# *The Electroweak Phase Transition: A Collider Target*

M.J. Ramsey-Musolf

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

*My pronouns: he/him/his*

IAS HEP Mini-Workshop
Hong Kong, January 2020

# *Next Gen Colliders: What is the Target?*

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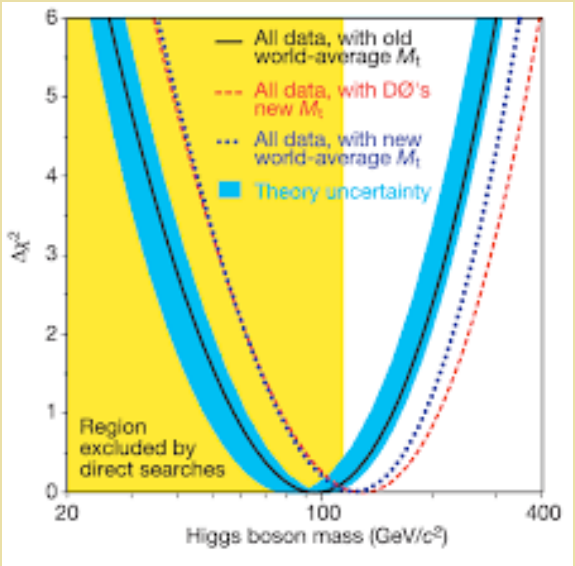
*LHC Target: Higgs*



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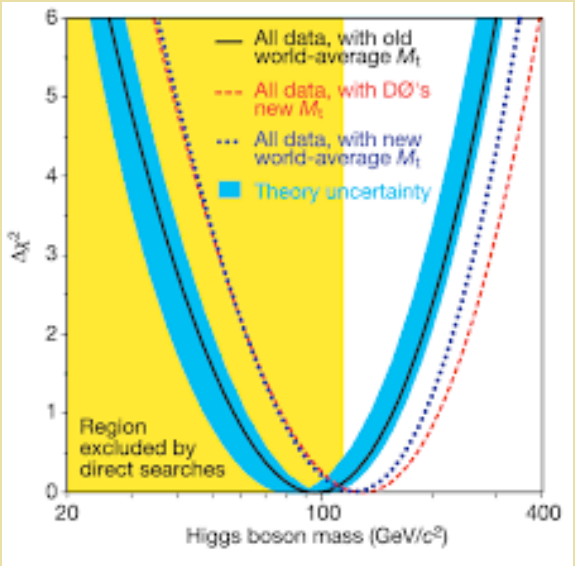


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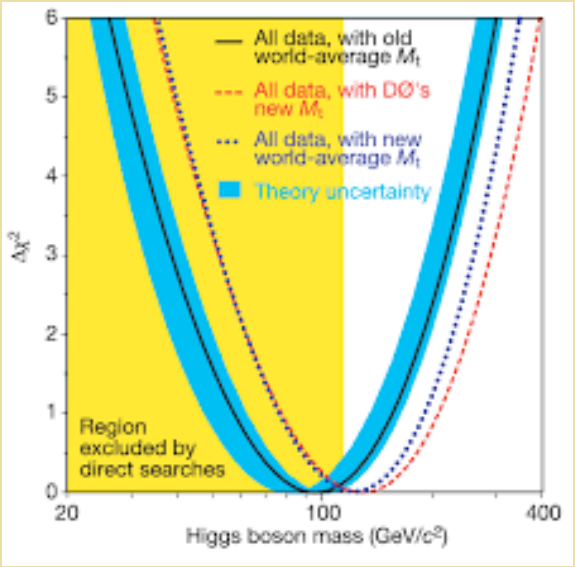
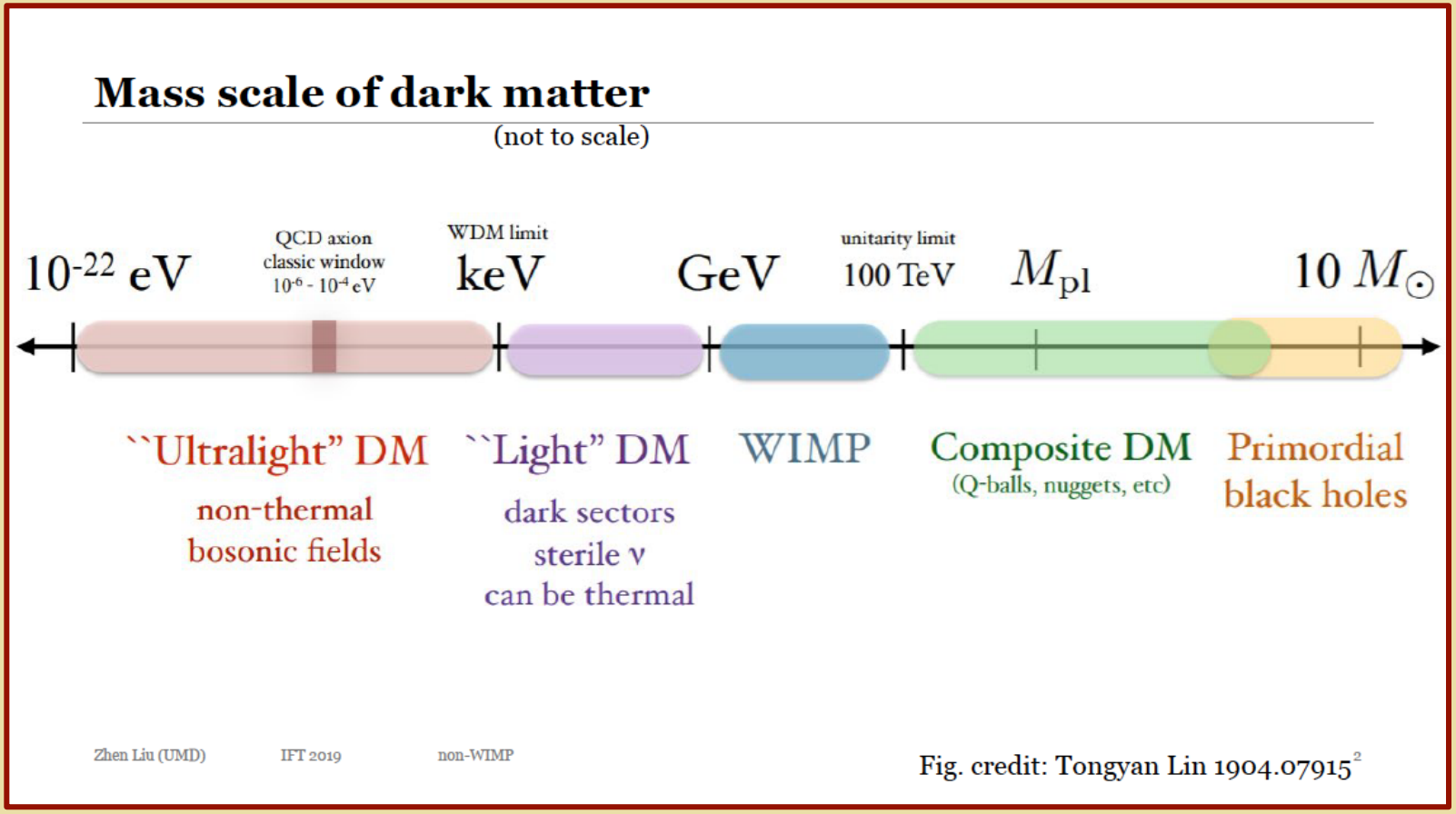



*Next Gen Colliders:*

- *Any definitively answerable questions ?*
- *What CM energy and precision are needed ?*
  - *Naturalness ?*
  - *Origin of $m_\nu$ ?*
  - *Flavor ?*
  - *Dark matter ?*
  - *Baryogenesis ?*

# Dark Matter




*Thanks: Z. Liu*

# Dark Matter

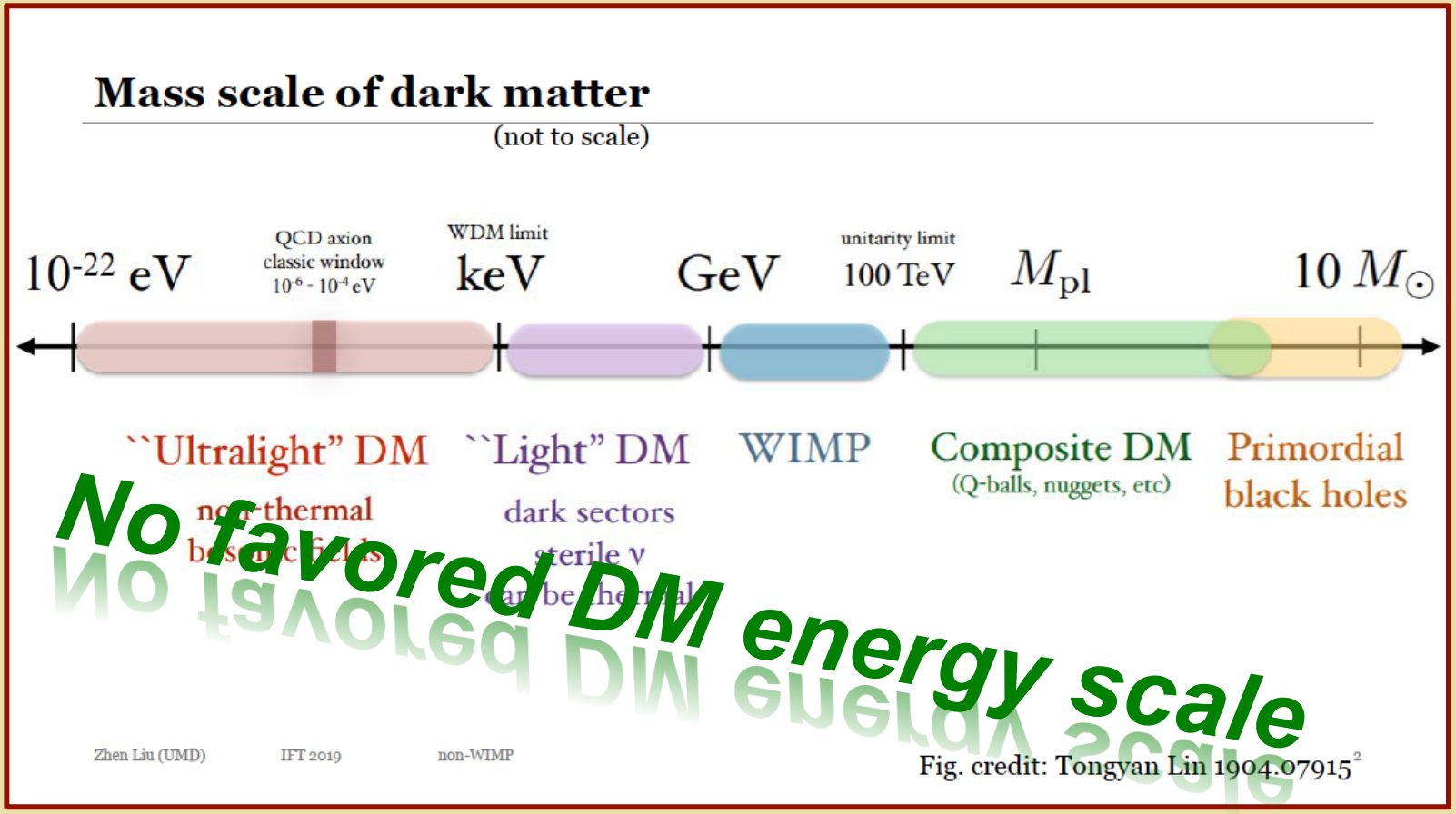



Fig. credit: Tongyan Lin 1904.07915[2]

*Thanks: Z. Liu*

# *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***

# *Key Ideas for this Talk*

***MJRM 1912.07189***

# *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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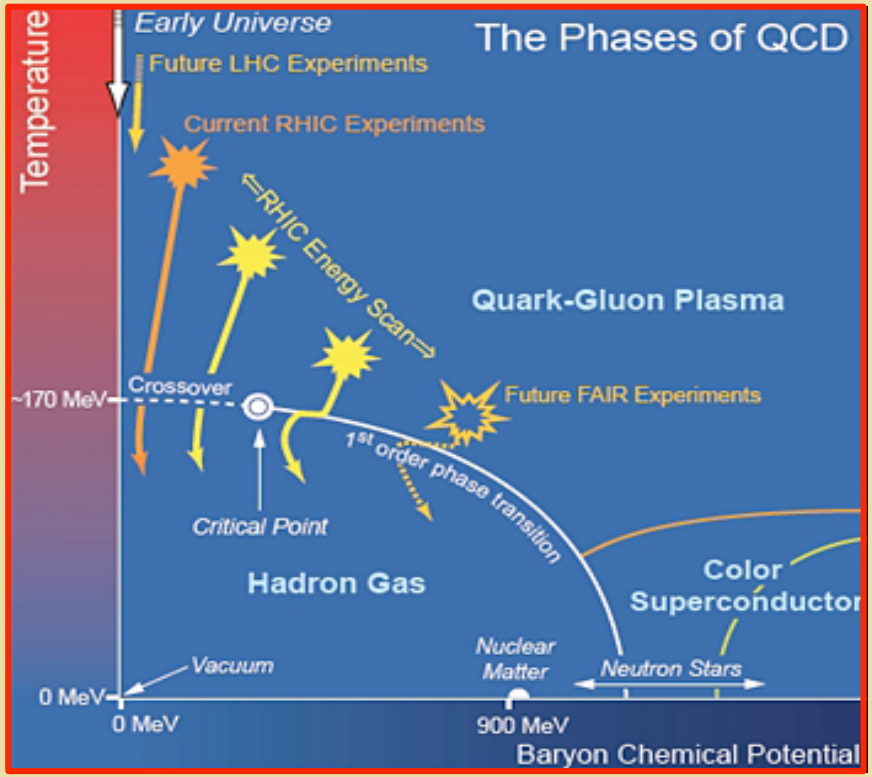
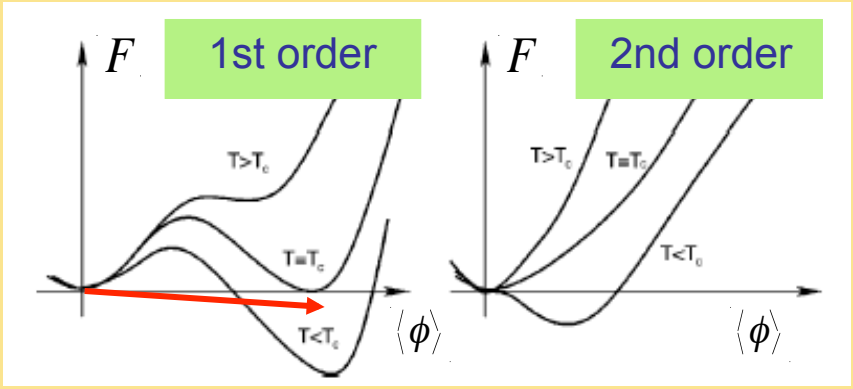
# Thermal History of Symmetry Breaking




*QCD Phase Diagram → EW Theory Analog?*

# EWSB Transition: St'd Model




*Increasing $m_h$* →

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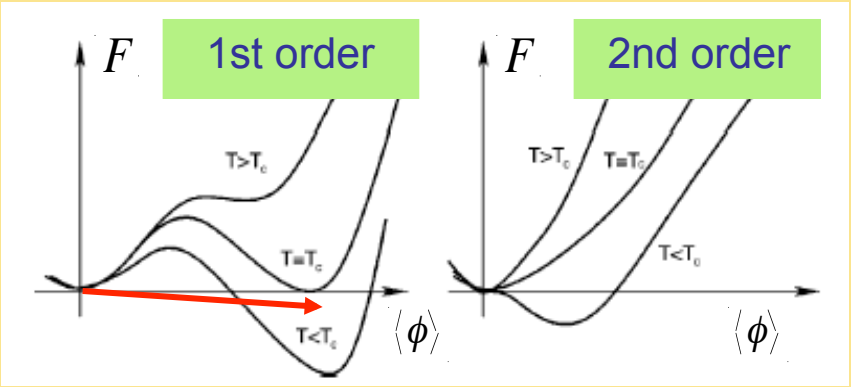


*Increasing $m_h$* →

| Lattice | Authors | $M_h^C$ (GeV) |
|---|---|---|
| 4D Isotropic | [76] | $80 \pm 7$ |
| 4D Anisotropic | [74] | $72.4 \pm 1.7$ |
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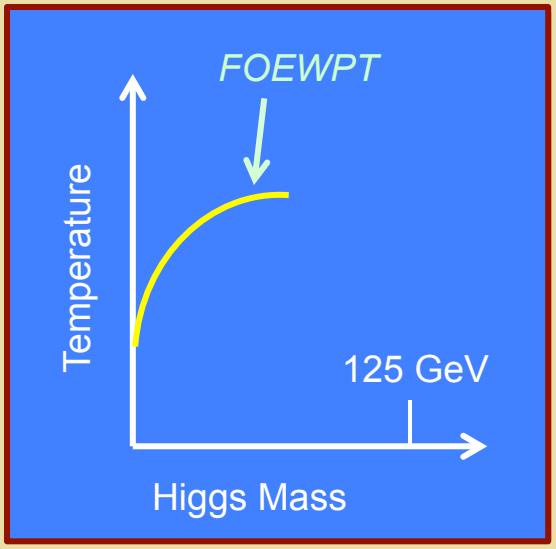
*SM EW: Cross over transition*




