What Future Linear Colliders Can Do For Baryogenesis ?

M.J. Ramsey-Musolf

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

My pronouns: he/him/his

Linear Collider Workshop
Sendai, October 2019

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Key Ideas for this Talk I

- ***Explaining the baryon asymmetry is "easy" theoretically . Determining which idea (if any) was realized in nature is challenging.***
- ***Experiment can help by discovering ingredients and/or falsifying scenarios.***
- ***We have an opportunity to determine whether or not the baryon asymmetry was produced in conjunction with EW symmetry breaking→ important role for LC's***

Key Ideas for this Talk II

- ***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

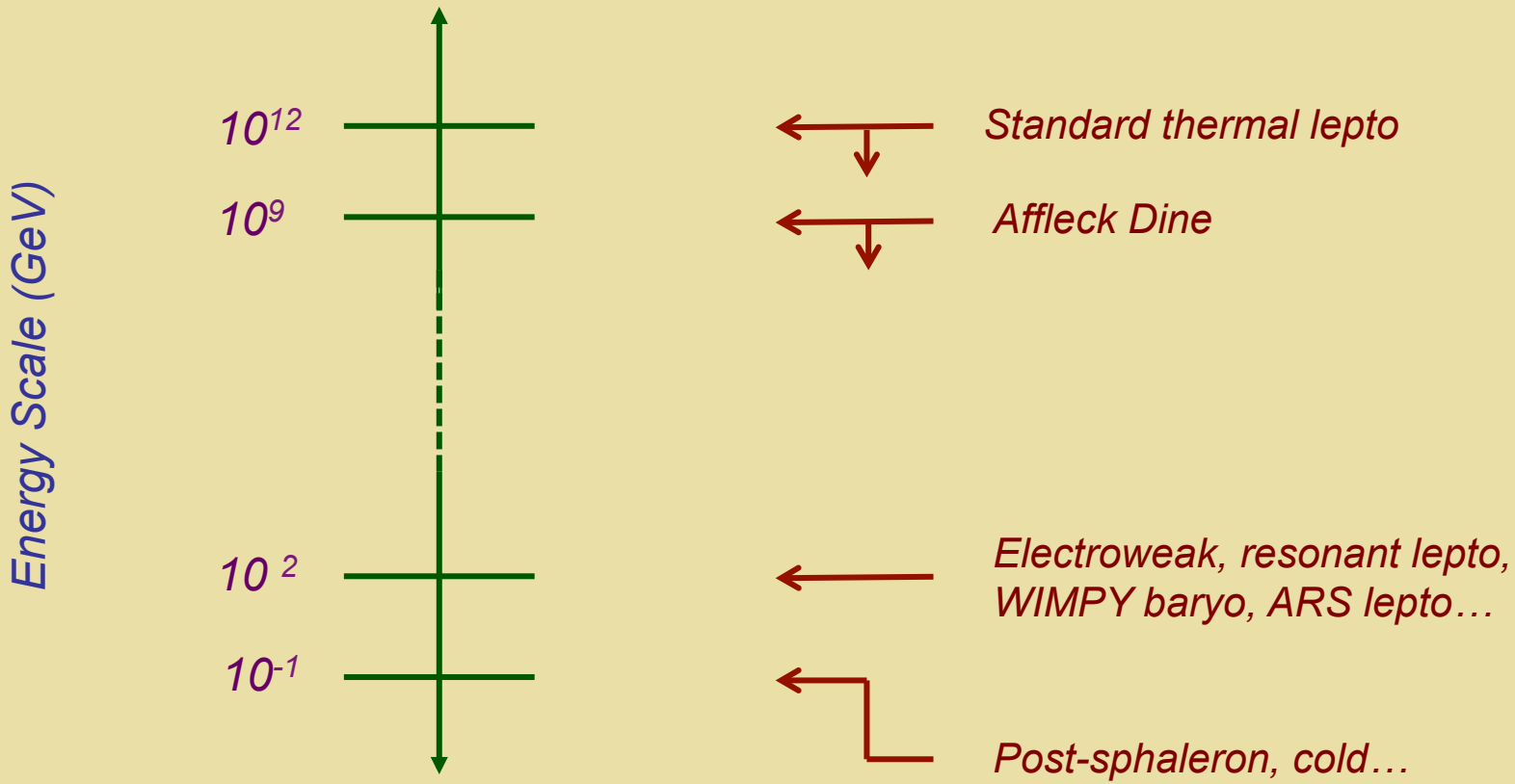
II. EWPT: A Collider Target

III. Model Illustrations

IV. Outlook

I. Context & Questions

Baryogenesis Scenarios



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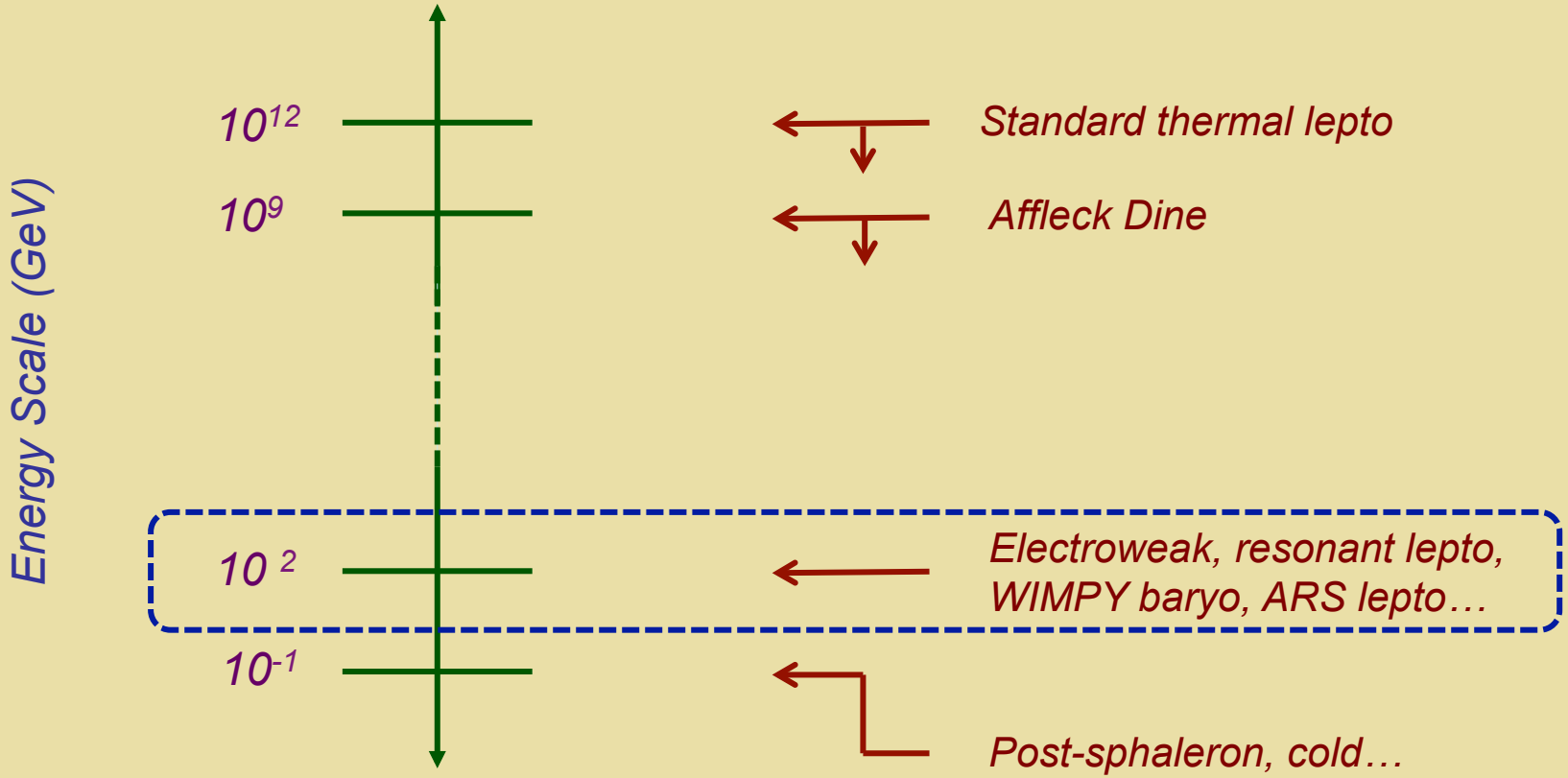
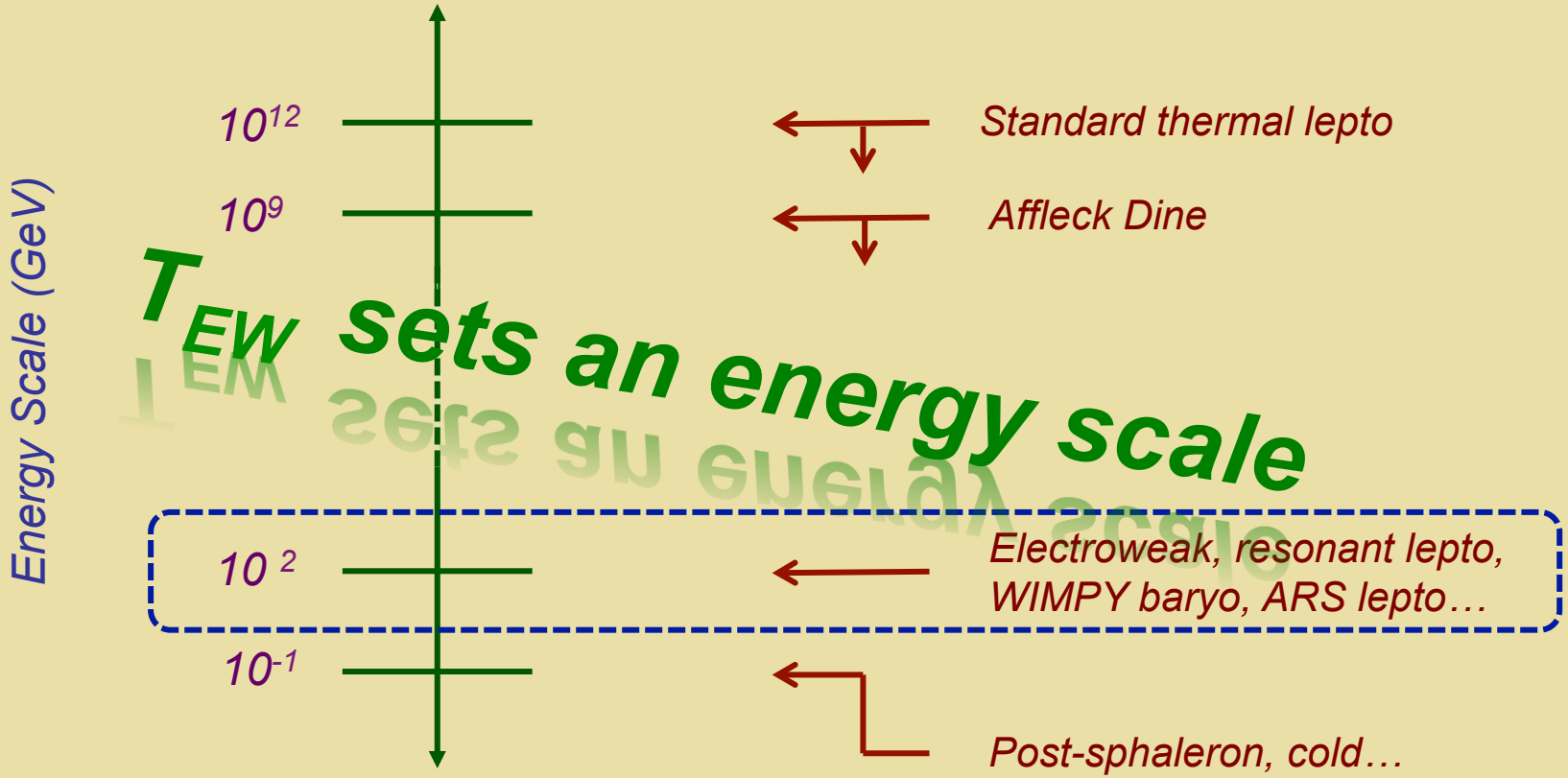


