Was There an Electroweak Phase Transition ?

M.J. Ramsey-Musolf

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- *UMass-Amherst*

My pronouns: he/him/his

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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***
- ***Precision tests and direct searches are vital***
- ***Robust test of theory requires a new era of EFT & non-perturbative computations → new results highlight this theoretical frontier***

Key Ideas for this Talk

- *MJRM: 1912.07189*
- *Recent EFT + Non-perturbative:*
    - *L. Niemi, H.H. Patel, MJRM, T.V.I. Tenkanen, D. J. Weir: 1802.10500*
    - *O. Gould, J. Kozaczuk, L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 1903.11604*
    - *L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 2005.11332*

Outline

I. Context & Questions
II. EWPT: A Collider Target
III. Higgs Boson Properties
IV. Theoretical Robustness
V. Outlook

I. Context & Questions

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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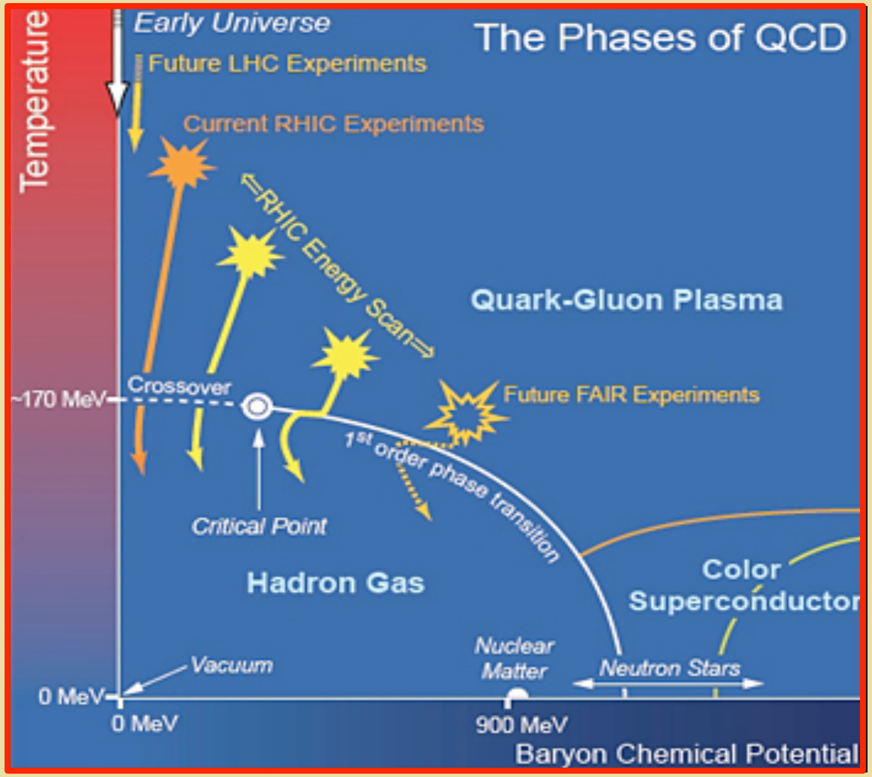
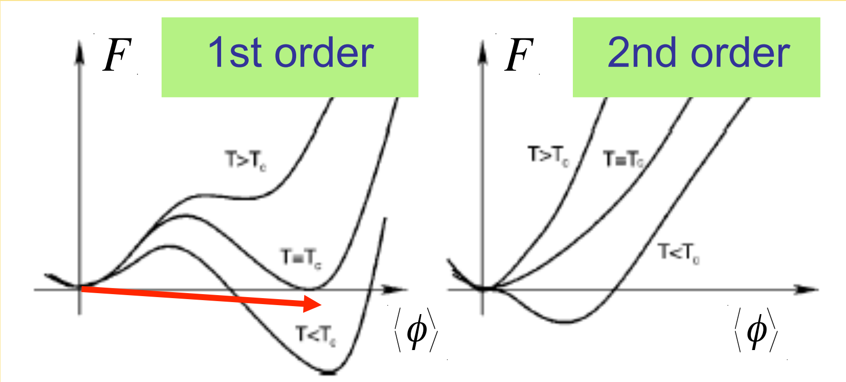
Thermal History of Symmetry Breaking



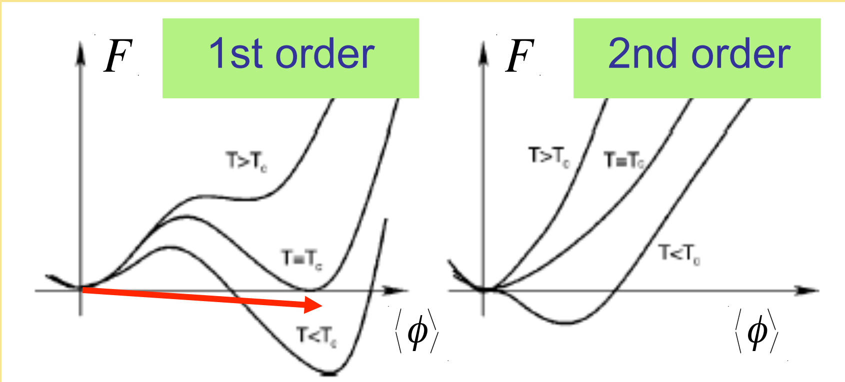
QCD Phase Diagram → EW Theory Analog?

EWSB Transition: St’d Model



Increasing m_h

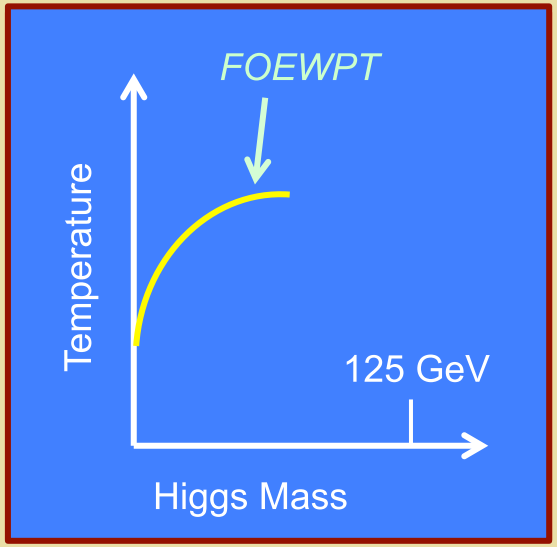
EWSB Transition: St'd Model



Increasing m_h

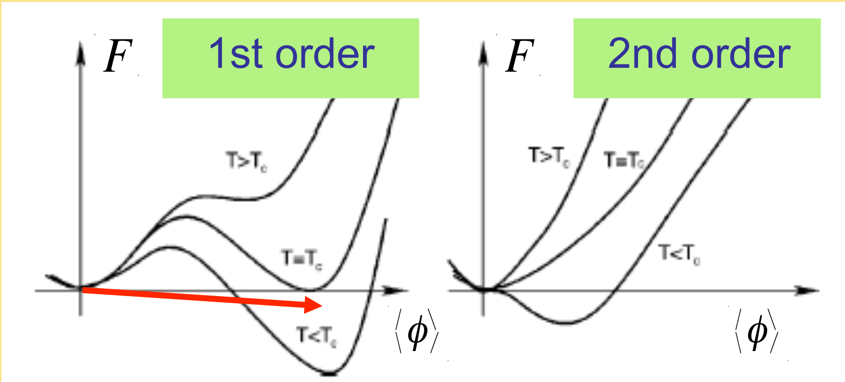
Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition



EW Phase Diagram

EWSB Transition: St'd Model



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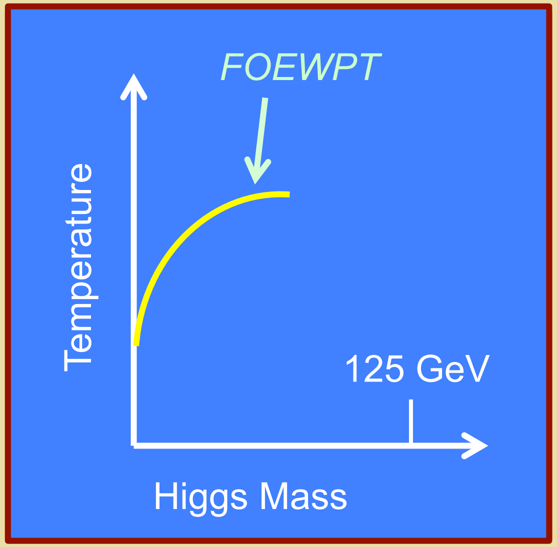
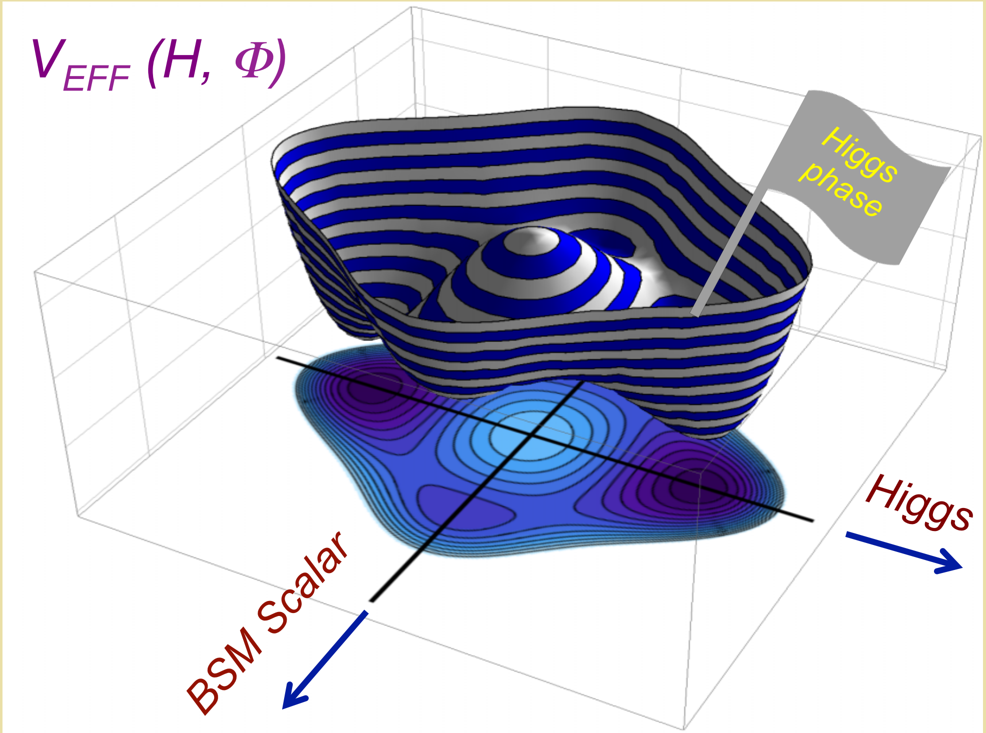


EW Phase Diagram

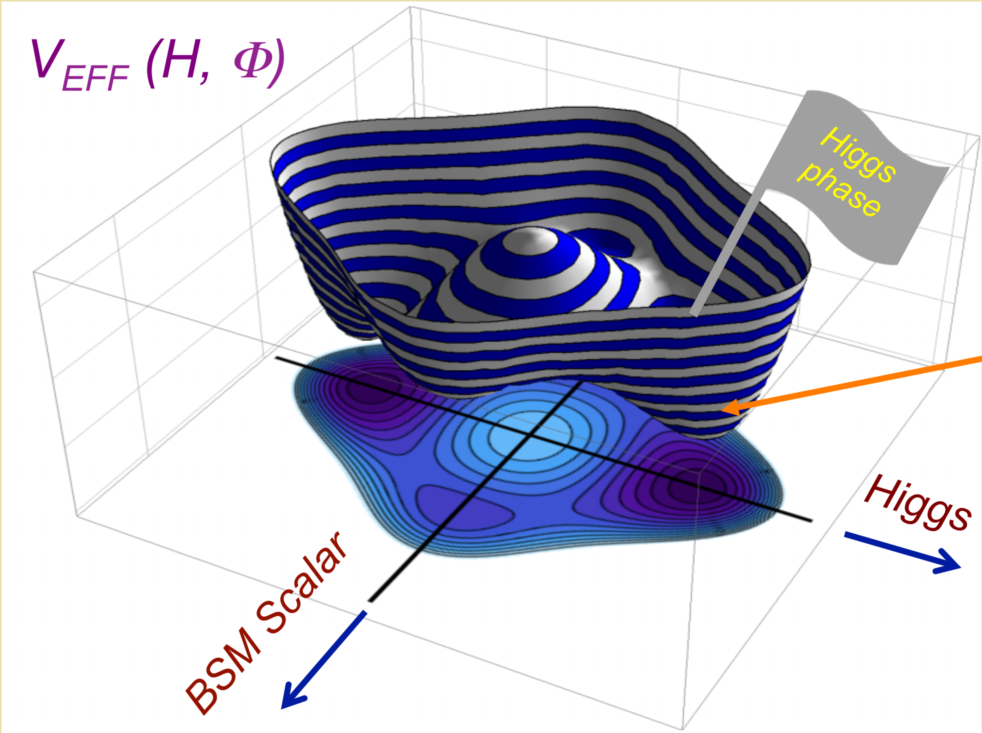
How does new TeV scale physics change this picture ? What is the phase diagram ? EWPT ? If so, what kind ?

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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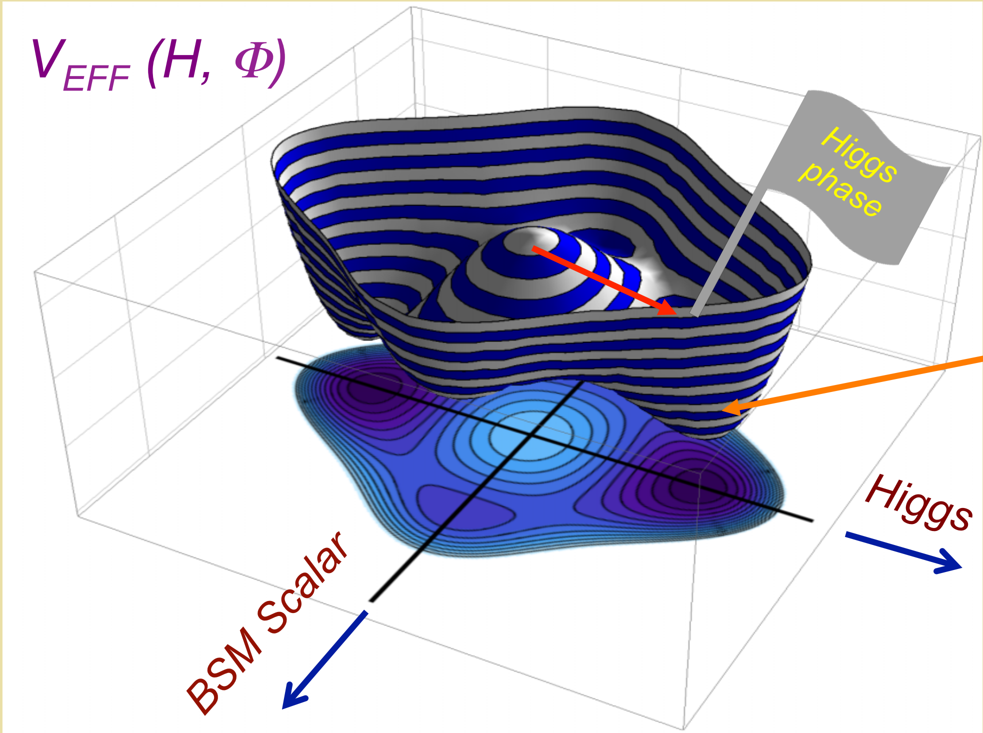
Patterns of Symmetry Breaking



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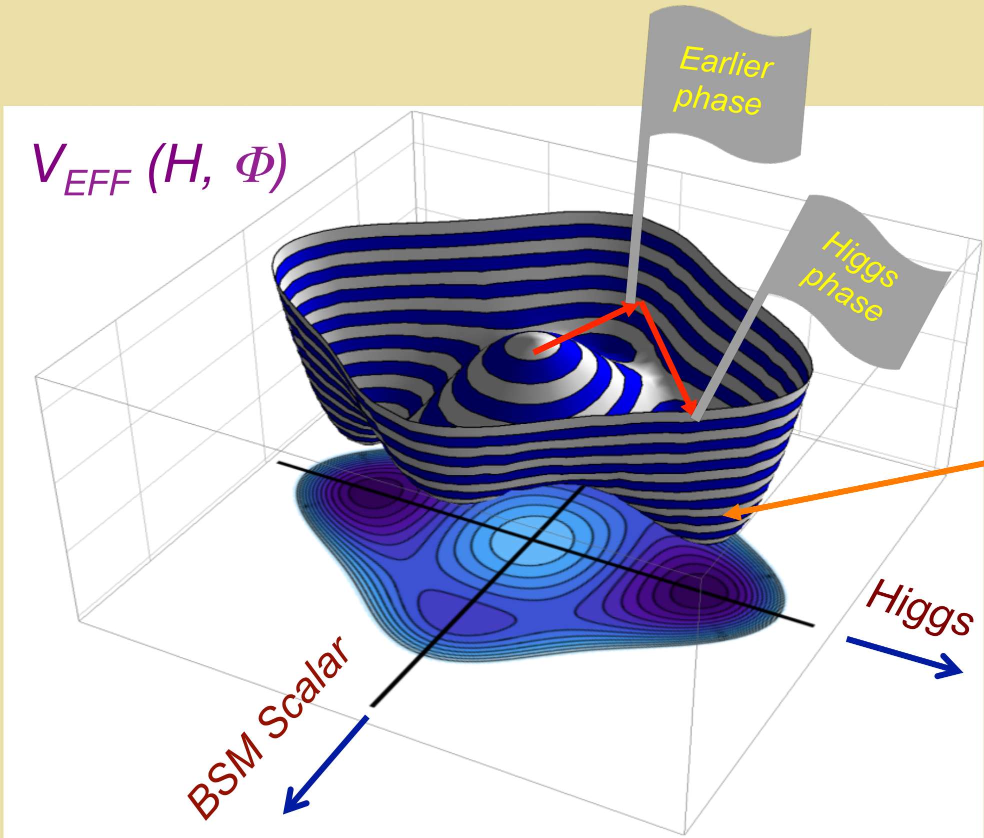

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Electroweak Phase Transition