*EW Phase Diagram*

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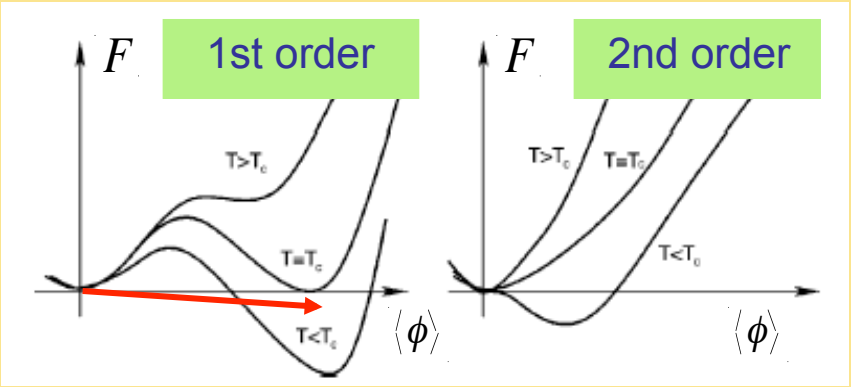


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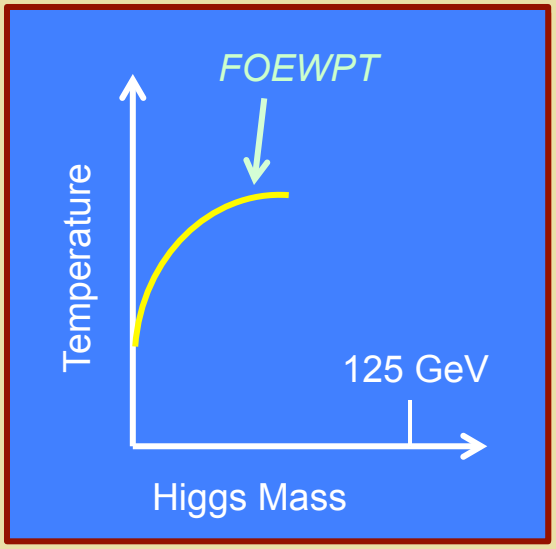
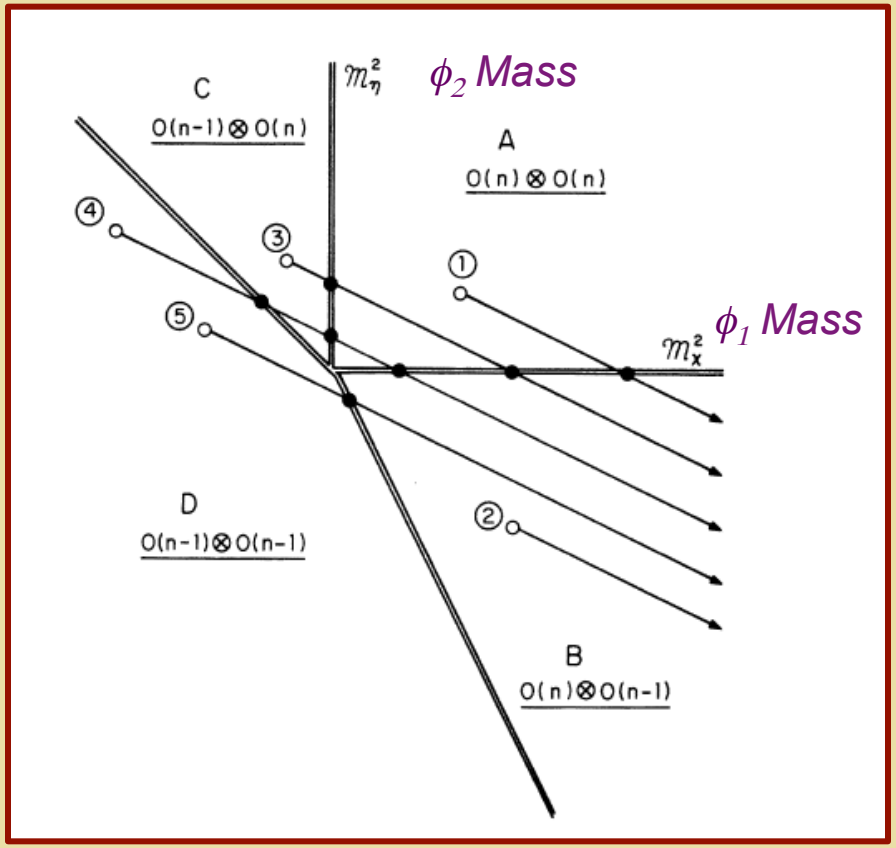



*EW Phase Diagram*

*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*

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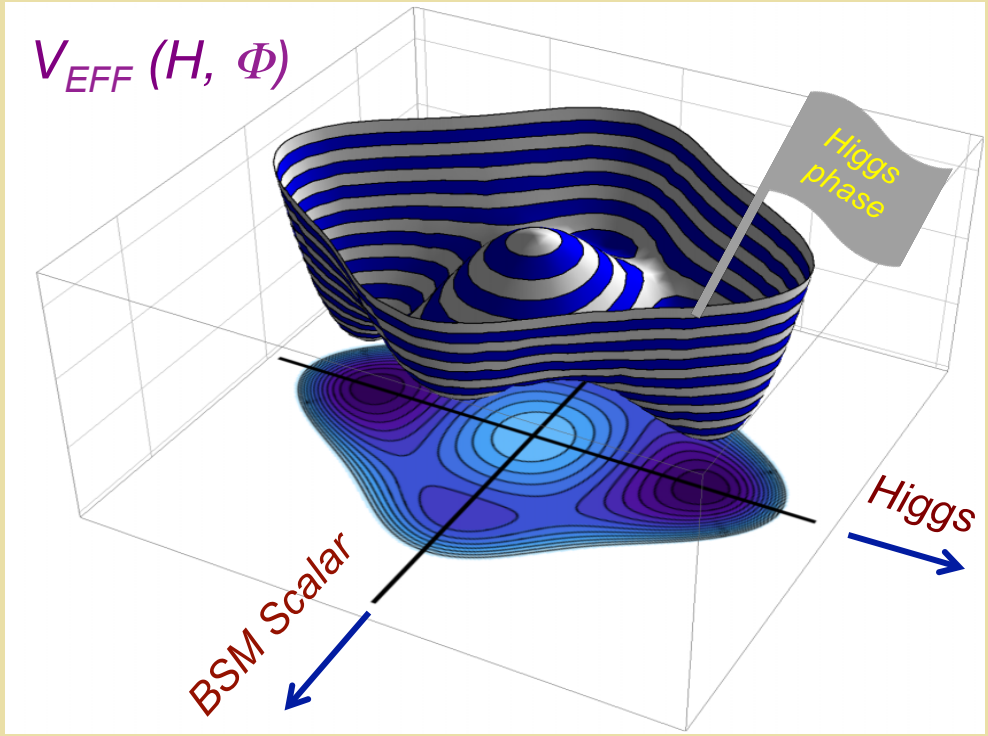


***Extrema can evolve differently as T evolves → rich possibilities for symmetry breaking***

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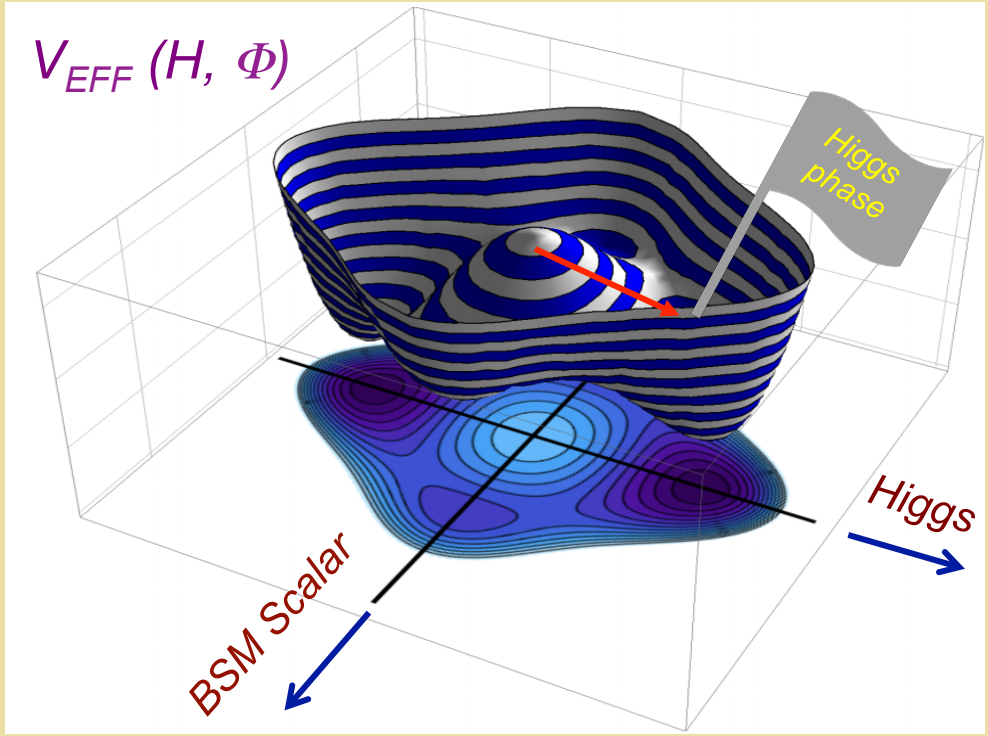


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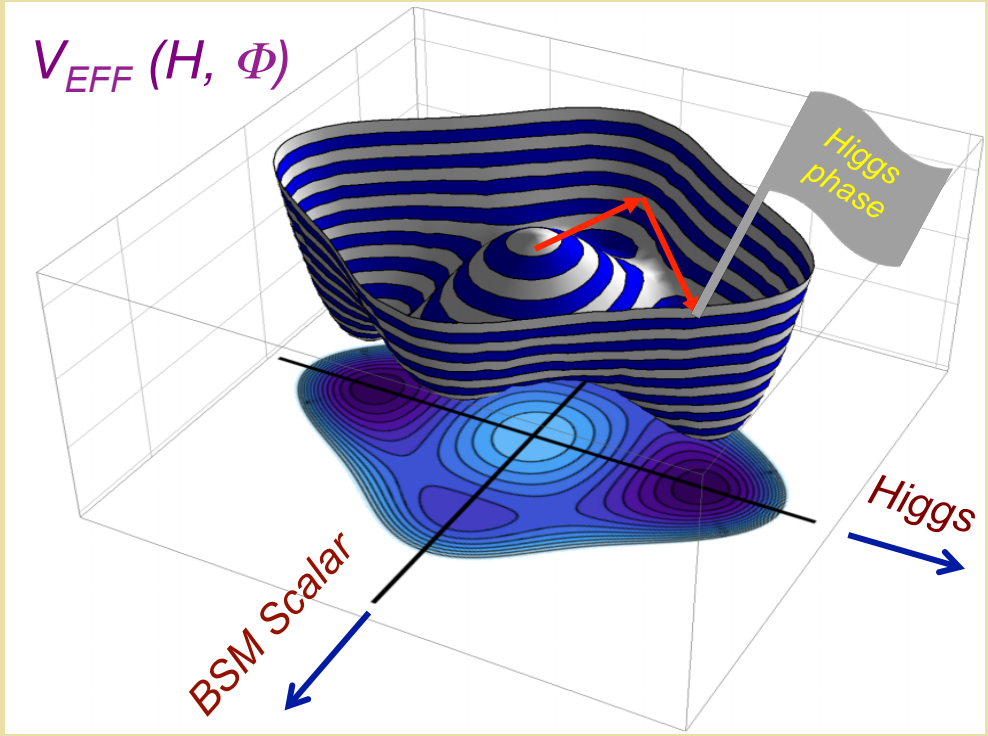


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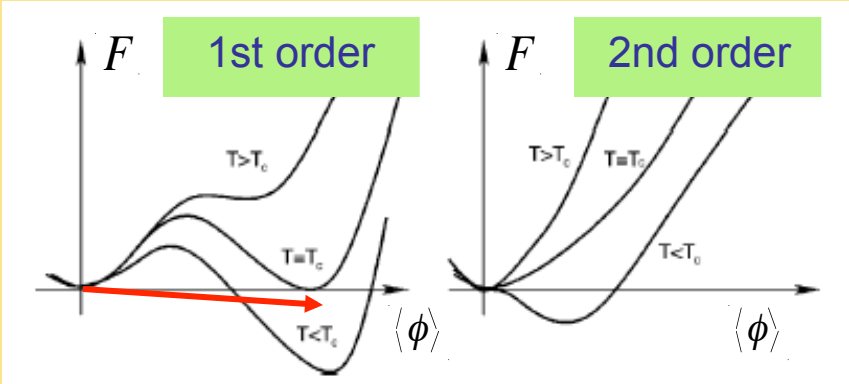
# EW Phase Transition: Baryogen & GW

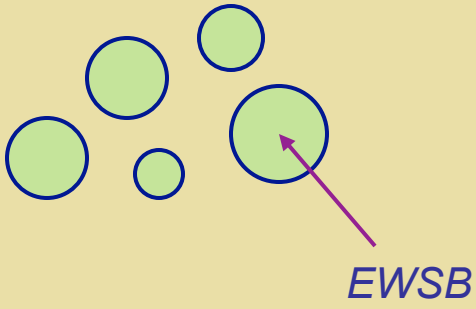



*Increasing $m_h$* →

← *New scalars*

*Baryogenesis*
*Gravity Waves*
*Scalar DM*
*LHC Searches*

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



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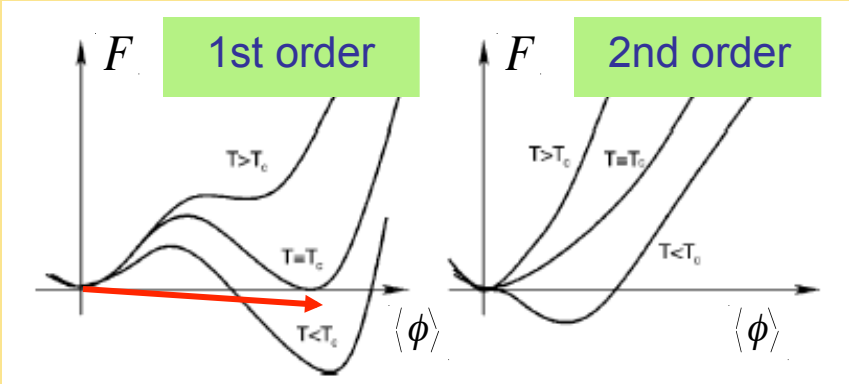


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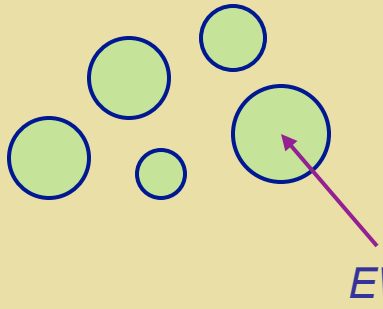
*"Strong"* | *1st order EWPT*

- *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 1912.07189*

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

# $T_{EW}$ Sets a Scale for Colliders

## High-T SM Effective Potential

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

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

**$T_0$ ~ 140 GeV**

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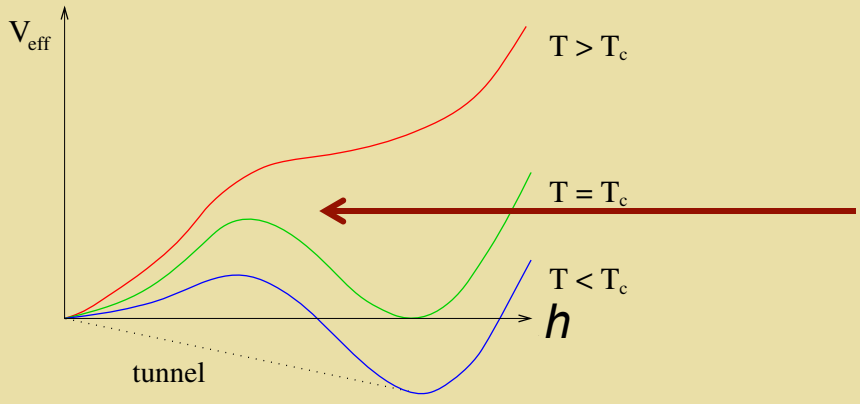
$T_0 \sim$ 140 GeV $\equiv \ T_{EW}$

