기초과학연구원
Institute for Basic Science

Higgs precision (new physics) at the ILC

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Osaka University, Osaka

Outline

- Higgs precision for cosmology (EW baryogenesis)
- Consequences of 1st-order EW phase transition (EWPT)
    - Higgs couplings & spectrum
    - Gravitational waves (GWs)
- Higgs CP nature ($h \rightarrow \tau\tau$)
- Summary

Report by the Committee on the Scientific Case of the ILC Operating at 250 GeV as a Higgs Factory (1710.08639)

ILC	Higgs & other SM precision measurements; electroweak baryogenesis; 2.1(b): higgsinos, and DM ligher than 62 GeV; 2.1(c): small tanβ.
HL-LHC	Higgs couplings; direct search of new phenomena; top quark mass; 2.1(a),(b): bino, wino; 2.1(c): large tanβ.
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EDM	Flavor-conserving additional CP violation; electroweak baryogenesis.
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Underground experiments	DM direct search; 2.1(b): heavy regions.

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EWBG tests

- We cannot redo EWPT in lab. exp. So, we test Sakharov cond. instead.

	$\not{B}$	$\not{CP}$	out of equilibrium
Sakharov conditions	sphaleron	CPV bubble-particle ints.	1^{st}-order EWPT w/ bubbles

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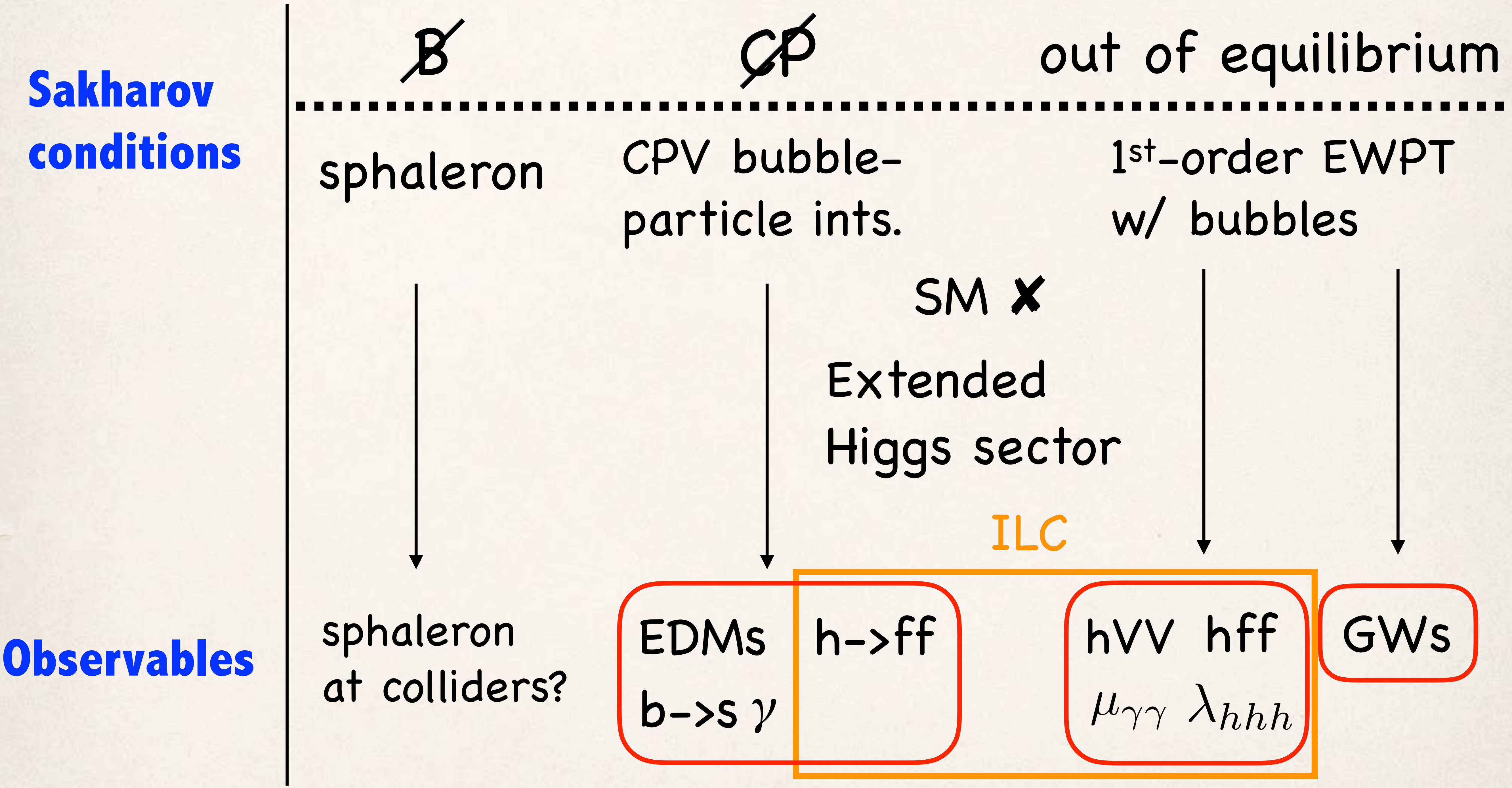
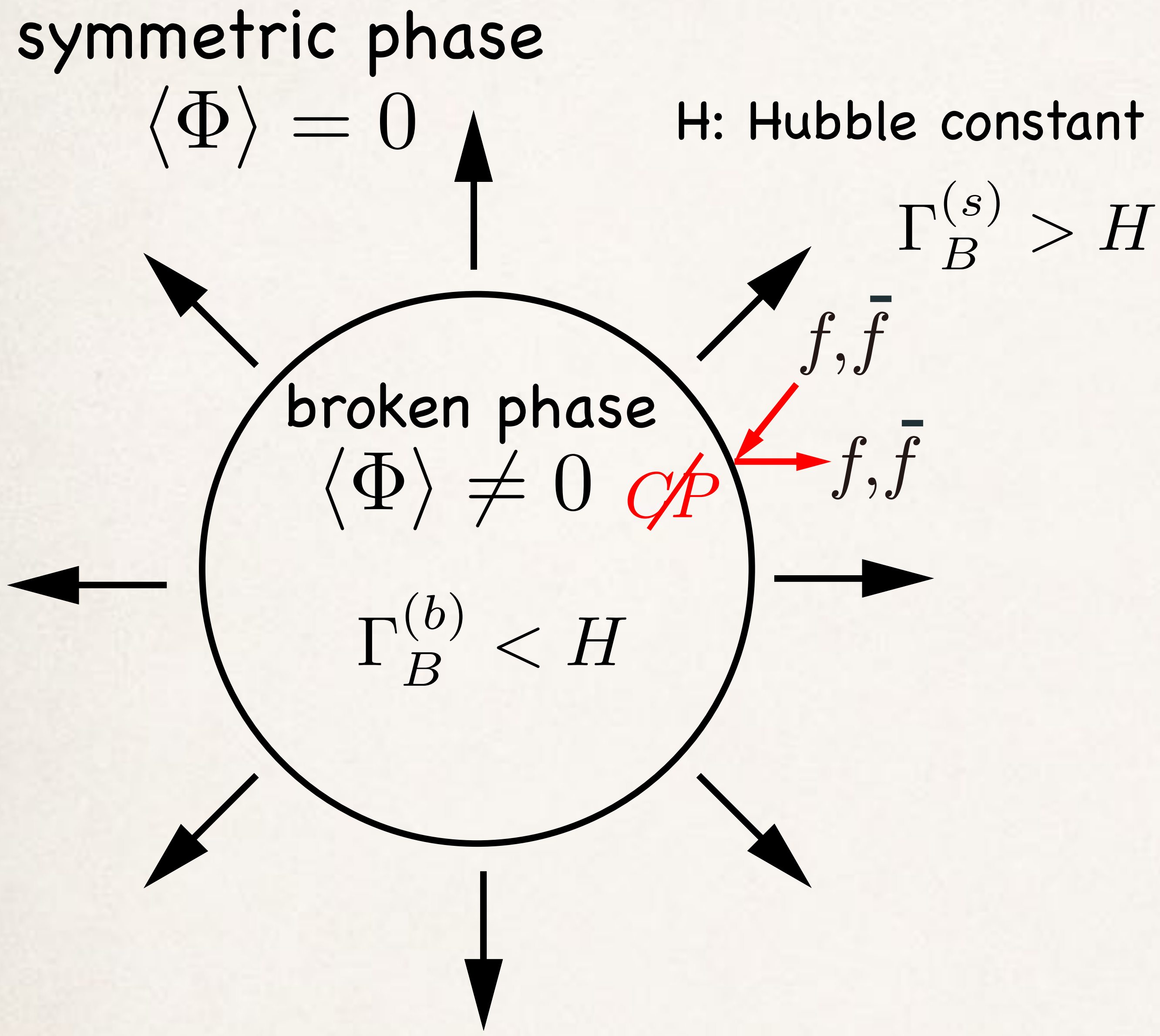


- Sizes of the deviations in the Higgs couplings and Higgs spectrum are determined by "B-preserving condition".

EWBG mechanism



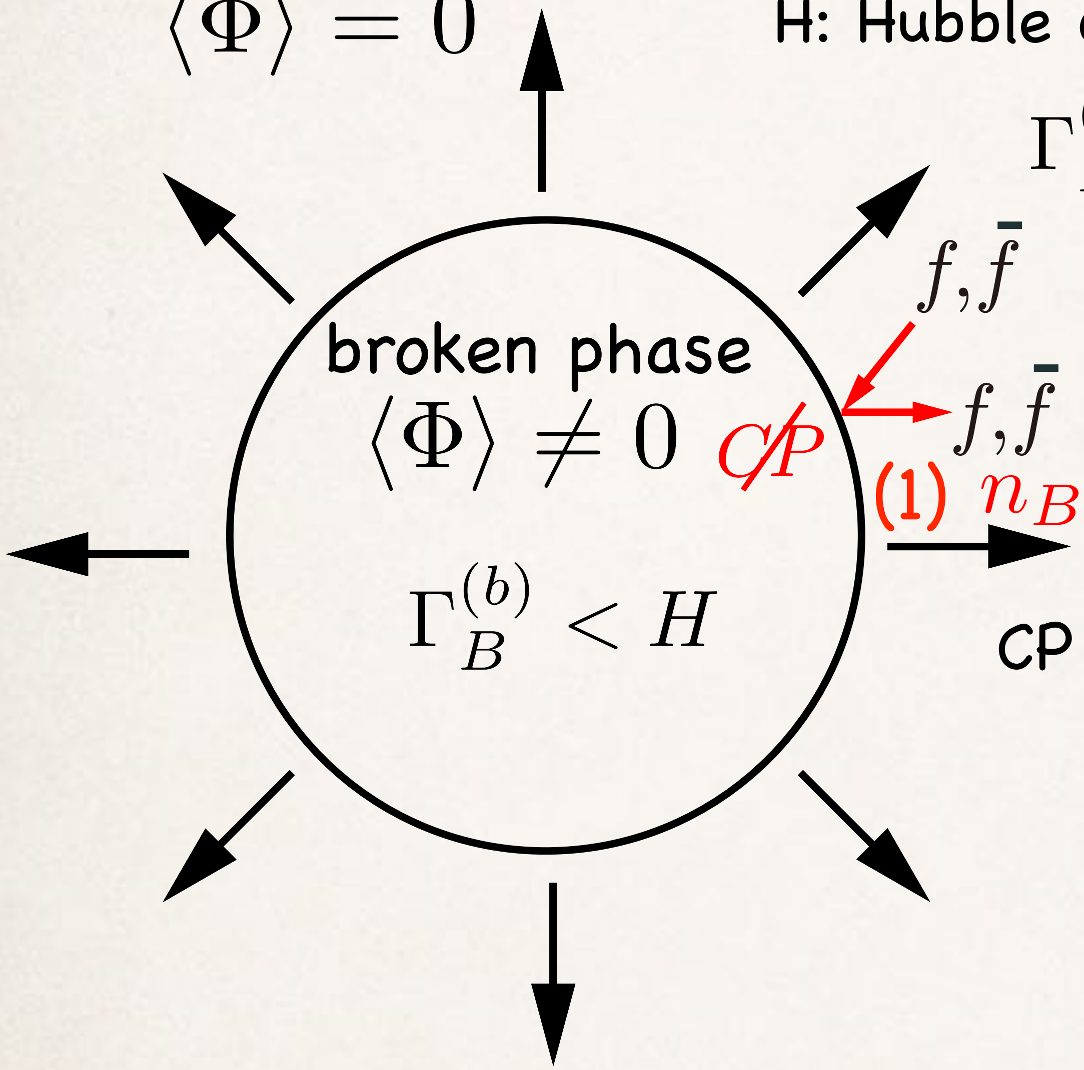
EWBG mechanism

symmetric phase

$\langle \Phi \rangle = 0$

H: Hubble constant

$\Gamma_B^{(s)} > H$



(1) $n_B = \underset{\neq 0}{n_B^L} + \underset{\neq 0}{n_B^R} = 0$

CP asymmetric but no B asymmetric

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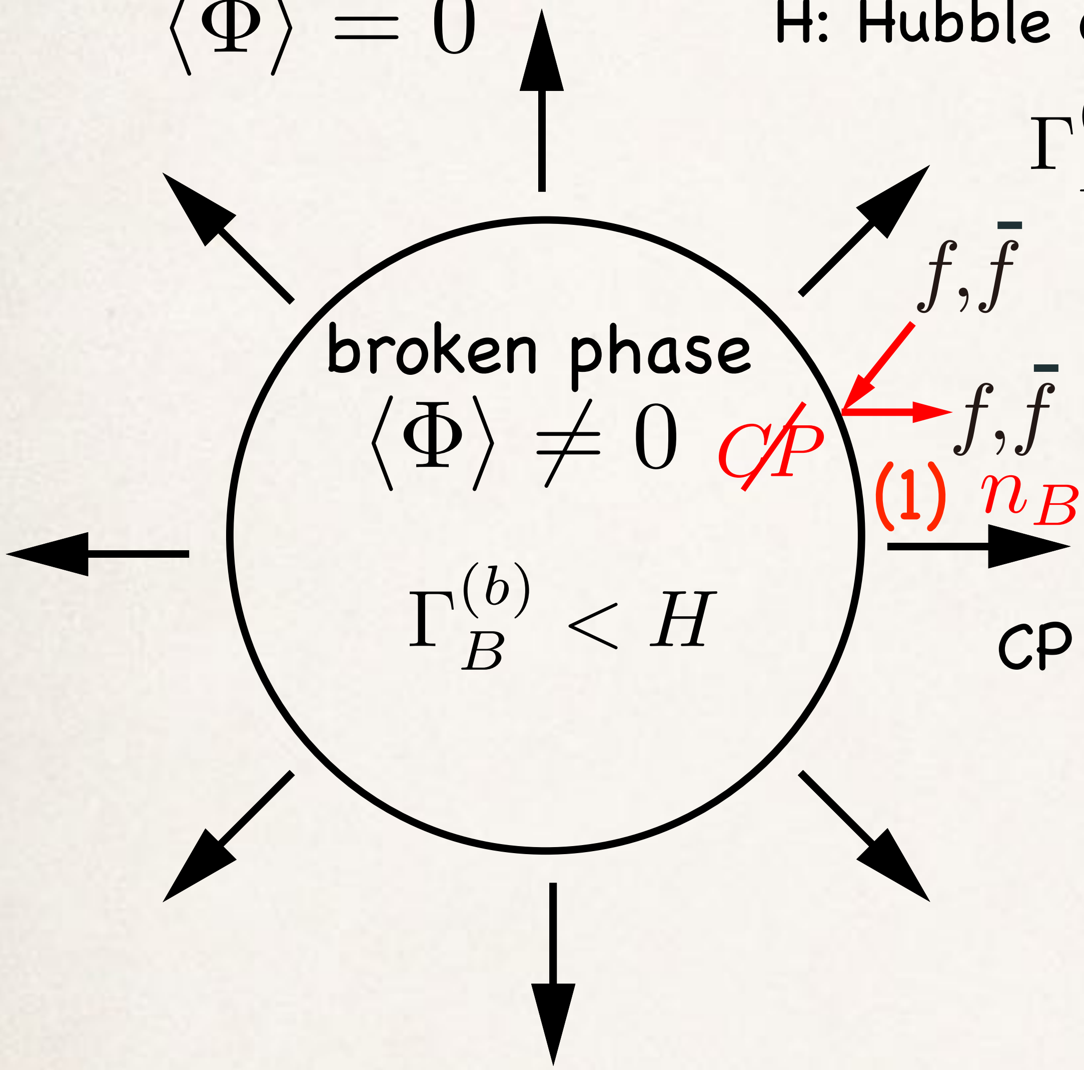

changed by sphaleron. $t_{\rm wall} < t_{\rm sph}$

(2) $n_B = \boxed{n_B^L} + n_B^R \to n_B \neq 0$

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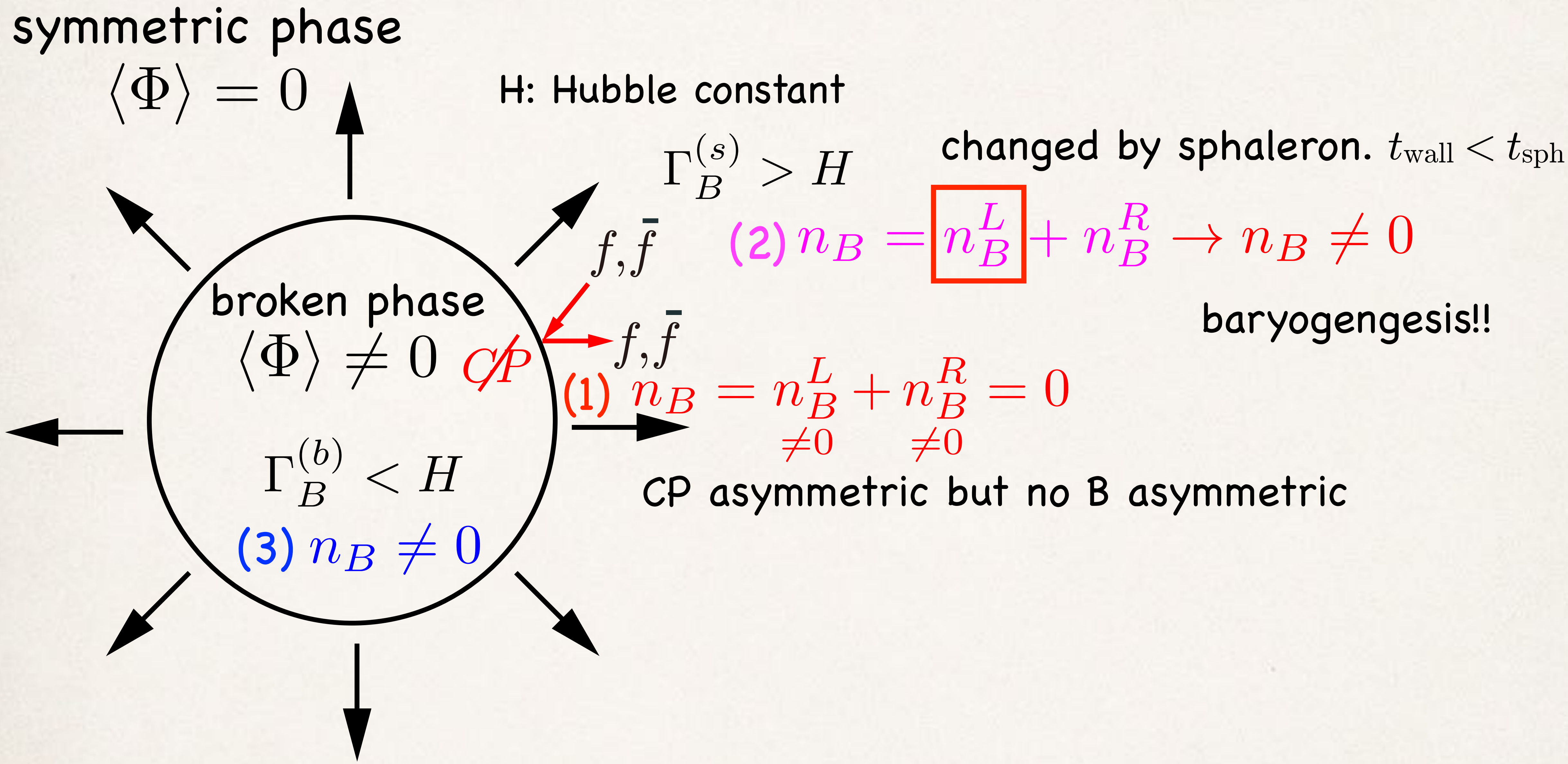

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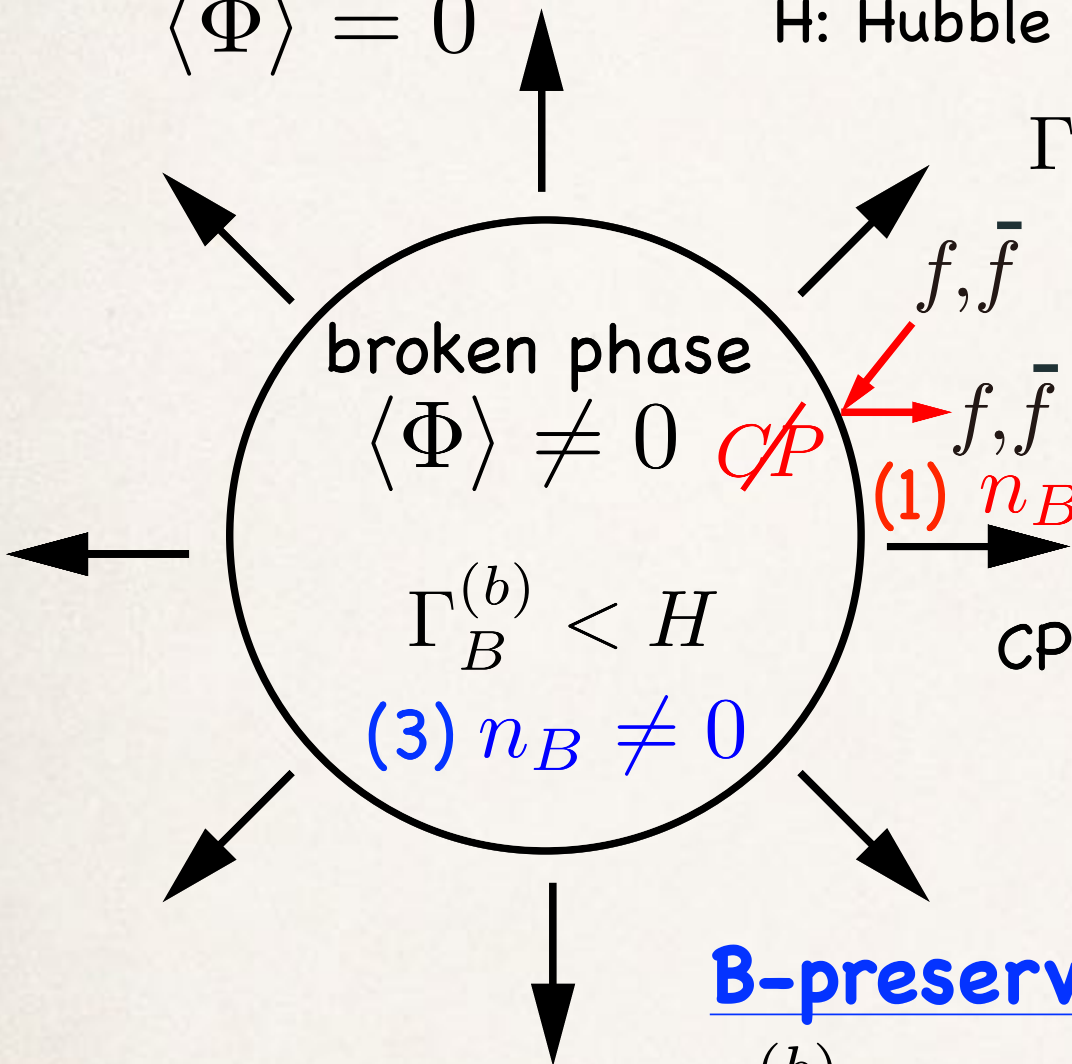