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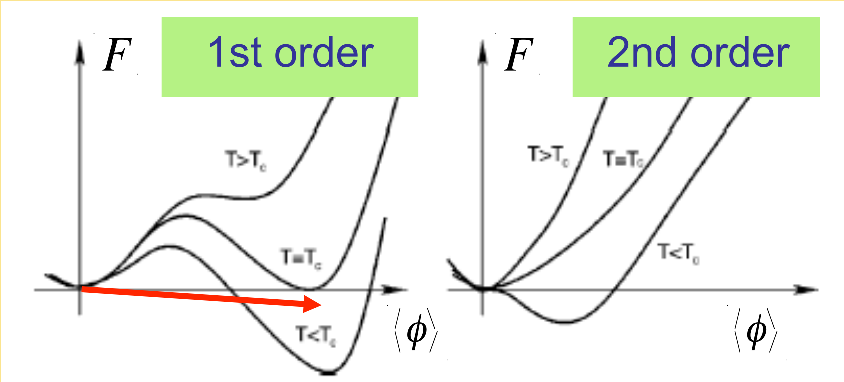
EW Phase Transition: Baryogen & GW



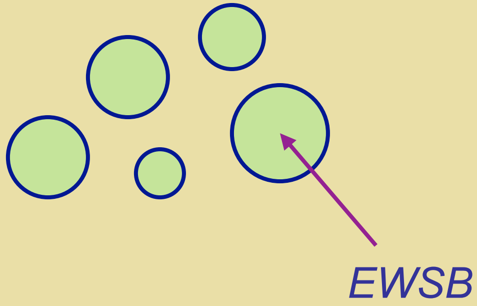
Increasing m_h →

← New scalars

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

Bubble nucleation



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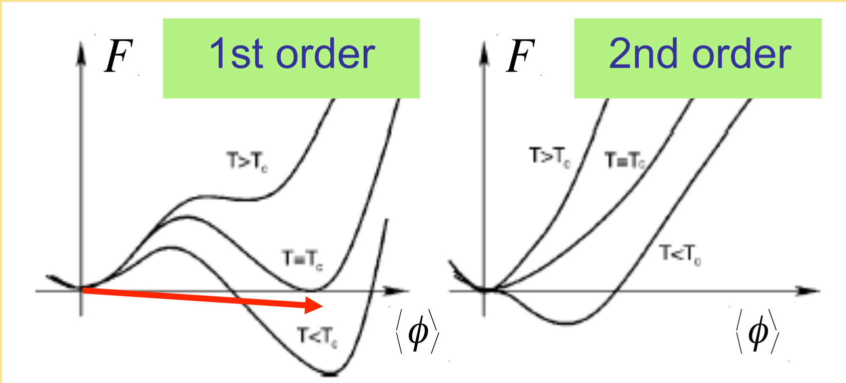

Increasing m_h →

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Gravity Waves
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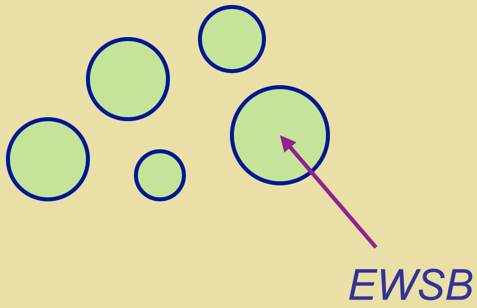
LHC Searches

"Strong" 1st order EWPT

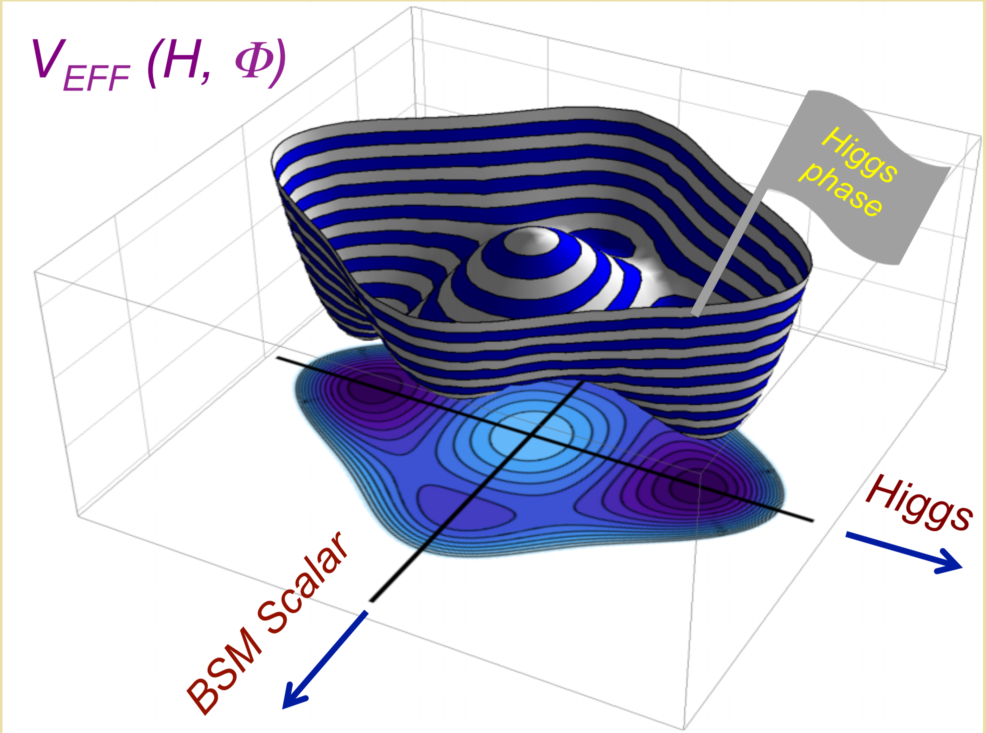
- *Baryogen**
- *GW*

Bubble nucleation



** Need BSM CPV: see P. Pasquini talk*

Thermal History of EWSB



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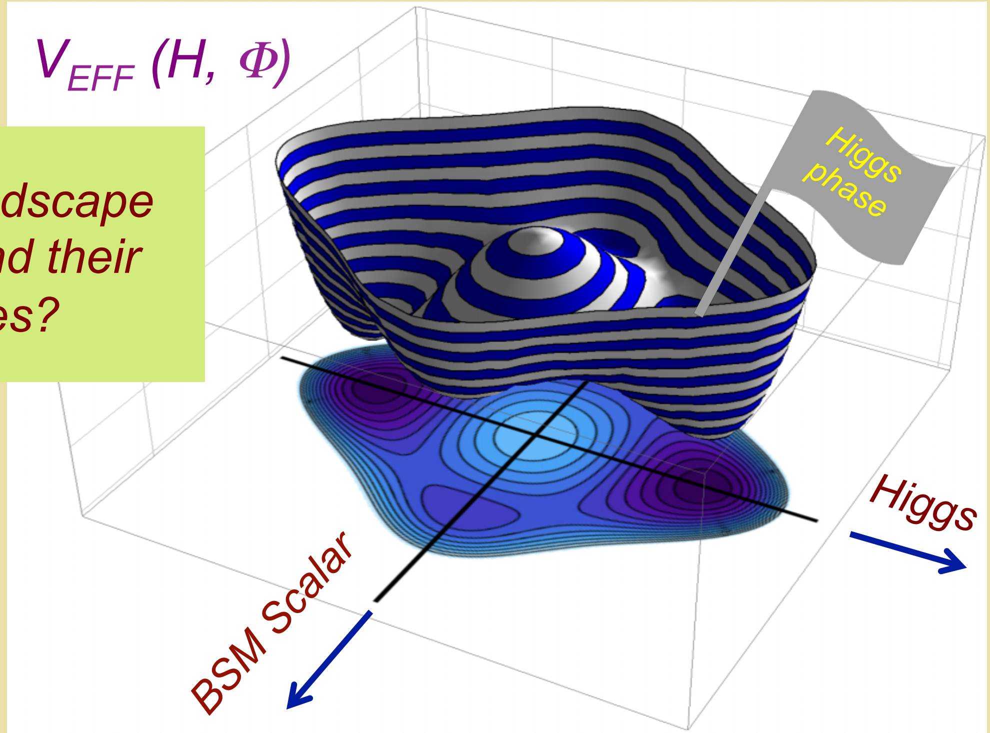
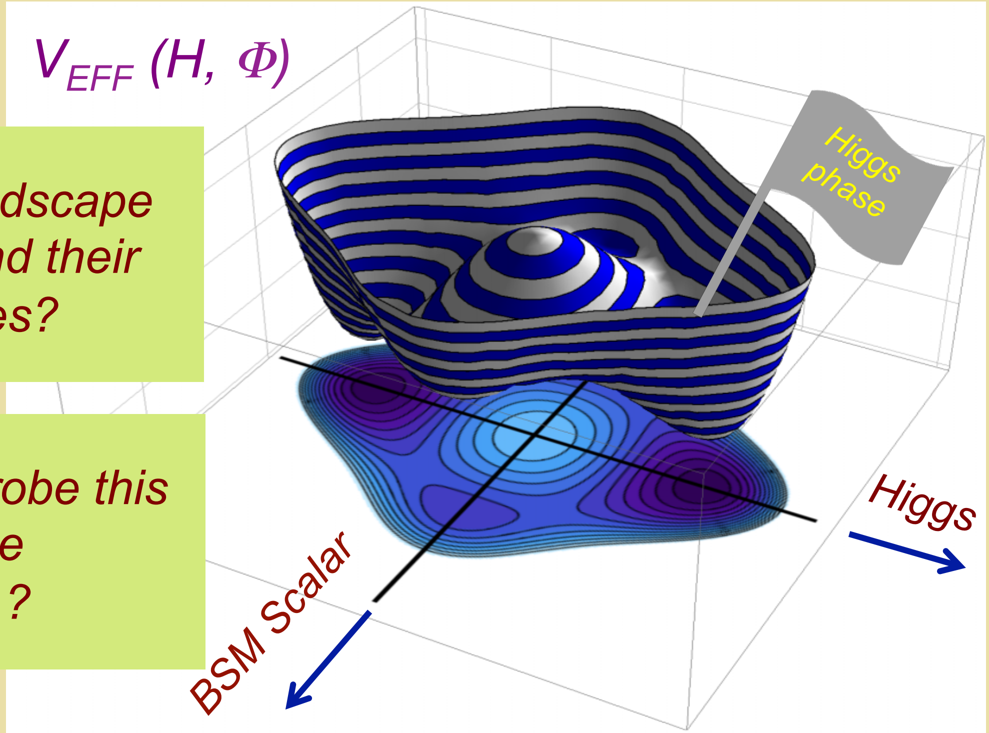


- *What is the landscape of potentials and their thermal histories?*

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

Thermal History of EWSB

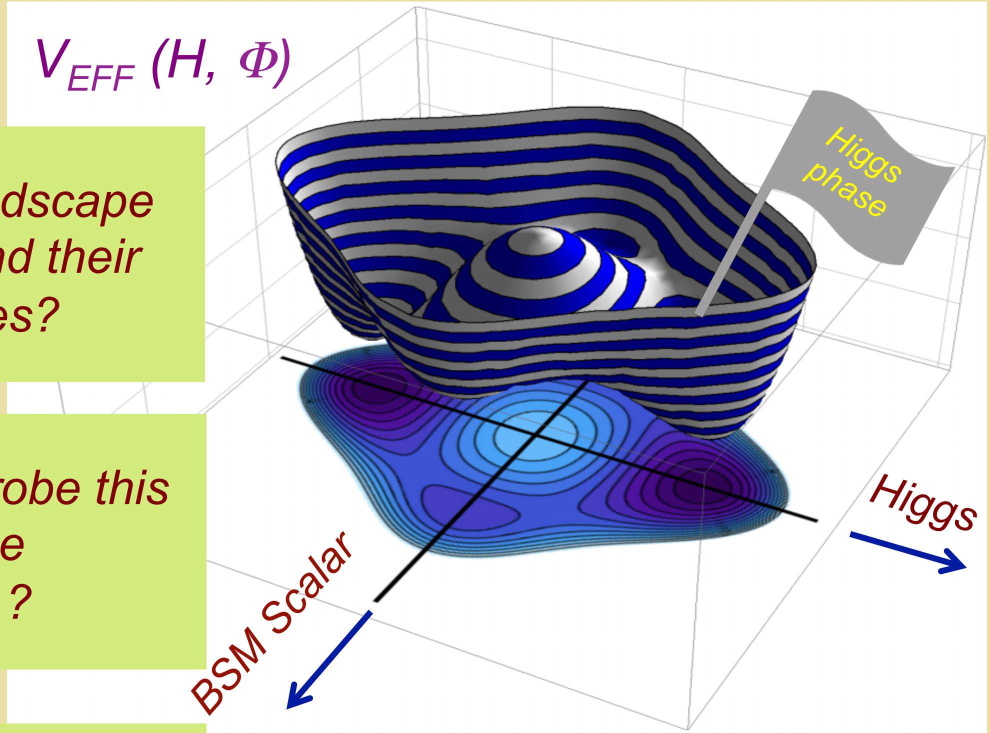


- *What is the landscape of potentials and their thermal histories?*

- *How can we probe this $T > 0$ landscape experimentally ?*

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

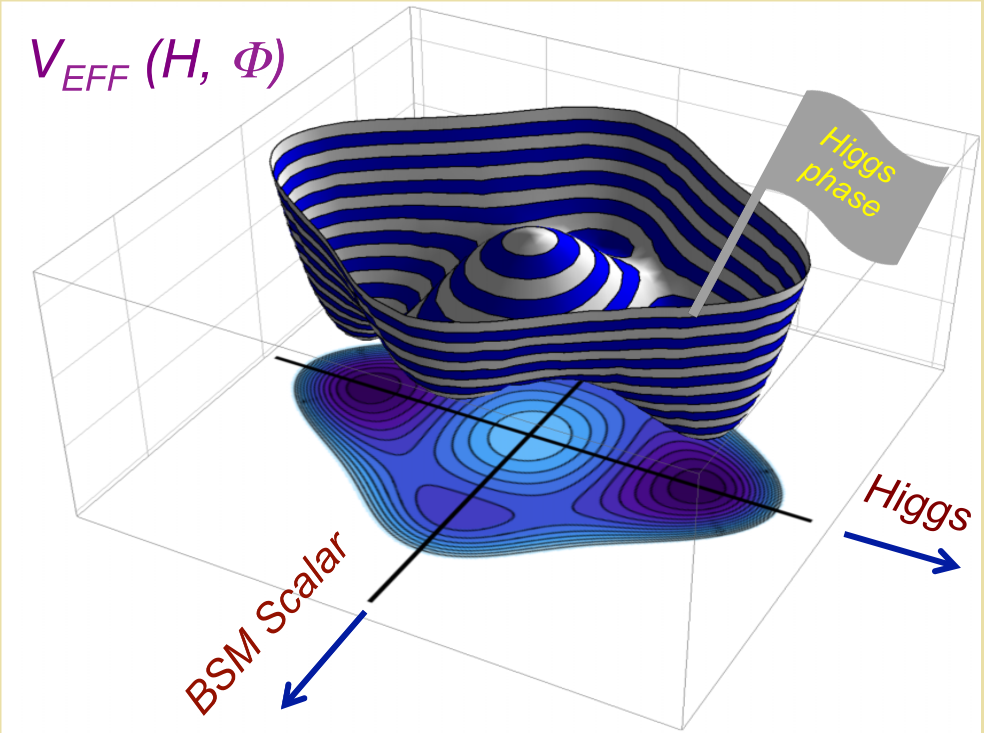
Thermal History of EWSB



- *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

Experimental Probes

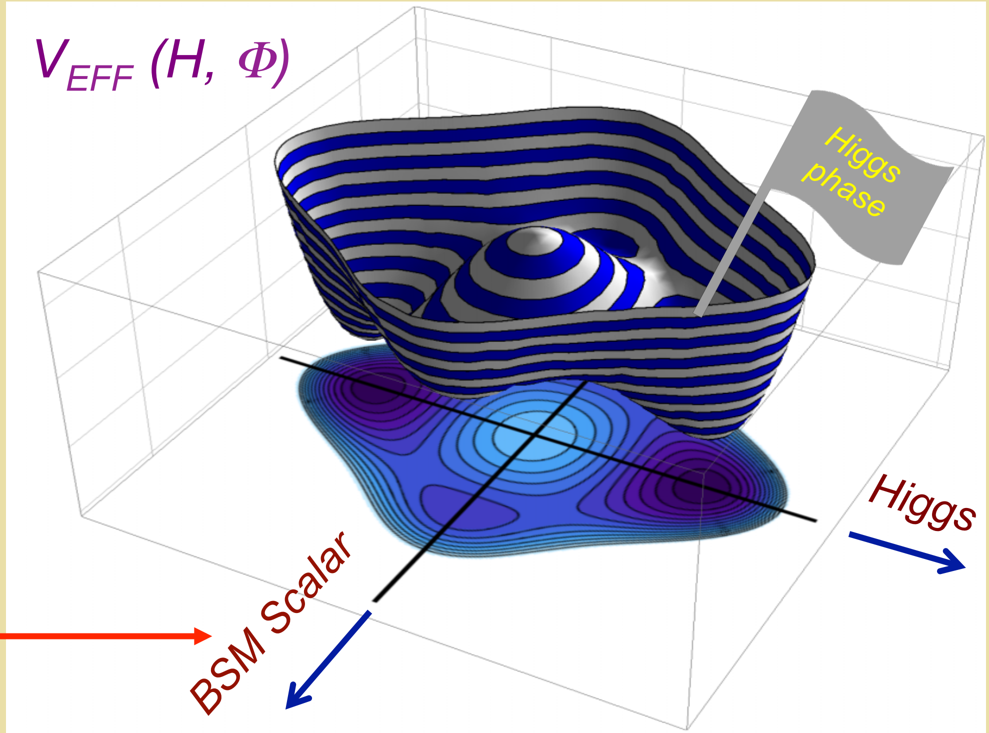


Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

Experimental Probes

Direct Production

BSM Higgs



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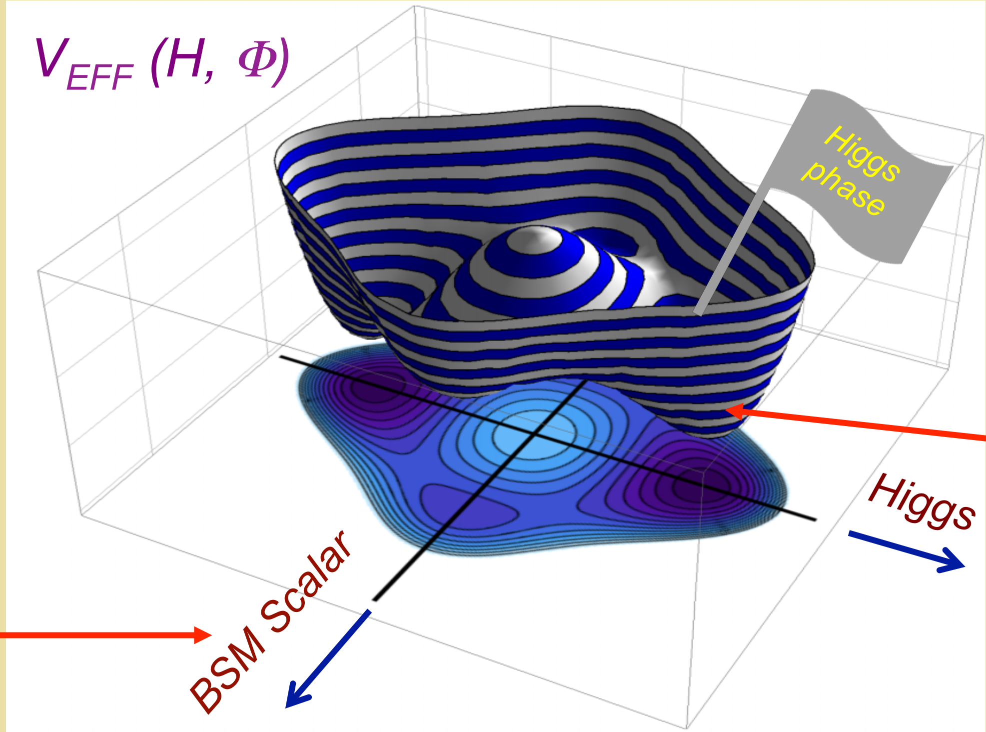