# First Order EWPT from BSM Physics




*Generate finite-T barrier*

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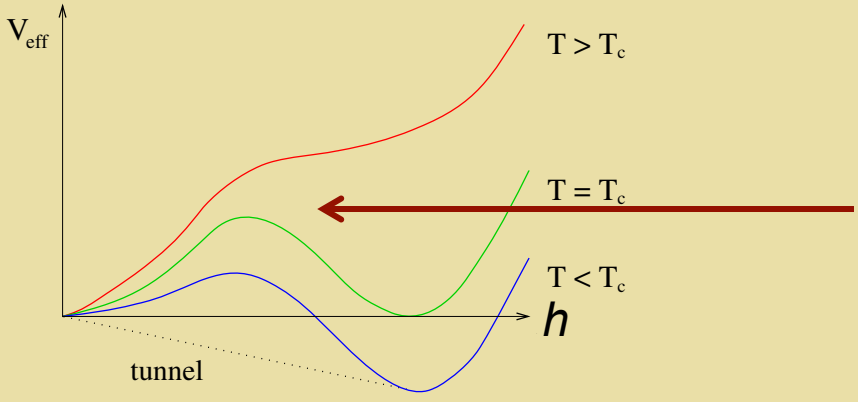
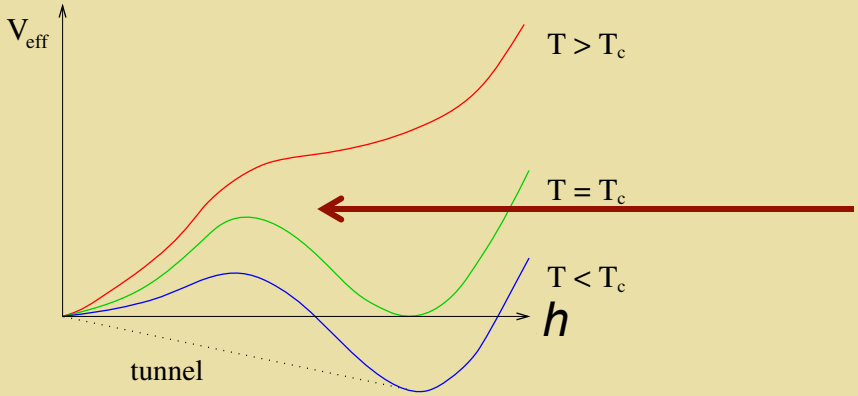



*Generate finite-T barrier*

***Introduce new scalar $\phi$ interaction with h via the Higgs Portal***

# First Order EWPT from BSM Physics

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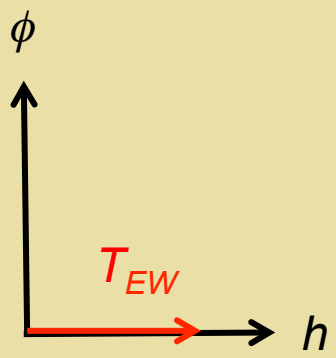


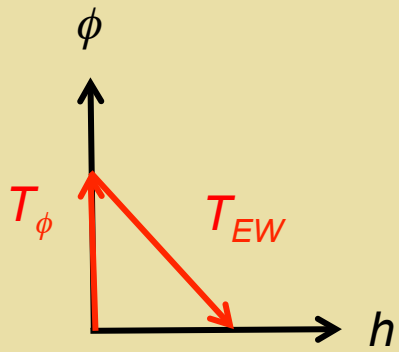


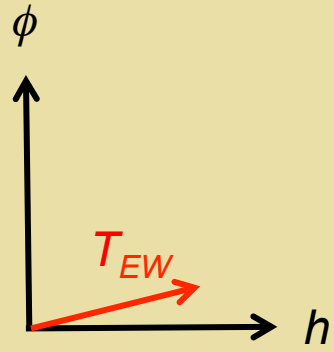


***$a_2 H^2\phi^2$ : $T > 0$***
***loop effect***

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

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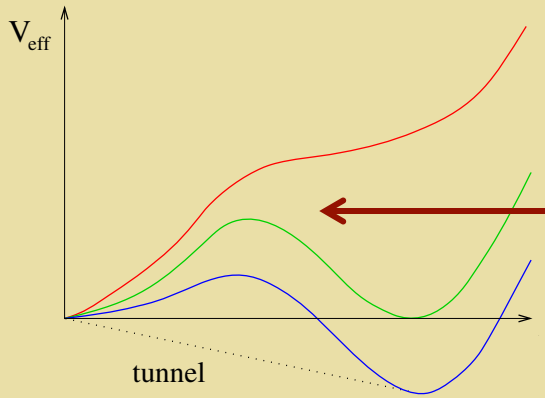
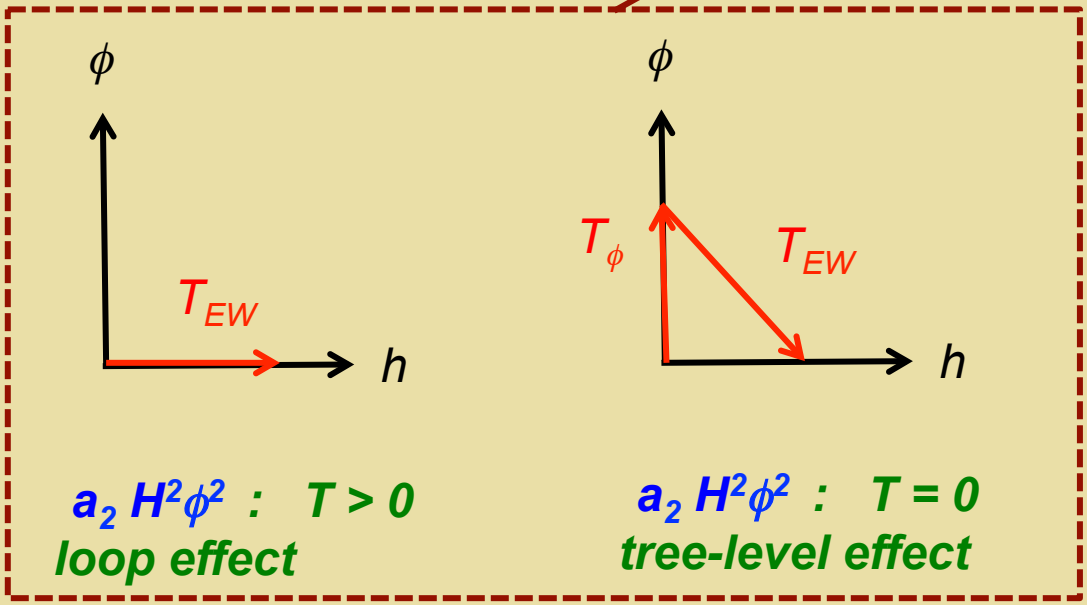



*Simple arguments: $T_{EW}$ + first order EWPT → $M_\phi \lesssim 700$ GeV*

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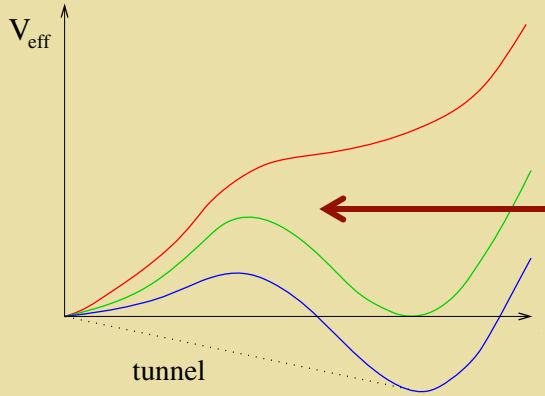


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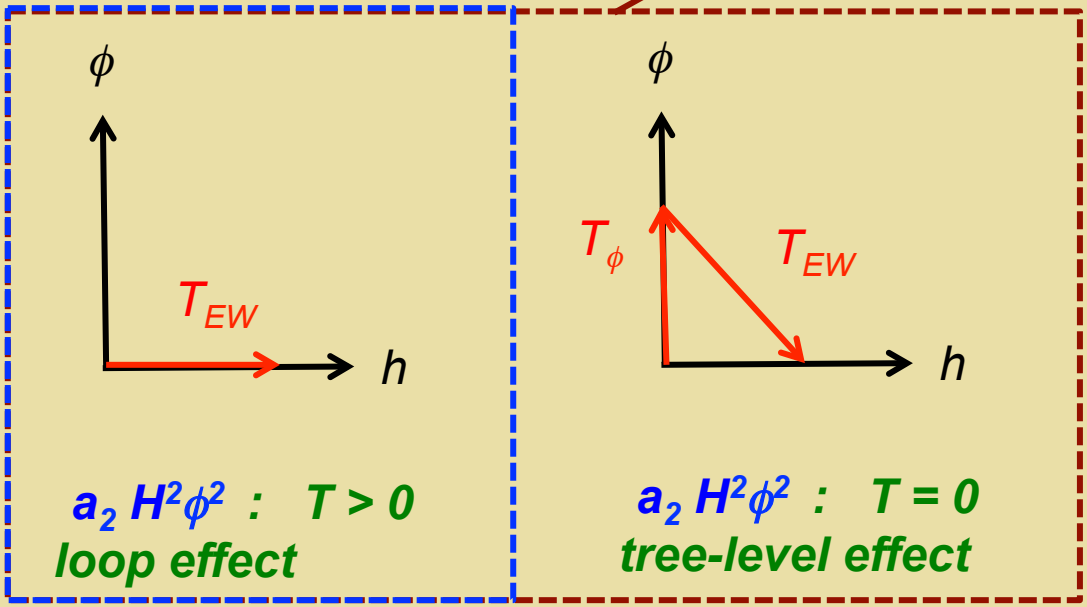


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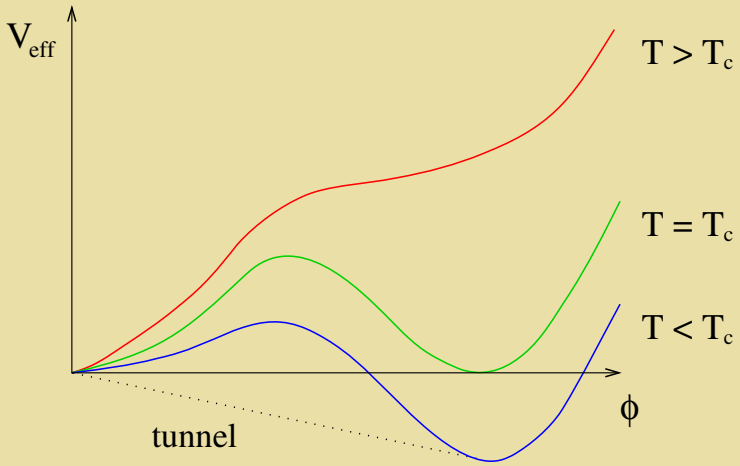


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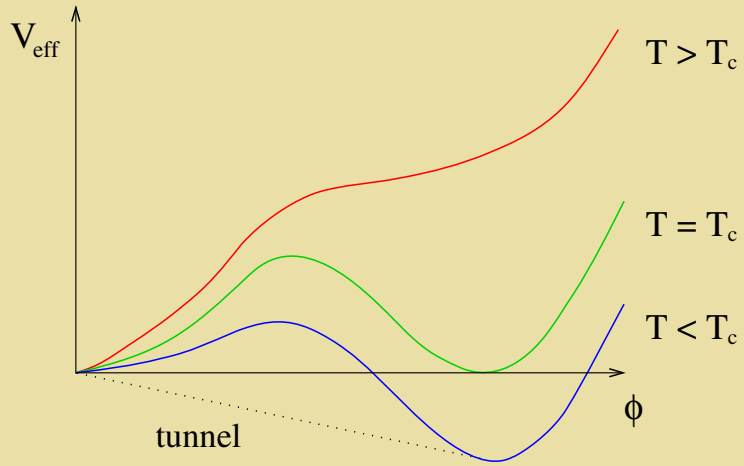


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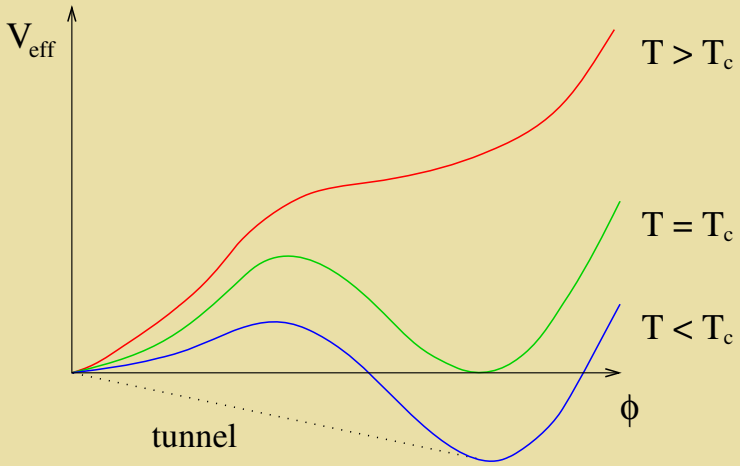


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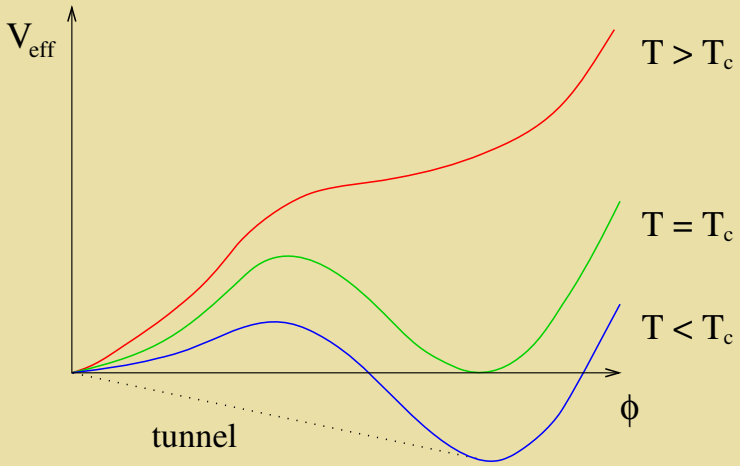


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***$M_\phi$ < 350 GeV for perturbative $a_2$***

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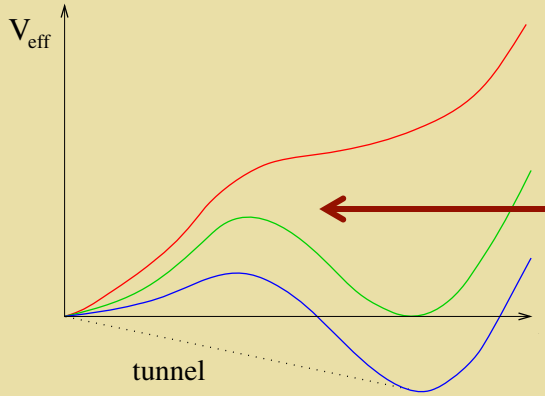


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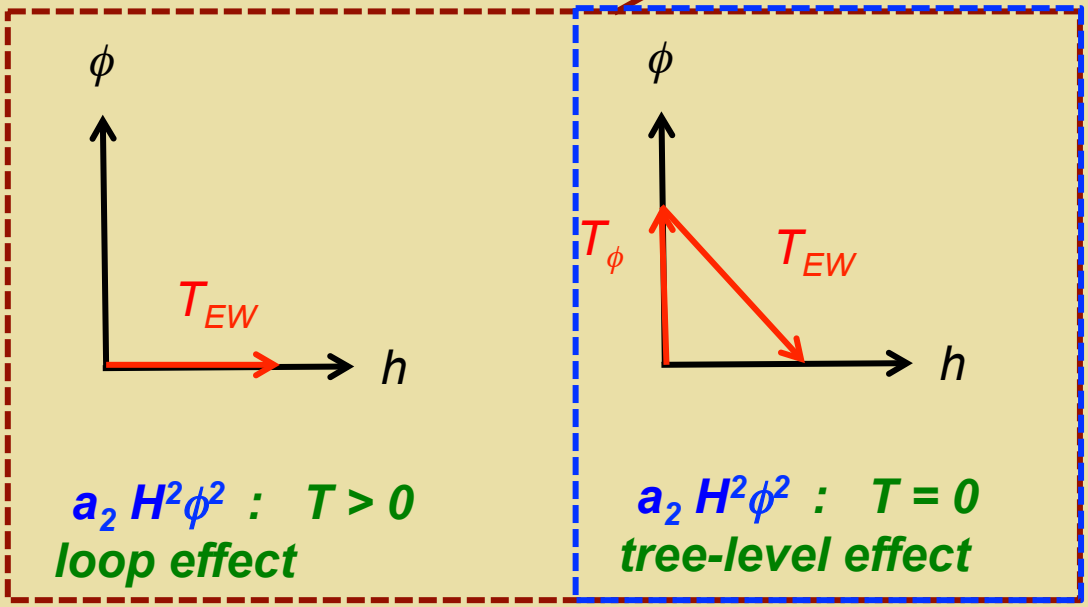
***Analogous logic***

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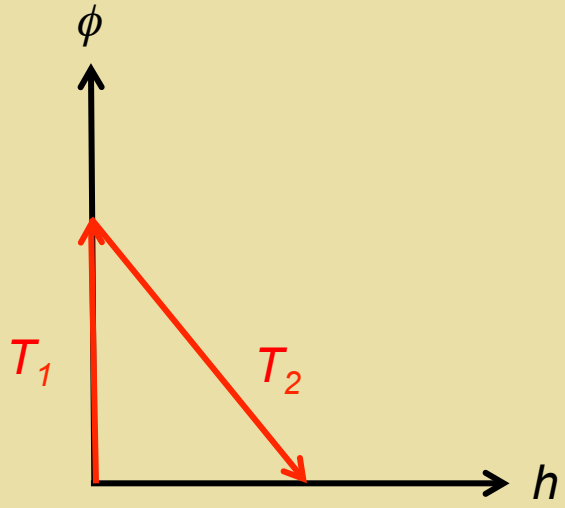