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$$\Gamma_B^{(b)} \sim e^{-4\pi \mathcal{E}_{\text{sph}} v / g_2 T} < H$$

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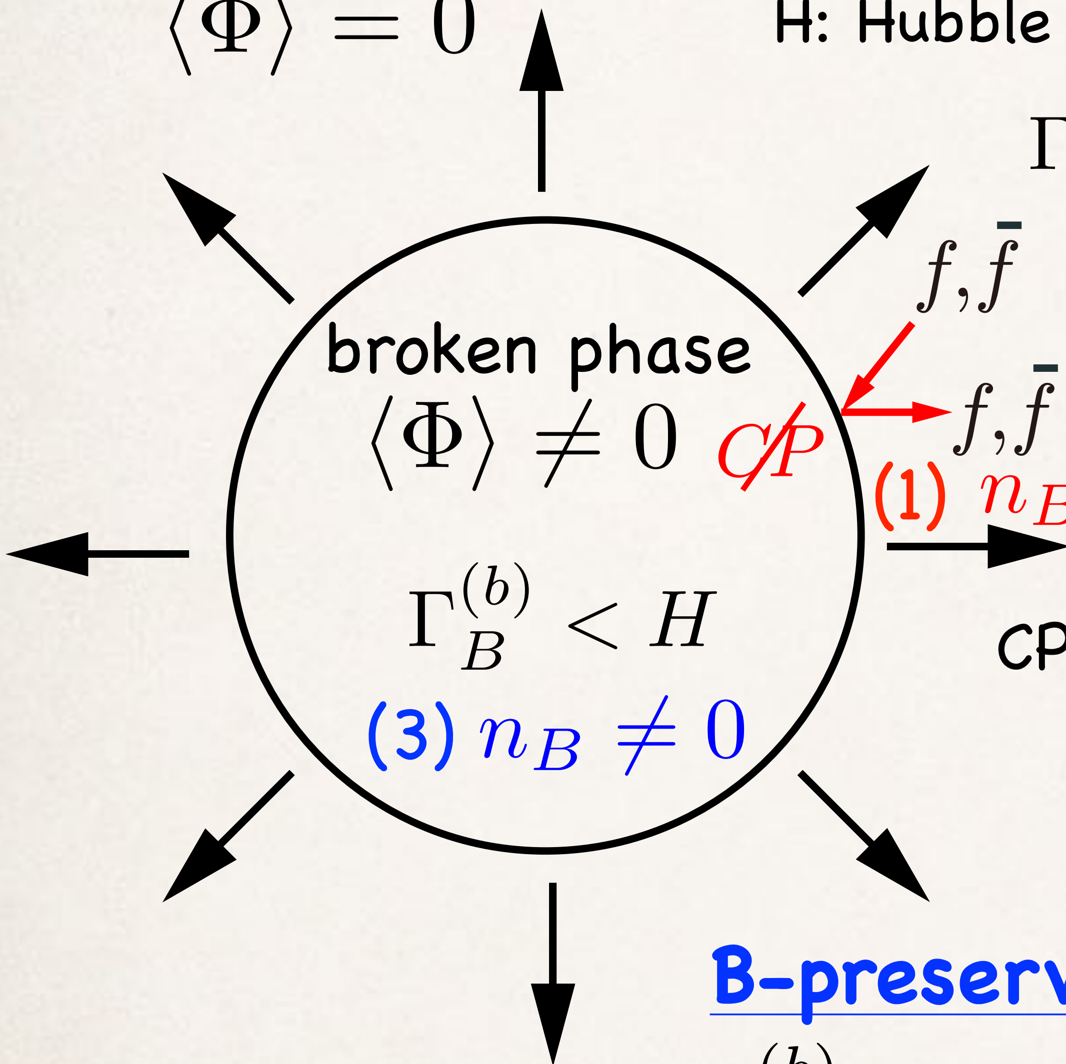

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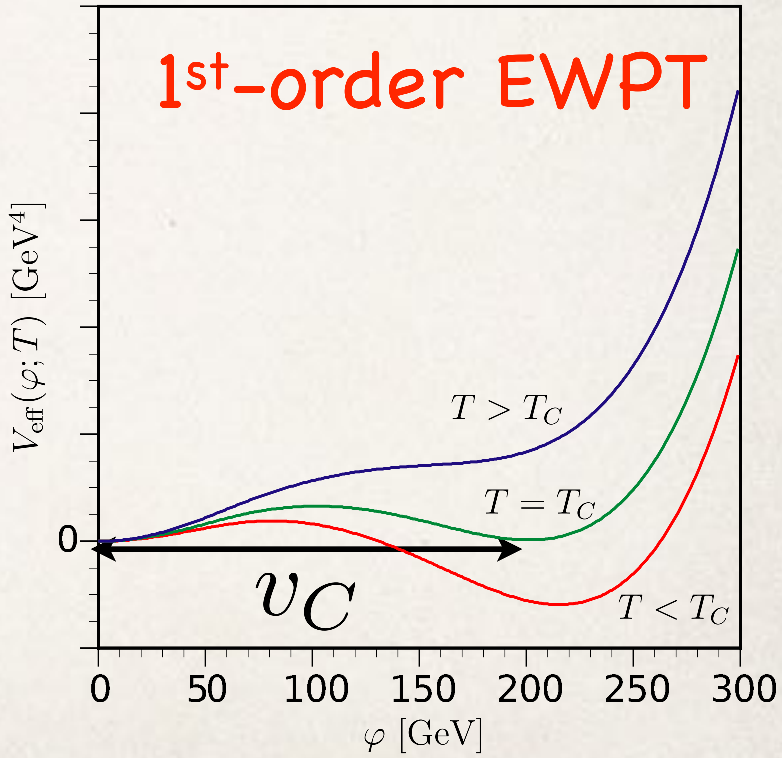

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$f, \bar{f}$

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broken phase

$\langle \Phi \rangle \neq 0$ $\not{CP}$

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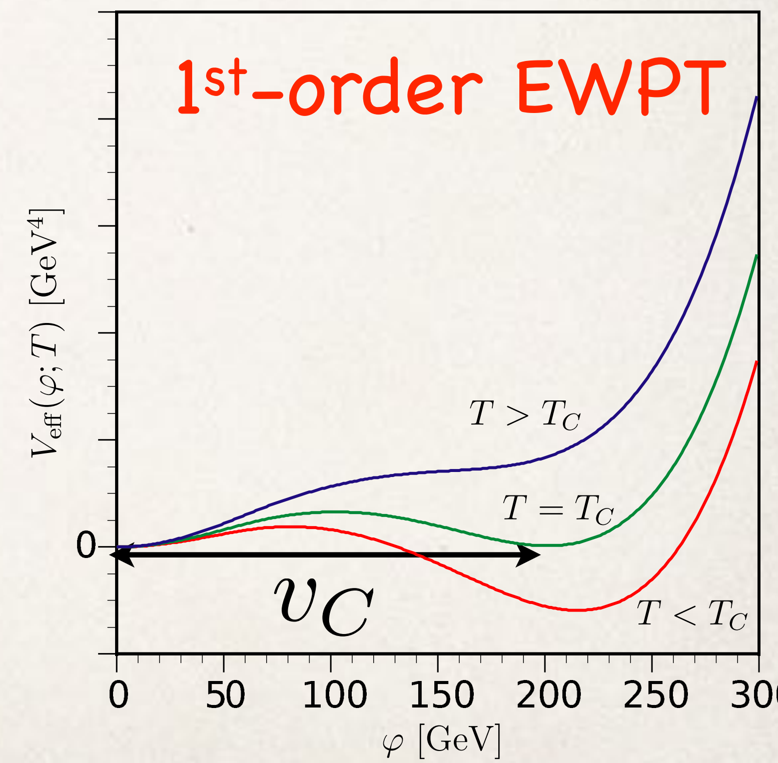

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$\rightarrow$ Higgs spectrum

EWBG mechanism

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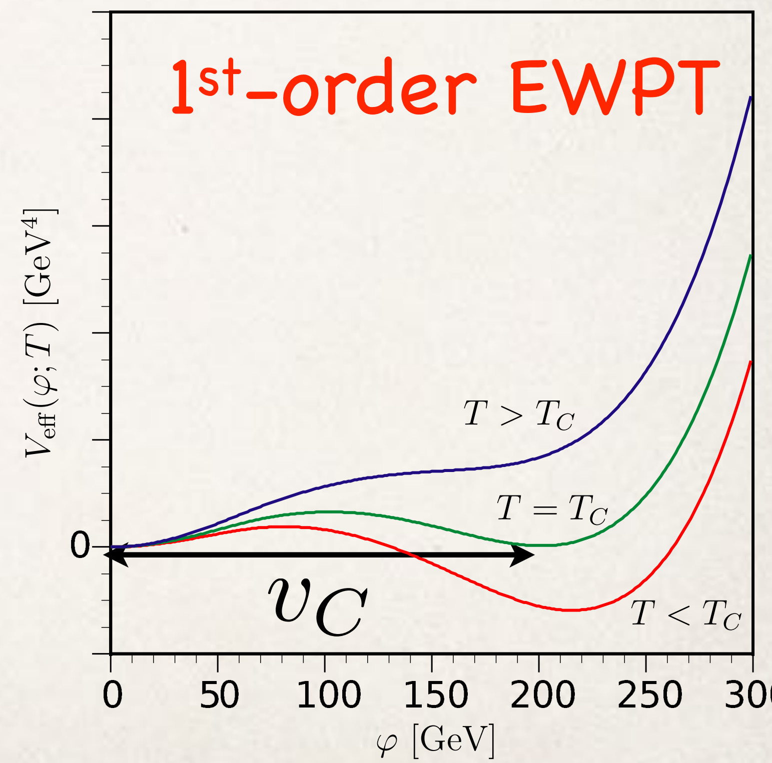

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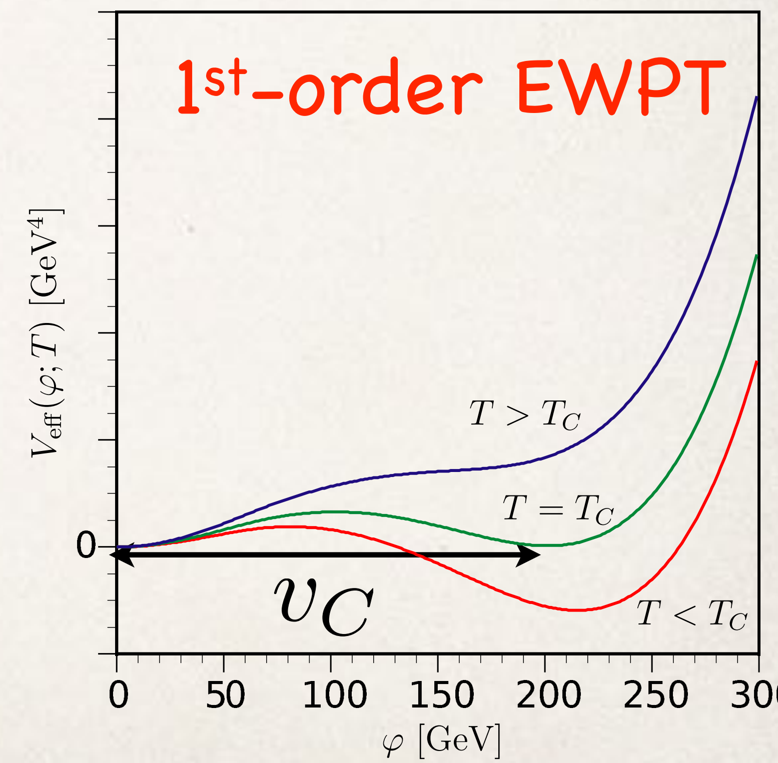

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→ Higgs spectrum

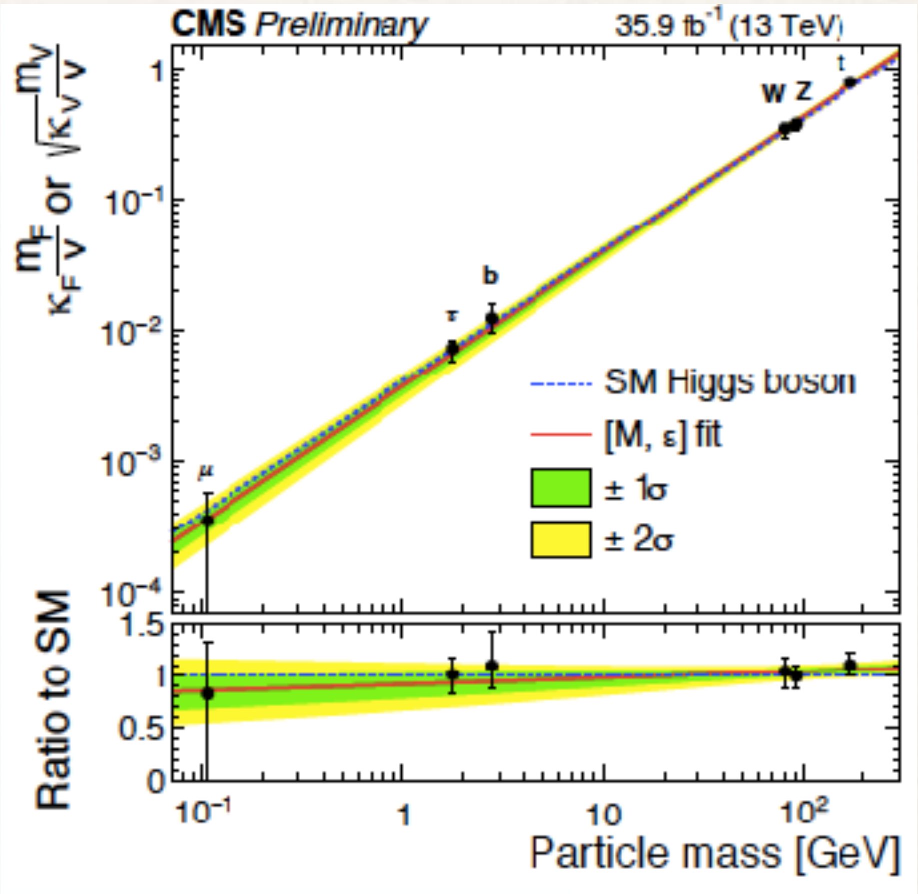
↑ constrained by exp. data

EWBG in our time

LHC data indicate

Higgs sector = SM-like

What is "SM-like Higgs sector" compatible with EWBG?



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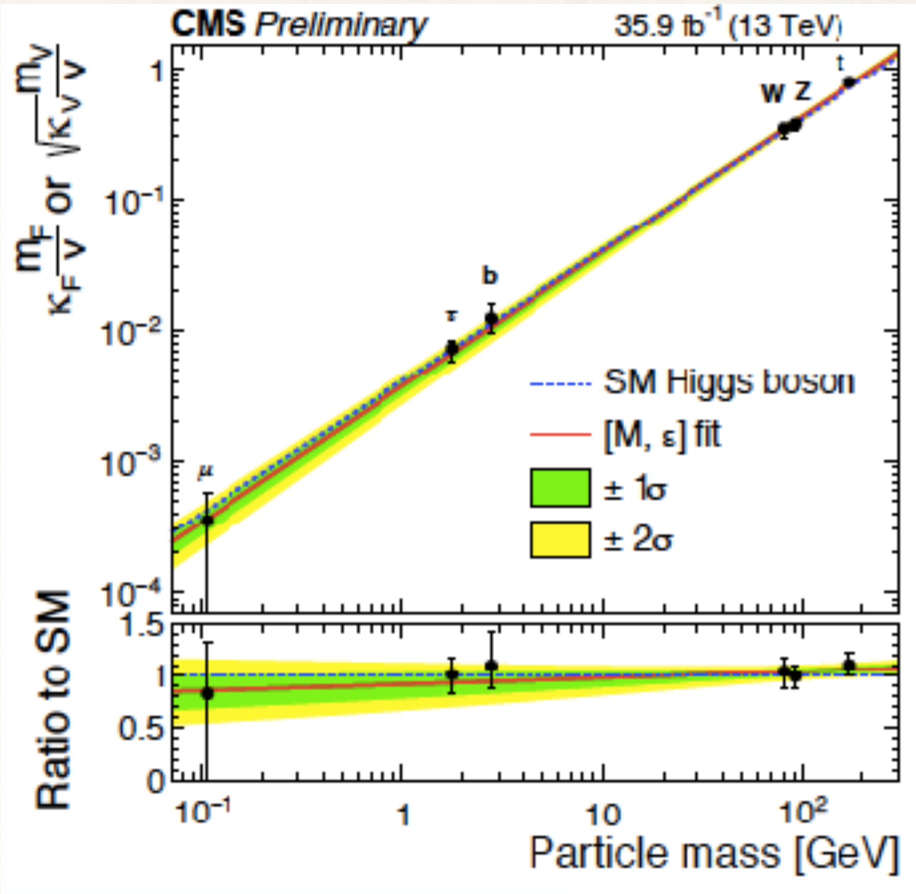

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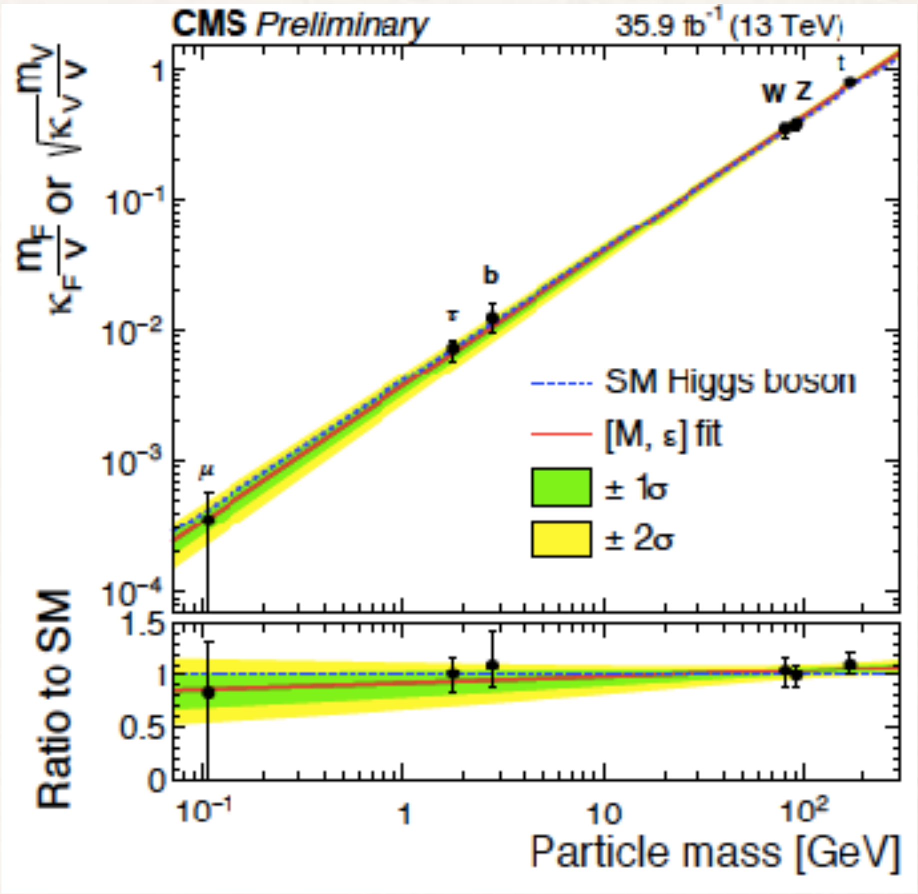
hVV and hff = SM-like

$$\sin(\beta - \alpha) \simeq 1$$



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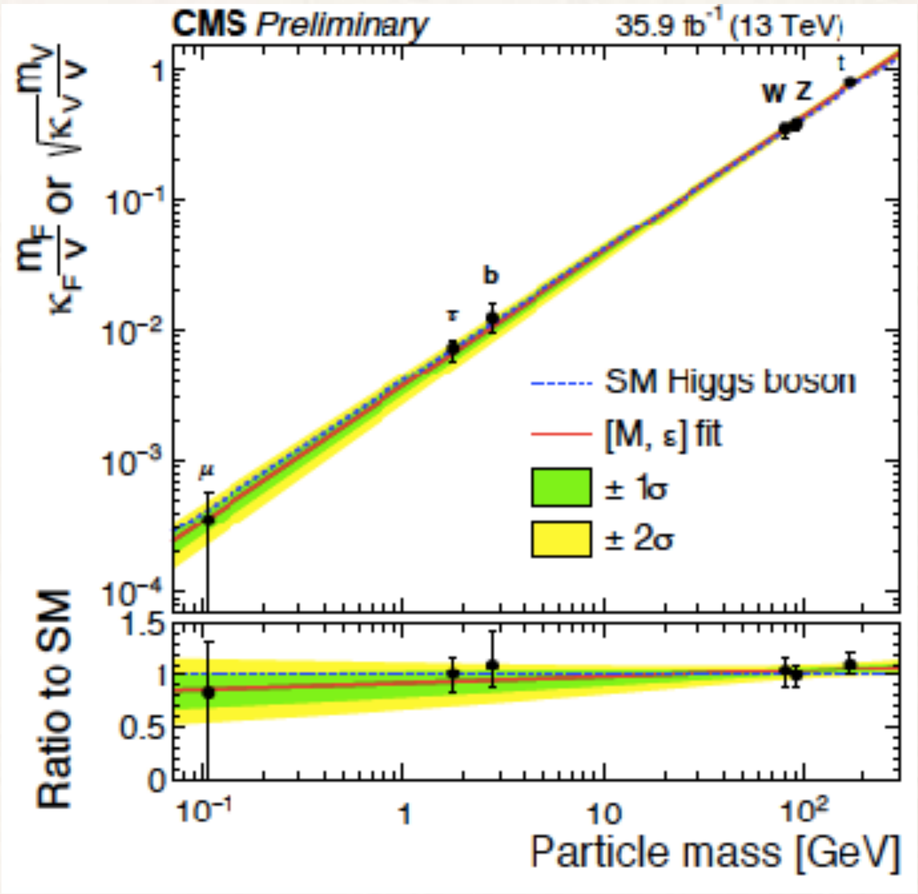