Higgs precision tests

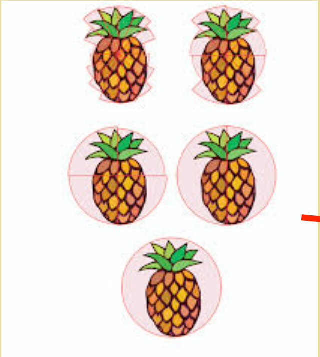
Direct Production

BSM Higgs

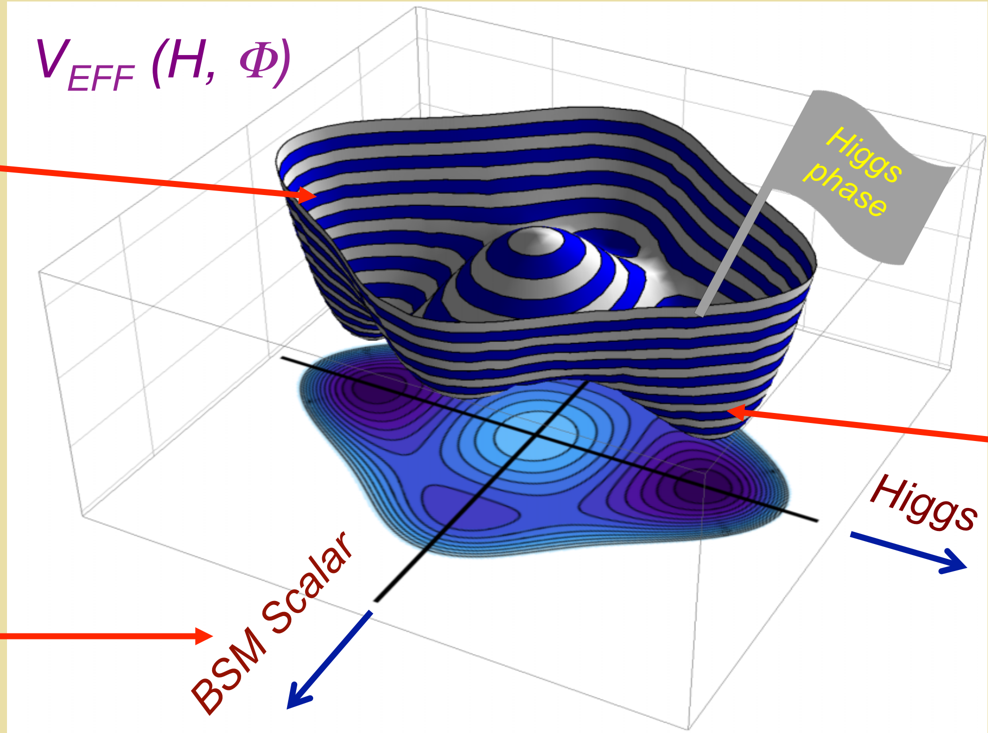
Extrema can evolve differently as T evolves → rich possibilities for symmetry breaking

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

II. EWPT: A Collider Target

MJRM 19010.07189

- ***Mass scale***
- ***Precision***

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 ~ 140 GeV

T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

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

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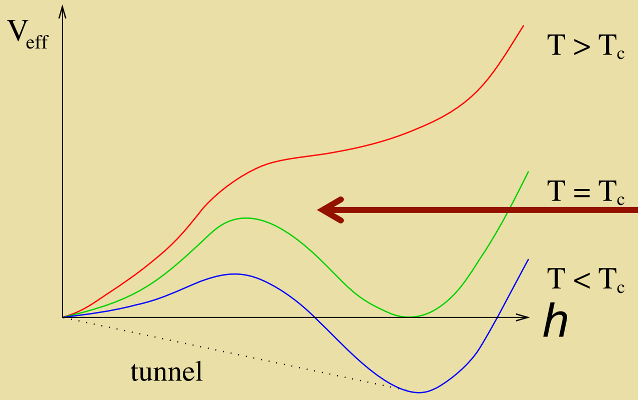
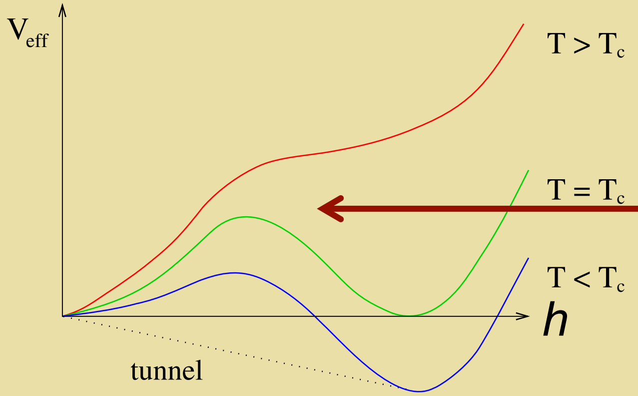
$\boxed{T_0 \sim 140 \text{ GeV}}$ $\boxed{\equiv \;\; T_{EW}}$

First Order EWPT from BSM Physics



Generate finite-T barrier

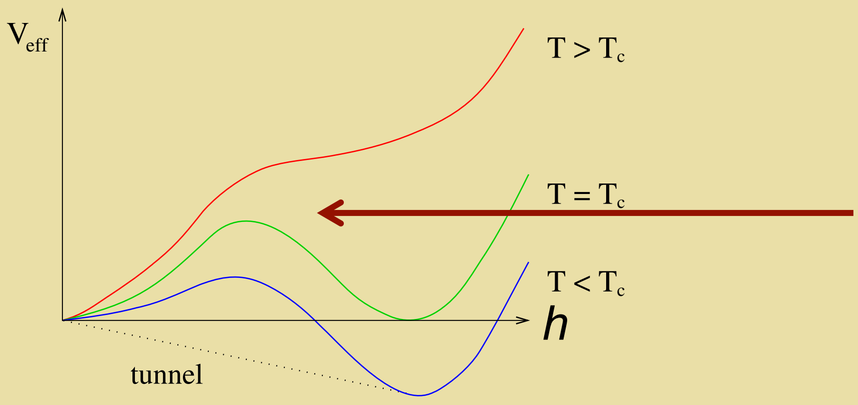
First Order EWPT from BSM Physics



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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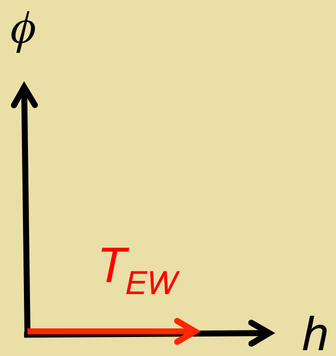
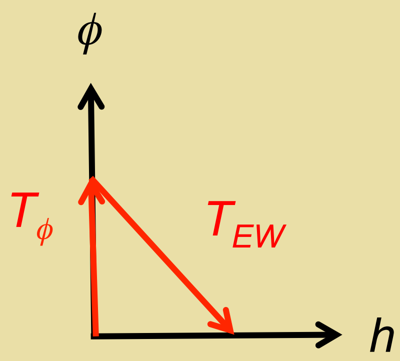
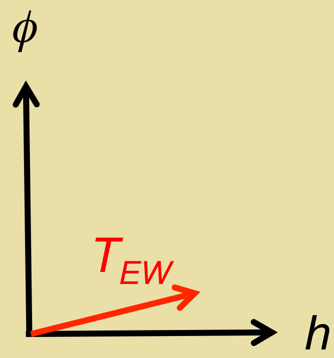


$a_2\, H^2\phi^2$: $T > 0$
loop effect

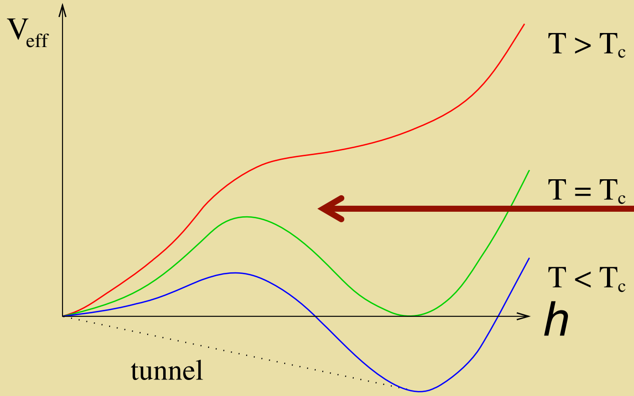


$a_2\, H^2\phi^2$: $T = 0$
tree-level effect

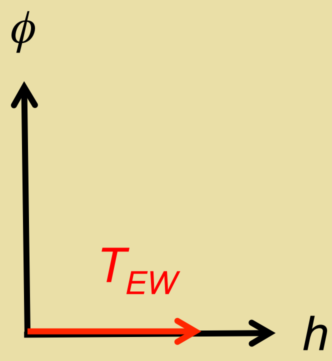


$a_1\, H^2\phi$: $T = 0$
tree-level effect

First Order EWPT from BSM Physics



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



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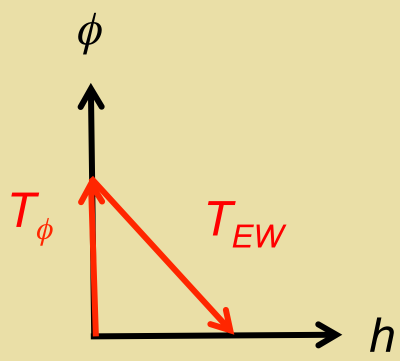

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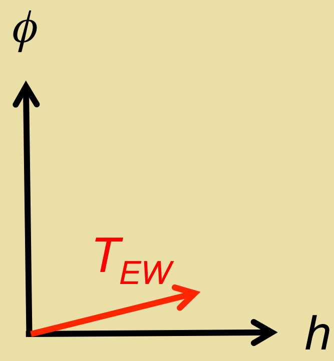

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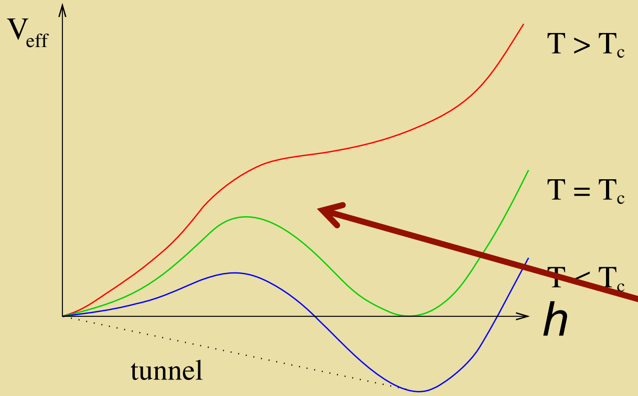
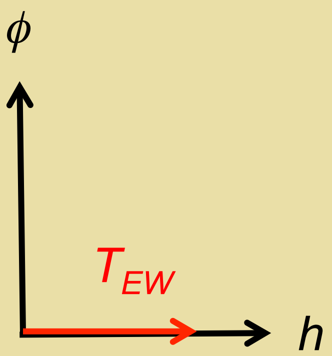
First Order EWPT from BSM Physics



Higgs – ϕ^0 Mixing

$| \sin\theta | > 0.01$



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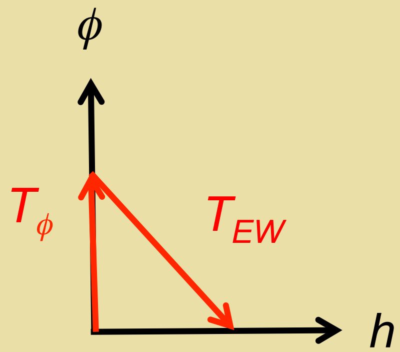
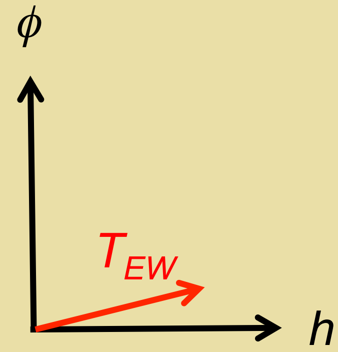


$a_2 H^2\phi^2$: $T = 0$

tree-level effect



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

tree-level effect

III. Higgs Boson Properties

First Order EWPT from BSM Physics

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

III. 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)*
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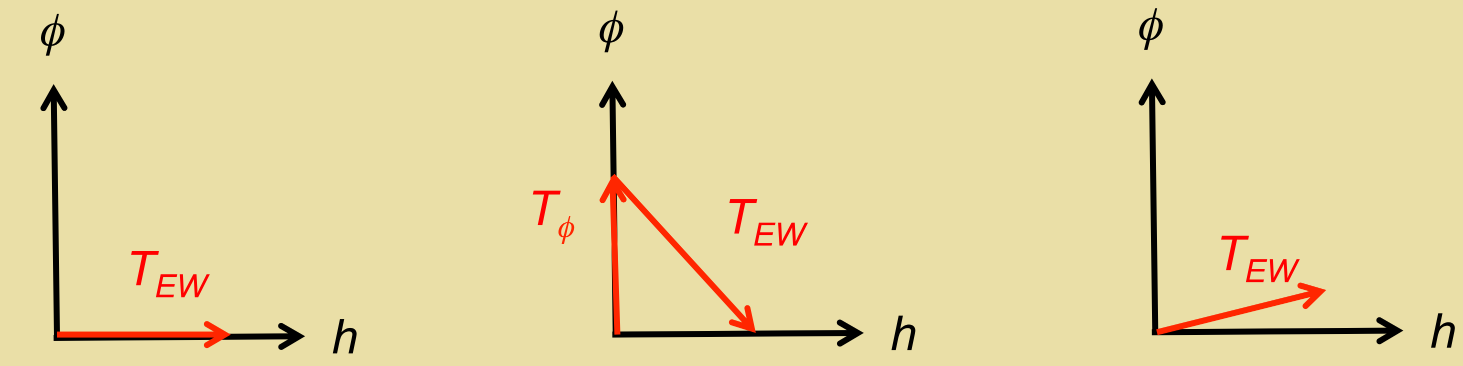
Real Singlet



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First Order EWPT from BSM Physics

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

$H^2\phi$ Barrier ?

First Order EWPT from BSM Physics

- ***Thermal*** Γ ***(h*** $\rightarrow \gamma\gamma$ ***)***

- ***Higgs signal strengths***

- ***Higgs self-coupling***

- ***Exotic Decays***

$H^2\phi$ Barrier ?

H-ϕ Mixing

First Order EWPT from BSM Physics

- ***Thermal $\Gamma\,(h \rightarrow \gamma\gamma)$***
- ***Higgs signal strengths***
- ***Higgs self-coupling***
- ***Exotic Decays***
- ***Single ϕ production***

$H^2\phi$ Barrier ?

H-ϕ Mixing

First Order EWPT from BSM Physics

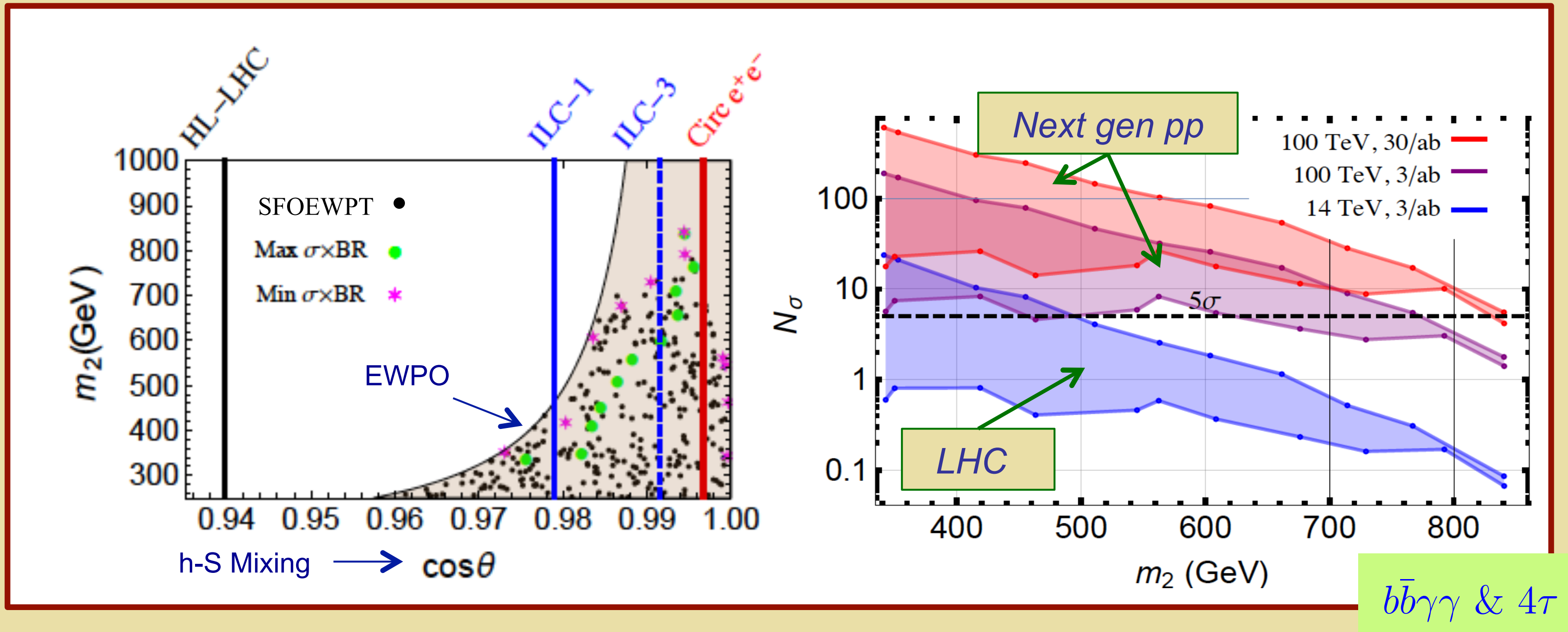
- *Thermal $\Gamma(h \to \gamma\gamma)$*
- *Higgs signal strengths*
- *Higgs self-coupling*
- *Exotic Decays*
- *Single ϕ production*

$H^2\phi$ Barrier ?

