VANLANG UNIVERSITY

Higgs as a probe of electroweak baryogenesis

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Outline

- Overview of Electroweak Baryogenesis (EWBG)
- Current status
  - 1^{st}-order EWPT and its consequences for Higgs physics
  - EWBG-related CP violation
- Summary and Outlook

Baryon Asymmetry of the Universe (BAU)

Our Universe is baryon-asymmetric.

$$\eta^{\rm BBN} = \frac{n_B}{n_\gamma} = (5.8 - 6.5) \times 10^{-10},$$
$$\eta^{\rm CMB} = \frac{n_B}{n_\gamma} = (6.105 - 0.055) \times 10^{-10}.$$

PDG2020

Sakharov's conditions [Sakharov, JETP Lett. 5 (1967) 24]

(1) Baryon number violation
(2) C and CP violation
(3) Out of equilibrium

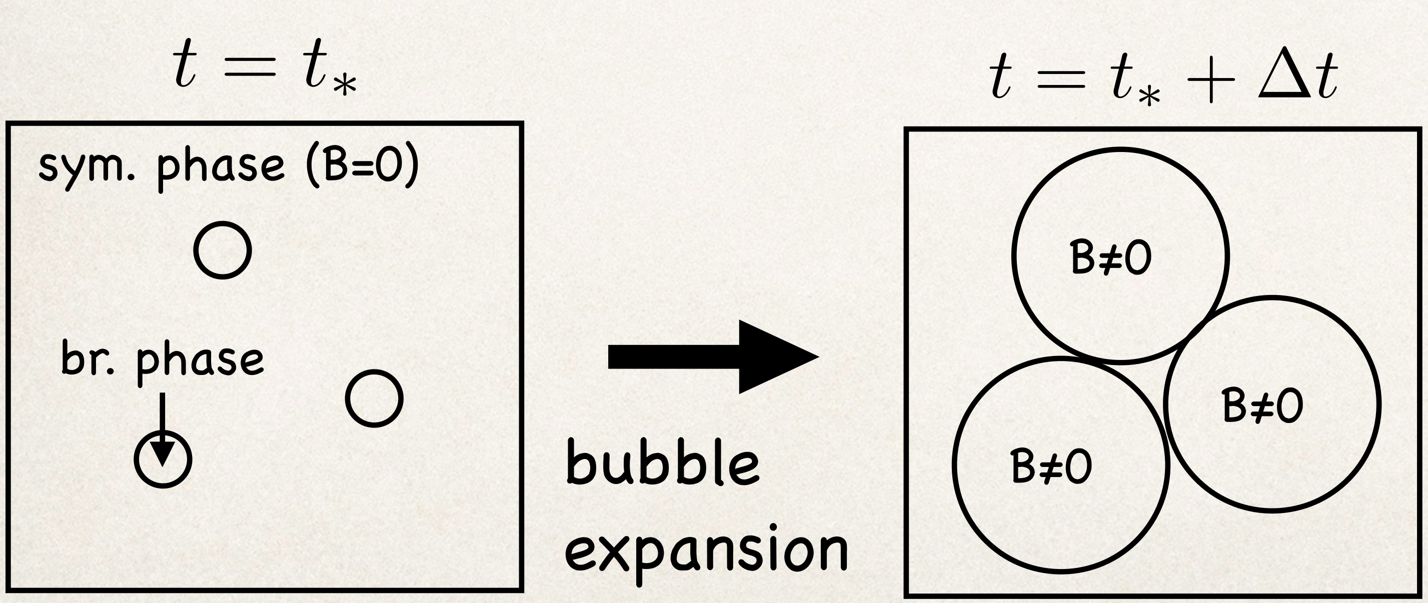
- ❒ after inflation (scale is model dependent)
- ❒ before Big-Bang Nucleosynthesis ($T \simeq O(1)$ MeV)

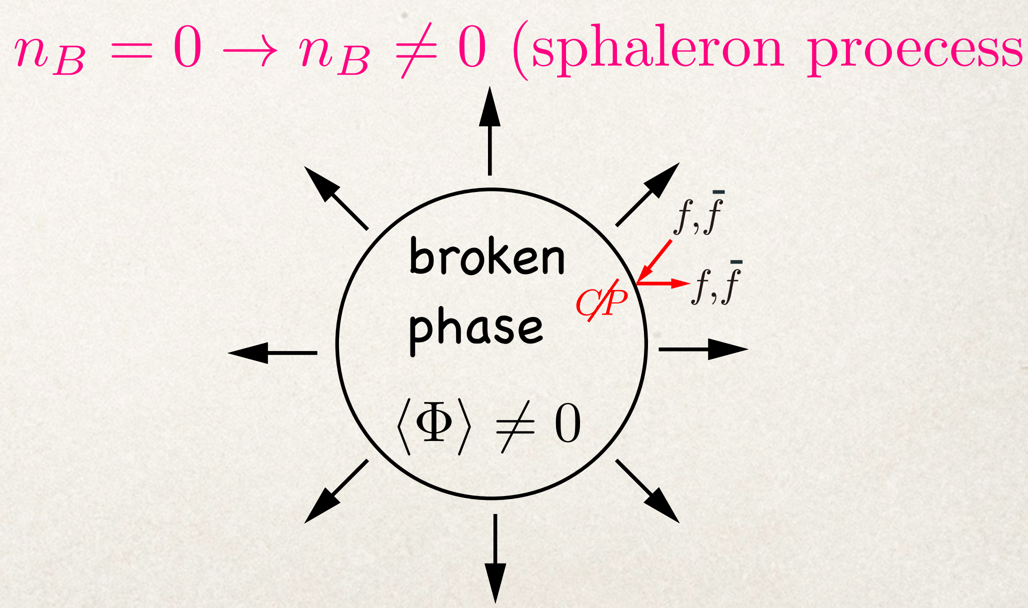
EW baryogenesis (EWBG)

Sakharov's conditions

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

- B violation: anomalous (sphaleron) process $0 \leftrightarrow \sum_{i=1,2,3} (3q_L^i + l_L^i)$ (LH fermions)
- C violation: chiral gauge interaction
- CP violation: CKM matrix and/or other sources in beyond the SM
- Out of equilibrium: 1st-order EW phase transition (EWPT) with expanding bubble walls

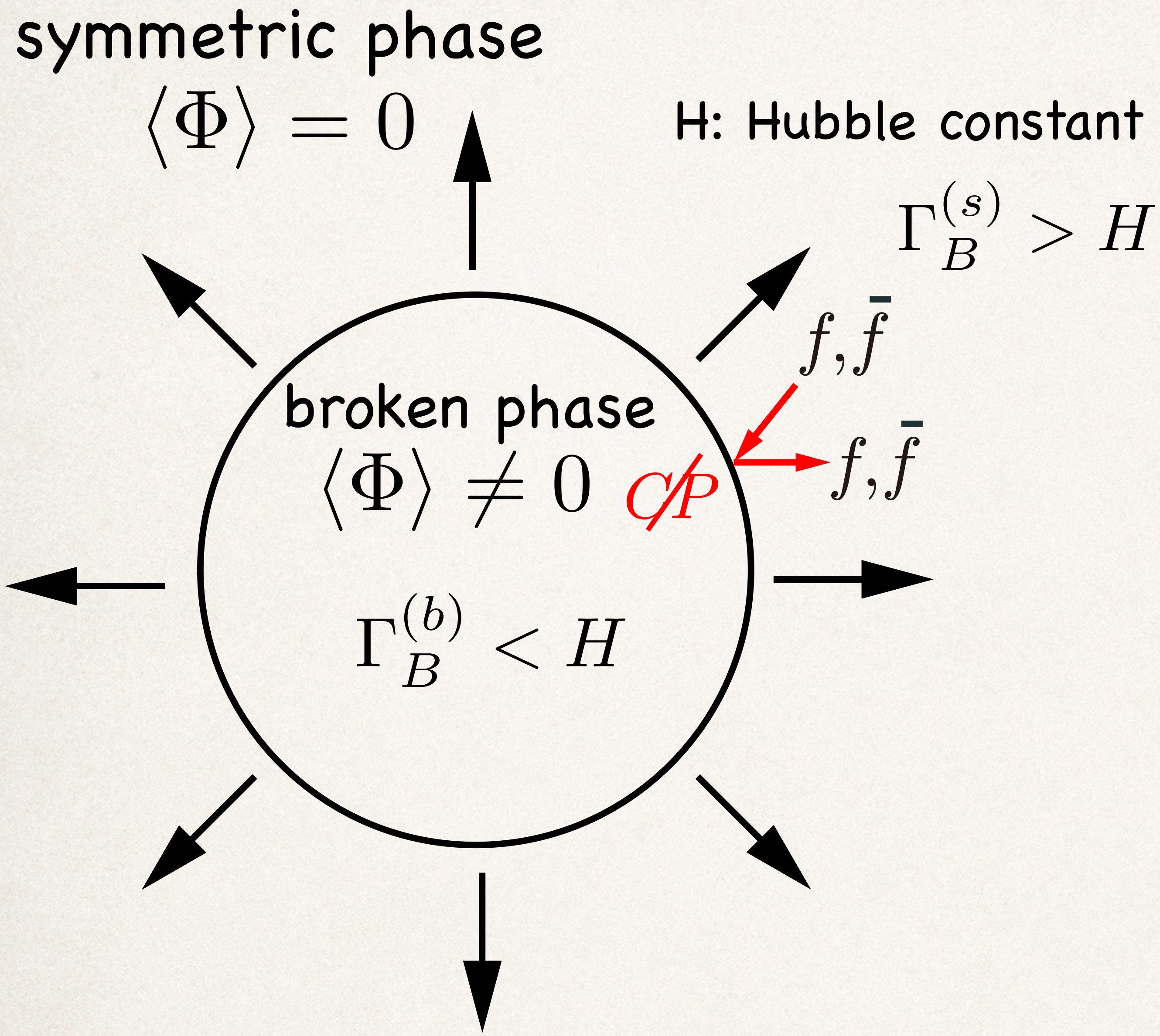




BAU can arise by the growing bubbles.

EWBG mechanism

H: Hubble constant



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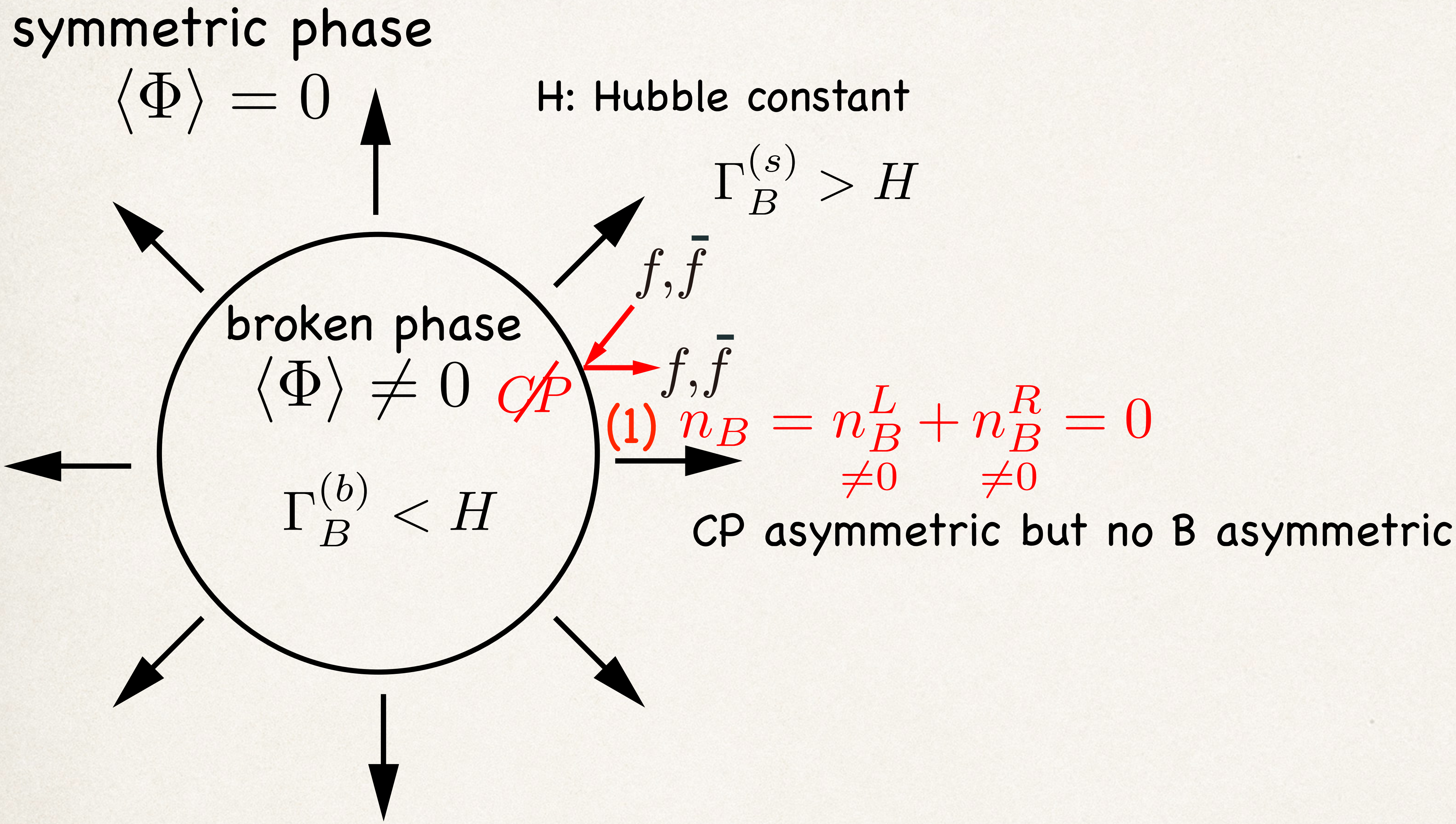

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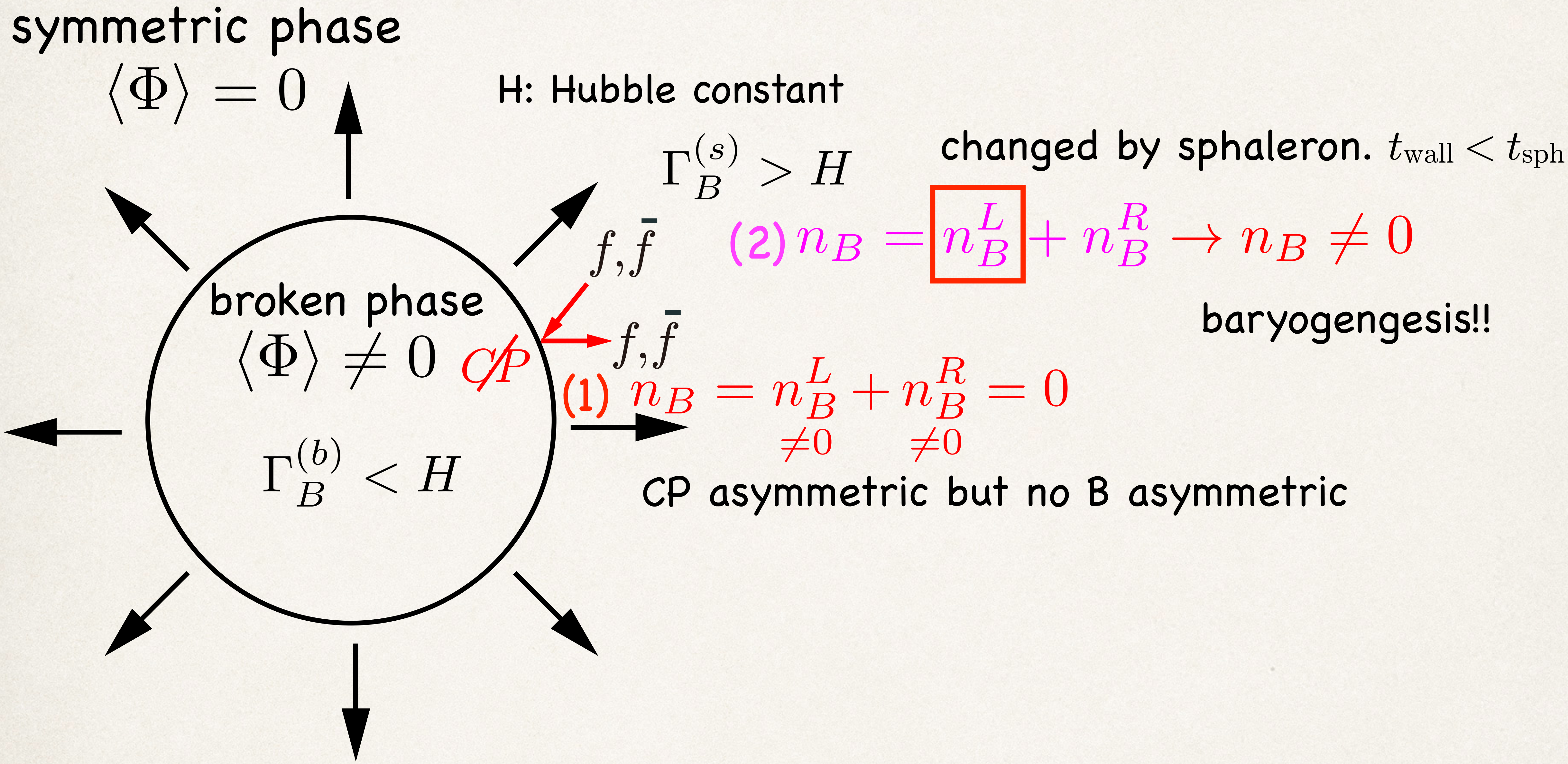

