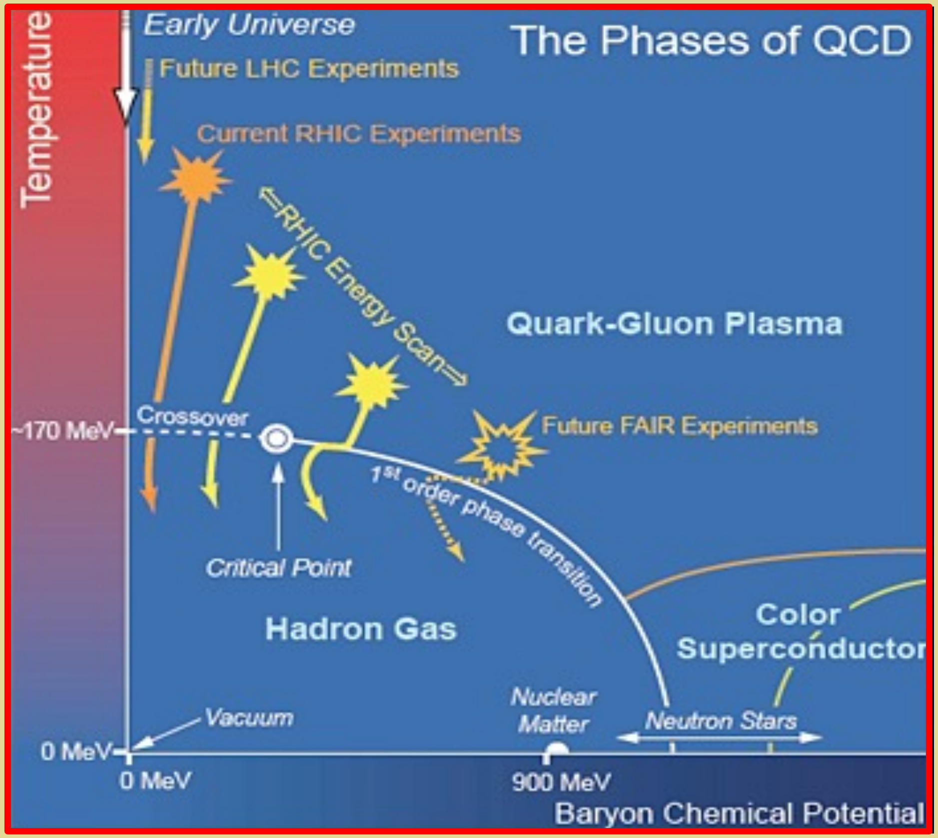
Electroweak Phase Transition

- *Higgs discovery $\rightarrow$ What was the thermal history of EWSB ?*

- *Baryogenesis $\rightarrow$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*

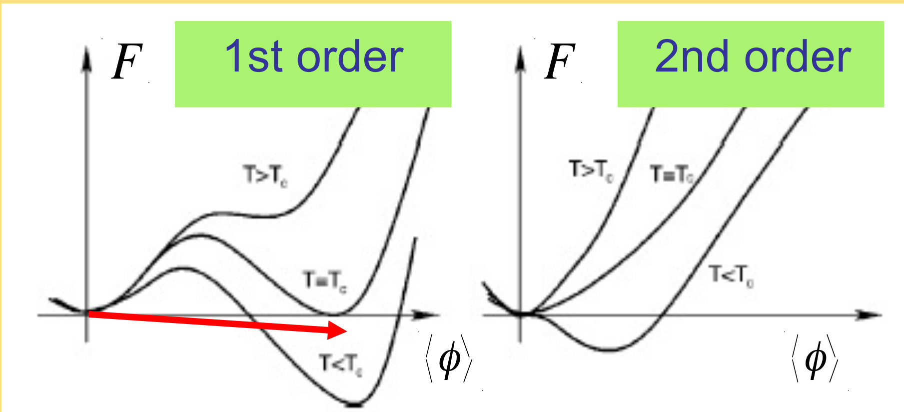
- *Gravitational waves $\rightarrow$ If a signal observed in next generation probes, could a cosmological phase transition be responsible ?*

Thermal History of Symmetry Breaking



QCD Phase Diagram → EW Theory Analog?

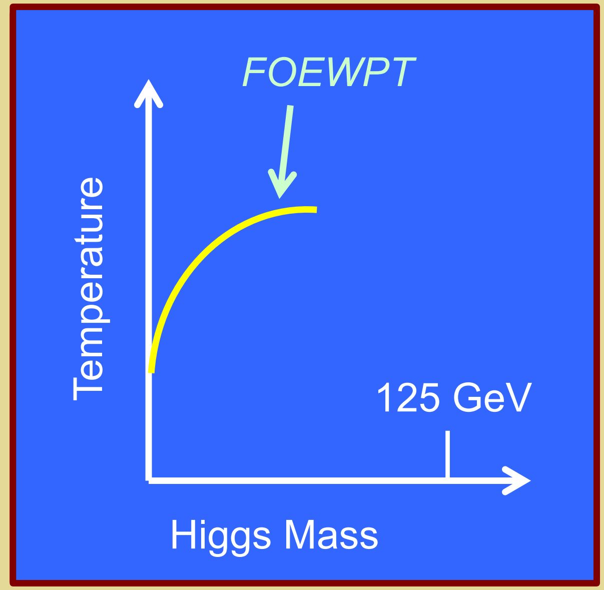
EWSB Transition: St'd Model



Increasing m_h →

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition



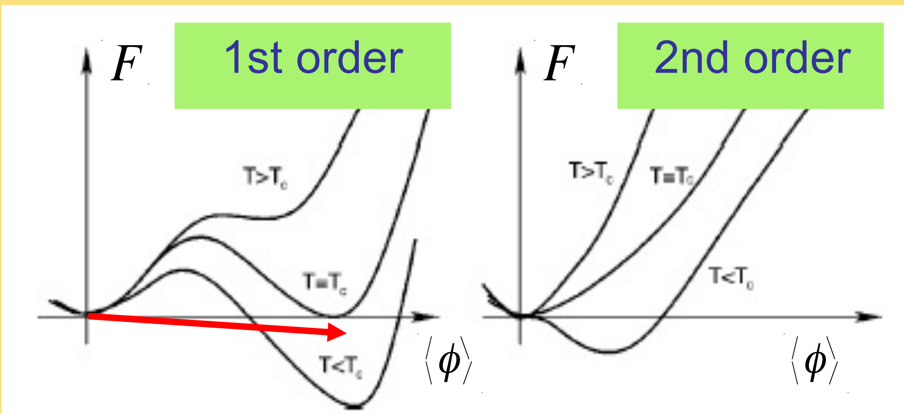
EW Phase Diagram

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

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 ?*

EW Phase Transition: Baryogen & GW



Increasing m_h →

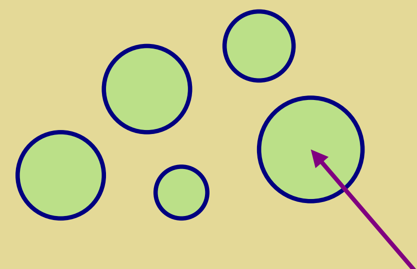
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
Collider Searches