H-ϕ Mixing

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



Kotwal, No, R-M, Winslow 1605.06123

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

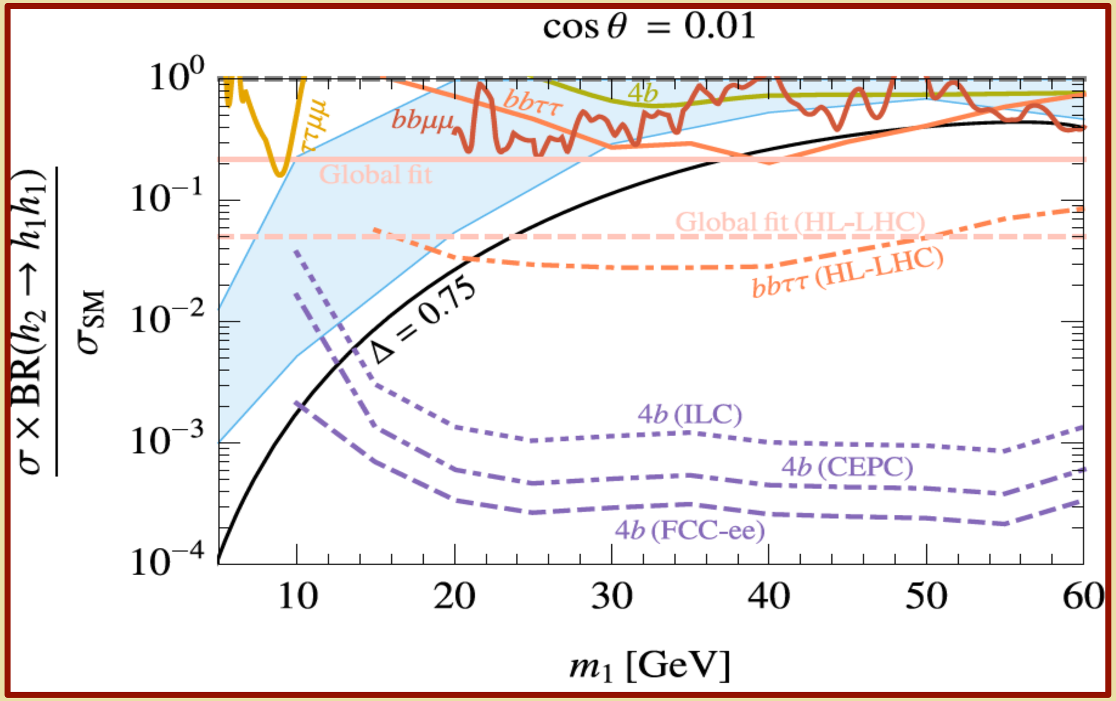
First Order EWPT from BSM Physics

- Thermal Γ (h → $\gamma\gamma$)
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays

$H^2\phi$ and/or $H^2\phi^2$
Barrier ?

Light Singlets: Exotic Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

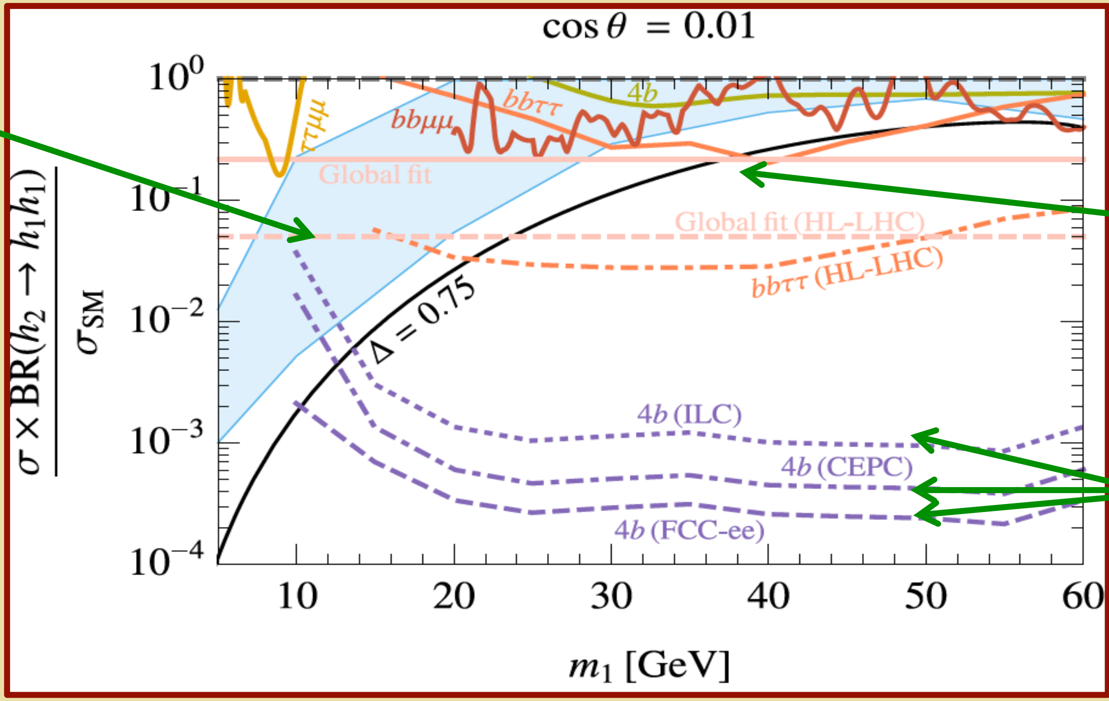


J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206
Z. Liu talk this meeting

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
Z. Liu talk this meeting

Model Illustrations

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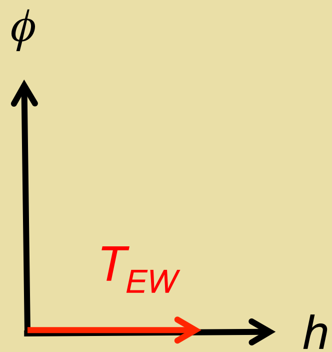
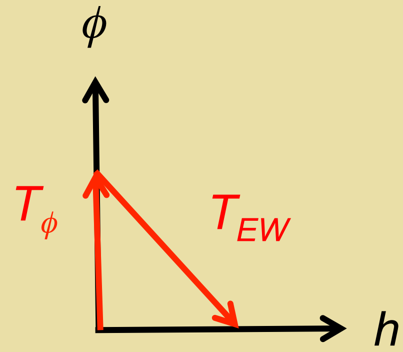
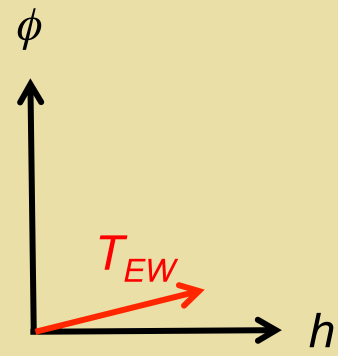
- ***Real gauge singlet (SM + 1)***
- ***Real EW triplet (SM + 3)***

Real Triplet







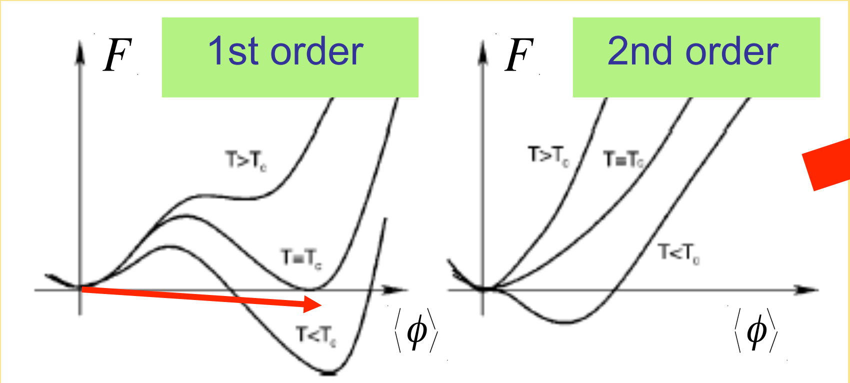
$a_2\, H^2\phi^2$: $T > 0$
loop effect

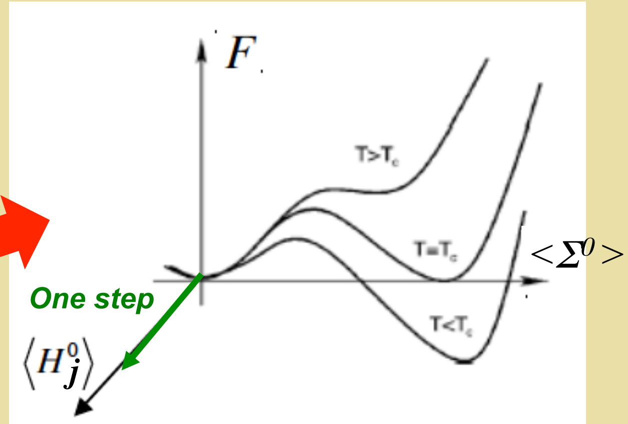
$a_2\, H^2\phi^2$: $T = 0$
tree-level effect

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

EW precision tests → too tiny

EW Multiplets: Two-Step EWPT





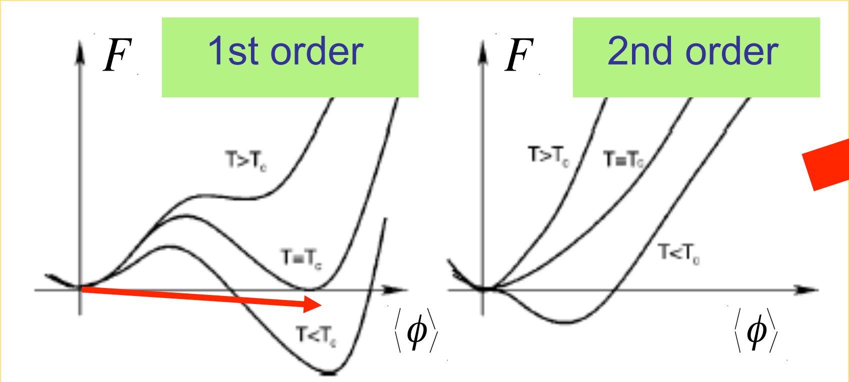
Increasing m_h →

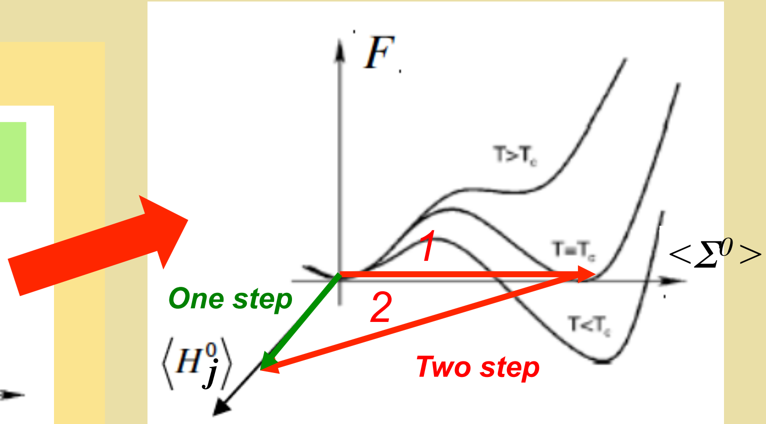
← *New scalars*

- *One-step: Sym phase → Higgs phase*

Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

EW Multiplets: Two-Step EWPT





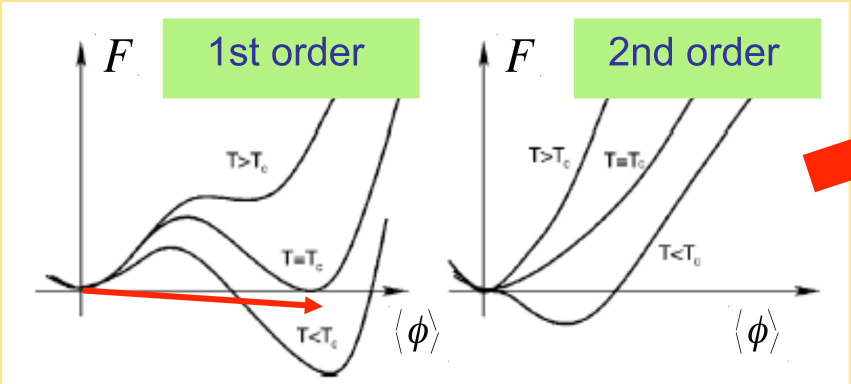
Increasing m_h

New scalars

- *One-step: Sym phase → Higgs phase*
- *Two-step: successive EW broken phases*

Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

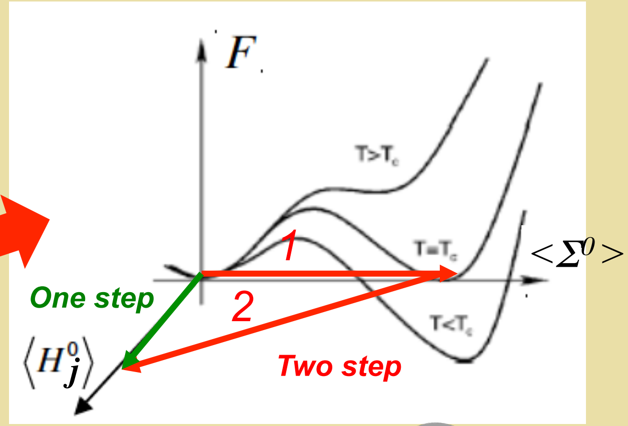
EW Multiplets: Two-Step EWPT

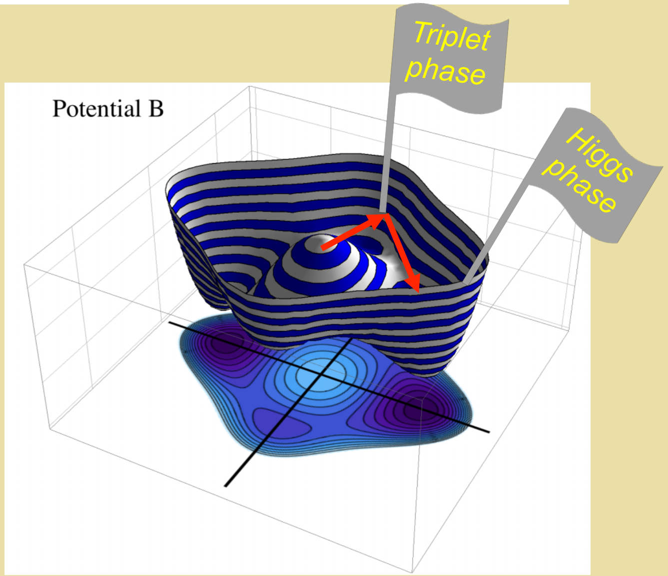


Increasing m_h

New scalars

- Two occasions for GW generation
- Step 1: create baryon asymmetry → Step 2: pass it to the Higgs phase





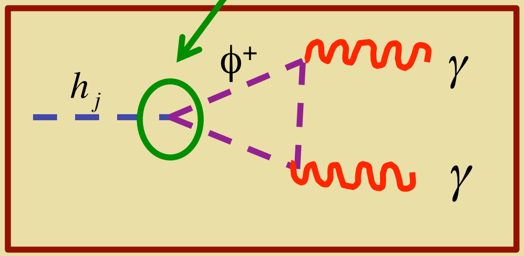
Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

First Order EWPT from BSM Physics

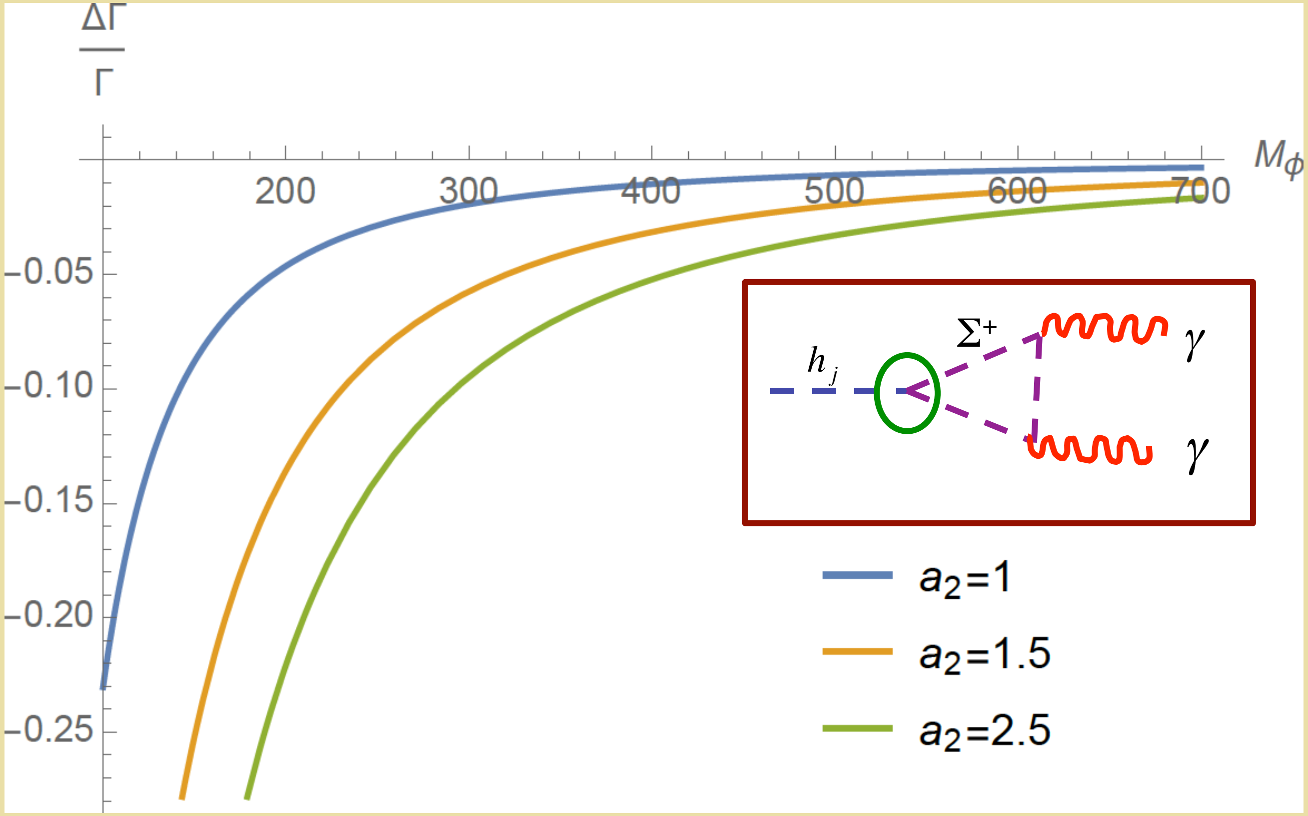
- $\Gamma(h \to \gamma\gamma)$
- *Higgs signal strengths*
- *Higgs self-coupling*
- *Exotic Decays*