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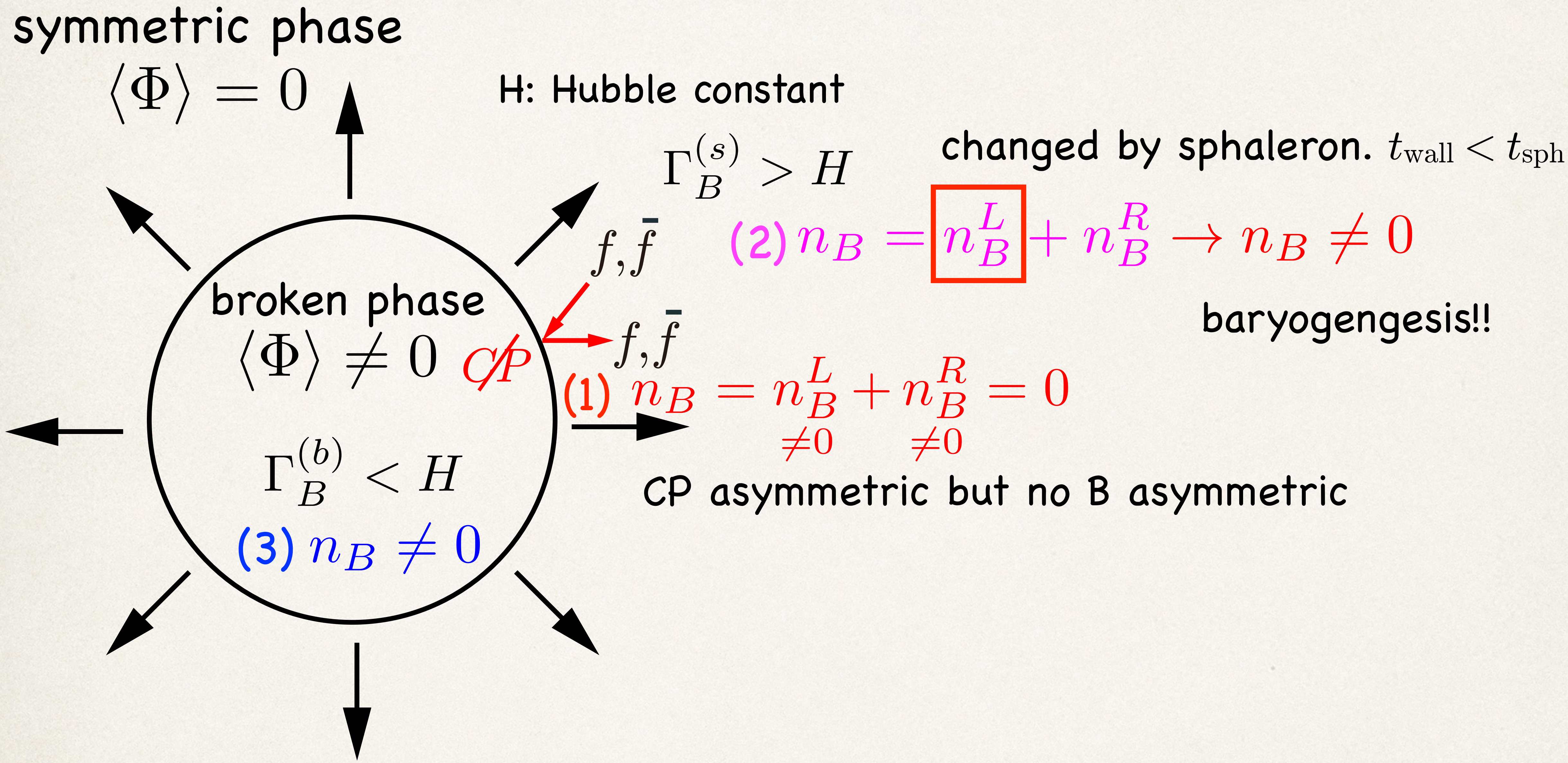

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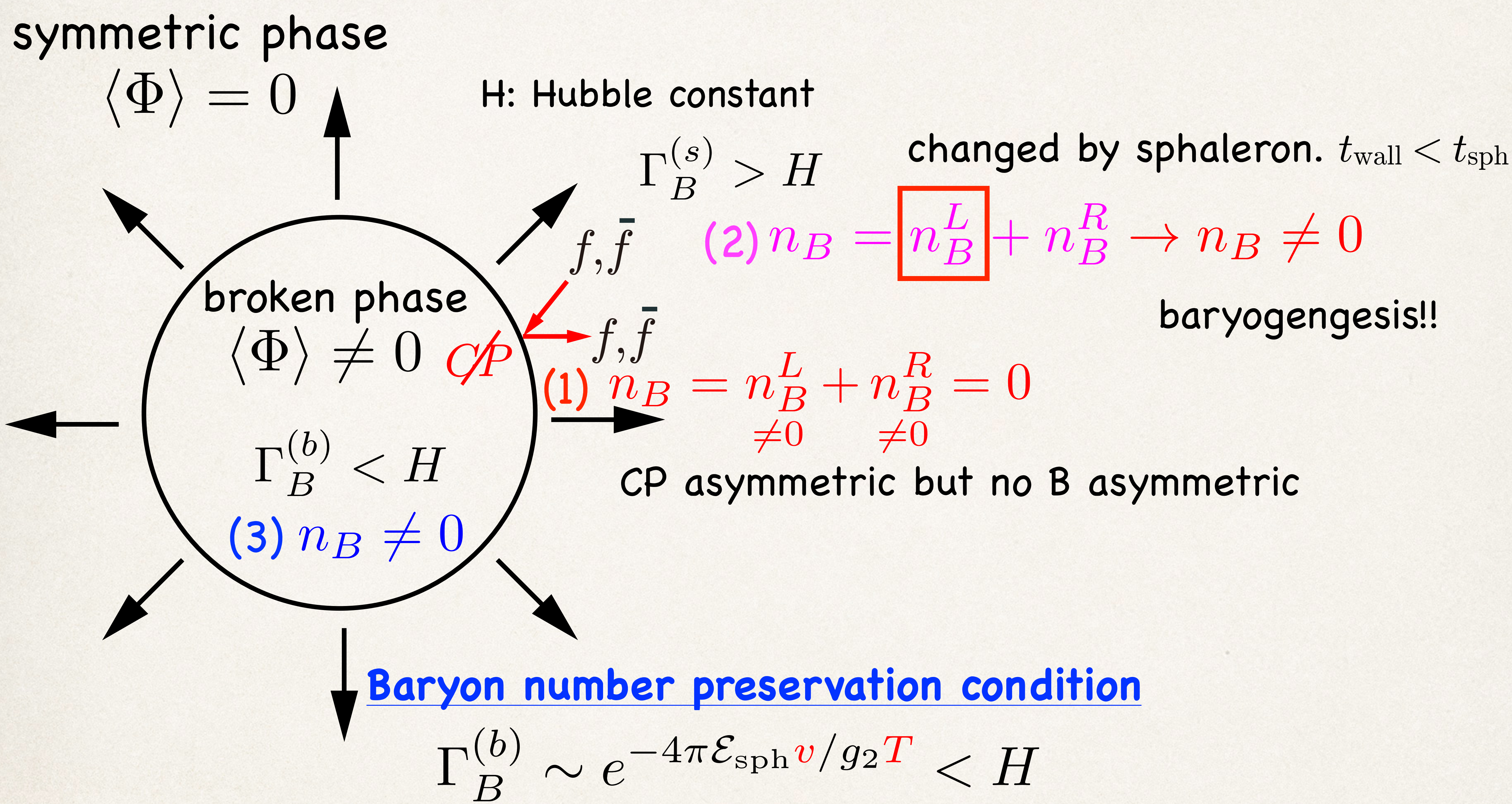


EWBG mechanism

symmetric phase

$\langle \Phi \rangle = 0$

H: Hubble constant

$\Gamma_B^{(s)} > H$ changed by sphaleron. $t_{\rm wall} < t_{\rm sph}$

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

baryogengesis!!

$f, \bar{f}$

$f, \bar{f}$

broken phase

$\langle \Phi \rangle \neq 0$ $\not{C}\not{P}$

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

CP asymmetric but no B asymmetric

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

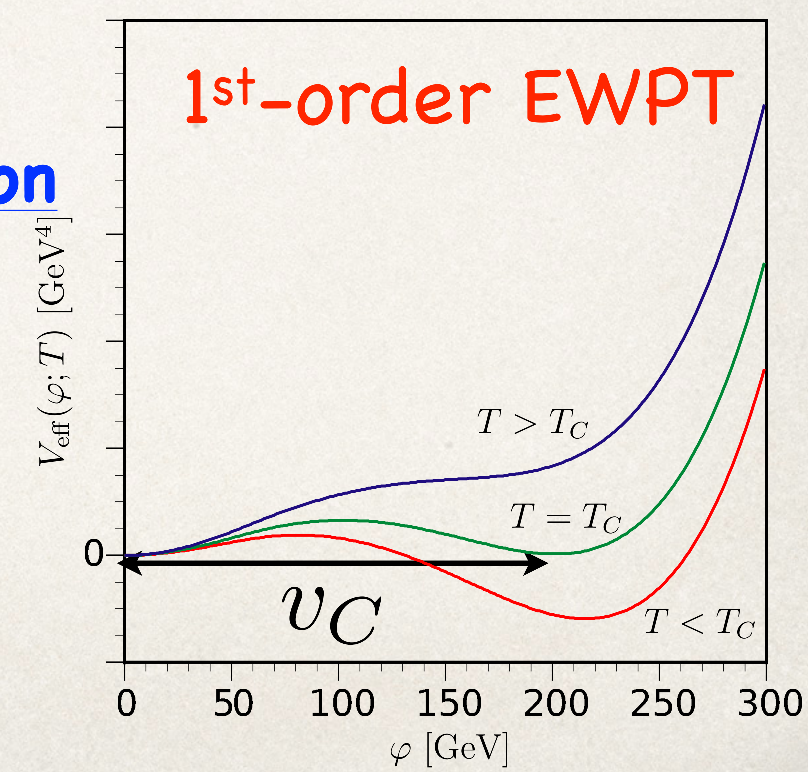
(3) $n_B \neq 0$

Baryon number preservation condition

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

To satisfy Γ_B<H, EWPT has to be 1st order,

$v_C/T_C \gtrsim 1$



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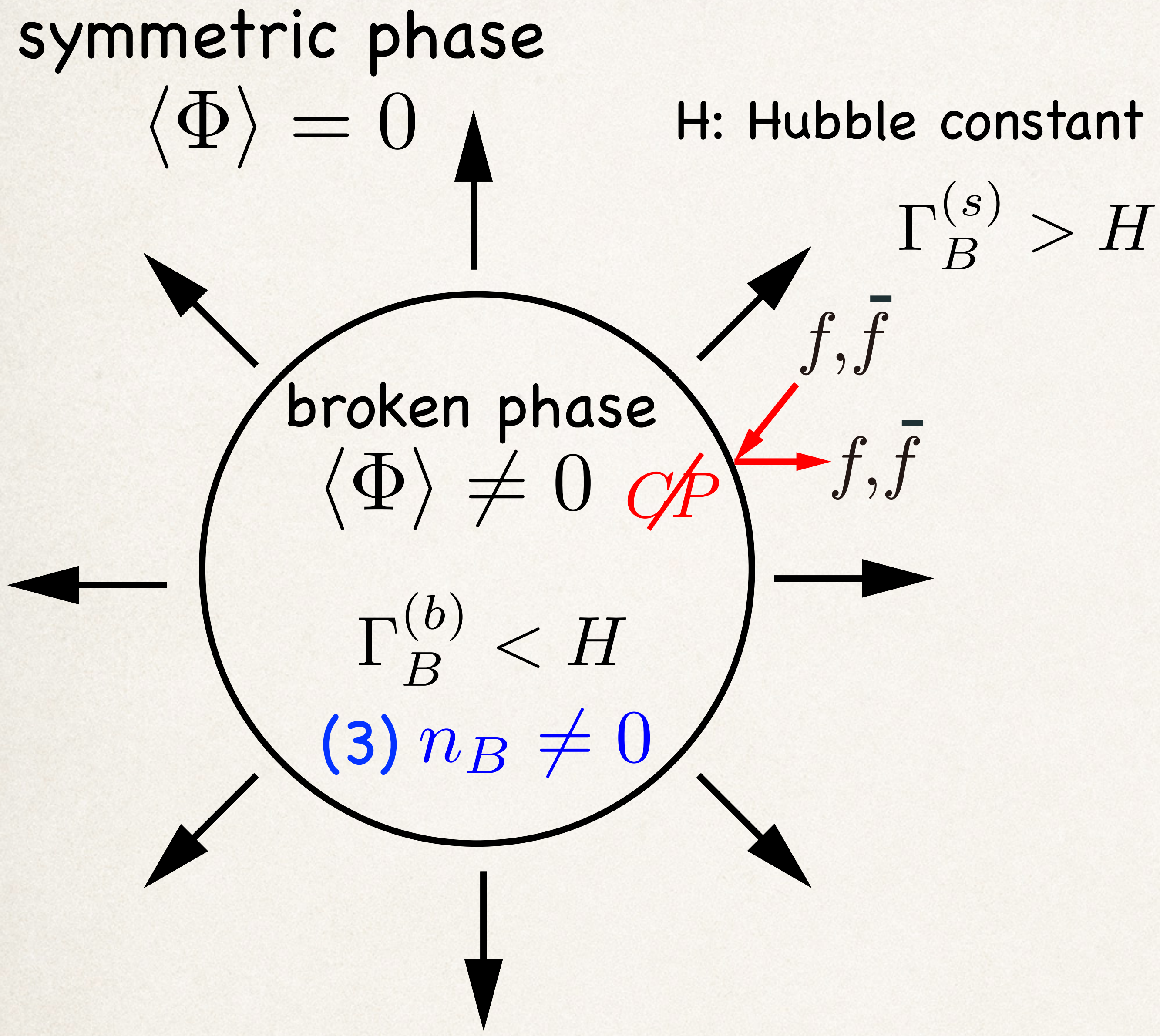

EWBG mechanism

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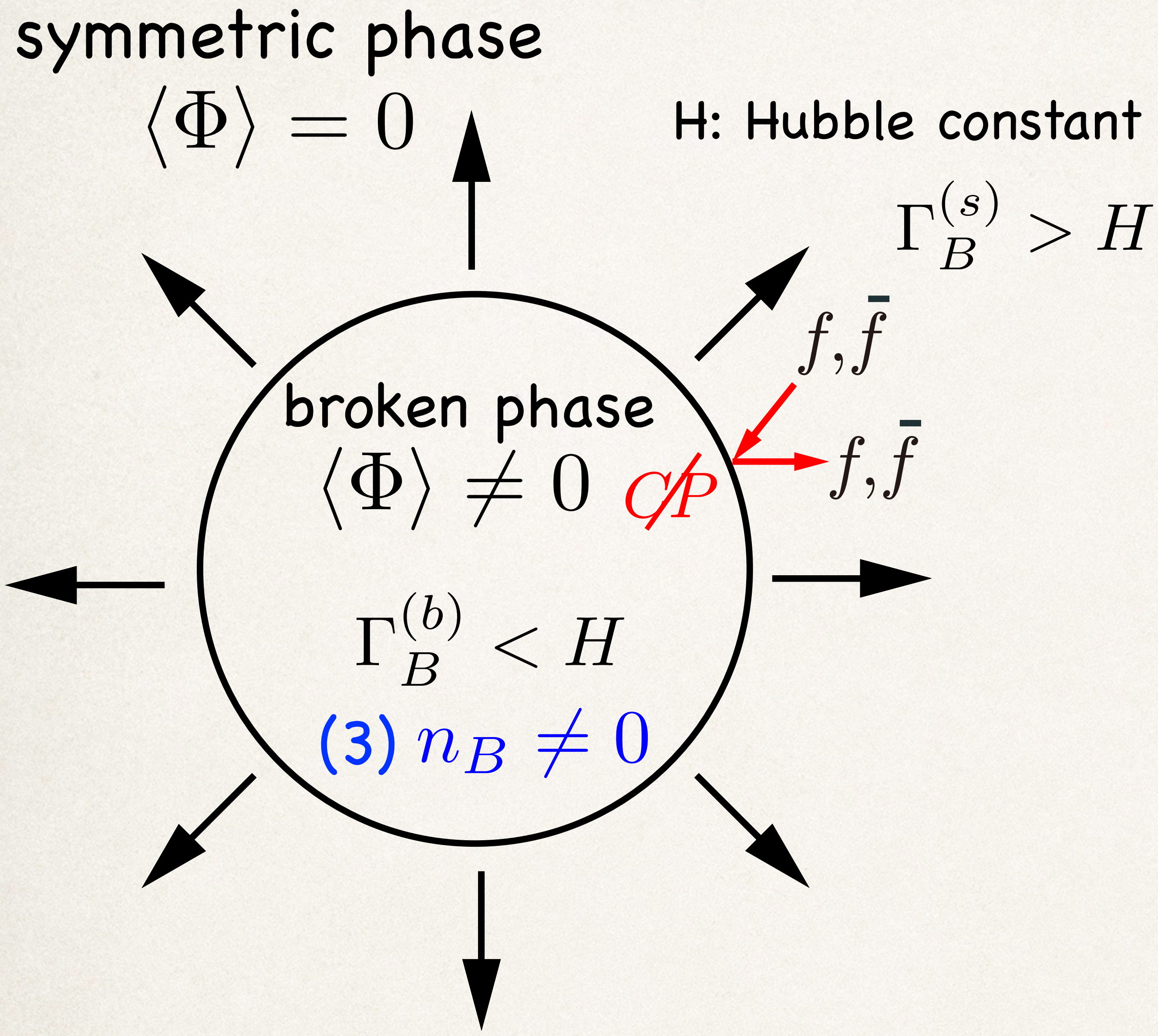

