The Electroweak Phase Transition: A Collider Target

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- *UMass-Amherst*

My pronouns: he/him/his

CEPC Workshop
Beijing, November 2019

Key Ideas for this Talk

- ***The "electroweak temperature" → a scale provided by nature that gives us a clear BSM target for colliders***
- ***Simple arguments → BSM physics that gives rise to a first order EW phase transition (needed for EW baryogenesis) cannot be too heavy or too feeble***
- ***Concrete BSM models → exemplify these arguments***

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- *Simple arguments → BSM physics that gives rise to a first order EW phase transition (needed for EW baryogenesis) cannot be too heavy or too feeble*
- *Concrete BSM models → exemplify these arguments*

Mass reach

Precision

Outline

I. Context & Questions

II. EWPT: A Collider Target

III. Model Illustrations

IV. 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 LISA, could a cosmological phase transition be responsible ?*

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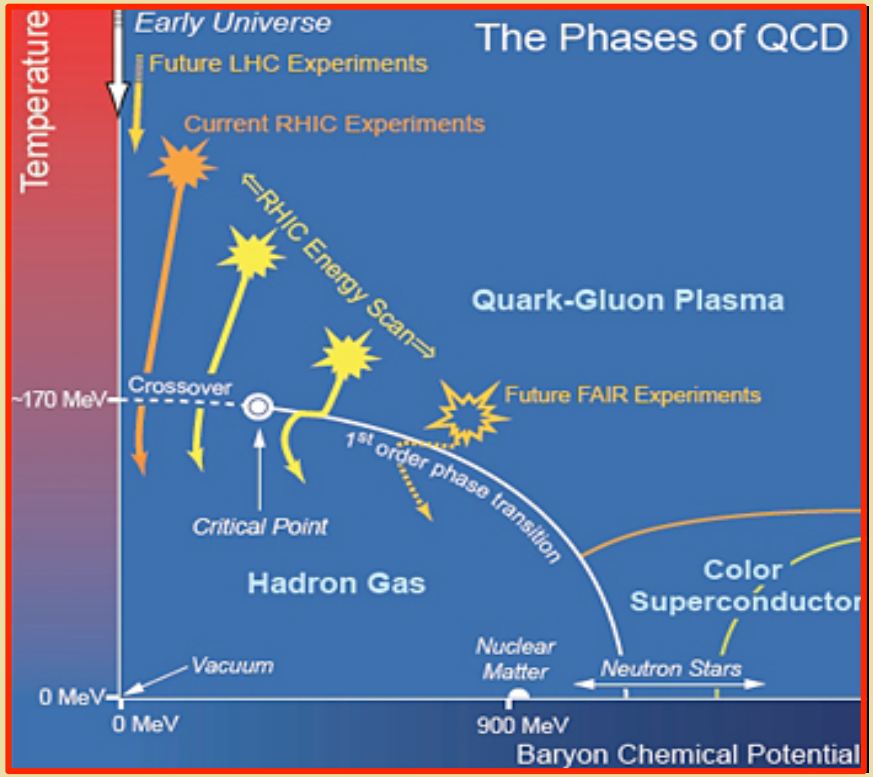
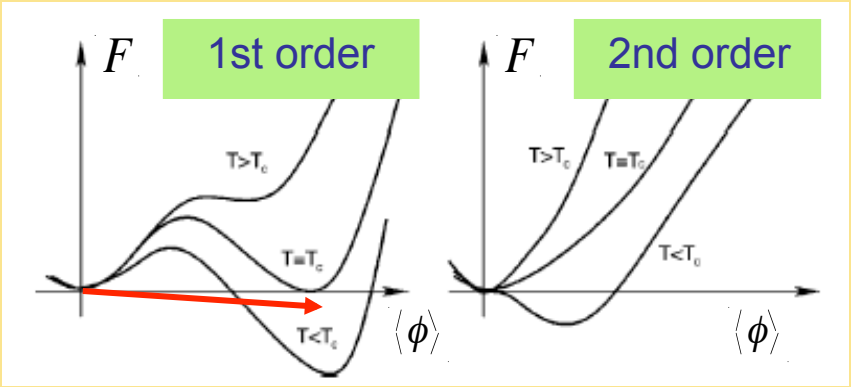
Thermal History of Symmetry Breaking



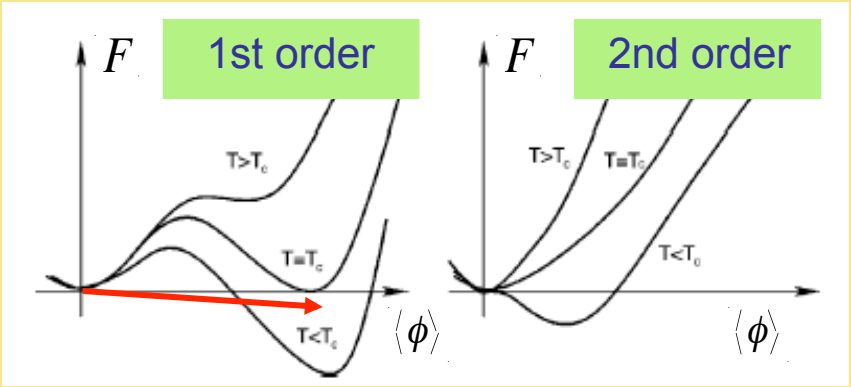
QCD Phase Diagram → EW Theory Analog?

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
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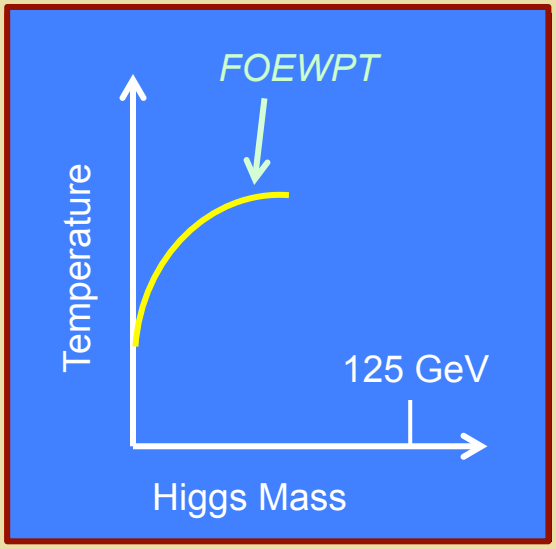
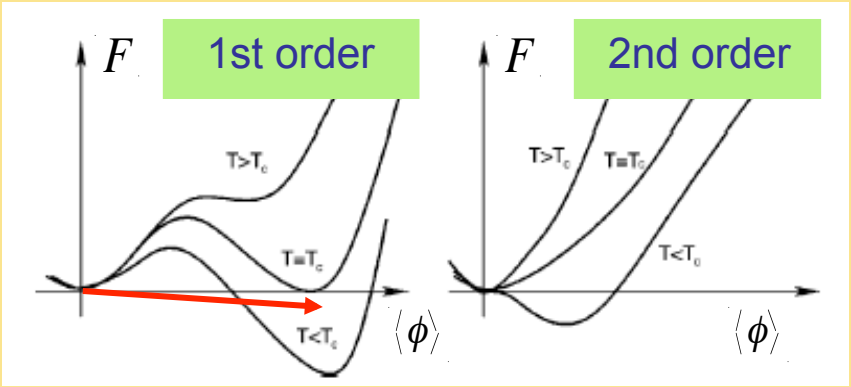
SM EW: Cross over transition



EW Phase Diagram

EWSB Transition: St'd Model



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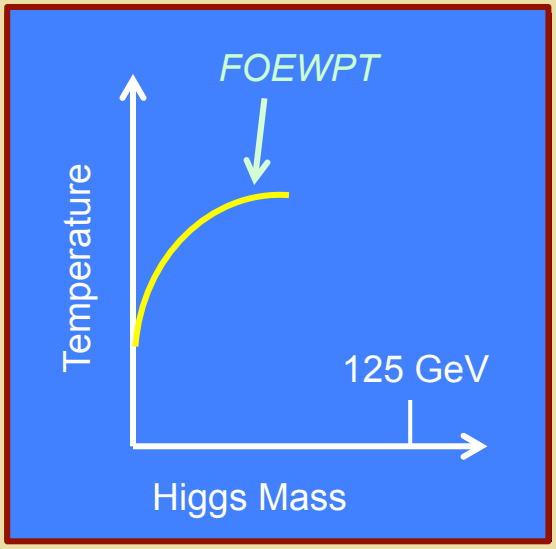
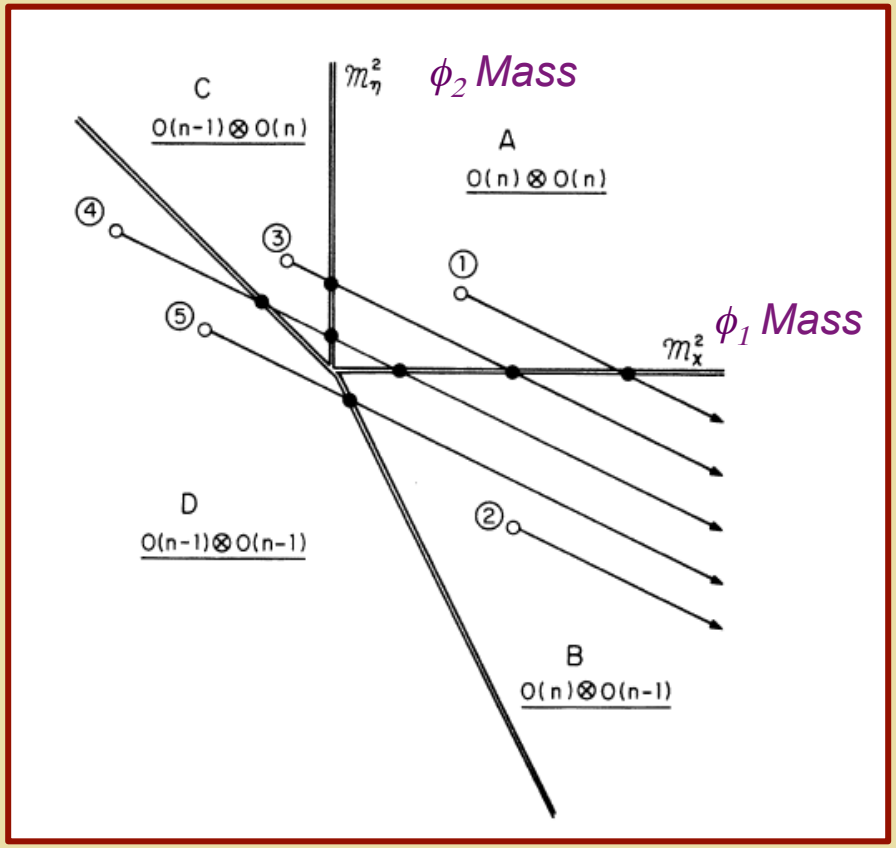


EW Phase Diagram

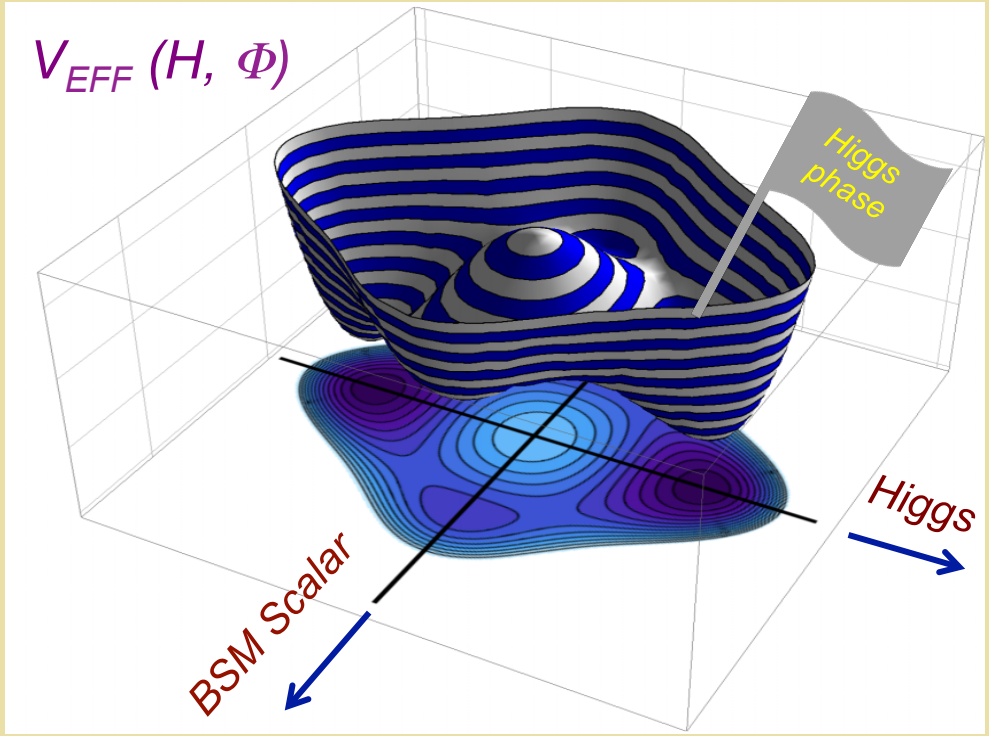
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

Patterns of Symmetry Breaking



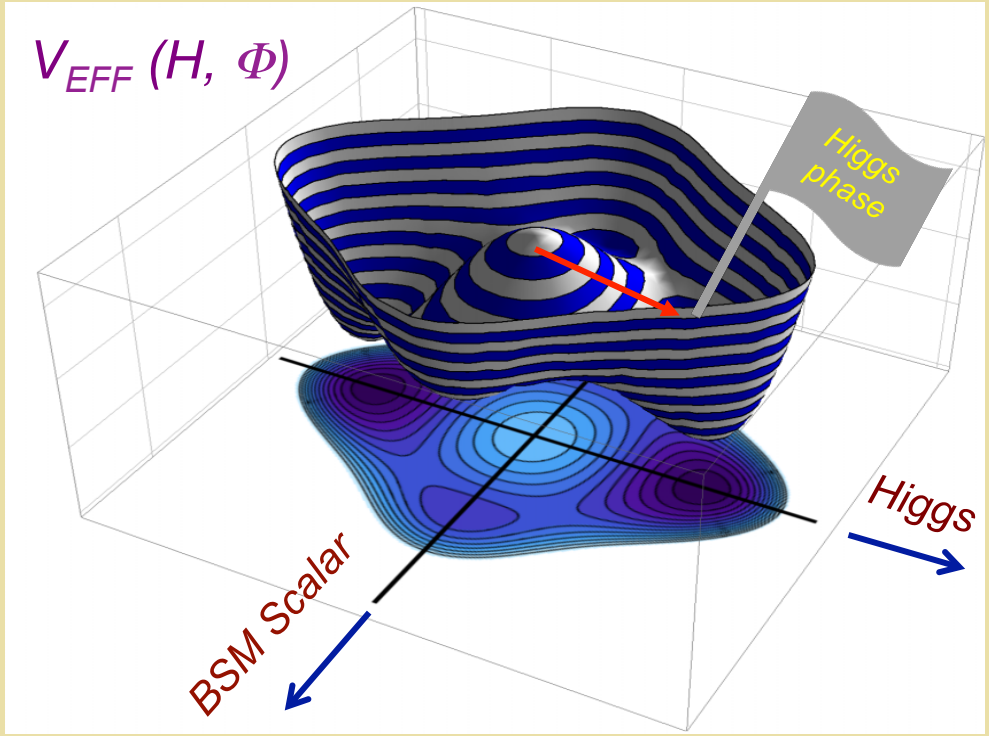
S. Weinberg, PRD 9 (1974) 3357

Patterns of Symmetry Breaking



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

Patterns of Symmetry Breaking



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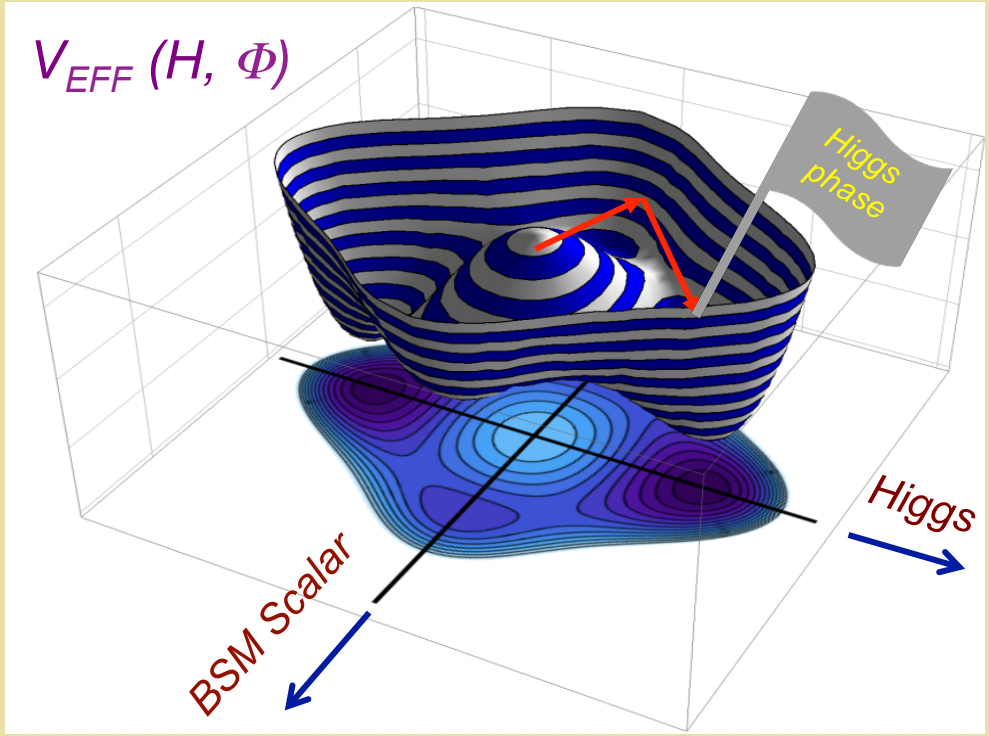