Era of EWSB: t_{univ} ~ 10 ps

Baryogenesis Scenarios



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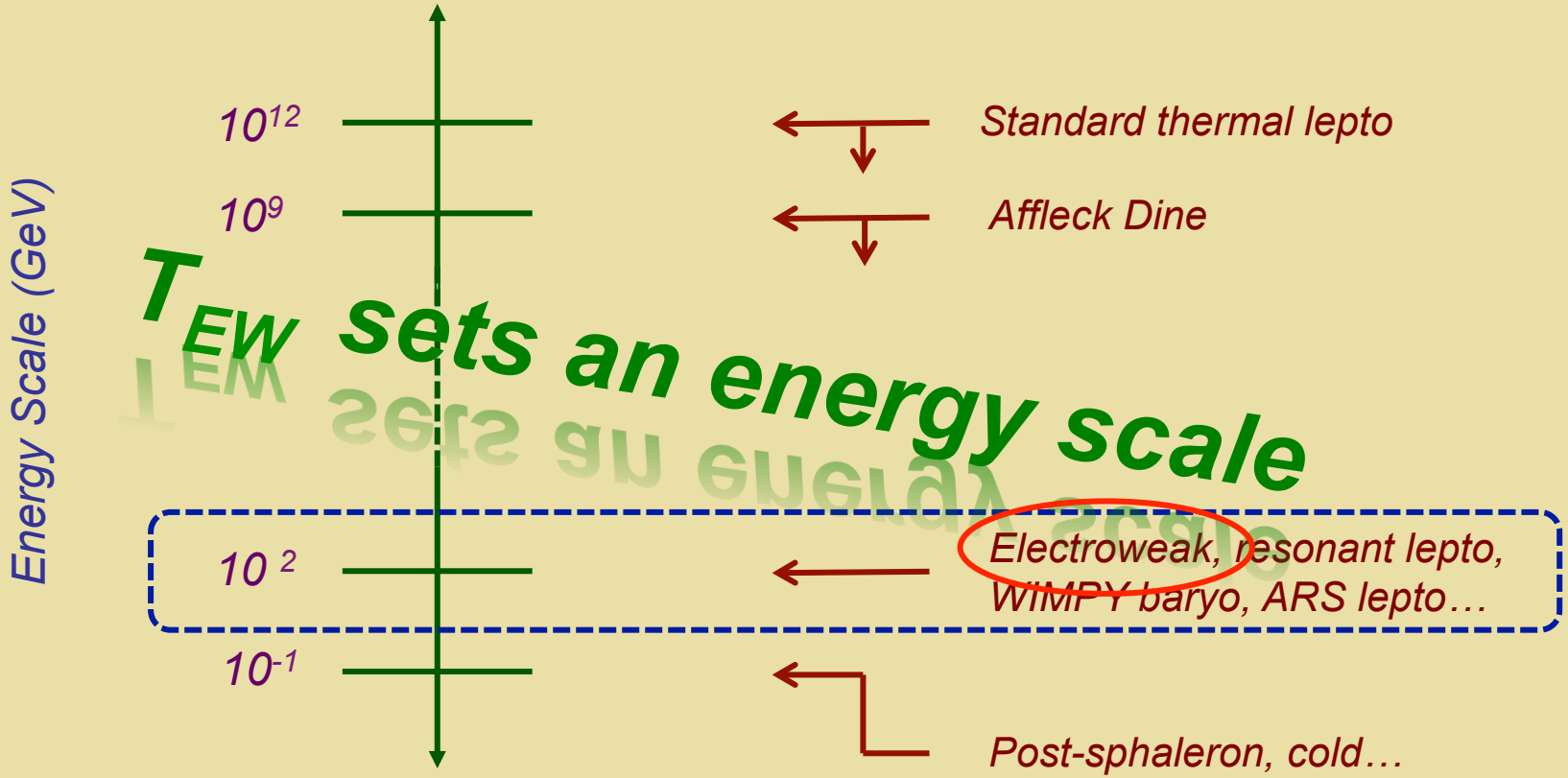

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Electroweak Baryogensis

- *Baryon number violation → SM electroweak sphalerons*
- *CPV → BSM*
- *Out of equilibrium → first order EW phase transition → BSM*

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Remainder of this talk

Electroweak Baryogensis

- *Baryon number violation → SM electroweak sphalerons*
- *CPV → BSM*

Questions, back up slides, informal discussions

- *Out of equilibrium → first order EW phase transition → BSM*

Remainder of this talk

Main Theme for This Talk

T_{EW} → EW phase transition is a target for the LHC & beyond

II. EWPT: A Collider Target

MJRM 19010.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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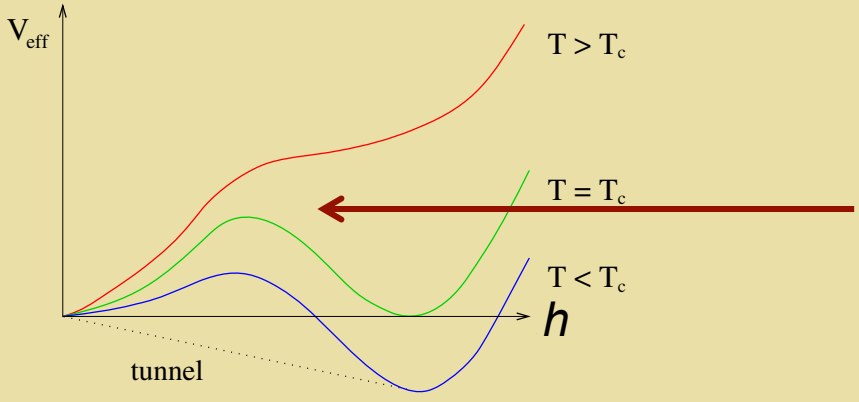
$T_0 \sim$ 140 GeV $\equiv \ T_{EW}$

First Order EWPT from BSM Physics



Generate finite-T barrier

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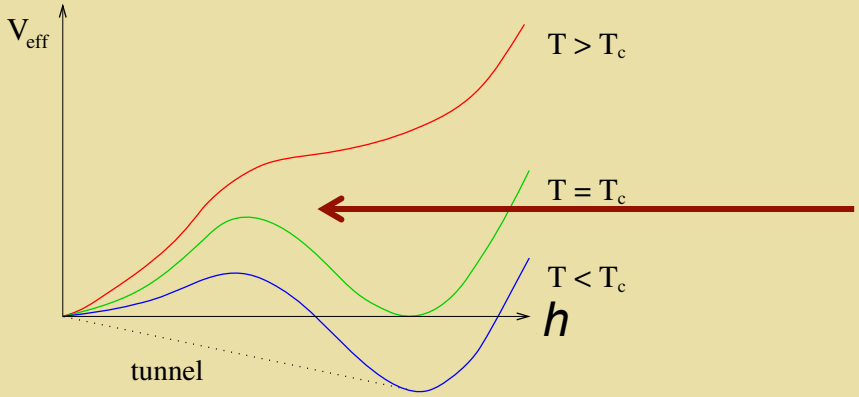
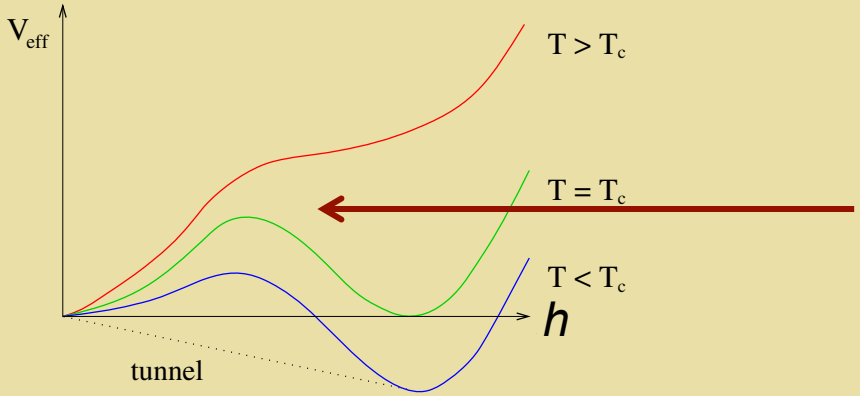


Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

First Order EWPT from BSM Physics



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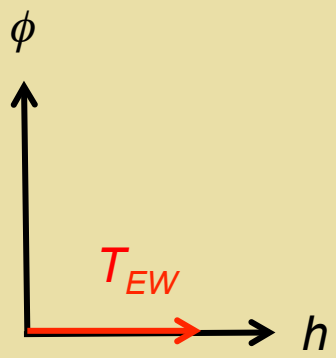

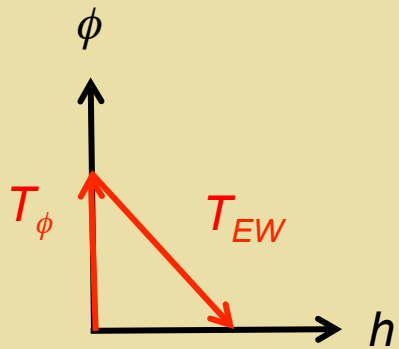

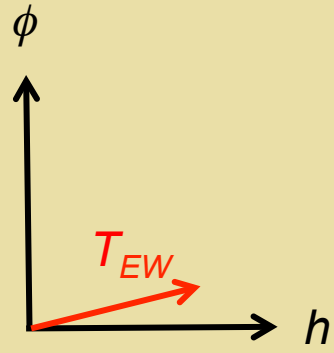

$a_2 H^2\phi^2$: $T > 0$
loop effect

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

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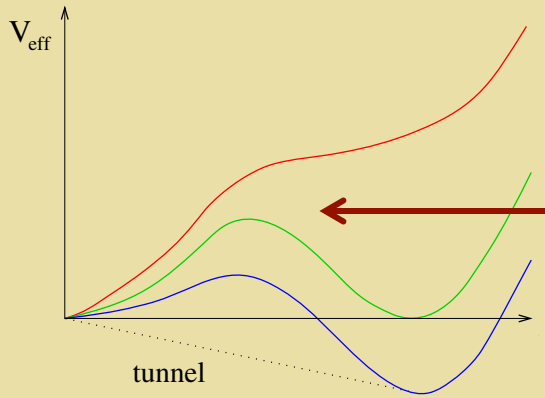
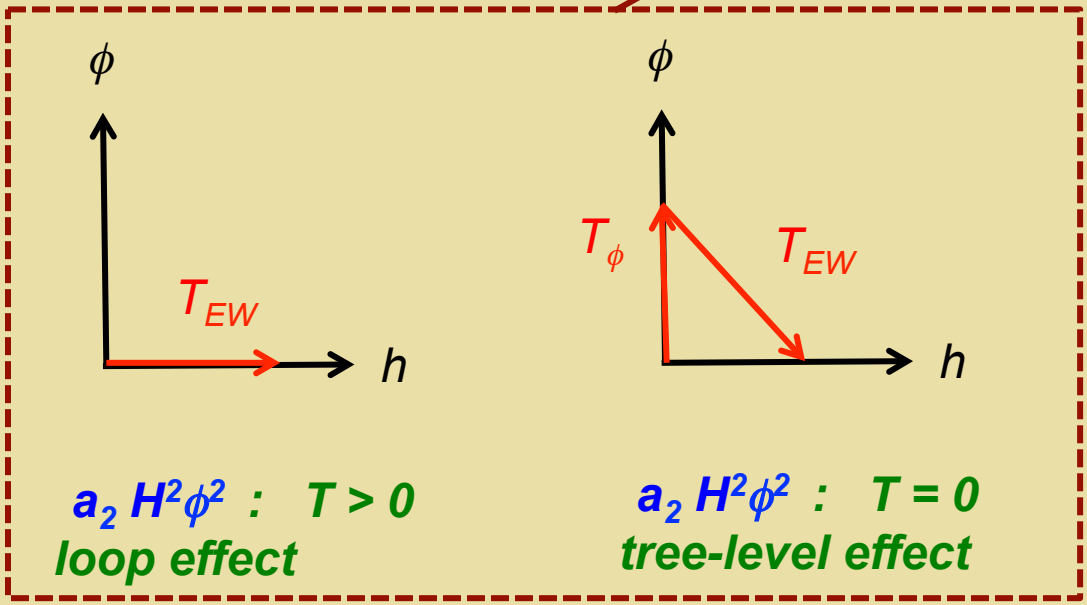


Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV



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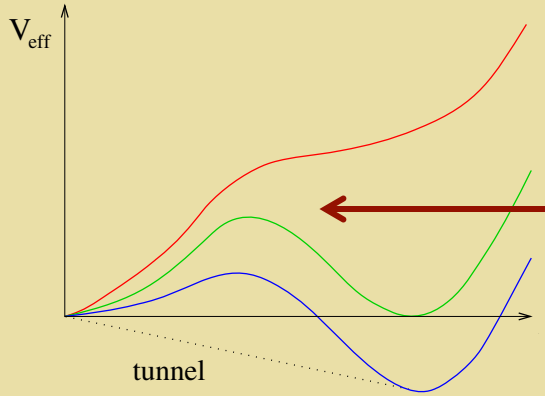

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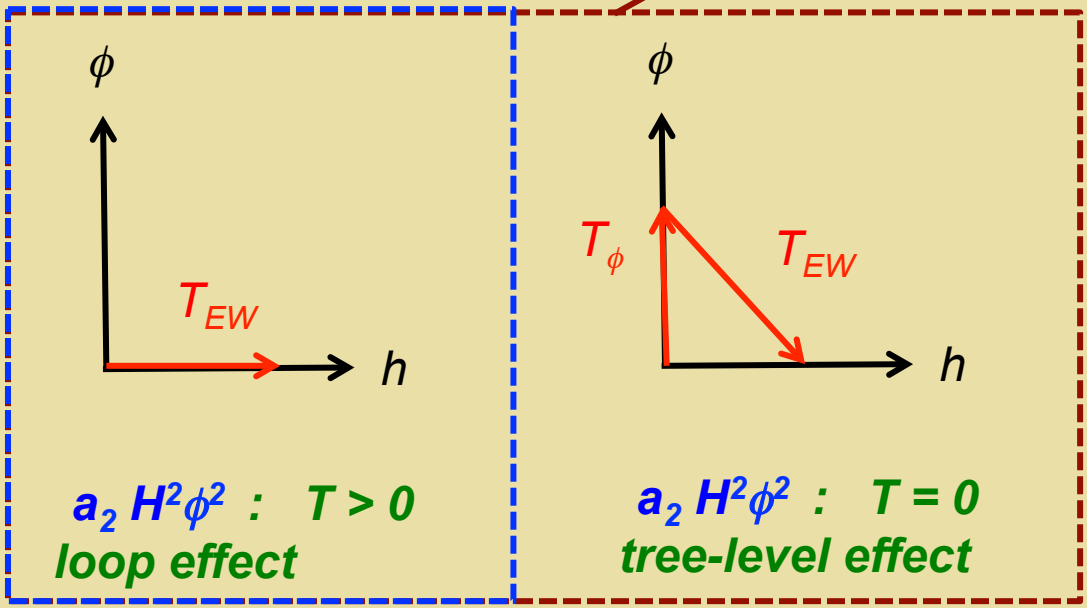

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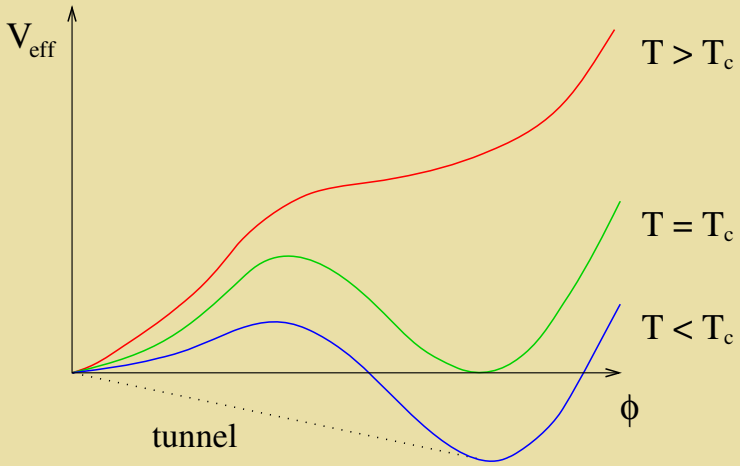

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$$M_\phi(h,T)^3 = \left[\frac{a_2}{6}T^2 + b_2 + \frac{a_2}{2}h^2\right]^{3/2}$$

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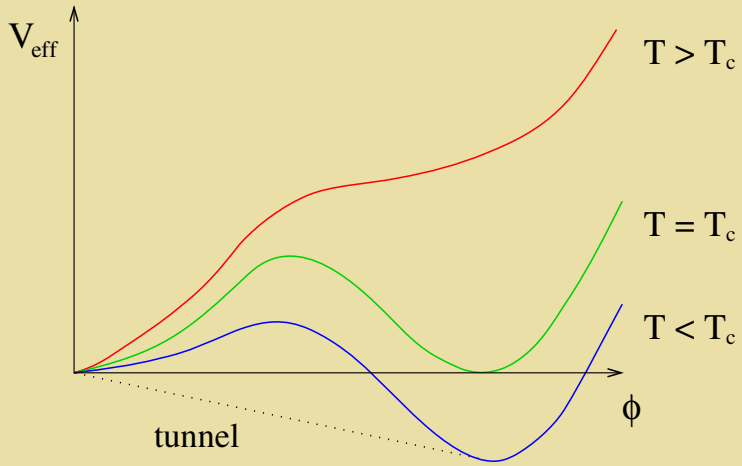

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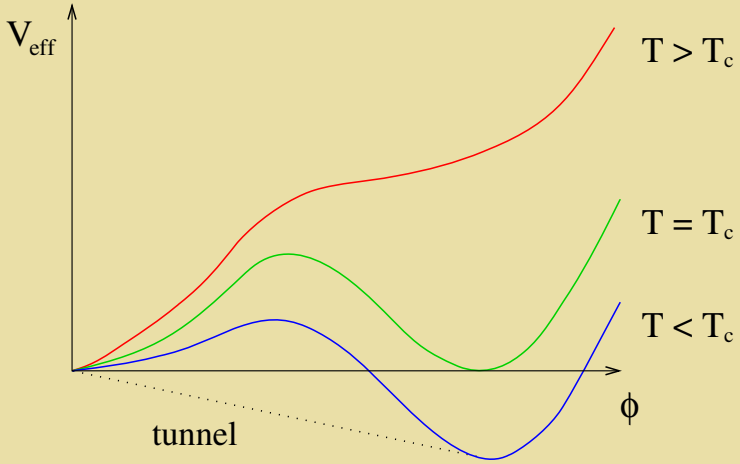

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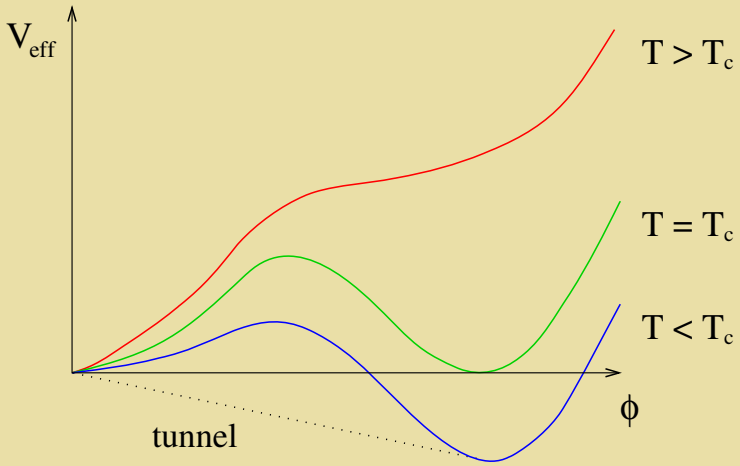

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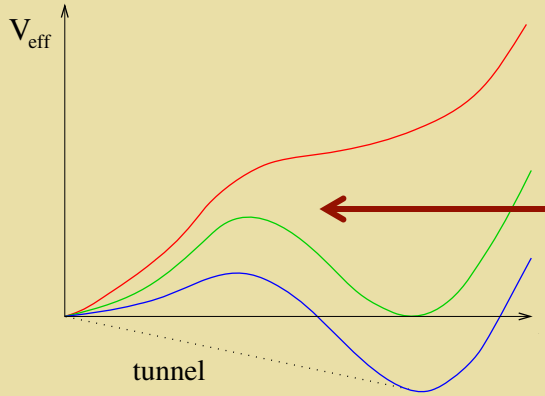
M_ϕ < 350 GeV for perturbative a_2

First Order EWPT from BSM Physics



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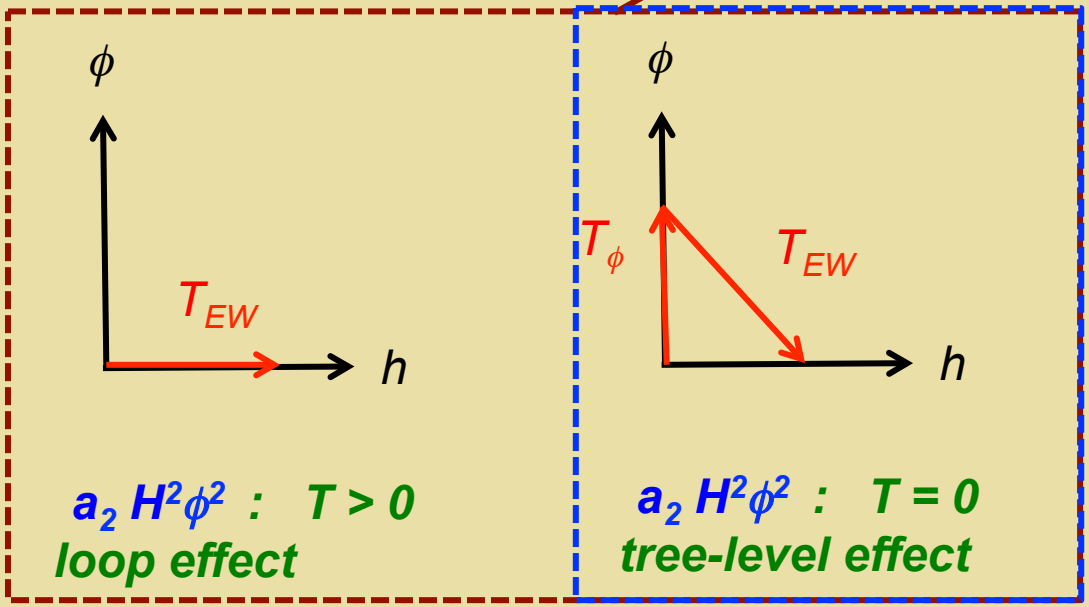
Analogous logic



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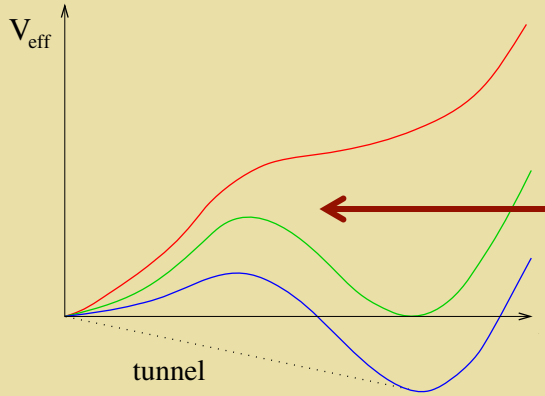