"Strong" 1st order EWPT

- *Baryogen**
- *GW*

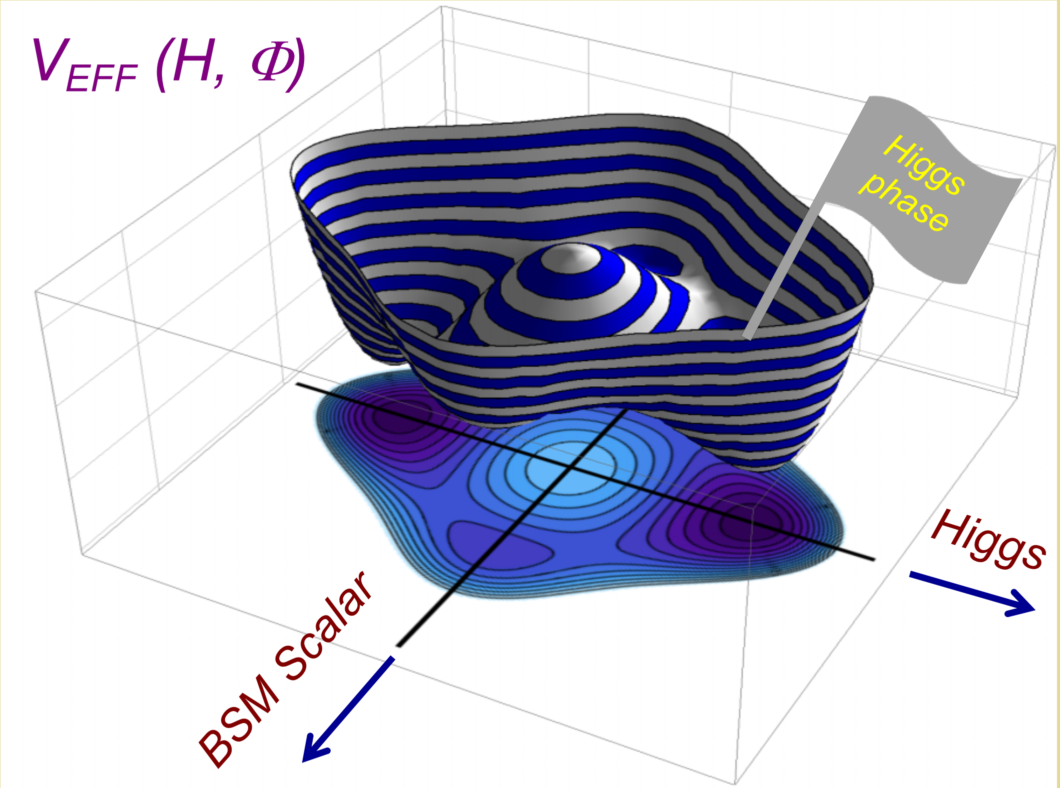
Bubble nucleation



* *Need BSM CPV*

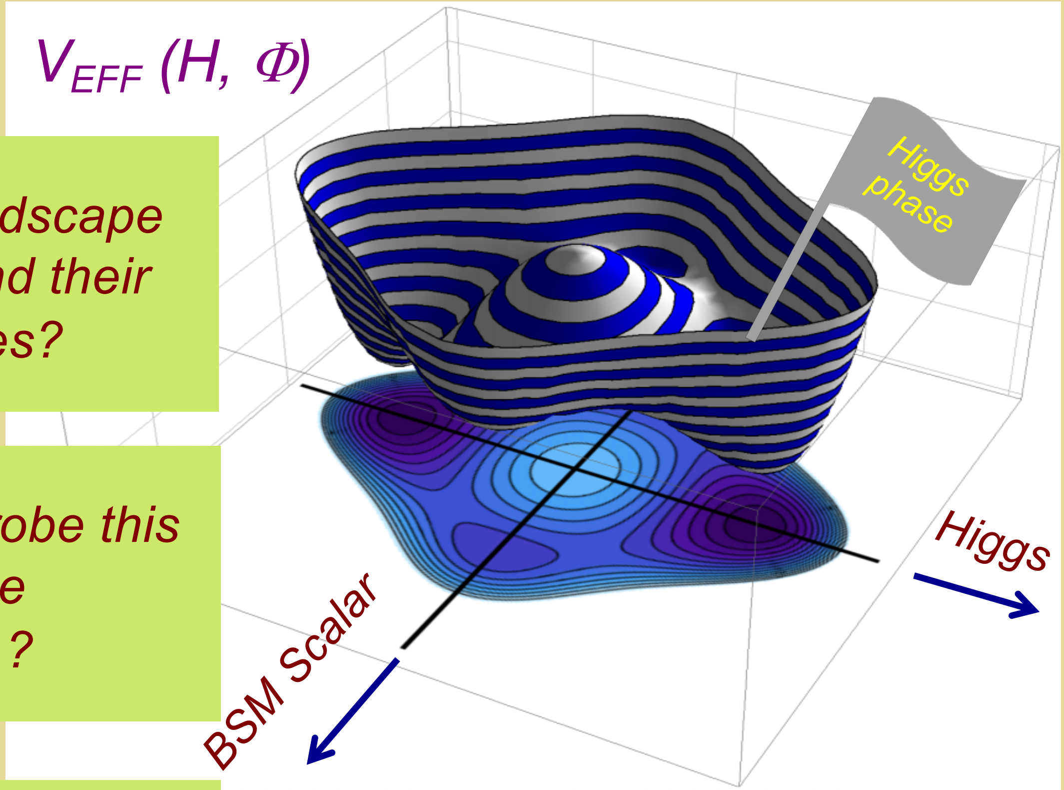
II. Was There an EW Phase Transition ?

Thermal History of EWSB



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

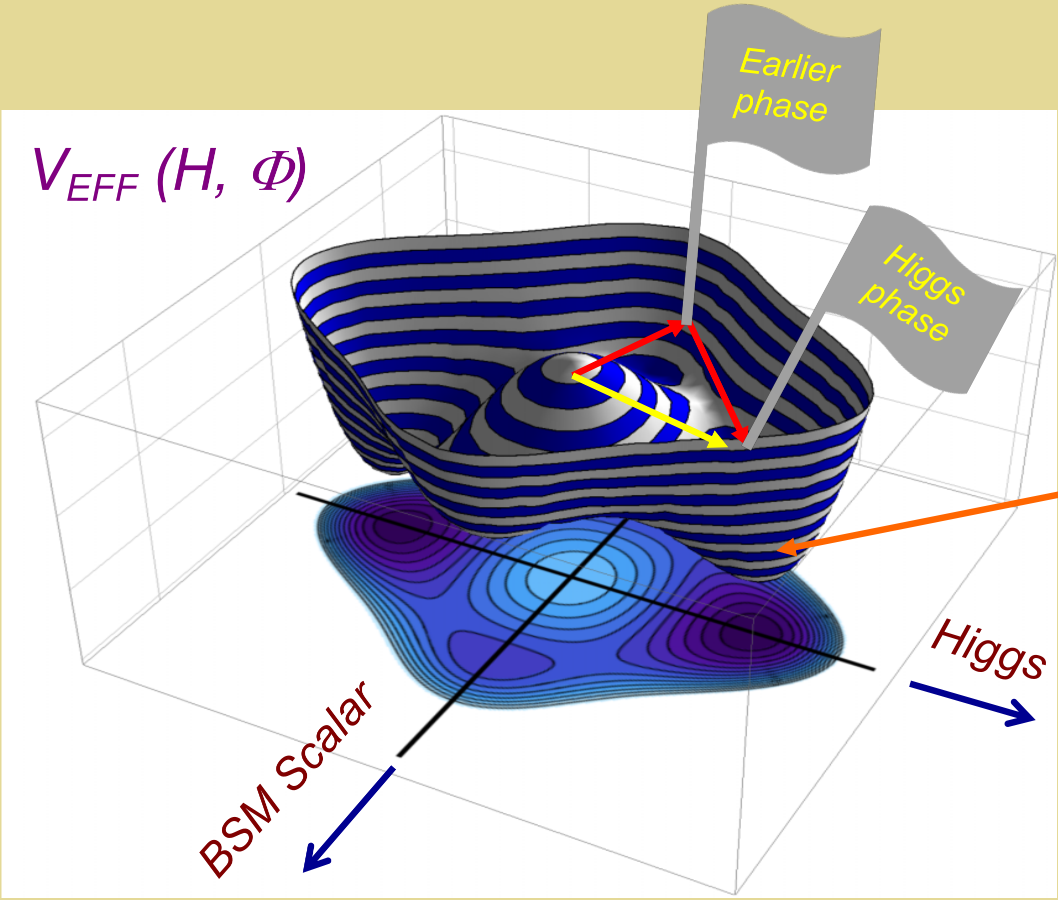
Thermal History of EWSB



- *What is the landscape of potentials and their thermal histories?*
- *How can we probe this T > 0 landscape experimentally ?*
- *How reliably can we compute the thermodynamics ?*

n evolve differently as T evolves →
ilities for symmetry breaking

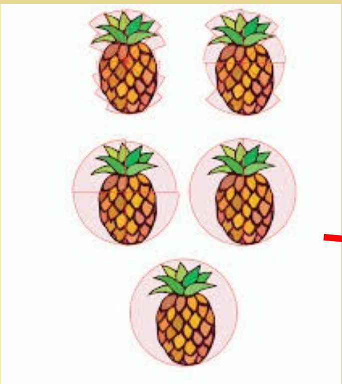
Patterns of Symmetry Breaking



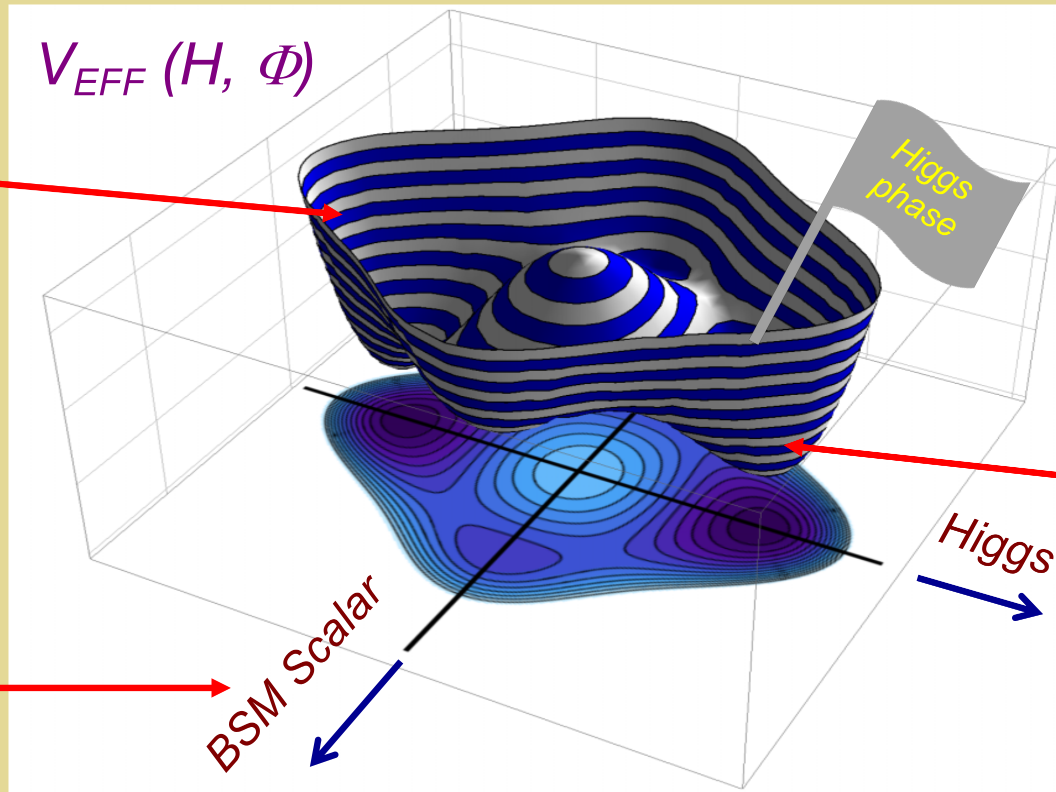
Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