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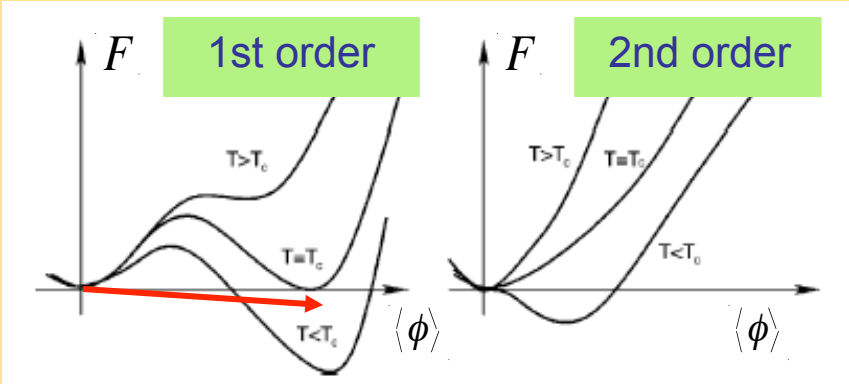
EW Phase Transition: Baryogen & GW

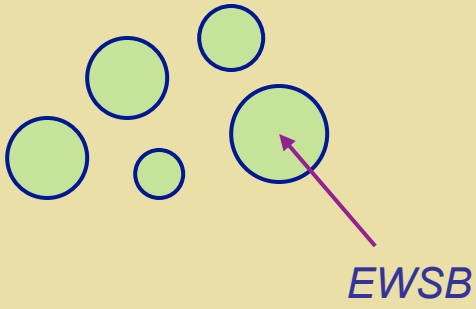


Increasing m_h →

← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" **1st order EWPT** → *Bubble nucleation*



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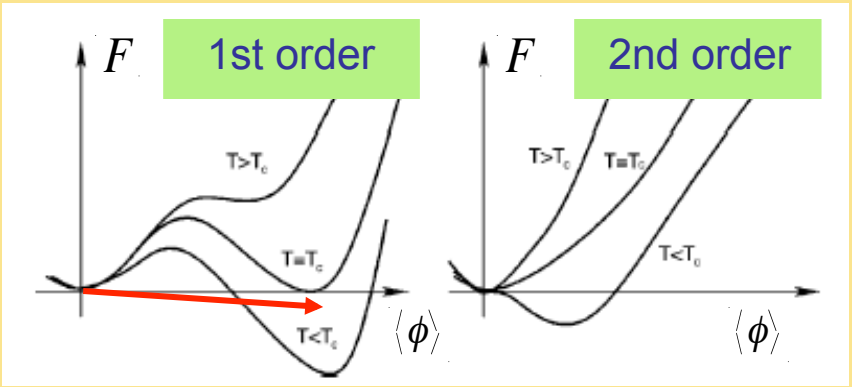

Increasing m_h →

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Baryogenesis
Gravity Waves
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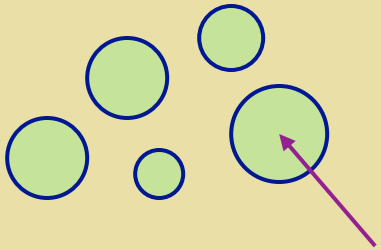
"Strong" 1st order EWPT

- *Baryogen**
- *GW*

Bubble nucleation



* *Need BSM CPV*

Main Themes for This Talk

- ***T_{EW} → EW phase transition is a target for the LHC & beyond***
- ***Important complementarity exists between e^+e^- and pp colliders***

II. EWPT: A Collider Target

MJRM 1911.NNNNN

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

T_{EW} Sets a Scale for Colliders

High-T SM Effective Potential

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

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

T_0 ~ 140 GeV

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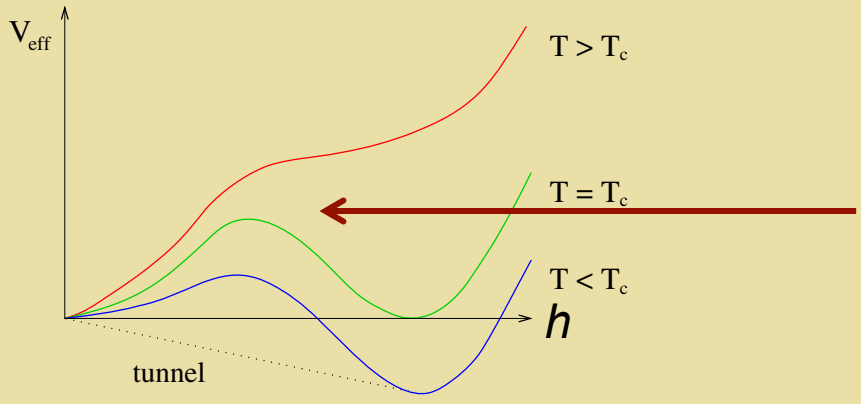
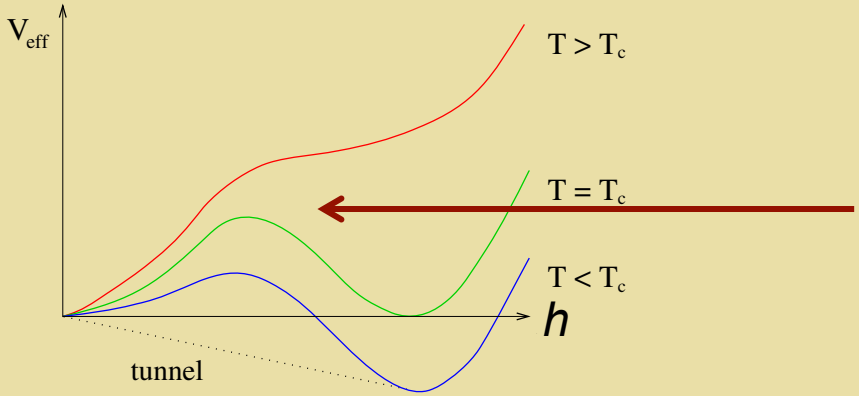
$T_0 \sim$ 140 GeV $\equiv \ T_{EW}$

First Order EWPT from BSM Physics



Generate finite-T barrier

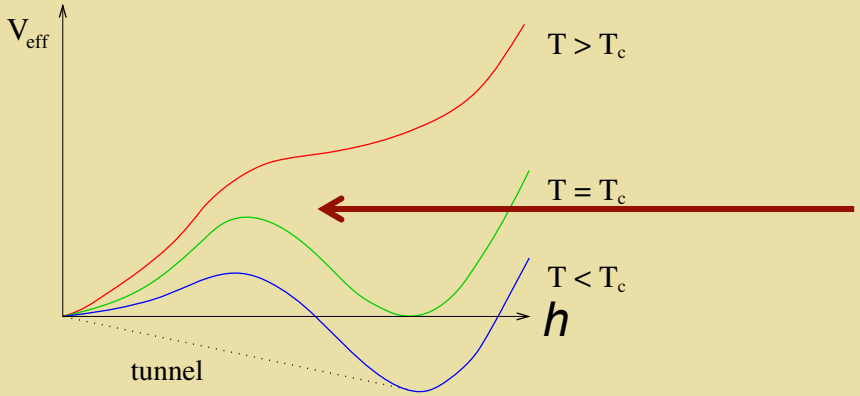
First Order EWPT from BSM Physics



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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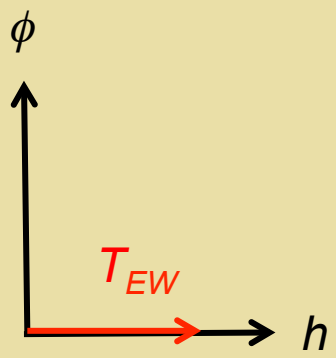
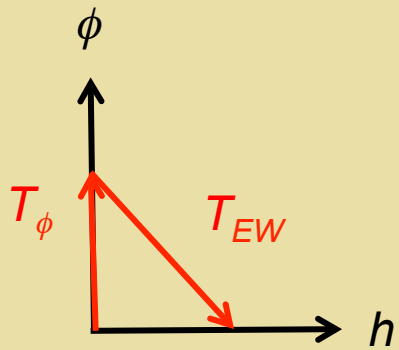
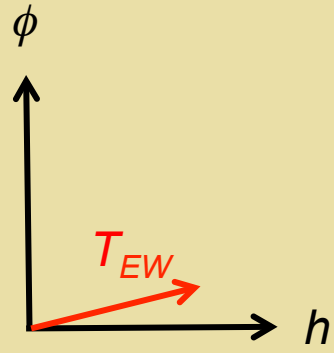




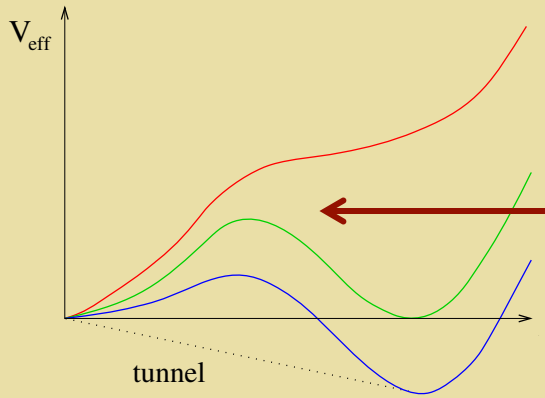


$a_2 H^2\phi^2$: $T > 0$
loop effect

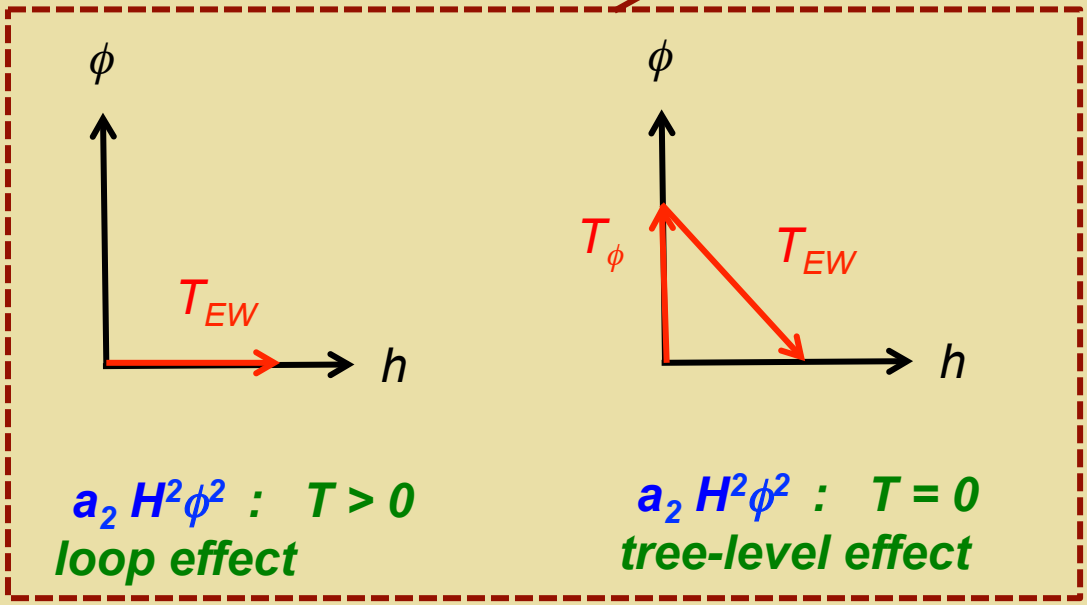
$a_2 H^2\phi^2$: $T = 0$
tree-level effect

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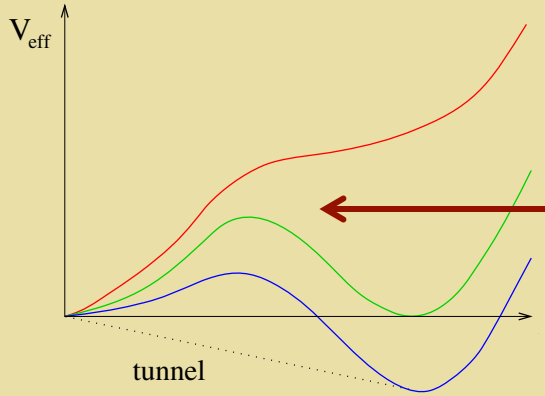

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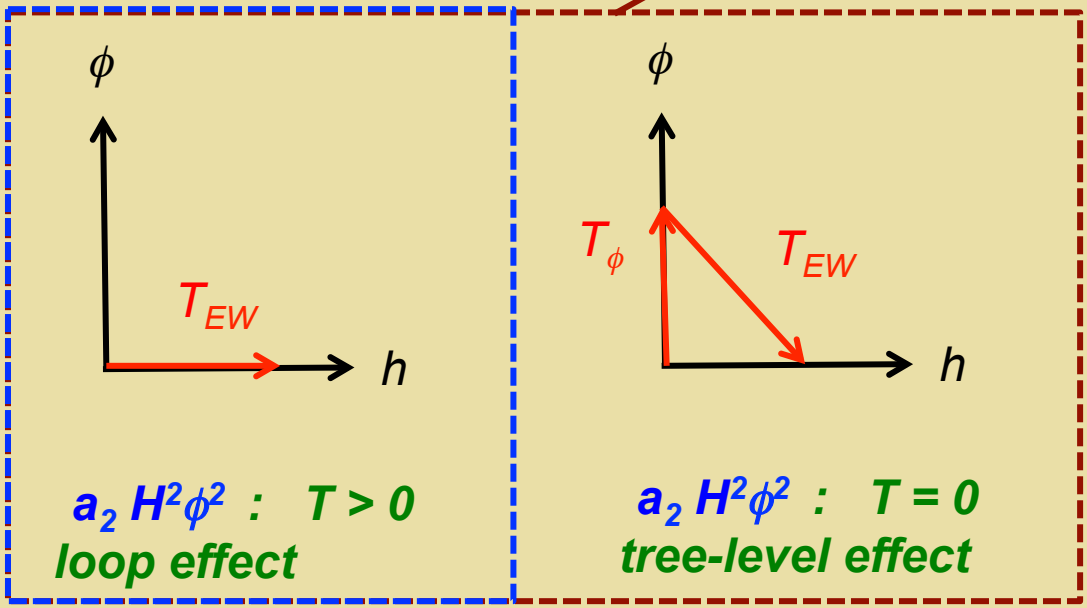