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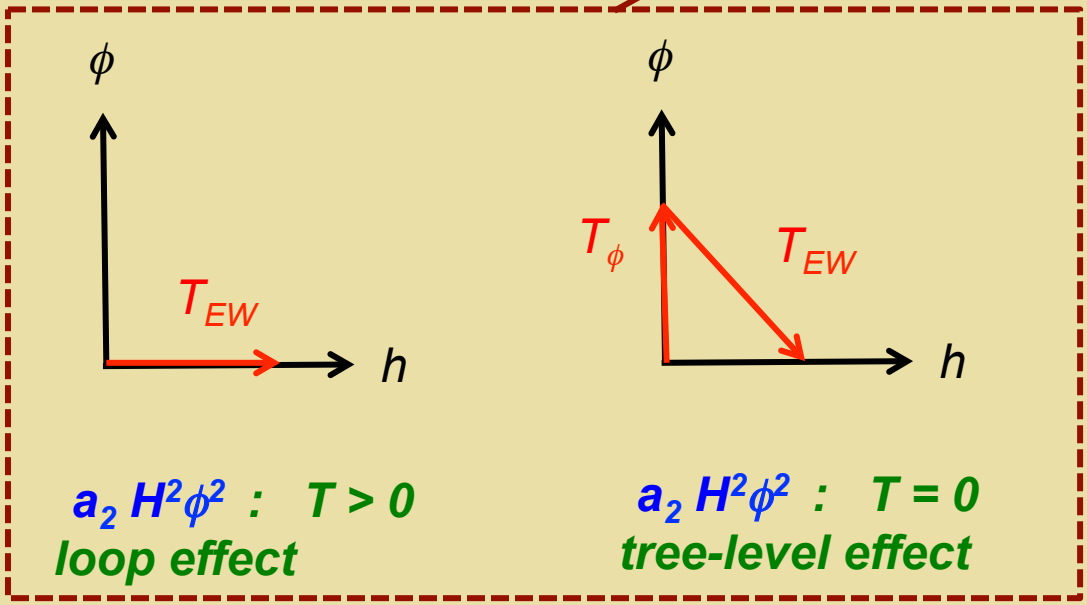

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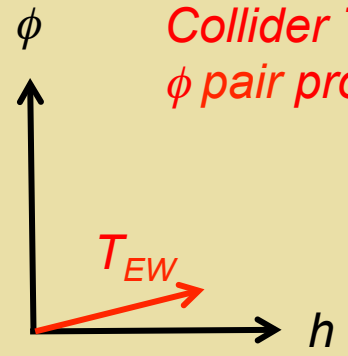


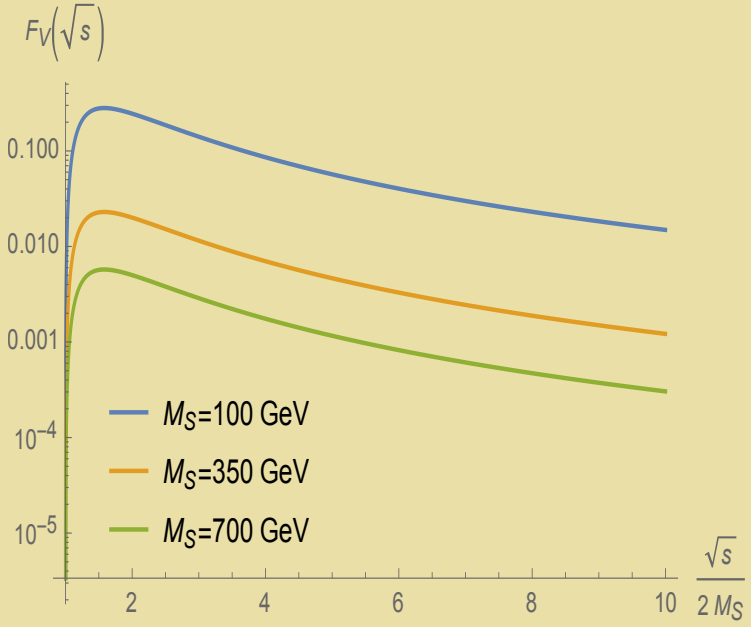
Collider Target: ϕ pair production

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

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

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

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	1.5	19.5
	440	7 fb	1.5	10.5
3000	440	3 fb	2	6
	700	2 fb	2	4

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***

First Order EWPT from BSM Physics

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$H^2\phi^2$ Barrier ?

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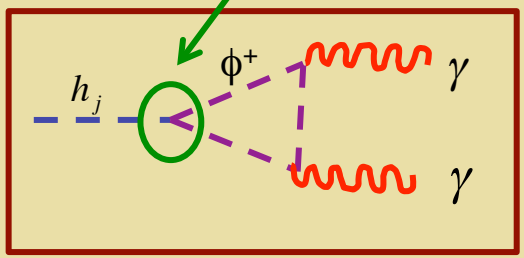
ϕ : EW Multiplet



First Order EWPT from BSM Physics

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- **Higgs signal strengths**
- **Higgs self-coupling**

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

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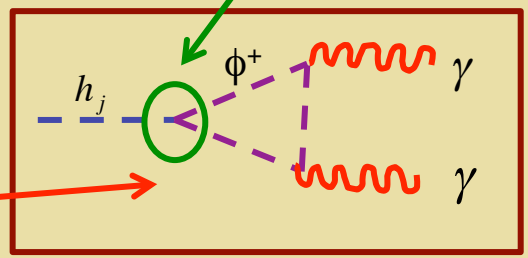


Collider Target: Precision

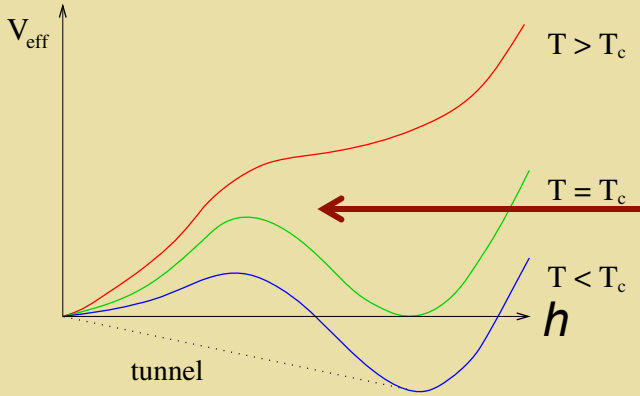
First Order EWPT from BSM Physics

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

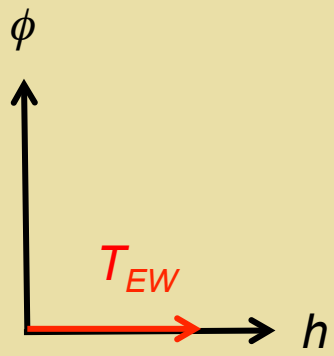
- Higgs signal strengths
- Higgs self-coupling

$H^2\phi$ Barrier ?

First Order EWPT from BSM Physics



Higgs − ϕ^0 Mixing



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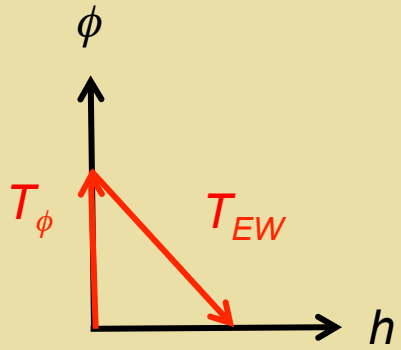
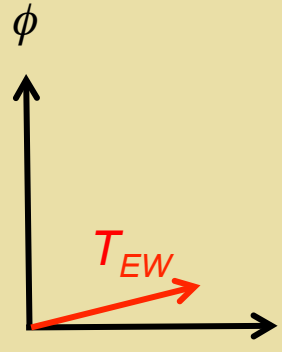
loop effect



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



$a_1 H^2\phi$: $T = 0$
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- Thermal $\Gamma(h \rightarrow \gamma\gamma)$

- Higgs signal strengths
- Higgs self-coupling

$H^2\phi$ Barrier ?

H-ϕ Mixing

First Order EWPT from BSM Physics

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

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H-ϕ Mixing

- Single ϕ production

Strong First Order EWPT

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

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

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

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

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

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

Strong First Order EWPT

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

Collider Target: Precision and single ϕ production

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

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

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

III. Models & Phenomenology

Model Illustrations

Simple Higgs portal models:

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

Model Illustrations

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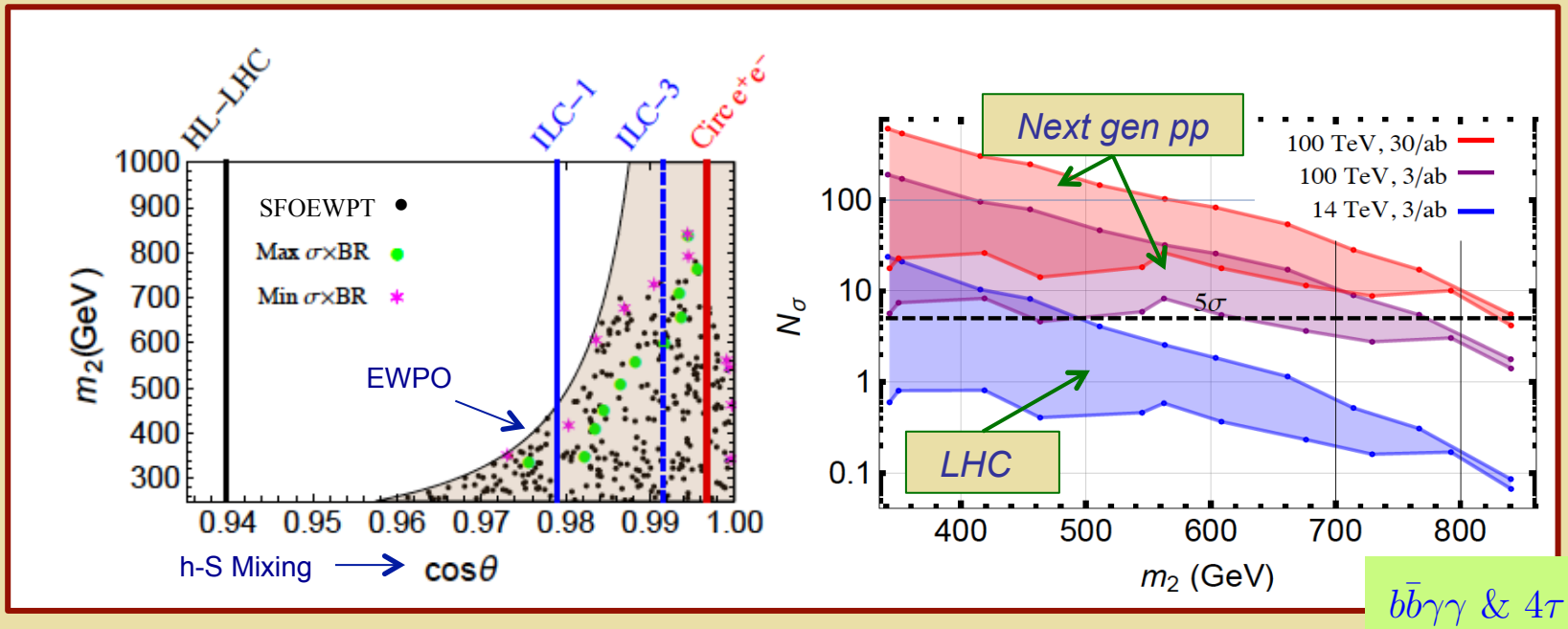
Singlets: Precision & Res Di-Higgs Prod

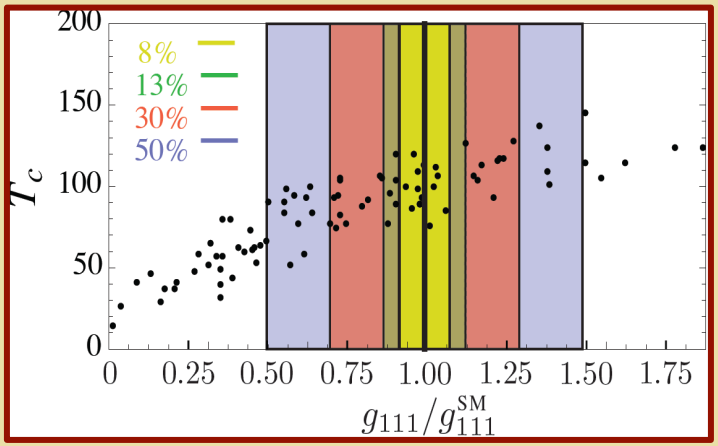
SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