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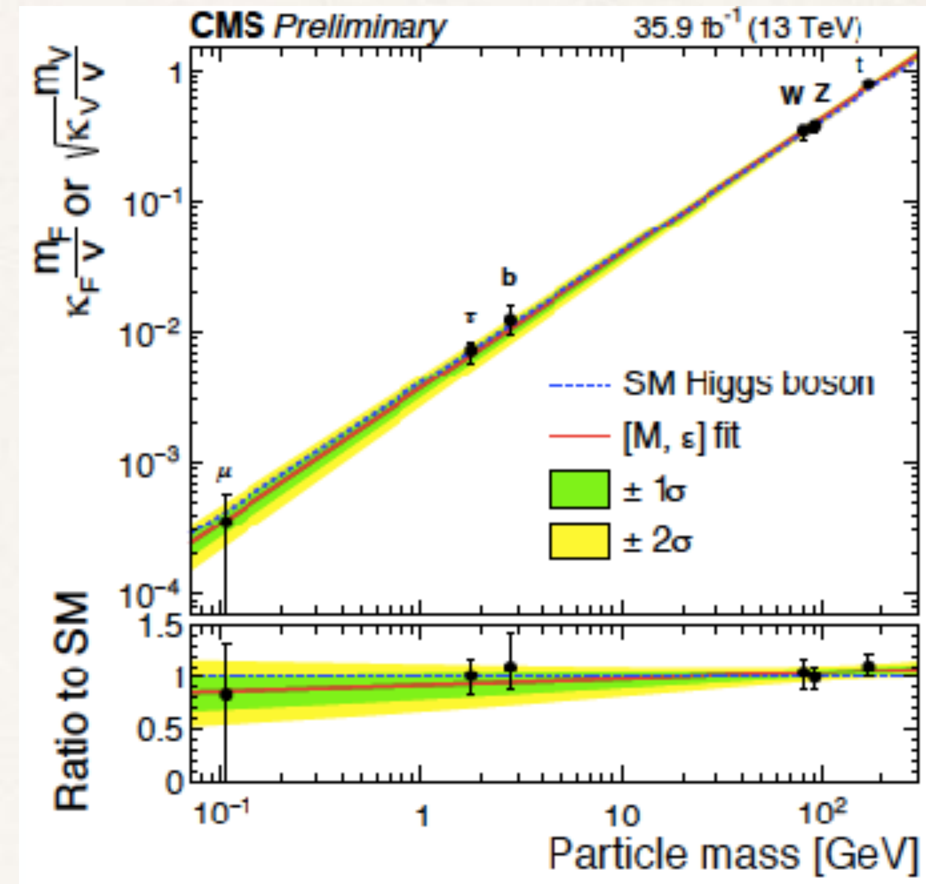

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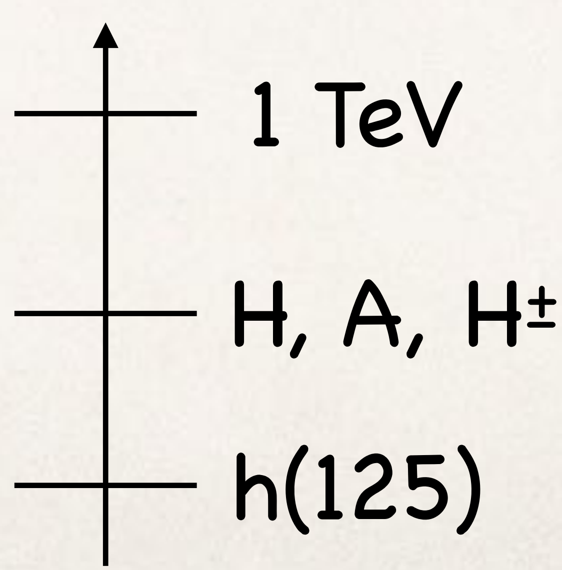

to satisfy $v_C/T_C \gtrsim 1$

$\lambda_{h\phi\phi} = \mathcal{O}(1)\ (\phi = H, A, H^{\pm})$

↓

hhh= NonSM-like

[S.Kanemura, Y.Okada, E.S, hep-ph/0411354 (PLB)]

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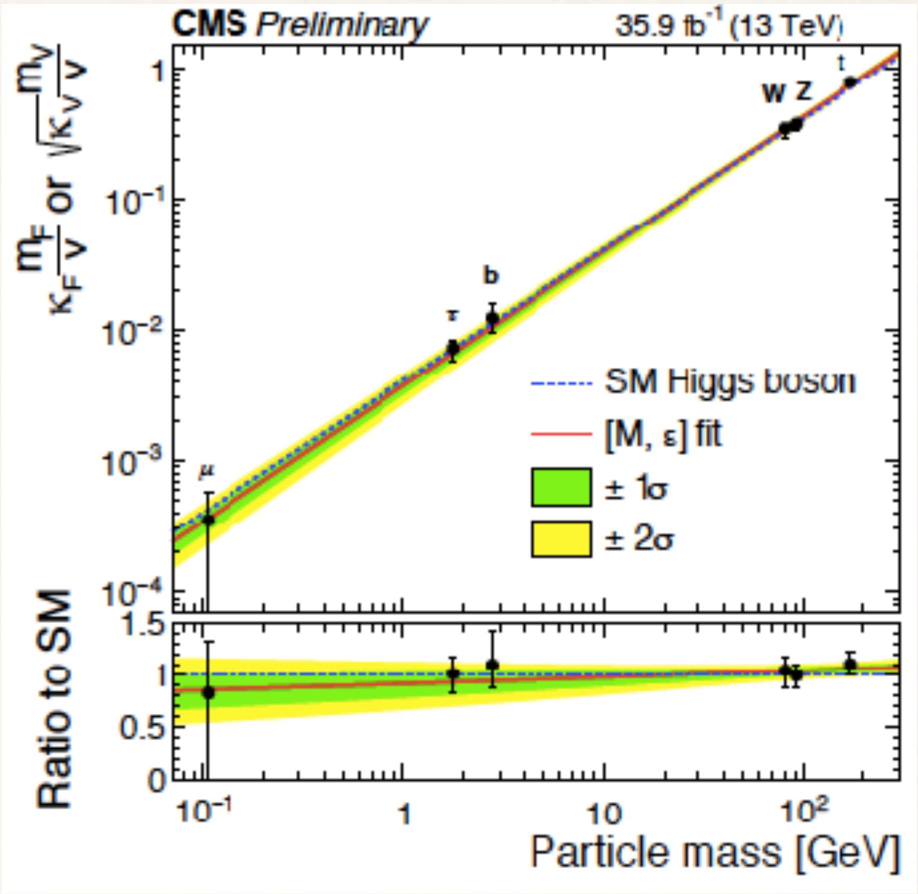

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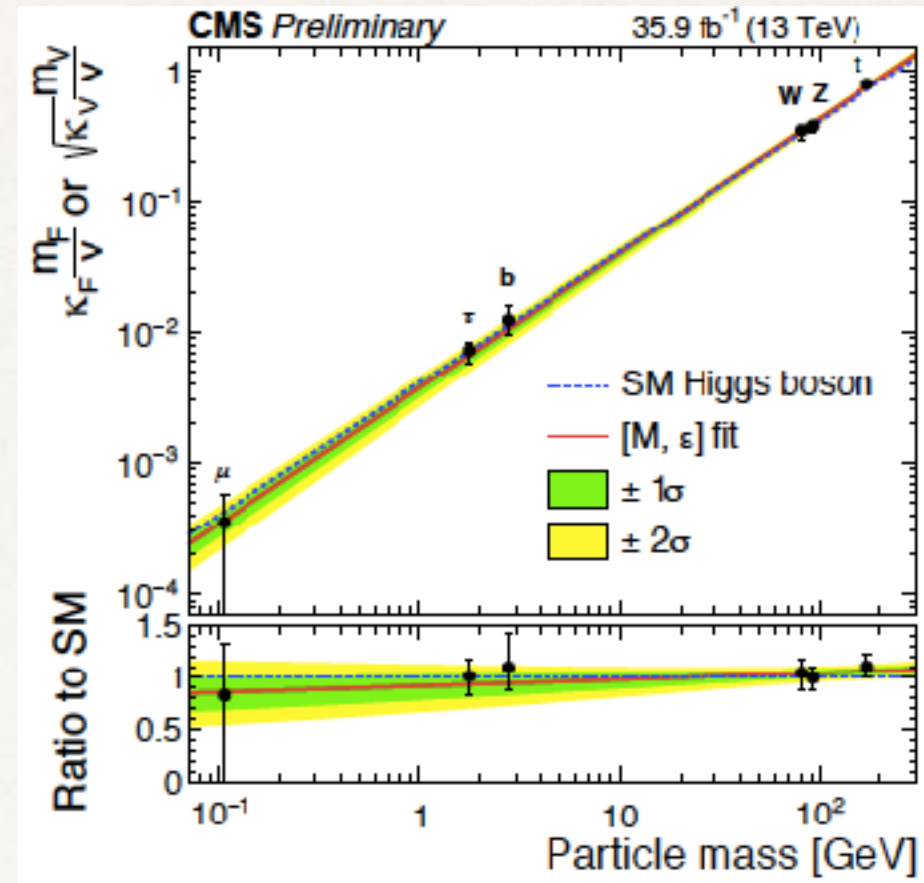

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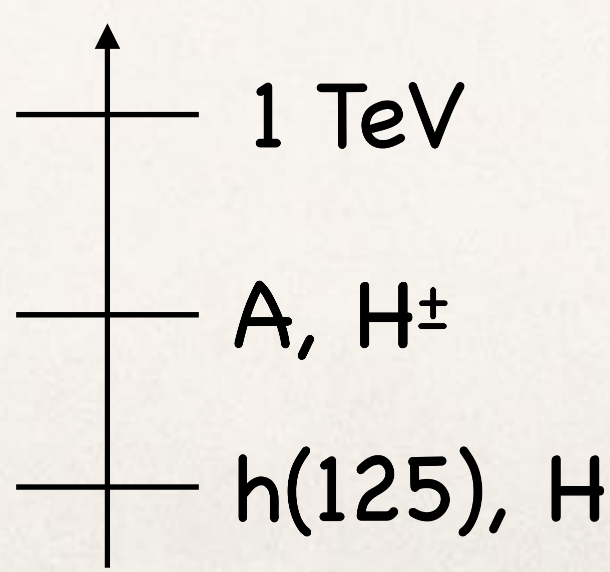


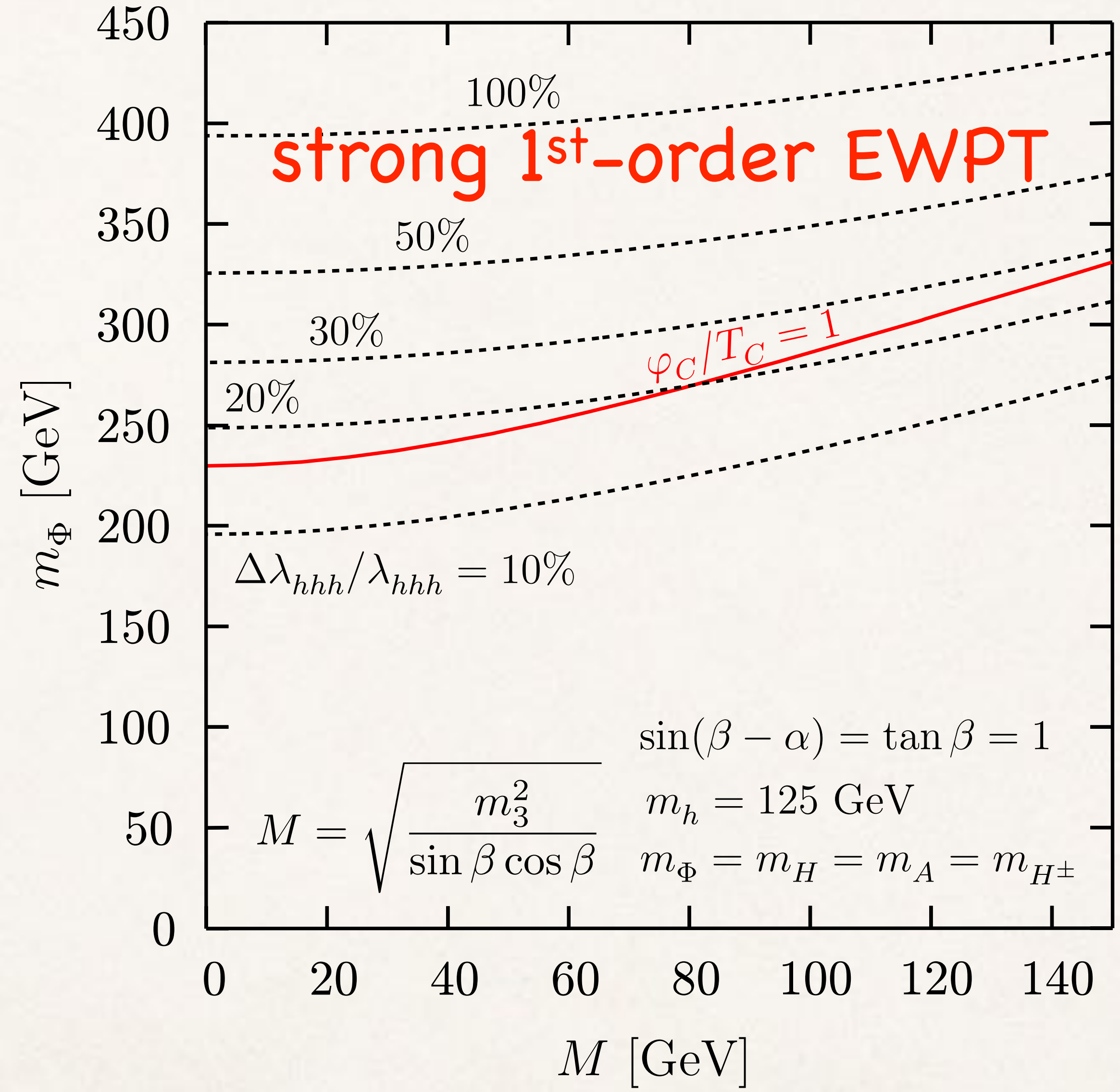
❒ A-> ZH $\propto \sin(\beta - \alpha)$

[G.C.Dorsch, S.J.Huber, K.Mimasu, J.M.No, 1405.4437(PRL)]

Parameter space of EWBG

2HDM

[Kanemura, Okada, E.S., PLB606,(2005)361]



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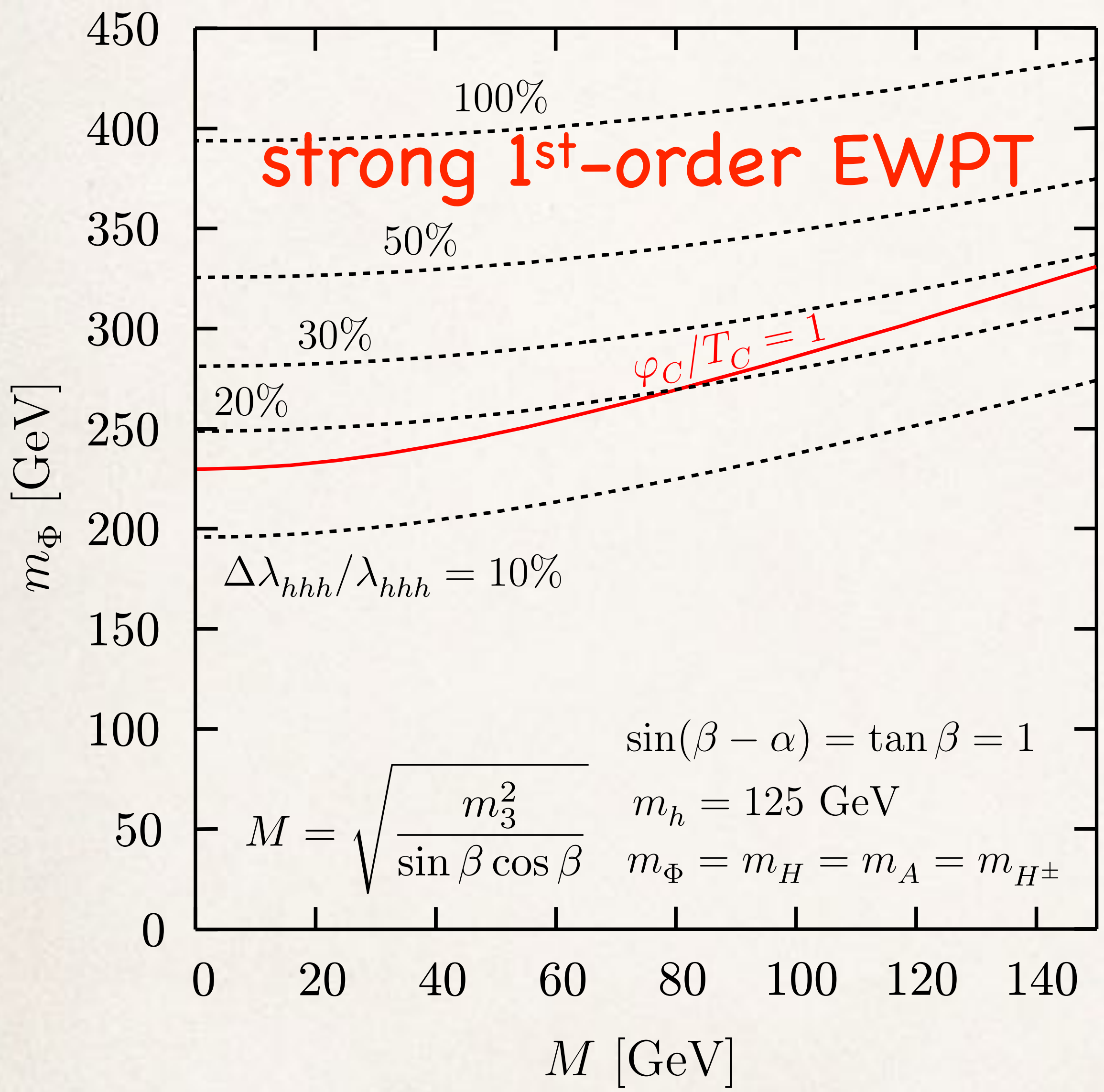

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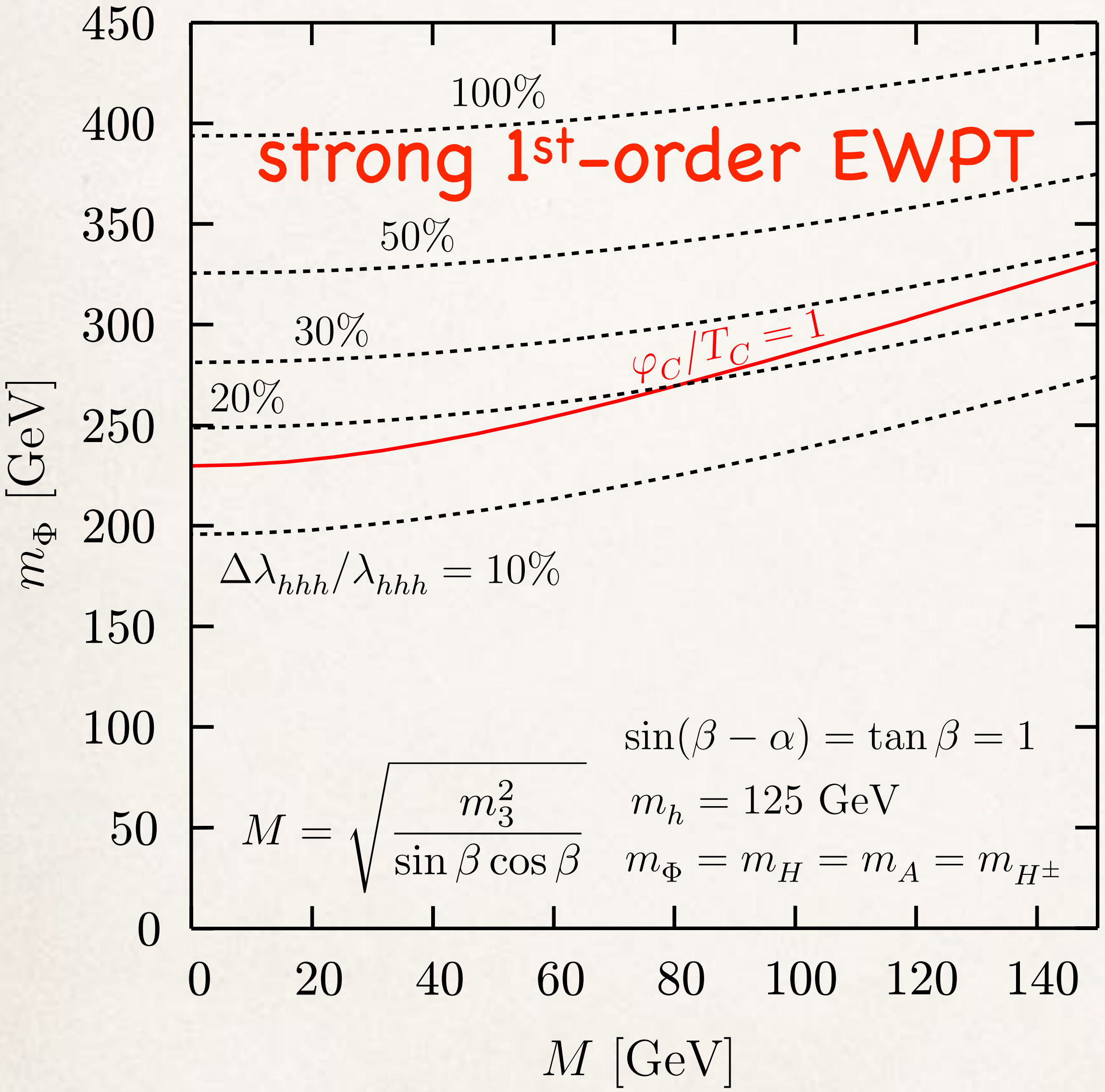
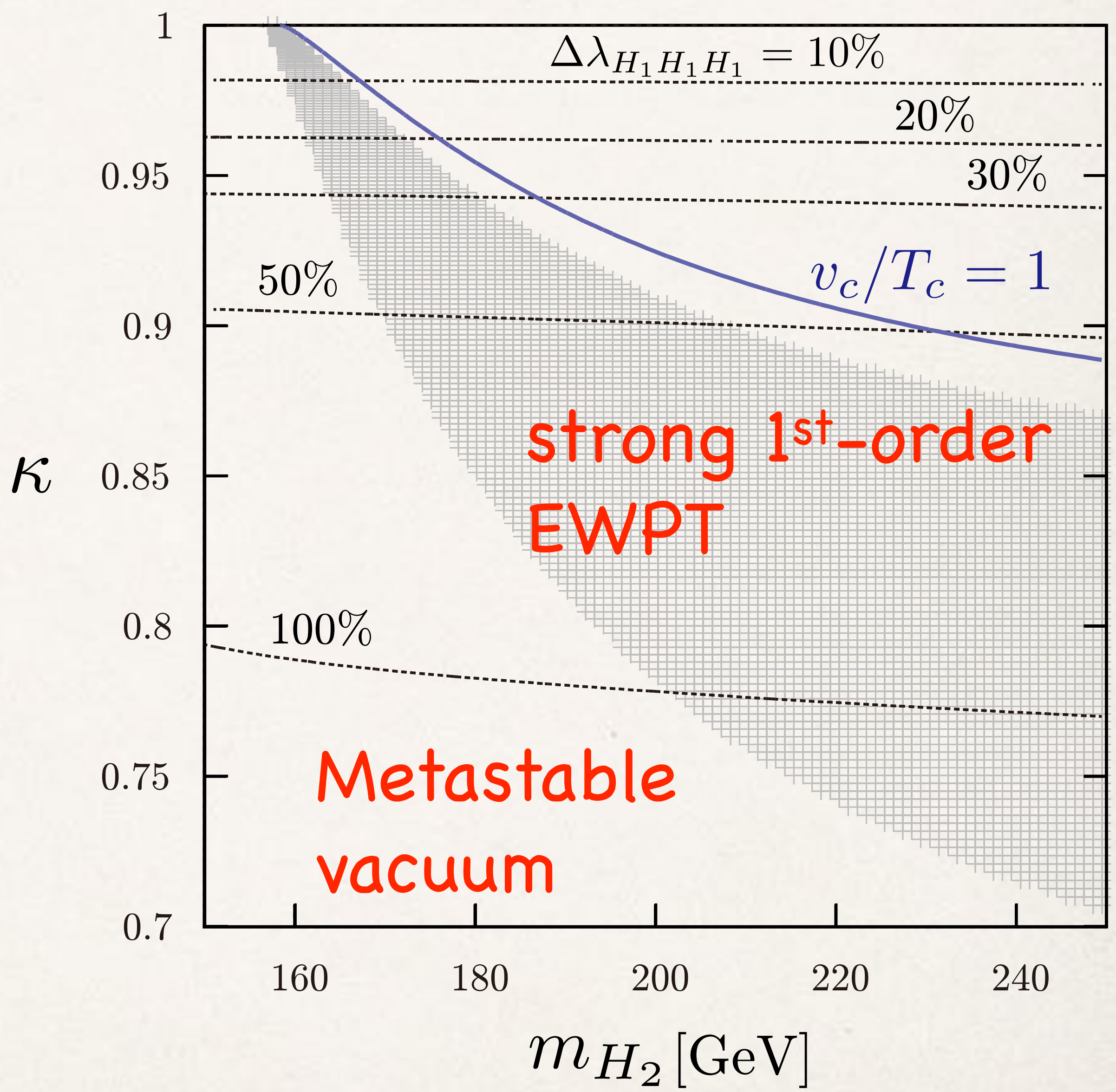