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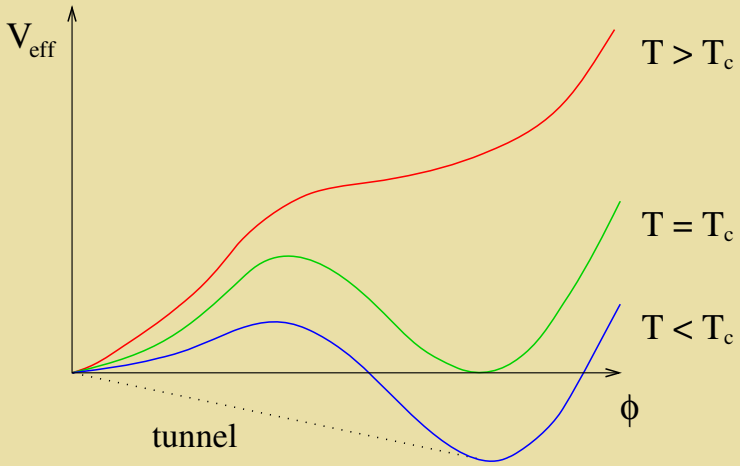

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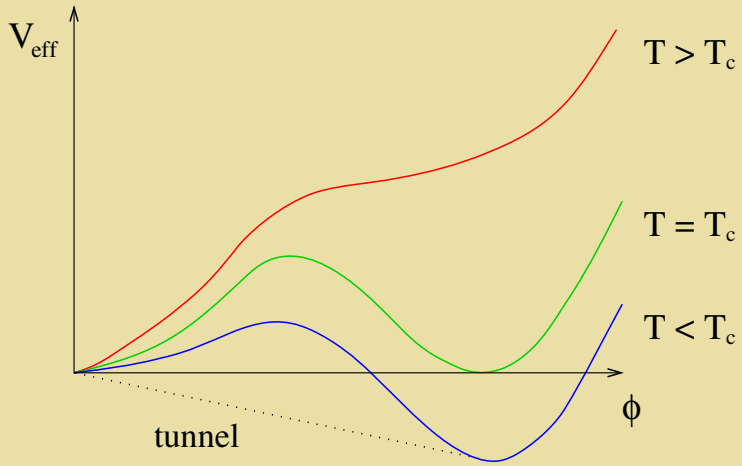

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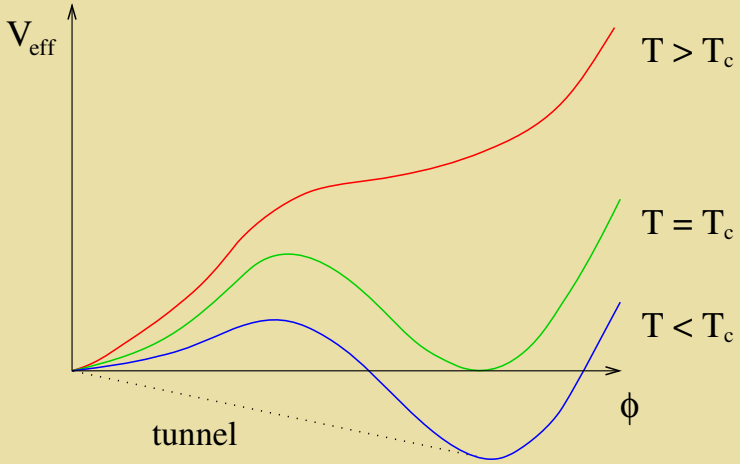

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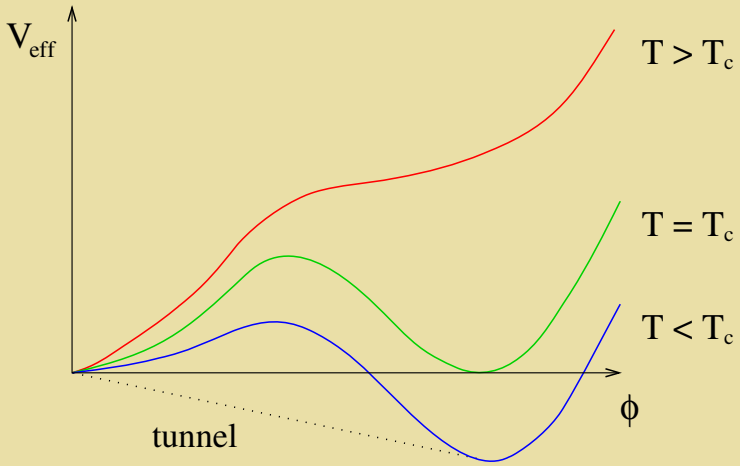

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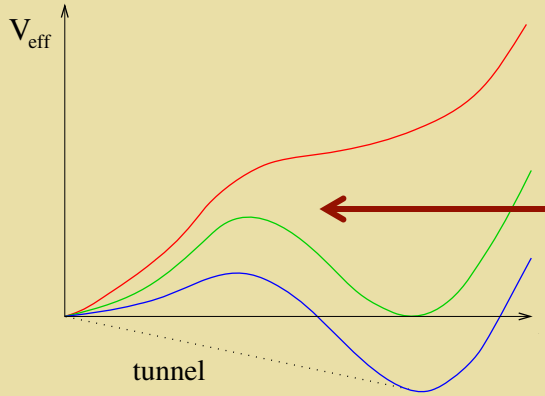
M_ϕ < 350 GeV for perturbative a_2

First Order EWPT from BSM Physics



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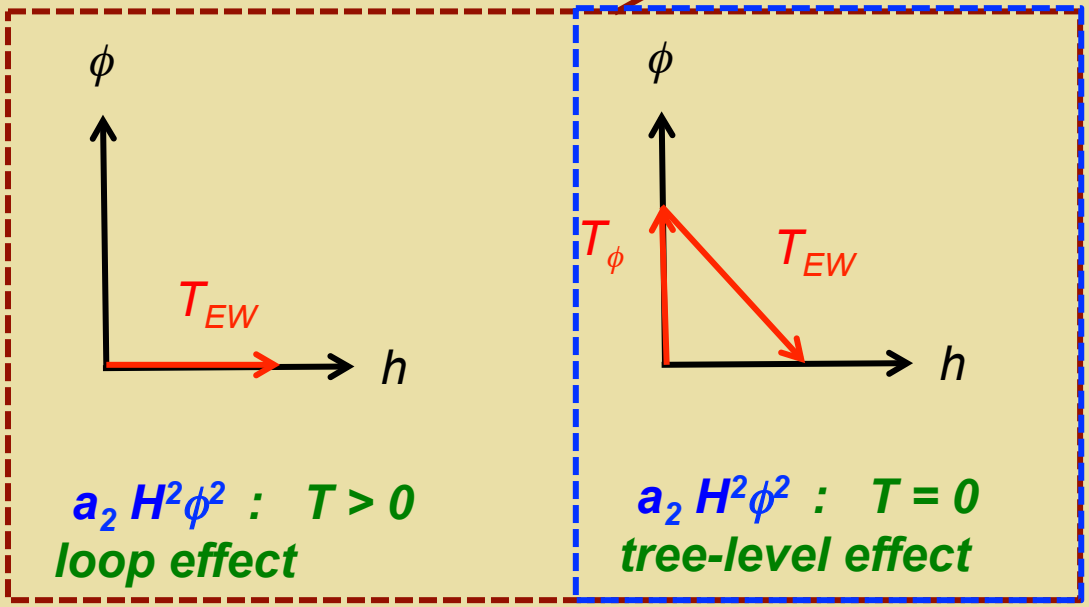
Analogous logic



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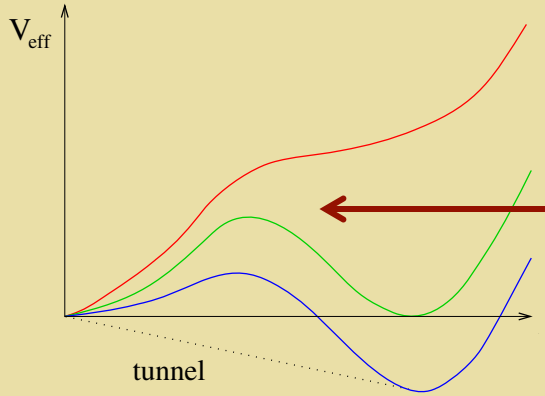

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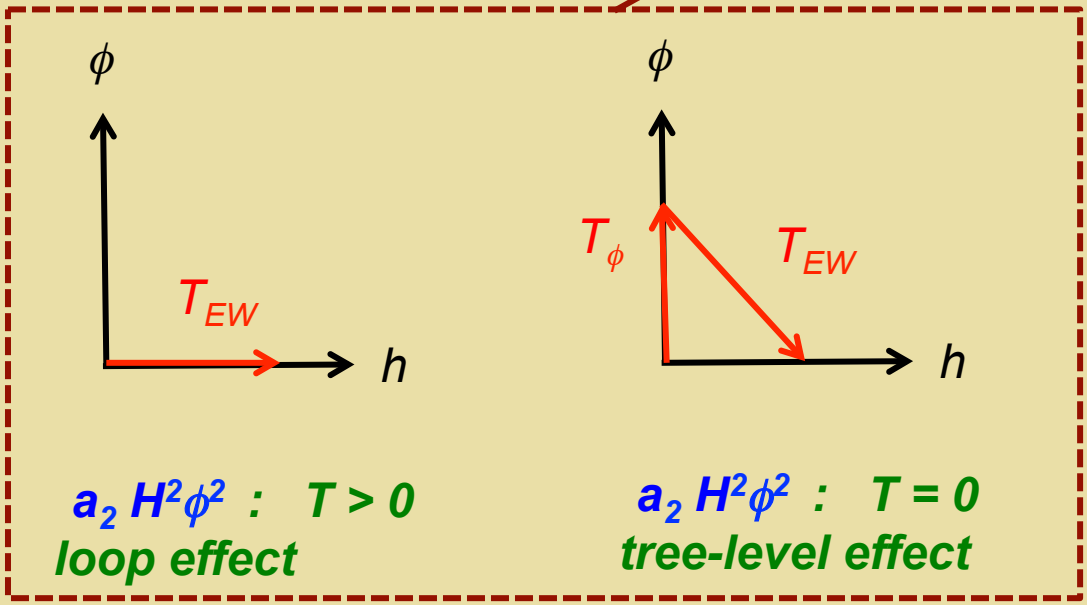

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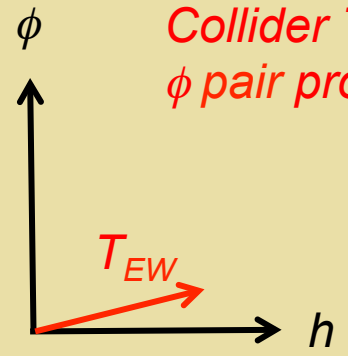

Collider Target: ϕ pair production

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

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···but need energy

Higgs Boson Properties

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

- $\Gamma(h \rightarrow \gamma\gamma)$

$H^2\phi^2$ Barrier ?

- Higgs signal strengths
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First Order EWPT from BSM Physics

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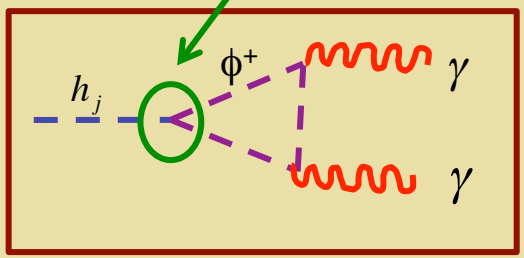
ϕ : EW Multiplet



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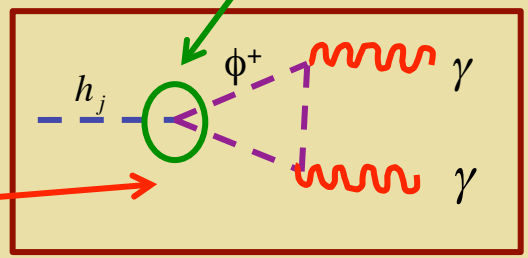
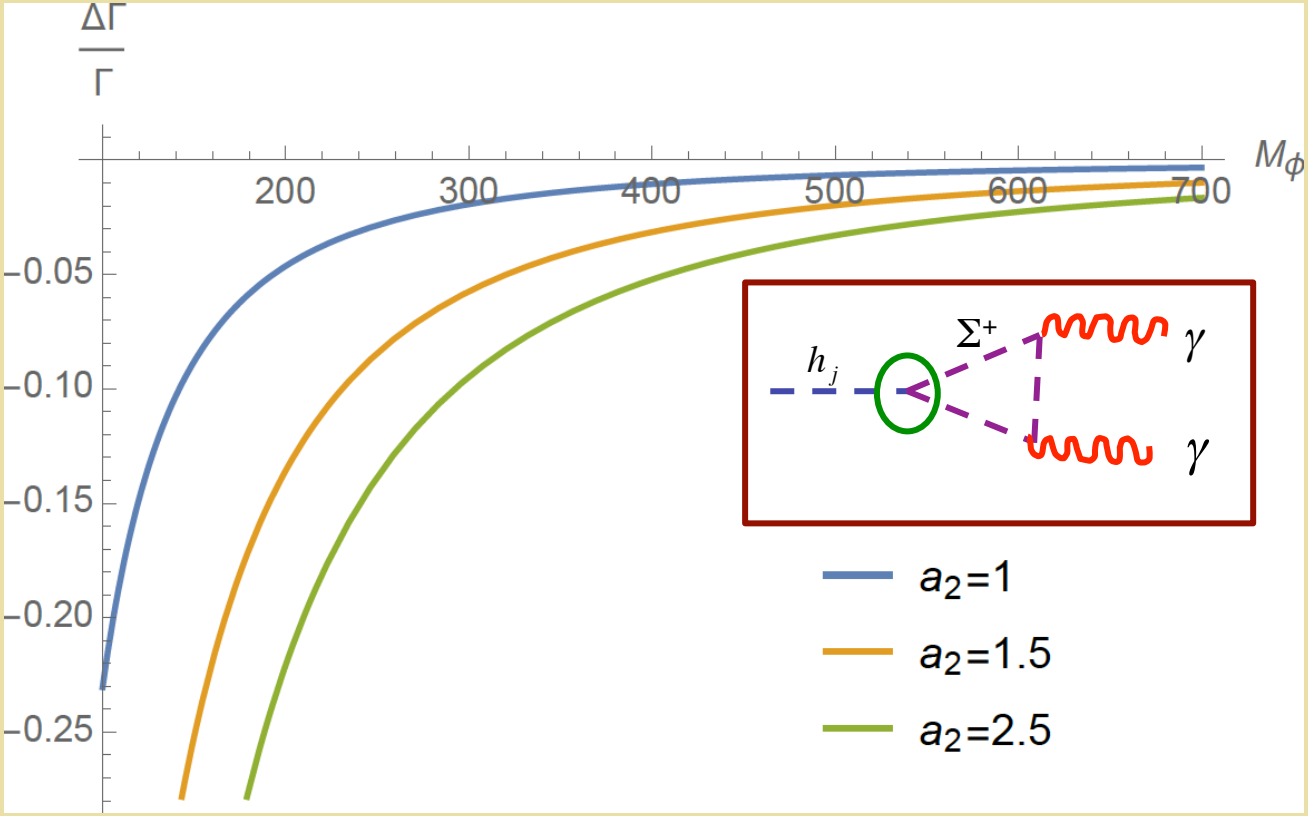


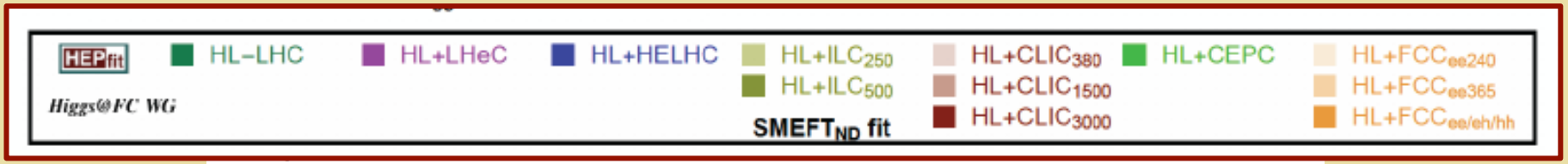
Collider Target:
Precision

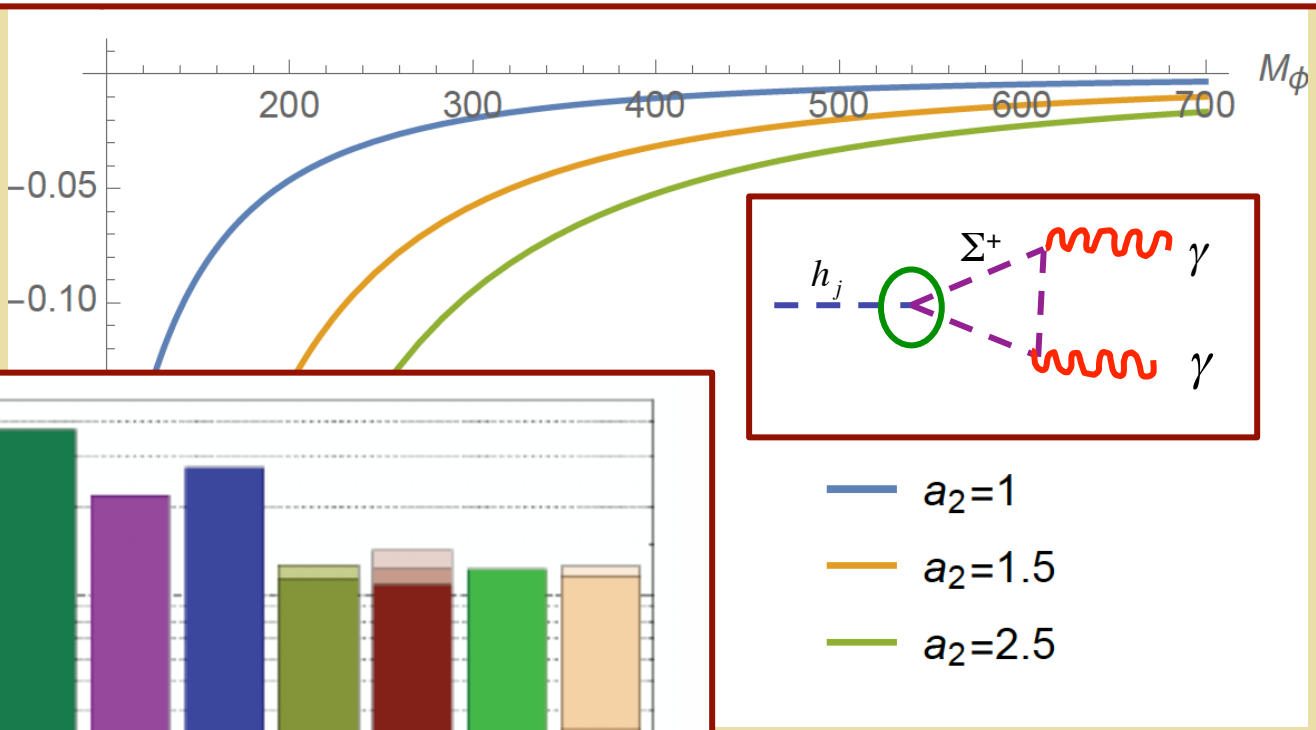
$H \to \gamma\gamma$: Is There a Barrier ?