$H^2\phi^2$ **Barrier ?**

ϕ : **EW Multiplet**

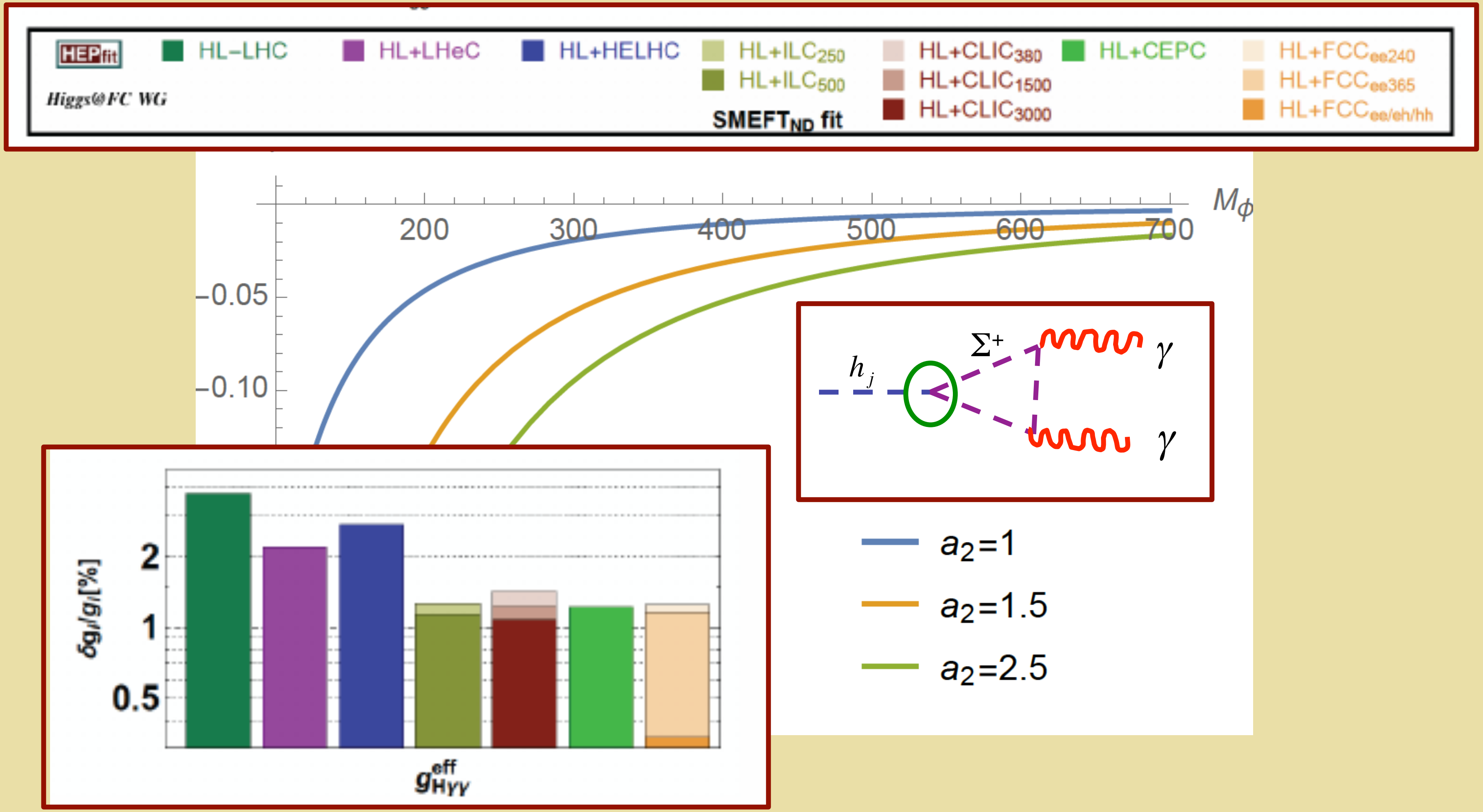


$H \rightarrow \gamma\gamma$: Is There a Barrier ?



EWPT → Decrease in rate

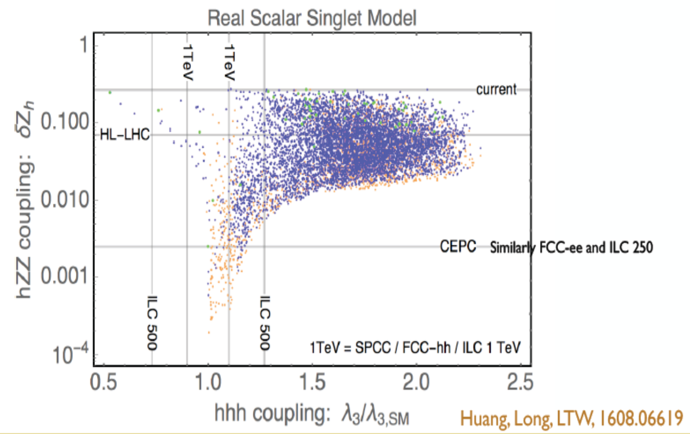
$H \rightarrow \gamma\gamma$: Is There a Barrier ?



Thanks: M. Cepeda

Associated Production

Real Singlet



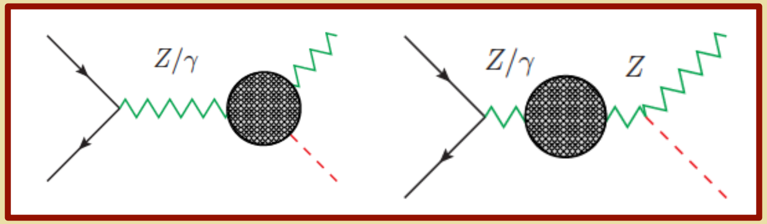
Higher Dim Operators

$$\tilde{V}_0(H) = \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2 + \frac{1}{\Lambda^2}\left(H^\dagger H - \frac{v^2}{2}\right)^3$$

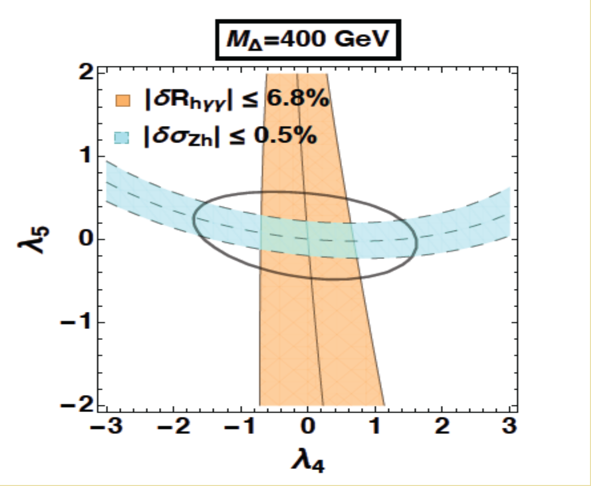
- *Cao, Huang, Xie, Zhang 2017...*
- *Grojean, Servant, Wells 2004…*
- *Grinstein, Trott 2008…*

Electroweak Multiplets

Loop contributions



MJRM, Jiang-Hao Yu, Jia Zhou 2010.NNNN



Complex Triplet

IV. Theoretical Robustness

- *L. Niemi, H. Patel, MRM, T. Tenkanen, D. Weir 1802.10500*
- *O. Gould, J. Kozaczuk, L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 1903.11604*
- *L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 2005.11332*

EWPT & Perturbation Theory

Expansion parameter

$$g_{\mathrm{eff}} \equiv \frac{g^2 T}{\pi m_T(\varphi)}$$

Infrared sensitive near phase trans

SM lattice studies: *g_{eff} ~ 0.8 in vicinity of EWPT for m_H ~ 70 GeV*

Theory Meets Phenomenology

A. Non-perturbative

- *Most reliable determination of character of EWPT & dependence on parameters*
- *Broad survey of scenarios & parameter space not viable*

B. Perturbative

- *Most feasible approach to survey broad ranges of models, analyze parameter space, & predict experimental signatures*
- *Quantitative reliability needs to be verified*

Theory Meets Phenomenology

A. Non-perturbative

- *Most reliable determination of character of EWPT & dependence on parameters*
- *Broad survey of scenarios & parameter space not viable*

B. Perturbative

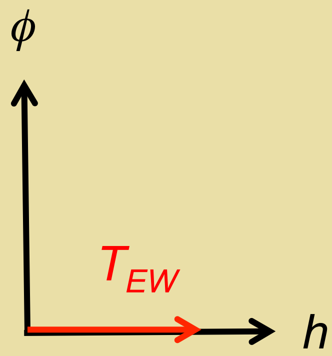
Benchmark pert theory

- *Most feasible approach to survey broad ranges of models, analyze parameter space, & predict experimental signatures*
- *Quantitative reliability needs to be verified*

Strategy

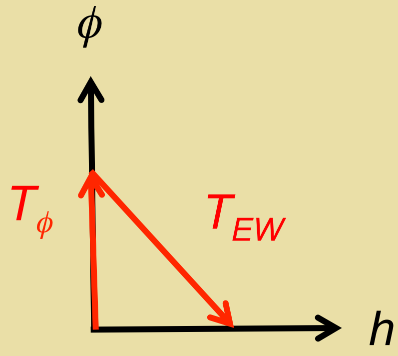
- *Employ dimensionally-reduced 3D EFT in two regimes:*
  - *Heavy BSM scalars → integrate out and "repurpose" existing lattice computations*
  - *Light BSM scalars → perform new lattice simulations*

Real Triplet



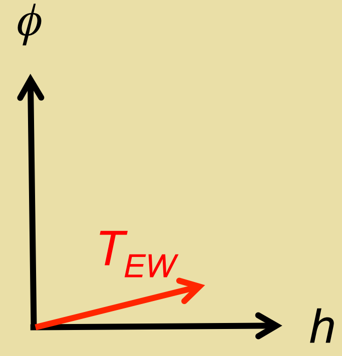
$a_2\, H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