Experimental Probes

Bubble Collisions



Grav Radiation



Higgs precision tests

Direct Production

BSM Higgs

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

T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

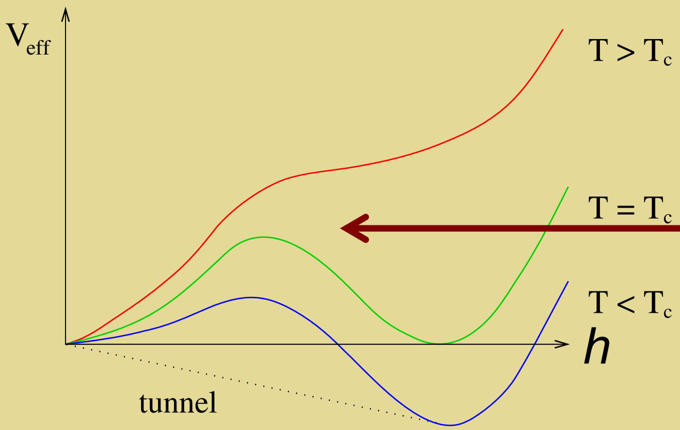
$$V(h,T)_{\rm SM} = D(T^2 - T_0^2)\, h^2 + \lambda\, h^4 \;+ \cdots$$

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

$T_0 \sim$ 140 GeV

$\equiv$ T_{EW}

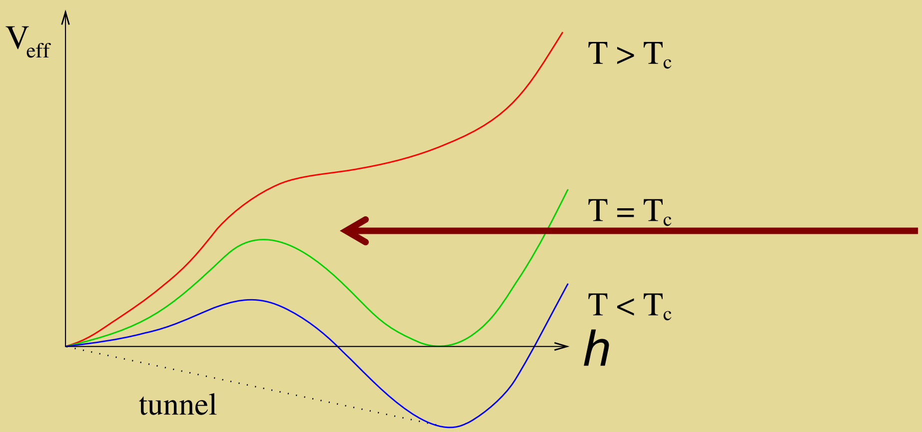
First Order EWPT from BSM Physics



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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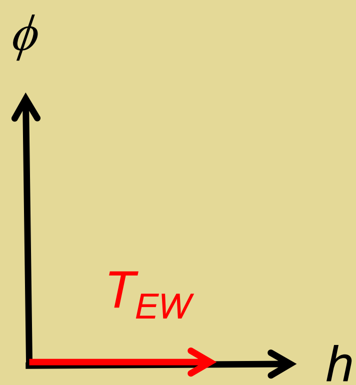
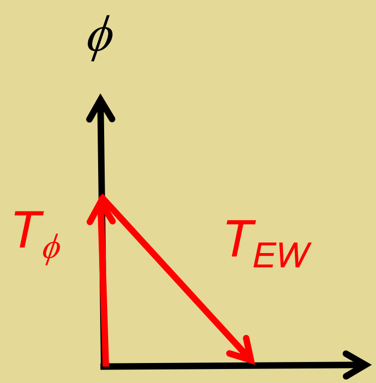
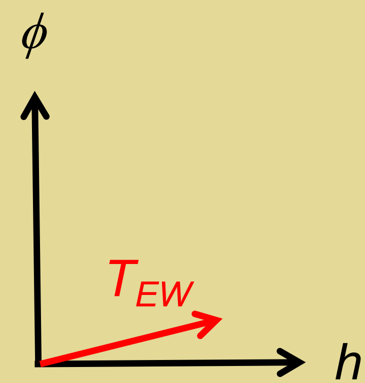


$a_2 H^2\phi^2$: $T > 0$
loop effect



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



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

III. Model Illustrations

Simple Higgs portal models:

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

Real Singlet

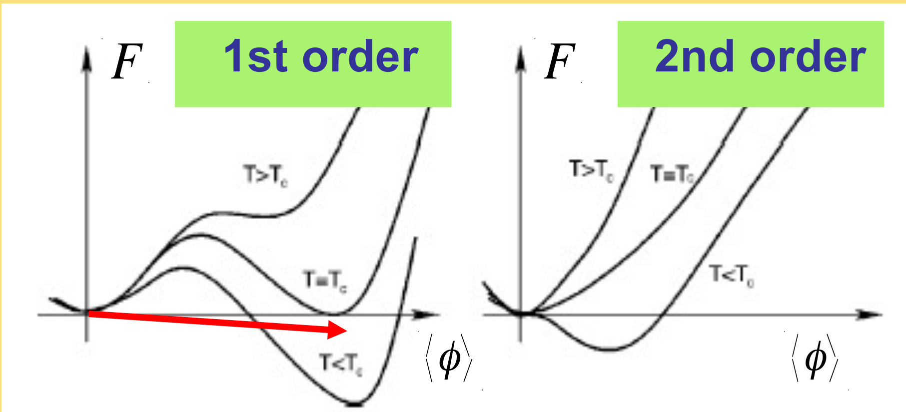
Potential & conventions

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

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

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

EW Phase Transition: Singlet Scalars



Increasing m_h ⟶

Lattice	Authors	M_h^C (GeV)
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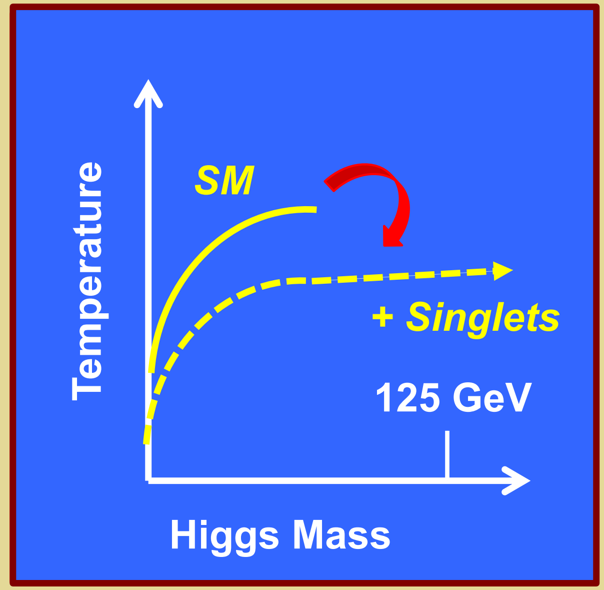
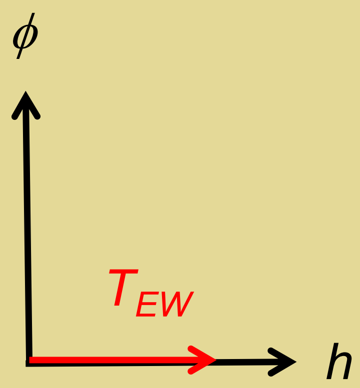