EWPT → Decrease in rate

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





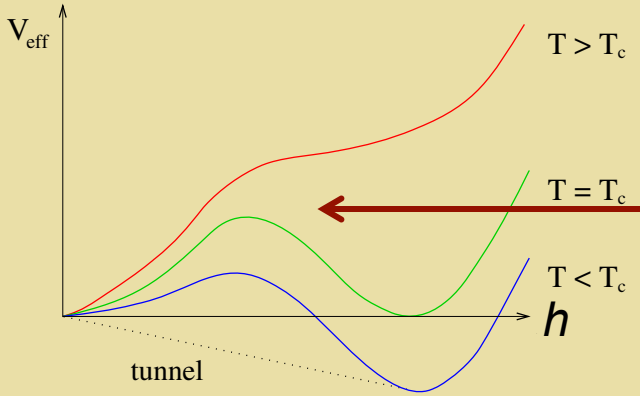
Thanks: M. Cepeda

First Order EWPT from BSM Physics

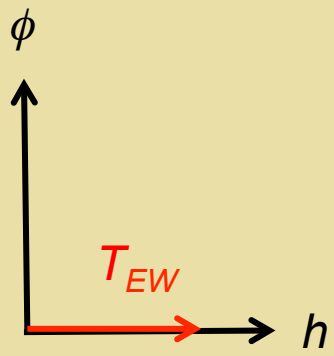
- Thermal $\Gamma(h \rightarrow \gamma\gamma)$
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays

$H^2\phi$ Barrier ?

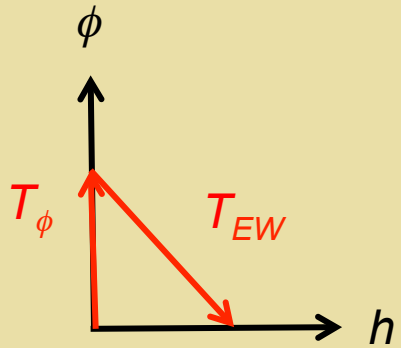
First Order EWPT from BSM Physics



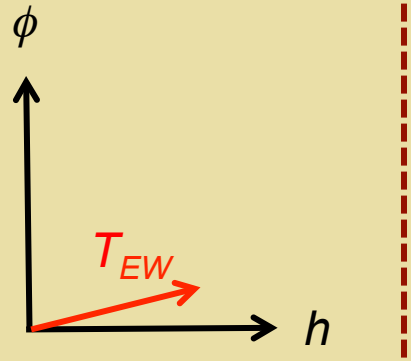
Higgs − ϕ^0 Mixing



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



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



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

First Order EWPT from BSM Physics

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

$H^2\phi$ Barrier ?

H-ϕ Mixing

First Order EWPT from BSM Physics

- Thermal $\Gamma(h \rightarrow \gamma\gamma)$
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- Single ϕ production

$H^2\phi$ Barrier ?

H-ϕ Mixing

Strong First Order EWPT

- ***Prevent baryon number washout***
- ***Observable GW***

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Strong First Order EWPT

- ***Prevent baryon number washout***
- ***Observable GW***

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

Strong First Order EWPT

- ***Prevent baryon number washout***
- ***Observable GW***

Collider Target: Precision and single ϕ production

$$\frac{|a_1|}{2\lambda T_{\rm EW}} \gtrsim 1$$

$$|\sin\theta| \gtrsim 0.01$$

$$|\Delta\lambda/\lambda| \gtrsim 0.003$$

First Order EWPT from BSM Physics

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

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

See this talk ahead & Z. Liu Tuesday

III. Models & Phenomenology

Model Illustrations

Simple Higgs portal models:

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

Model Illustrations

Simple Higgs portal models:

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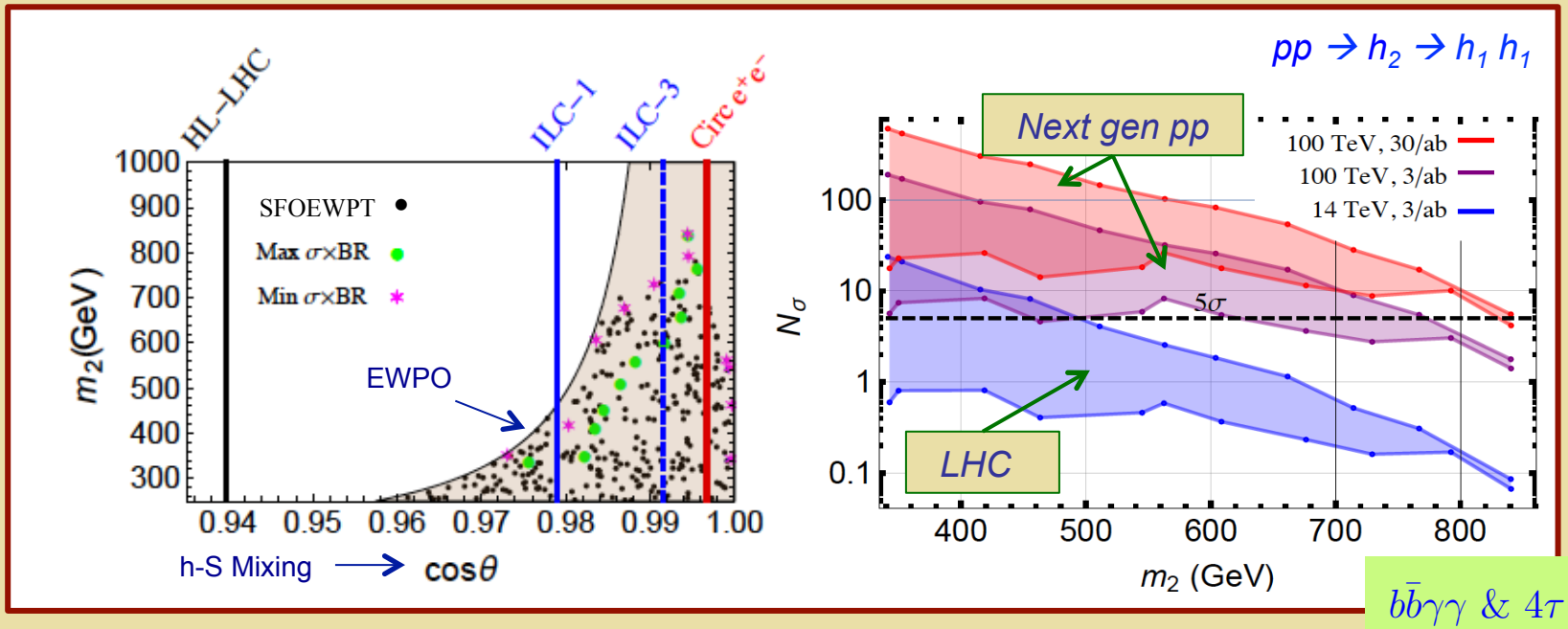
- *Real EW triplet (SM + 3)*

Singlets: Precision & Res Di-Higgs Prod

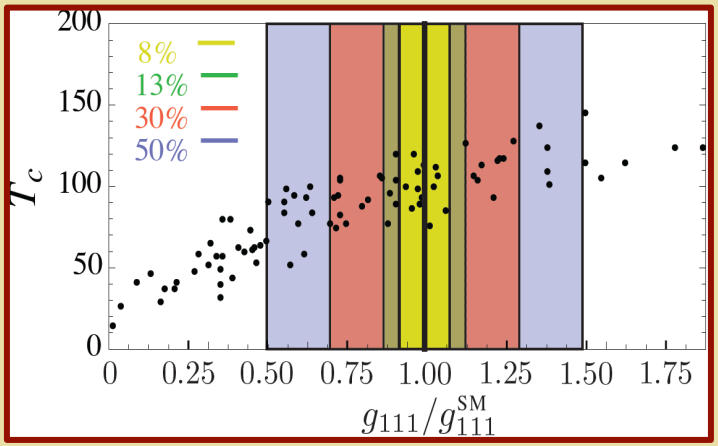
SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

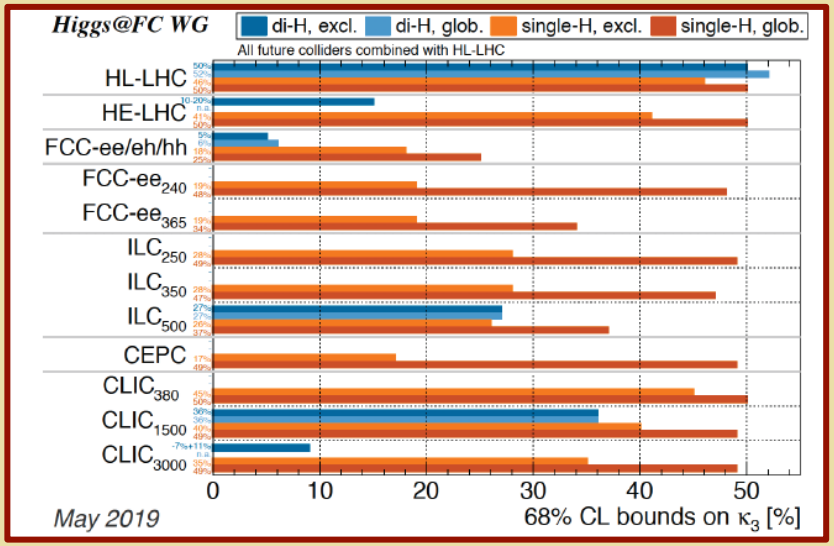


Kotwal, No, R-M, Winslow 1605.06123

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

Singlets: Higgs Self Coupling

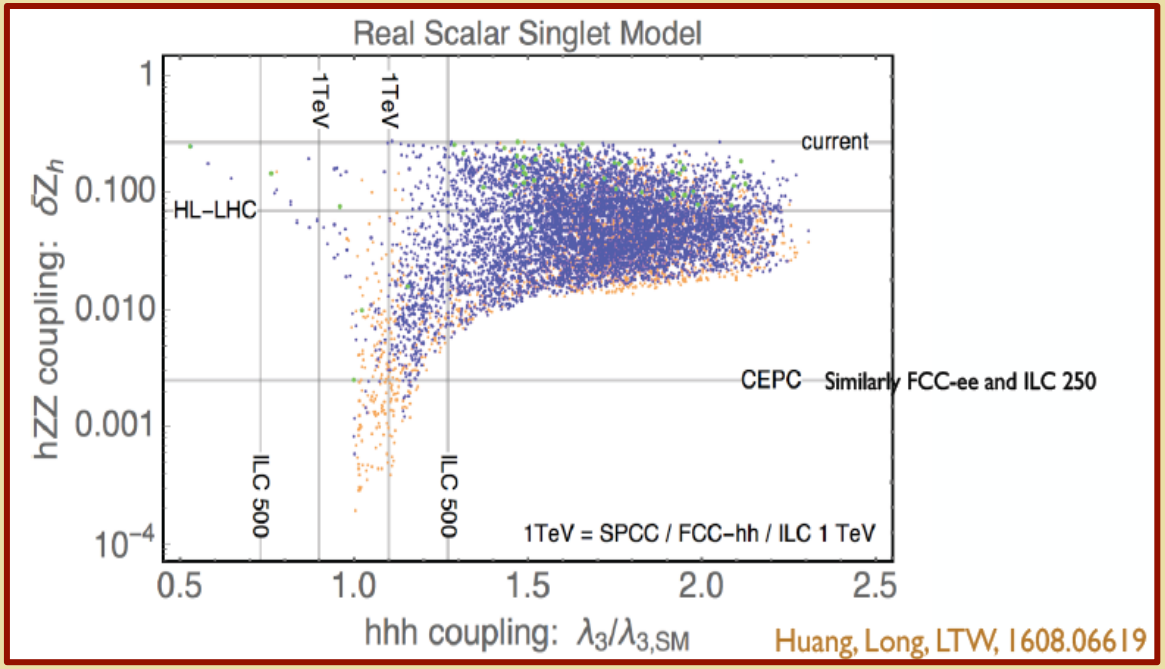




- *Profumo, R-M, Wainwright, Winslow: 1407.5342;*
- *see also Noble & Perelstein 0711.3018*