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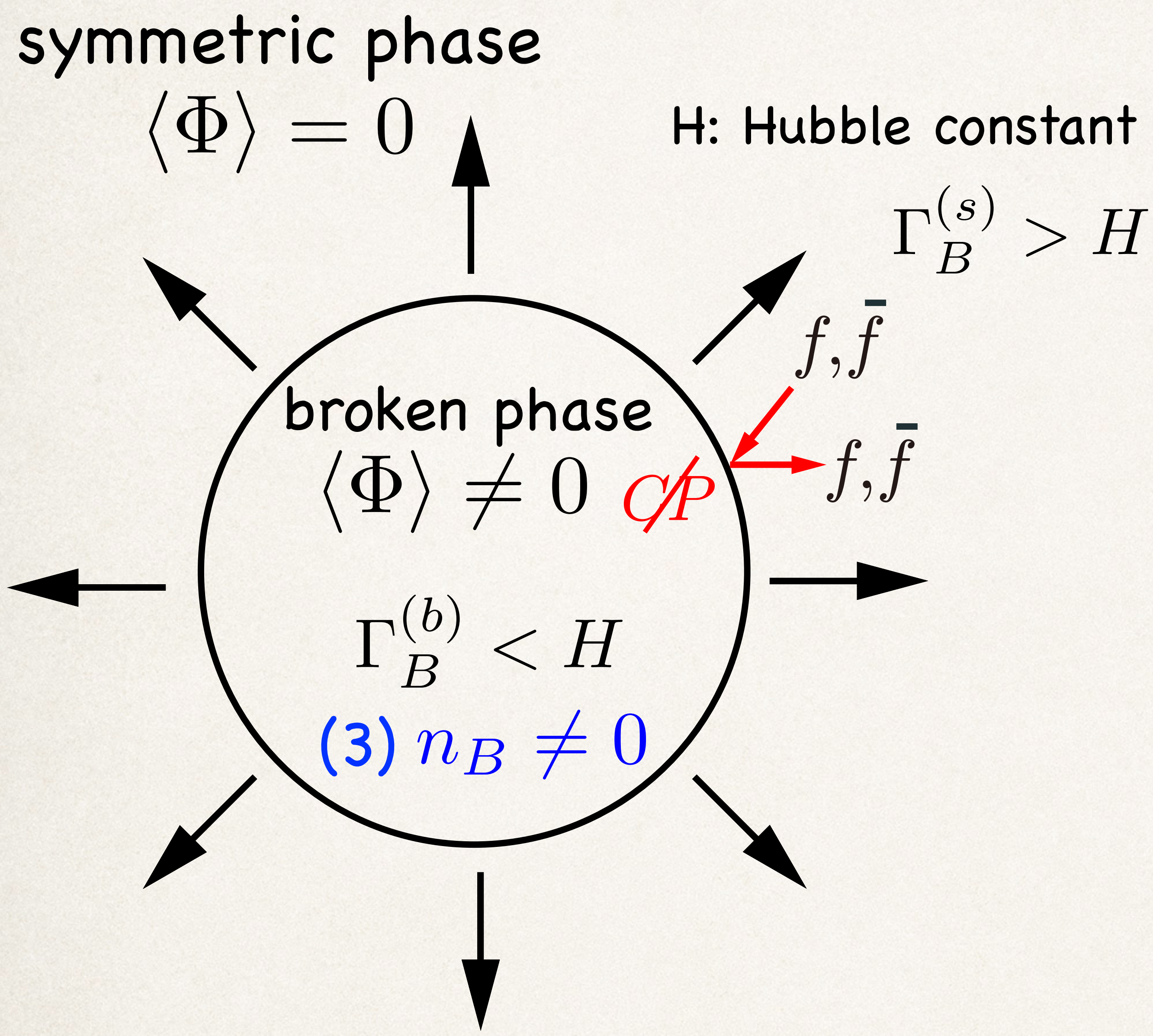

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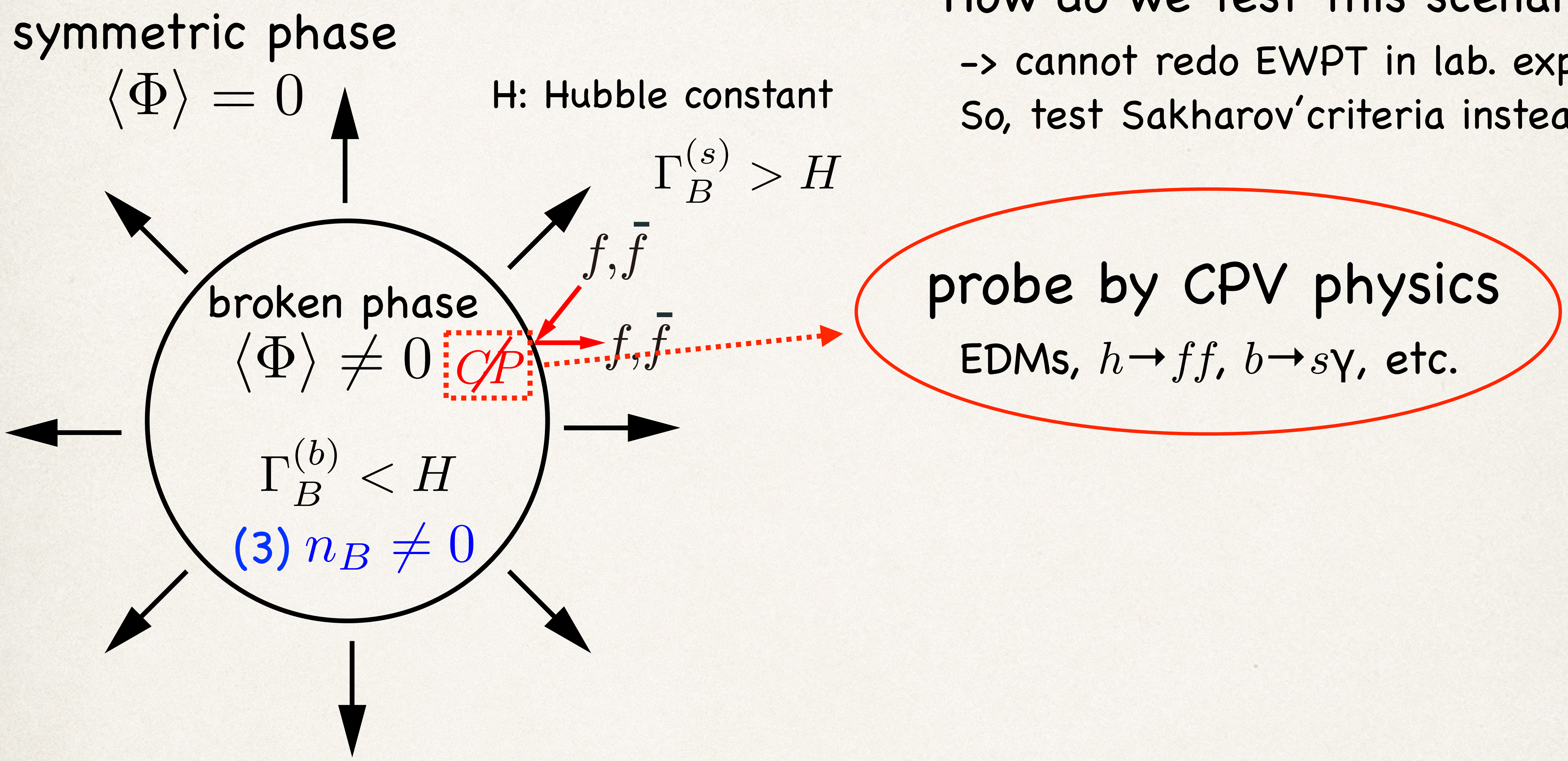

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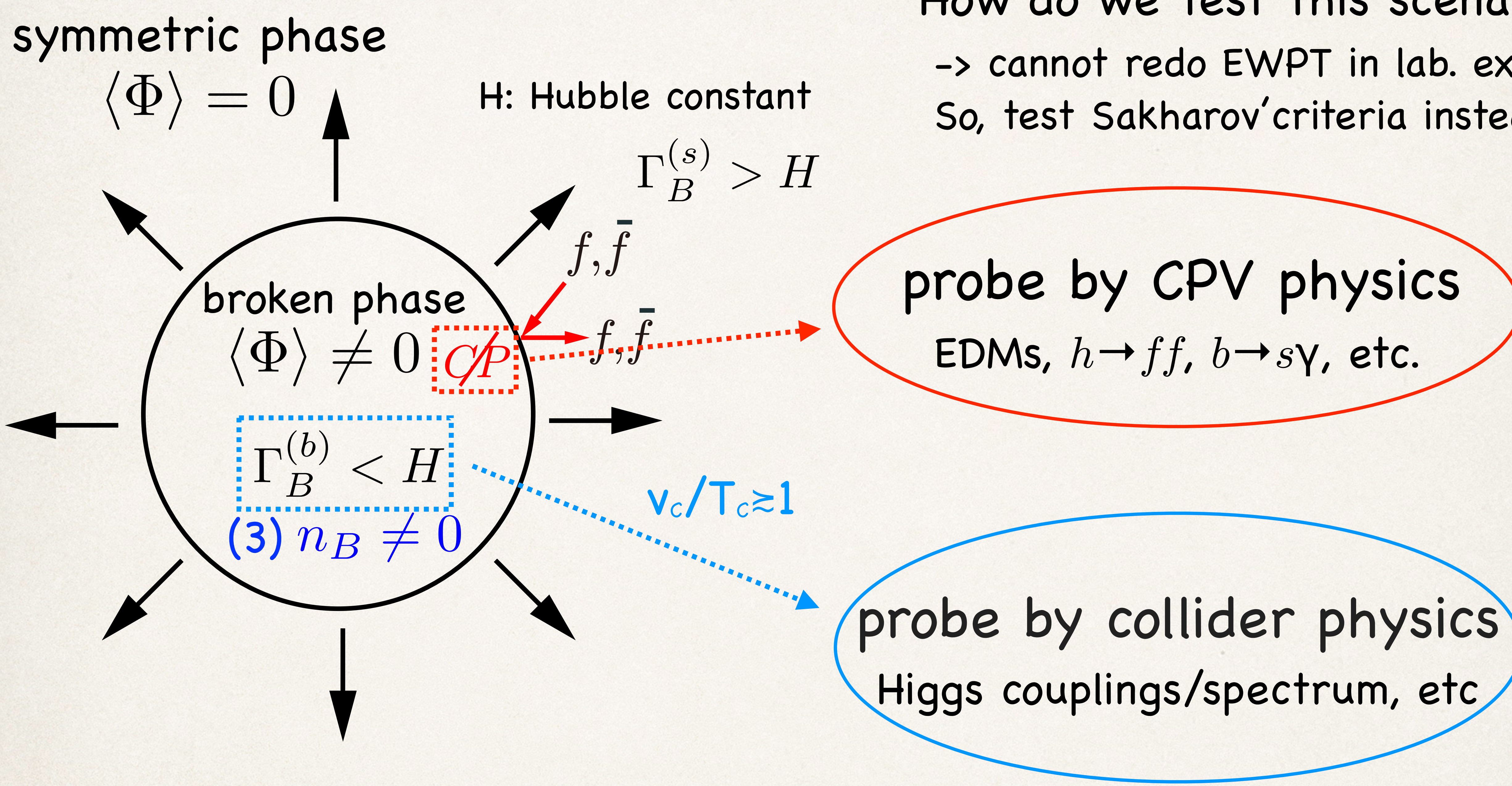

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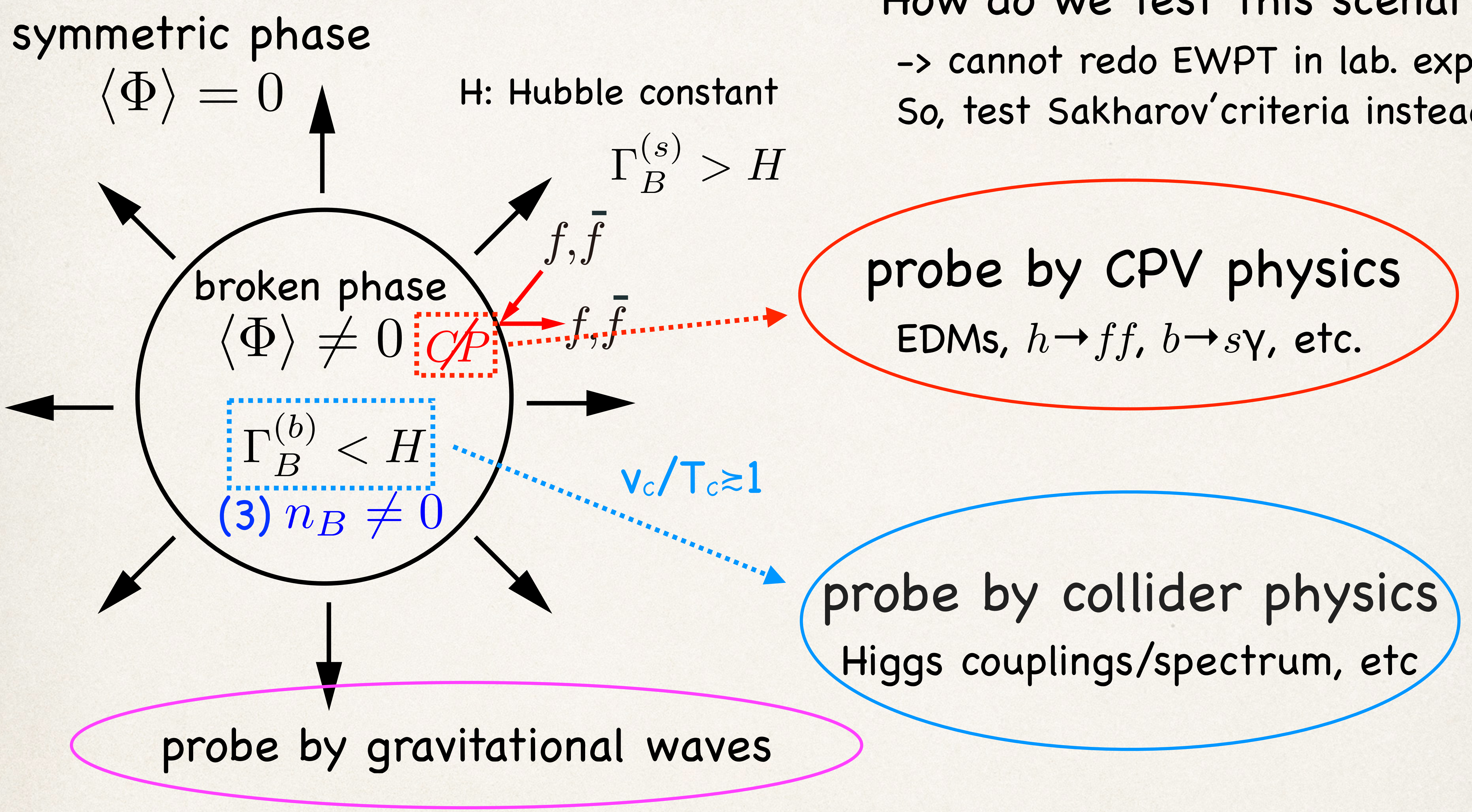