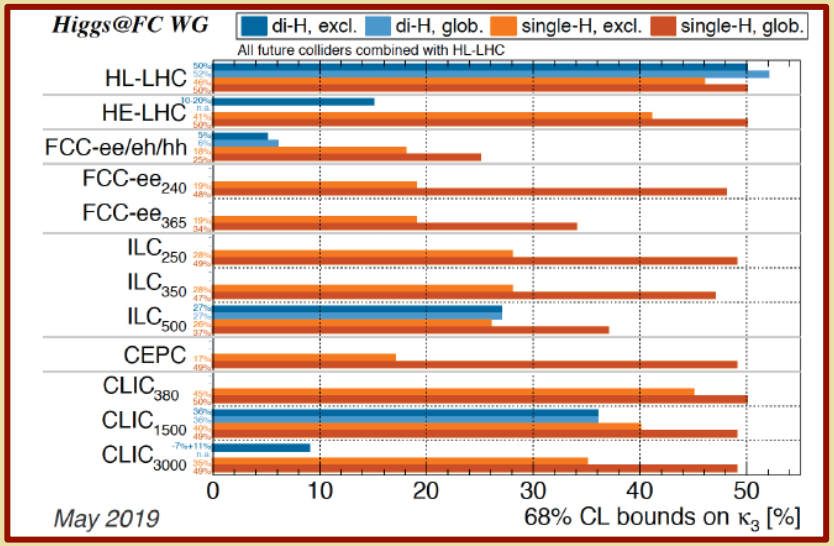


Kotwal, No, R-M, Winslow 1605.06123

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

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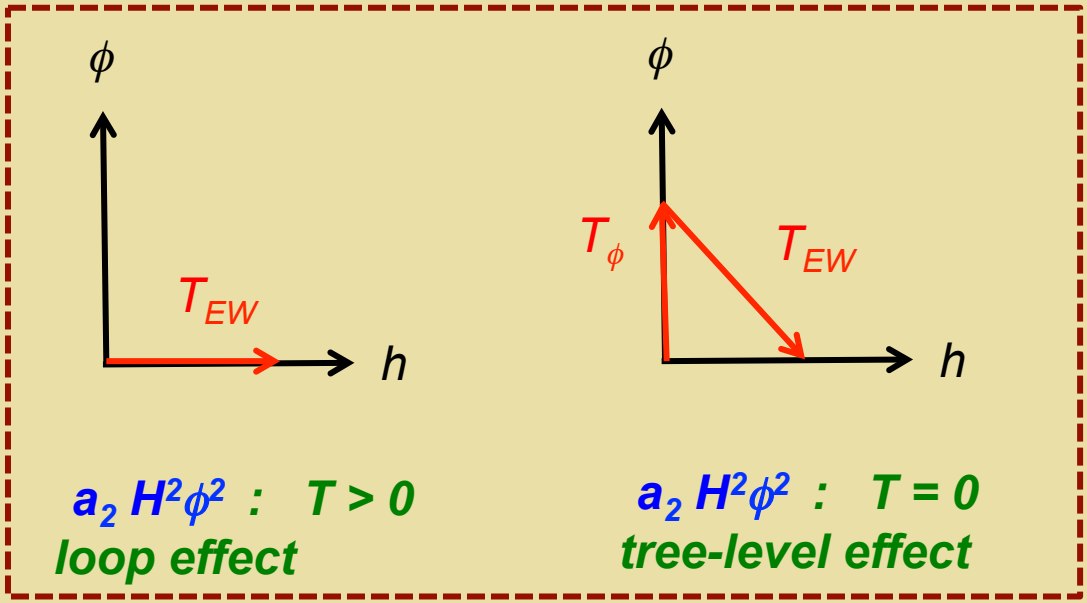
Real Triplet



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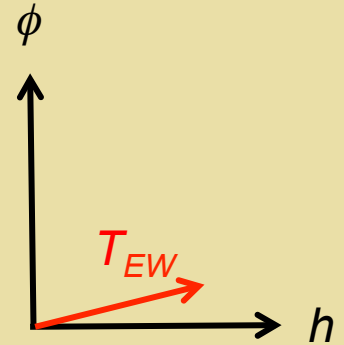
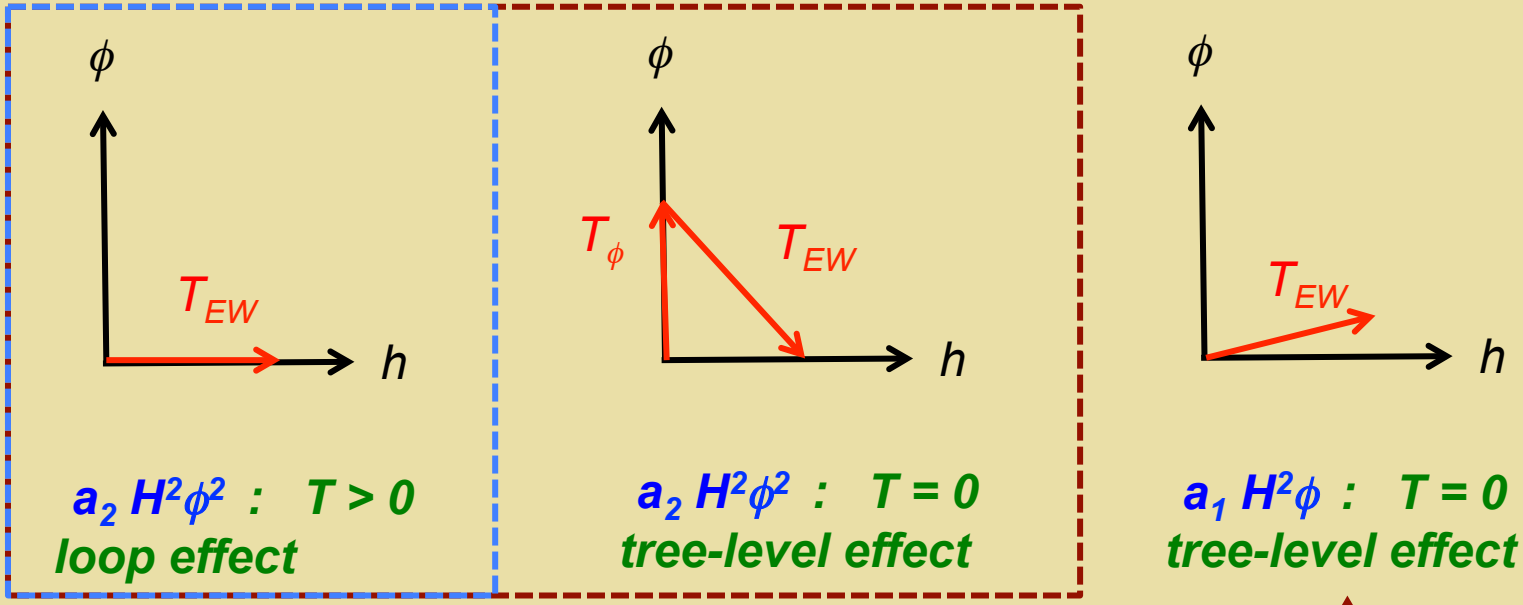