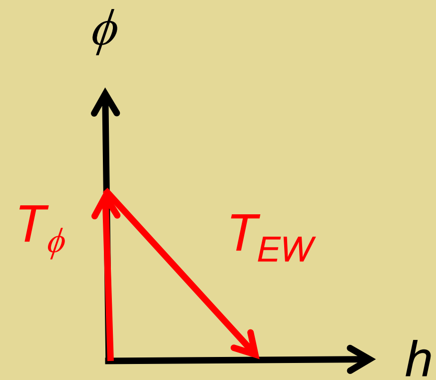
EW Phase Diagram

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

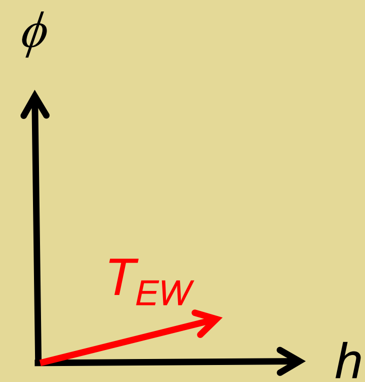
Real Singlet



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



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

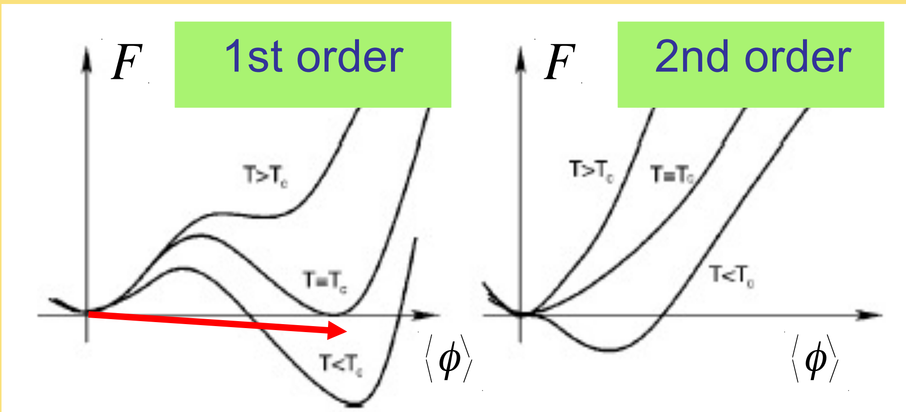


$a_1\, H^2\phi$: $T = 0$
tree-level effect

No Z_2 breaking at $T = 0$ required

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

EW Phase Transition: New Scalars

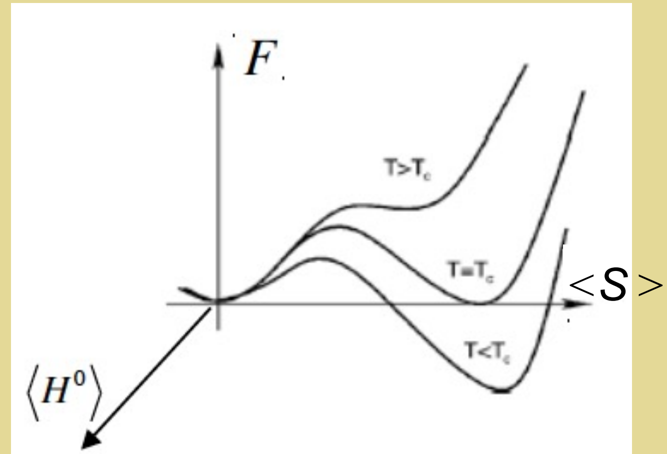


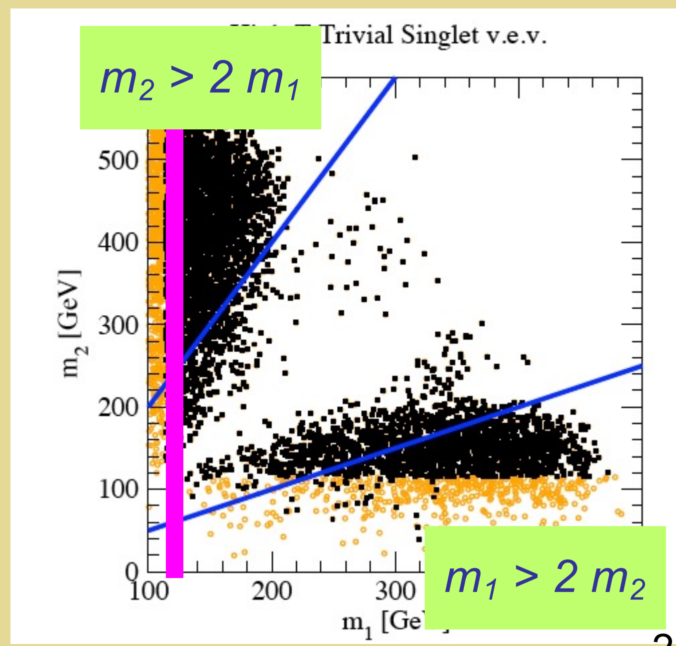
Increasing m_h →

← *New scalars*

Real Singlet: $\phi \rightarrow S$

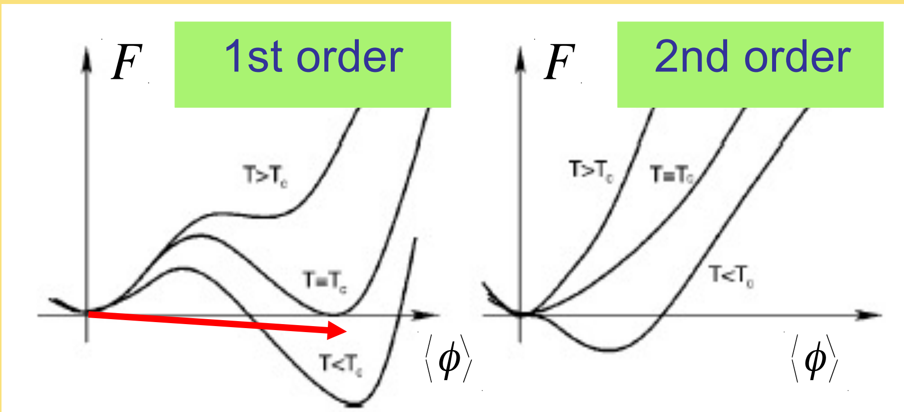
Simplest Extension:
two states h_1 & h_2





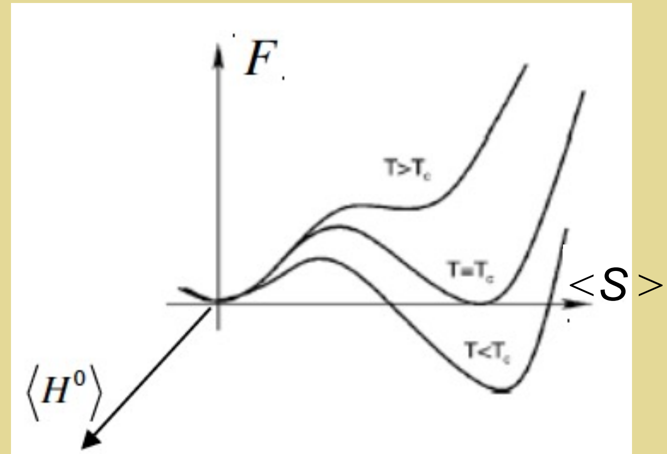
Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010
Espinosa, Konstandin, Riva NPB 854 (2012) 592

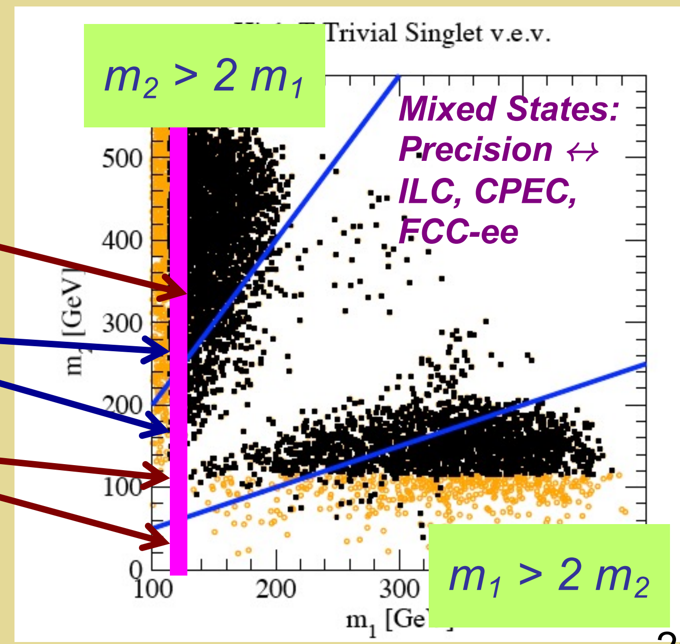
EW Phase Transition: Singlet Scalars



Collider probes

- *Resonant di-Higgs production*
- *Precision Higgs measurements*
- *Non-resonant di-Higgs & exotic Higgs decays*





Profumo, MJRM, Shaugnessy '07

Real Singlet: Triple Scalar Couplings

$$\lambda_{211} = \frac{1}{4}[(a_1 + 2a_2x_0)\cos^3\theta + 4v_0(a_2 - 3\lambda)\cos^2\theta\sin\theta + (a_1 + 2a_2x_0 - 2b_3 - 6b_4x_0)\cos\theta\sin^2\theta - 2a_2v_0\sin^3\theta] \quad (12)$$

Resonant di-Higgs

$h_2 \rightarrow h_1 h_1$

$$g_{111} = \lambda v_0 \cos^3\theta + \frac{1}{4}(a_1 + 2a_2x_0)\cos^2\theta\sin\theta + \frac{1}{2}a_2v_0\cos\theta\sin^2\theta + \frac{b_3}{3}\sin^3\theta + b_4x_0\sin^3\theta \quad .$$