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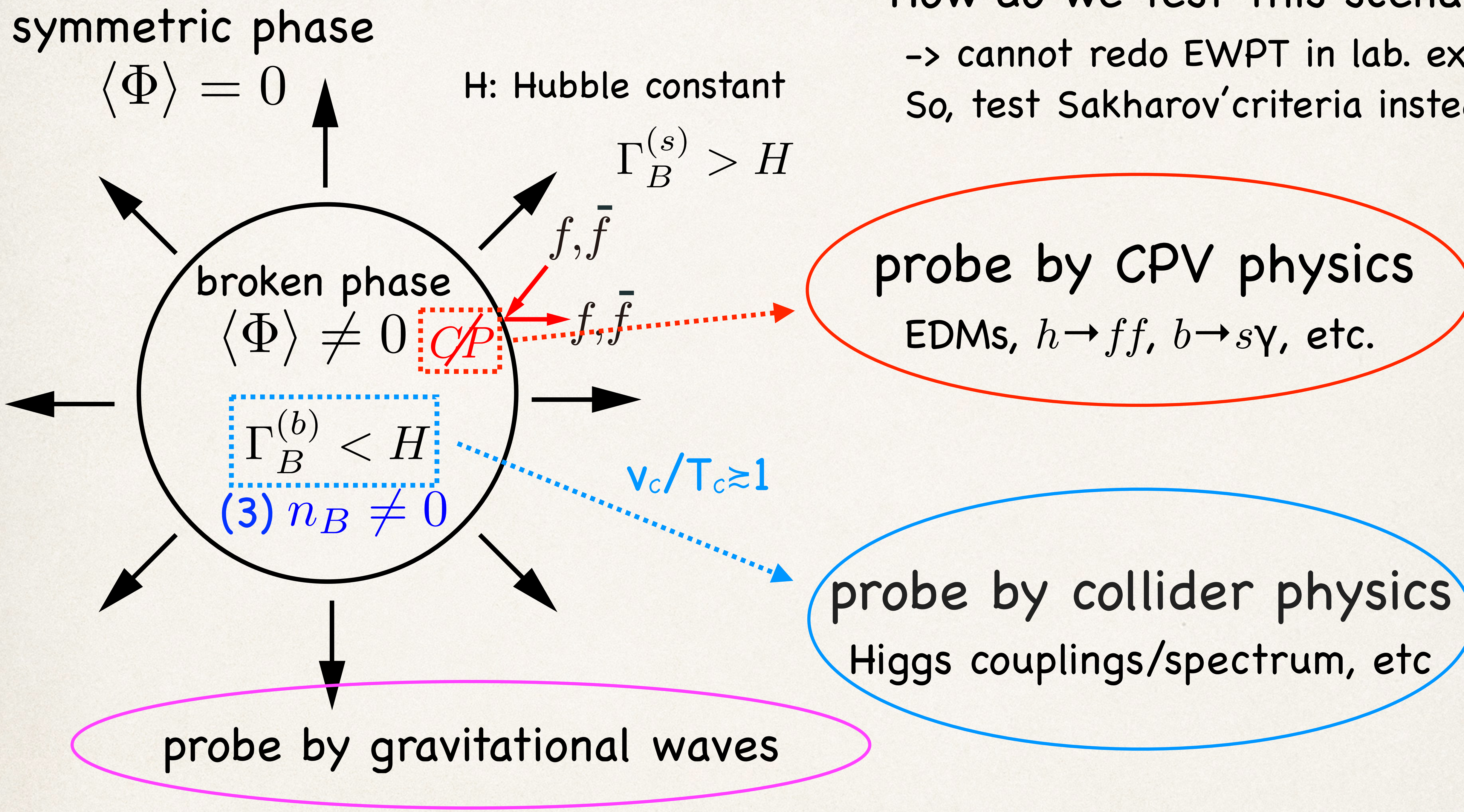

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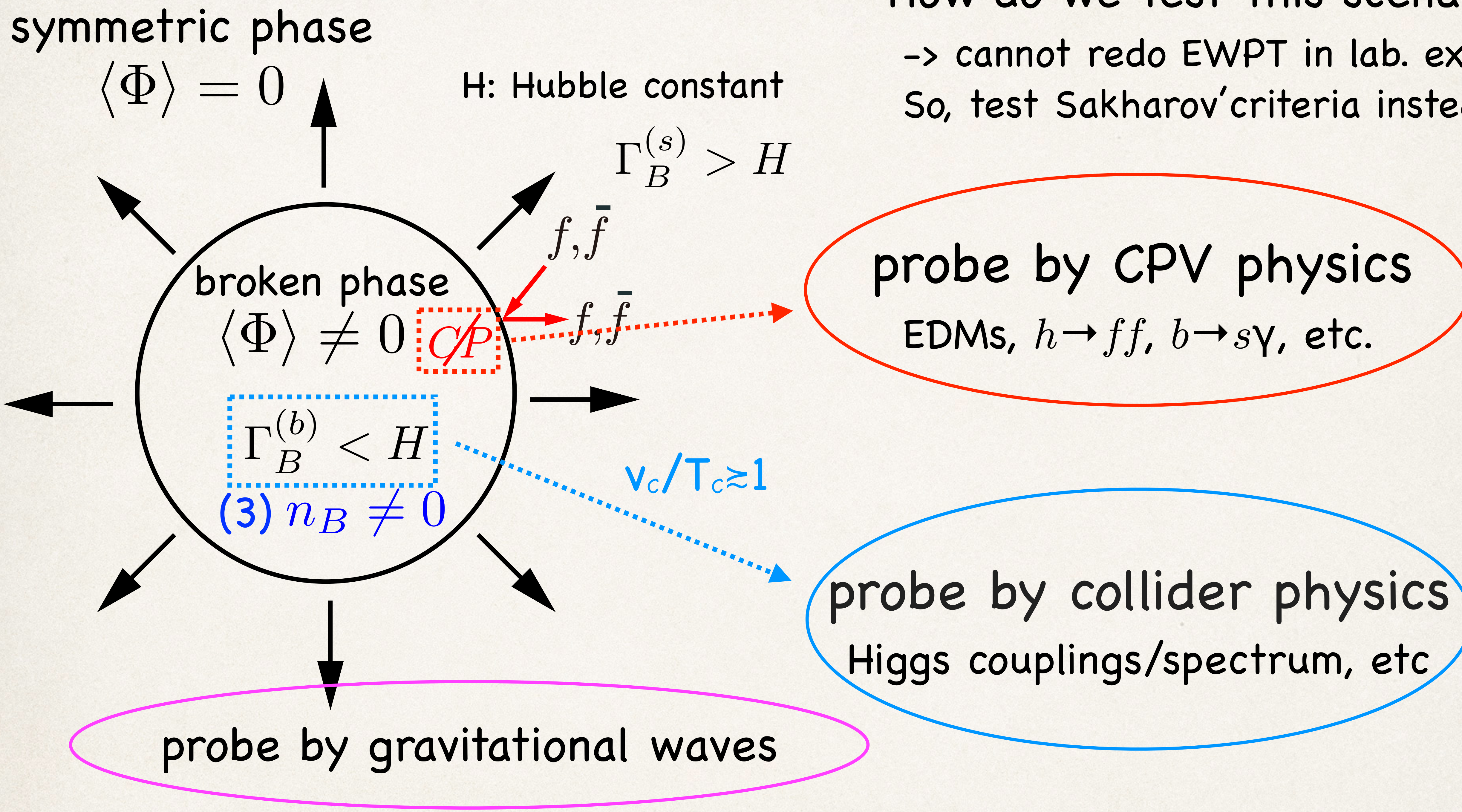

In SM

$v_C/T_C \gtrsim 1$ is not satisfied for m_h=125 GeV.

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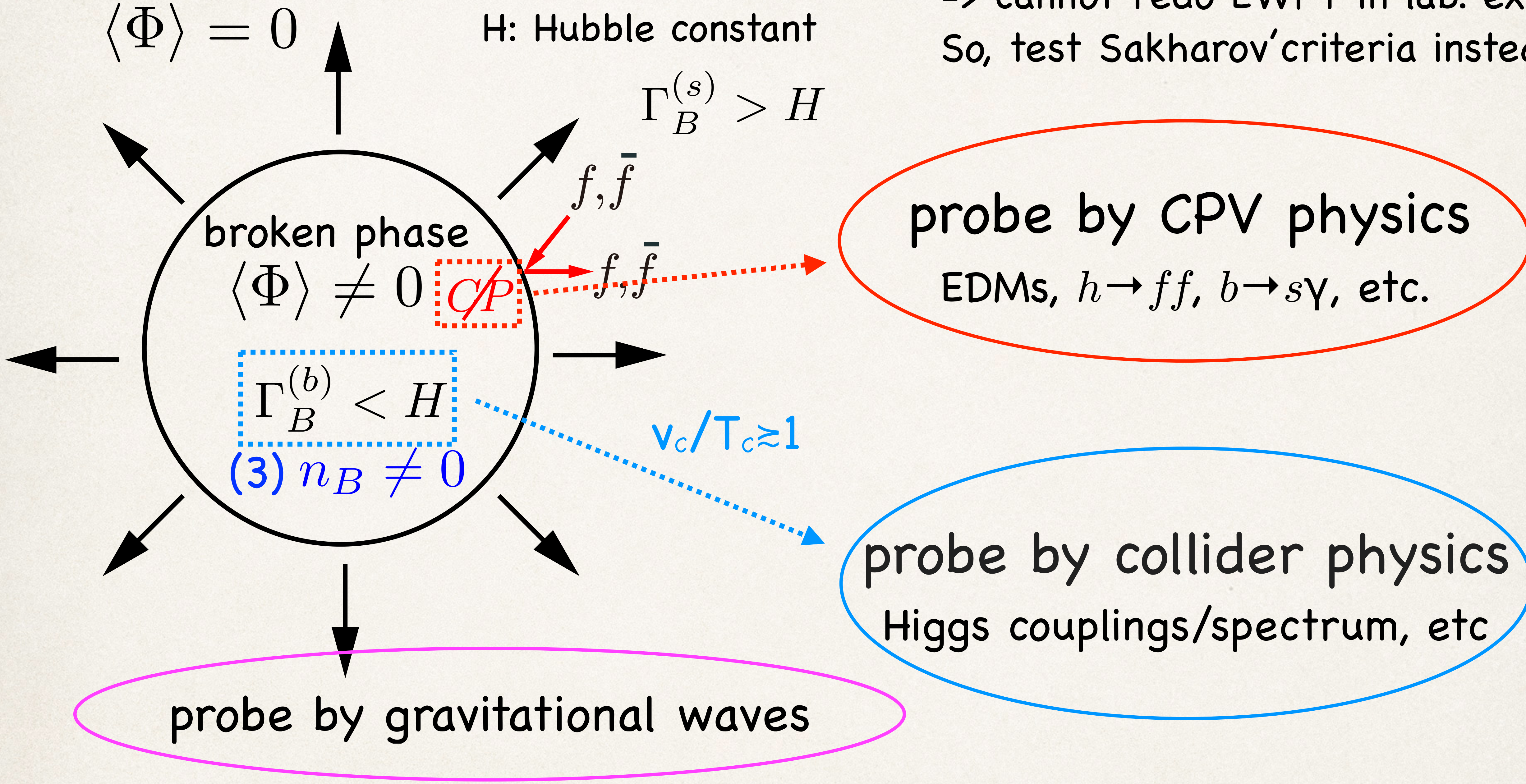

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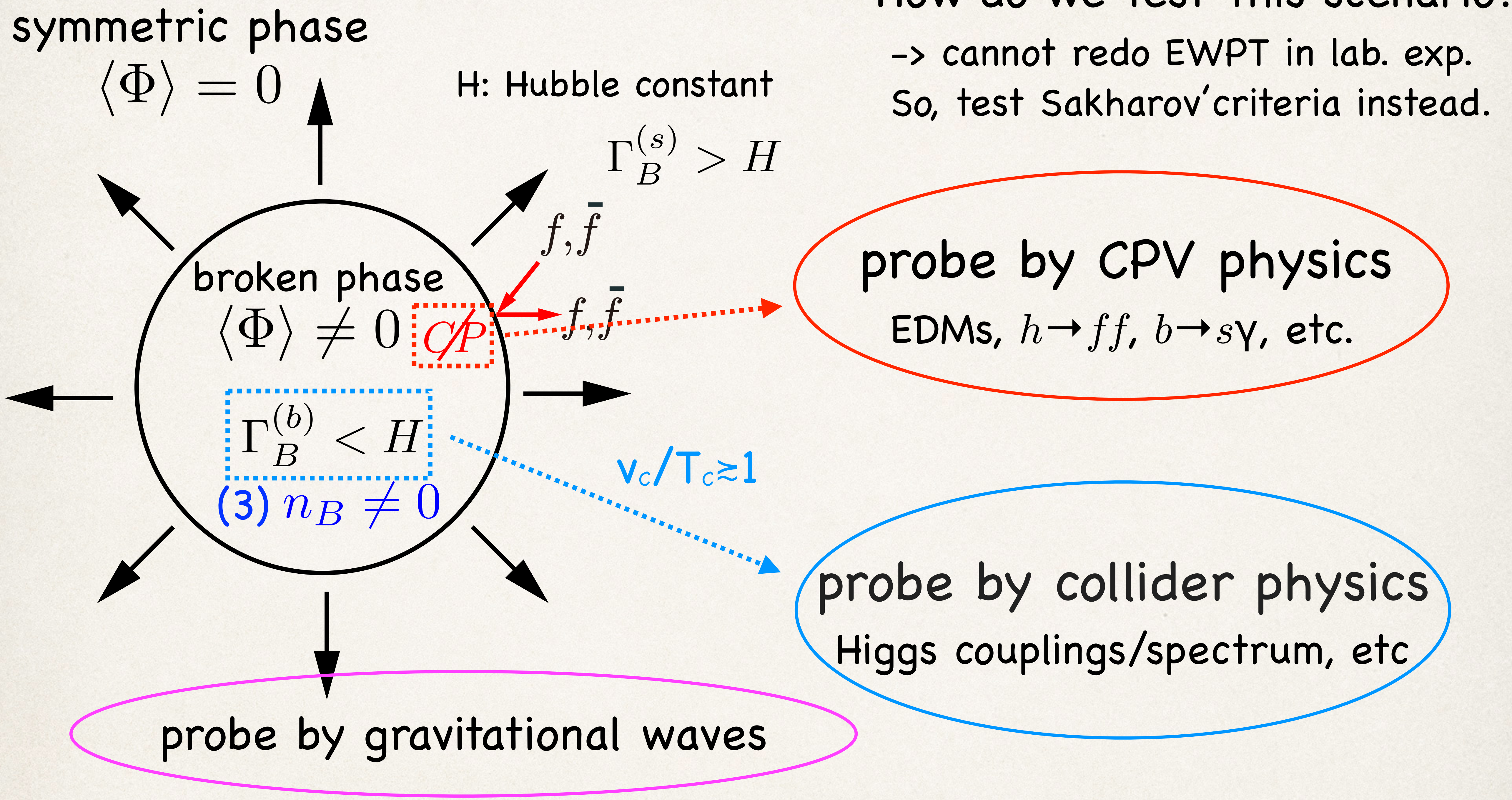

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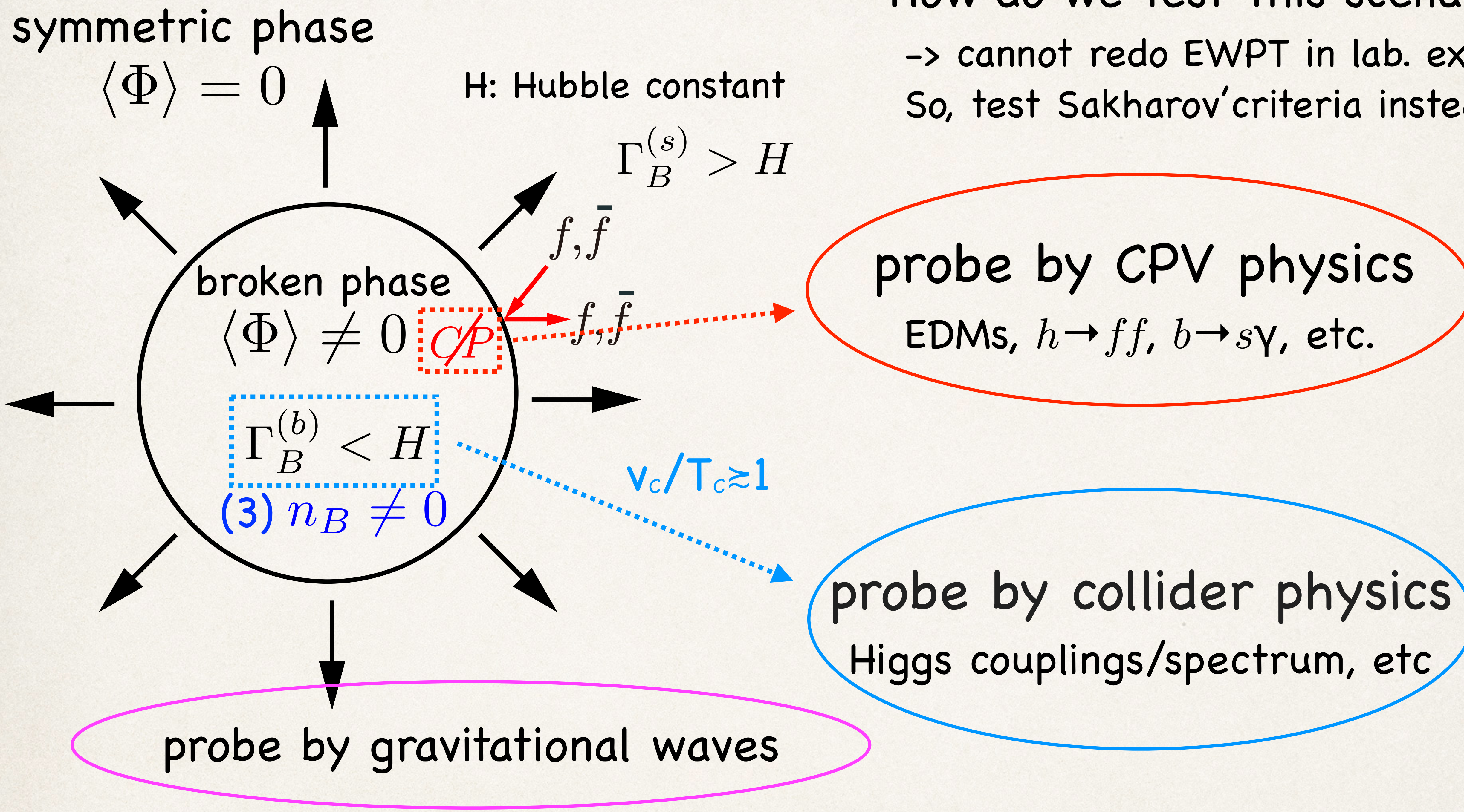


In SM

$v_C/T_C \gtrsim 1$ is not satisfied for m_h=125 GeV. -> Multi-Higgs

CPV in CKM is not sufficient. -> new Yukawa, Higgs-self couplings

BSM models

SUSY models

- Minimal Supersymmetric SM (MSSM)

strong 1st-order EWPT

light stop (< top mass)

CPV

chariginos, neutralinos

-> viable window is closed.