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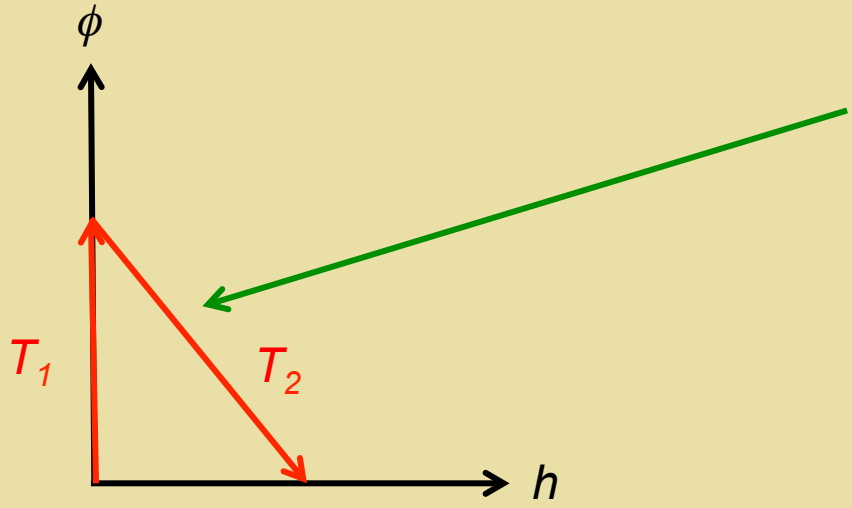
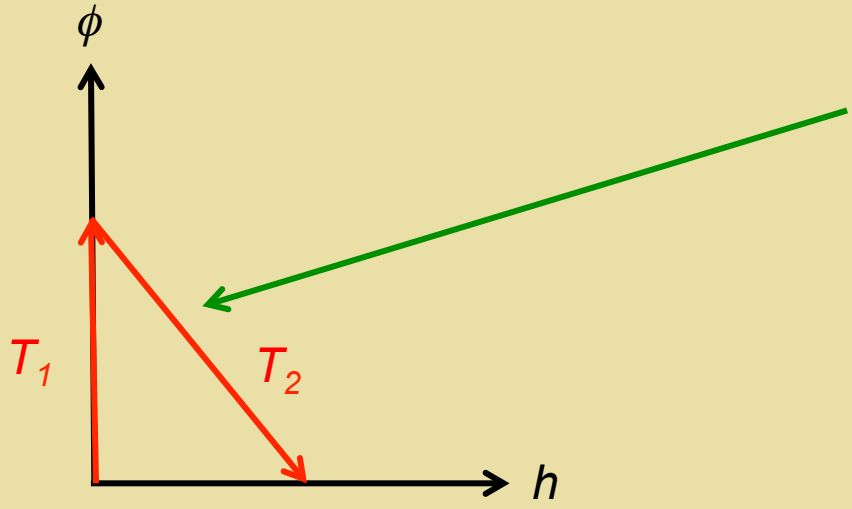



- *Tree-level barrier: $a_2\ \phi^+\phi\ H^+H$*
- *Want $T_1 > T_2 \sim T_{EW}$*

# First Order EWPT from BSM Physics

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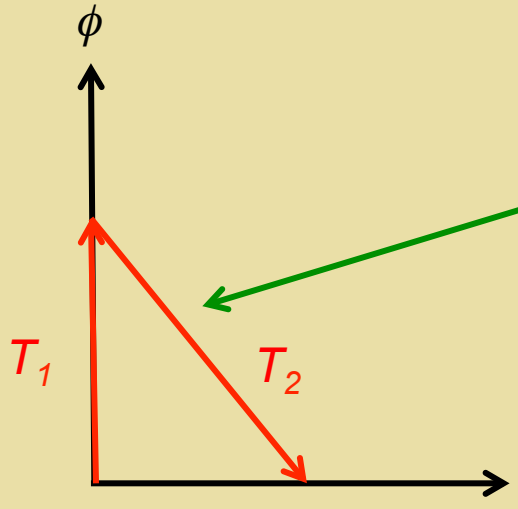
$$V(\varphi, T) = \frac{1}{2}\left[-|b_2| + \frac{T^2}{6}\left(a_2 + \frac{3}{2}b_4\right)\right]\varphi^2 + \frac{b_4}{4!}\varphi^4$$

# First Order EWPT from BSM Physics




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

*Negative for $T_1 > T_2 \sim T_{EW}$*

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

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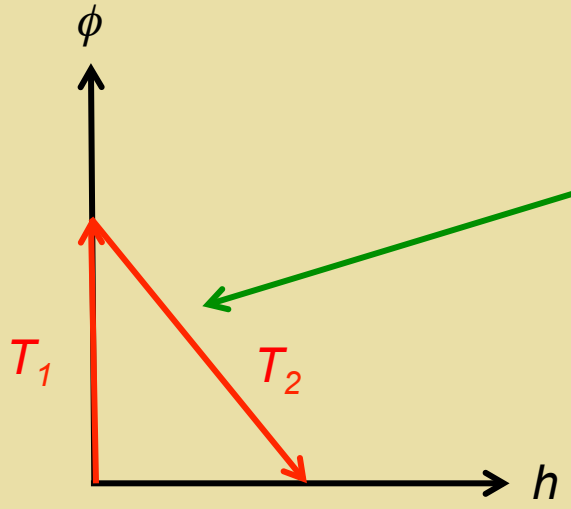
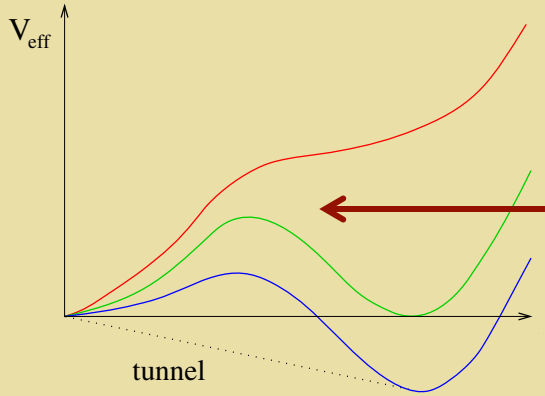



- *Tree-level barrier: $a_2\,\phi^+\phi\,H^+H$*
- *Want $T_1 > T_2 \sim T_{EW}$*

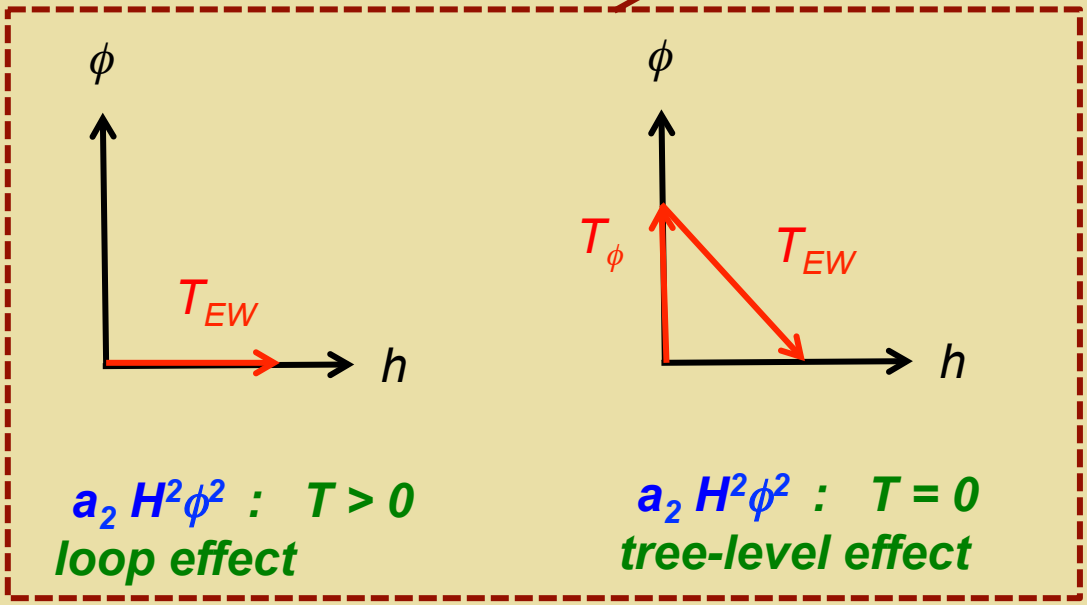
$$M_\phi(T=0) < \left[\frac{a_2}{4}v^2 - \frac{T_{\rm EW}^2}{6}\left(a_2 + \frac{3}{2}b_4\right)\right]^{1/2}$$

***$M_\phi$ < 350 GeV for perturbative $a_2$, $b_4$***

# First Order EWPT from BSM Physics




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




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

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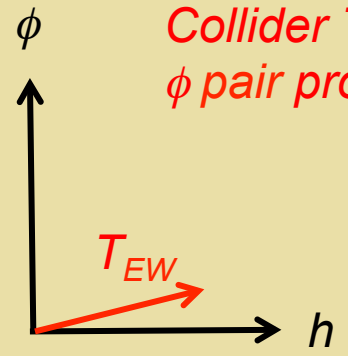


*Collider Target: $\phi$ pair production*

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

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

***Mass Reach:***

| $E_{\rm CM}$(GeV) | $M_\phi$ (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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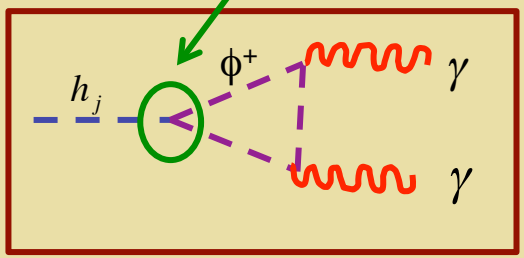
$H^2\phi^2$ Barrier ?

$\phi$ : EW Multiplet



# First Order EWPT from BSM Physics

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$H^2\phi^2$ Barrier ?

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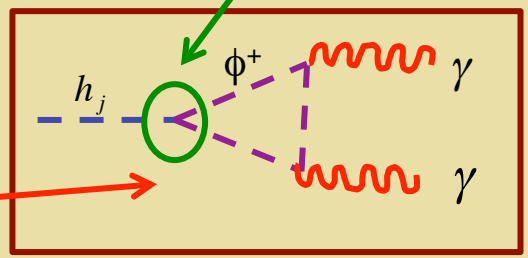
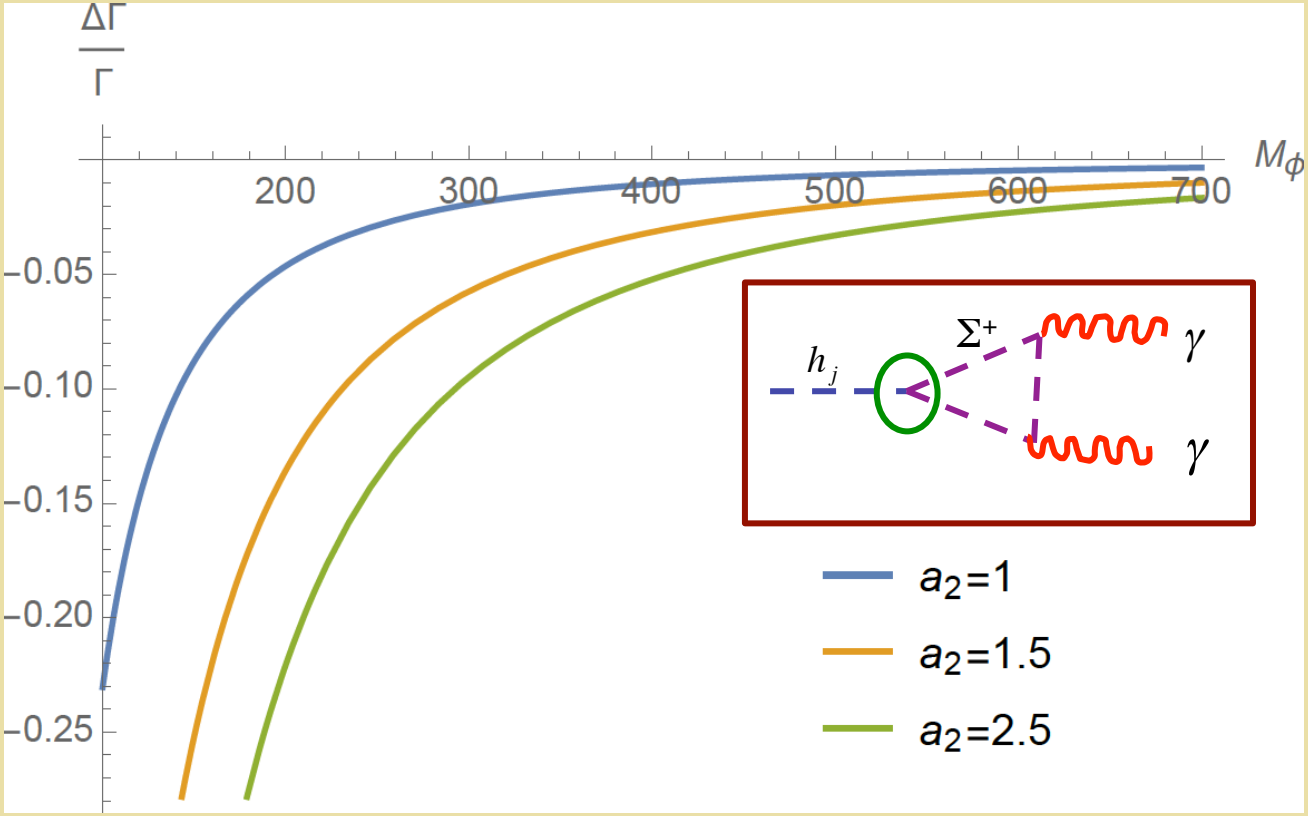


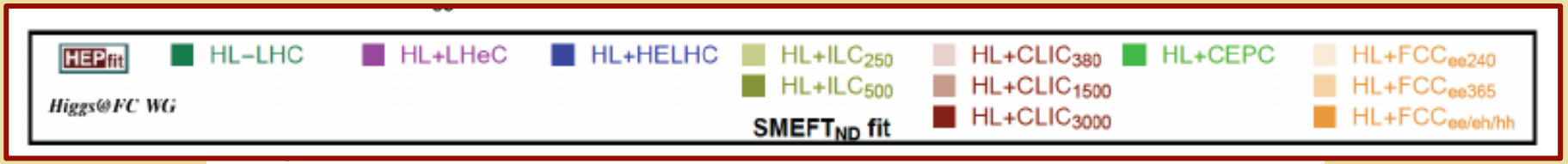

Collider Target: Precision

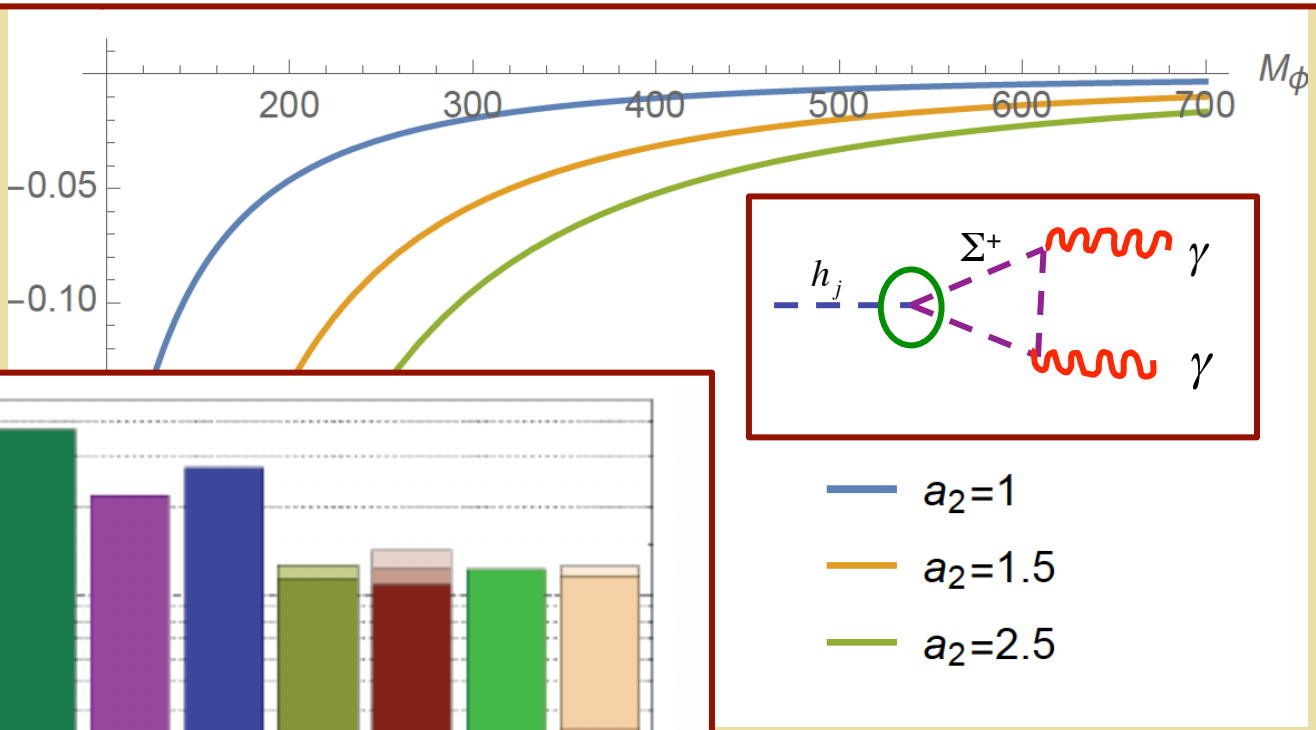
# $H \rightarrow \gamma\gamma$ : Is There a Barrier ?