Higgs self-coupling

$h_1 h_1 h_1$

$$g_{122} = \frac{v_0\, c_\theta}{2}\left(a_2(c_\theta^2 - 2s_\theta^2) + 6\lambda s_\theta^2\right) + \frac{a_1 + 2a_2x_0}{2}\left(s_\theta^3 - c_\theta^2 s_\theta\right) + +(b_3 + 3b_4x_0)\ c_\theta^2 s_\theta, \qquad [s_\theta \equiv \sin\theta,\ c_\theta \equiv \cos\theta].$$

Exotic decays

$h_1 \rightarrow h_2 h_2$

Real Singlet: Triple Scalar Couplings

Insensitive to θ and x_0

$$\lambda_{211} = \frac{1}{4}[(a_1 + 2a_2x_0)\cos^3\theta + 4v_0(a_2 - 3\lambda)\cos^2\theta\sin\theta + (a_1 + 2a_2x_0 - 2b_3 - 6b_4x_0)\cos\theta\sin^2\theta - 2a_2v_0\sin^3\theta] \quad (12)$$

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Exotic decays

$h_1 \rightarrow h_2 h_2$

Real Singlet: Triple Scalar Couplings

Same combination *θ suppression*

$$\lambda_{211} = \frac{1}{4}[(a_1 + 2a_2x_0)\cos^3\theta + 4v_0(a_2 - 3\lambda)\cos^2\theta\sin\theta + (a_1 + 2a_2x_0 - 2b_3 - 6b_4x_0)\cos\theta\sin^2\theta - 2a_2v_0\sin^3\theta] \quad (12)$$

Resonant di-Higgs

$h_2 \rightarrow h_1 h_1$

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Higgs self-coupling

$h_1 h_1 h_1$

$$g_{122} = \frac{v_0\ c_\theta}{2}(a_2(c_\theta^2 - 2s_\theta^2) + 6\lambda s_\theta^2) + \frac{a_1 + 2a_2x_0}{2}(s_\theta^3 - c_\theta^2 s_\theta) + +(b_3 + 3b_4x_0)\ c_\theta^2 s_\theta, \qquad [s_\theta \equiv \sin\theta,\ c_\theta \equiv \cos\theta].$$

Exotic decays & non-res di-Higgs

$h_1 \rightarrow h_2 h_2$

Real Singlet: Triple Scalar Couplings

Portal coupling sensitivity without θ suppression

$$\lambda_{211} = \frac{1}{4}[(a_1 + 2a_2 x_0)\cos^3\theta + 4v_0(a_2 - 3\lambda)\cos^2\theta\sin\theta + (a_1 + 2a_2 x_0 - 2b_3 - 6b_4 x_0)\cos\theta\sin^2\theta - 2a_2 v_0 \sin^3\theta] \quad (12)$$

Resonant di-Higgs

$h_2 \rightarrow h_1 h_1$

$$g_{111} = \lambda v_0 \cos^3\theta + \frac{1}{4}(a_1 + 2a_2 x_0)\cos^2\theta\sin\theta + \frac{1}{2}a_2 v_0 \cos\theta\sin^2\theta + \frac{b_3}{3}\sin^3\theta + b_4 x_0 \sin^3\theta \quad .$$

Higgs self-coupling

$h_1 h_1 h_1$

$$g_{122} = \frac{v_0\ c_\theta}{2}\left(a_2(c_\theta^2 - 2s_\theta^2) + 6\lambda s_\theta^2\right) + \frac{a_1 + 2a_2 x_0}{2}\left(s_\theta^3 - c_\theta^2 s_\theta\right) + +(b_3 + 3b_4 x_0)\ c_\theta^2 s_\theta, \qquad [s_\theta \equiv \sin\theta,\ c_\theta \equiv \cos\theta].$$

Exotic decays & non-res di-Higgs

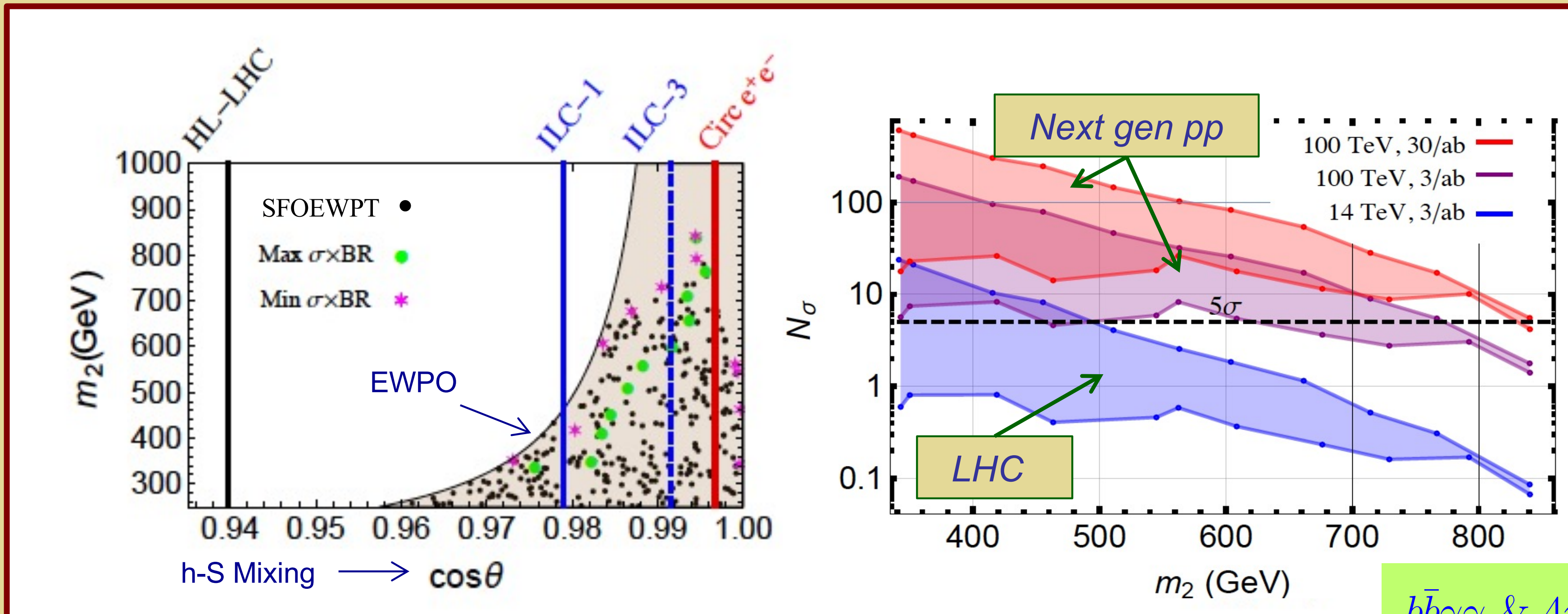
$h_1 \rightarrow h_2 h_2$

IV. Di-Higgs: Opportunities

Apologies to all whose work
I cannot cover here !