∵ light stop scenario is inconsistent with LHC data $\frac{v_C}{T_C} \gtrsim 1$ not satisfied

[D. Curtin, P. Jaiswall, P. Meade., JHEP08(2012)005; T. Cohen, D. E. Morrissey, A. Pierce, PRD86, 013009 (2012); K. Krizka, A. Kumar, D. E. Morrissey, PRD87, 095016 (2013)]

- Extensions of MSSM

Next-to-MSSM (NMSSM), nearly-MSSM (nMSSM), U(1)′-MSSM, etc

Non-SUSY models

SM + additional scalars/fermions

2 Higgs doublet model, SM + singlet scalar/fermions, etc.

EWBG after LHC-Run2

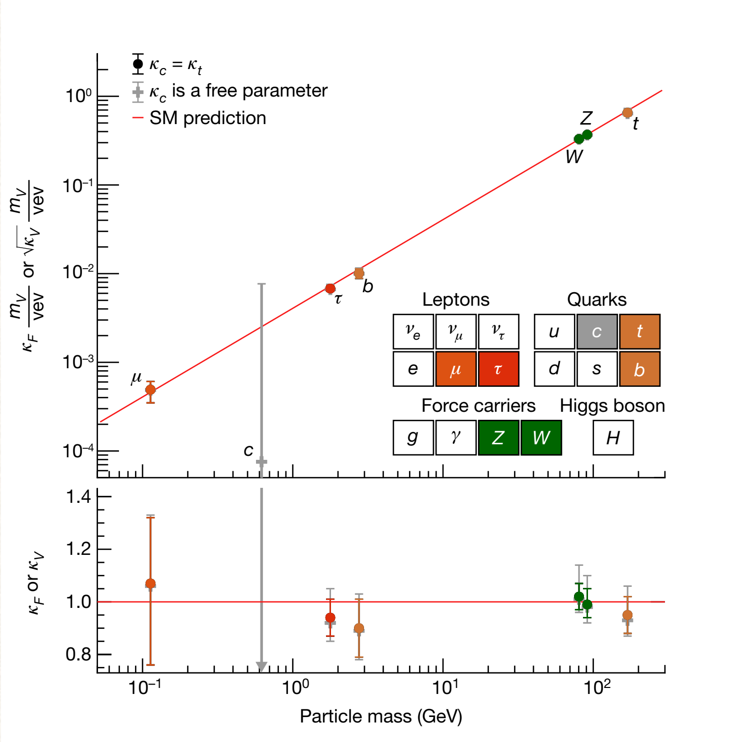
LHC indicates

Higgs sector = SM-like

SM-like ≠ SM

What is SM-like Higgs sector compatible with EWBG?

Nature 607, 52-59 (2022)



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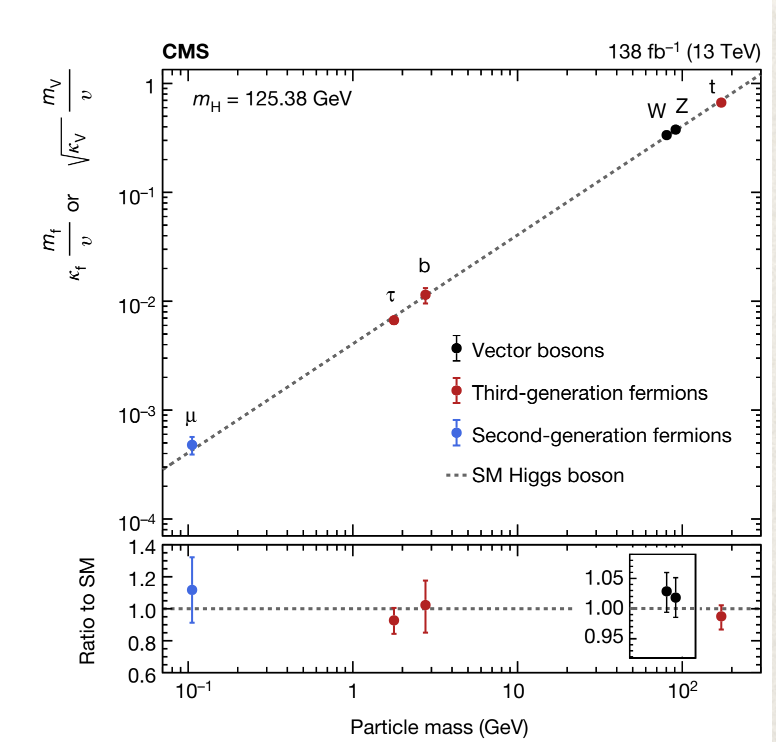

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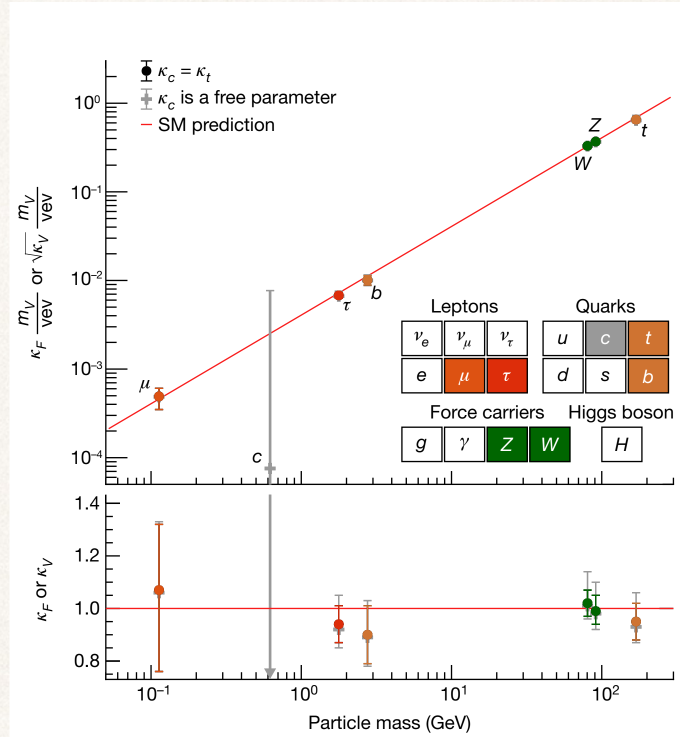

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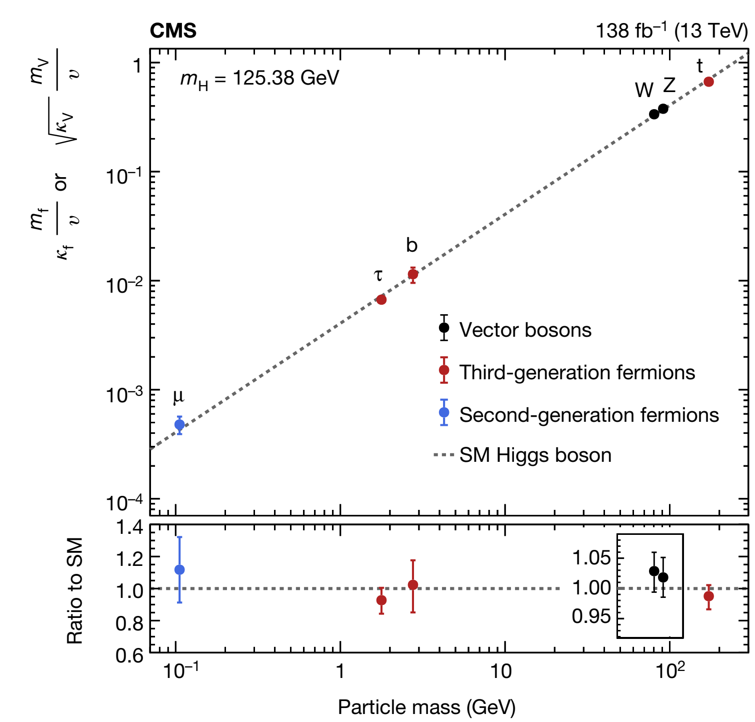

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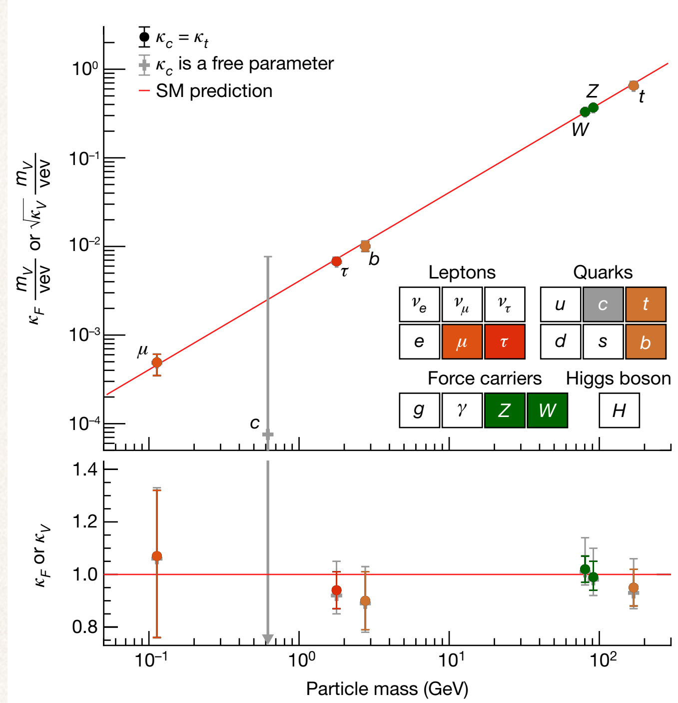

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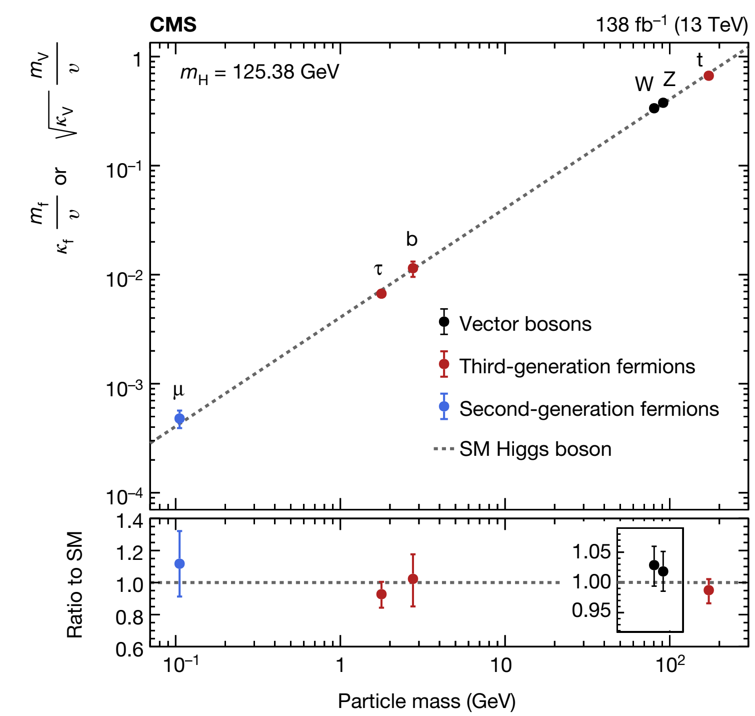

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E.g. SM+2nd Higgs doublet (2HDM)

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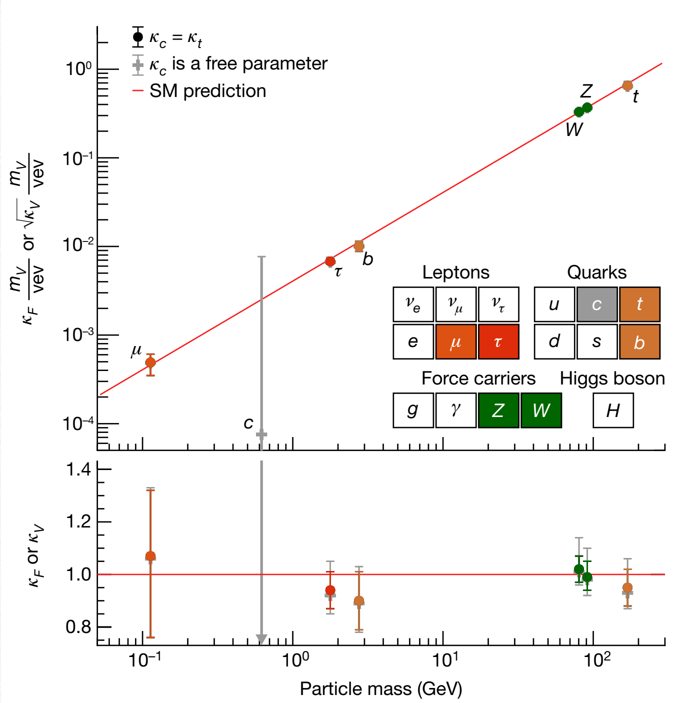

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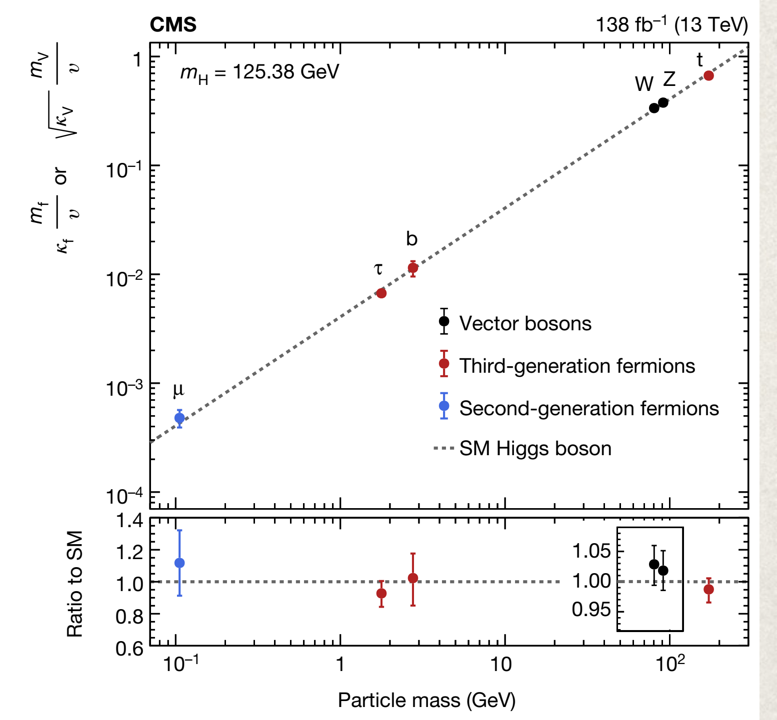

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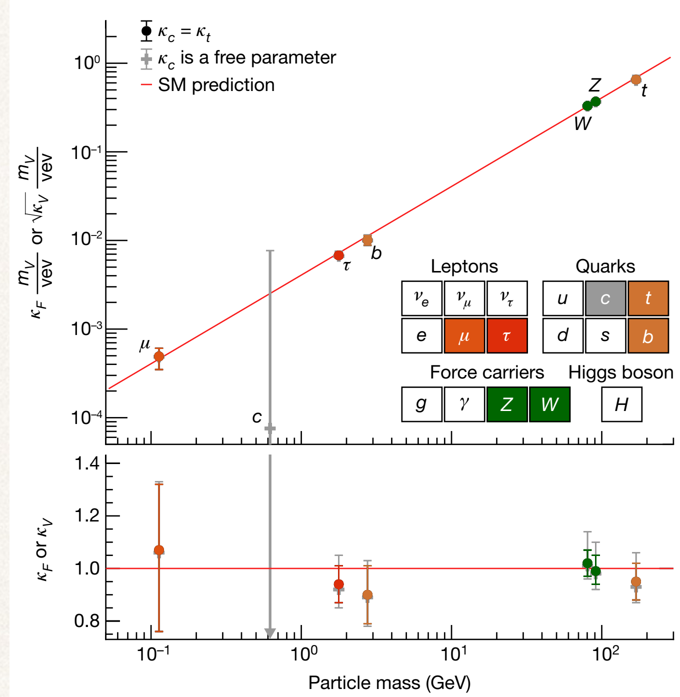