***EWPT → Decrease in rate***

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







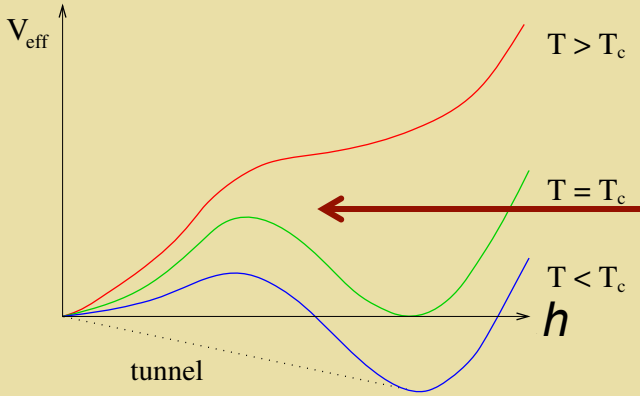
*Thanks: M. Cepeda*

# First Order EWPT from BSM Physics

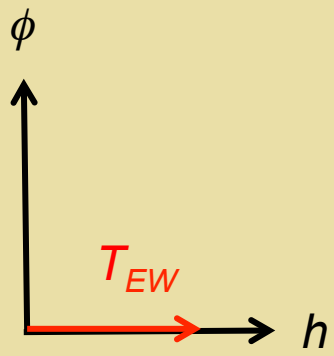
- Thermal $\Gamma(h \rightarrow \gamma\gamma)$
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays

$H^2\phi$ Barrier ?

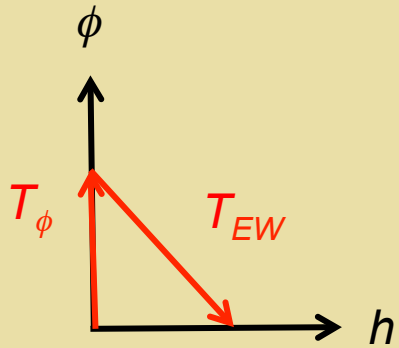
# First Order EWPT from BSM Physics



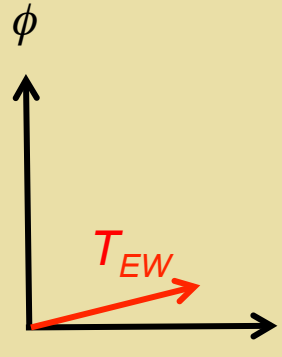

Higgs − $\phi^0$ Mixing




$a_2 H^2\phi^2$ : $T > 0$
*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-$\phi$ Mixing

# First Order EWPT from BSM Physics

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

$H^2\phi$ Barrier ?

H-$\phi$ Mixing

# *Strong First Order EWPT*

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

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- ***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 $\phi$ 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 ?

Back up slides

# *III. Models & Phenomenology*

# *Model Illustrations*


***Simple Higgs portal models:***

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

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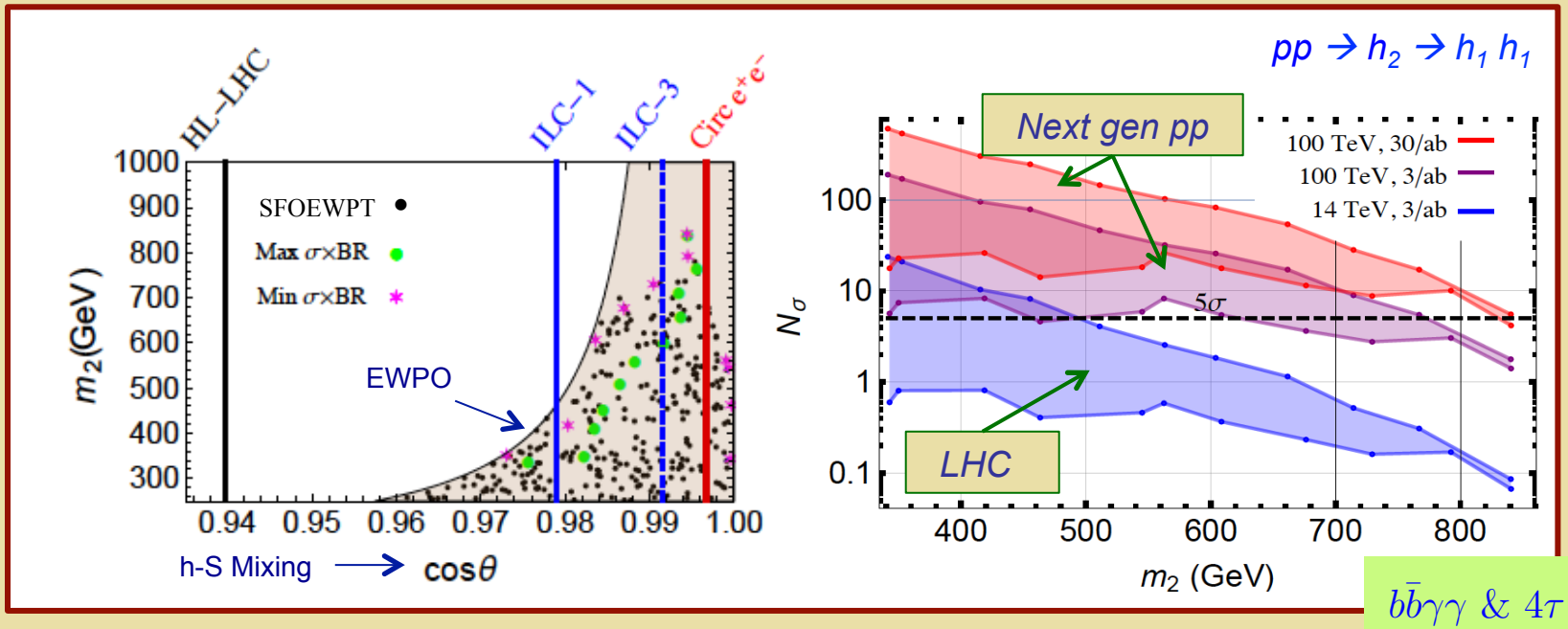
# Singlets: Precision & Res Di-Higgs Prod

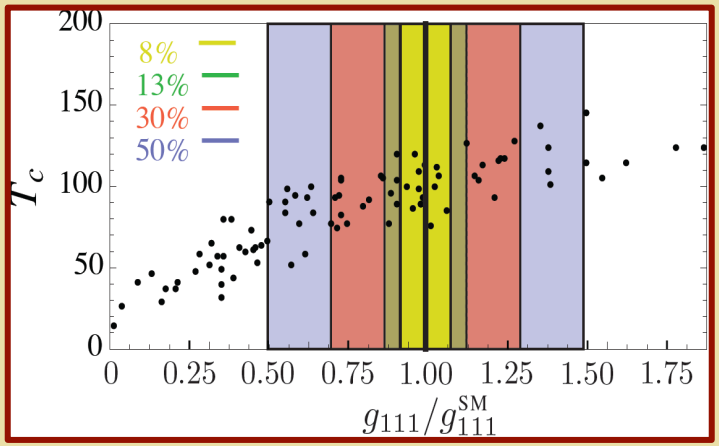
*SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies*

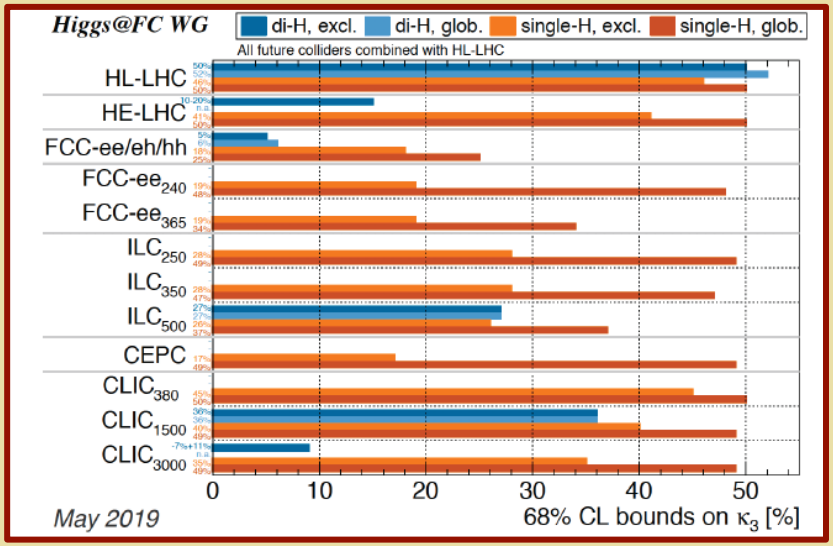



*Kotwal, No, R-M, Winslow 1605.06123*

*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*

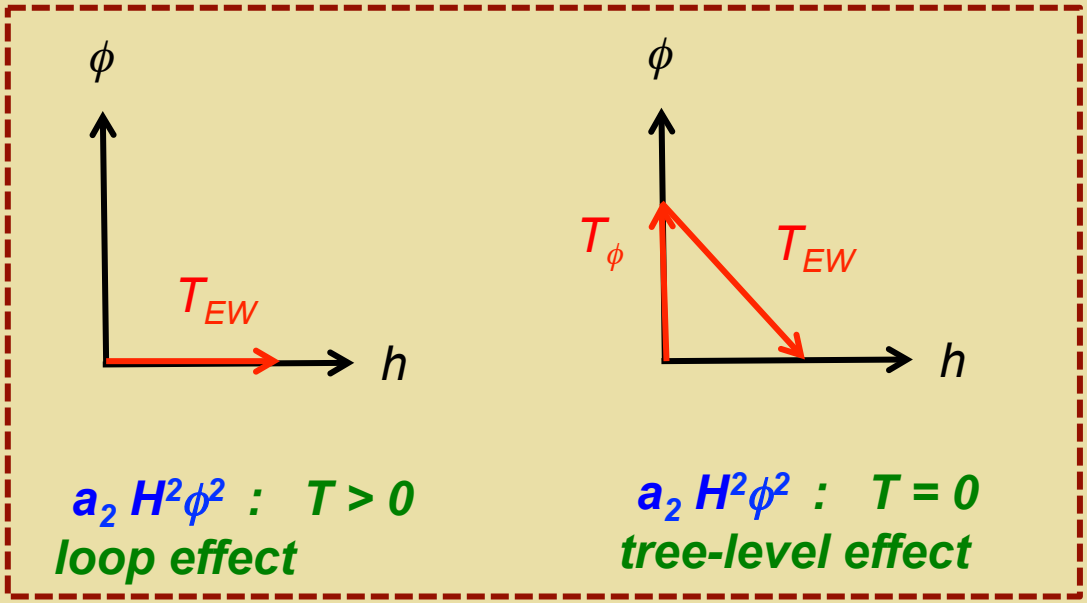
***Thanks: M. Cepeda***

# *Model Illustrations*


***Simple Higgs portal models:***

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

# Real Triplet

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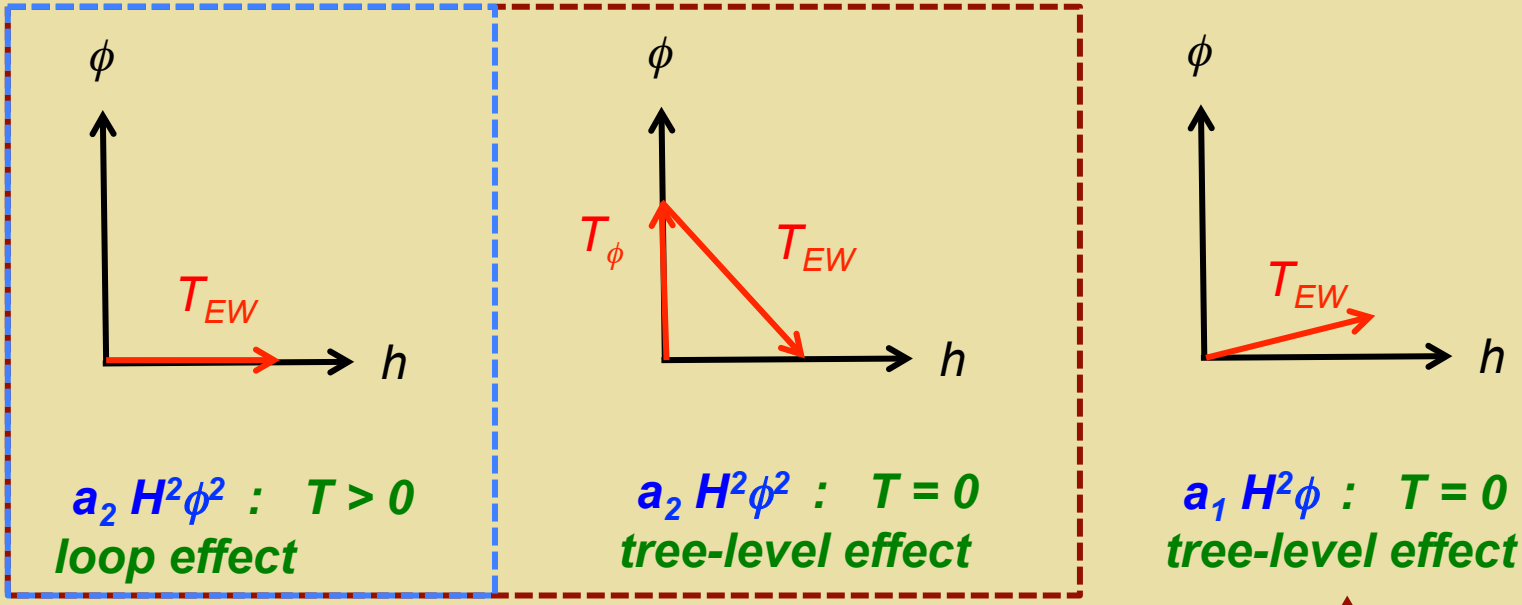
*loop effect*