$a_1 H^2\phi$: $T = 0$
tree-level effect

EW precision tests → too tiny

Real Triplet

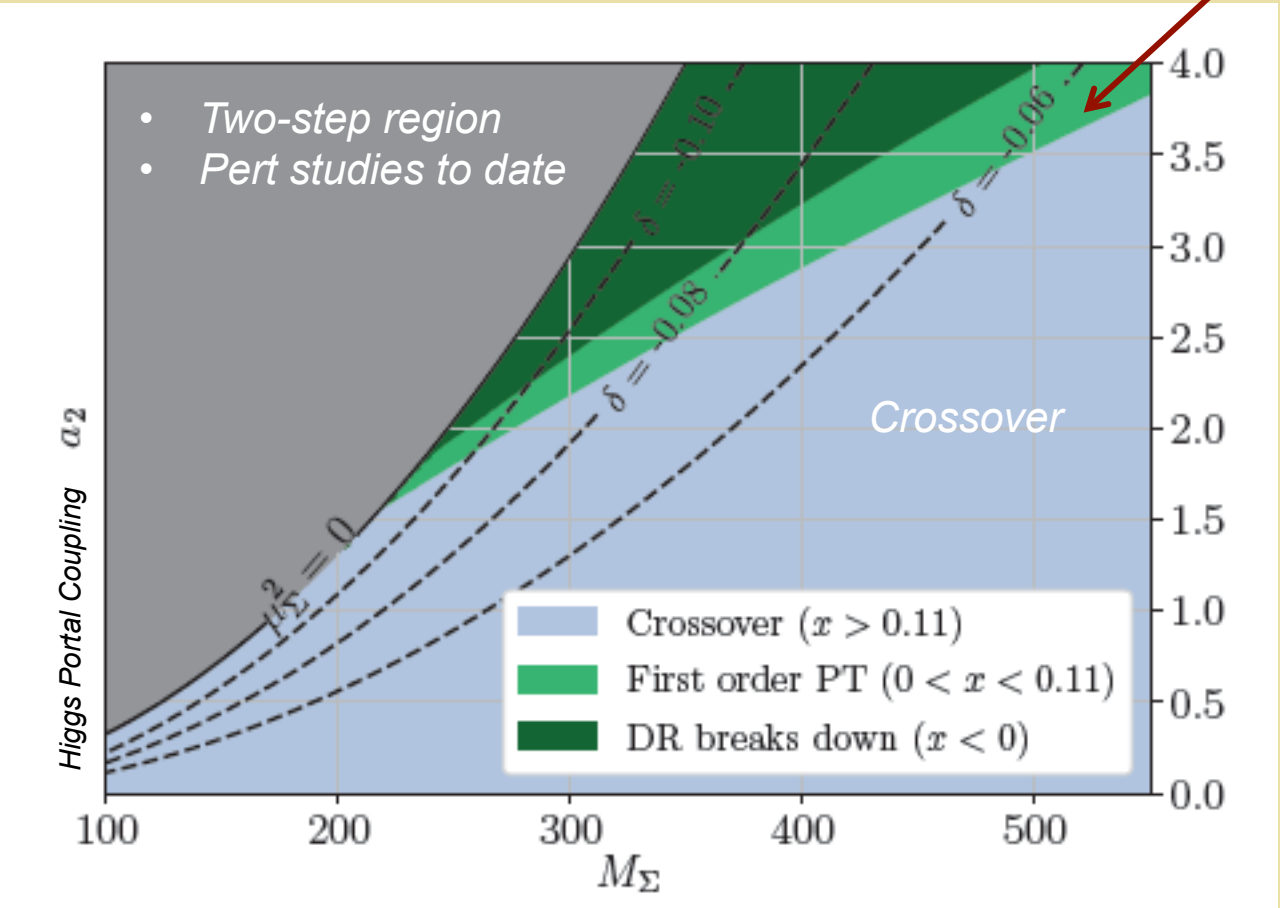


Non-perturbative results

EW precision tests → too tiny

Real Triplet: One-Step EWPT

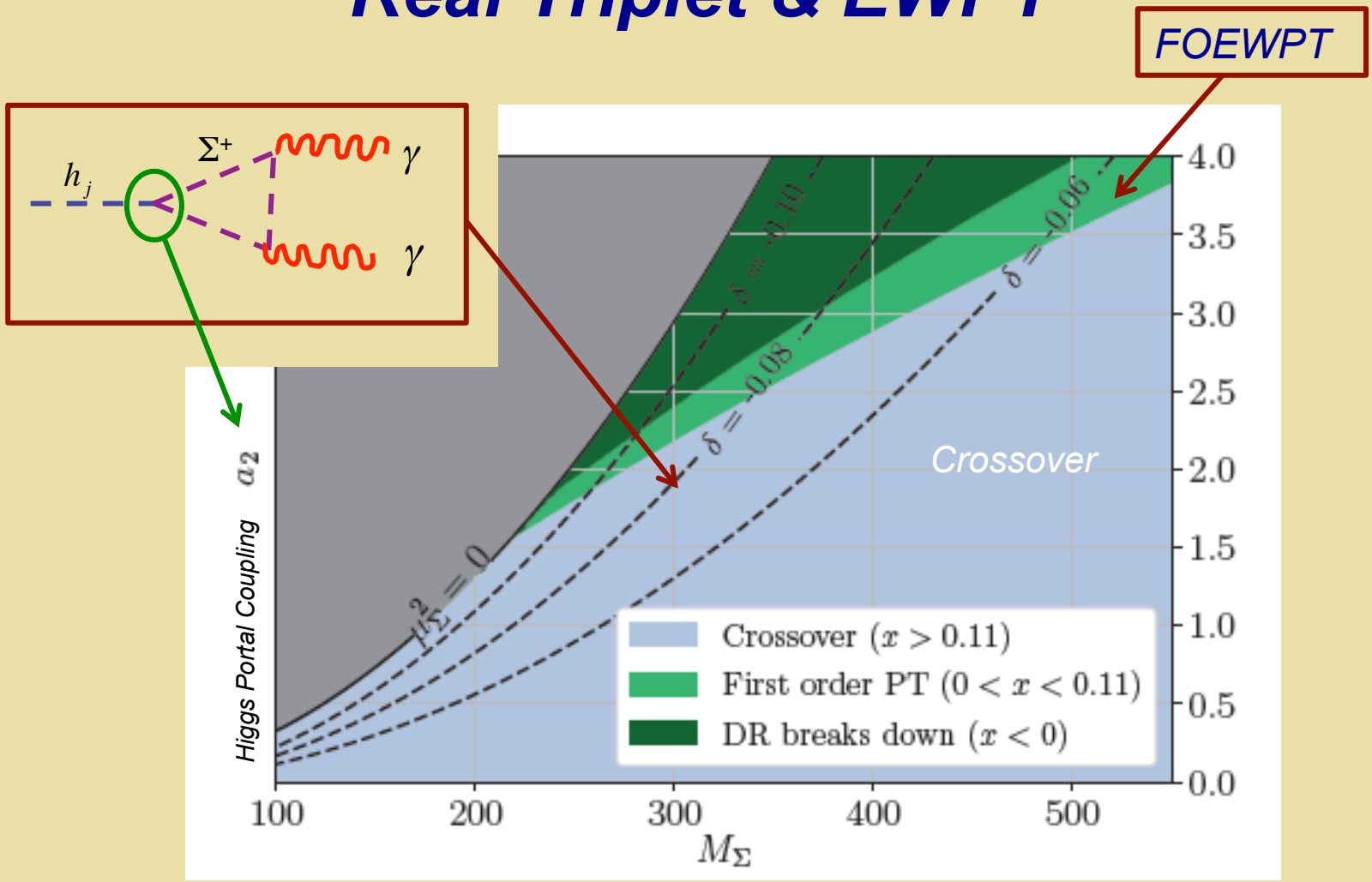
FOEWPT



- One-step
- Non-perturbative

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

Real Triplet & EWPT

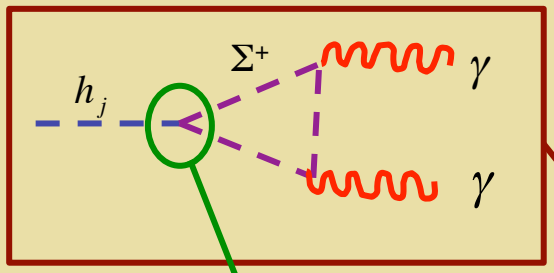


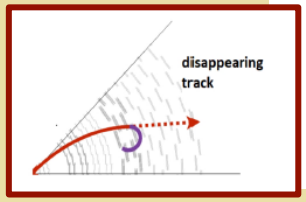
- *One-step*
- *Non-perturbative*

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

Real Triplet & EWPT

FOEWPT





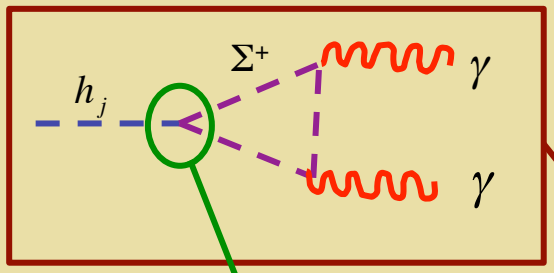
Disappearing charge track

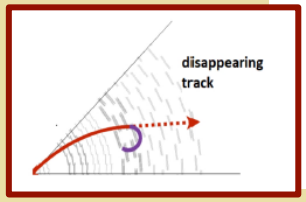
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

- One-step
- Non-perturbative

Real Triplet & EWPT

FOEWPT





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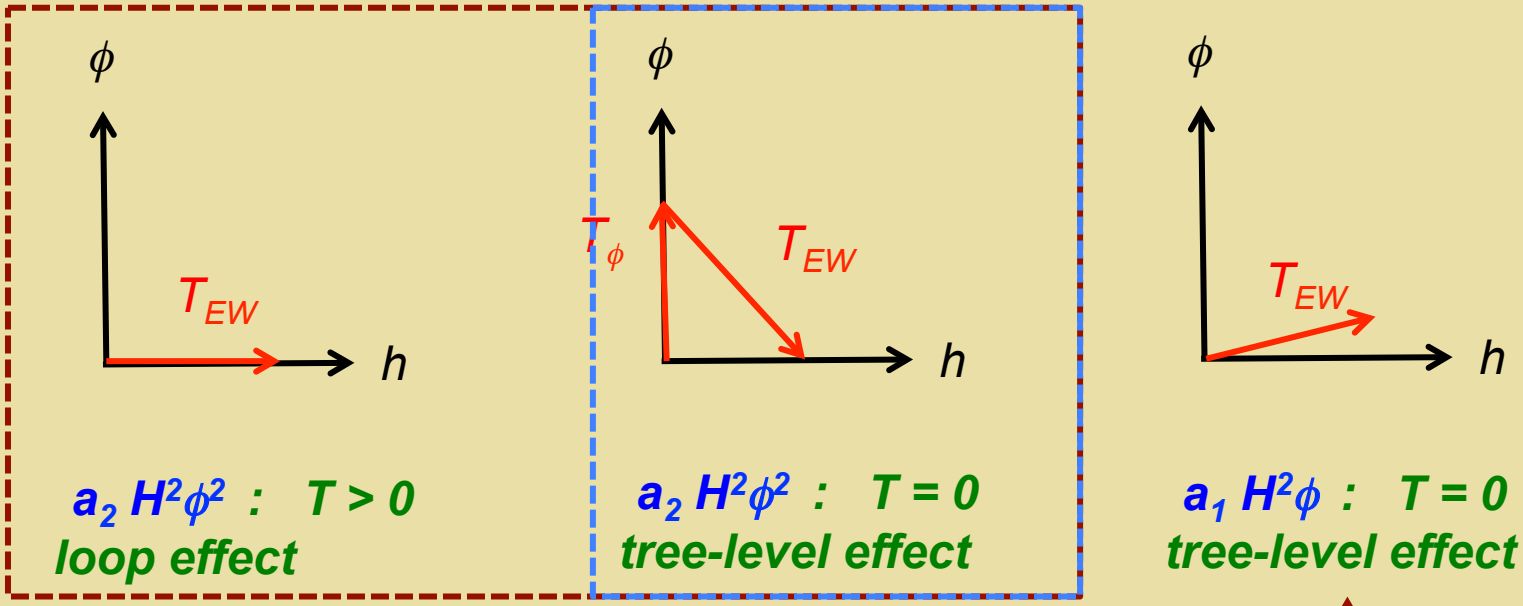
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

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

Pert theory: back-up slides

EW precision tests → too tiny

V. Outlook

- ***Explaining Y_B is "easy" . Determining which idea (if any) was realized in nature is challenging.***
- ***Experiment can help by discovering ingredients and/ or falsifying theoretical ideas***
- ***The present and prospective future collider program can "map out" the thermal history of EWSB and determine whether or not the preconditions (out of equilibrium) existed for producing Y_B in conjunction ~ 10ps after the big bang in conjunction with EWSB***

谢谢

Back Up Slides

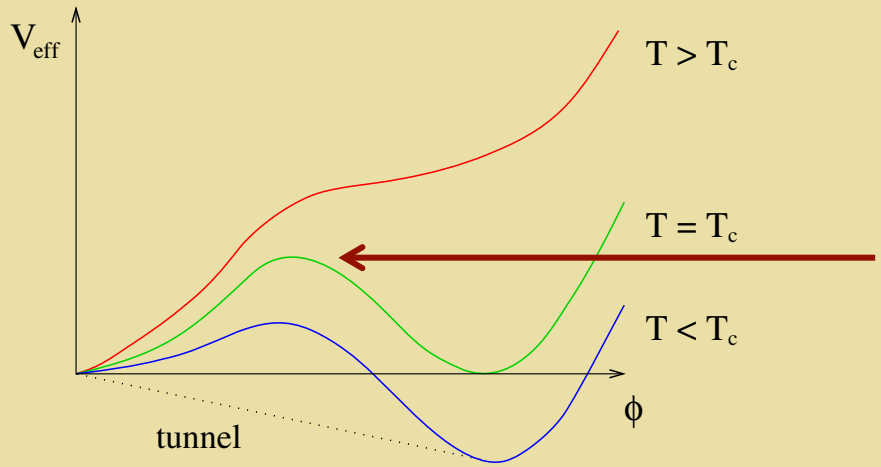
First Order EWPT from BSM Physics

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

First Order EWPT from BSM Physics

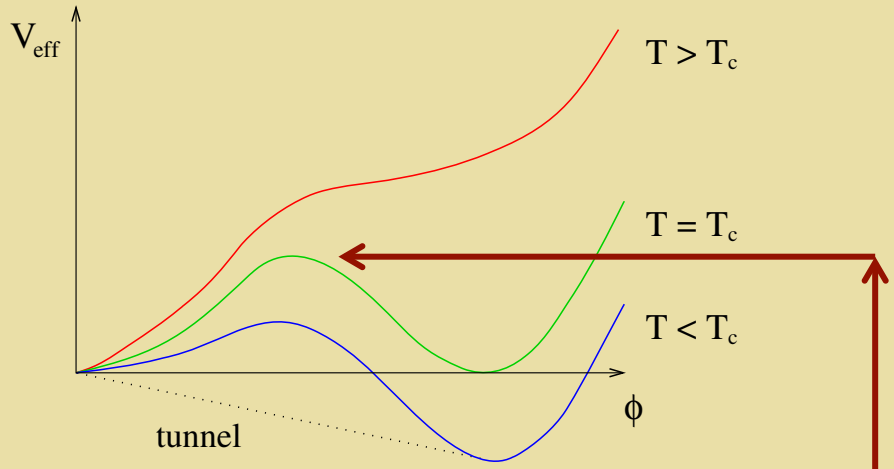
- *Thermal loops involving new bosons*
- *T=0 loops (CW Potential)*
- *Change tree-level vacuum structure*