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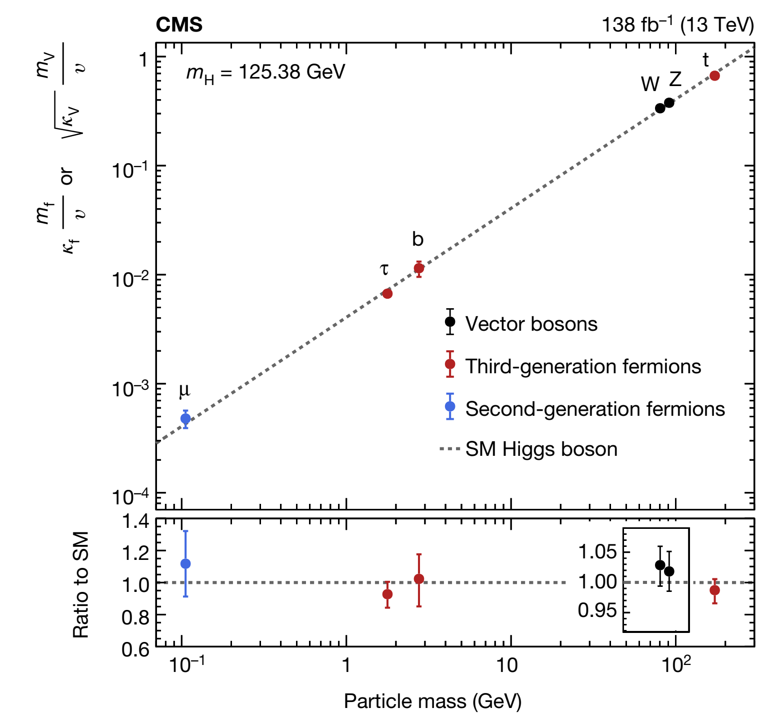

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but, (H, A, $H^{\pm}$) are sub-TeV

without decoupling

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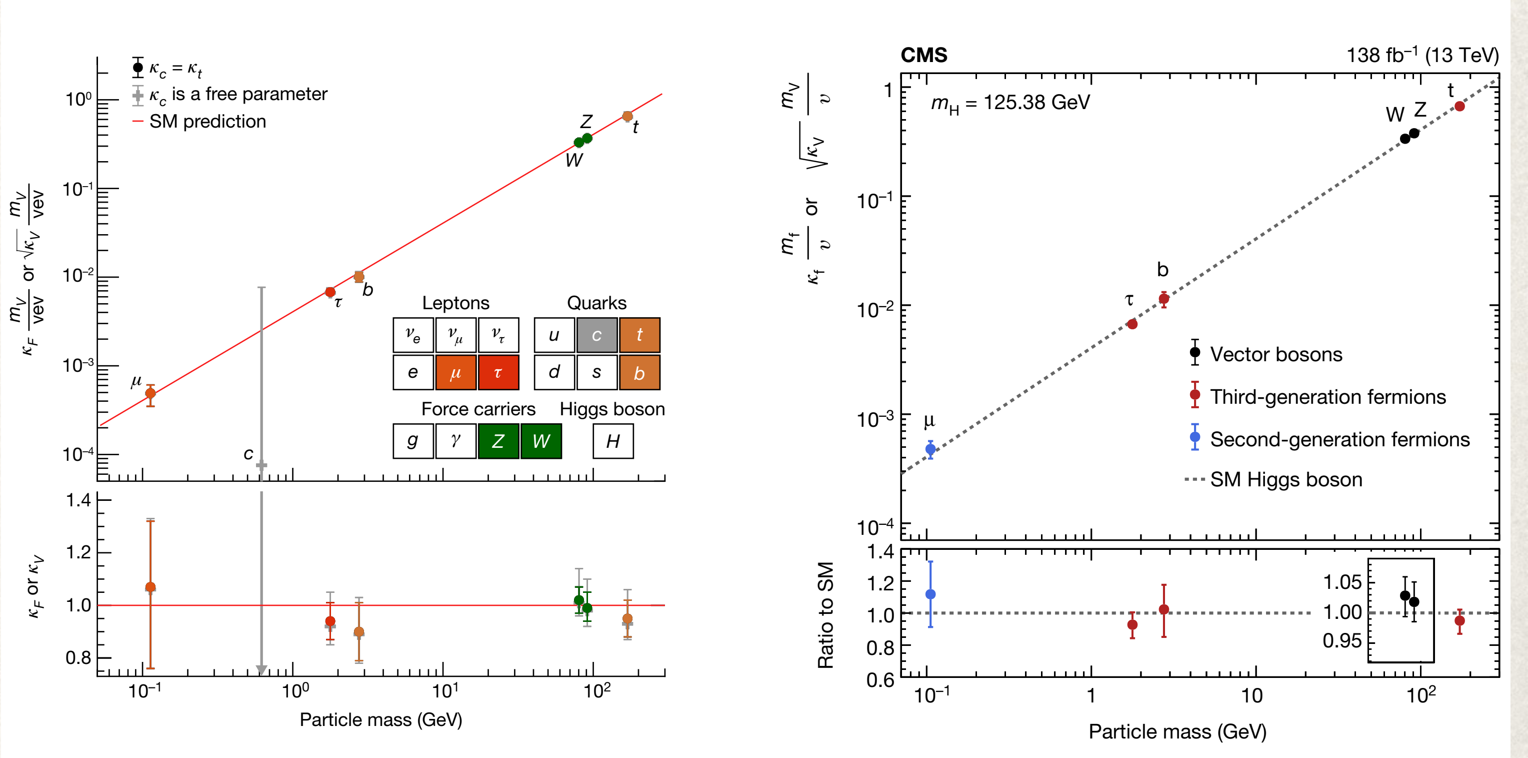

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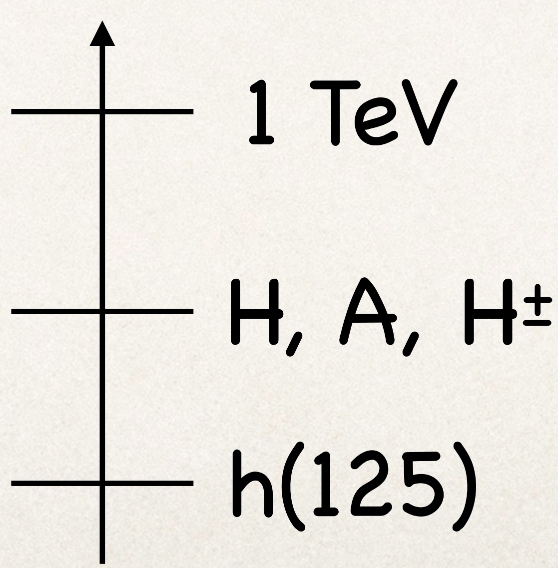

to satisfy $v_C/T_C \gtrsim 1$

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

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h->2γ, hhh= NonSM-like

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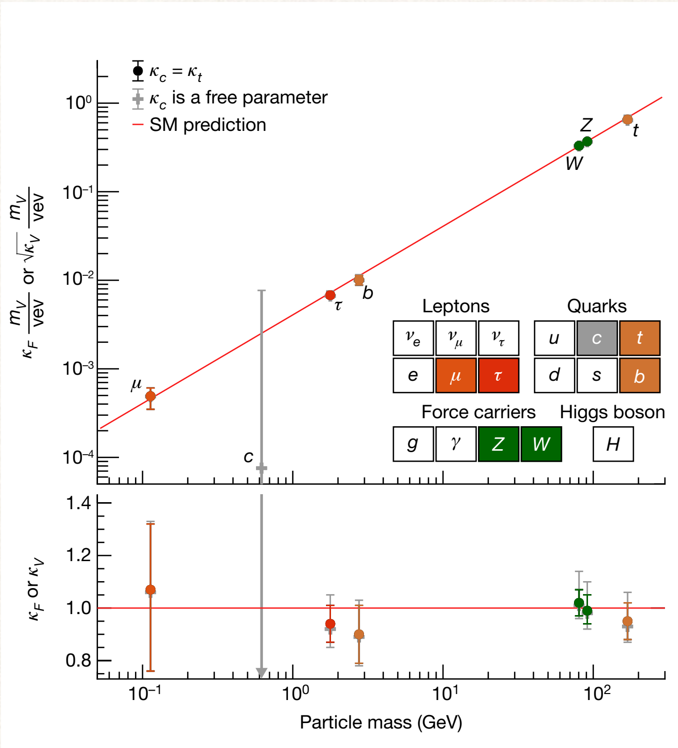

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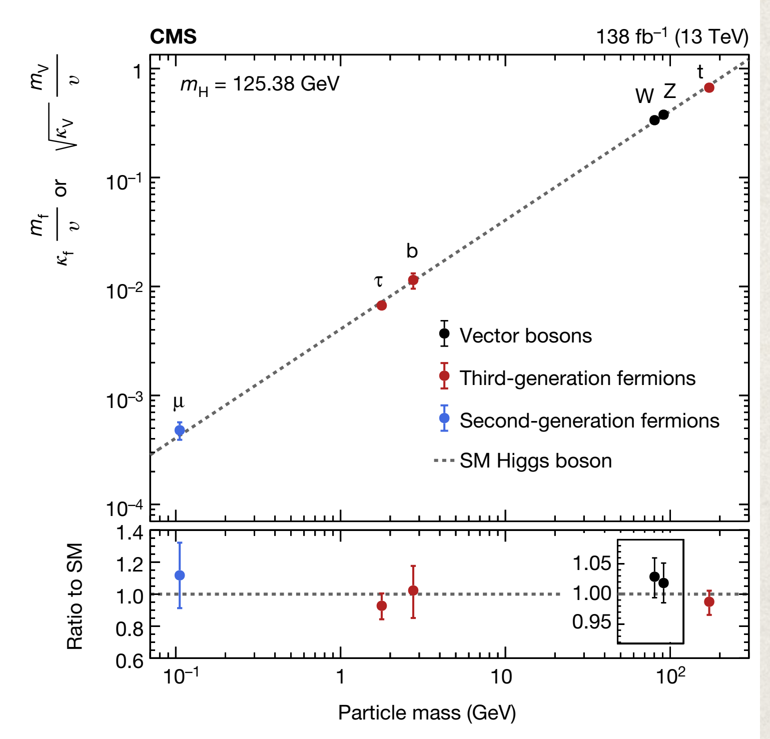

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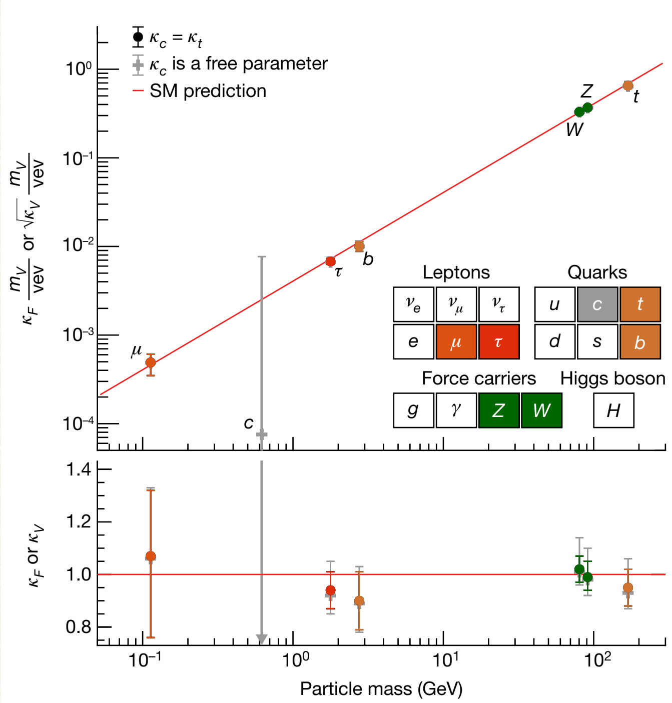

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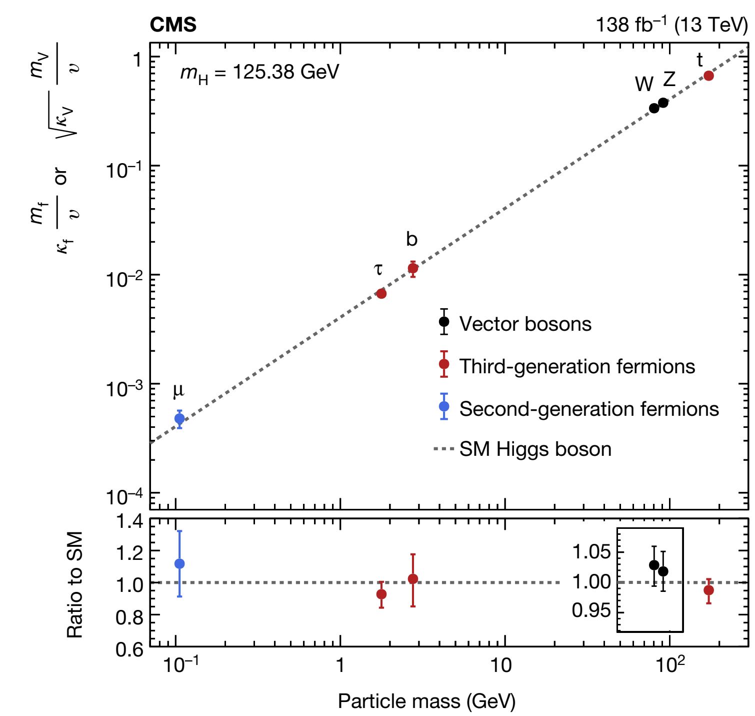

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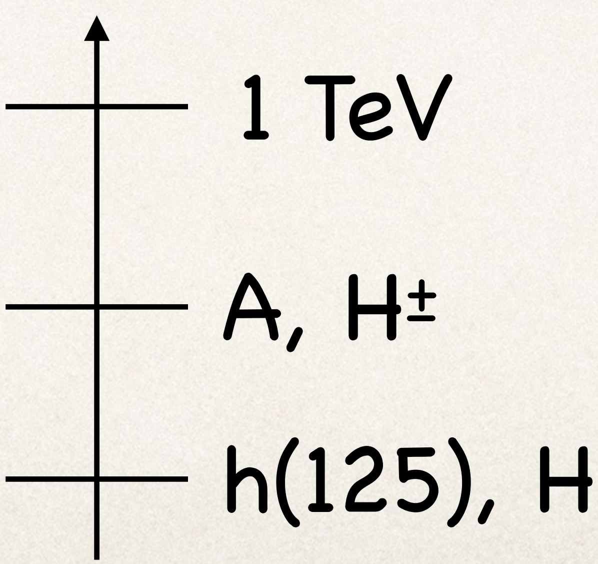

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A-> ZH $\propto \sin(\beta - \alpha)$

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

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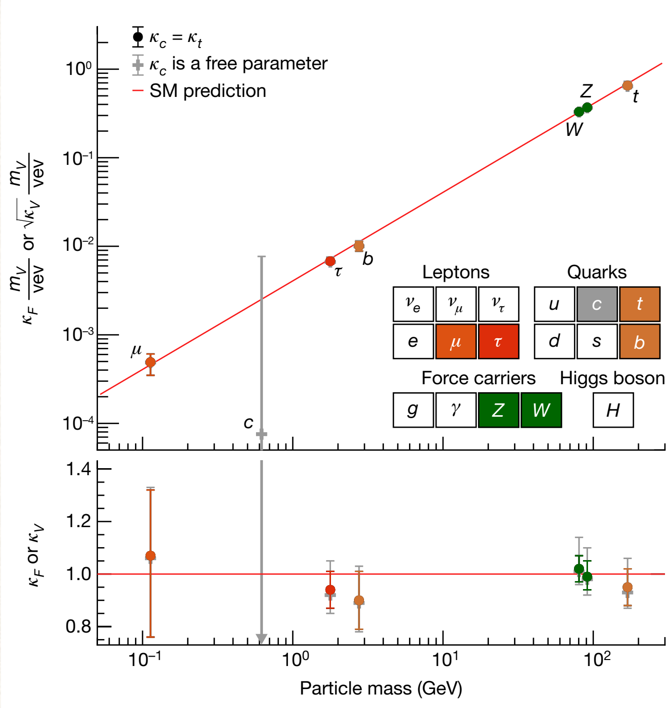

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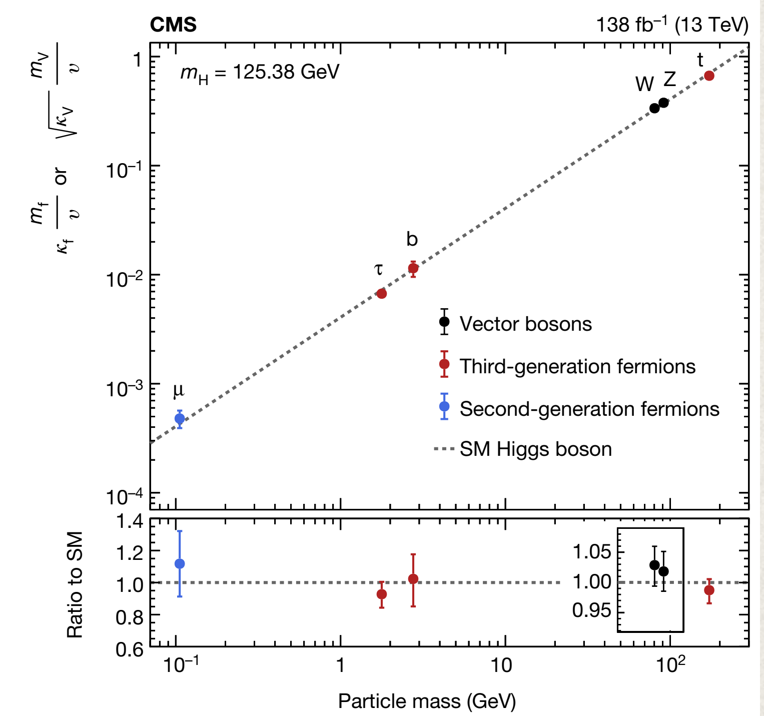