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

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

*EW precision tests → too tiny*

# Real Triplet

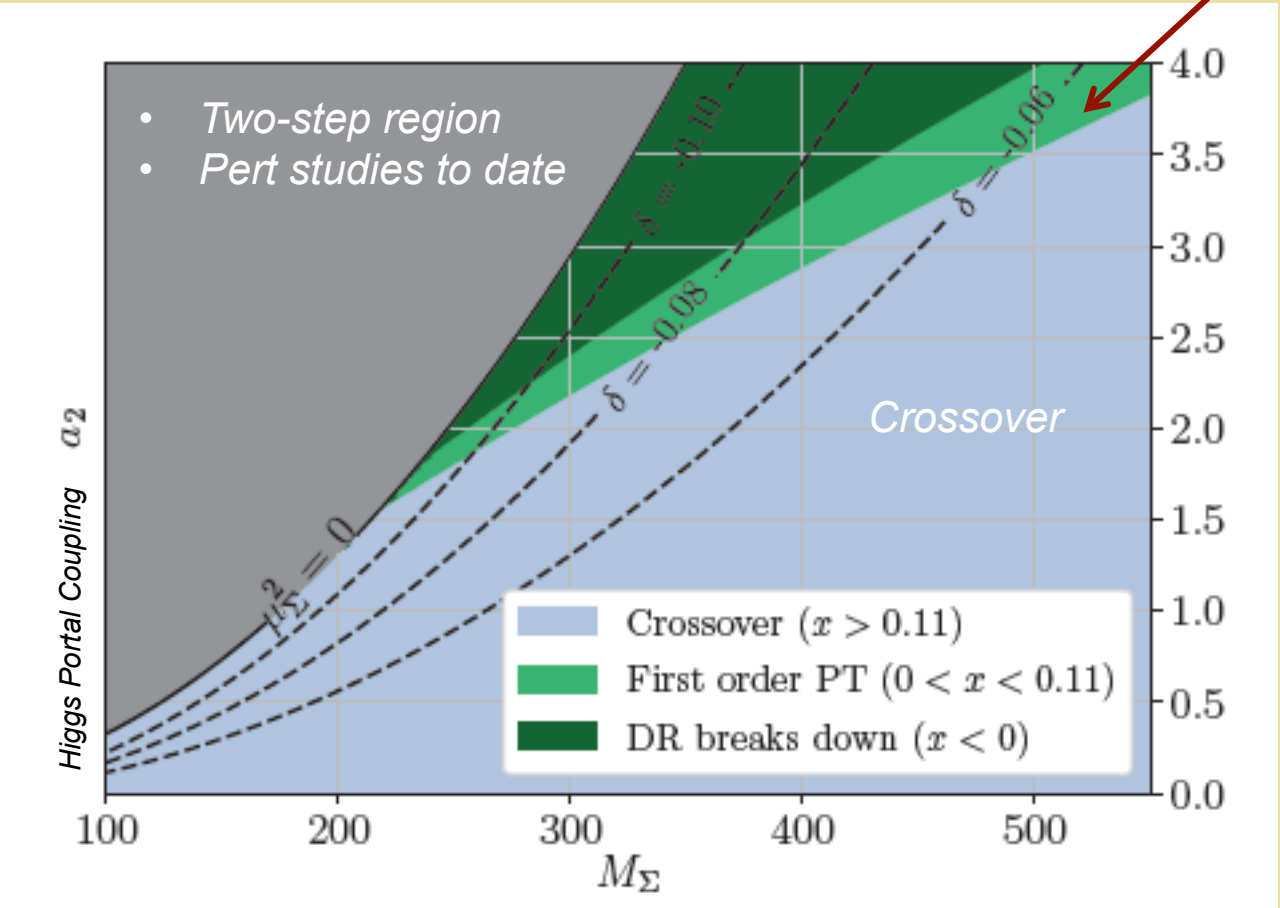



*Non-perturbative results*

*EW precision tests → too tiny*

# Real Triplet: One-Step EWPT

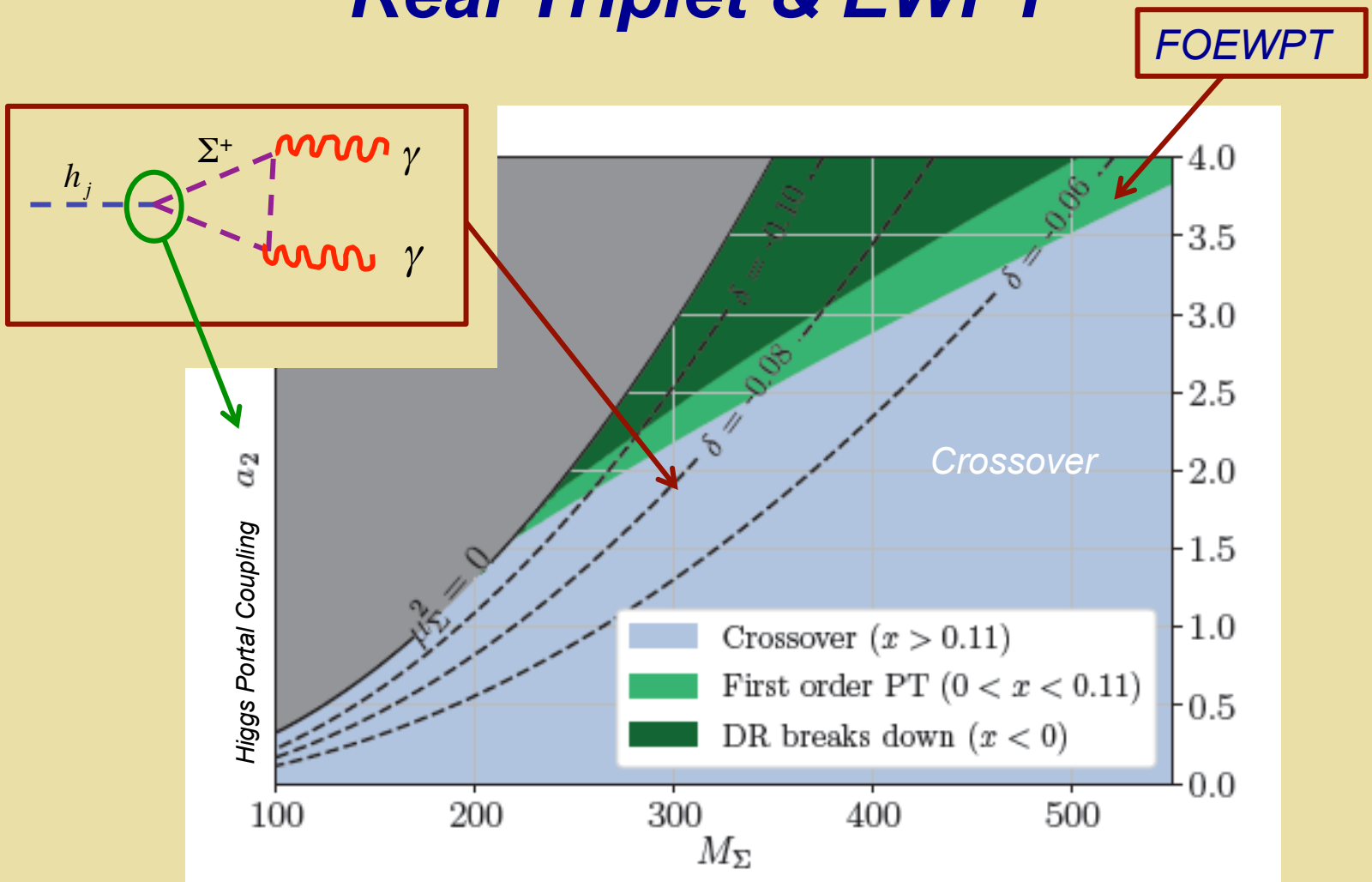
FOEWPT




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

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

# Real Triplet & EWPT

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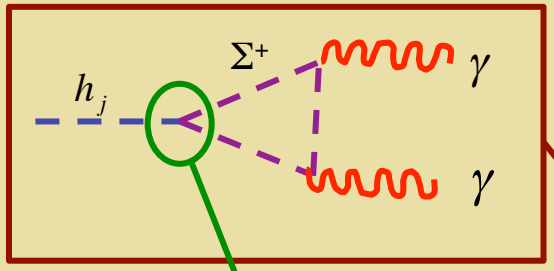
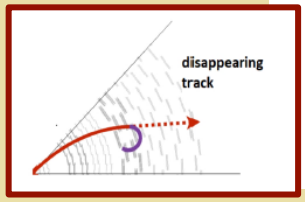






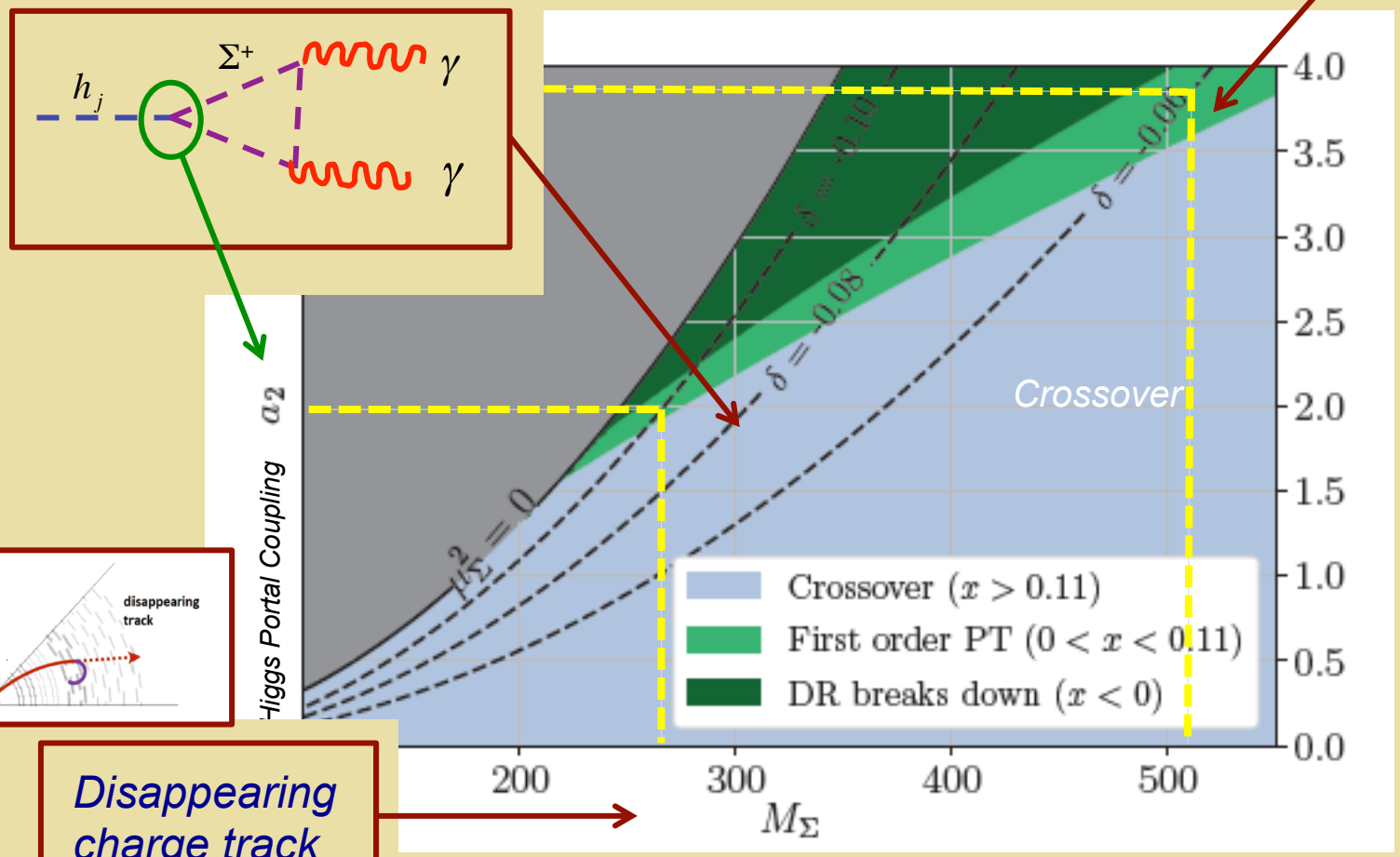
FOEWPT

Disappearing charge track

- One-step
- Non-perturbative

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

# Real Triplet & EWPT




- *One-step*
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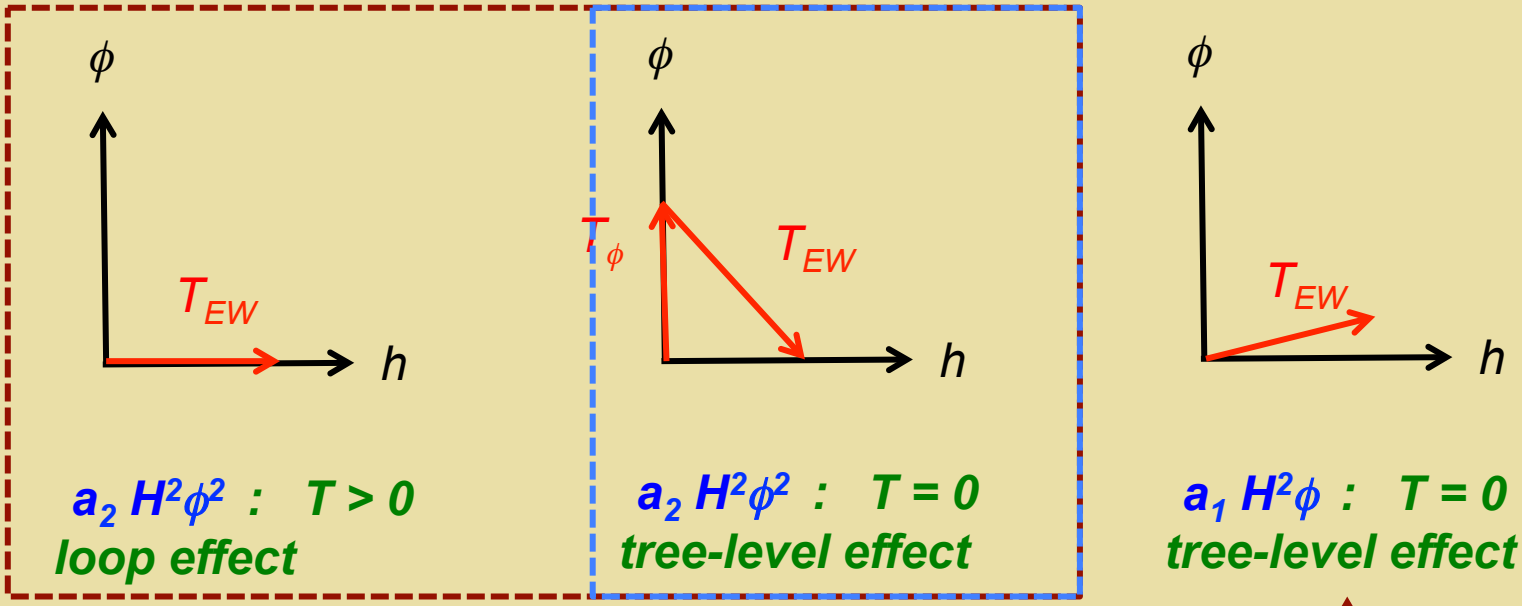


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$a_1 H^2\phi$ : $T = 0$
*tree-level effect*

*Pert theory: back-up slides*

*EW precision tests → too tiny*

# *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*

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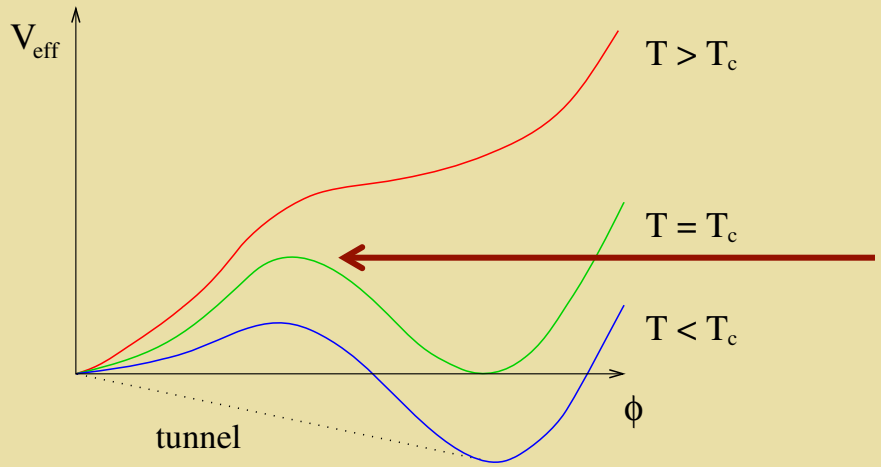
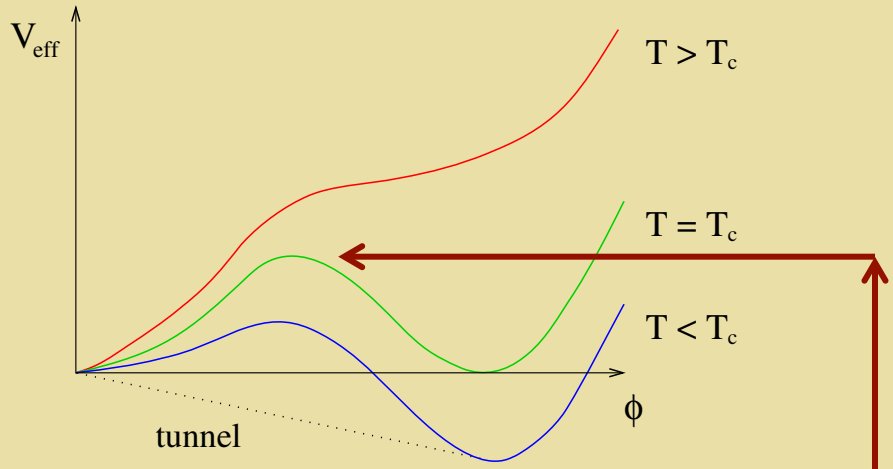



*Generate finite-T barrier*

# First Order EWPT from BSM Physics




*Generate finite-T barrier*

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

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

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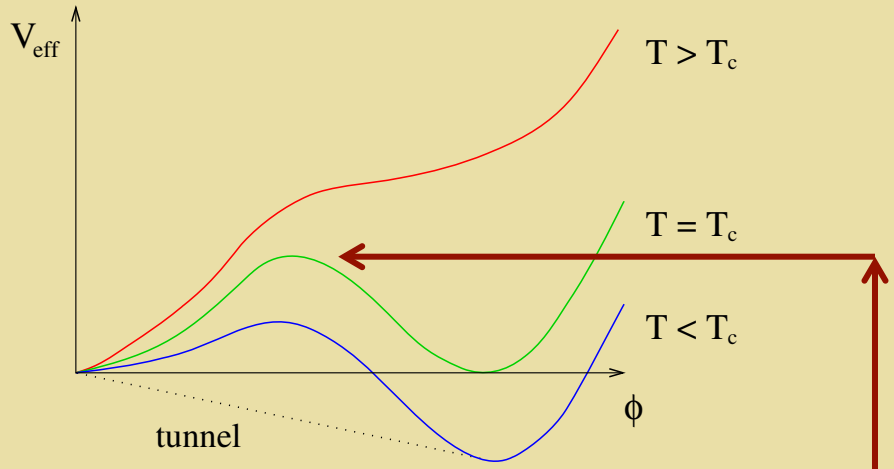
# First Order EWPT from BSM Physics

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# *First Order EWPT from BSM Physics*

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

# $T_{EW}$ : A Mass Scale for Colliders

- *Foregoing arguments: good up to factor of ~ 2 → $M_\phi$ < 800 GeV (-ish)*
- *QCD production: LHC exclusion → $\phi$ is colorless*
- *Electroweak or Higgs portal (h-$\phi$ mixing…) production → $\sigma_{PROD}$ ~ (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-$\phi$ 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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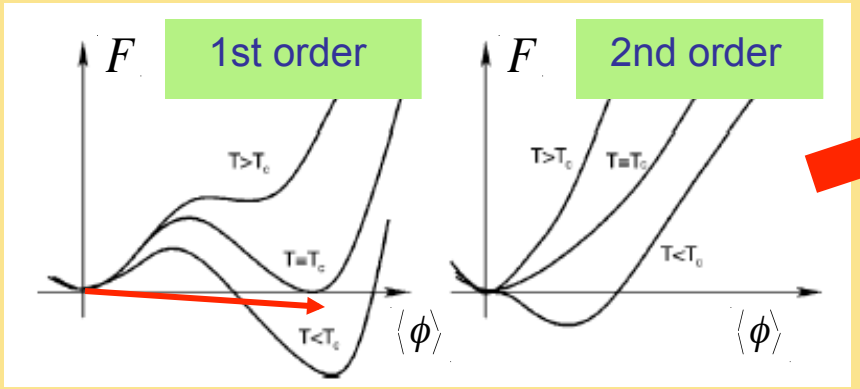
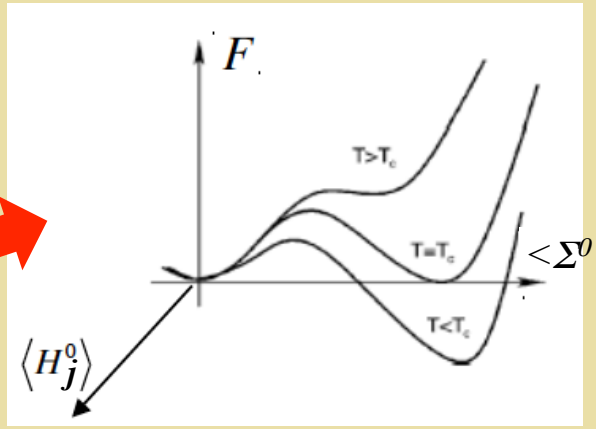
# EW Multiplets: EWPT