First Order EWPT from BSM Physics



Generate finite-T barrier

First Order EWPT from BSM Physics



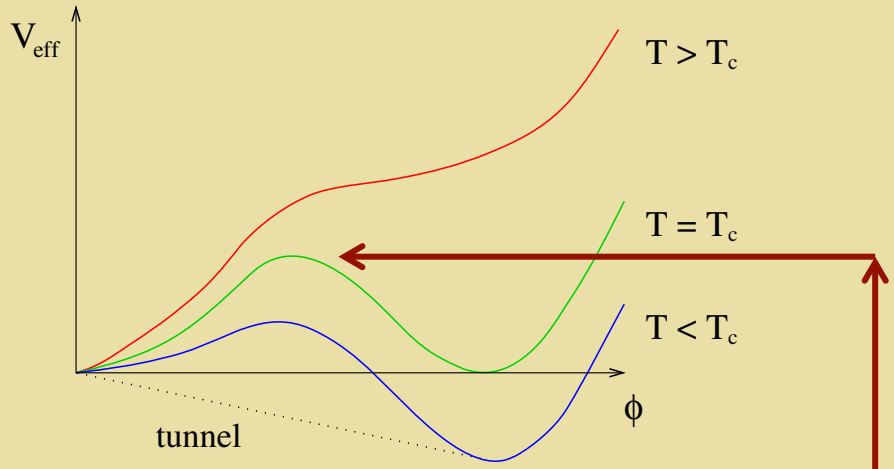
Generate finite-T barrier

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

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

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

First Order EWPT from BSM Physics



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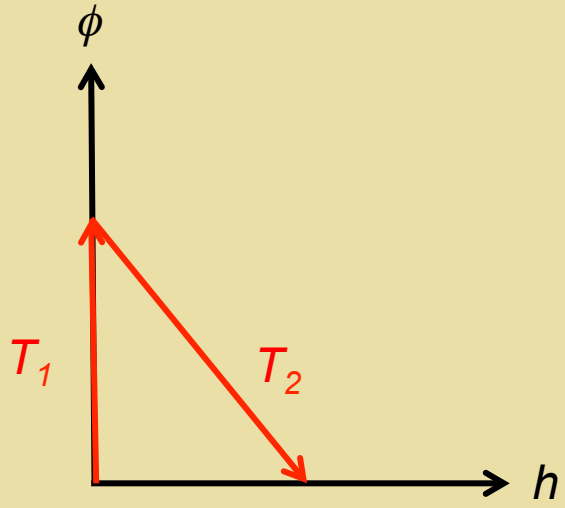
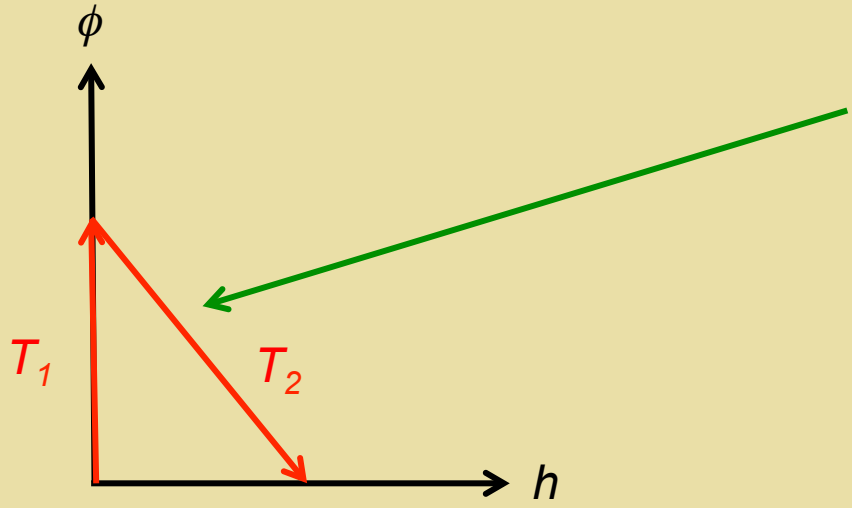
First Order EWPT from BSM Physics

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

First Order EWPT from BSM Physics

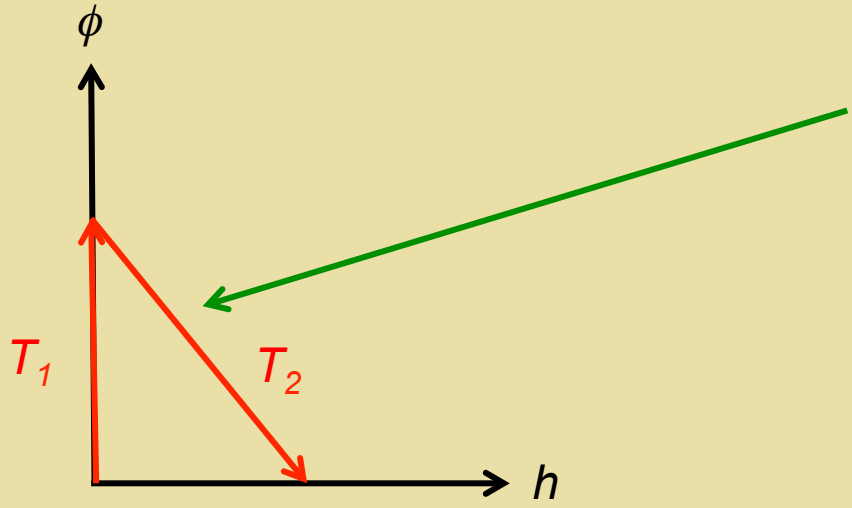


First Order EWPT from BSM Physics



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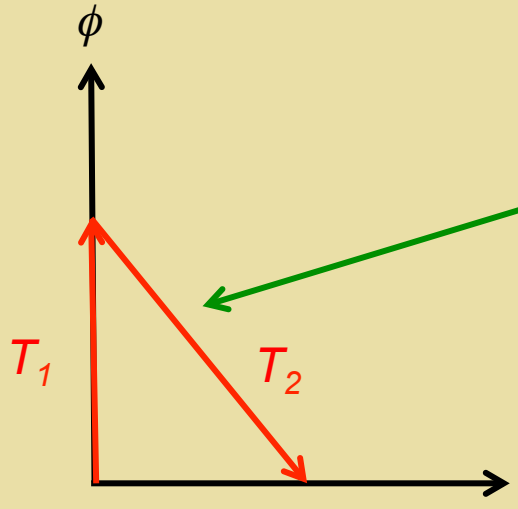
$$V(\varphi,T)=\frac{1}{2}\left[-|b_2|+\frac{T^2}{6}\left(a_2+\frac{3}{2}b_4\right)\right]\varphi^2+\frac{b_4}{4!}\varphi^4$$

First Order EWPT from BSM Physics

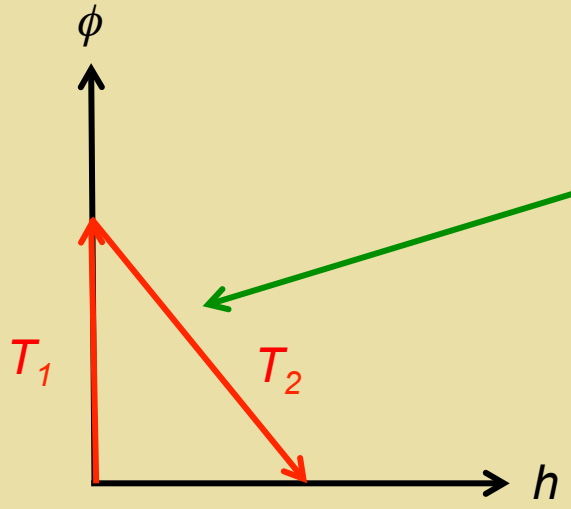


- *Tree-level barrier: $a_2\,\phi^+\phi\,H^+H$*
- *Want $T_1 > T_2 \sim T_{EW}$*

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

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

First Order EWPT from BSM Physics



- *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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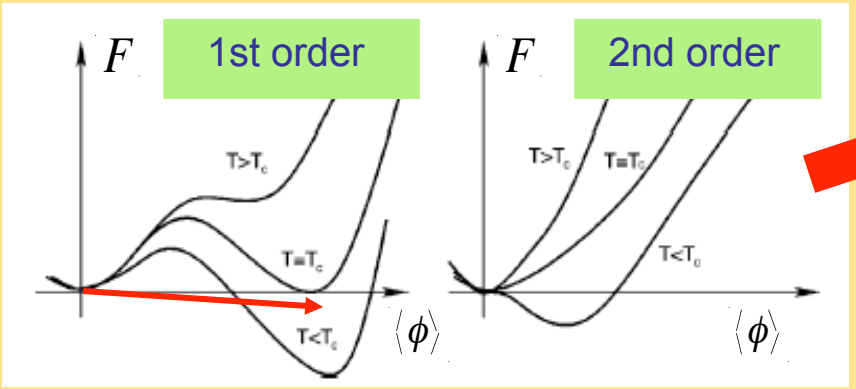
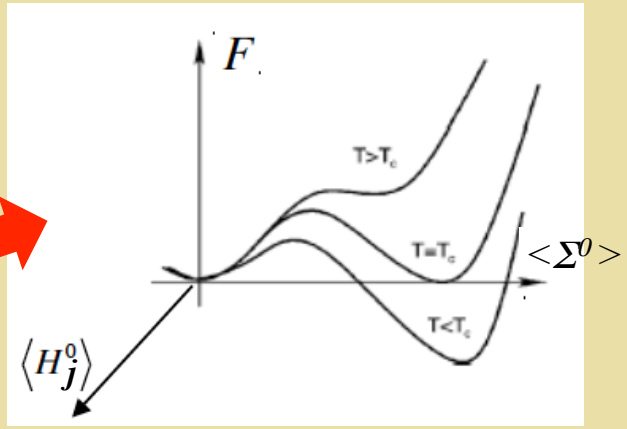
EW Multiplets: EWPT





Increasing m_h →

← *New scalars*

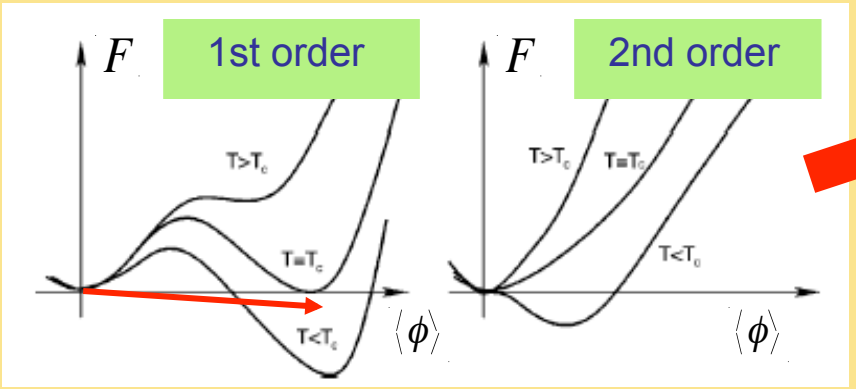
- *Thermal loops*
- *Tree-level barrier*

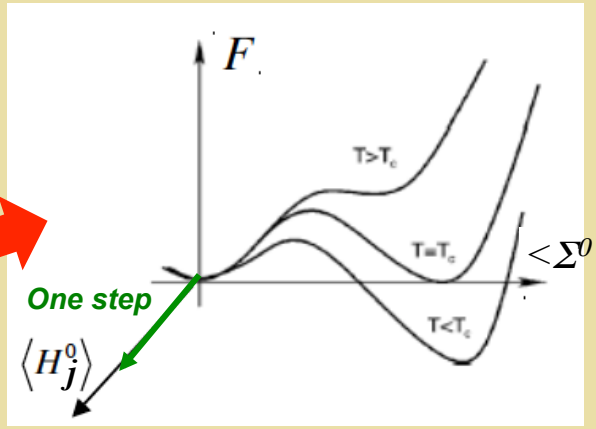
Illustrate with real triplet: $\Sigma \sim (1,3,0)$

$H^2\phi^2$ Barrier ?

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

EW Multiplets: One-Step EWPT





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 ?