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



$b\bar{b}\gamma\gamma$ & 4τ

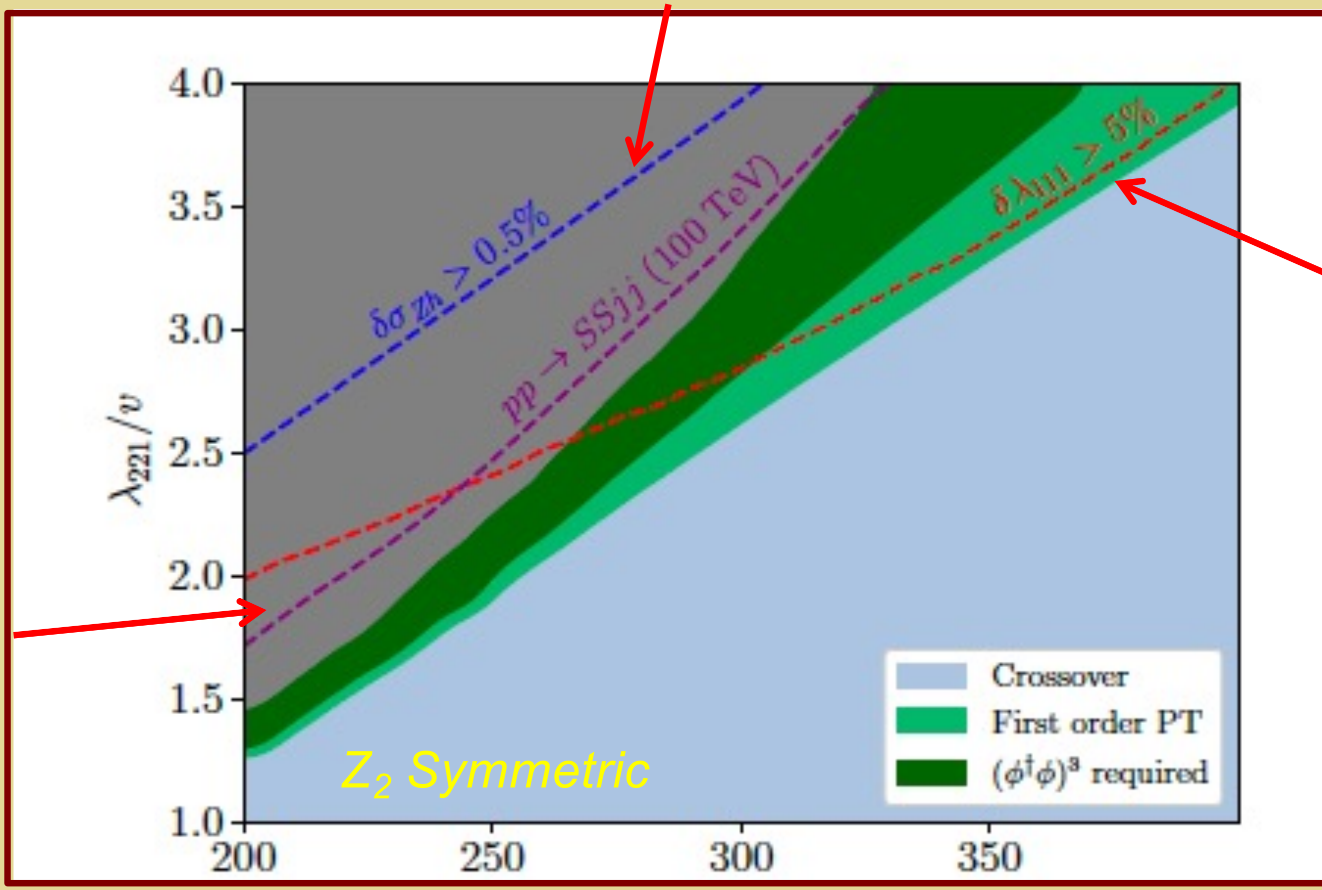
Kotwal, No, R-M, Winslow 1605.06123

See also: Huang et al, 1701.04442;
Li et al, 1906.05289

Singlets: Non-Resonant Di-Higgs Prod

Phase Diagram: EFT + Lattice

$e^+e^- \rightarrow Zh$
@FCC, CEPC



Higgs self-coupling

VBF 100 TeV
pp (non-res)

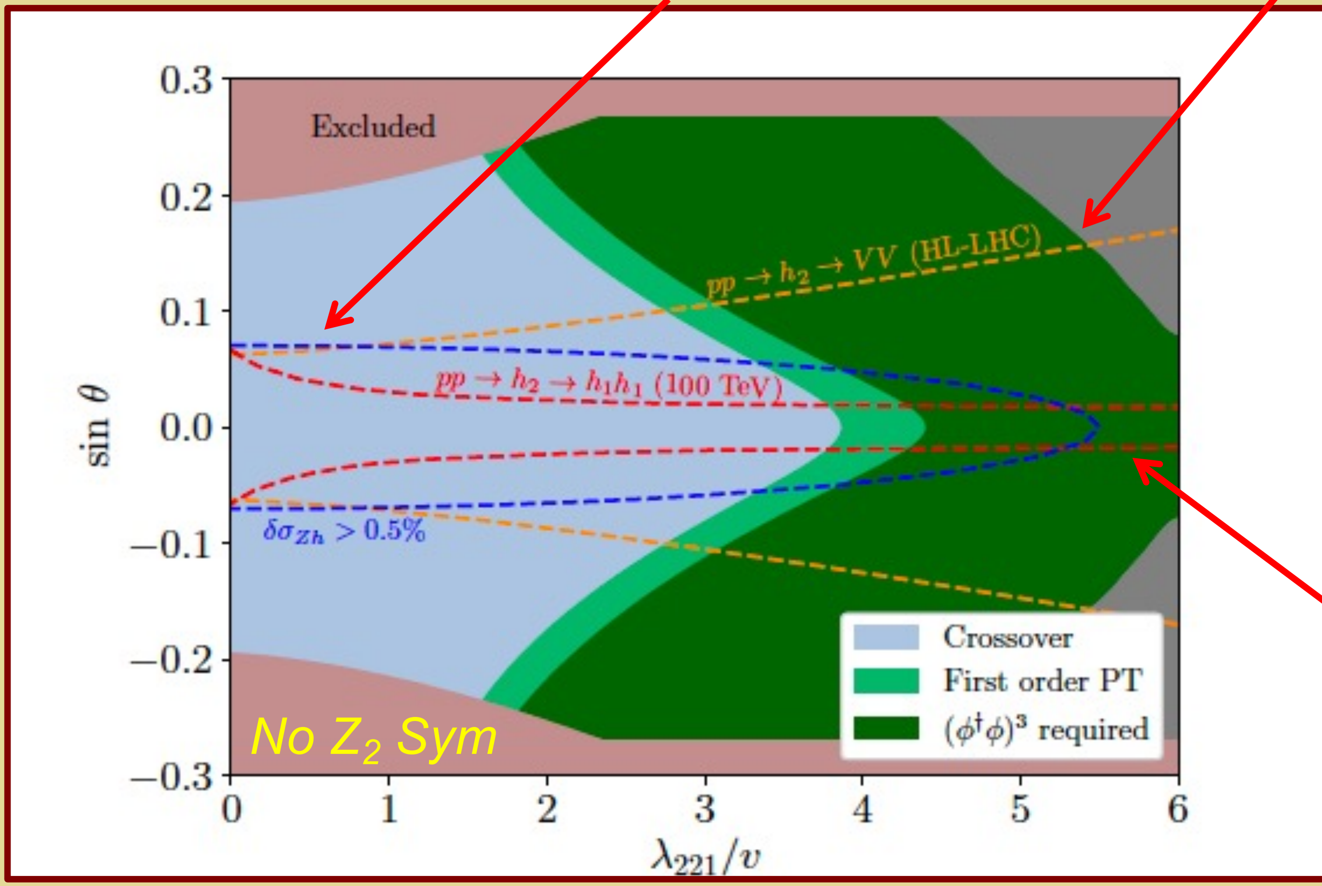
O. Gould, J. Kozaczuk, L. Niemi, MJRM, TVI Tenkanen, D.J. Weir, 1903.11604