Thanks: M. Cepeda

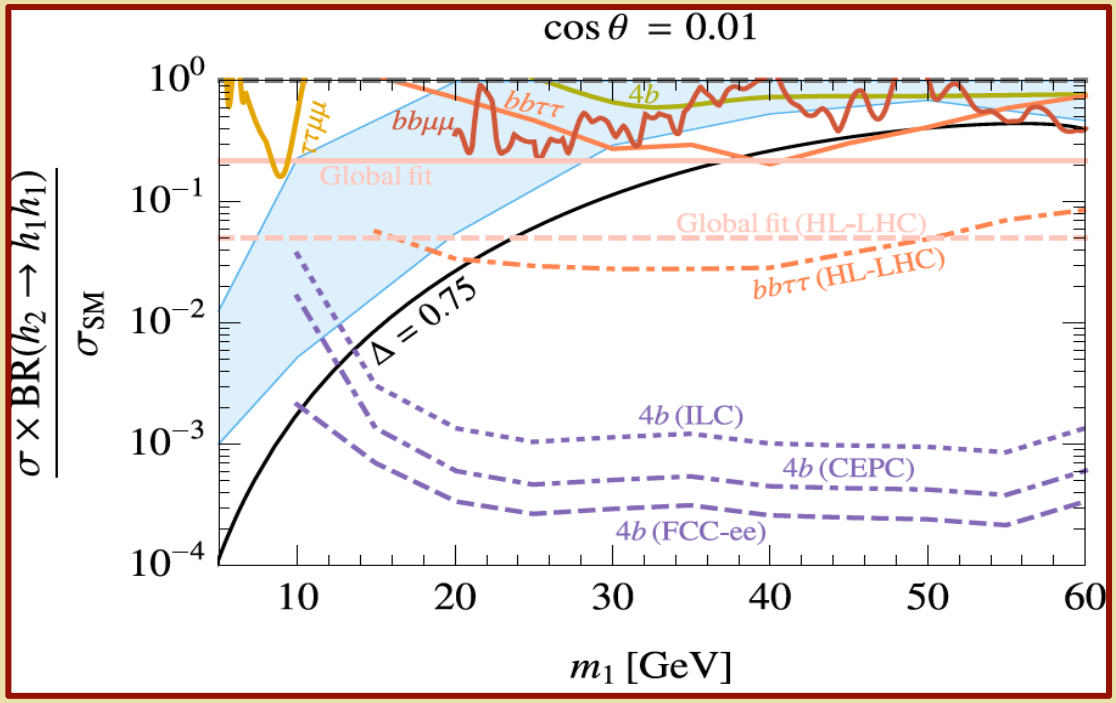
Singlets: Associated Production



Huang, Long, Wang 2016

Singlets: Exotic Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

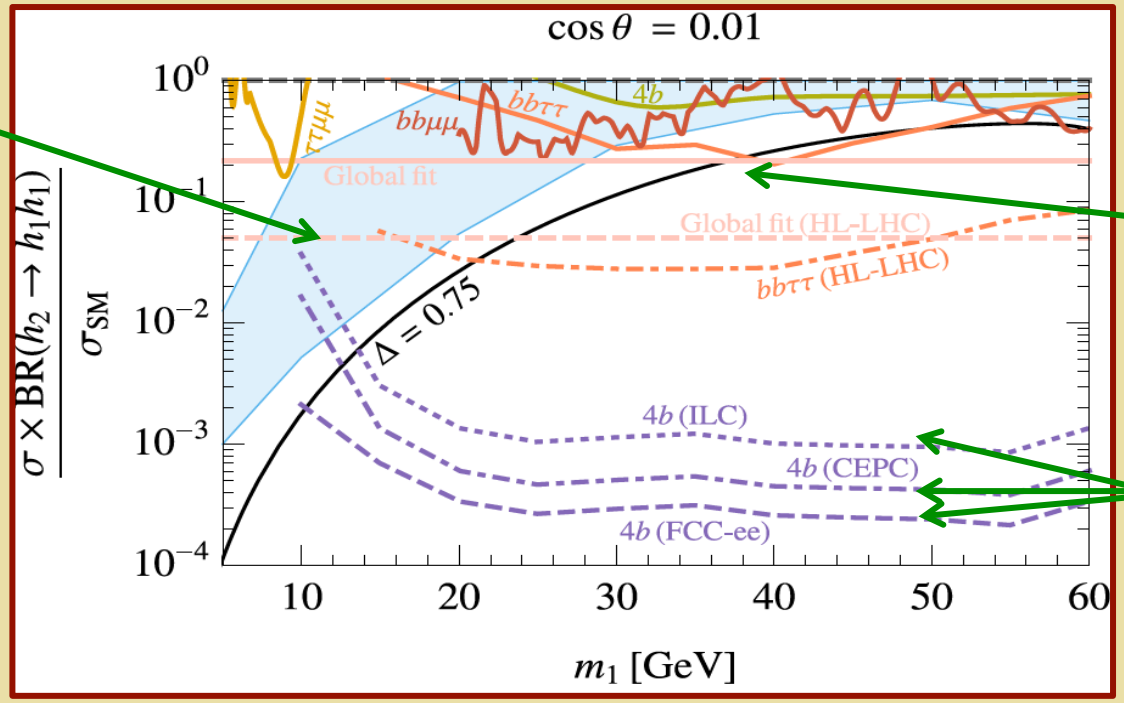


J. Kozaczuk, MR-M, J. Shelton
1911.NNNNN

Singlets: Exotic Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical



EWPT viable: Semi analytic

Future e^+e^-

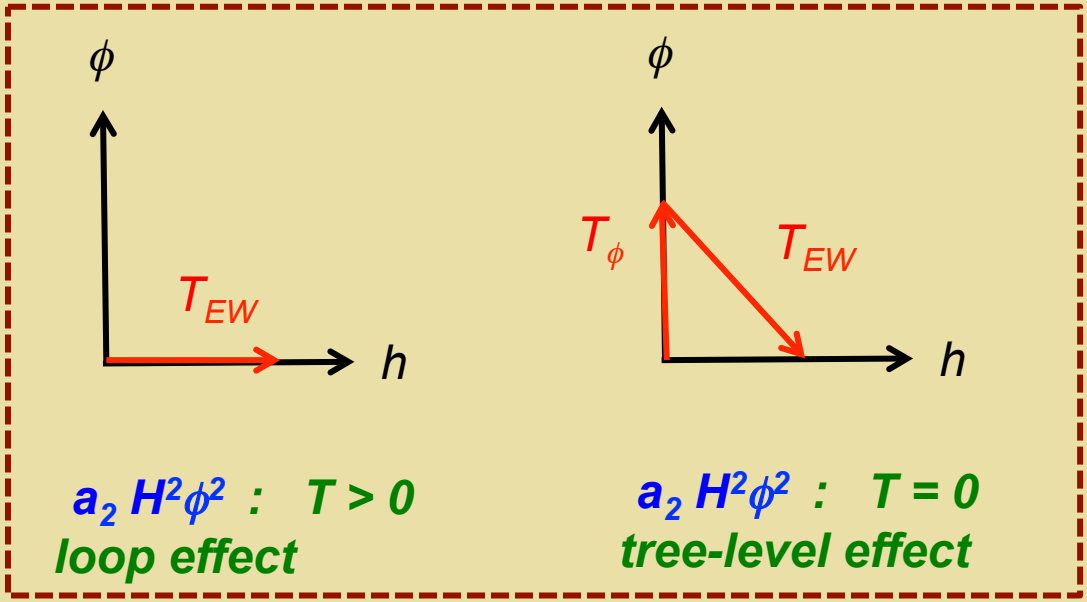
J. Kozaczuk, MR-M, J. Shelton
1911.NNNNN

Model Illustrations

Simple Higgs portal models:

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

Real Triplet



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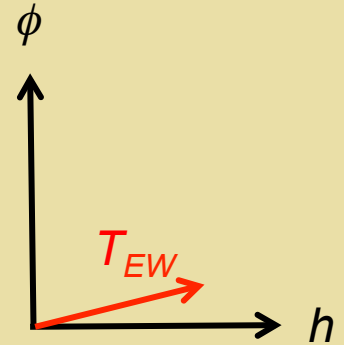
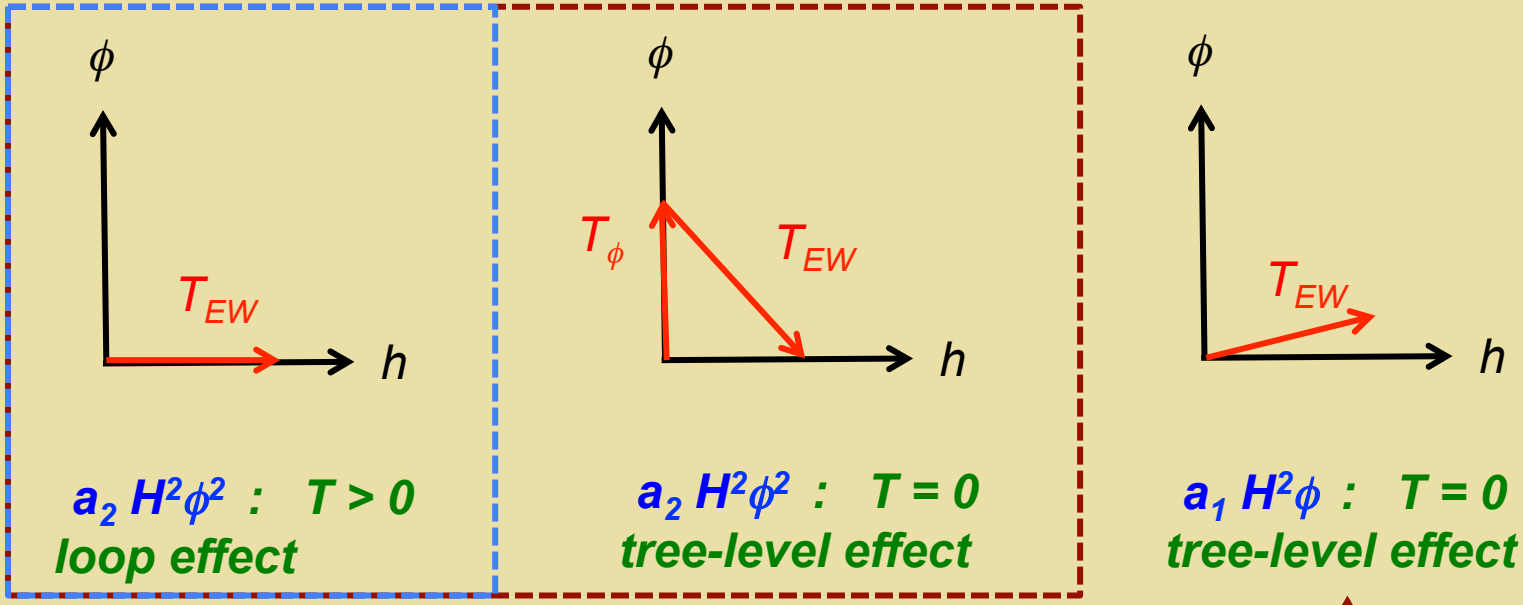
tree-level effect