SM+S

[K.Fuyuto, E.S., PRD90, 015015 (2014)]



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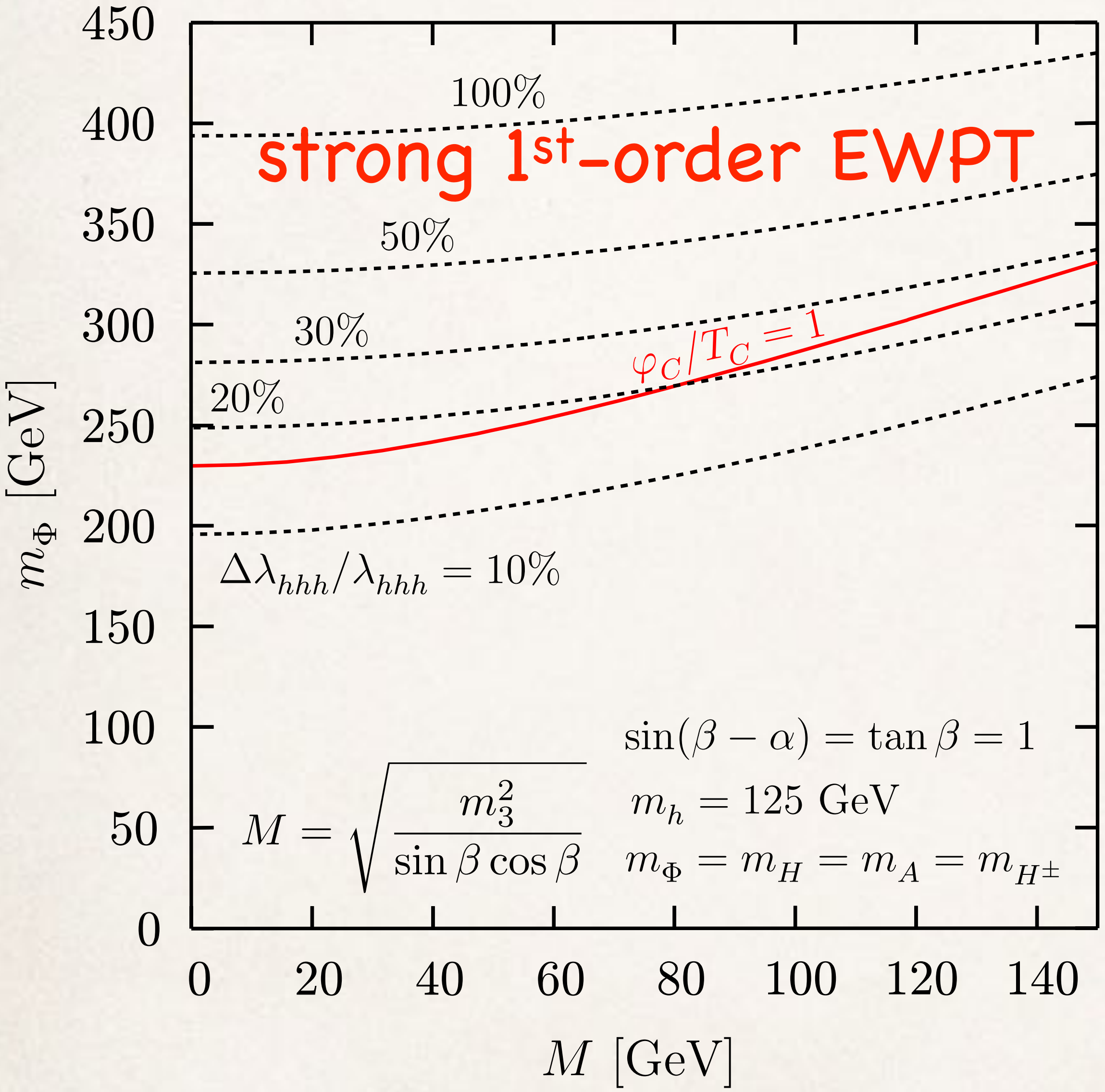

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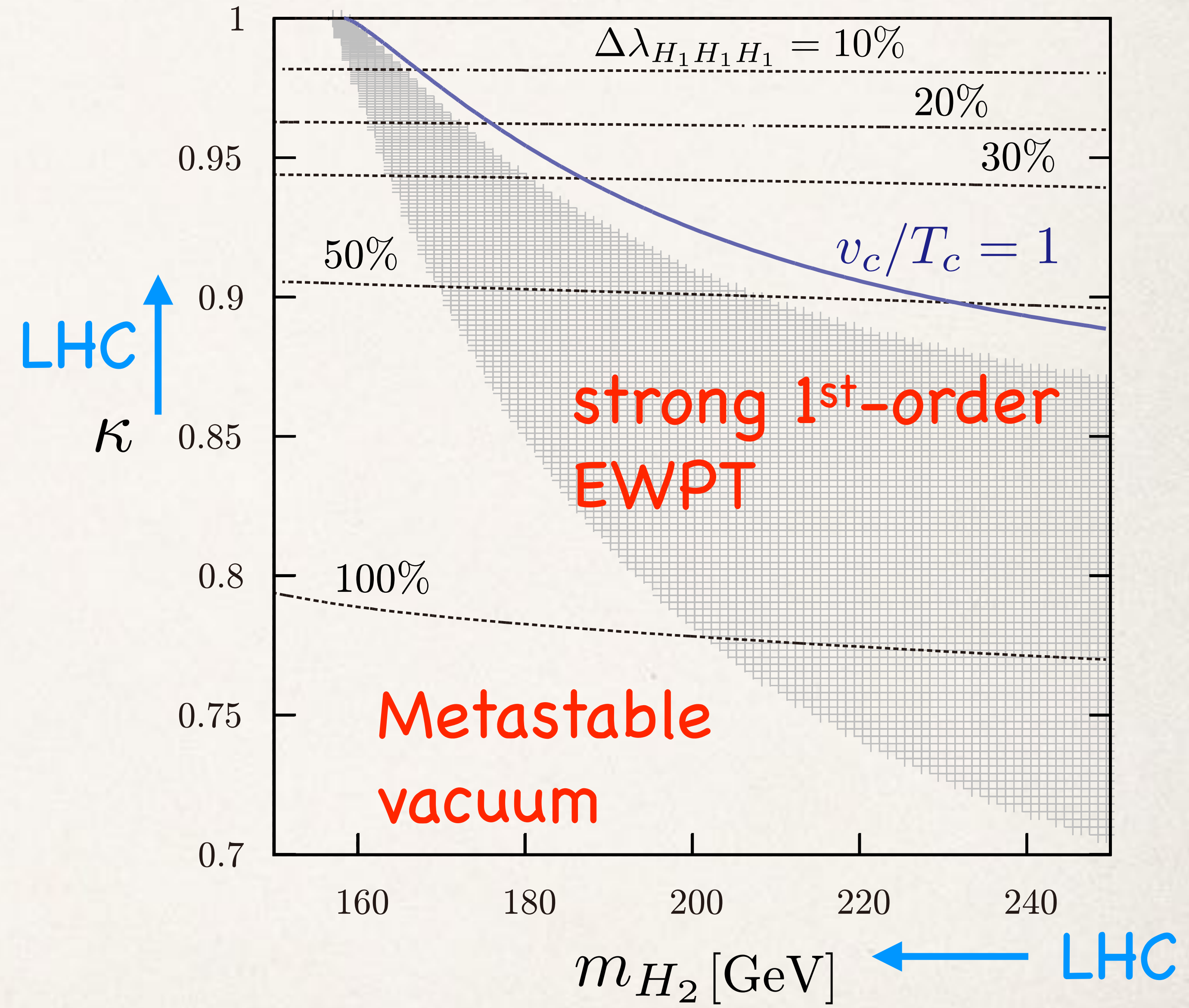
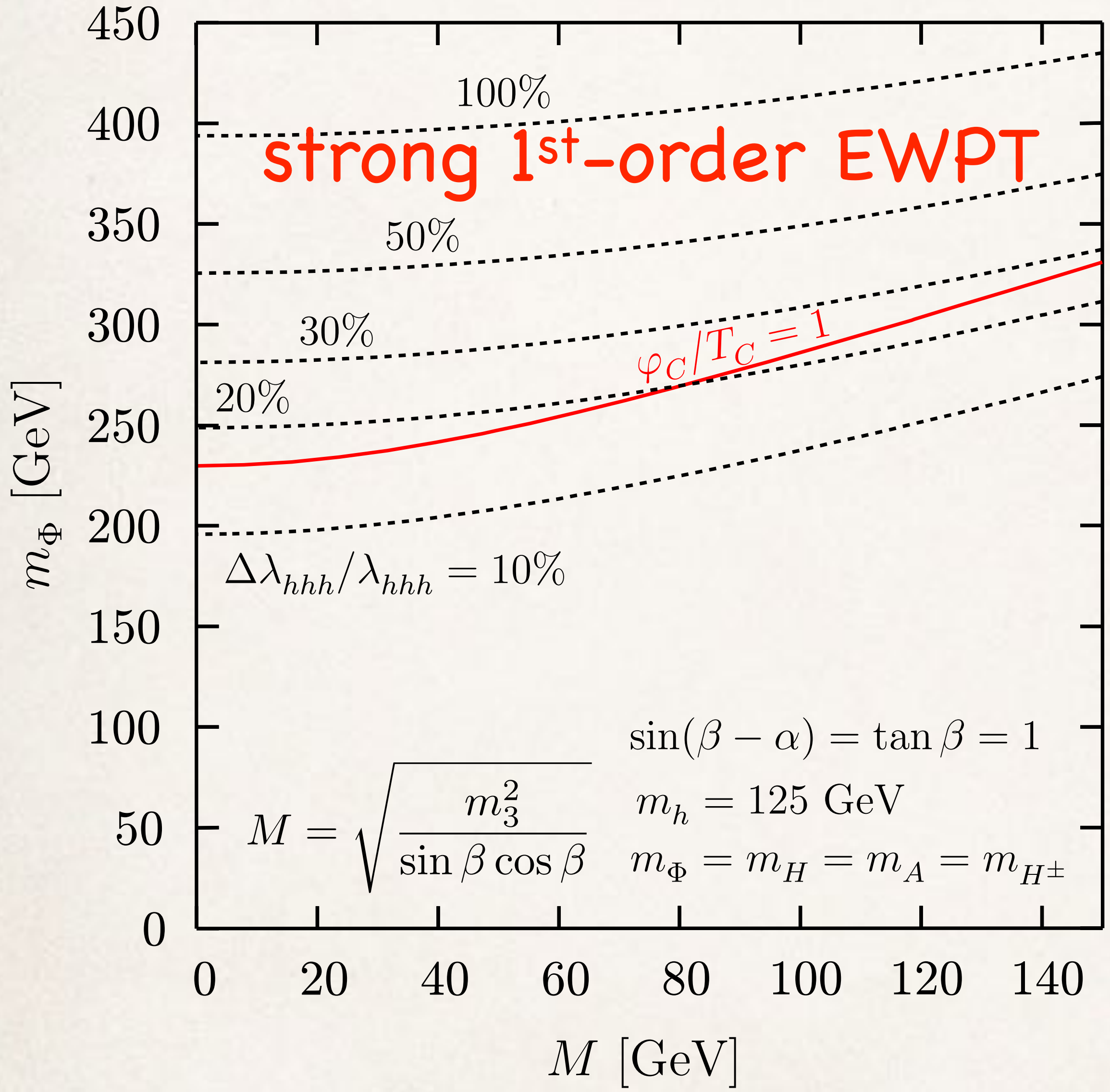


Parameter space of EWBG

2HDM

[Kanemura, Okada, E.S., PLB606,(2005)361]



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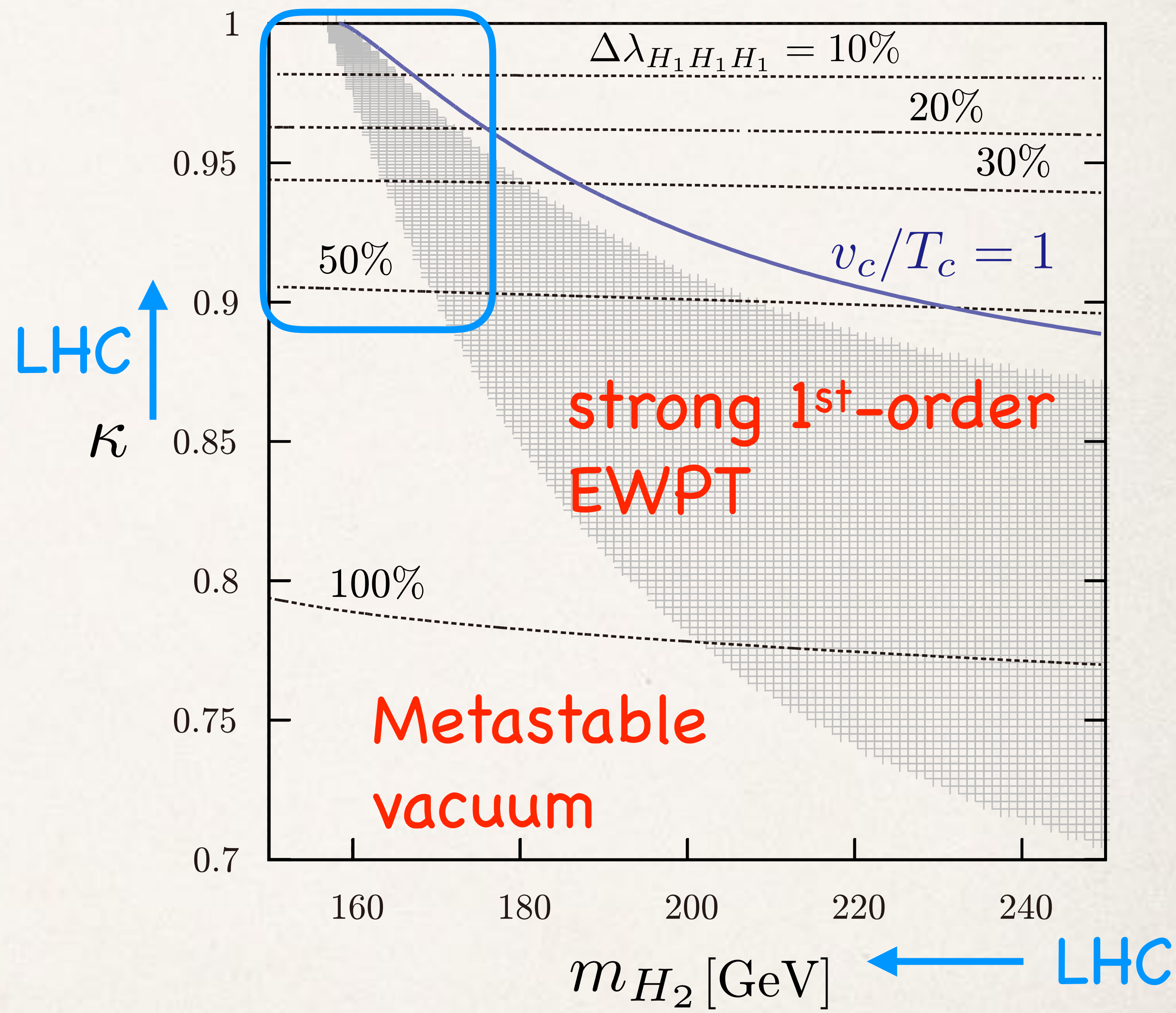

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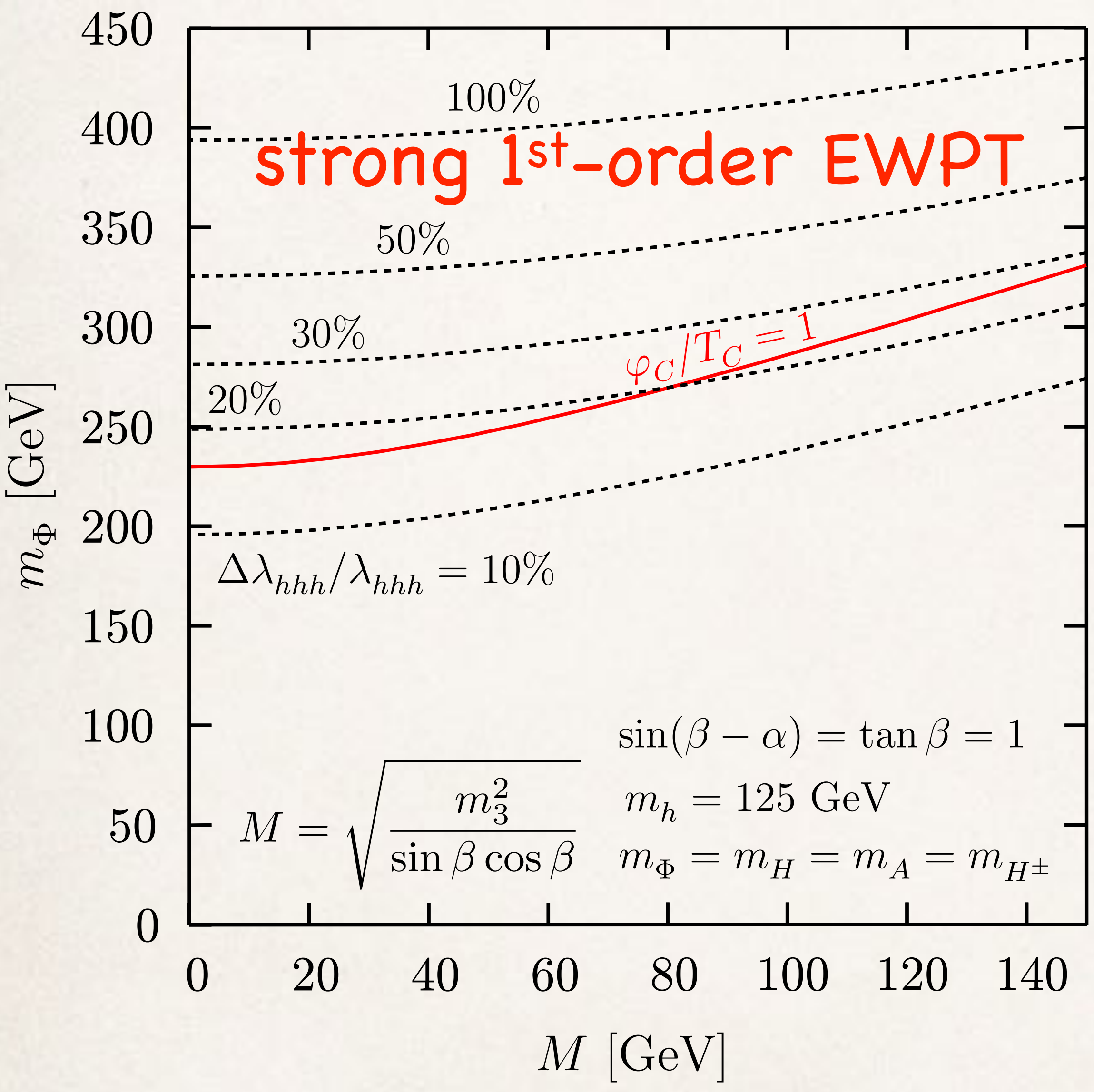

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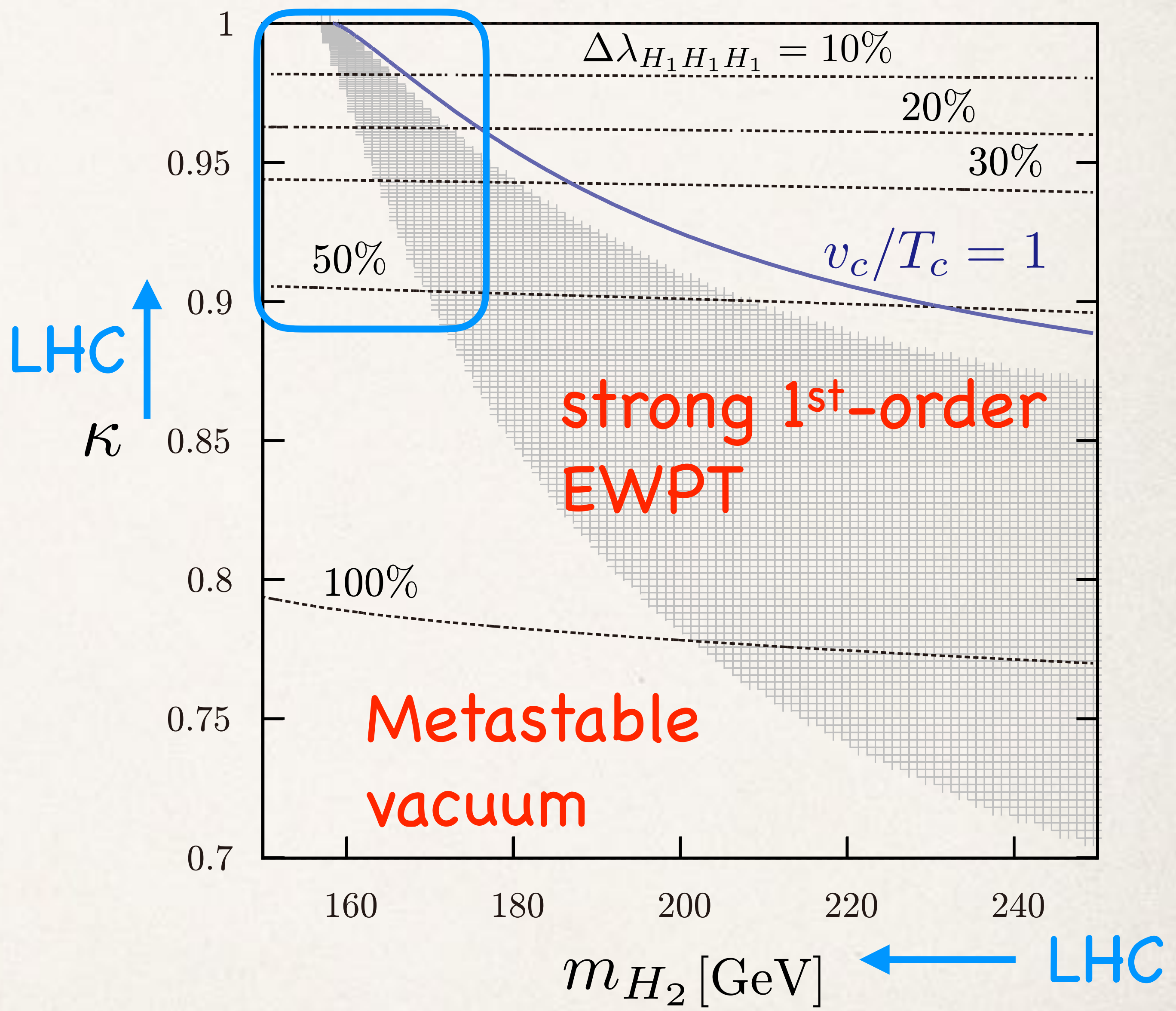

- Strong 1st-order EWPT leads to specific Higgs spectrum and couplings.