Singlets: Non-Resonant Di-Higgs Prod

Phase Diagram: EFT + Lattice

$e^+e^- \to Zh$ @FCC, CEPC

Heavy Higgs (VV) HL-LHC



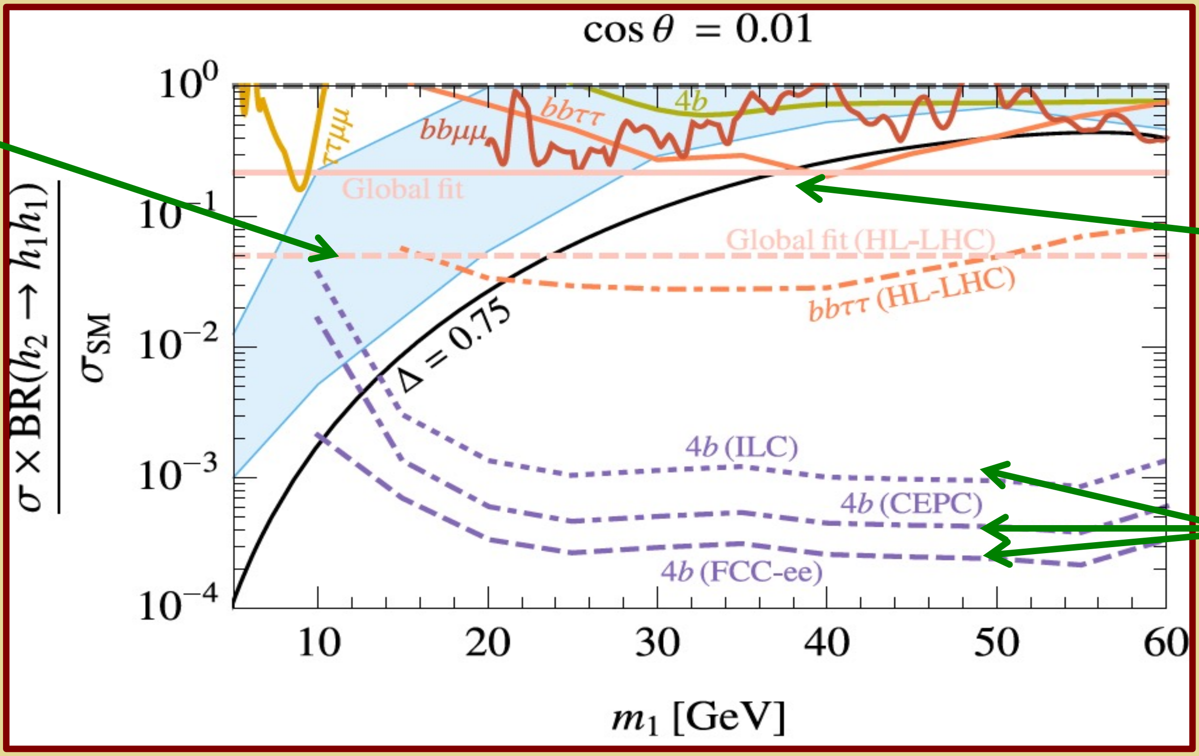
Res Di-Higgs 100 TeV pp

O. Gould, J. Kozaczuk, L. Niemi, MJRM, TVI Tenkanen, D.J. Weir, 1903.11604

Light Singlets: Exotic Decays

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

EWPT viable: numerical

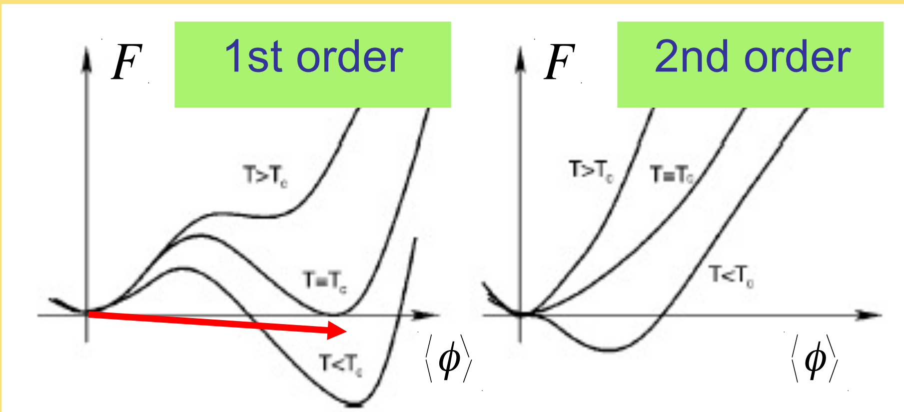


EWPT viable: Semi analytic

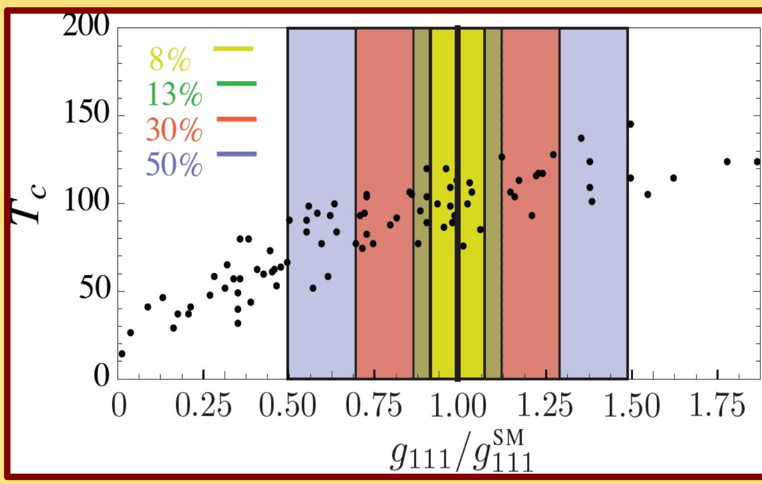
Future e^+e^-

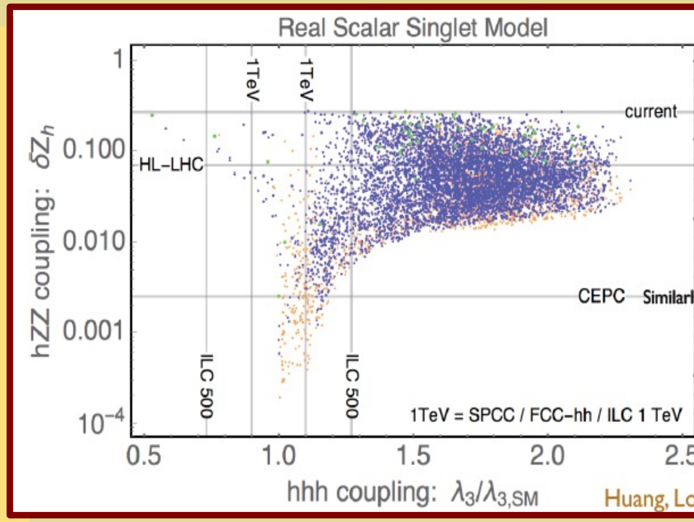
J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206

Singlets: Triple Self-Coupling

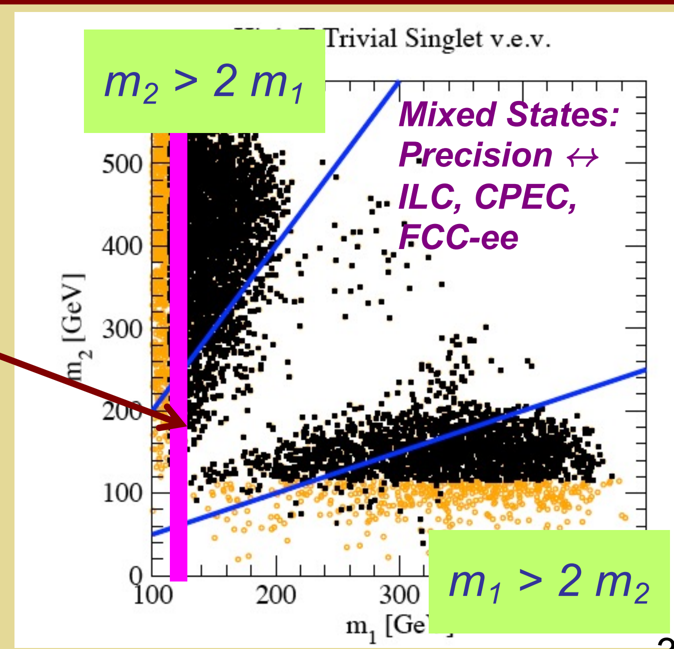


Modified Higgs Self-Coupling



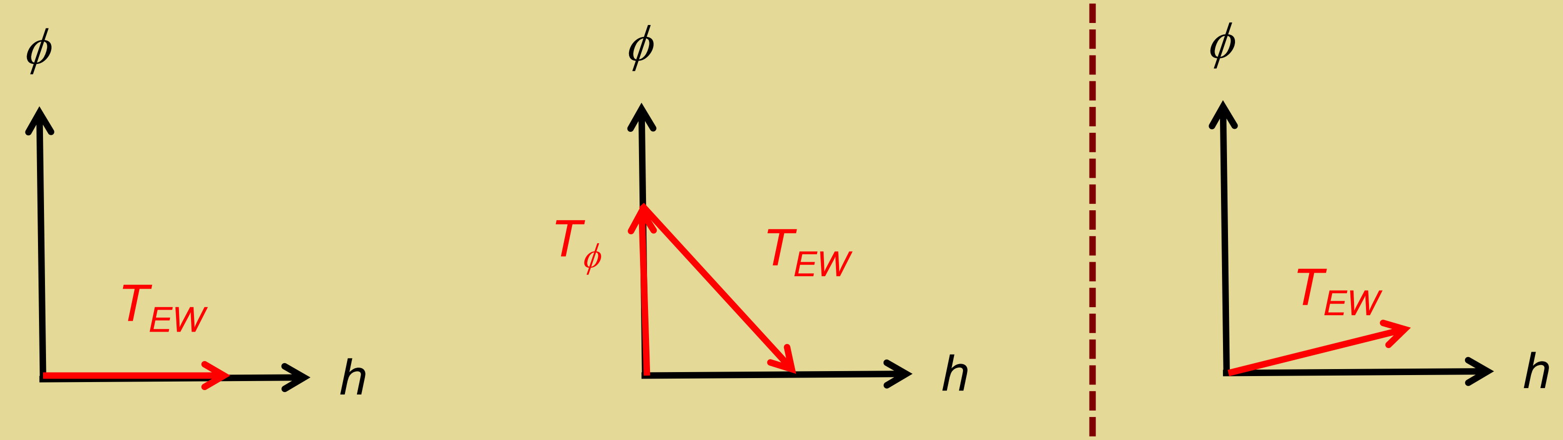


Scan includes $m_2 > 2m_1$



Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

Muon Collider: Comments



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

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

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

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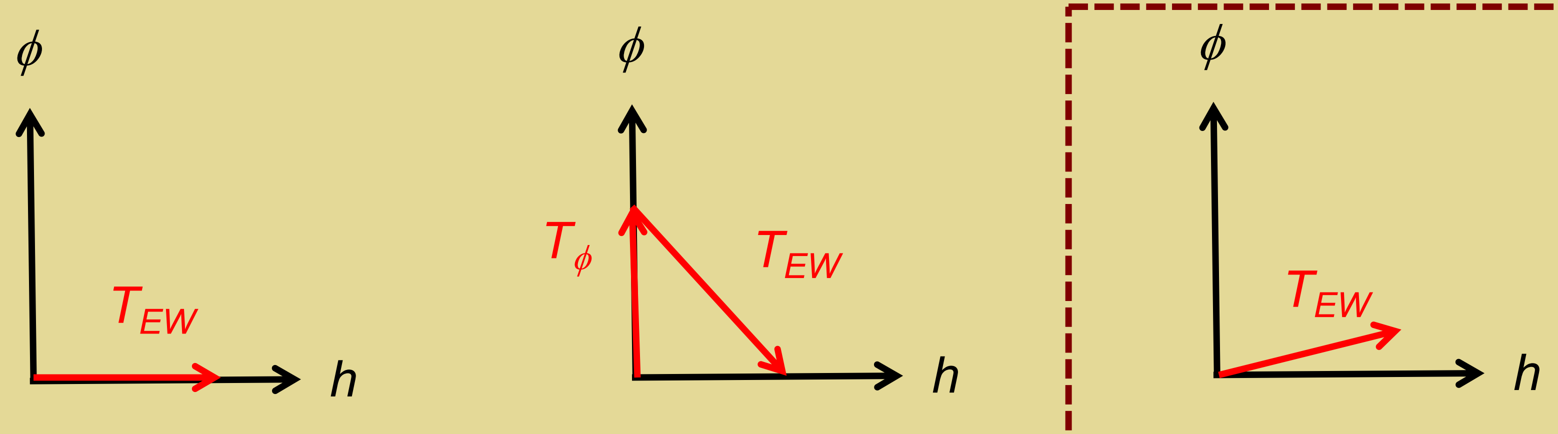
Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV