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

EW precision tests → too tiny

Real Triplet

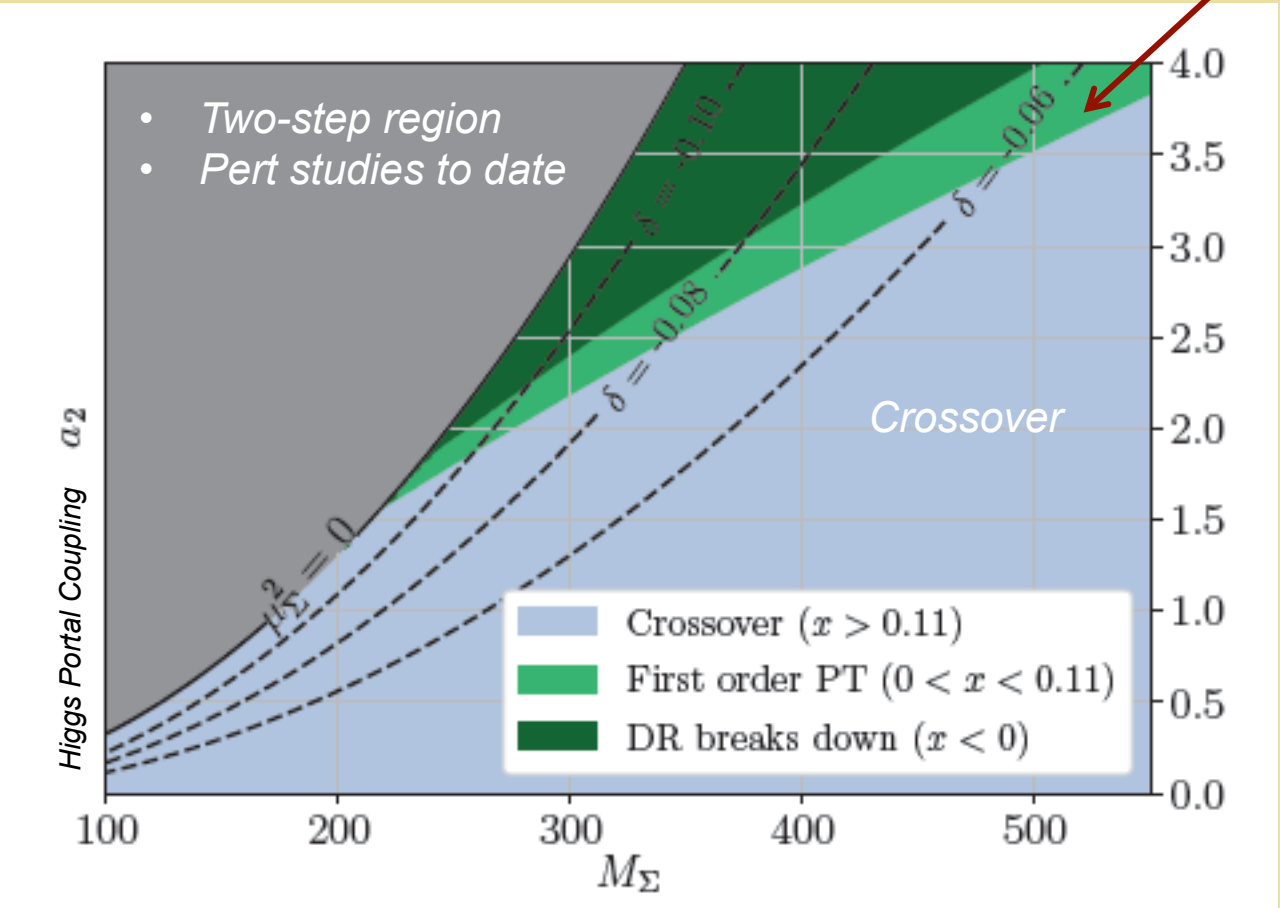


Non-perturbative results

EW precision tests → too tiny

Real Triplet: One-Step EWPT

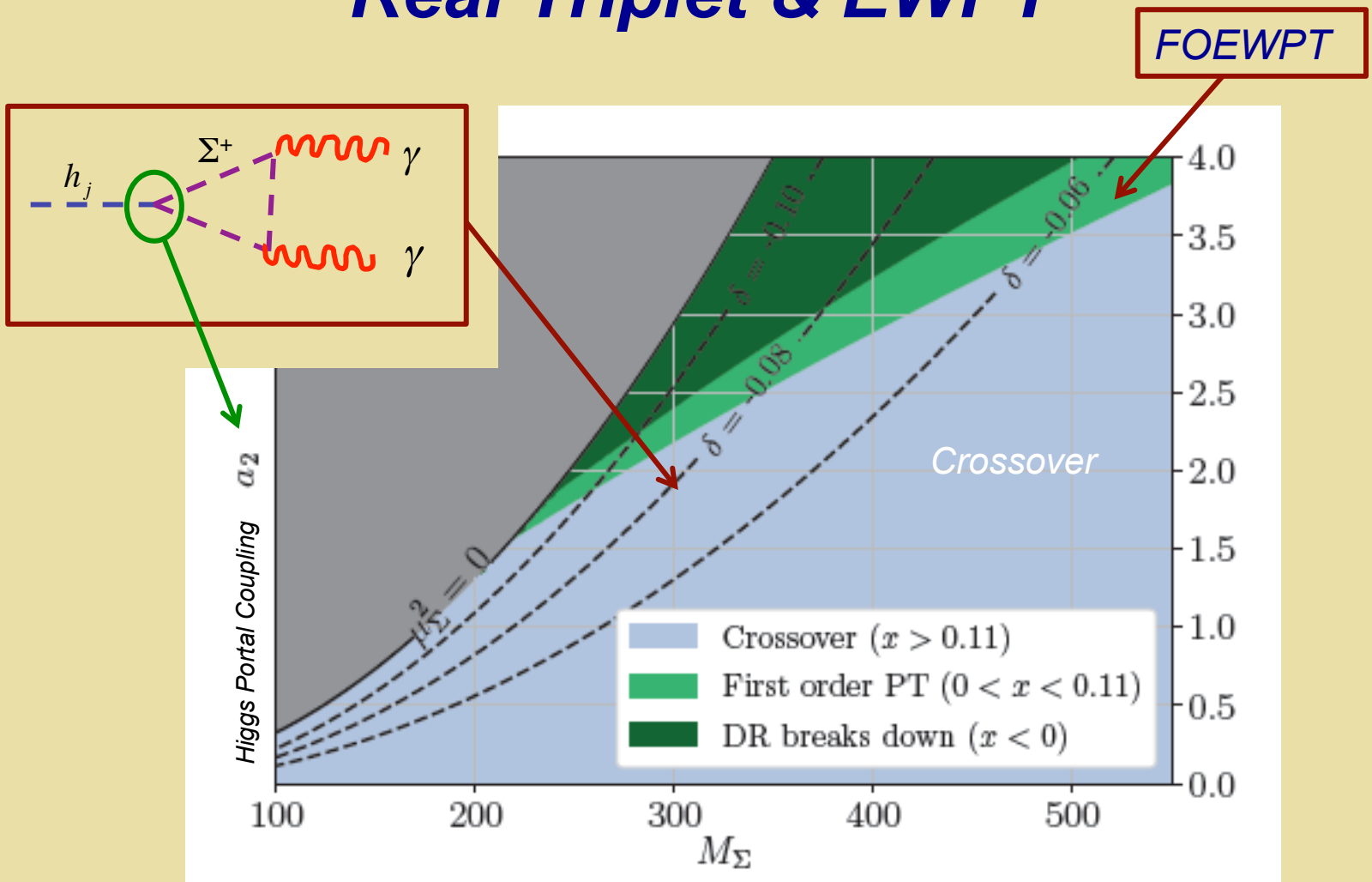
FOEWPT



- One-step
- Non-perturbative

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

Real Triplet & EWPT



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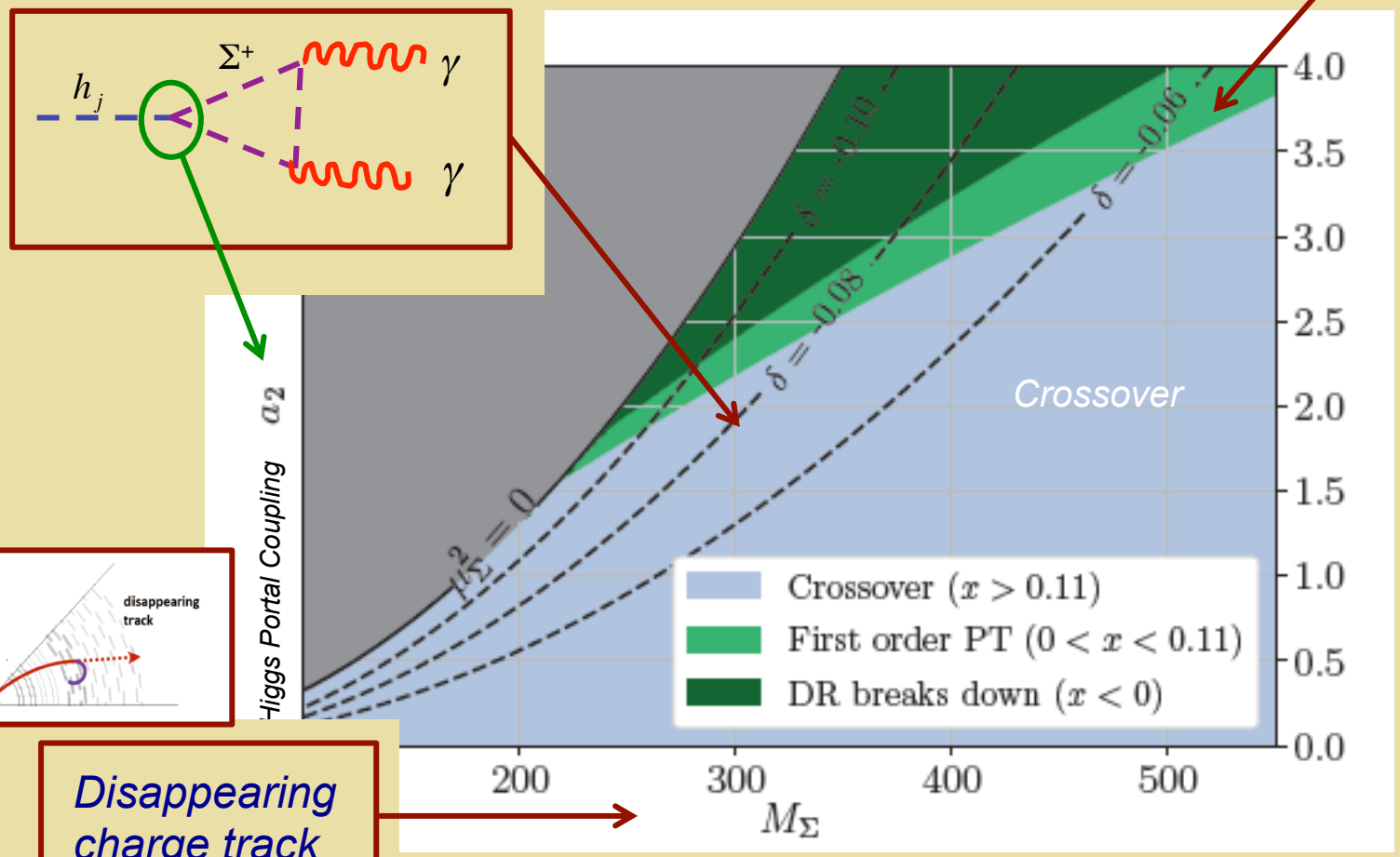
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT

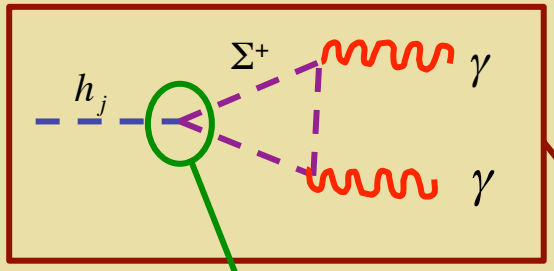


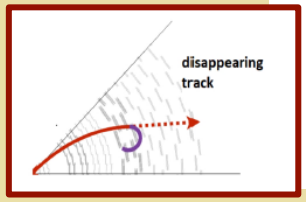
Disappearing charge track

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

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

Real Triplet & EWPT





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

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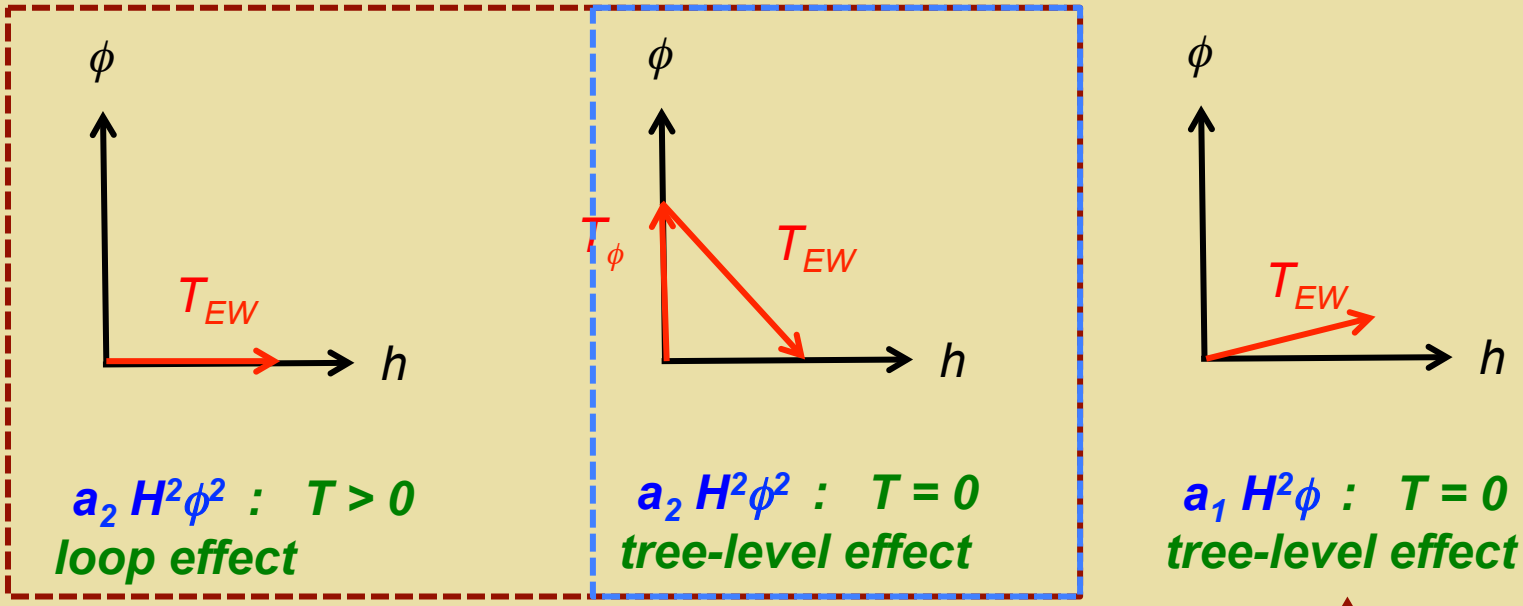

Pert theory: back-up slides

EW precision tests → too tiny

Higher Dim Operators: $(\phi^+\phi)^6$

$$V(H) = \mu^2|H|^2 + \lambda|H|^4 - c_6|H|^6$$

$$\frac{1}{(0.89\ \mathrm{TeV})^2} < -c_6 < \frac{1}{(0.55\ \mathrm{TeV})^2}$$

→ *Implications for* σ_{Zh}

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

IV. Outlook

- *Determining the thermal history of EWSB is field theoretically interesting in its own right and of practical importance for baryogenesis and GW*

- *The scale T_{EW} → any new physics that modifies the SM crossover transition to a first order transition must live at M < 1 TeV*

- *Searches for new scalars and precision Higgs measurements at the LHC and prospective next generation colliders could conclusively determine the nature of the EWSB transition*

Back Up Slides

First Order EWPT from BSM Physics

- ***Thermal loops involving new bosons***
- ***T=0 loops (CW Potential)***
- ***Change tree-level vacuum structure***

First Order EWPT from BSM Physics

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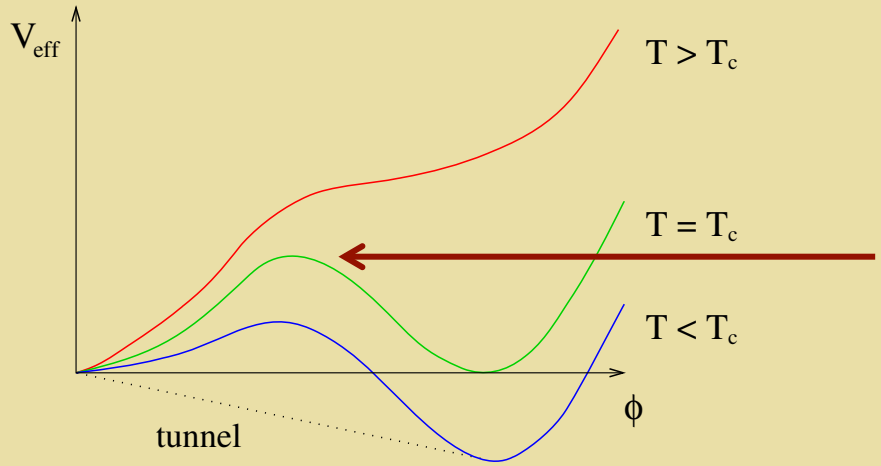
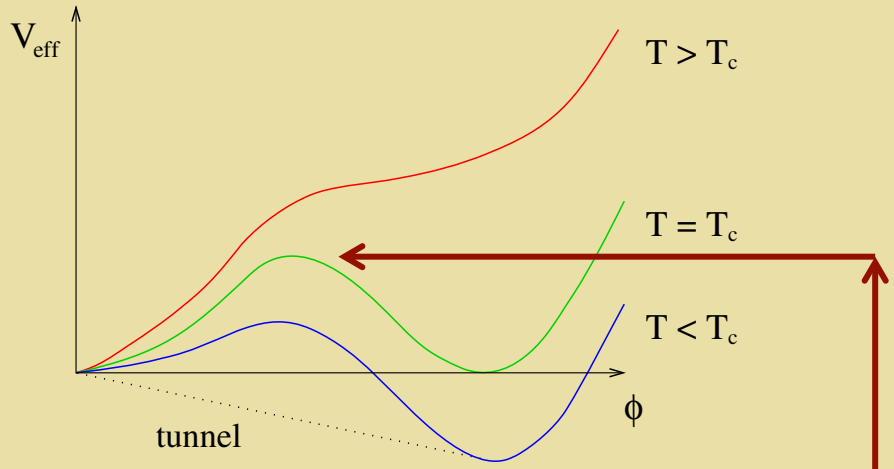
First Order EWPT from BSM Physics



Generate finite-T barrier

First Order EWPT from BSM Physics



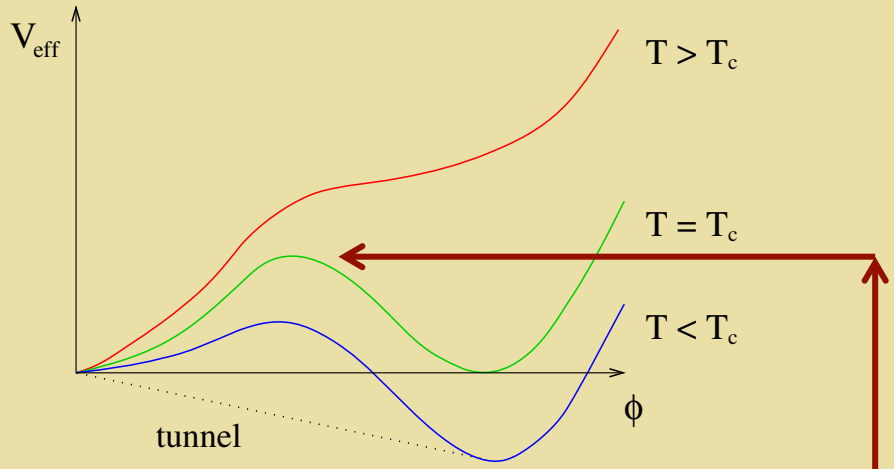
Generate finite-T barrier

$$V(H,\phi)_{T=0} = V(H) + \frac{a_2}{2}\phi^\dagger\phi H^\dagger H + V(\phi)$$

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$V(\phi) = \frac{b_2}{2}\phi^\dagger\phi + \frac{b_4}{4!}(\phi^\dagger\phi)^2$$

First Order EWPT from BSM Physics



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- *Change tree-level vacuum structure*

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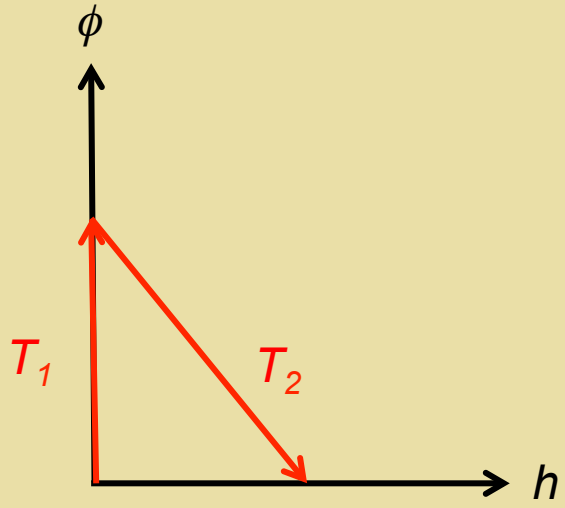
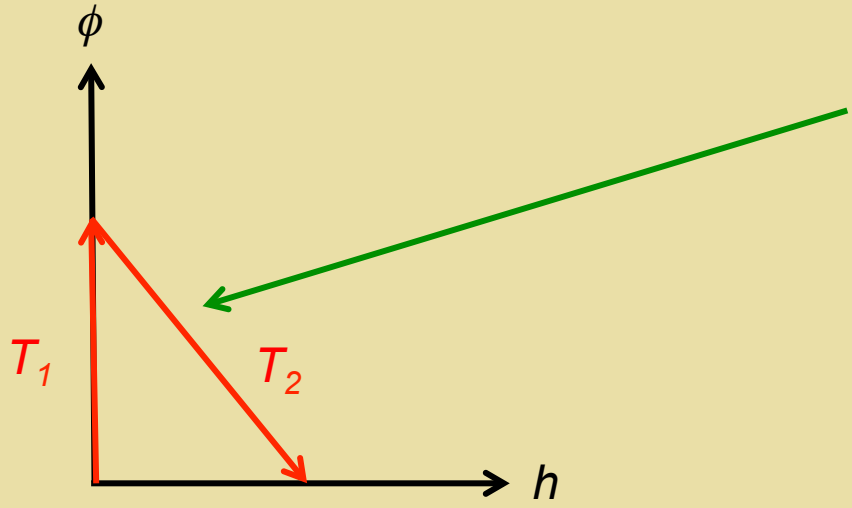
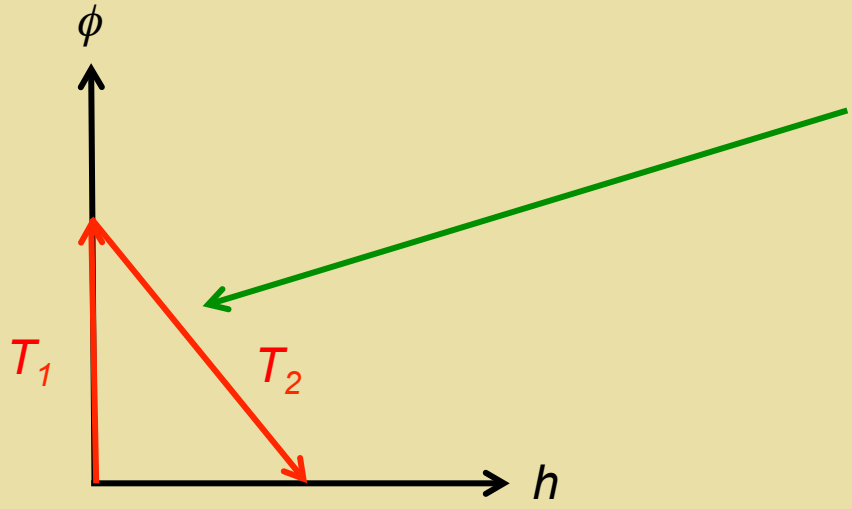