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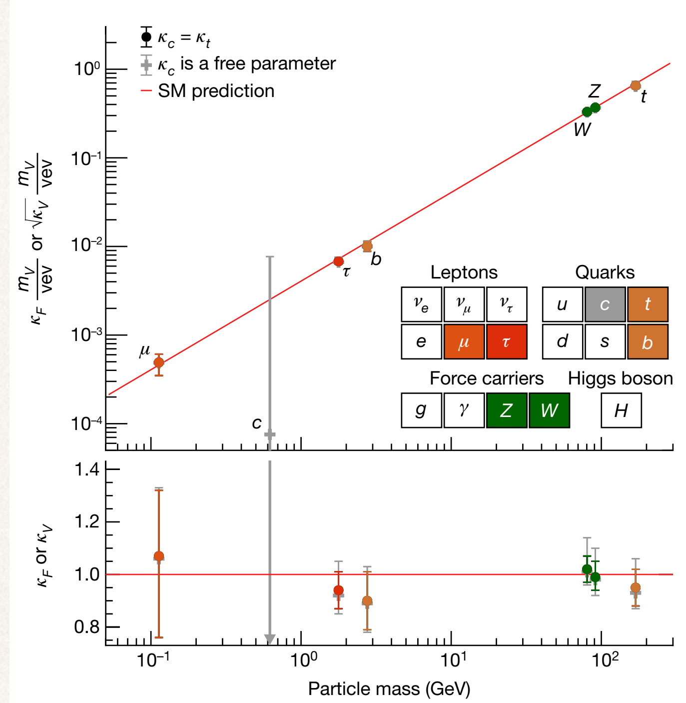

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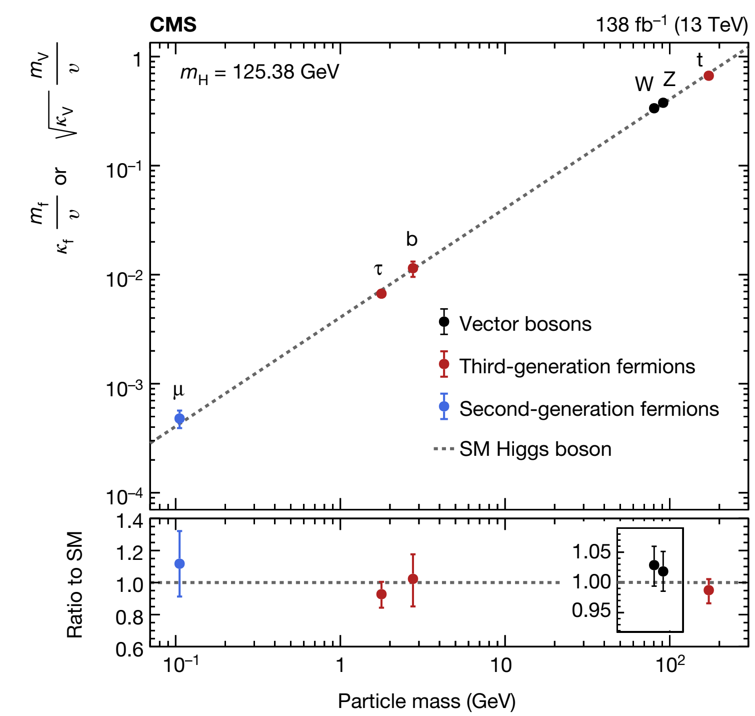

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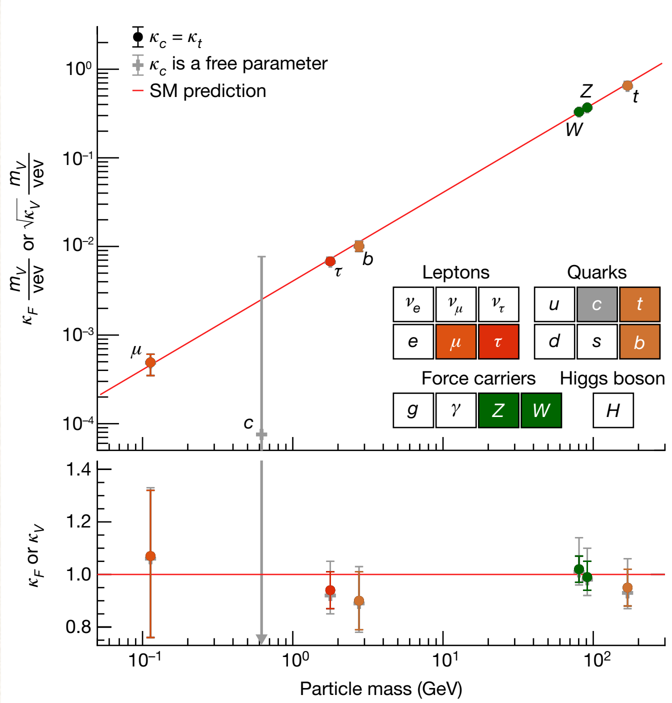

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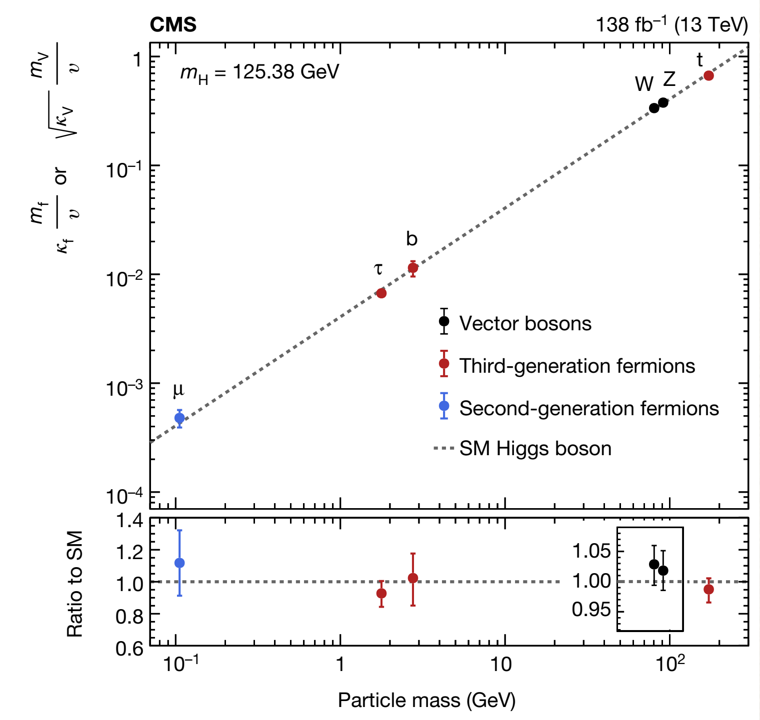

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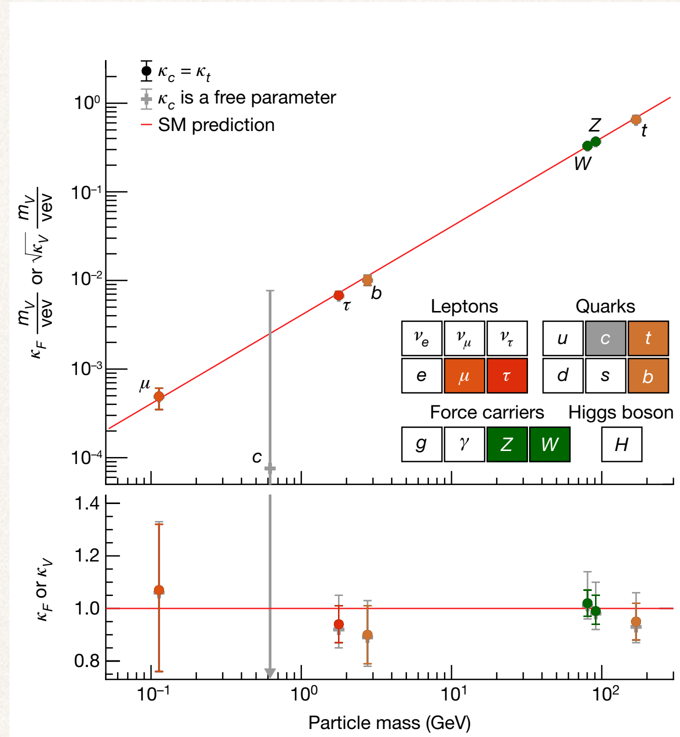

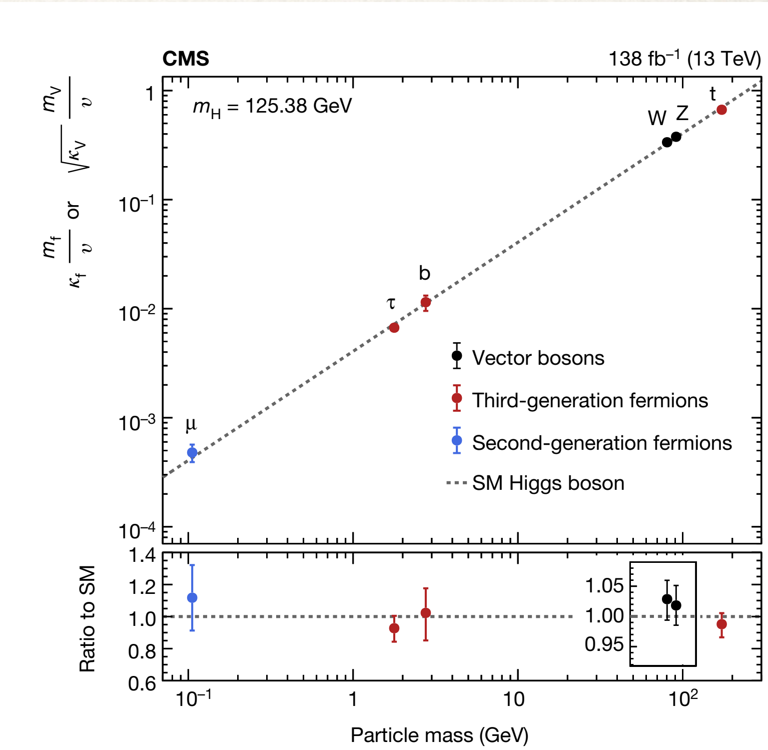

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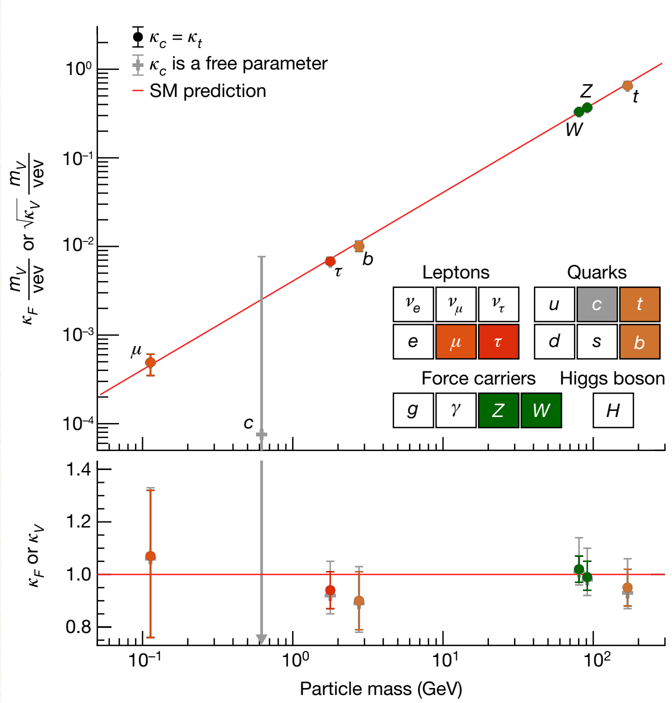

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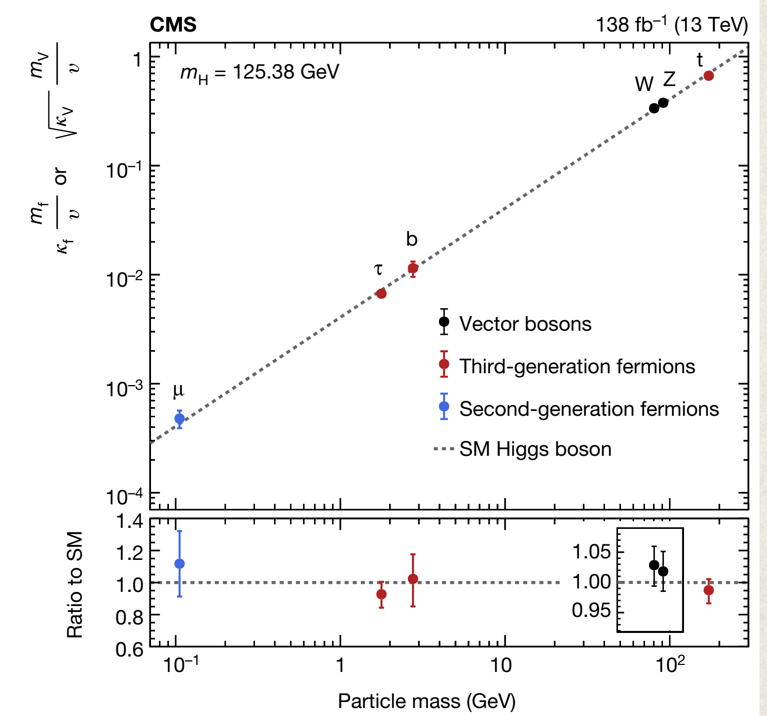

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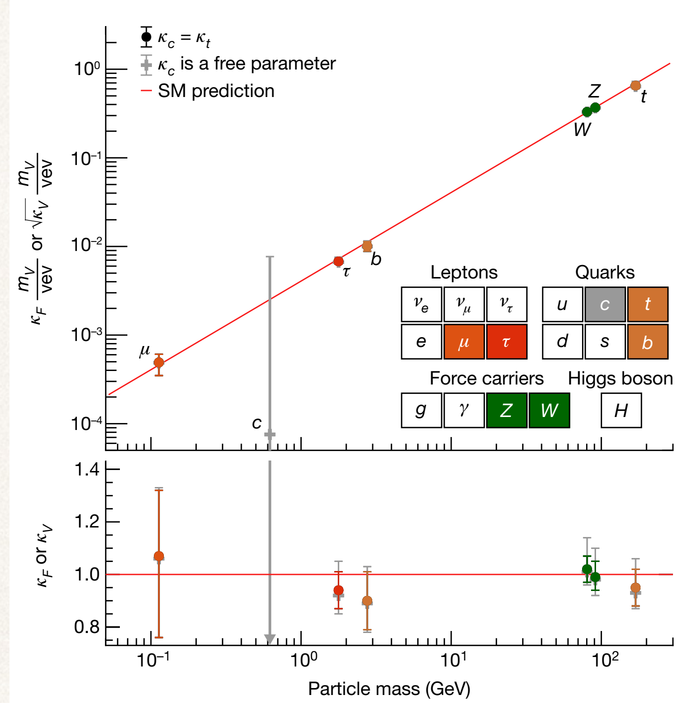

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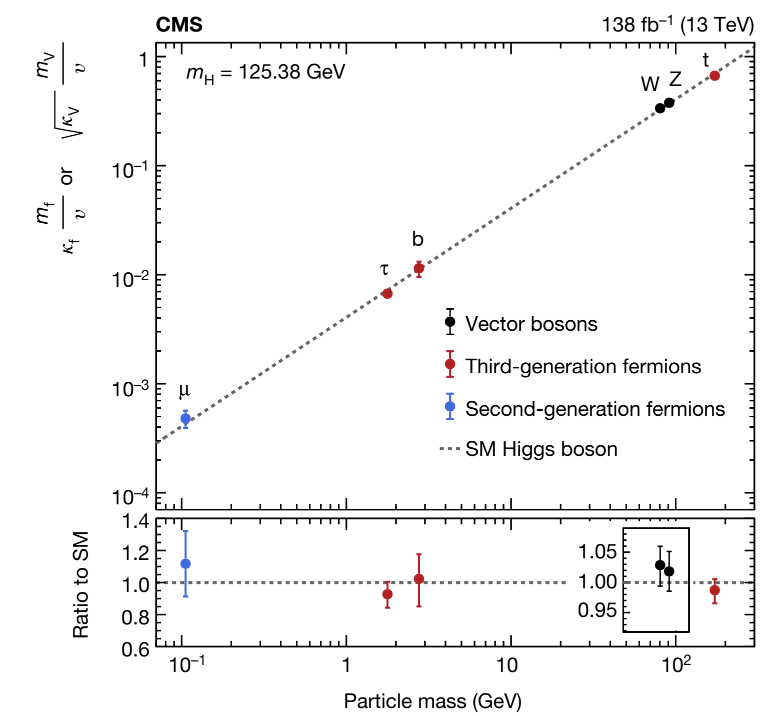