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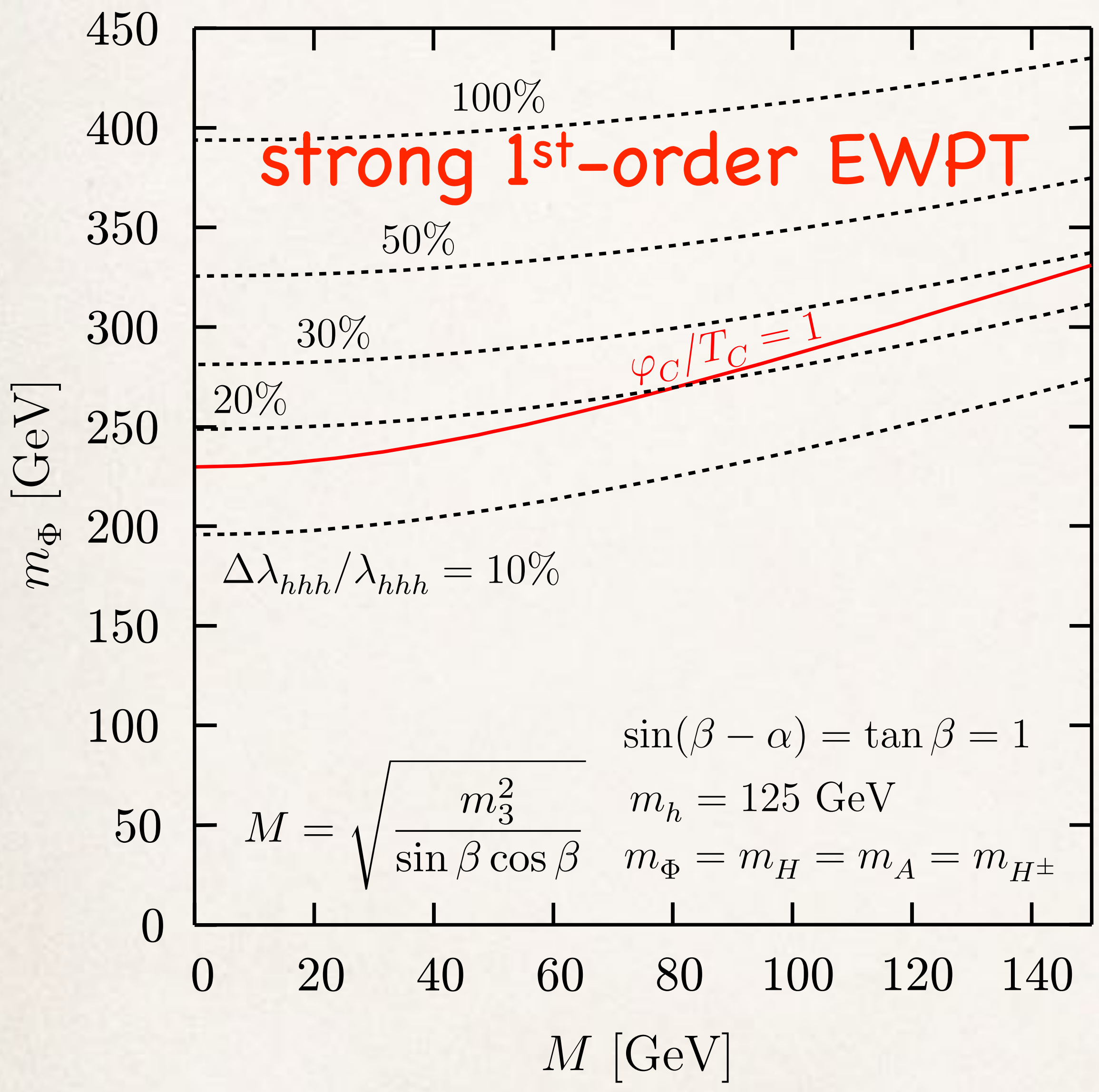

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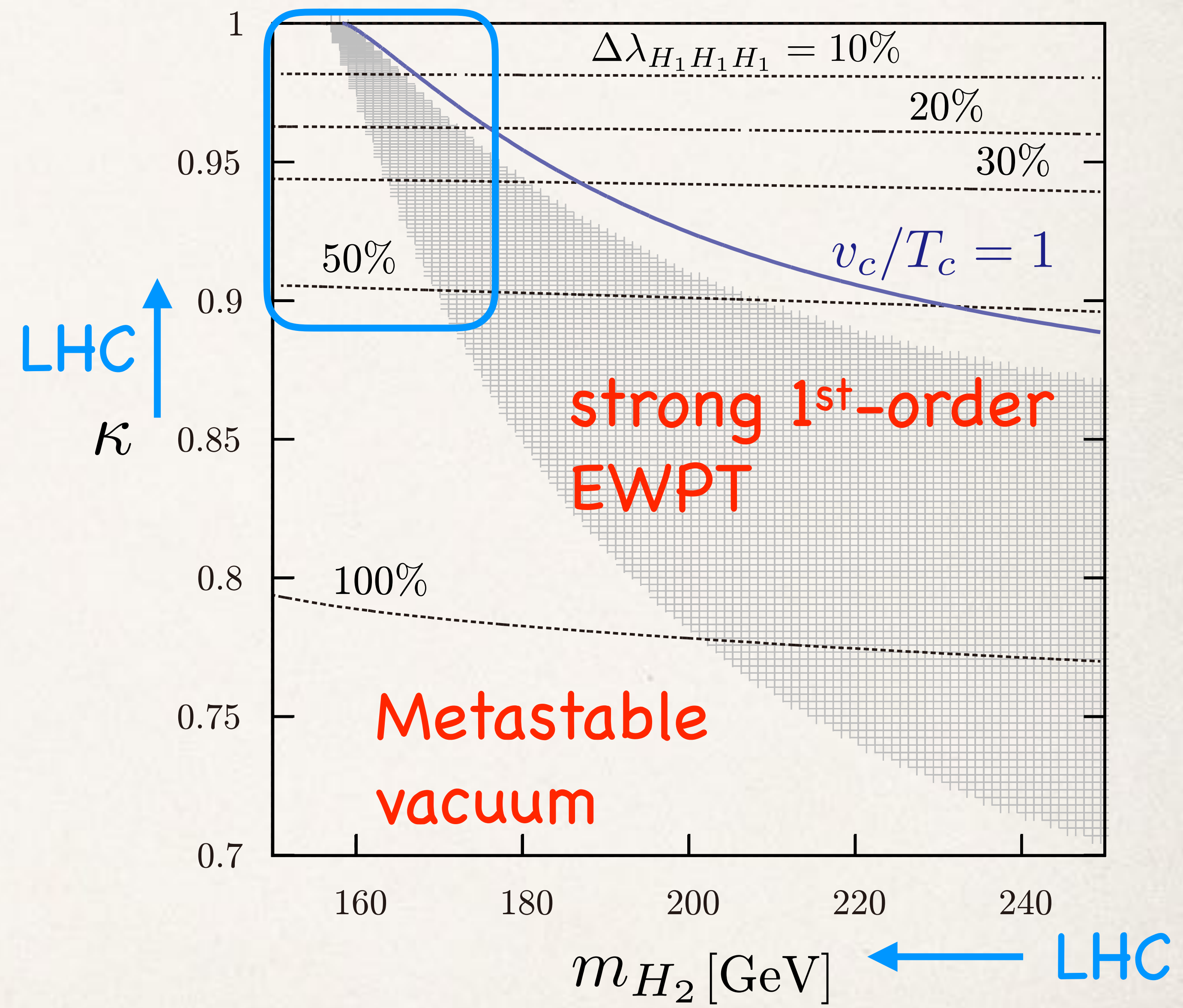


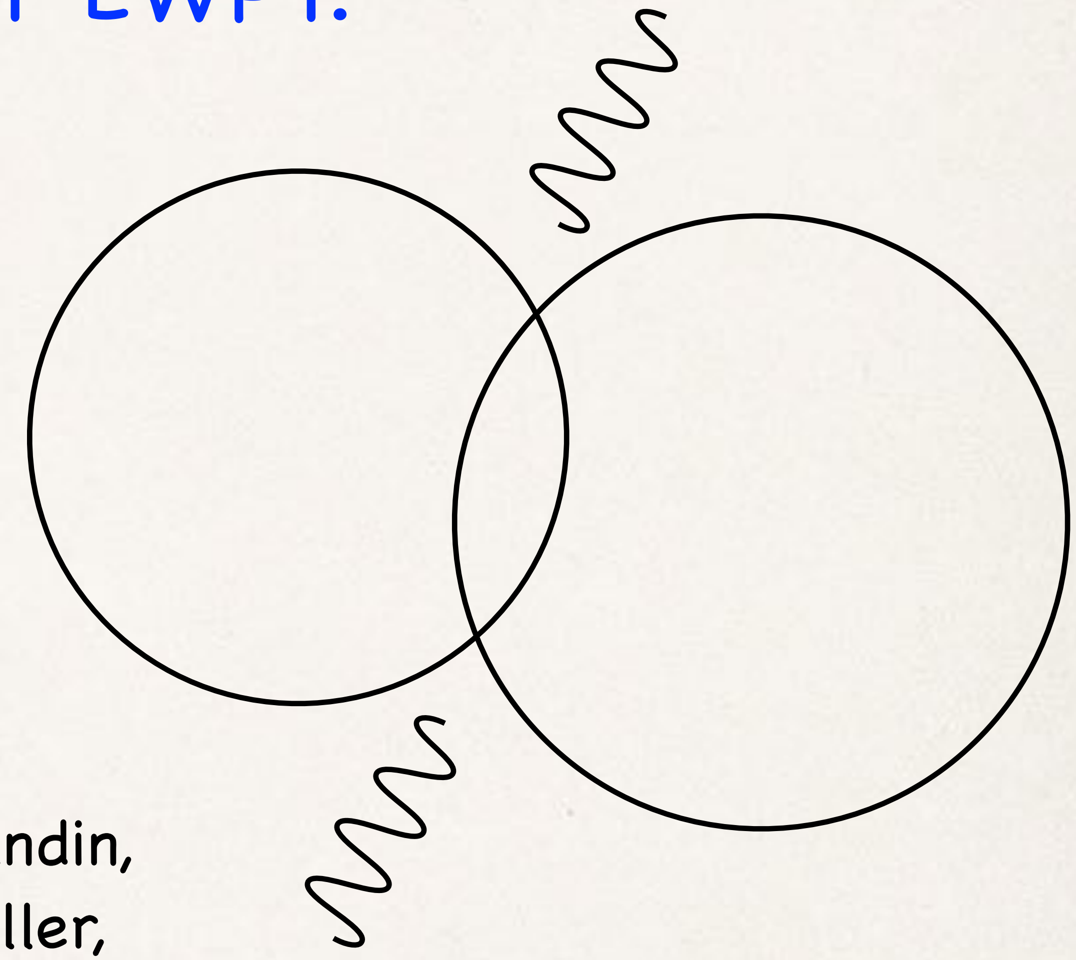
- Strong 1st-order EWPT leads to specific Higgs spectrum and couplings.
- $\Delta\lambda_{hhh}$ is not large enough to be detected at ILC250. -> probe by GWs

Gravitational Waves from 1st-order EWPT

GWs are induced by the 1st-order EWPT.

Sources of GW

(1) Bubble collisions,
(2)Sound waves,
(3)Turbulence



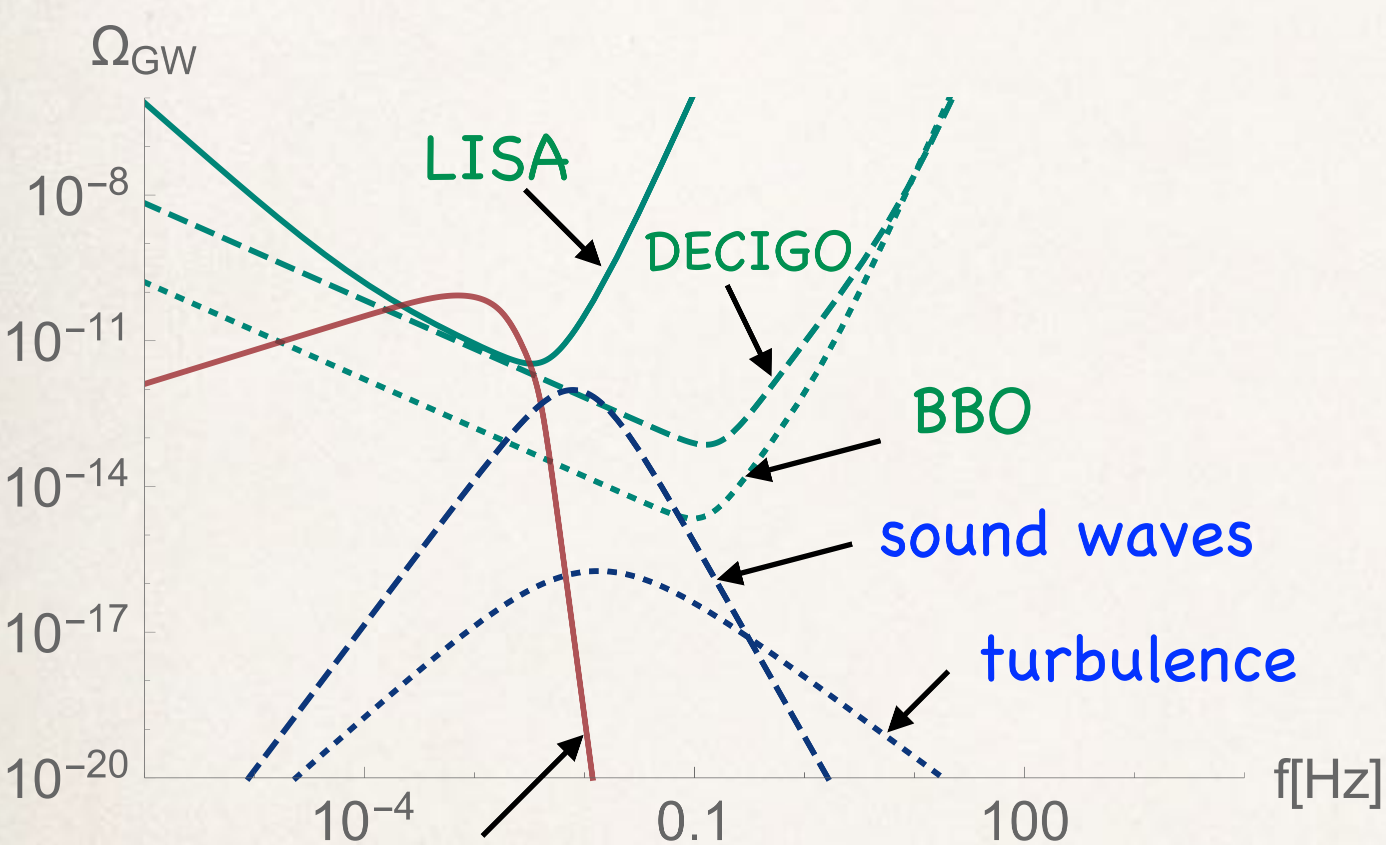
See Ref.[C.Caprini, M.Hindmarsh, S.Huber, T.Konstandin, J.Kozaczuk, G.Nardini, J.M.No, A.Petiteau, P.Schwaller, G.Servant, 1512.06239(JCAP)]

- GWs play a complementary role in probing Higgs sector.

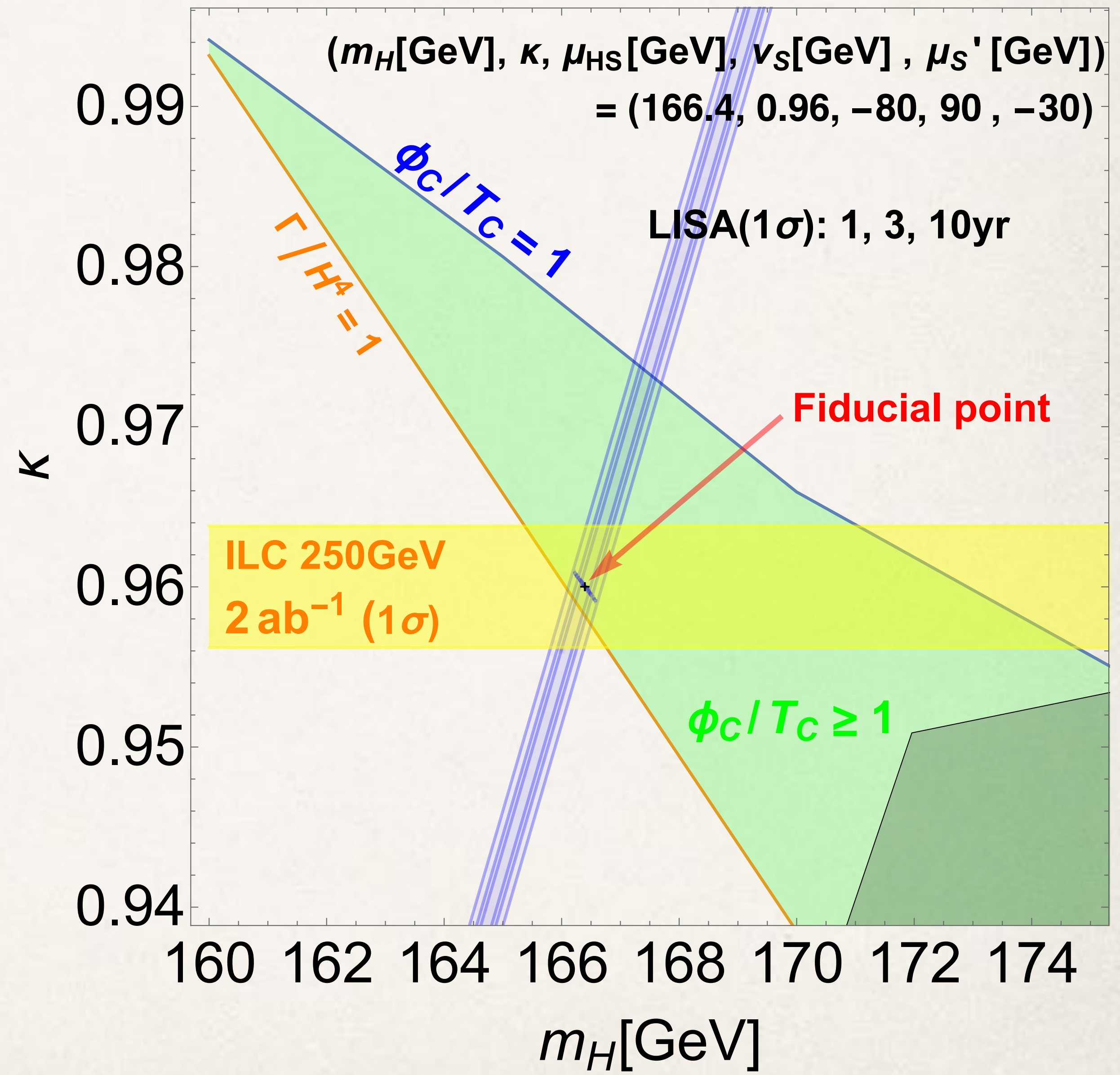
Gravitational Waves from 1st-order EWPT

[K.Hashino, R.Jinno, M.Kakizaki, S.Kanemura, T.Takahashi, M.Takimoto, 1809.04994]

e.g. SM+S



For details, see Hashino's poster



GWs also provide exquisite probes of the Higgs sector!!