First Order EWPT from BSM Physics



- *Tree-level barrier:* $a_2\, \phi^+\phi\, H^+H$
- *Want* $T_1 > T_2 \sim T_{EW}$

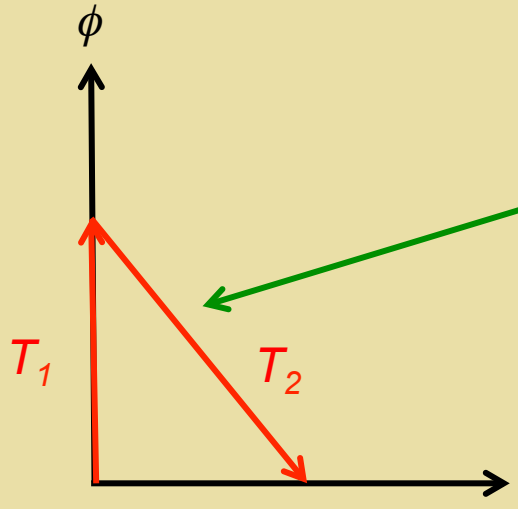
First Order EWPT from BSM Physics



- *Tree-level barrier: $a_2\, \phi^+\phi\, H^+H$*
- *Want $T_1 > T_2 \sim T_{EW}$*

$$V(\varphi, T) = \frac{1}{2}\left[-|b_2| + \frac{T^2}{6}\left(a_2 + \frac{3}{2}b_4\right)\right]\varphi^2 + \frac{b_4}{4!}\varphi^4$$

First Order EWPT from BSM Physics



- *Tree-level barrier: $a_2\,\phi^+\phi\,H^+H$*
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Negative for $T_1 > T_2 \sim T_{EW}$

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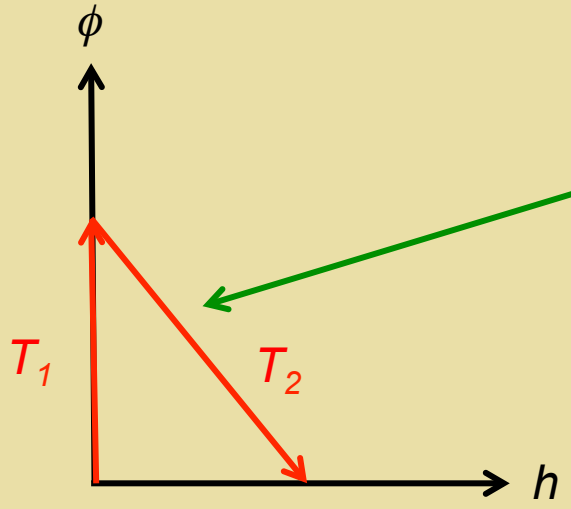

- *Tree-level barrier: $a_2\,\phi^+\phi\,H^+H$*
- *Want $T_1 > T_2 \sim T_{EW}$*

$$M_\phi(T=0) < \left[\frac{a_2}{4}v^2 - \frac{T_{\rm EW}^2}{6}\left(a_2 + \frac{3}{2}b_4\right)\right]^{1/2}$$

M_ϕ < 350 GeV for perturbative a_2, b_4

T_{EW} : A Mass Scale for Colliders

- *Foregoing arguments: good up to factor of ~ 2 → M_ϕ < 800 GeV (-ish)*
- *QCD production: LHC exclusion → ϕ is colorless*
- *Electroweak or Higgs portal (h-ϕ mixing…) production → σ_{PROD} ~ (1- 500) fb (LHC) and (0.1-25) pb (100 TeV pp)*
- *Precision Higgs studies: see ahead*

First Order EWPT from BSM Physics

- Thermal $\Gamma(h \to \gamma\gamma)$

- Higgs signal strengths
- Higgs self-coupling

$H^2\phi$ Barrier ?

H-ϕ Mixing

Z_2 - breaking

$$\Delta V_0(H,\phi) = \frac{b_3}{3!}\phi^3 + \frac{a_1}{2}H^\dagger\phi H + \text{h.c.}$$

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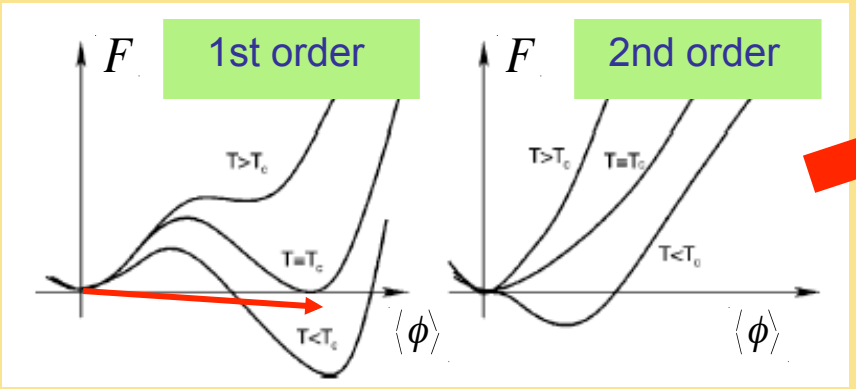
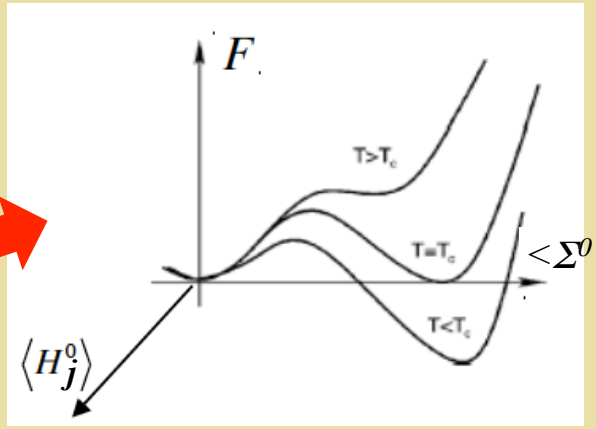
EW Multiplets: EWPT





Increasing m_h →

← *New scalars*

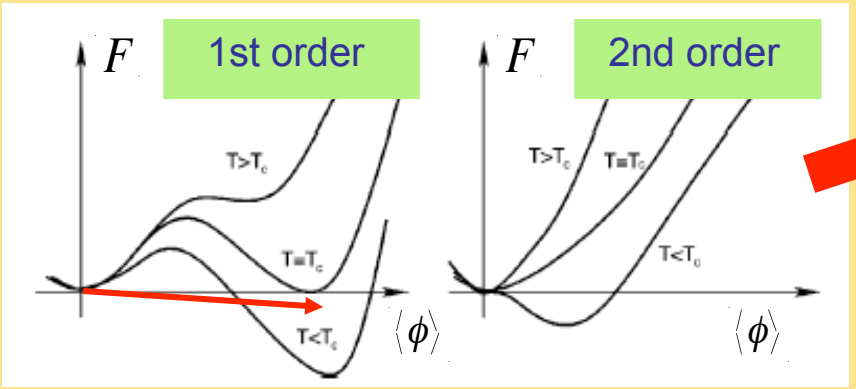
- *Thermal loops*
- *Tree-level barrier*

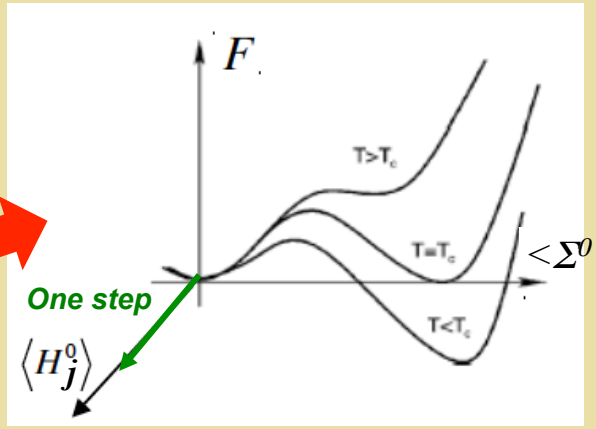
Illustrate with real triplet: $\Sigma \sim (1,3,0)$

$H^2\phi^2$ Barrier ?

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

EW Multiplets: One-Step EWPT





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- *One-step: Sym phase → Higgs phase*

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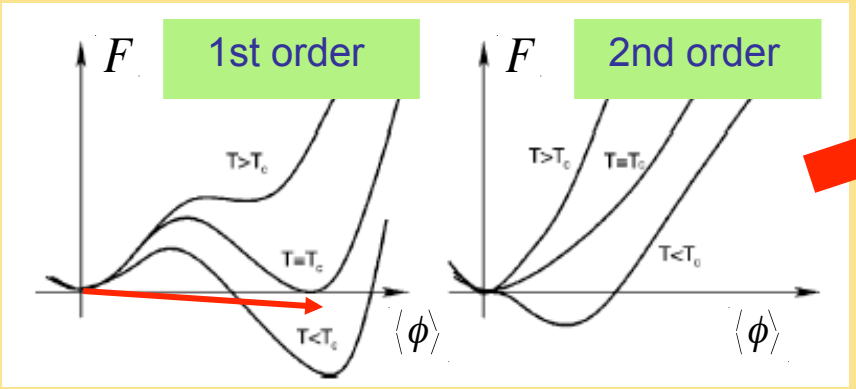
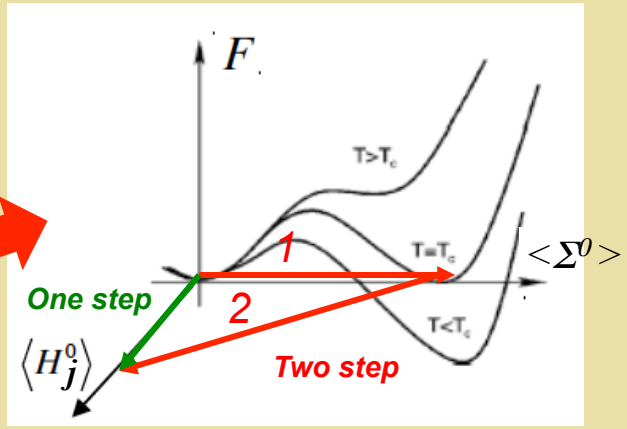




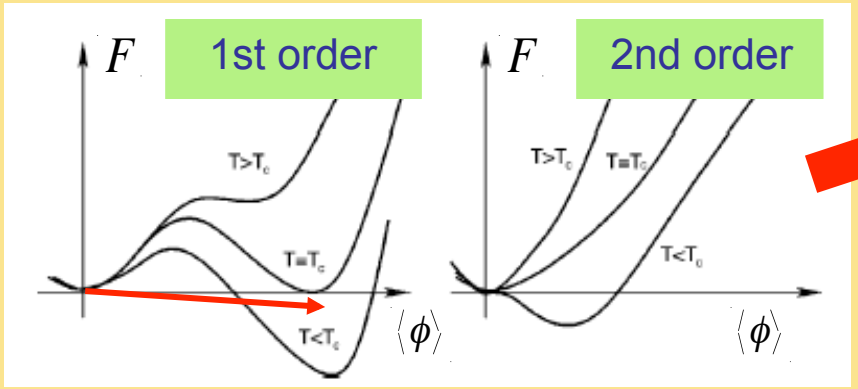
Increasing m_h →

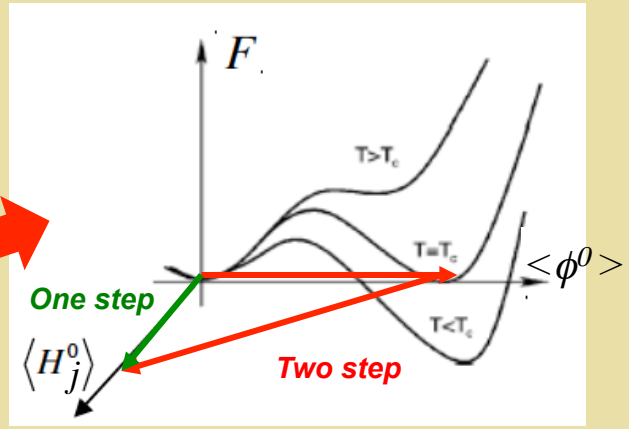
← *New scalars*

- *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

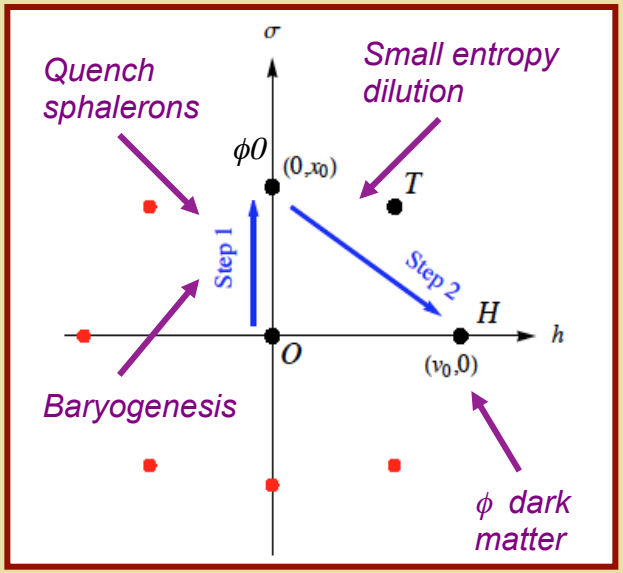




Increasing m_h →

← *New scalars*

- *Step 1: thermal loops*
- *Step 2: tree-level barrier*



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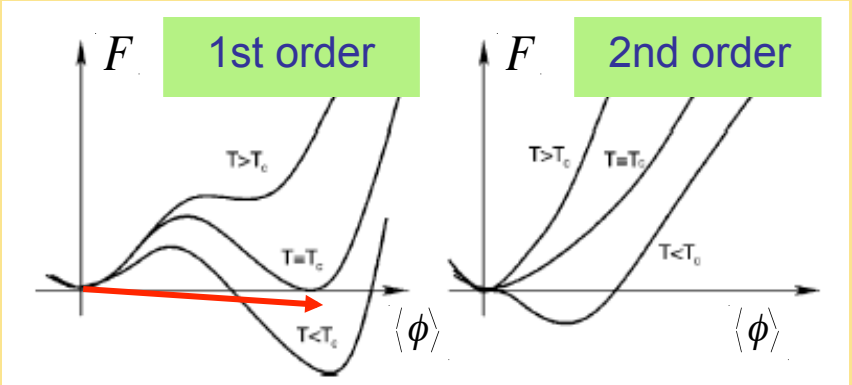
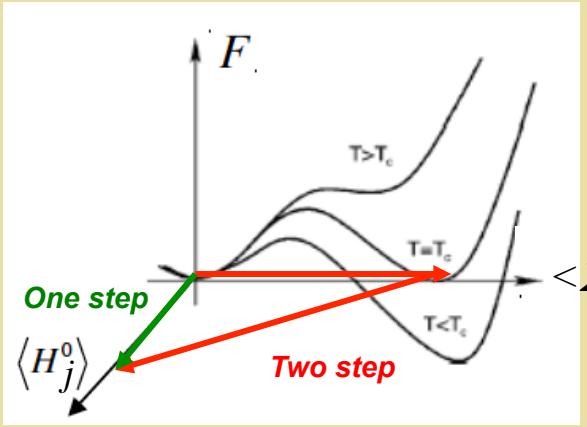
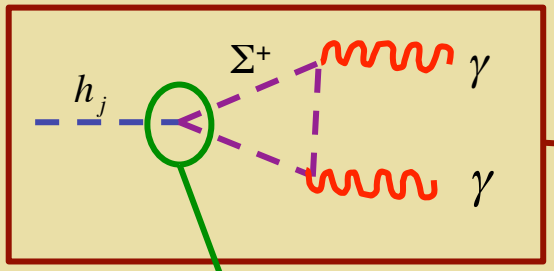
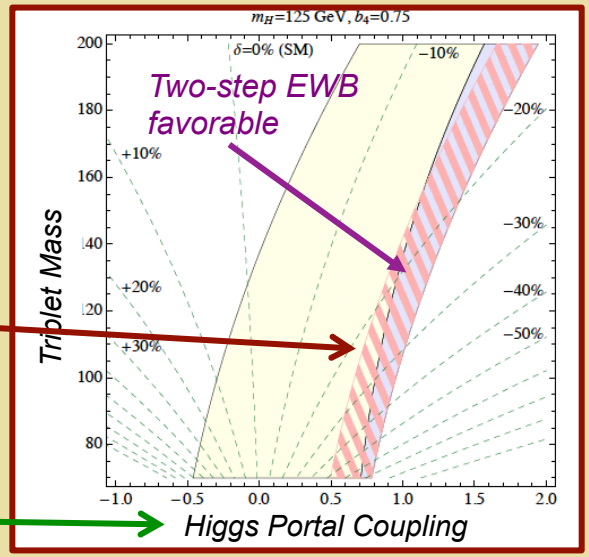