MJRM 1912.07189

Muon Collider: Comments



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

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

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

Simple arguments: T_{EW} *+ strong first order EWPT* → $|\sin\theta| \gtrsim 0.01$

MJRM 1912.07189

V. Outlook

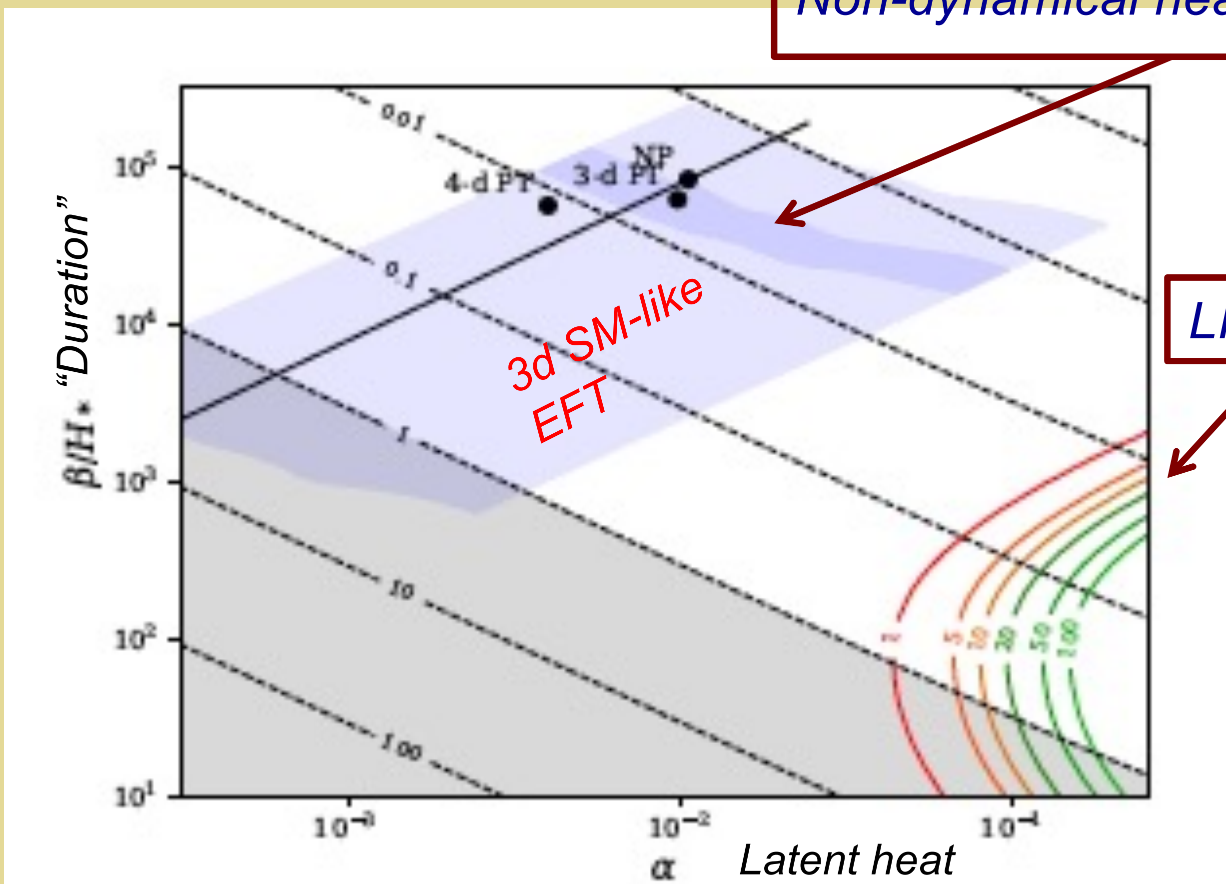
- *Extensions of the Standard Model scalar sector can address key open questions in cosmology*
- *Di-Higgs searches provide one important window on the cosmological implications of extended scalar sectors*
- *This talk: focus on delineating the thermal history of EWSB and consequences for baryogenesis and gravitation wave searches*
- *There are exciting opportunities and synergies involving the LHC and prospective future colliders*
  → how might a muon collider fit into this picture?

Back Up Slides

References

- *EWPT & Colliders General: MJRM 1912.07189*
- *EWPT & Di-Higgs:*
  - *Profumo, MJRM, Shaugnessy 0705.2425*
  - *No & MJRM 1310.6035*
  - *Kotwal, No, MJRM, Winslow 1605.06123*
  - *Huang, Pernie, MJRM, Safanov, Spannowsky, Winslow 1701.04442*
  - *Li, MJRM, Willocq 1906.05289*
  - *Papaefstathiou and White, 2010.00597*
  - *Ren et al 1706.05980*

Heavy Real Singlet: EWPT & GW



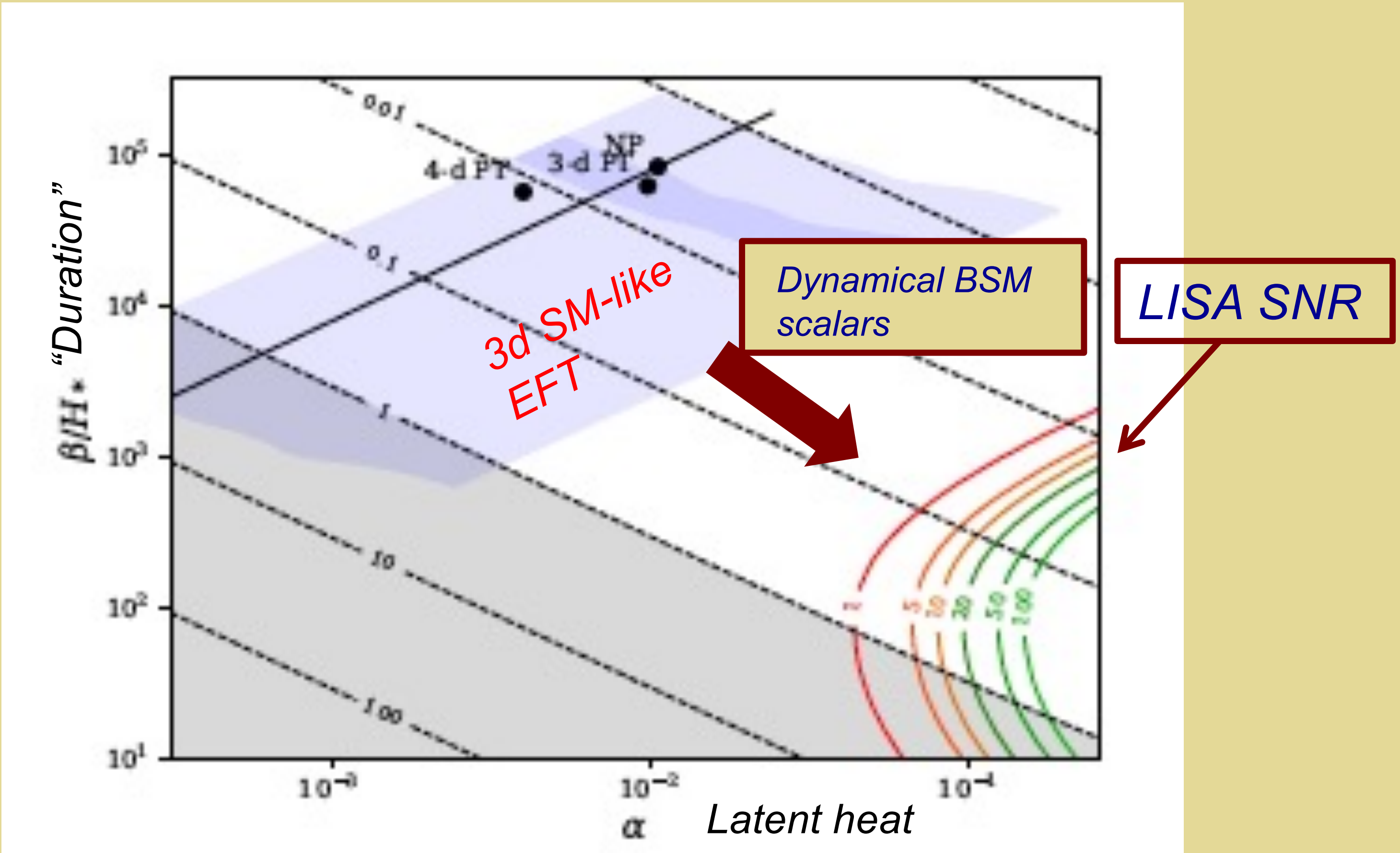
Non-dynamical heavy BSM scalars

LISA SNR

Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

- One-step
- Non-perturbative

Heavy Real Singlet: EWPT & GW



Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

- One-step
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