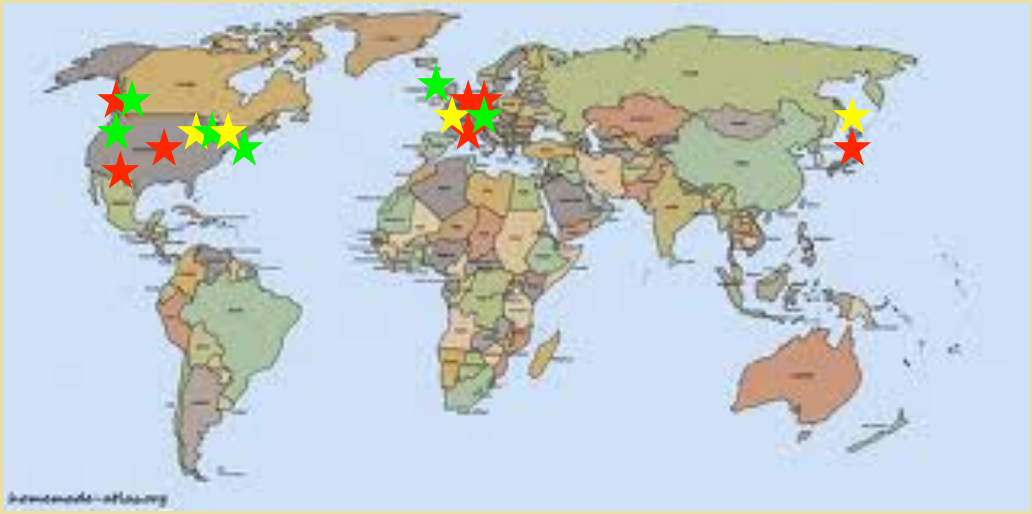
Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

CPV for EW Baryogenesis

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-35}	10^{-30}
ThO	1.1×10^{-29} **	10^{-38}	10^{-29}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent



★ neutron

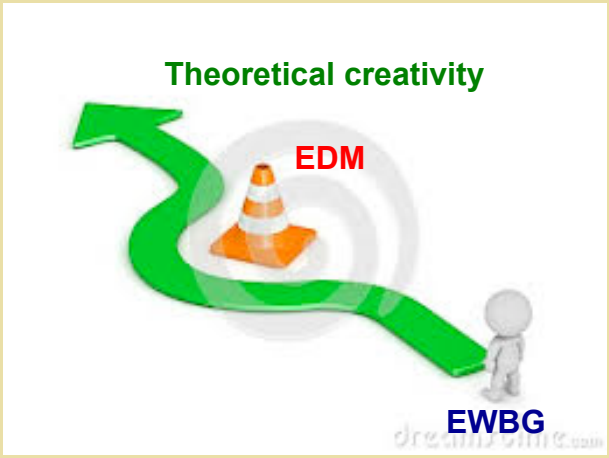
★ proton & nuclei

★ atoms

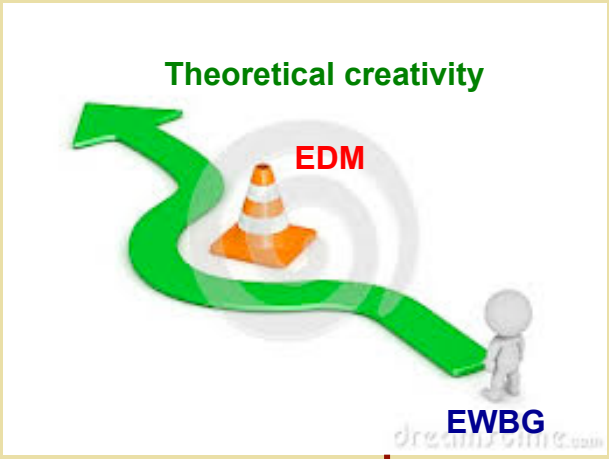
~ 100 x better sensitivity

Not shown: muon

CPV for EWBG



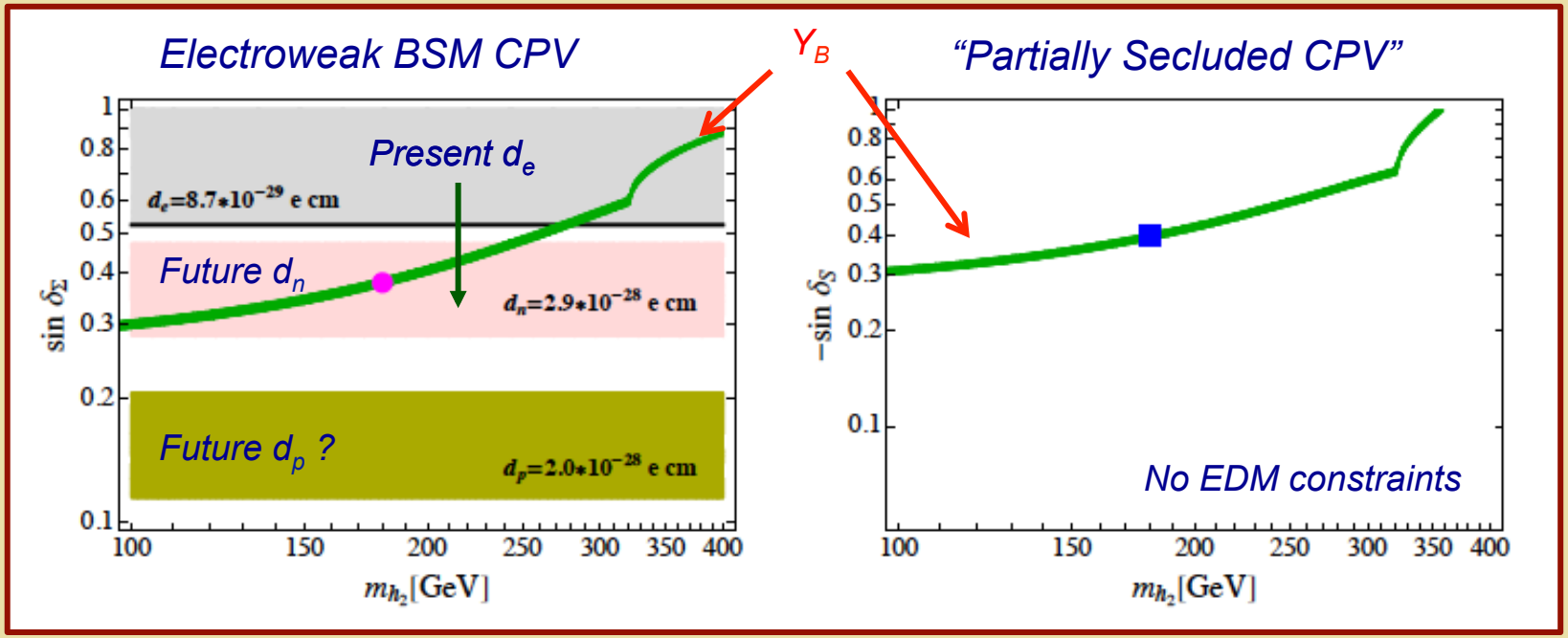
CPV for EWBG



- *Flavored CPV*
- *"Partially secluded" CPV*
- *CPV w/ vector-like fermions*
- *…*

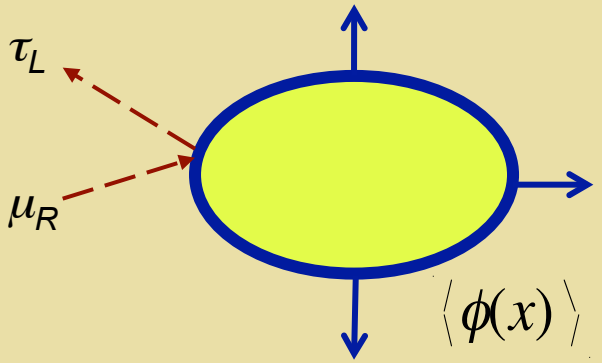
"Two-Step EW Baryogenesis"

Two CPV sources for baryon asymmetry



Inoue, Ovanesyan, R-M: 1508.05404

Flavored EW Baryogenesis



Jarlskog invariant

$$J_A = \frac{1}{v^2 \mu_{12}^{\rm HB}} \sum_{a,b,c=1}^{2} v_a v_b^* \mu_{bc} {\rm Tr}\left[Y_c Y_a^\dagger\right]$$

T=0 Higgs couplings

Im (y_τ) ~ Im (J_A)

EWBG CPV Source

S^{CPV} ~ Im (J_A)

Flavor basis (high T)

$$\mathscr{L}_{\rm Yukawa}^{\rm Lepton} = -\overline{E_L^i}\left[(Y_1^E)_{ij}\Phi_1 + (Y_2^E)_{ij}\Phi_2\right] e_R^j + h.c.$$

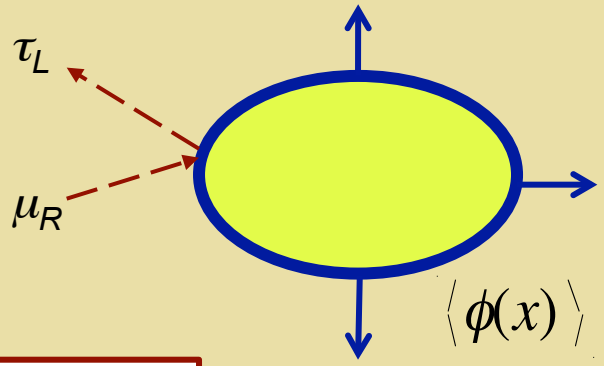
Mass basis (T=0)

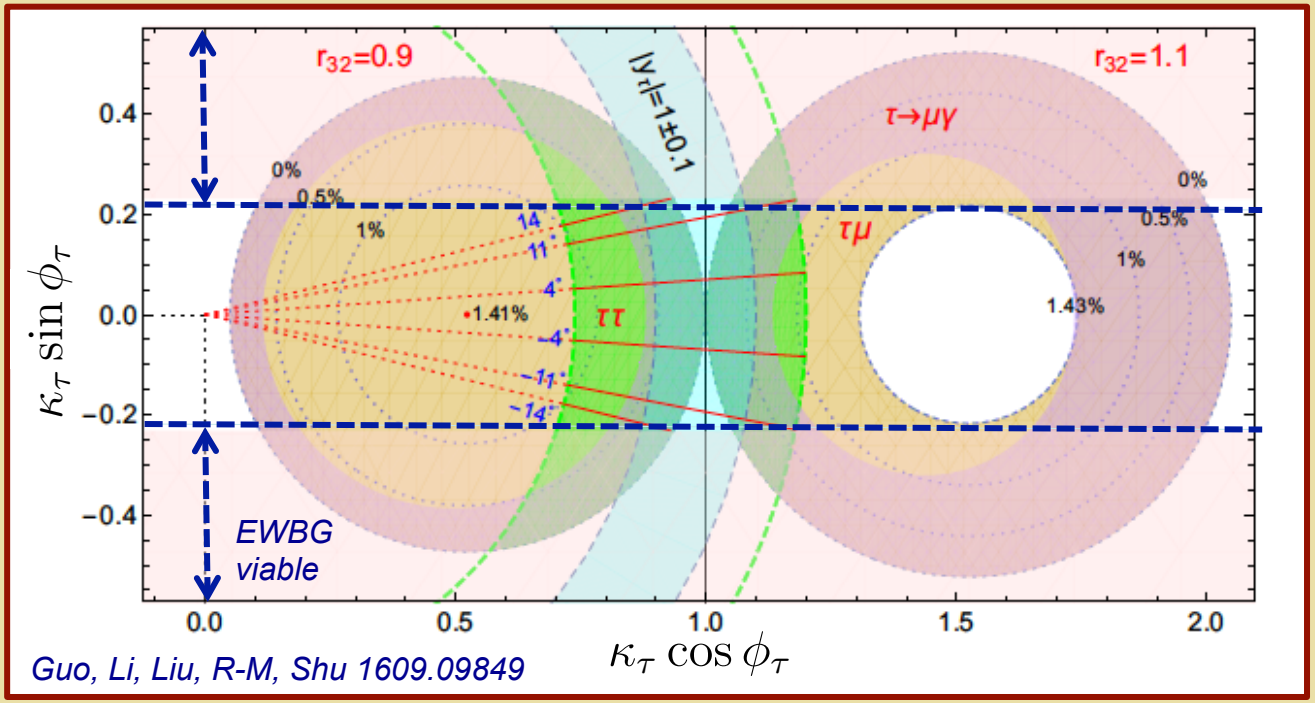
CPV $h \to \tau\tau$

$$\frac{m_f}{v}\kappa_\tau(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau)h$$

Guo, Li, Liu, R-M, Shu 1609.09849
Chiang, Fuyuto, Senaha 1607.07316

Flavored EW Baryogenesis





Guo, Li, Liu, R-M, Shu 1609.09849

$\Delta\phi_\tau \sim 10^o$:

3 ab^{-1} @ LHC 14