Increasing m_h →



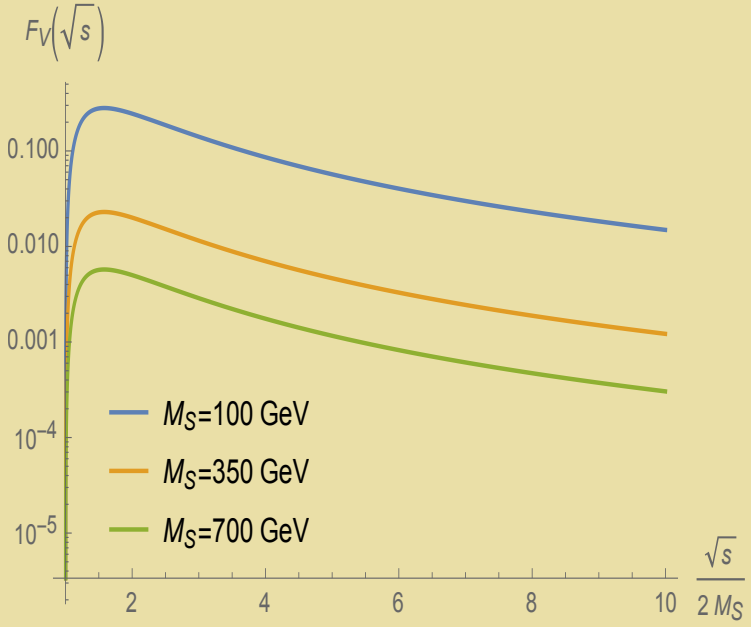


Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

T_{EW} : Direct $\phi^+\phi^-$ Production at LC

$$\hat{\sigma}(f_1\bar{f}_2 \to V^* \to \phi_1\phi_2) = g_\phi^2 \times \mathcal{G}_V \times F_V(\hat{s}, M_\phi)$$

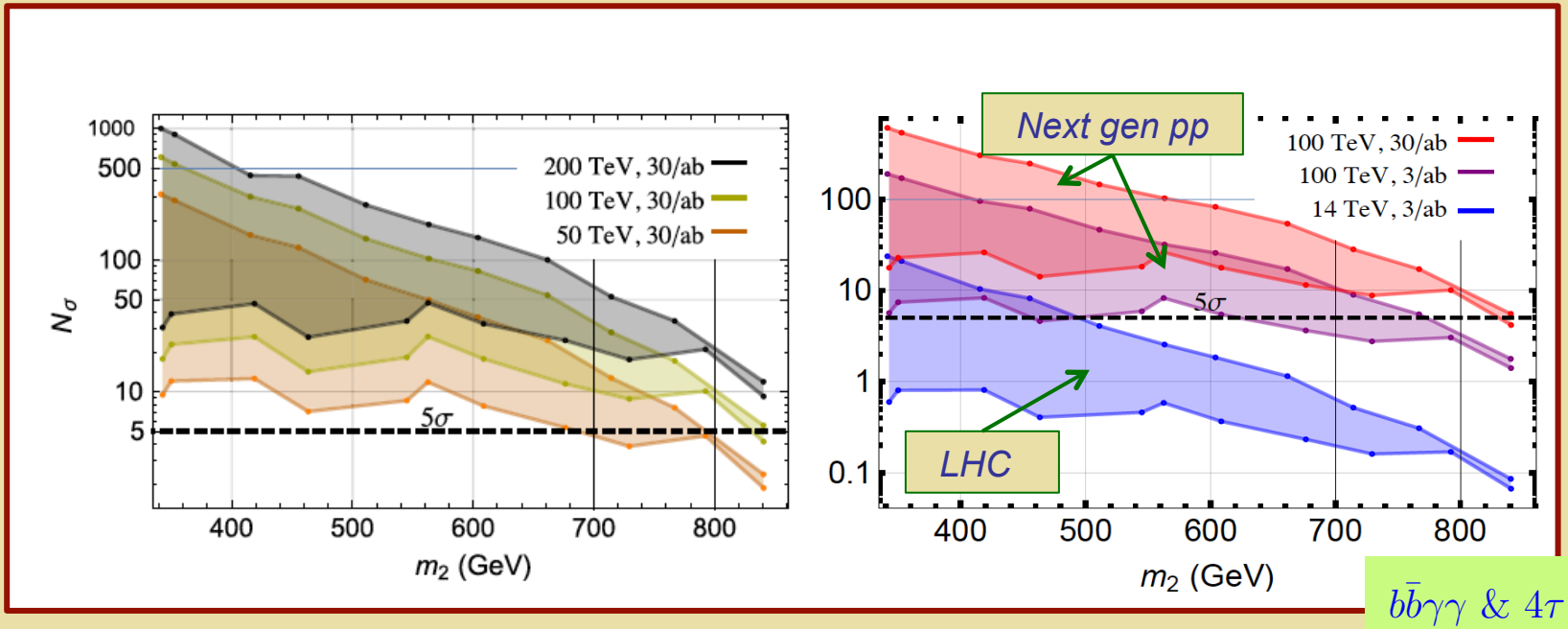
$$\mathcal{G}_V = \left(\frac{g^4}{4\pi}\right)\left(\frac{g_V^2 + g_A^2}{12}\right) v^{-2}$$



Max sensitivity:
E_{CM} ~ 3.4 x M_ϕ

EW Phase Transition: Singlet Scalars

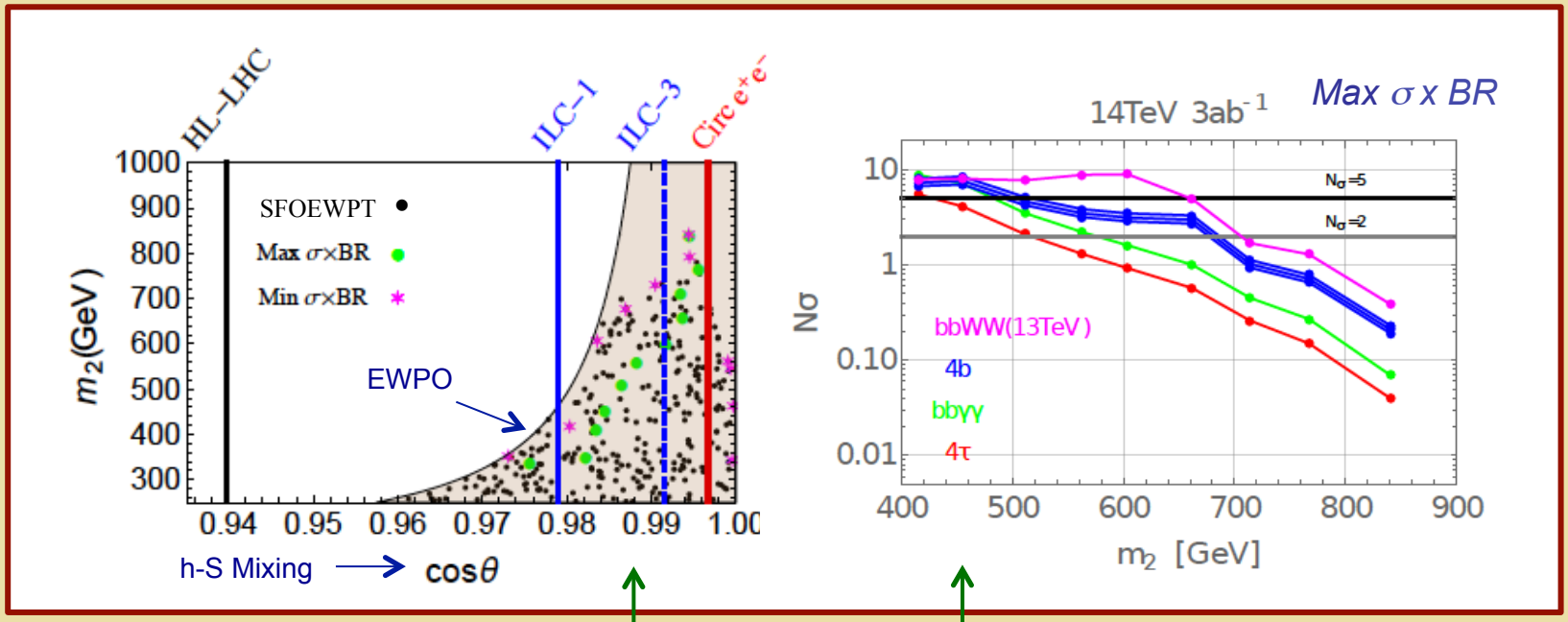
SFOEWPT Benchmarks: Resonant di-Higgs



Kotwal, No, R-M, Winslow 1605.06123

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

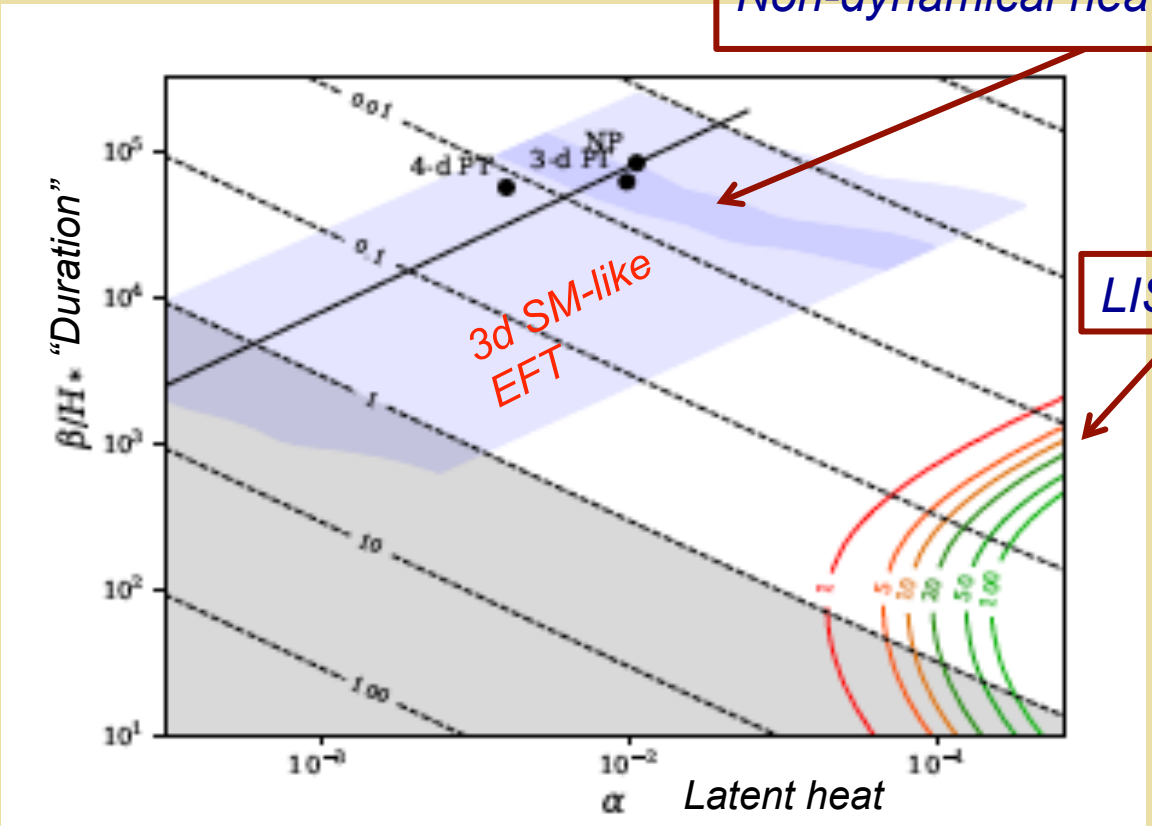


Kotwal, No, R-M, Winslow 1605.06123

Li, R-M, Willocq 1906.05289
See also: Huang et al, 1701.04442

Heavy Real Singlet: EWPT & GW

Non-dynamical heavy BSM scalars

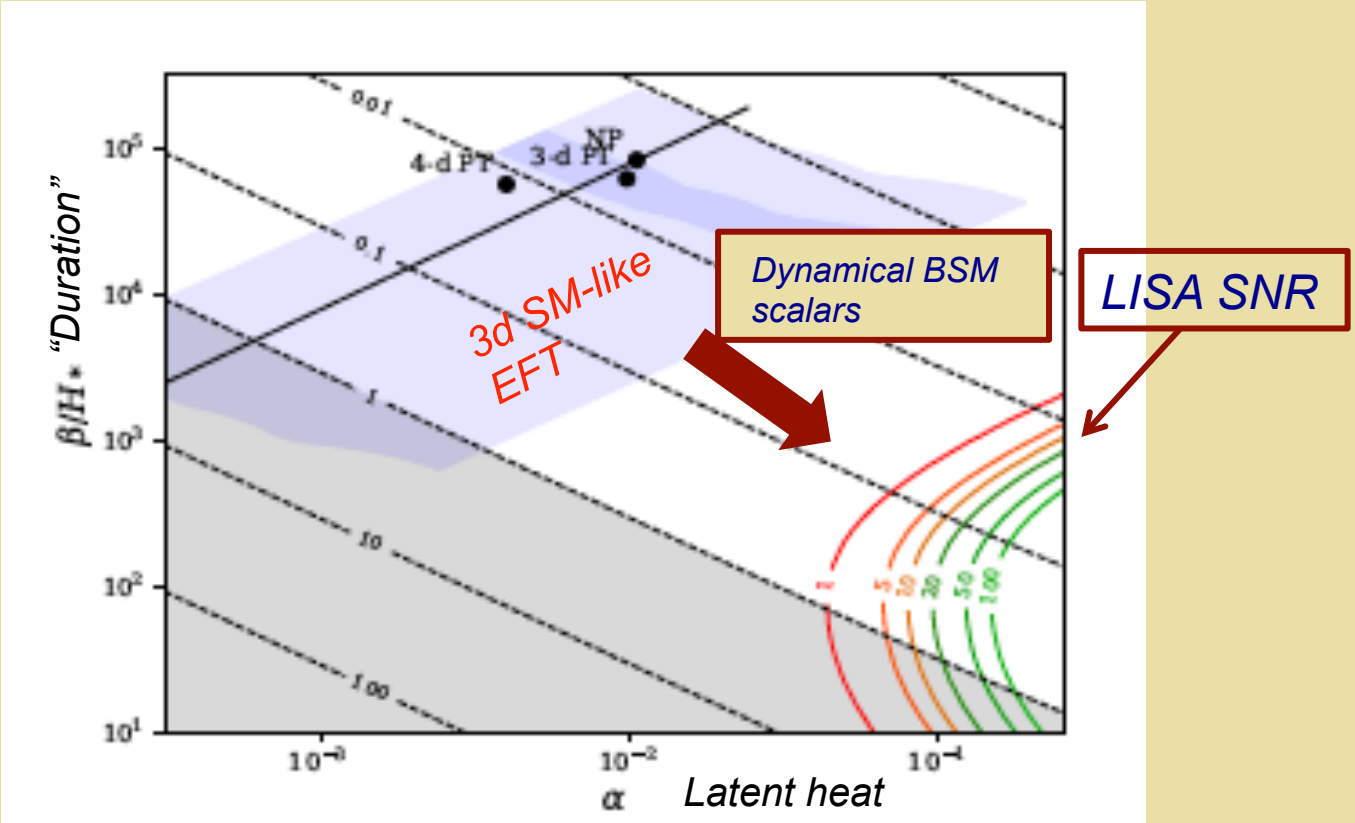


LISA SNR

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
- Non-perturbative