Higgs CP nature

CP-violating Higgs-fermion-fermion coupling

$$\mathcal{L}_{hff} = -\frac{\kappa_f y_f}{\sqrt{2}} h\bar{f}(\cos\Psi_{\mathrm{CP}} + i\gamma_5 \sin\Psi_{\mathrm{CP}})f$$

$\Psi_{\mathrm{CP}} = 0 \;\rightarrow\; h$ is pure CP-even

$\Psi_{\mathrm{CP}} = \pi/2 \;\rightarrow\; h$ is pure CP-odd

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1212.6639(CMS), 1307.1432(ATLAS)

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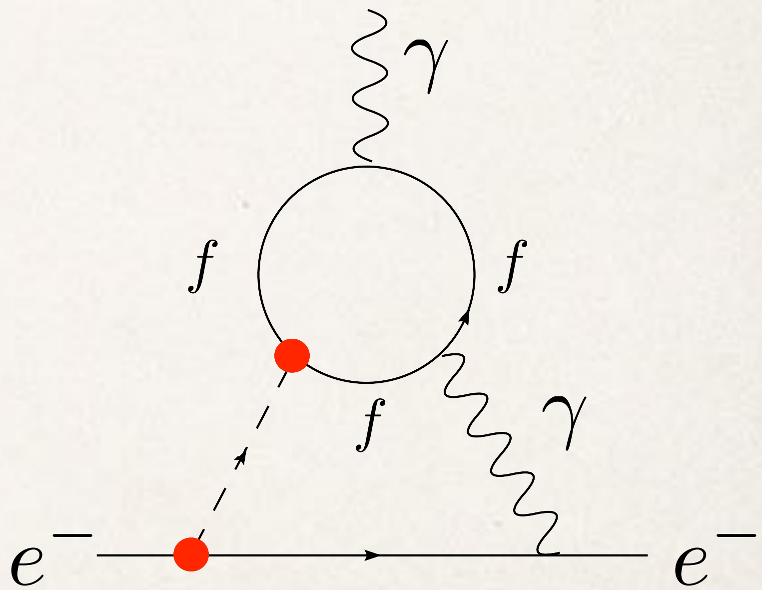
EDM constraint

CP phase is highly constrained by electric dipole moment (EDM) of electron.

$$|d_e| < 1.1 \times 10^{-29} \ e \ {\rm cm}$$

[ACME, Nature 562,355(2018)]



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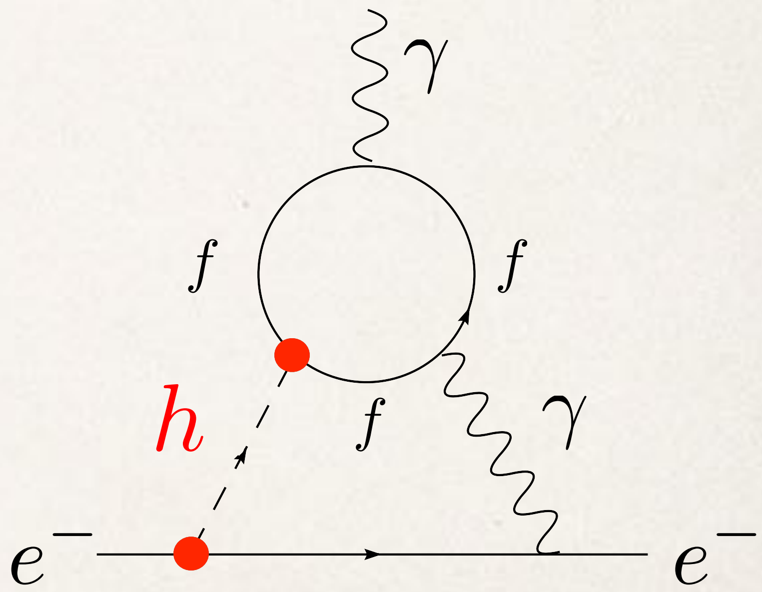

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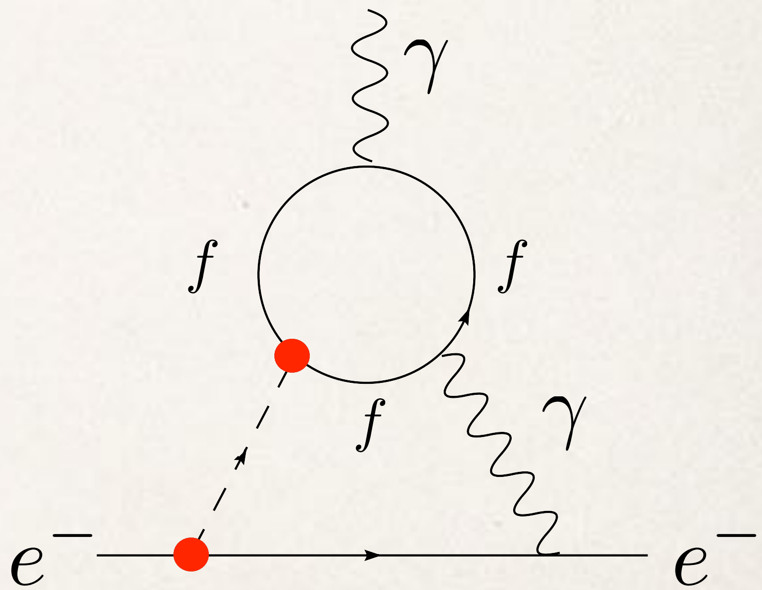

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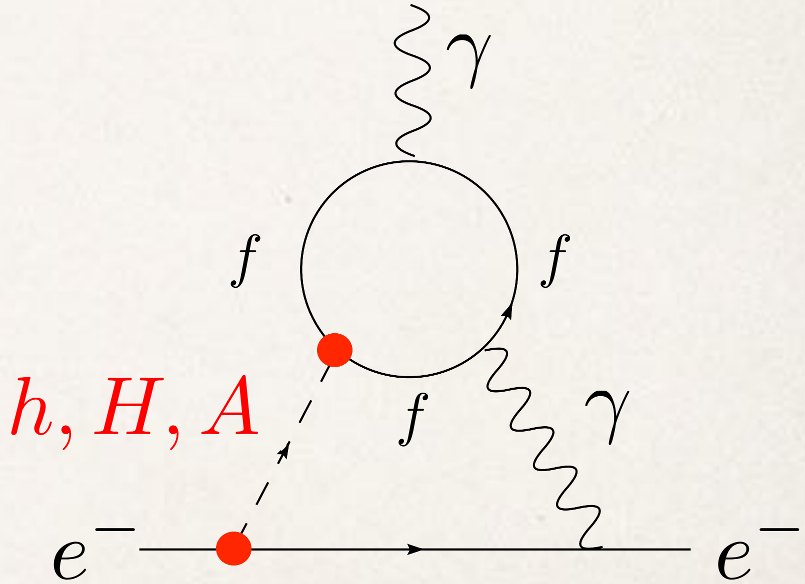

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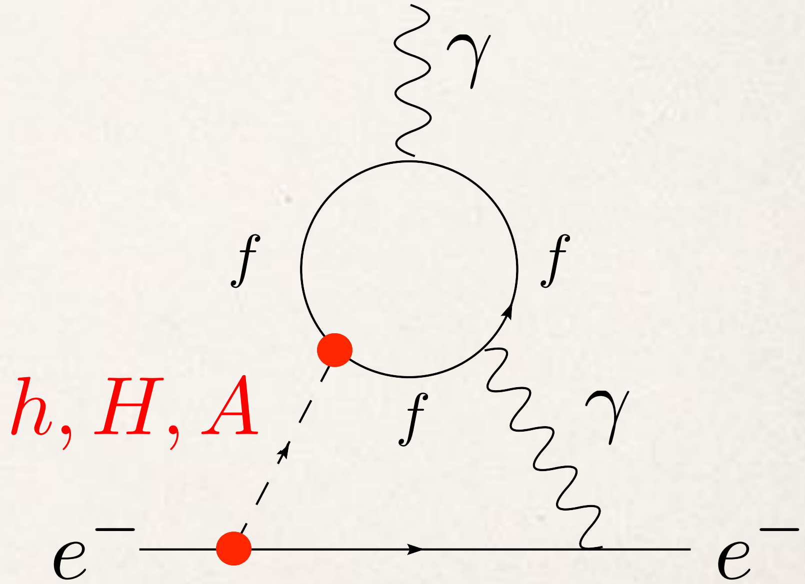


However, this constraint can be avoidable if cancellation mechanism is at work. -> collider probes play a complementary role!

h(125)→ττ

CP-violating Higgs-tau-tau coupling:

$$\mathcal{L}_{h\tau\tau} = -\frac{\kappa_\tau y_\tau}{\sqrt{2}} h\bar{\tau}(\cos\Psi_{\rm CP} + i\gamma_5 \sin\Psi_{\rm CP})\tau$$

❒ LHC: $\sqrt{s} = 13$ TeV

[X.Chen, Y.Wu, PLB790(2019)332]

$\Psi_{\rm CP}$: 270 mrad (15.5°) (300 fb^{-1})
$\Psi_{\rm CP}$: 90 mrad (5.2°) (3000 fb^{-1})

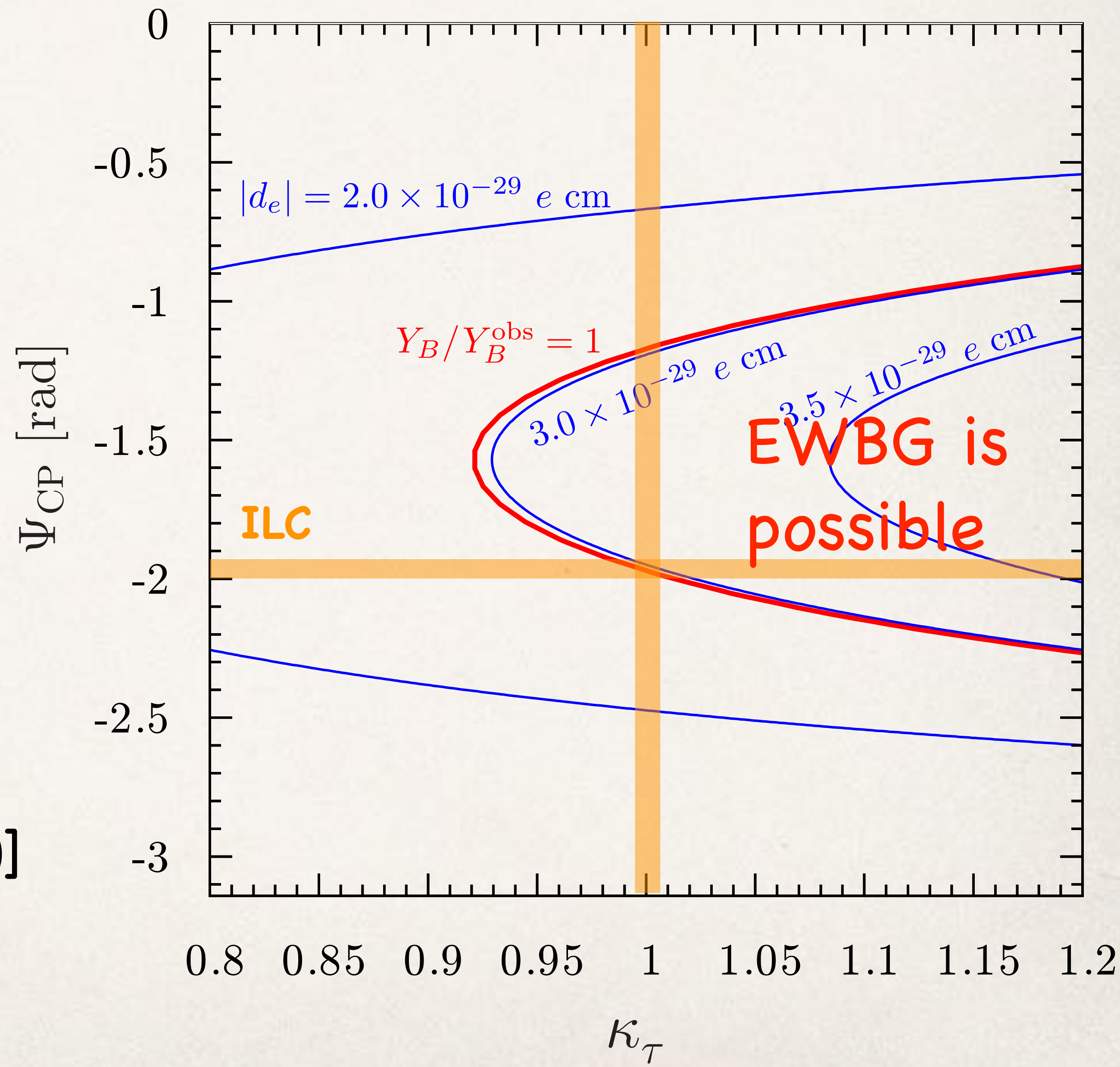
❒ ILC250 w/ 2000fb^{-1}

[D.Jeans, G.W. Wilson, PRD98,013007(2018)]

$\Psi_{\rm CP}$: 75mrad (4.3°)

EWBG driven by extra tau Yukawa:

e.g., general 2HDMs:
1607.07316(PLB), 1609.09849(PRD),



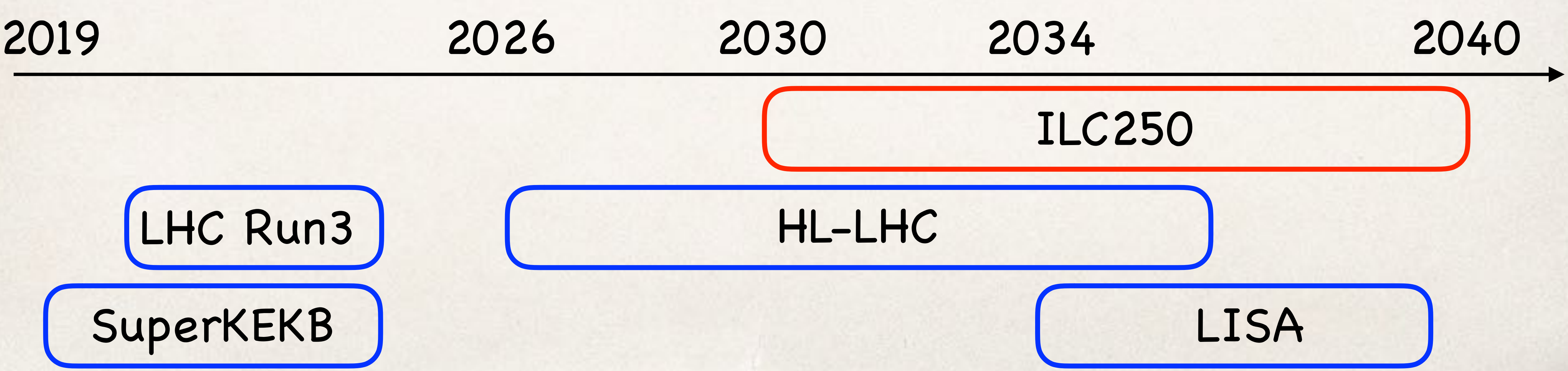
$\kappa_\tau \sim 1.0\%$ ILC250+HL-LHC

Summary

- Higgs precision measurements have huge impacts on probes of electroweak baryogenesis.

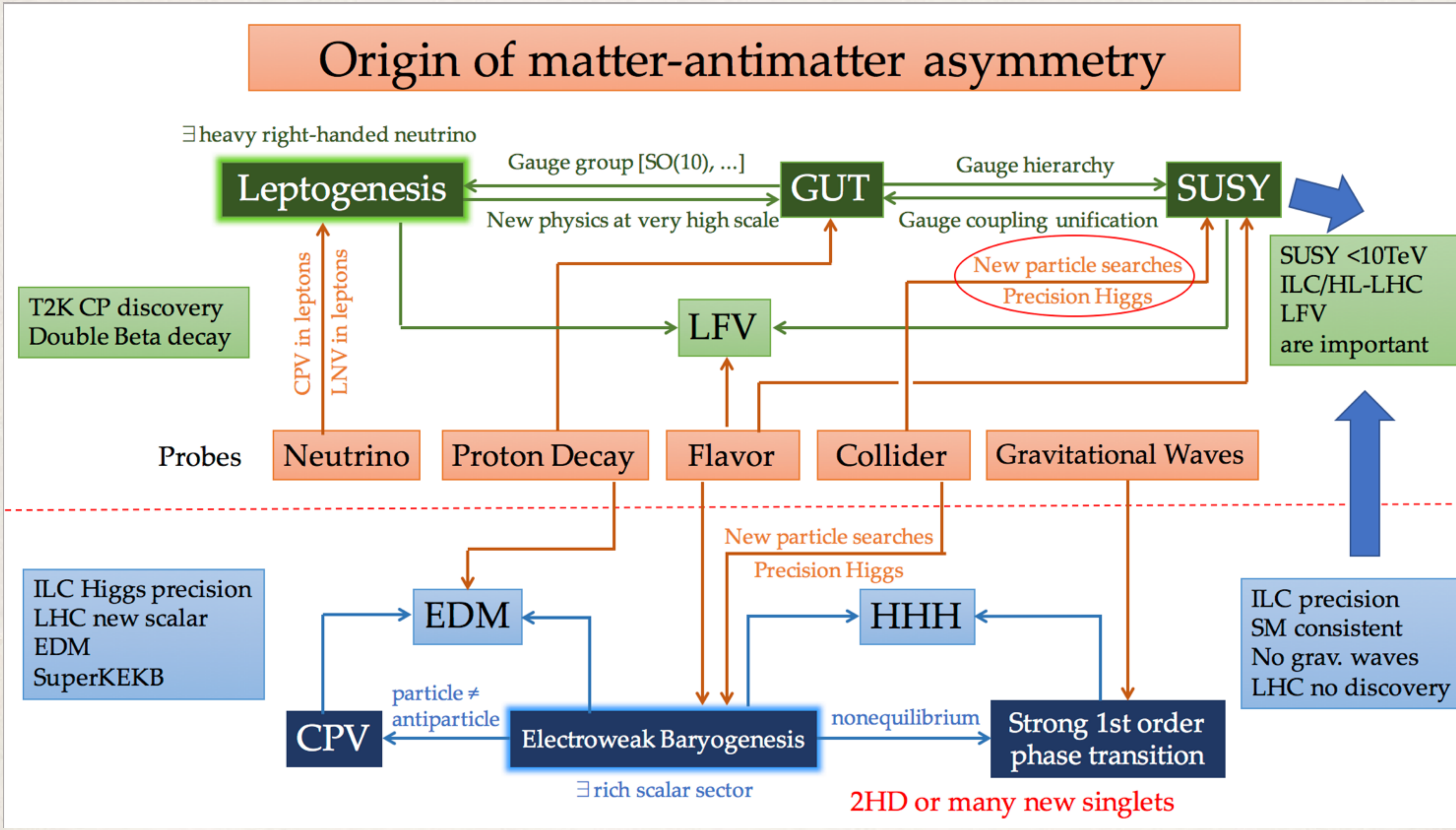
- Gravitational waves play a complimentary role in investigating nature of electroweak phase transition.

- h(125)->$\tau\tau$ measurement is the powerful probe of CP violation regardless of accidental cancellation of electron EDM.



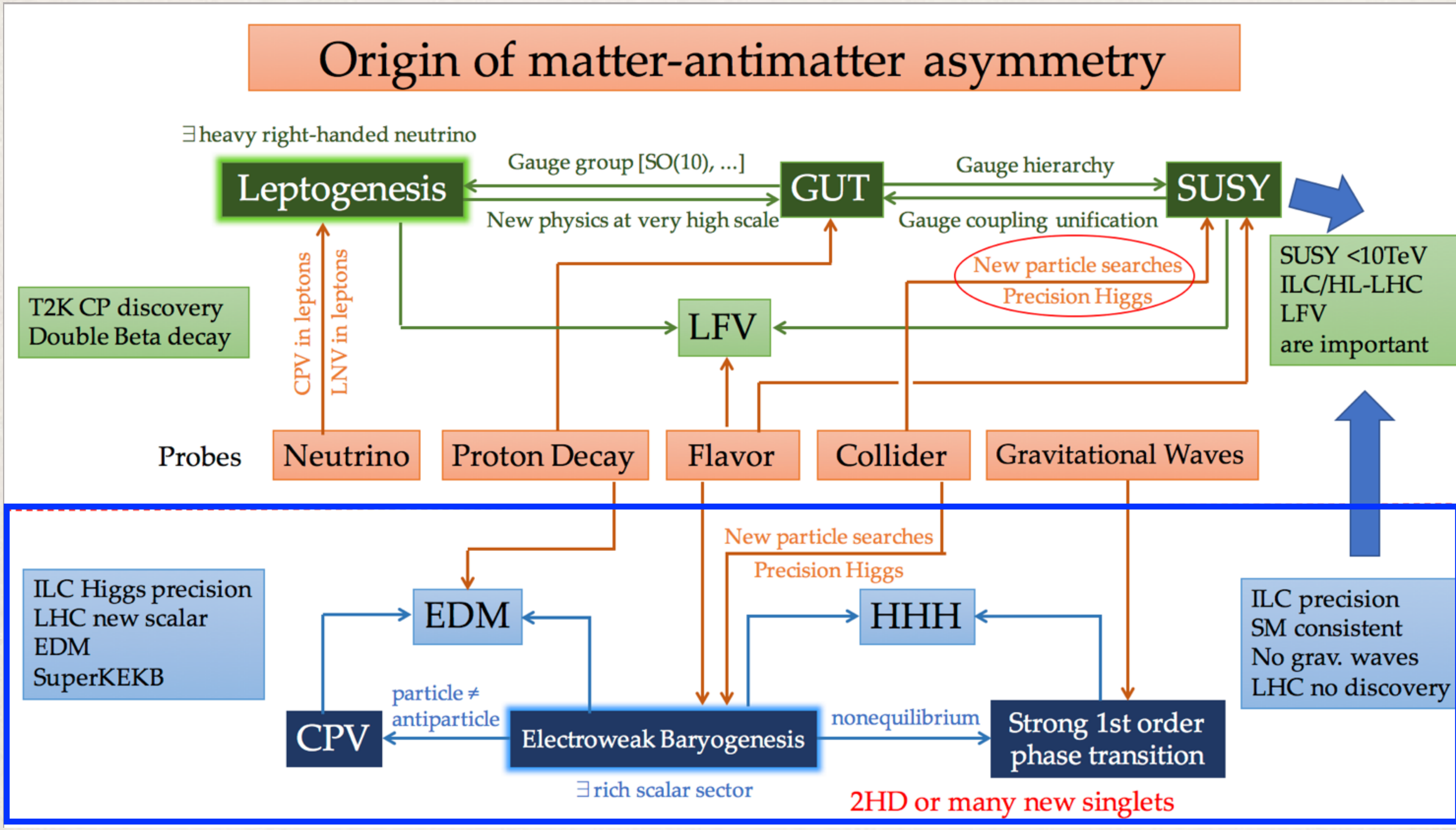
Backup

1710.08639



ILC (Higgs factory) provides exquisite probes of Electroweak Baryogenesis (EWBG).