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

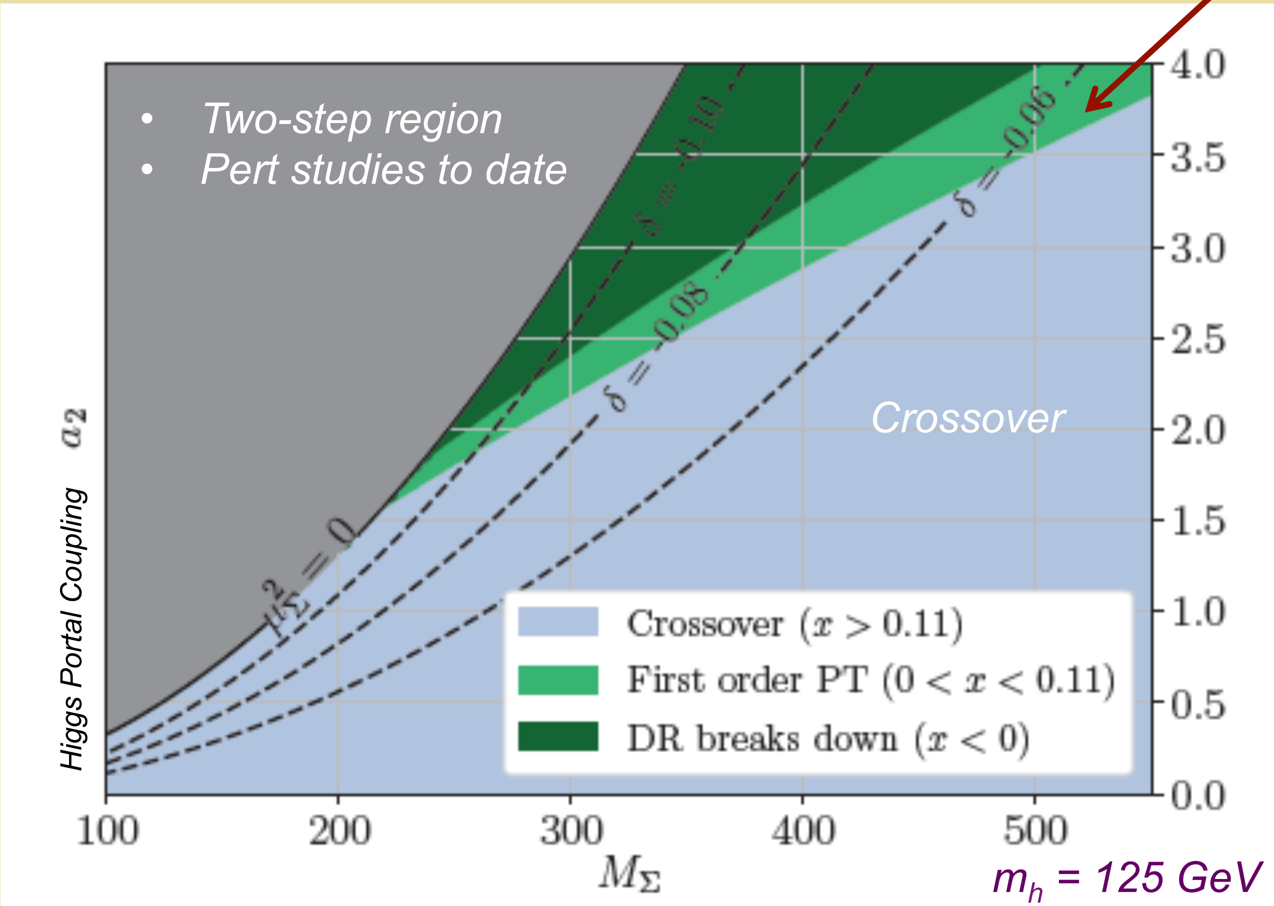
tree-level effect

Non-perturbative results:
EFT + "repurposed" lattice

EW precision tests → too tiny

Real Triplet: One-Step EWPT

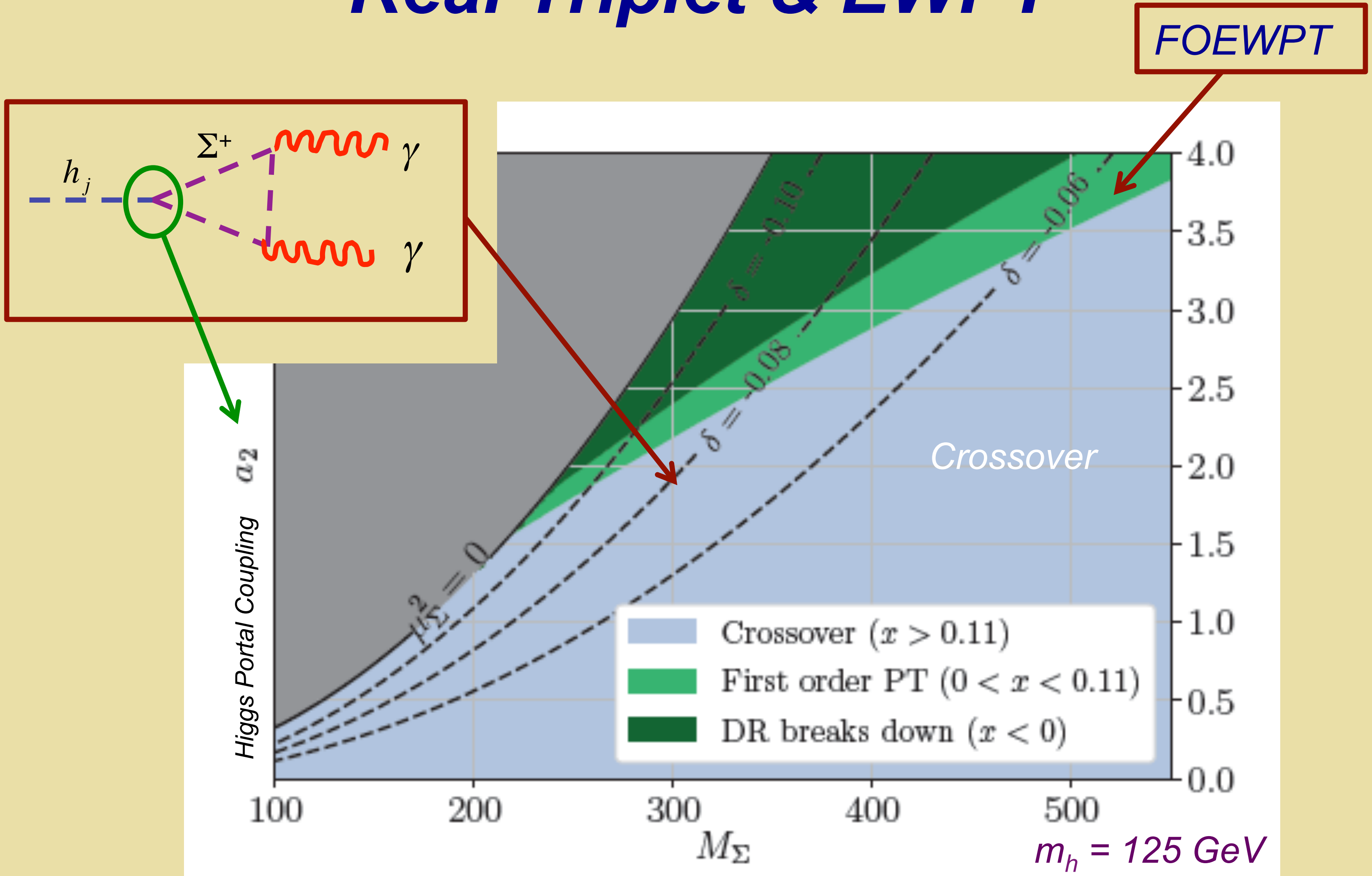
FOEWPT



- One-step
- Non-perturbative

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT

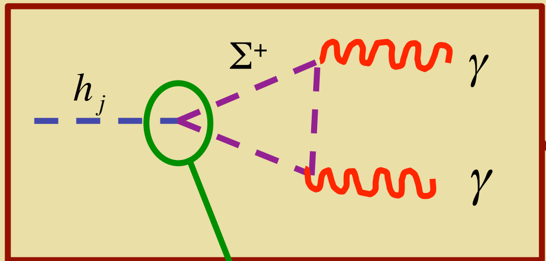


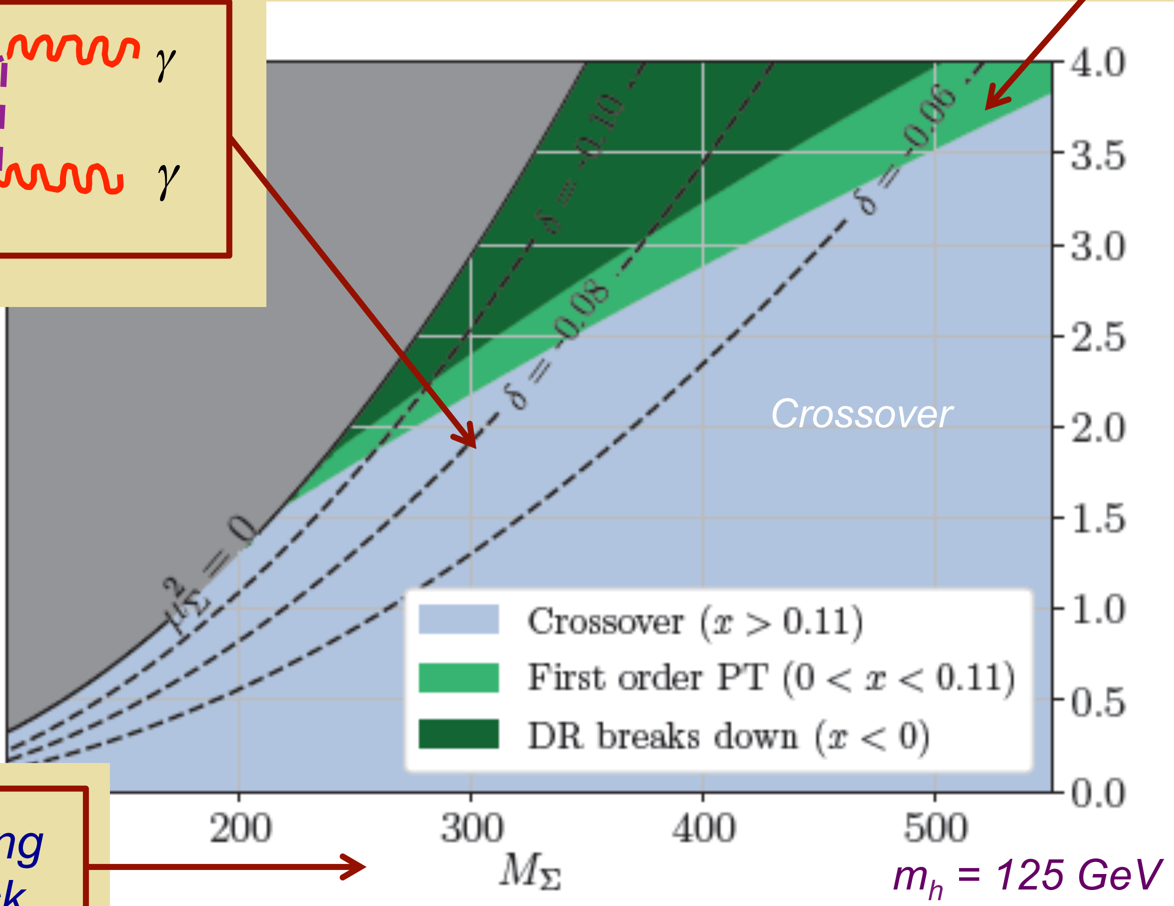
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

- *One-step*
- *Non-perturbative*

Real Triplet & EWPT

FOEWPT



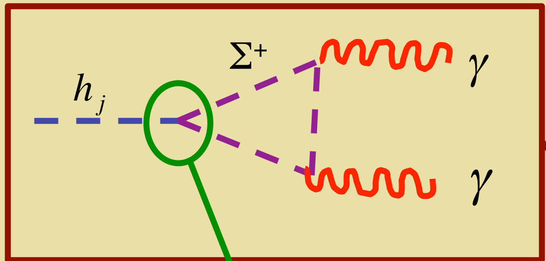


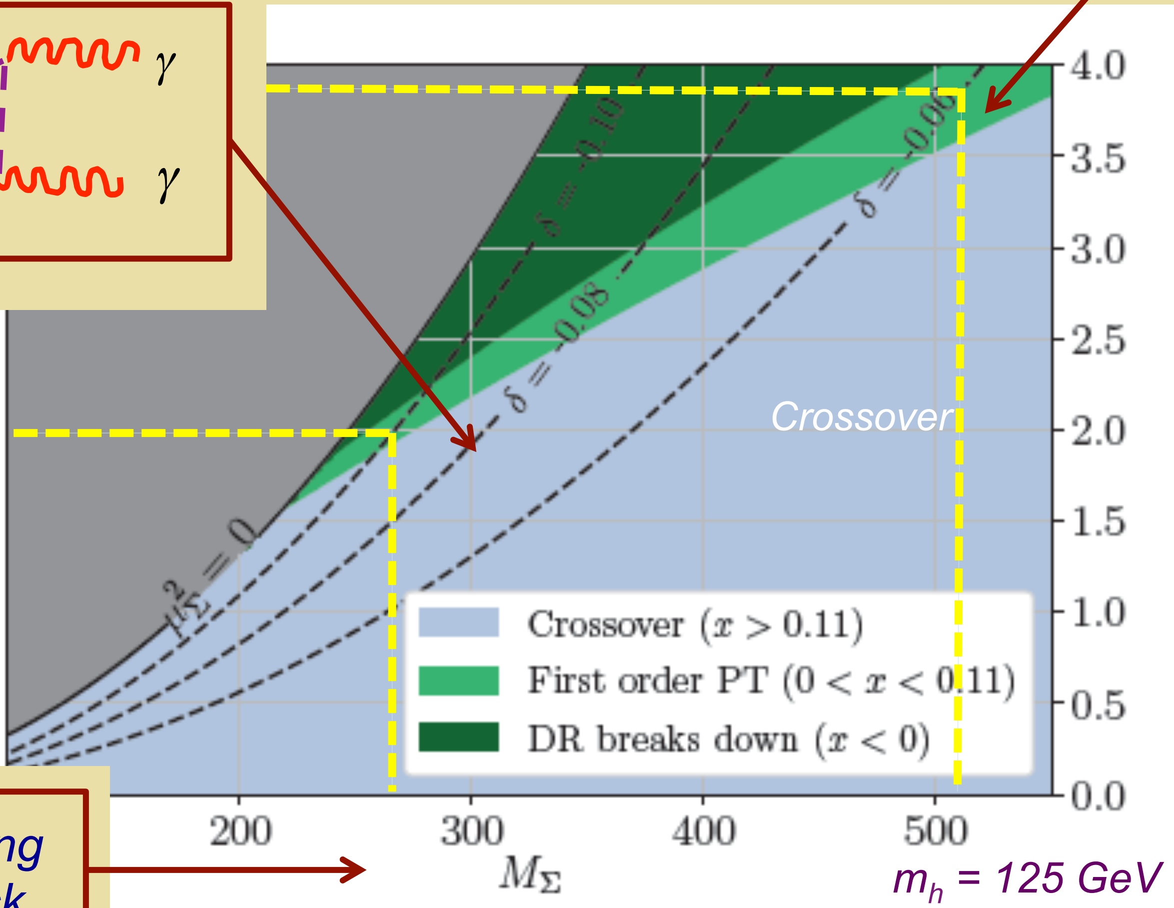
Disappearing charge track

- *One-step*
- *Non-perturbative*

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT





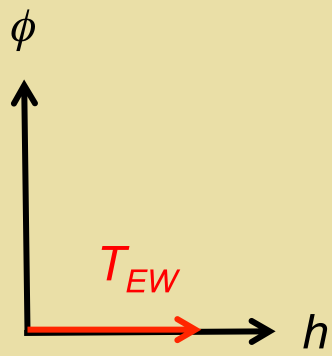
FOEWPT

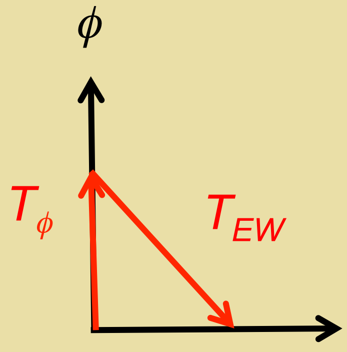
Disappearing charge track

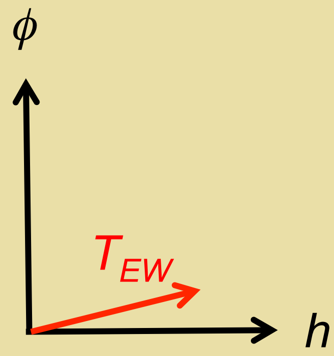
- *One-step*
- *Non-perturbative*

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet







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

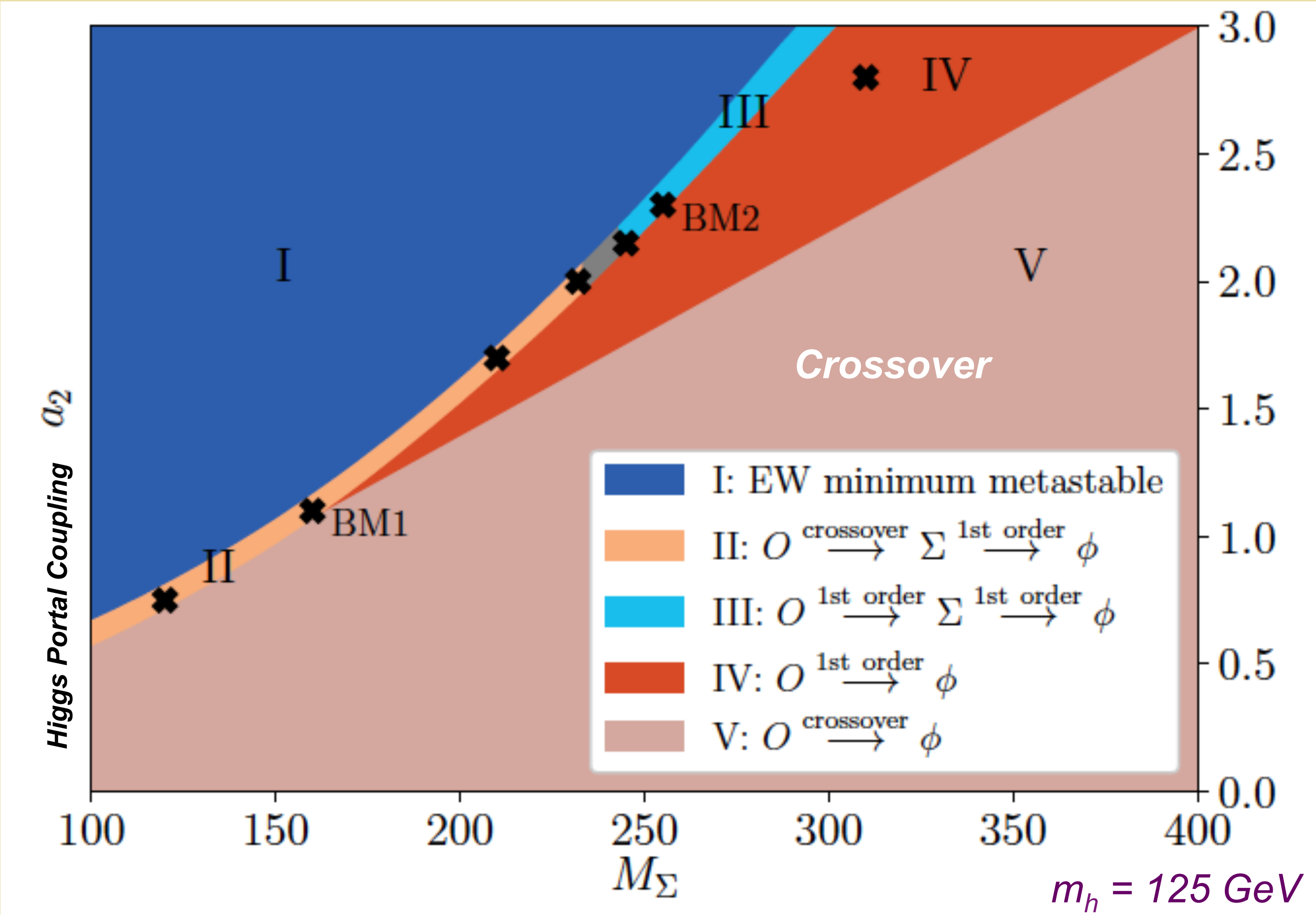
$a_2\ H^2\phi^2$: $T = 0$
tree-level effect

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

Non-perturbative results: EFT + lattice w/ dynamical triplet

EW precision tests → too tiny

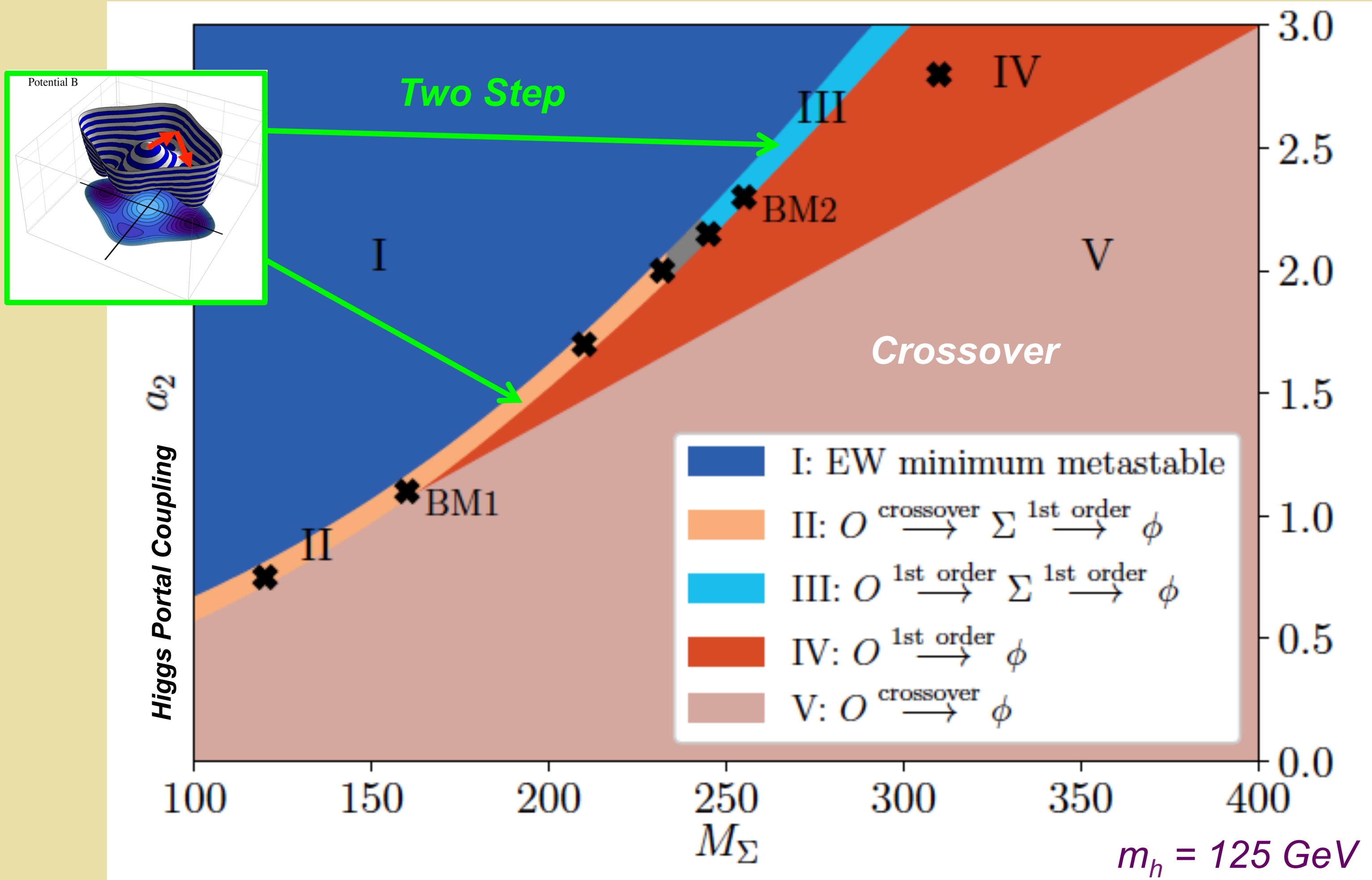
Real Triplet & EWPT: Novel EWSB



- *1 or 2 step*
- *Non-perturbative*

Niemi, R-M, Tenkanen, Weir 2005.11332

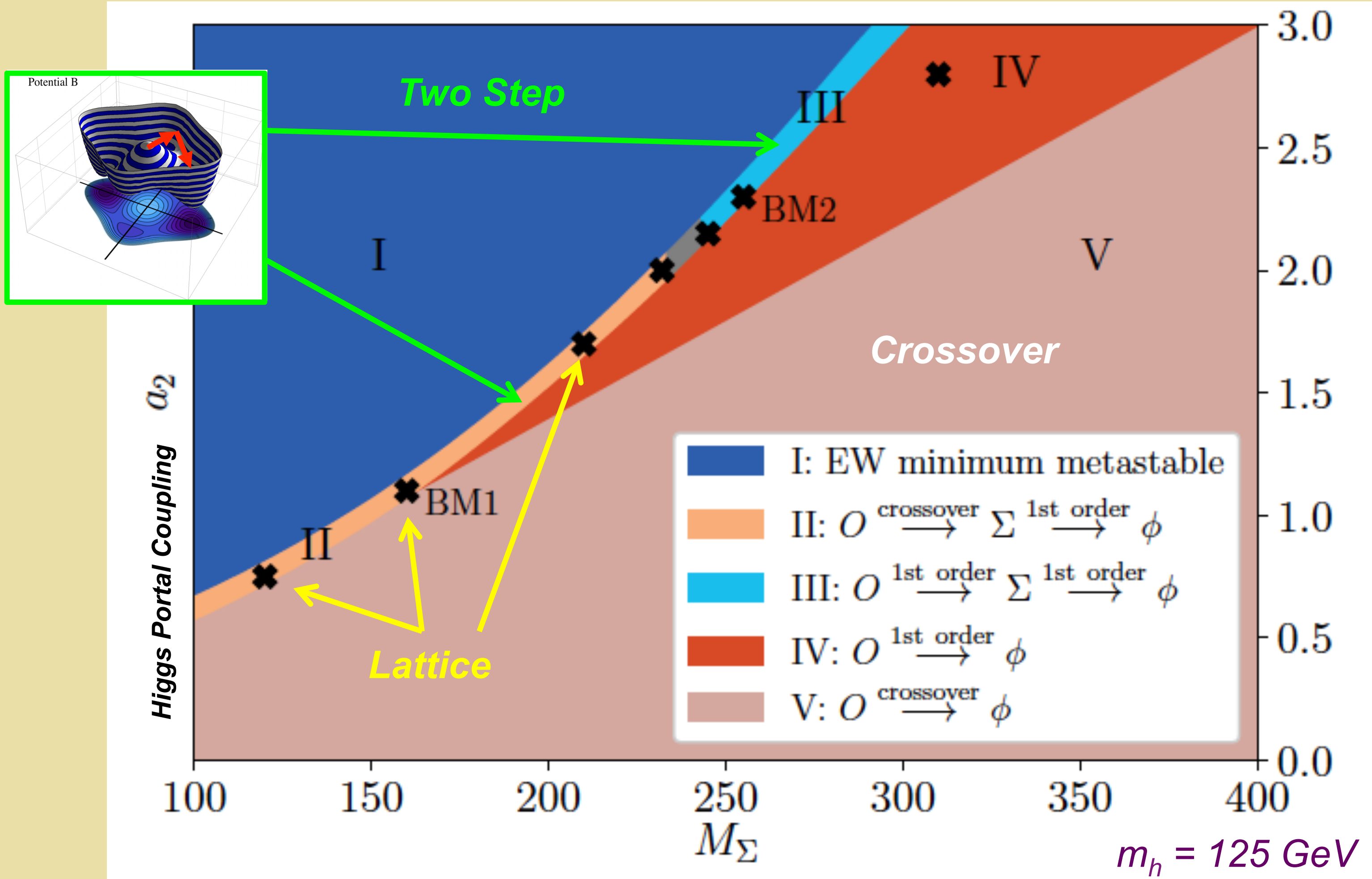
Real Triplet & EWPT: Novel EWSB



- *1 or 2 step*
- *Non-perturbative*

Niemi, R-M, Tenkanen, Weir 2005.11332

Real Triplet & EWPT: Novel EWSB



- *1 or 2 step*
- *Non-perturbative*

Niemi, R-M, Tenkanen, Weir 2005.11332

Opportunities

TDLI/SJTU Program

Model building & cosmological scenarios

Pheno: Collider, EDM, Gravitational Radiation

EW Phase Transition & EW Baryogenesis

Robust theory computations: formal "machinery", analytic, non-perturbative

Global EWPT+ Seminar

indico

Asia/S

Home Create event Room booking

Home » Institute Events » Electroweak Phase Transition +

Electroweak Phase Transition +

Create event

This is a global seminar on the physics of the electroweak phase transition and related topics, open to interested colleagues throughout the world. It is jointly hosted by the T.D. Lee Institute/Shanghai Jiao Tong U., Sydney U., Monash U., and the U. Mass Amherst Center for Fundamental Interactions.