*Increasing $m_h$* →

← *New scalars*

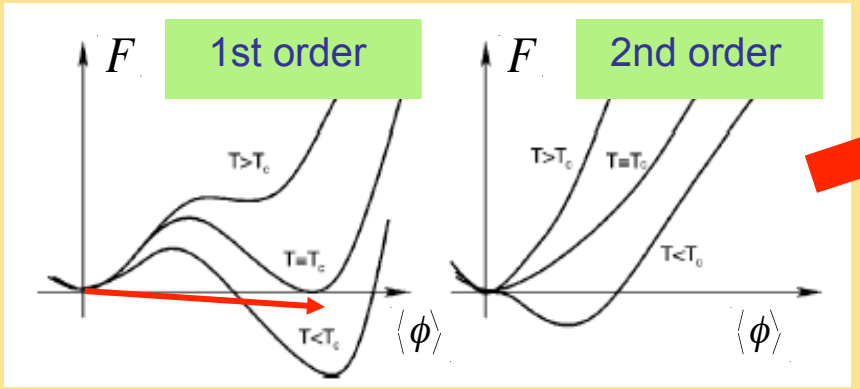
- *Thermal loops*
- *Tree-level barrier*

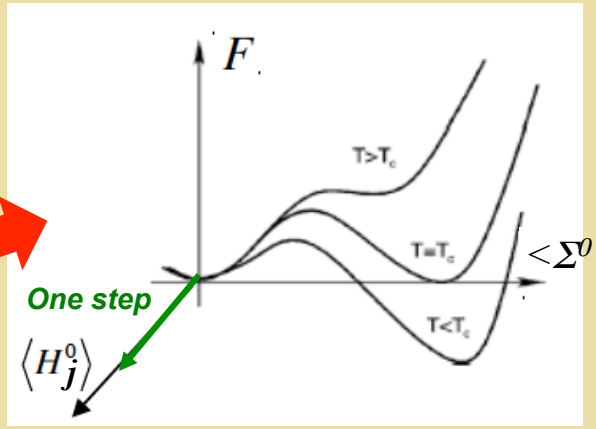
*Illustrate with real triplet: $\Sigma \sim (1,3,0)$*

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

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

# EW Multiplets: One-Step EWPT




*Increasing $m_h$* →

← *New scalars*

- *One-step: Sym phase → Higgs phase*

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

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

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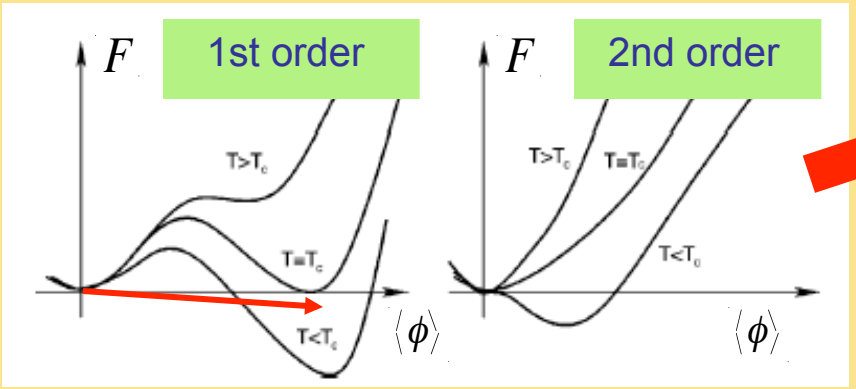
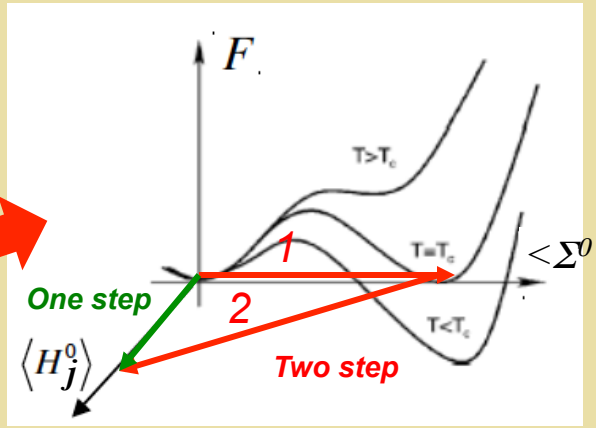
# EW Multiplets: Two-Step EWPT



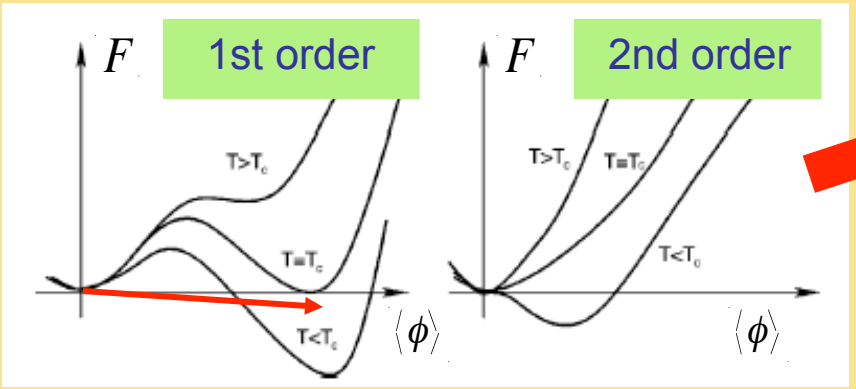

*Increasing $m_h$* →

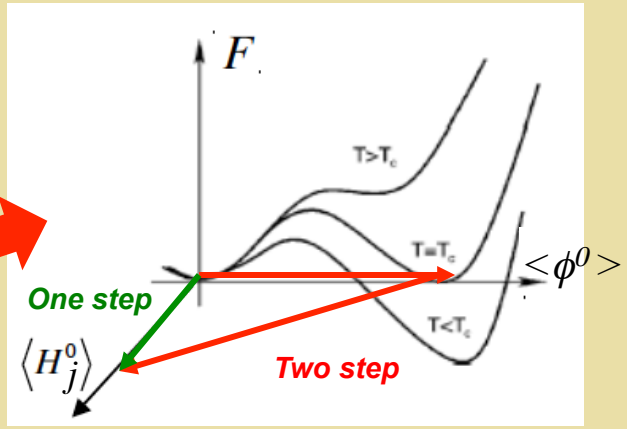
← *New scalars*

- *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

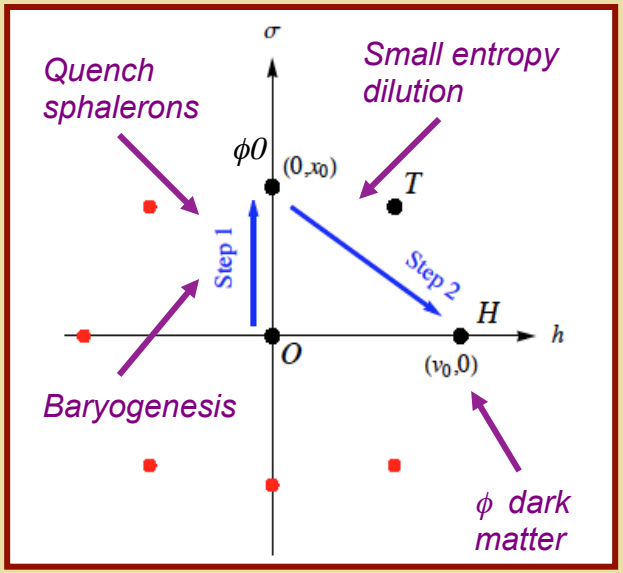



*Increasing $m_h$* →

← *New scalars*

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




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

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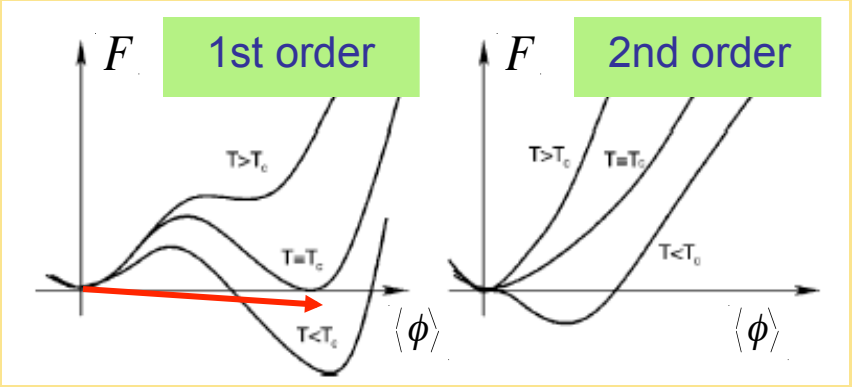
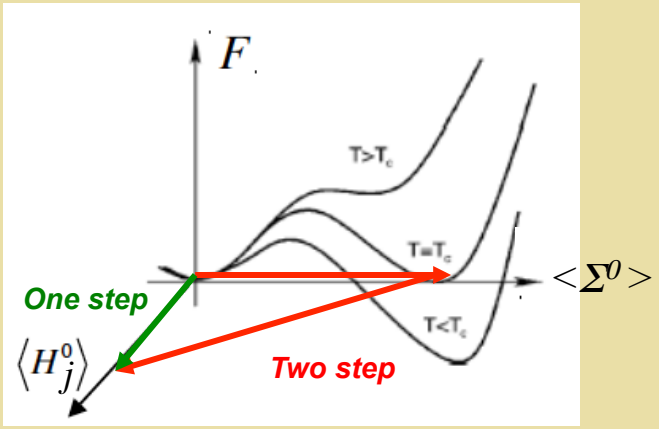
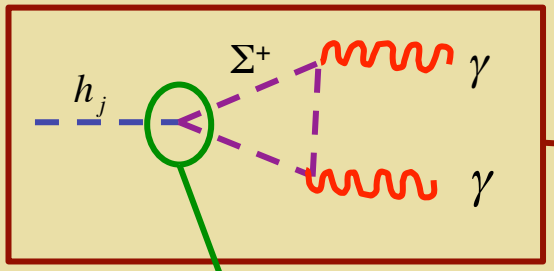
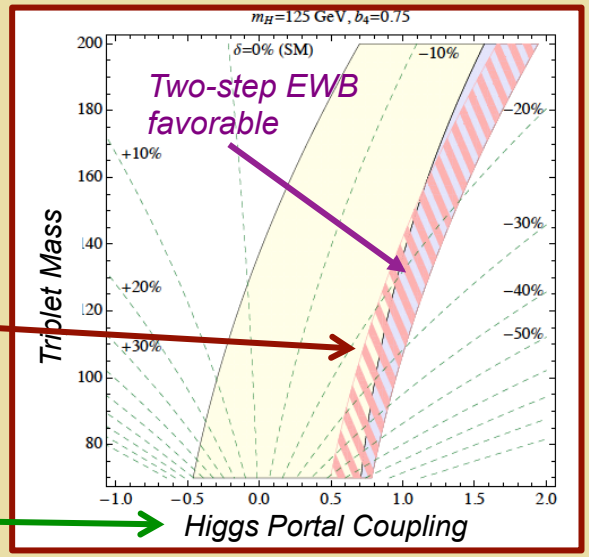



*Increasing $m_h$* →

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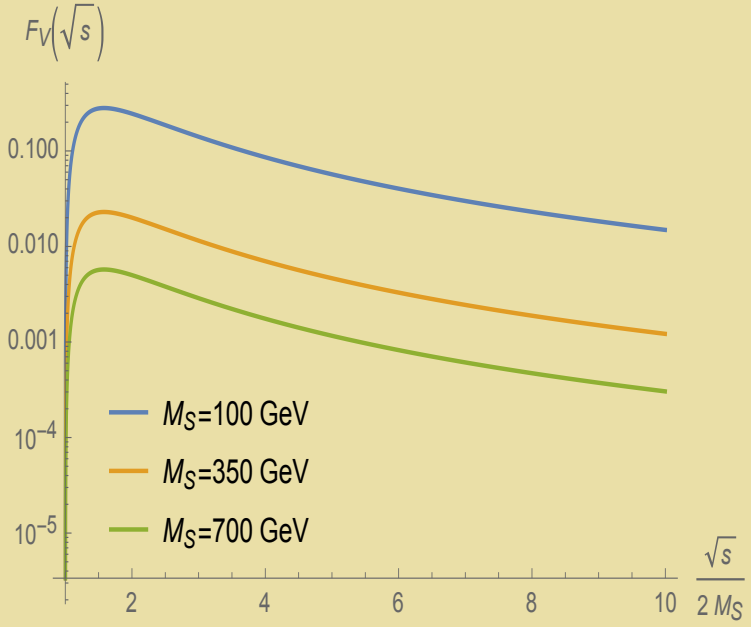
# $T_{EW}$ : Direct $\phi^+\phi^-$ Production at LC

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

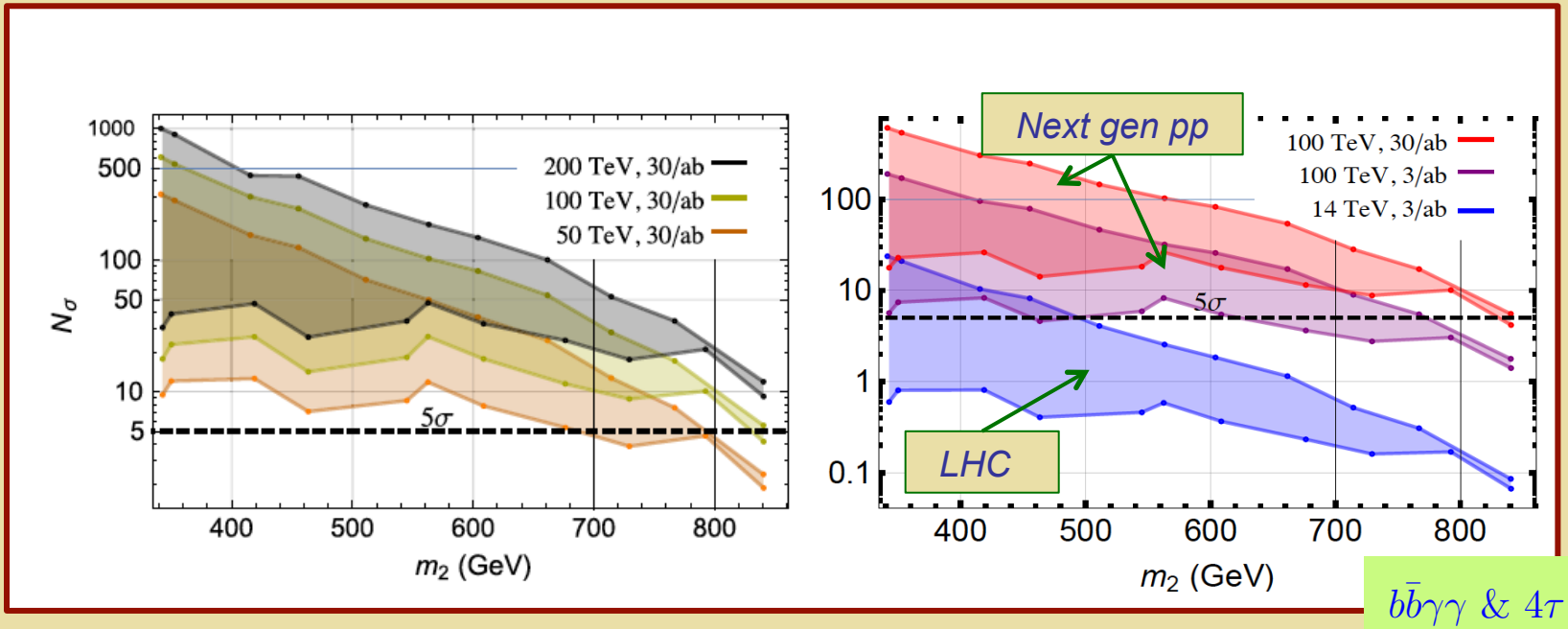
$$\mathcal{G}_V = \left(\frac{g^4}{4\pi}\right)\left(\frac{g_V^2 + g_A^2}{12}\right) v^{-2}$$