1710.08639



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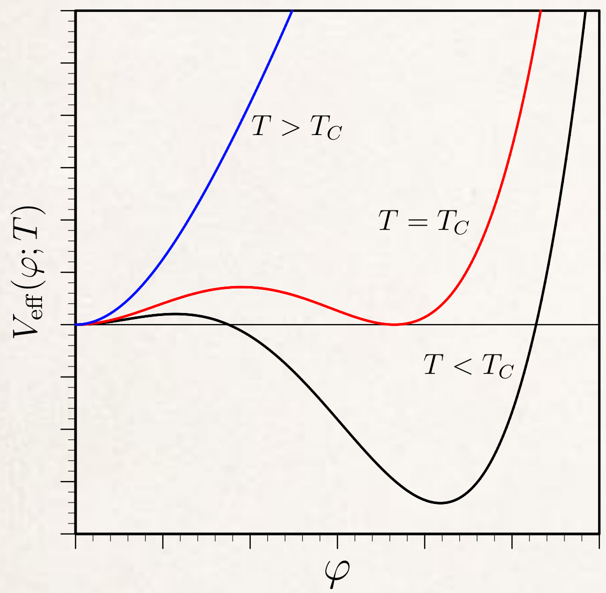
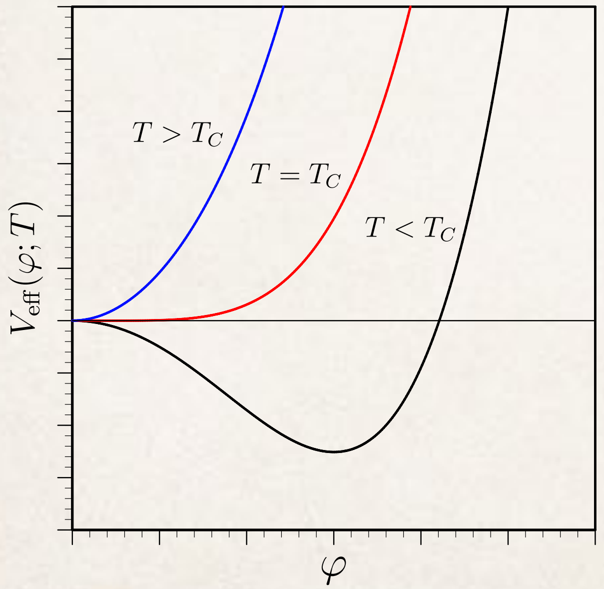
[S.Kanemura, Y.Okada, E.S., PLB606 (2005) 361;
C.Grojean, G.Servant, J.Wells, PRD71 (2005) 036001]



1st-order phase transition (needed for EW baryogenesis)

$$\lambda_{hhh} > \lambda_{hhh}^{\rm SM}$$



2nd-order phase transition

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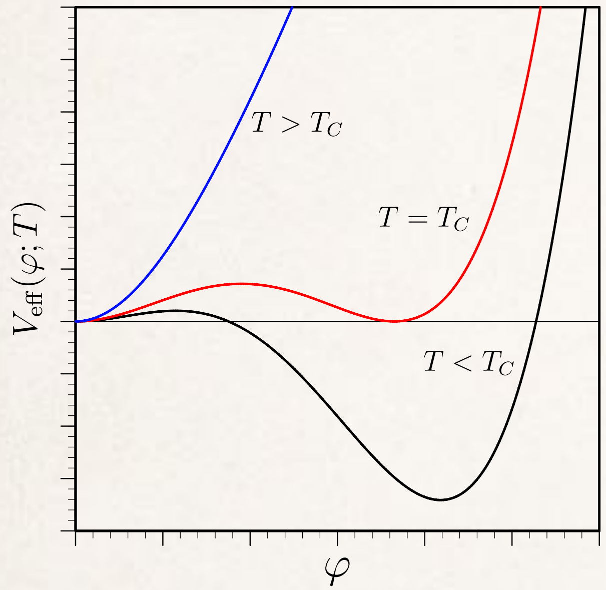

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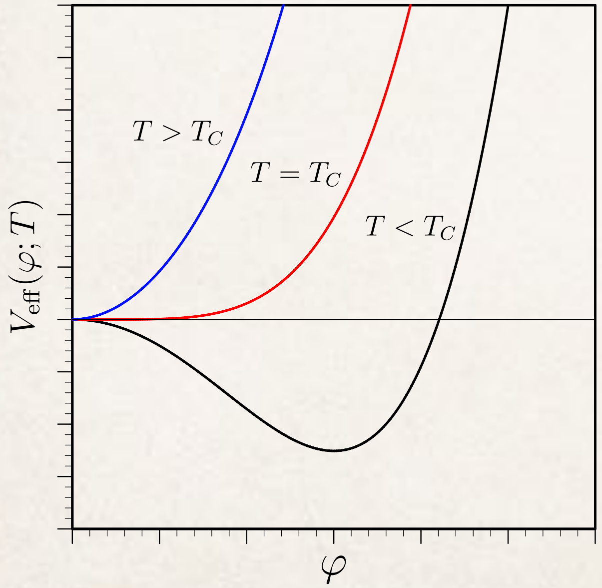
couplings btw. Higgs and new particle(s) ≈ O(1).



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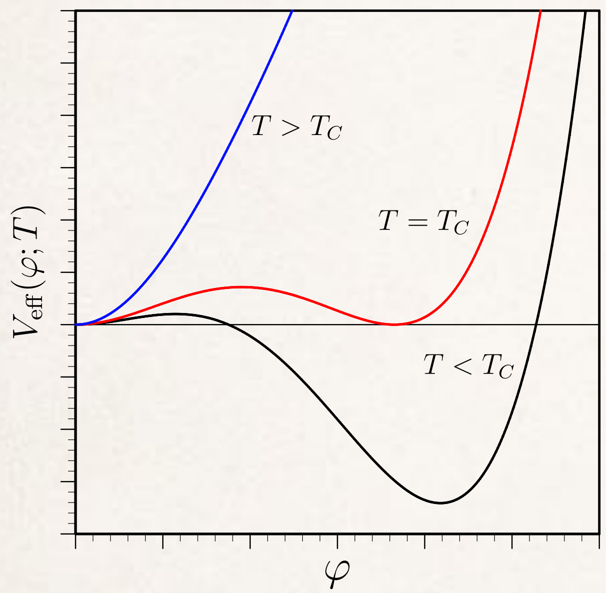

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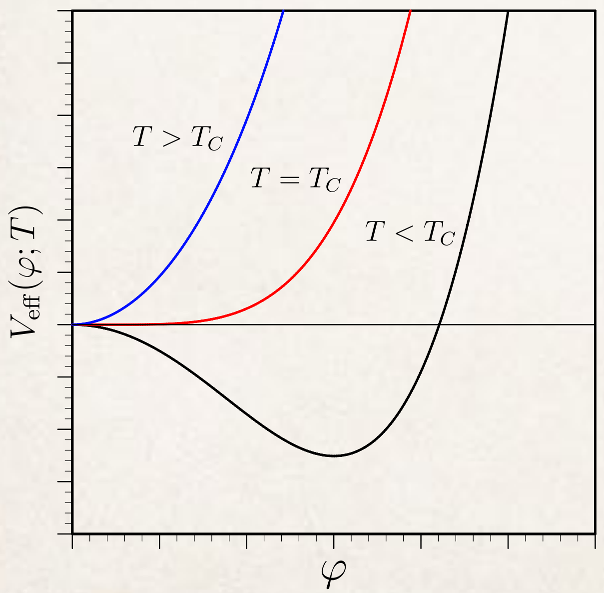

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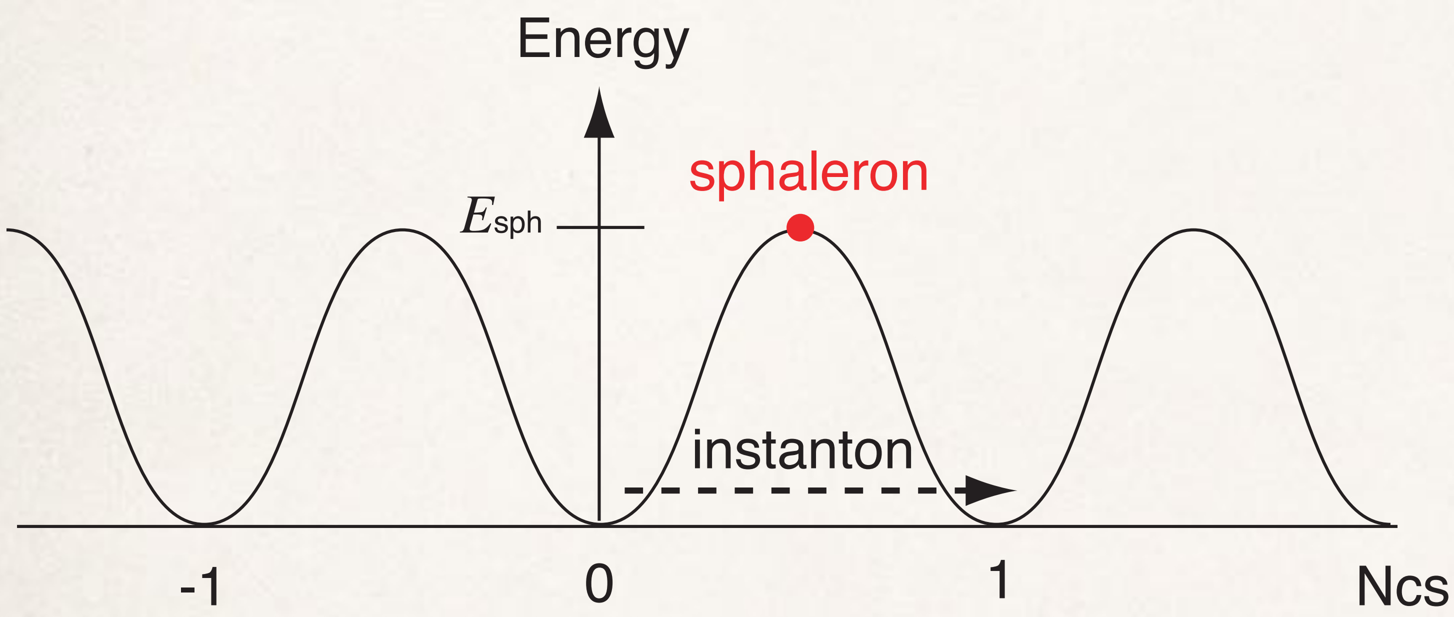
B+L violation

- A static saddle point solution w/ finite energy of the gauge-Higgs system. [N.S. Manton, PRD28 ('83) 2019]



$\underline{\Delta B \neq 0}$

Instanton: quantum tunneling

Sphaleron: thermal fluctuation

$\Delta(B+L) = 3\Delta N_{CS}$

B+L anomaly

$$\partial_\mu j^\mu_{B+L} = \frac{3}{16\pi^2}\left[g_2^2 \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right],$$

$$\partial_\mu j^\mu_{B-L} = 0,$$

# of Left-handed fermions can change!!

$$0 \leftrightarrow \sum_{i=1,2,3} (3q_L^i + l_L^i)$$

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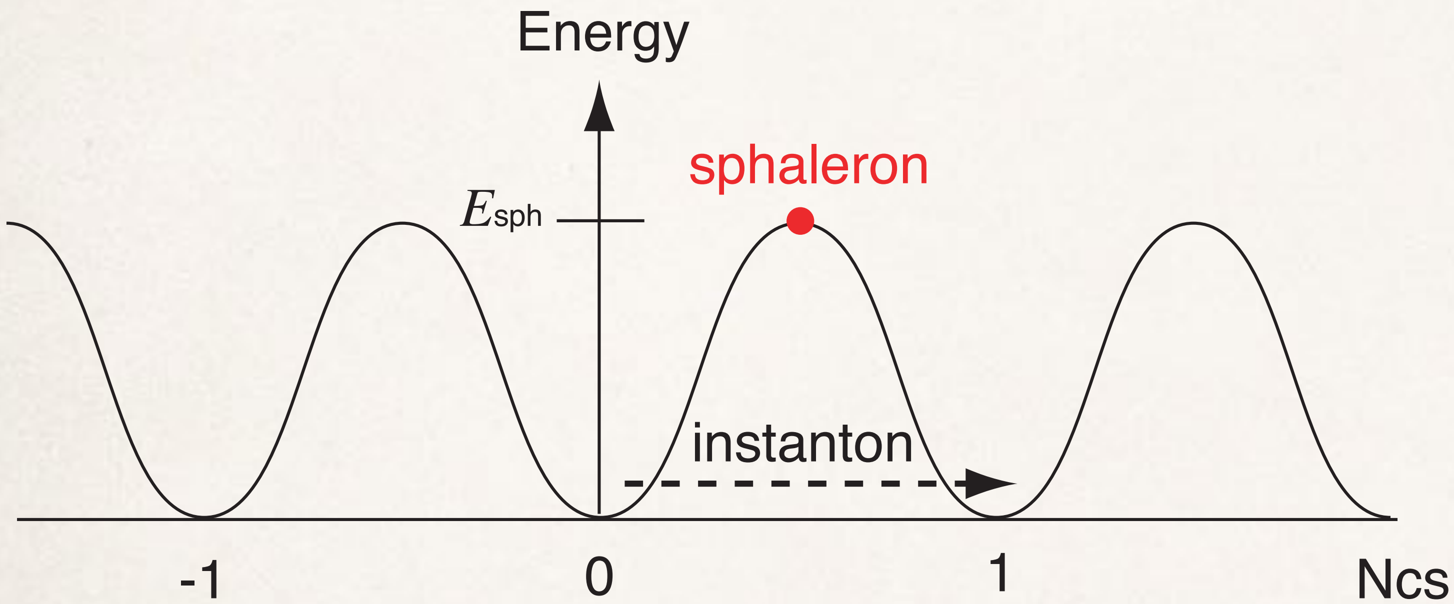

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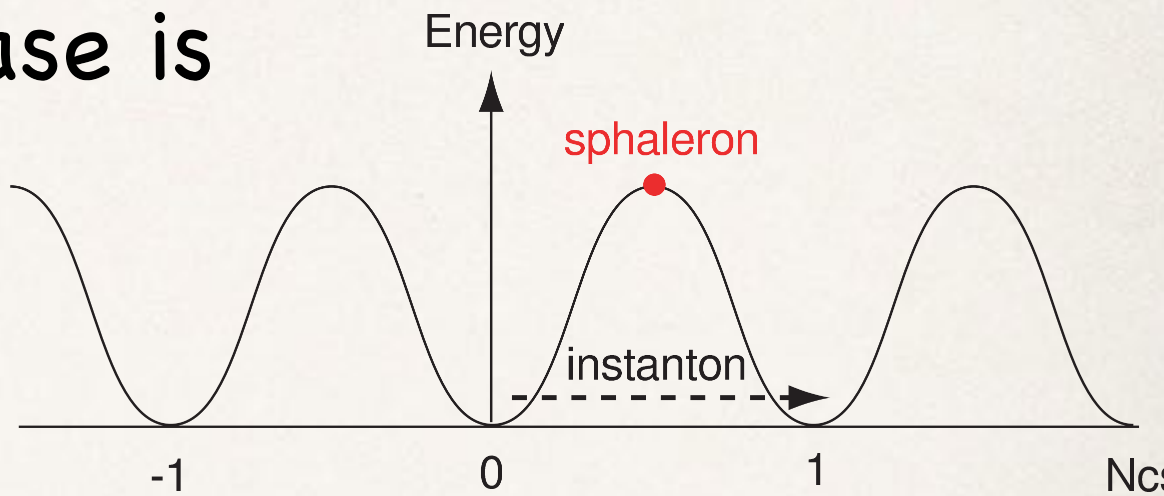
LHC can see this process?

still under debate...

$$\Gamma_B^{(b)} < H$$

B-changing rate in the broken phase is

$$\Gamma_B^{(b)} \simeq (\text{prefactor})e^{-E_{\rm sph}/T}$$



$$\Delta B = 3\Delta n_{\rm CS}$$

$E_{\rm sph}$ is proportional to the Higgs VEV

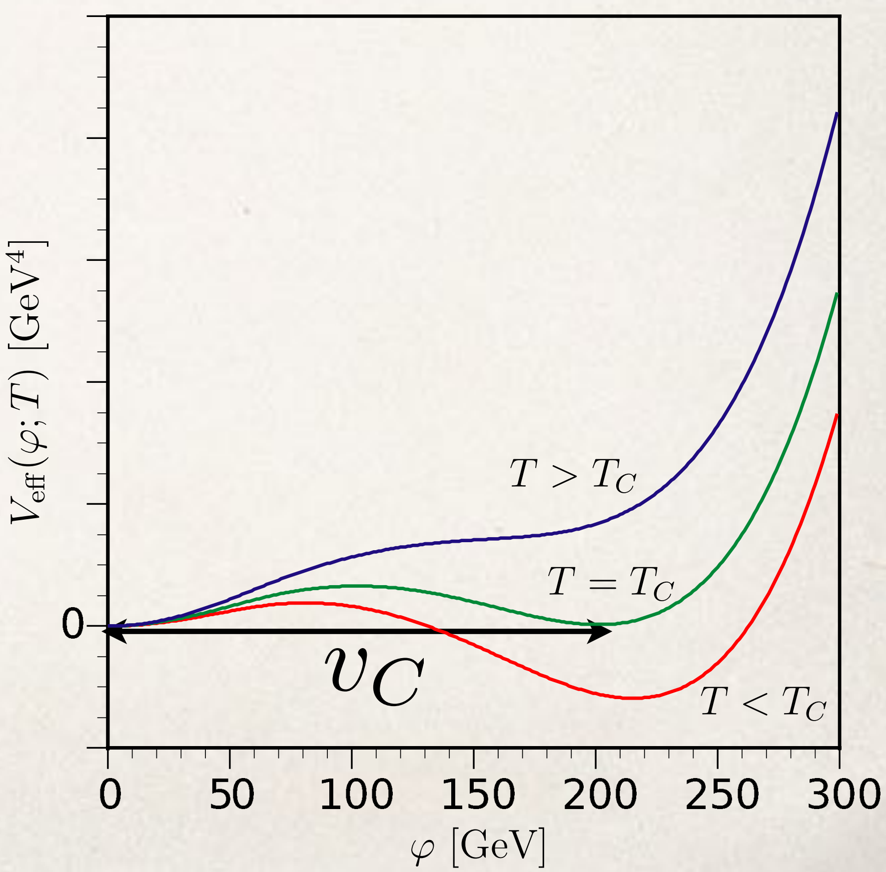
$$E_{\rm sph} \propto v(T)$$

what we need is

large Higgs VEV after the EWPT

➡ EWPT has to be "**strong**" 1st order!!

$$\Gamma_B^{(b)}(T_C) < H(T_C) \quad \rightarrow \quad \frac{v_C}{T_C} \gtrsim 1$$



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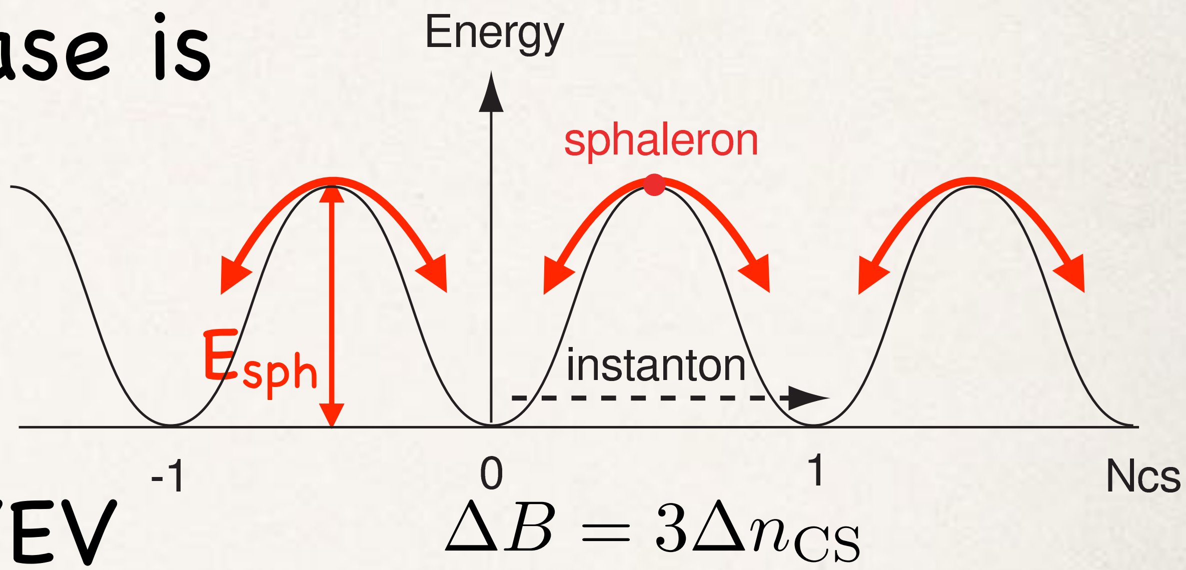

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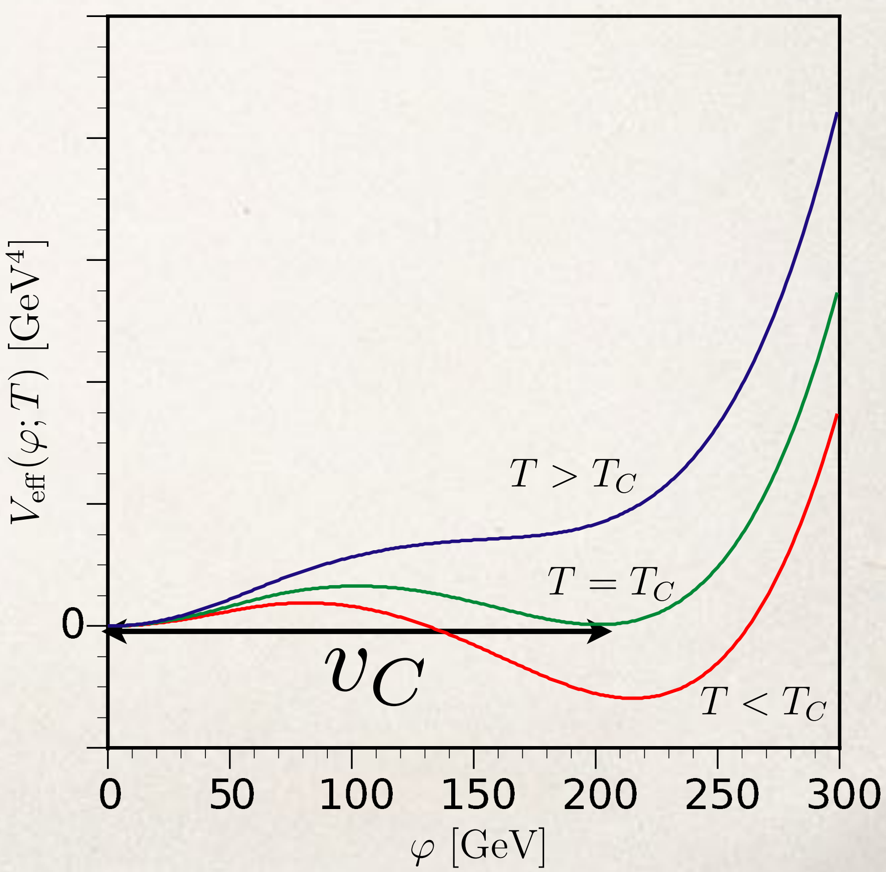

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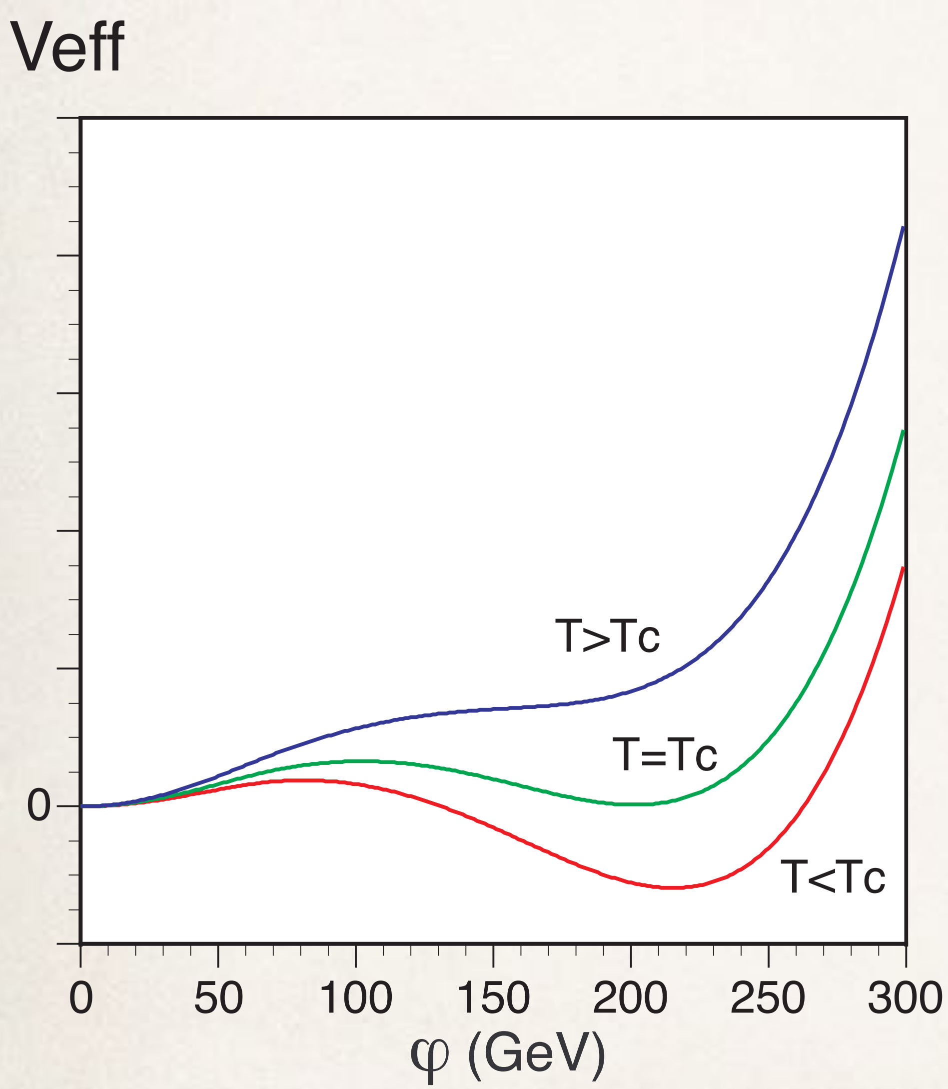
1st-order phase transition

$$V_{\rm eff} \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 \underset{T=T_C}{\rightarrow} \frac{\lambda_{T_C}}{4}\varphi^2(\varphi - v_C)^2$$



$$v_C = \frac{2ET_C}{\lambda_{T_C}} \quad \Rightarrow \quad \frac{v_C}{T_C} = \frac{2E}{\lambda_{T_C}}$$

e.g., 2HDM

Heavy Higgs loops can enhance E.