The regular date/time are Fridays, 10:00 Shanghai. For each meeting, a zoom connection will be provided.

For further information, please contact Prof. Michael Ramsey-Musolf: mjrm(at)sjtu.edu.cn, Csaba Balazs: csaba.balazs(at)monash.edu, Prof. Andrew Fowlie: andrew.j.fowlie(at)qq.com, or Prof. Archil Kobakhidze: archil.kobakhidze(at)sydney.edu.au

There is one event in the future. Show

October 2020

- 30 Oct Andreas Papaefstathiou, "The Electro-Weak Phase Transition at Future Colliders: Confronting Theoretical Uncertainties and Complementary Channels"
- 16 Oct Ville Vaskonen, "Gravitational Waves From Strongly Supercooled Phase Transitions"
- 09 Oct Tuomas V.I. Tenkanen, "Reinvigorating High-T 3d EFT Approach for the EWPT"
- 02 Oct Juan Cruz, "Gradient Effects on False Vacuum Decay in Gauge Theory"

https://indico-tdli.sjtu.edu.cn/category/19/

Fridays 10:00

TDLI Di-Higgs Workshop

Di-Higgs 2020: Opportunities and Challenges

19-21 November 2020
The Redding Mann Hotel/雷汀曼精选酒店(交大店)
Asia/Shanghai timezone

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Accomodation
- Transportation

The study of di-Higgs production at the LHC and prospective future high-energy colliders provides a unique window on the dynamics of electroweak symmetry-breaking. Within the Standard Model, non-resonant di-Higgs production provides access to the Higgs tri-linear self-coupling, providing a key test of the Higgs mechanism. Beyond the Standard Model, both resonant and non-resonant di-Higgs production are sensitive to extended Higgs sectors and their implications for a possible first order electroweak phase transition in the early universe. Experimentally, di-Higgs production offers a rich array of channels to be studied, with their associated challenges.

This workshop will bring together theorists and experimentalists to discuss the theoretical implications and interpretation of di-Higgs production, the status of planned di-Higgs searches at the LHC, and the opportunities for new experimental searches at the LHC and beyond.

Online Zoom Link:

November 19-21 Shanghai

Kun Liu
MJRM

https://indico-tdli.sjtu.edu.cn/event/283/

IV. Outlook

- *Determining the thermal history of EWSB is field theoretically interesting in its own right and of practical importance for baryogenesis and GW → a key challenge for particle physics*

- *The scale T_{EW} → any new physics that modifies the SM crossover transition to a first order transition must live at M < 1 TeV and couple with sufficient strength to yield (in principle) observable shifts in Higgs boson properties*

- *A robust confrontation of of experiment and theory requires new level of theoretical rigor combining EFT methods with lattice simulations and new advances in theoretical tools*

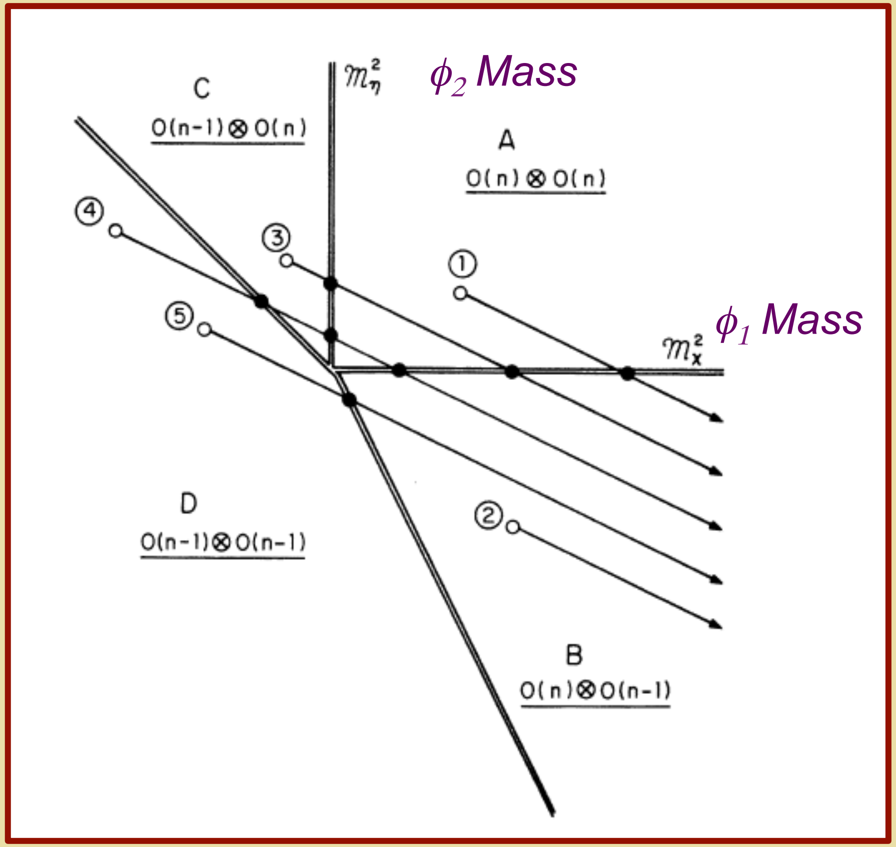
Was There an Electroweak Phase Transition?

Answering this question is an exciting frontier at the interface of particle physics and cosmology, with ample opportunities for significant theoretical and experimental advances

谢谢

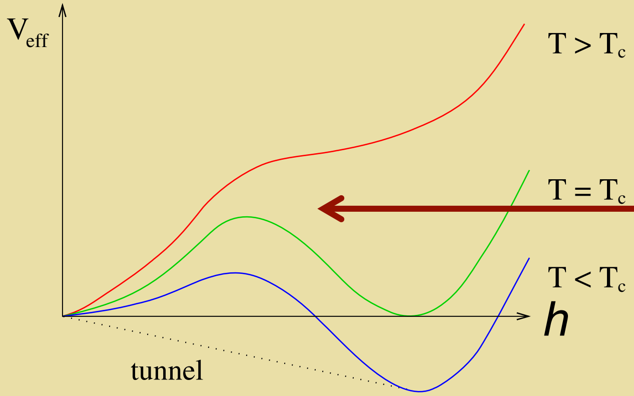
Back Up Slides

Patterns of Symmetry Breaking

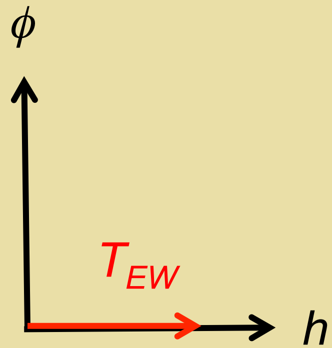


S. Weinberg, PRD 9 (1974) 3357

First Order EWPT from BSM Physics

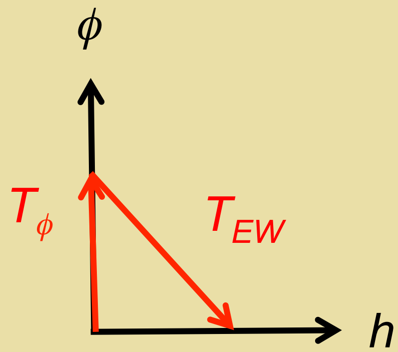


Higgs − ϕ^0 Mixing



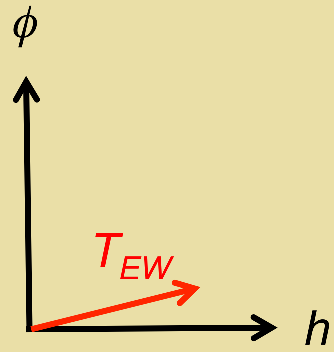
$a_2\ H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



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

tree-level effect

Strong First Order EWPT

- ***Prevent baryon number washout***

$$\boxed{\frac{|a_1|}{2\lambda T_{\rm EW}} \gtrsim 1} \longrightarrow \boxed{\begin{array}{l} |\sin\theta| \gtrsim 0.01 \\ \\ |\Delta\lambda/\lambda| \gtrsim 0.003 \end{array}}$$

T_{EW} : Direct $\phi^+\phi^-$ Production in e^+e^-

Mass Reach:

$E_{\rm CM}$(GeV)	M_ϕ (GeV)	$\hat\sigma$ (fb)	$\int dt\mathcal{L}$ (ab^{-1})	$N \times 10^{-3}$
340	100	142 fb	5	710
500	100	94 fb	2	188
	150	63 fb	2	126
1500	150	13 fb	2.5	32.5
	440	7 fb	2.5	17.5
3000	440	3 fb	5	15
	700	2 fb	5	10

Lots of events$\cdots$but need energy

T_{EW} : Direct $\phi^+\phi^0$ Production in pp

Mass Reach:

$E_{\rm CM}$(TeV)	M_ϕ (GeV)	σ (fb)	$\int dt\mathcal{L}$ (ab^{-1})	$N \times 10^{-3}$
14	415	7.7	3	23
	714	0.63	3	1.9
27	415	26	30	720
	714	3	30	90
100	415	183	30	5490
	714	29	30	870

Lots of events⋯but need energy

T_{EW} : Single ϕ^0 Production in e^+e^- & pp

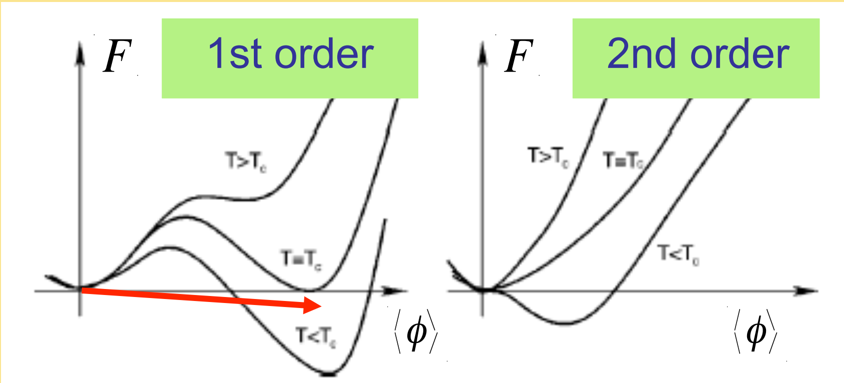
Z ϕ production in e^+e^- :

$E_{\rm CM}$(TeV)	M_ϕ (GeV)	$\lvert\sin\theta\rvert$	σ (fb)	$\int dt\mathcal{L}$ (ab^{-1})	N
340	150	0.01	0.01	5	50
500	150	0.01	0.005	2	10
	240	0.01	0.003	2	6
1500	150	0.01	5×10^{-4}	2.5	1
	400	0.01	4×10^{-4}	2.5	1
	700	0.01	2×10^{-4}	2.5	< 1
3000	150	0.01	1×10^{-4}	5	< 1
	400	0.01	1×10^{-4}	5	< 1
	700	0.01	1×10^{-4}	5	< 1

Single ϕ production in pp via GF:

$E_{\rm CM}$(TeV)	M_ϕ (GeV)	$\lvert\sin\theta\rvert$	σ (fb)	$\int dt\mathcal{L}$ (ab^{-1})	$N \times 10^{-3}$
14	415	0.01	1	3	3
	714	0.01	0.1	3	0.3
100	415	0.01	59	30	1770
	714	0.01	12	30	360

EW Phase Transition: New Scalars

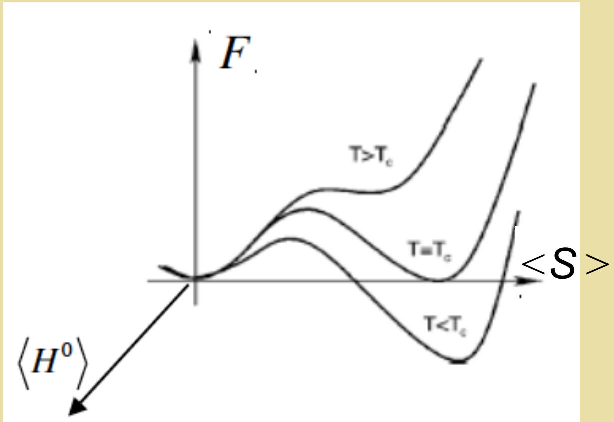


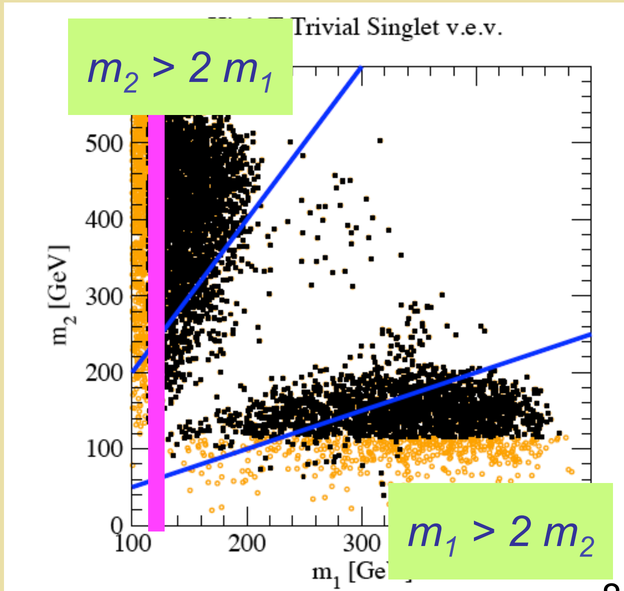
Increasing m_h ⟶

⟵ *New scalars*

Real Singlet: $\phi \to S$

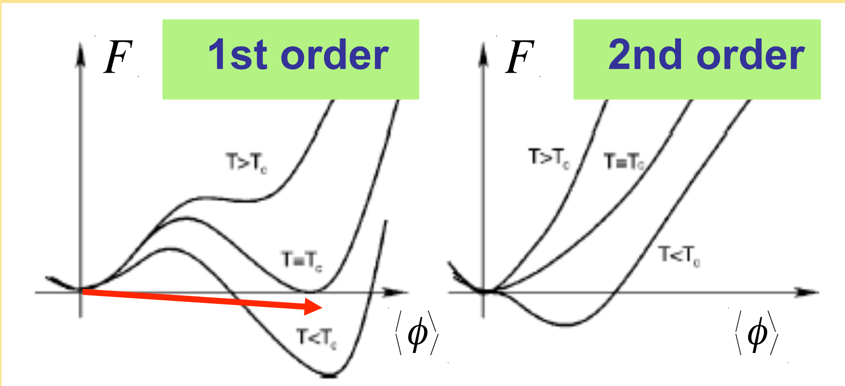
Simplest Extension:
two states h_1 & h_2