***Max sensitivity:***
***$E_{CM}$ ~ 3.4 x $M_\phi$***

# EW Phase Transition: Singlet Scalars

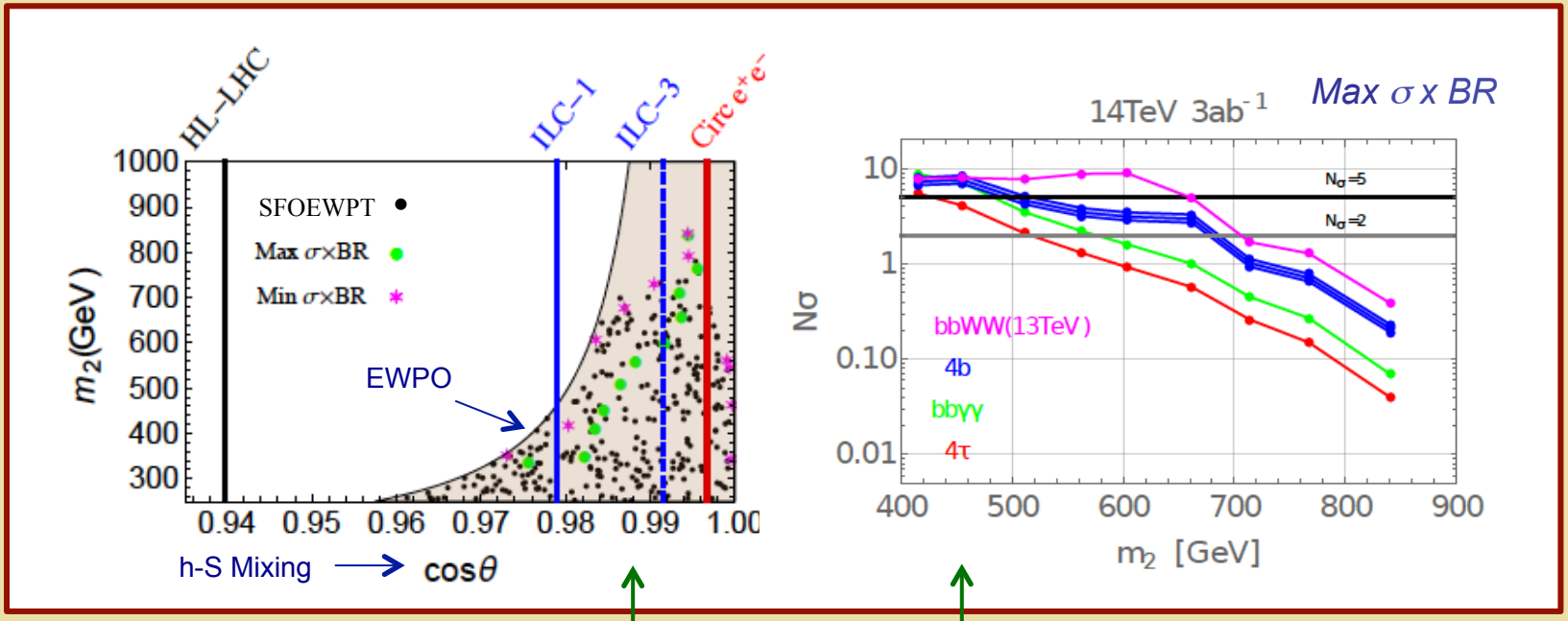
*SFOEWPT Benchmarks: Resonant di-Higgs*




*Kotwal, No, R-M, Winslow* 1605.06123

# Singlets: Precision & Res Di-Higgs Prod

*SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies*

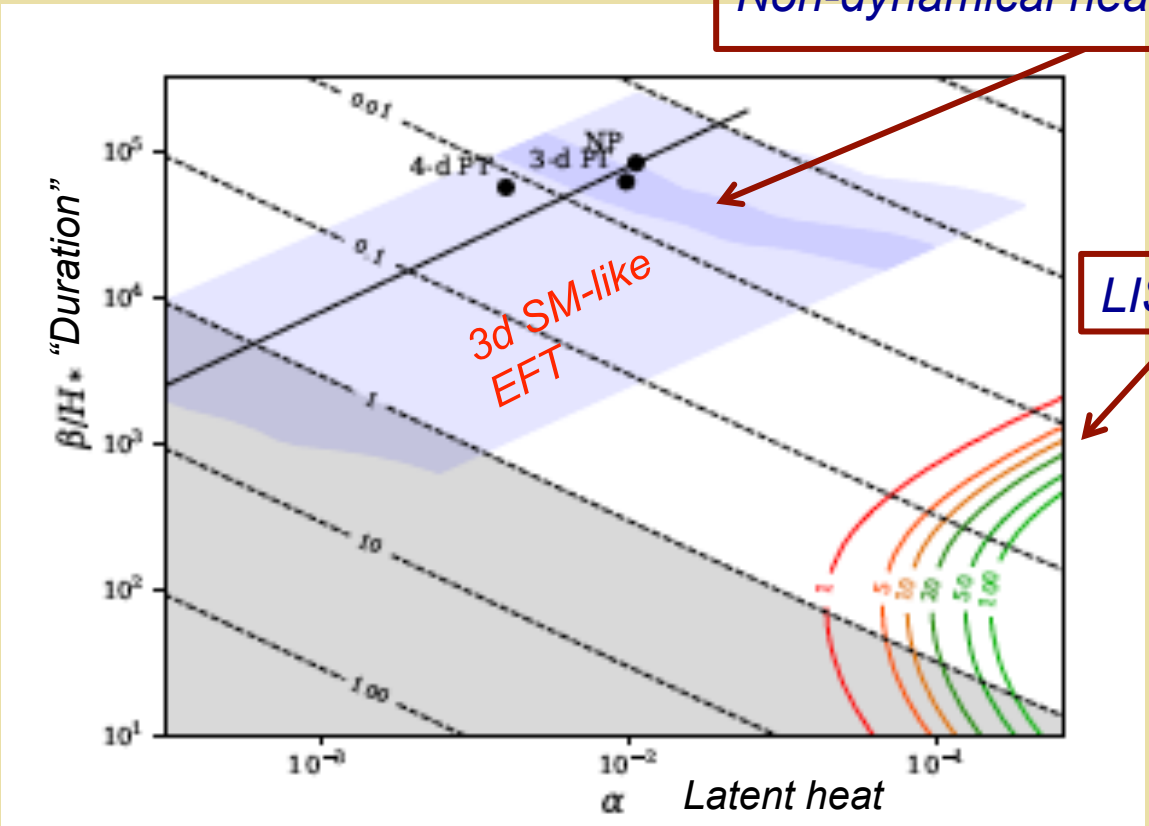



*Kotwal, No, R-M, Winslow 1605.06123*

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

# Heavy Real Singlet: EWPT & GW

*Non-dynamical heavy BSM scalars*

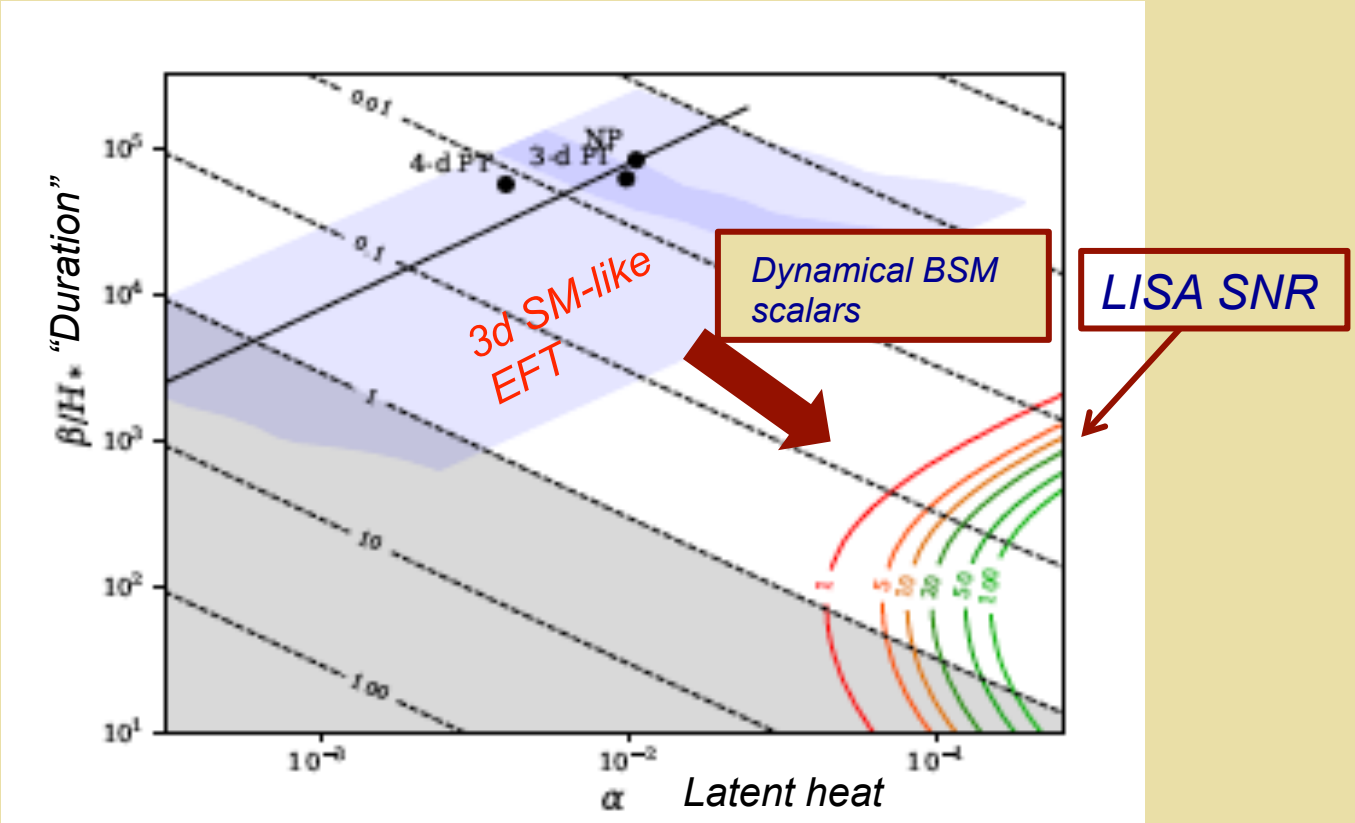



*LISA SNR*

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

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

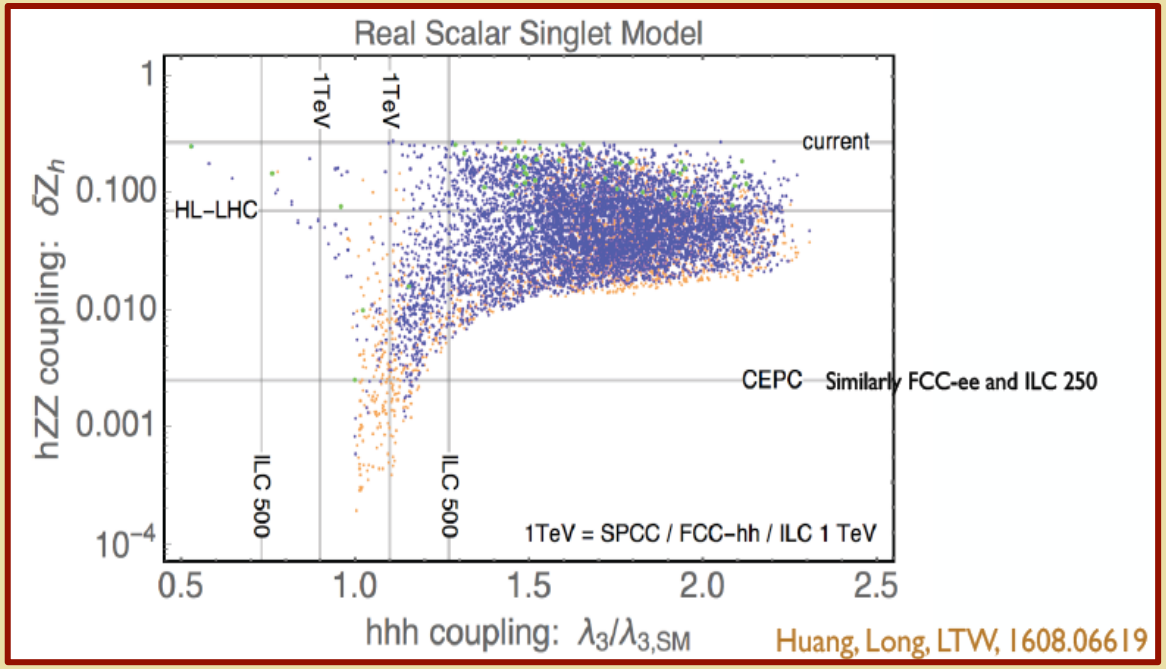
# Heavy Real Singlet: EWPT & GW




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

- One-step
- Non-perturbative

# Singlets: Associated Production




*Huang, Long, Wang 2016*

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

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

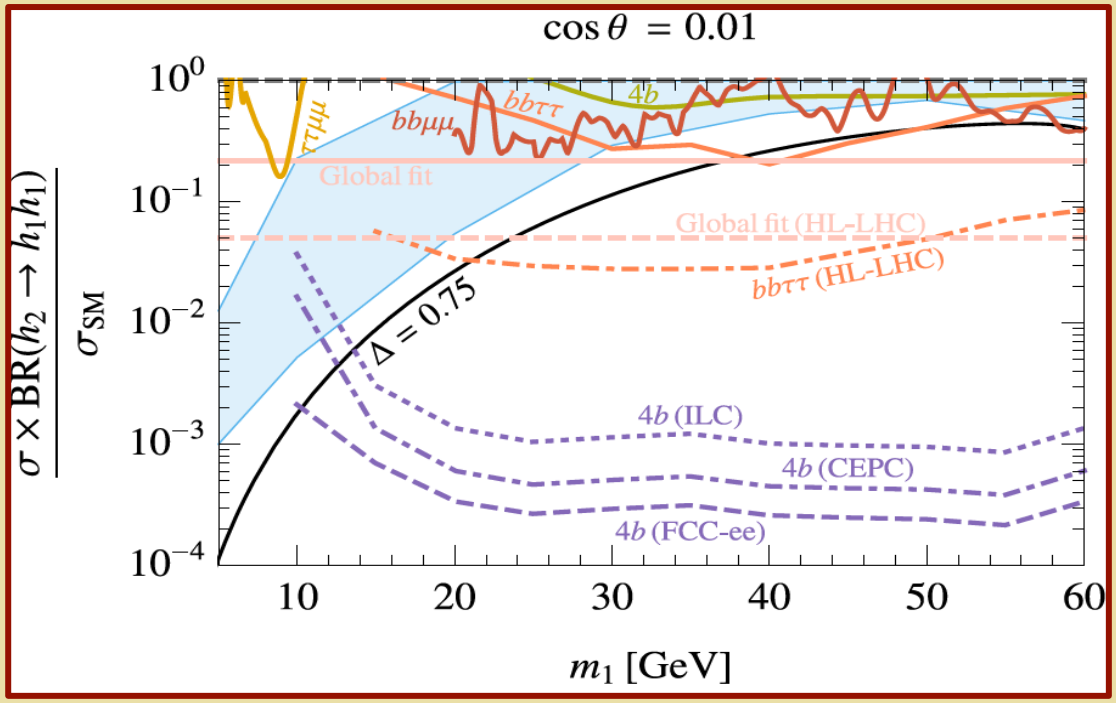
$$\frac{1}{(0.89\ \mathrm{TeV})^2} < -c_6 < \frac{1}{(0.55\ \mathrm{TeV})^2}$$

→ *Implications for* $\sigma_{Zh}$

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

# Singlets: Exotic Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

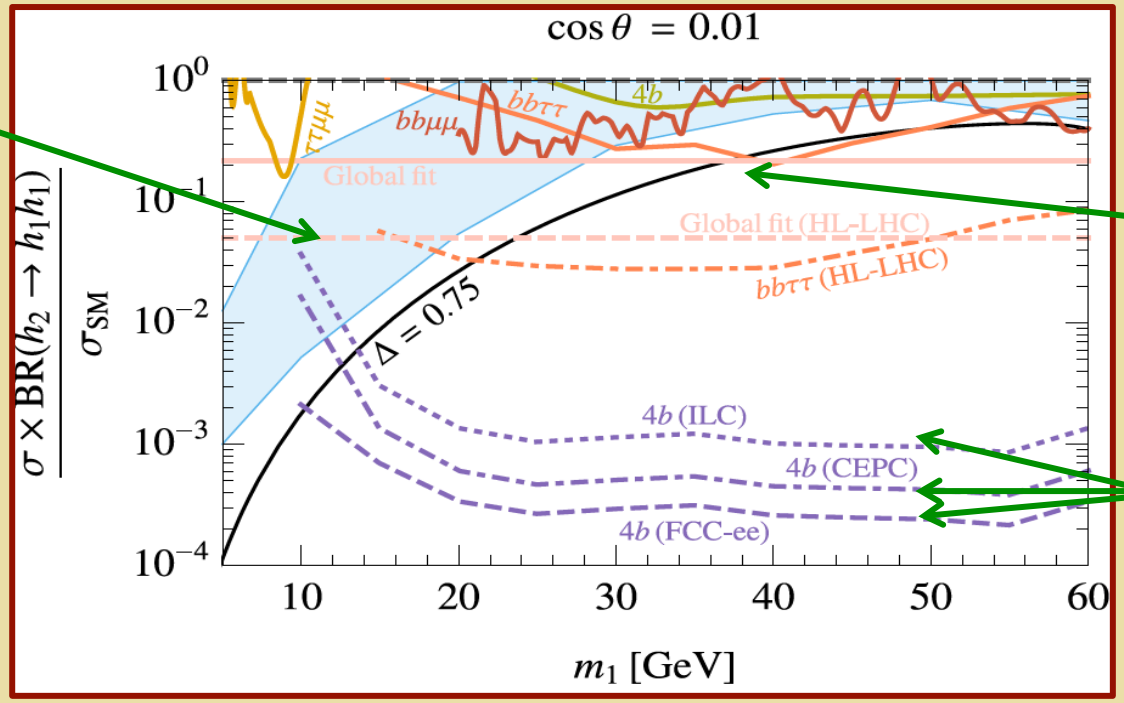



*J. Kozaczuk, MR-M, J. Shelton*
*1911.NNNNN*

# 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*