$$m^2_{i=H,A,H^\pm} = M^2 + \tilde{\lambda}_i\varphi^2$$

$$V_{\rm eff} \ni \begin{cases} -\tilde{\lambda}^{3/2}T\varphi^3\left(1+\frac{M^2}{\tilde{\lambda}\varphi^2}\right)^{3/2}, & \text{for } M^2 \ll \tilde{\lambda}\varphi^2, \\ -|M|^3T\left(1+\frac{\tilde{\lambda}\varphi^2}{M^2}\right)^{3/2}, & \text{for } M^2 \gtrsim \tilde{\lambda}\varphi^2. \end{cases}$$

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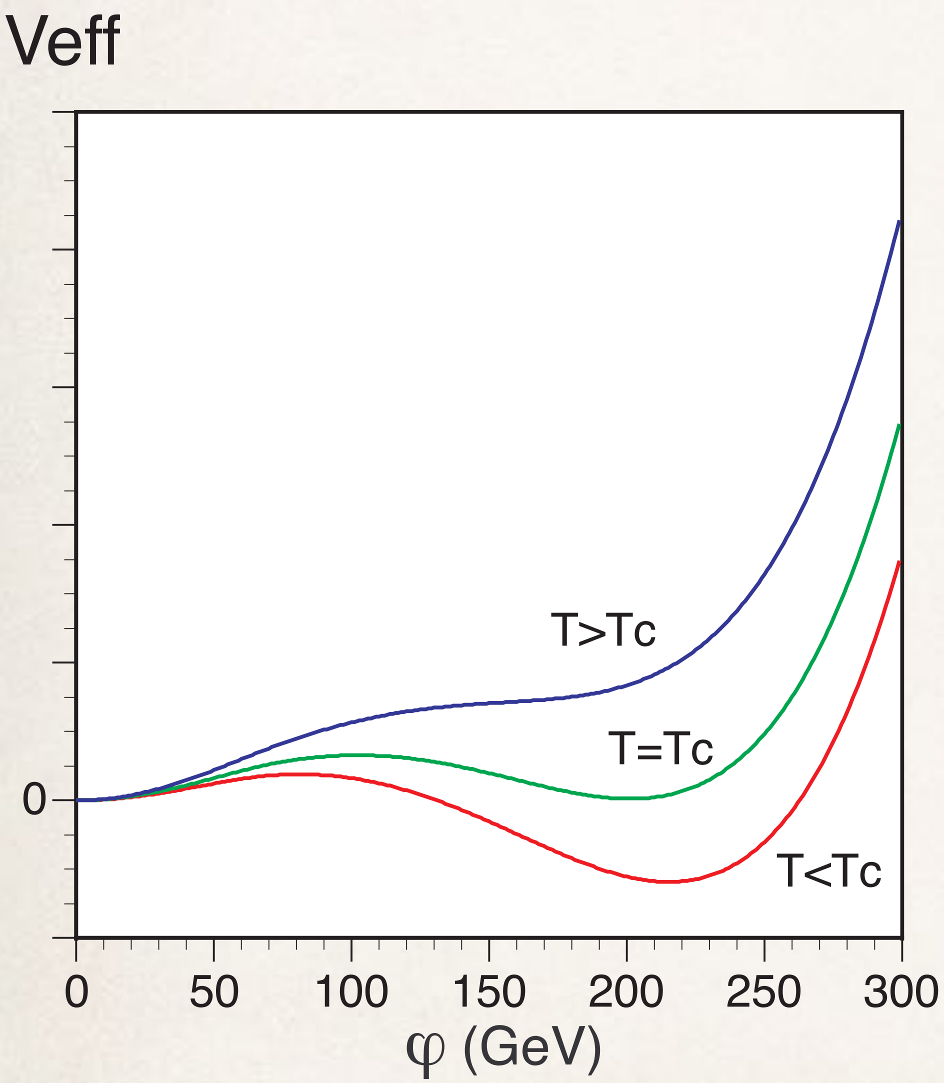

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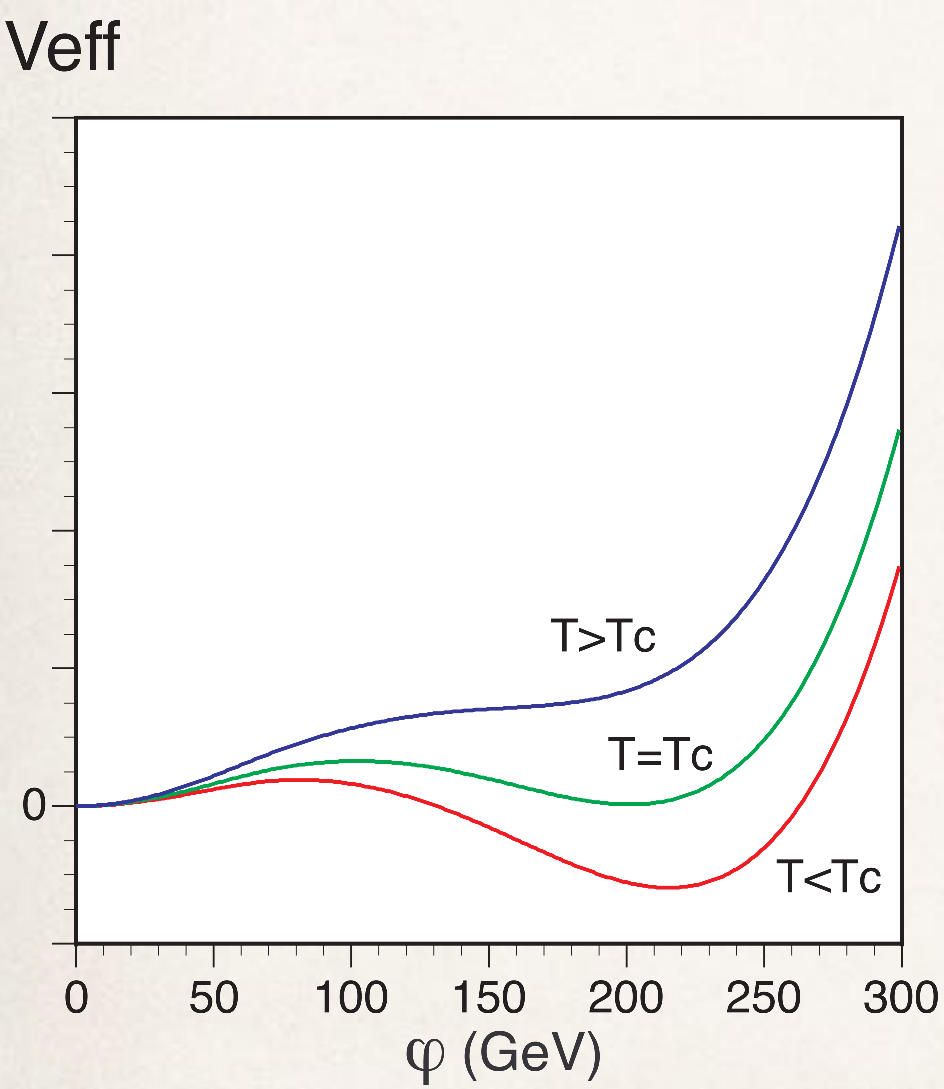

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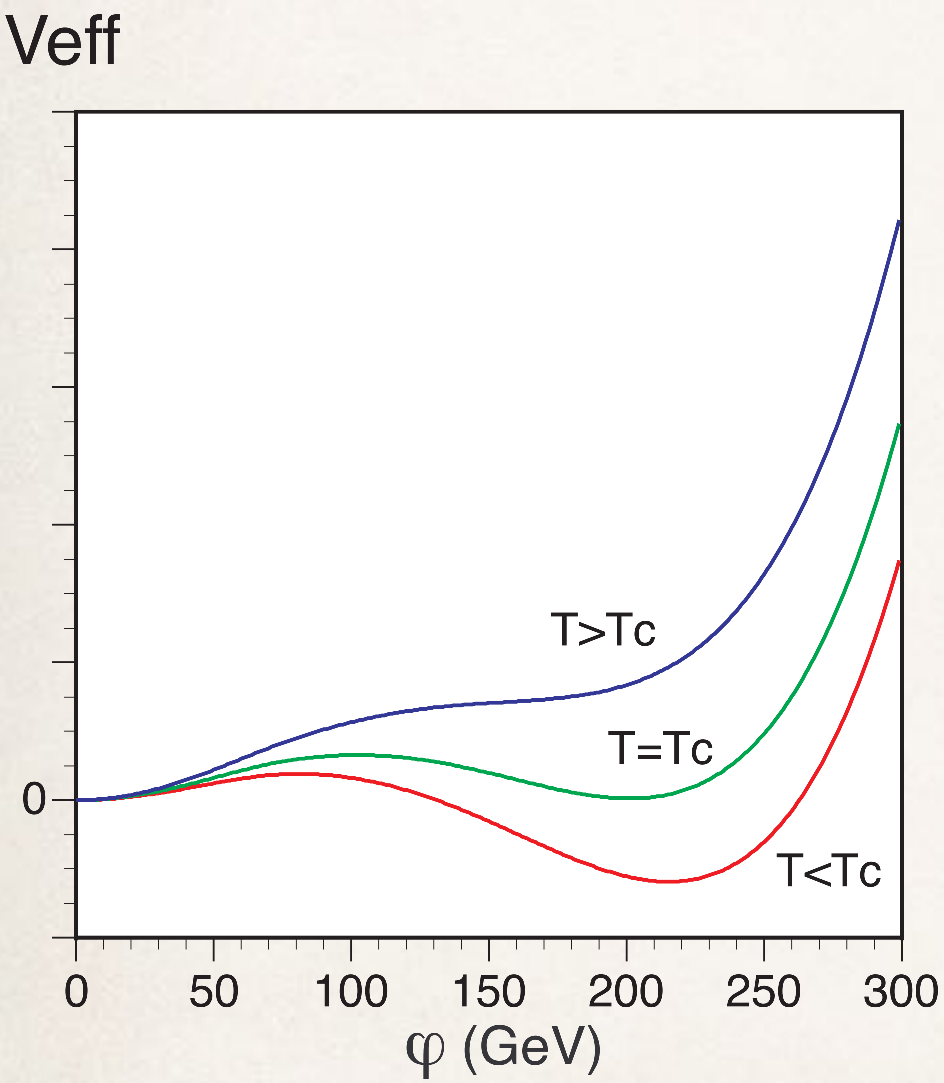
$$V_{\rm eff} \ni \begin{cases} -\tilde{\lambda}^{3/2}T\boxed{\varphi^3}\left(1+\frac{M^2}{\tilde{\lambda}\varphi^2}\right)^{3/2}, & \text{for } M^2 \ll \tilde{\lambda}\varphi^2, \\ -|M|^3T\left(1+\frac{\tilde{\lambda}\varphi^2}{M^2}\right)^{3/2}, & \text{for } M^2 \gtrsim \tilde{\lambda}\varphi^2. \end{cases}$$

1st-order phase transition

$$V_{\rm eff} \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 \underset{T=T_C}{\rightarrow} \frac{\lambda_{T_C}}{4}\varphi^2(\varphi - v_C)^2$$



$$v_C = \frac{2ET_C}{\lambda_{T_C}} \quad \Rightarrow \quad \frac{v_C}{T_C} = \frac{2E}{\lambda_{T_C}} \gtrsim 1$$

e.g., 2HDM

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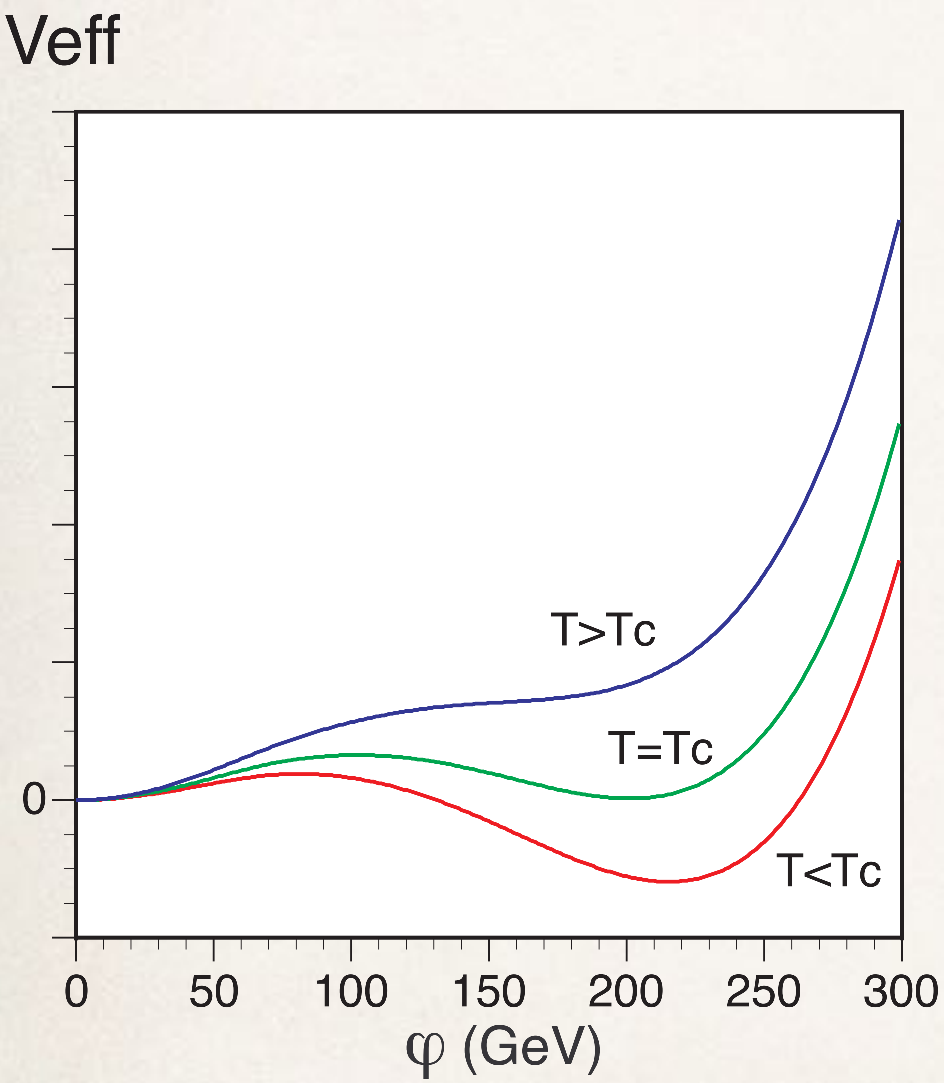

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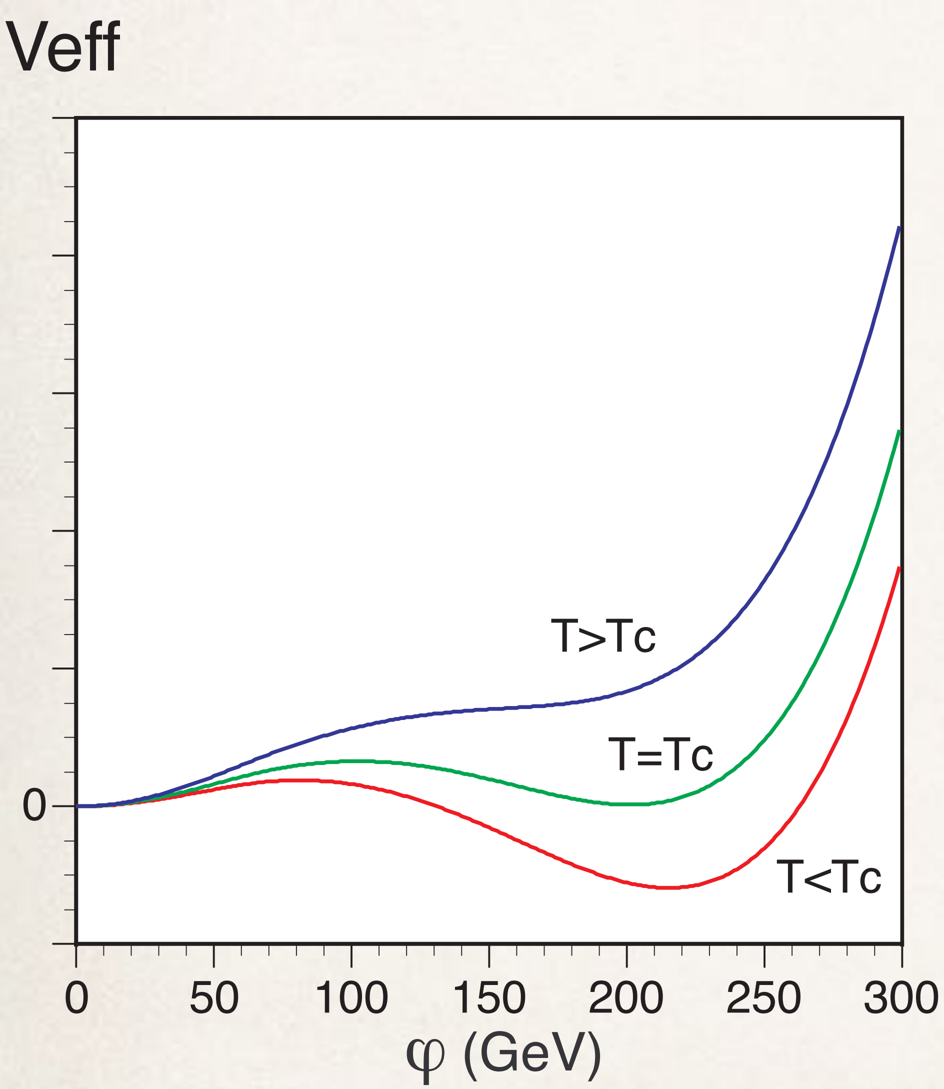

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decoupling

Non-decoupling heavy Higgs bosons play a central role in enhancing E.

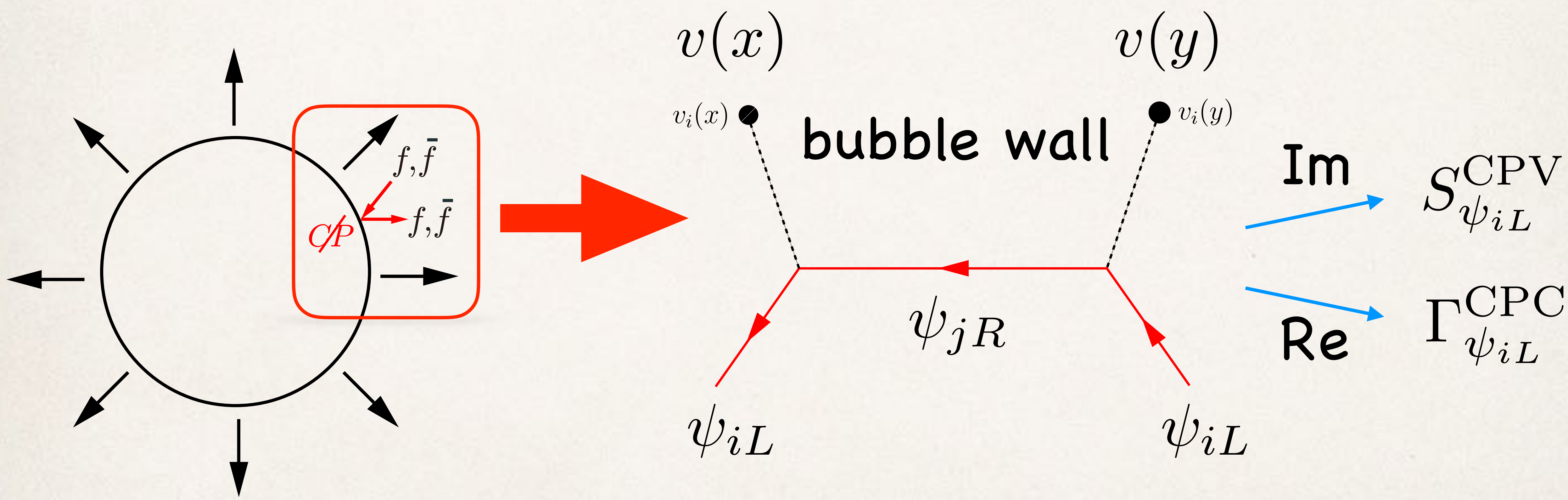
EWBG-related CP violation

Diffusion eq. for n_B: $\bar{z} < 0$: sym-phase, $\bar{z} > 0$: br-phase

$$D_Q n''_B(\bar{z}) - v_w n'_B(\bar{z}) - \theta(-\bar{z})\mathcal{R} n_B(\bar{z}) = \theta(-\bar{z})\frac{3}{2}\Gamma_B^{(\mathrm{sym})} n_{\mathrm{left}}(\bar{z})$$

diffusion const. wall velocity back reaction sph. rate

n_{left} is generated by scatterings b/w particles and bubbles.



$$n_B \propto n_{\mathrm{left}} \propto S^{\mathrm{CPV}}_{\psi_{iL}} \Big/ \sqrt{\Gamma^{\mathrm{CPC}}_{\psi_{iL}}}$$

EWBG-related CP violation

If you have, e.g.,

$$-\mathcal{L}_Y = \bar{\psi}_i \Big[c_L(x) P_L + c_R(x) P_R \Big] \psi_j + \text{h.c.},$$

you could generate

$$S^{\text{CPV}}_{\psi_{iL}}(x) = C_{\text{BAU}} \Big[c_R(x) \dot{c}^*_R(x) - c^*_R(x) \dot{c}_R(x) \Big]$$

$$S^{\text{CPV}}_{\psi_{iR}}(x) = C_{\text{BAU}} \Big[c_L(x) \dot{c}^*_L(x) - c^*_L(x) \dot{c}_L(x) \Big]$$

$$S^{\text{CPV}}_{\psi_{iL}}(x) = -S^{\text{CPV}}_{\psi_{iR}}(x) \quad (i = j); \qquad S^{\text{CPV}}_{\psi_{iL}}(x) = -S^{\text{CPV}}_{\psi_{jR}}(x) \quad (i \neq j)$$