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

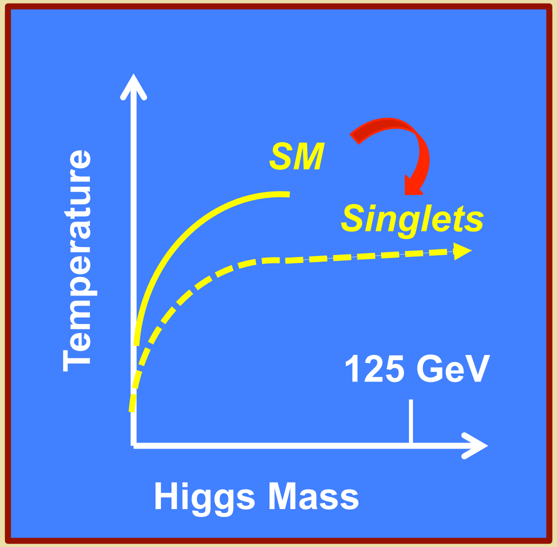
EW Phase Transition: Singlet Scalars



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

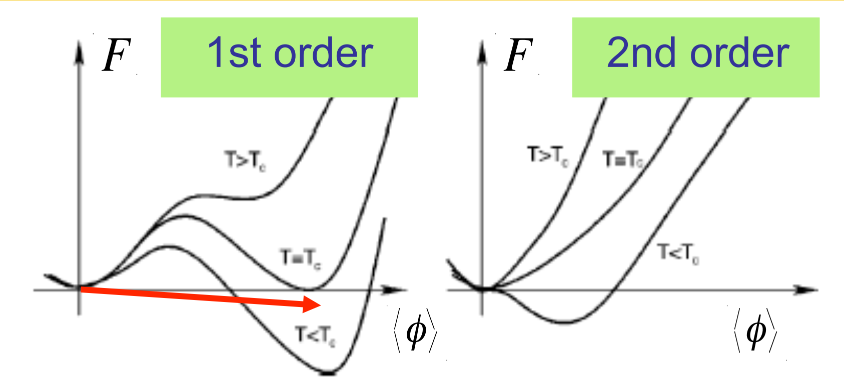
SM EW: Cross over transition

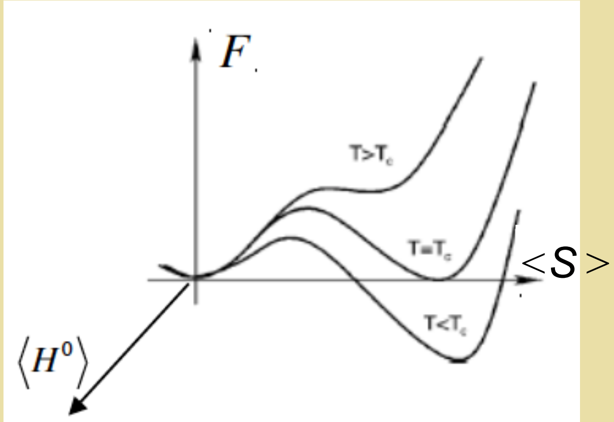


EW Phase Diagram

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

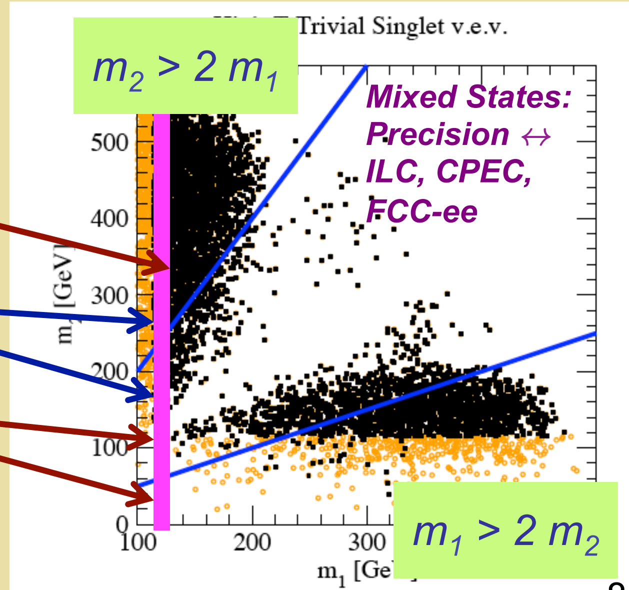
EW Phase Transition: Singlet Scalars





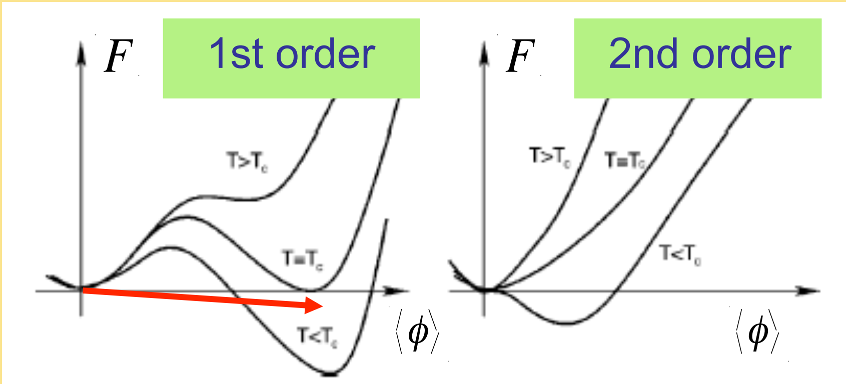
Collider probes

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

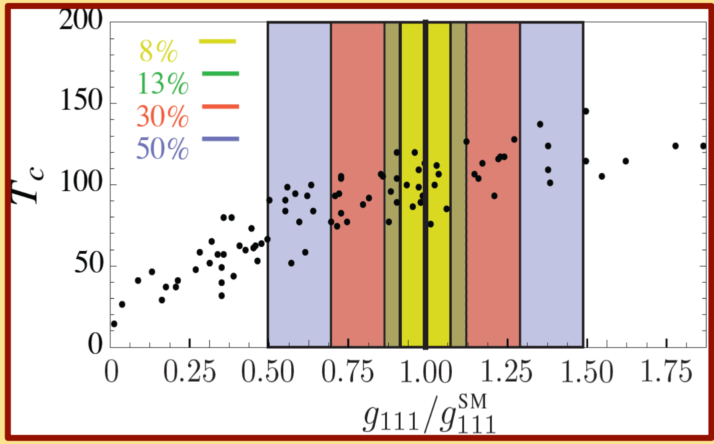


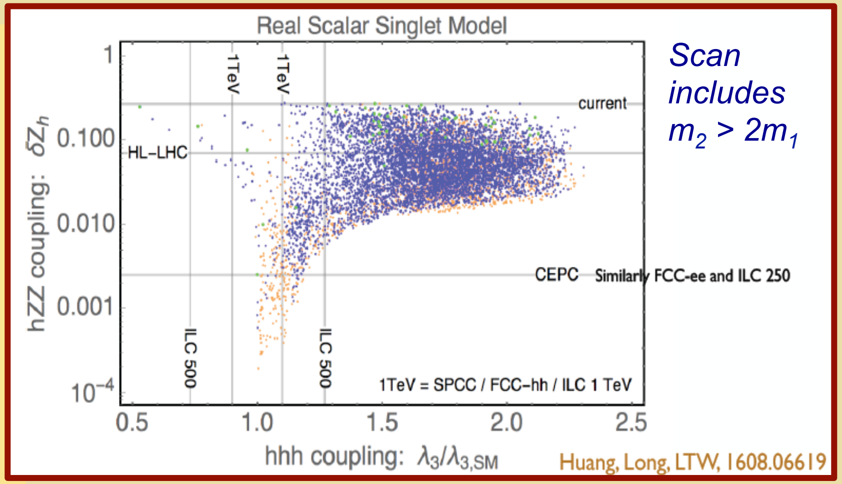
Profumo, MJRM, Shaugnessy '07

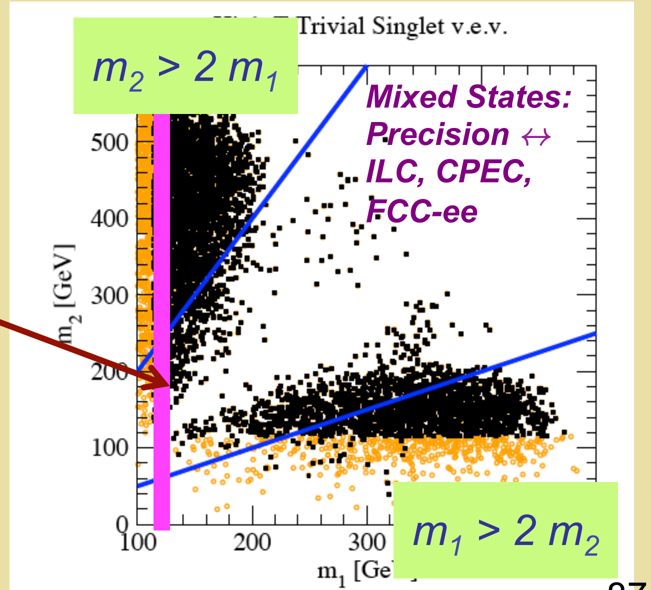
EW Phase Transition: Singlet Scalars



Modified Higgs Self-Coupling







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

Thanks: M. Cepeda

Higher Dimensional Operators

$$\tilde{V}_0(H) = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2 + \frac{1}{\Lambda^2} \left(H^\dagger H - \frac{v^2}{2} \right)^3$$

$$\tilde{V}_0(h) = \tilde{V}_0 - \frac{\tilde{\mu}^2}{2} h^2 + \frac{\tilde{\lambda}}{4} h^4 + \frac{1}{8\Lambda^2} h^6$$

$$\tilde{\mu}^2 = \left[\lambda - \frac{3v^2}{4\Lambda^2} \right] v^2$$

$$\tilde{\lambda} < 0$$ → FO EWPT → Λ < 840 GeV

$$\tilde{\lambda} = \lambda - \frac{3v^2}{2\Lambda^2}$$

→ *Implications for σ_{Zh}*

- *Cao, Huang, Xie, Zhang 2017*
- *Grojean, Servant, Wells 2004…*
- *Grinstein, Trott 2008…*

CW Potential: Vacuum Uplift

Vacuum Energy Difference

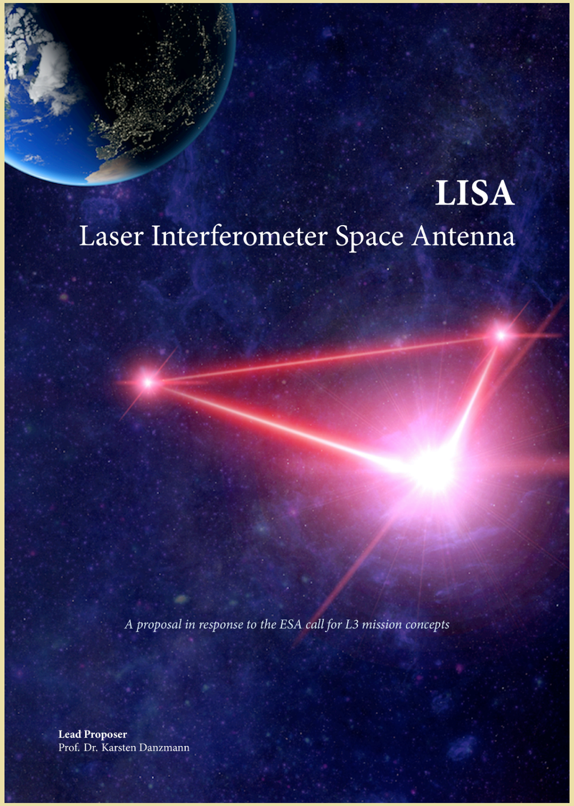
$$\Delta V = -\frac{\lambda(\mu) v^4}{4}$$

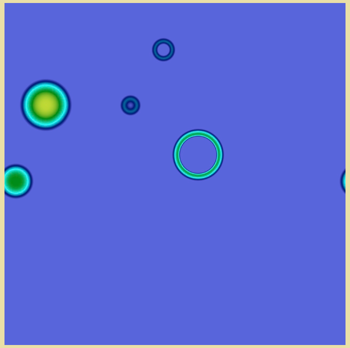
$$+ \sum_k \frac{(-1)^{2s_k}}{64\pi^2} \left\{ \frac{3}{2} \left([M_k^2(\phi)]^2 - [M_k^2(0)]^2 \right) + \left([M_k^2(0)]^2 \ln \frac{M_k^2(0)}{\mu^2} - [M_k^2(\varphi)]^2 \ln \frac{M_k^2(\varphi)}{\mu^2} \right) \right\}$$

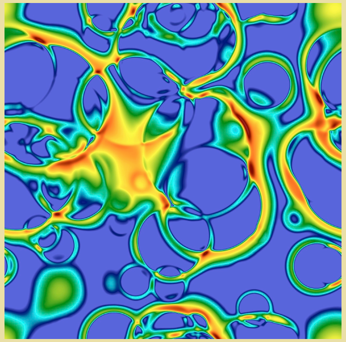
Can raise Higgs vac energy → lowers T_{EW}

- *Huang et al '15 (NMSSM)*
- *Dorsch et al '17 (2HDM)*

Gravitational Radiation





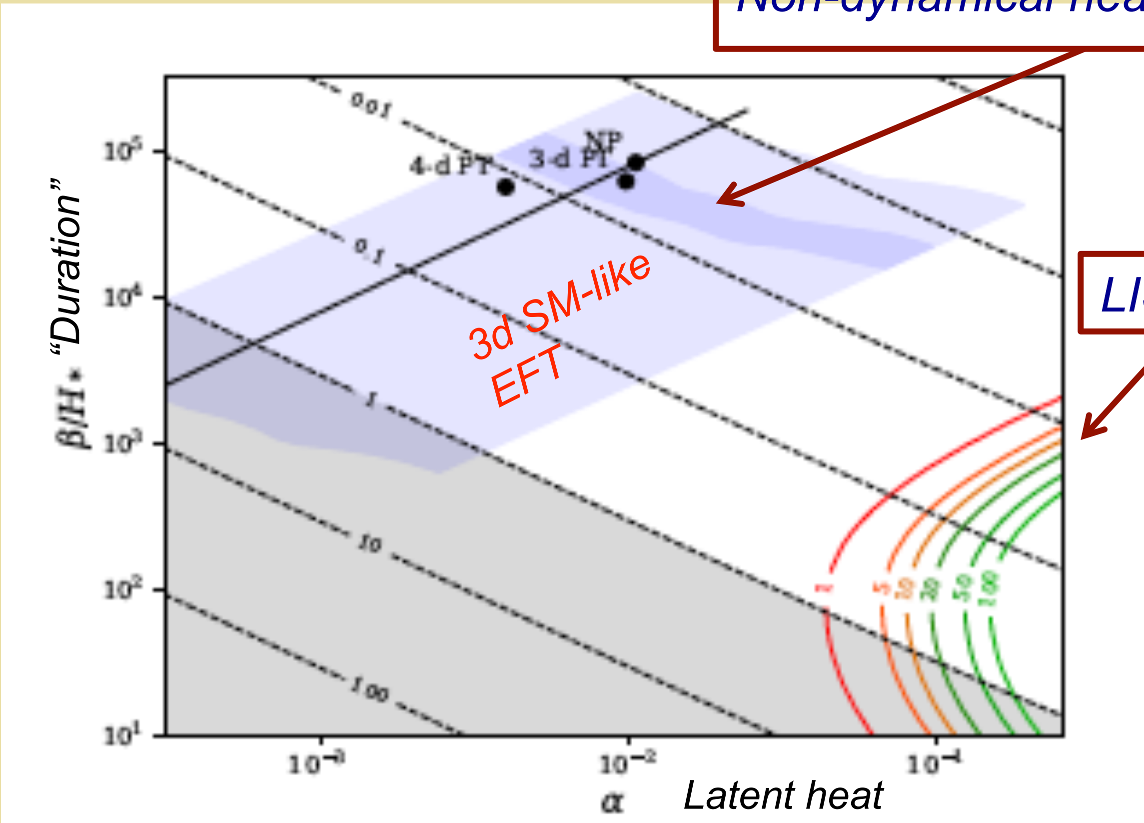


1. Bubbles nucleate and grow
2. Expand in a plasma - create reaction fronts
3. Bubbles + fronts collide - violent process
4. Sound waves left behind in plasma
5. Turbulence; damping

Thanks: D. Weir

Heavy Real Singlet: EWPT & GW

Non-dynamical heavy BSM scalars

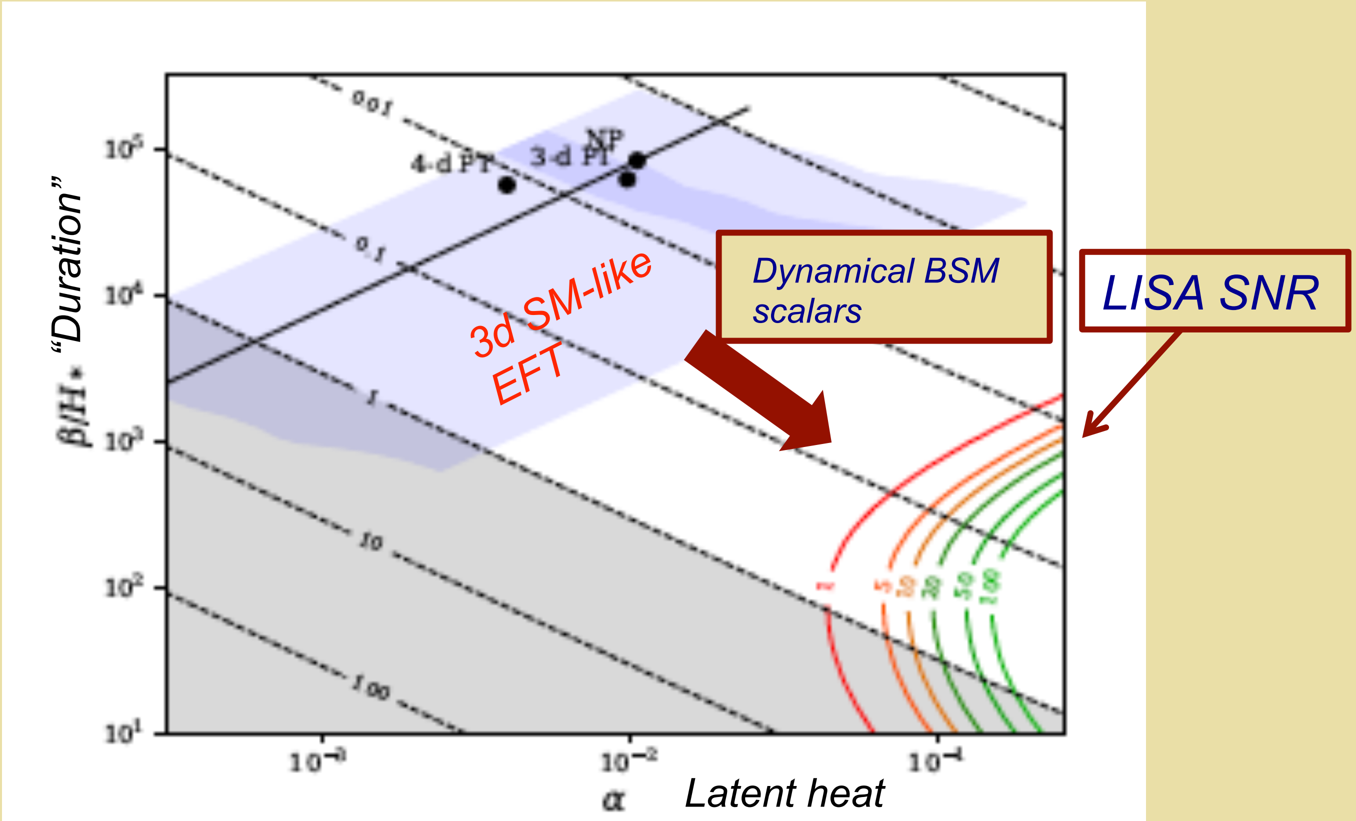


LISA SNR

- One-step
- Non-perturbative

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

Heavy Real Singlet: EWPT & GW



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

- One-step
- Non-perturbative