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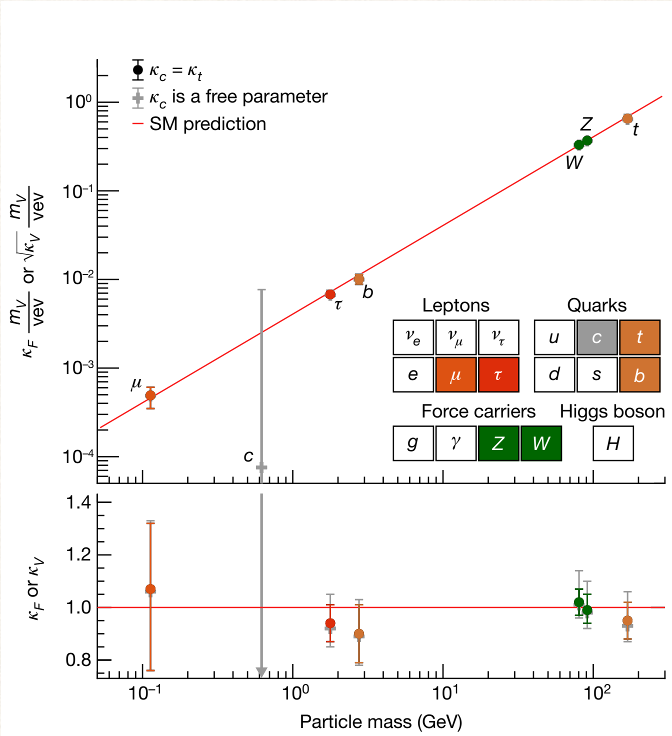

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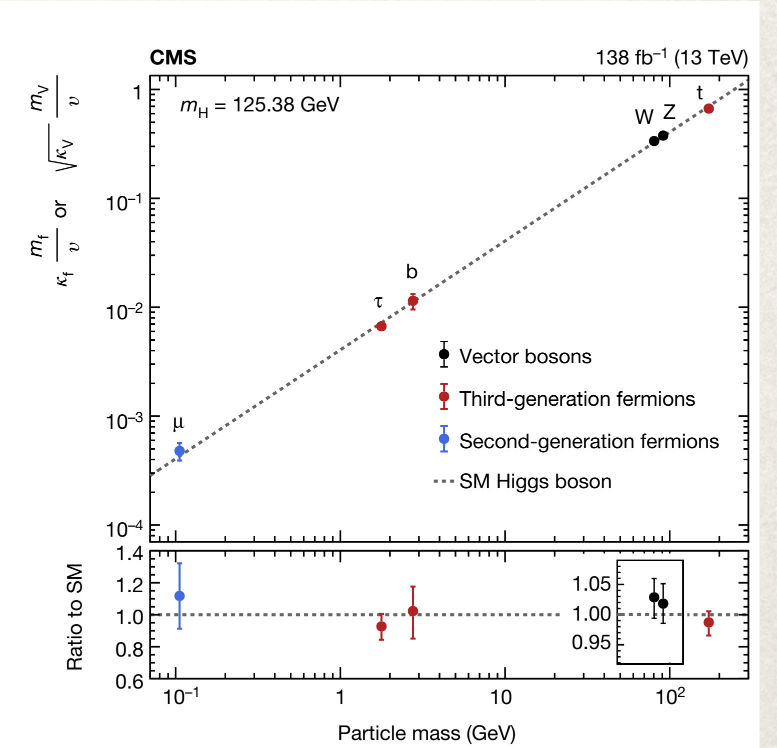

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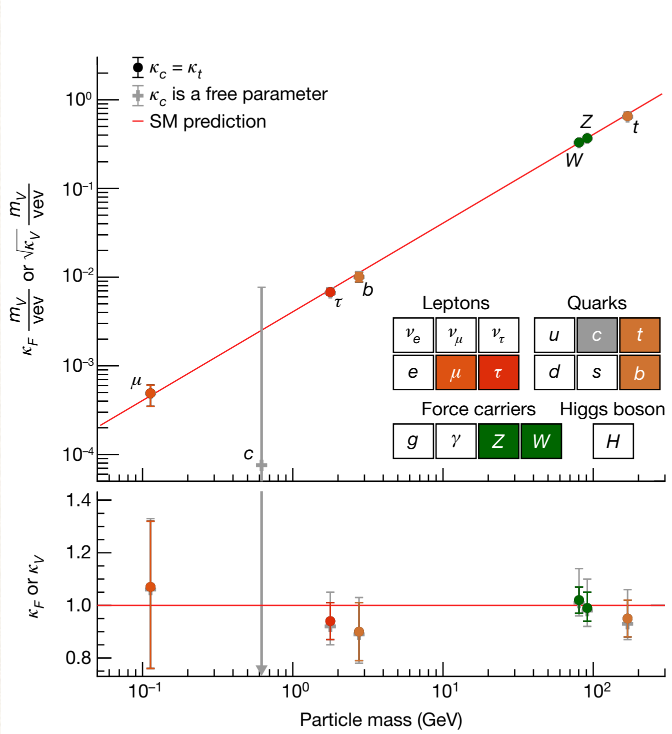

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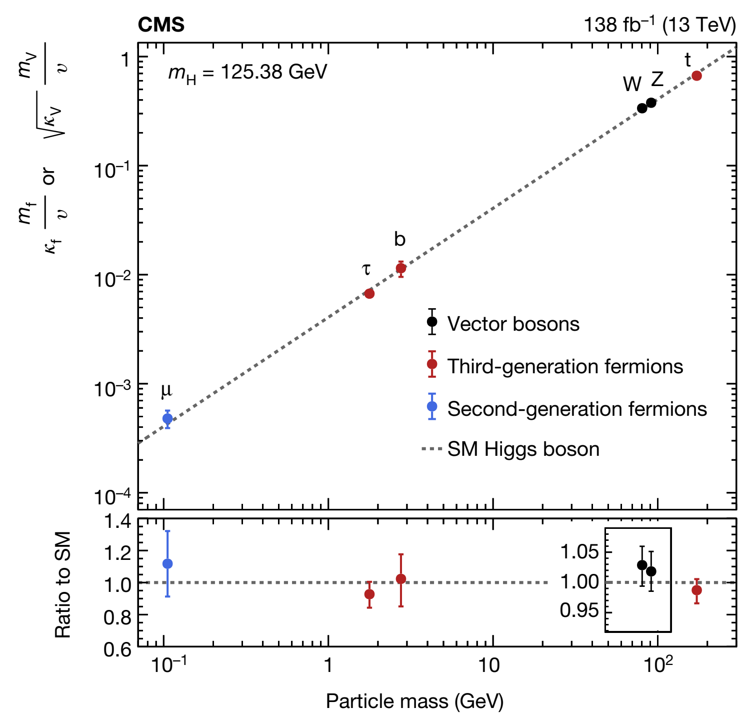

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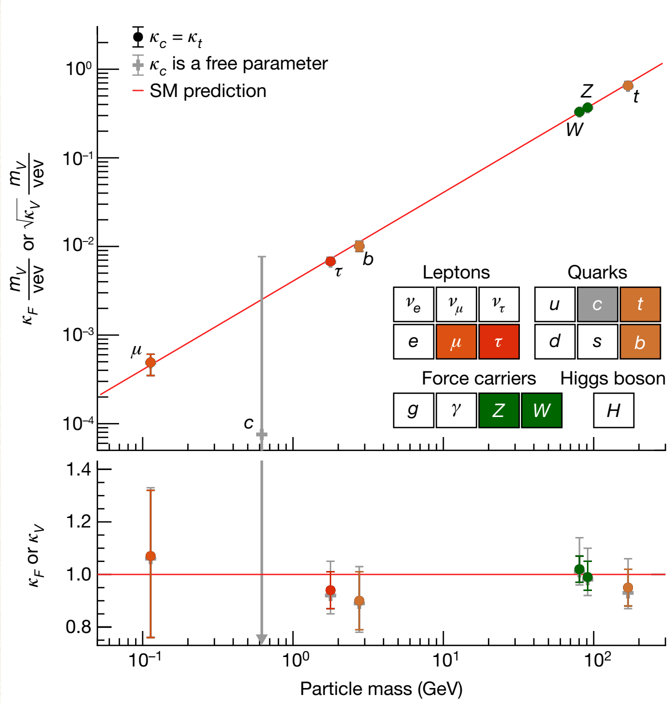

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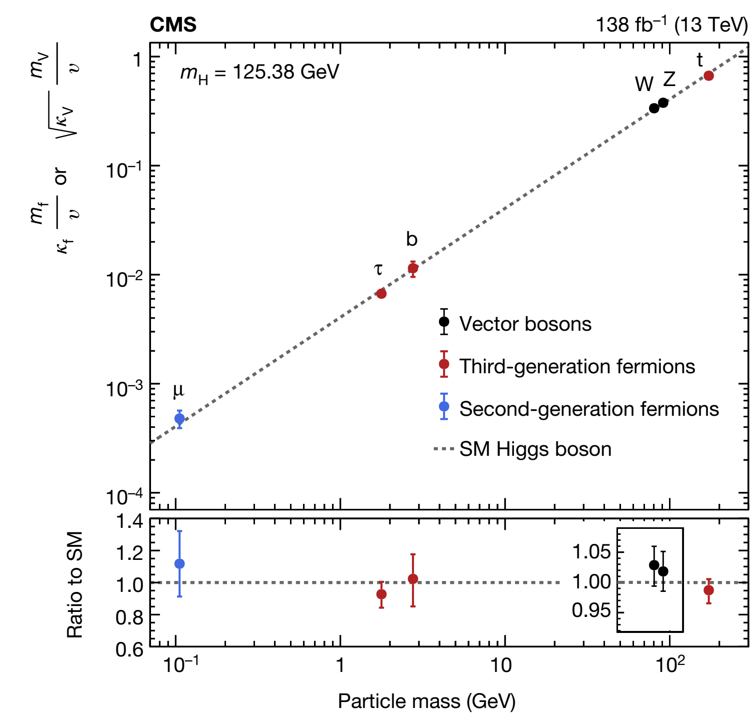

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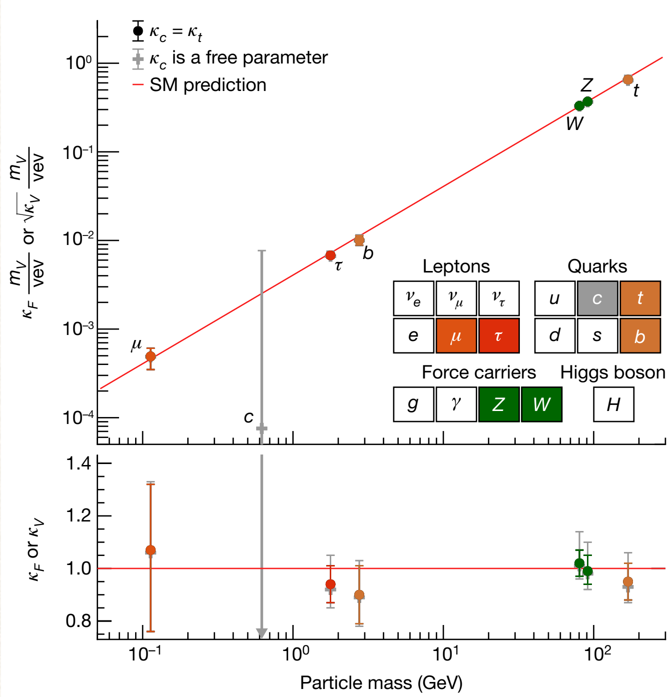

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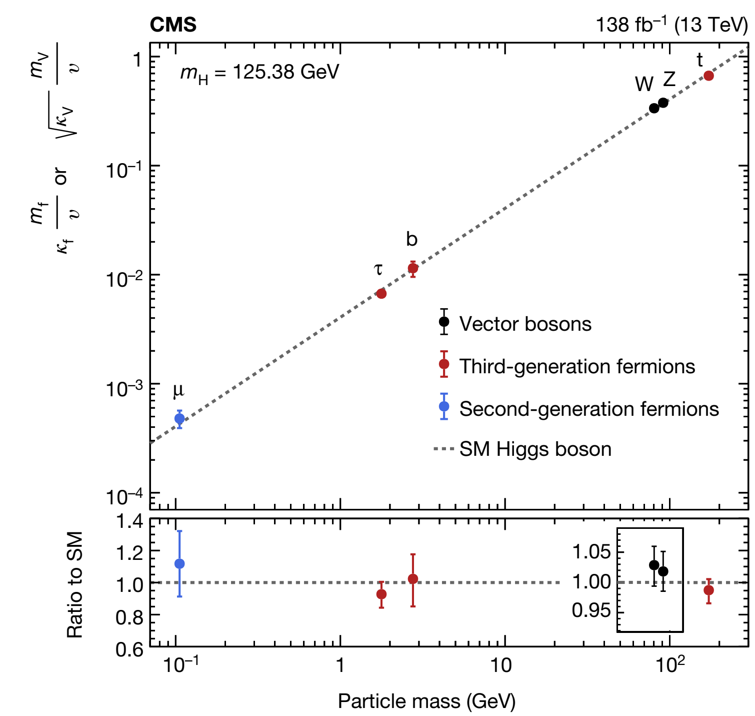

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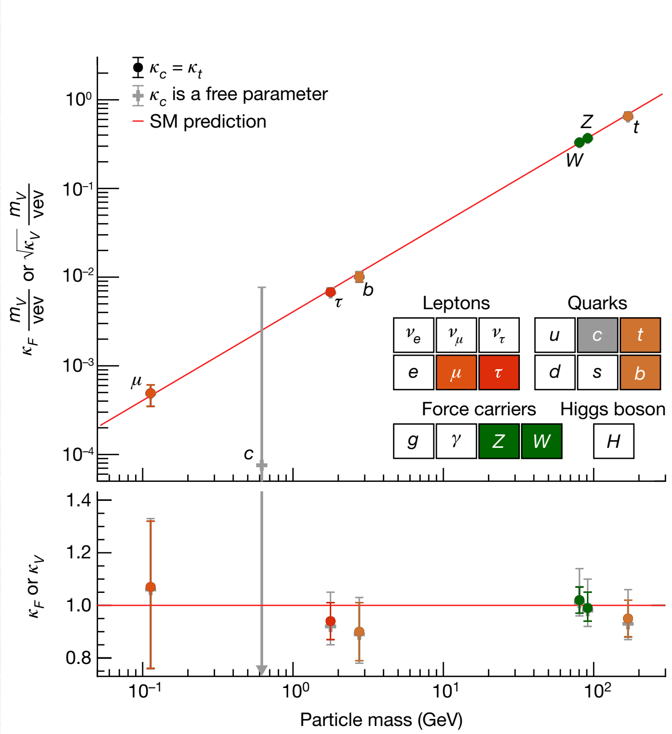

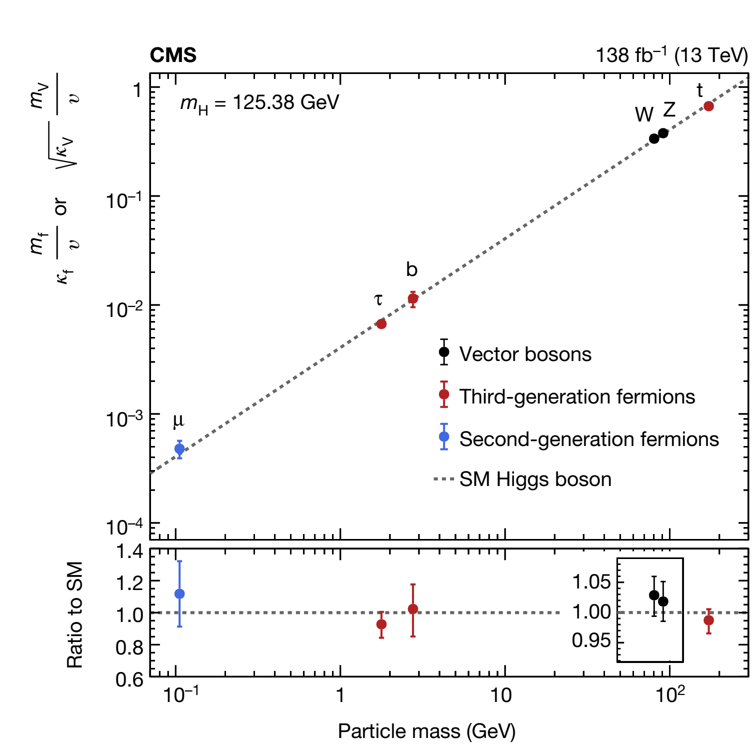

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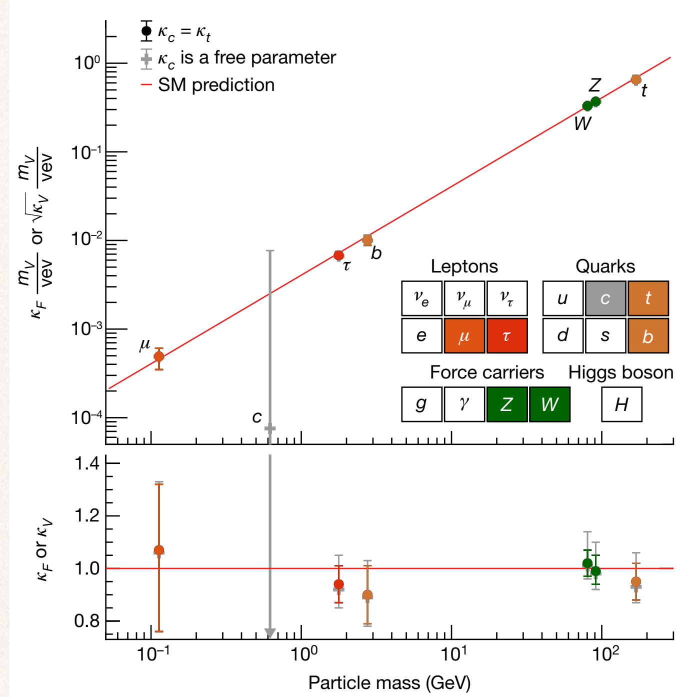

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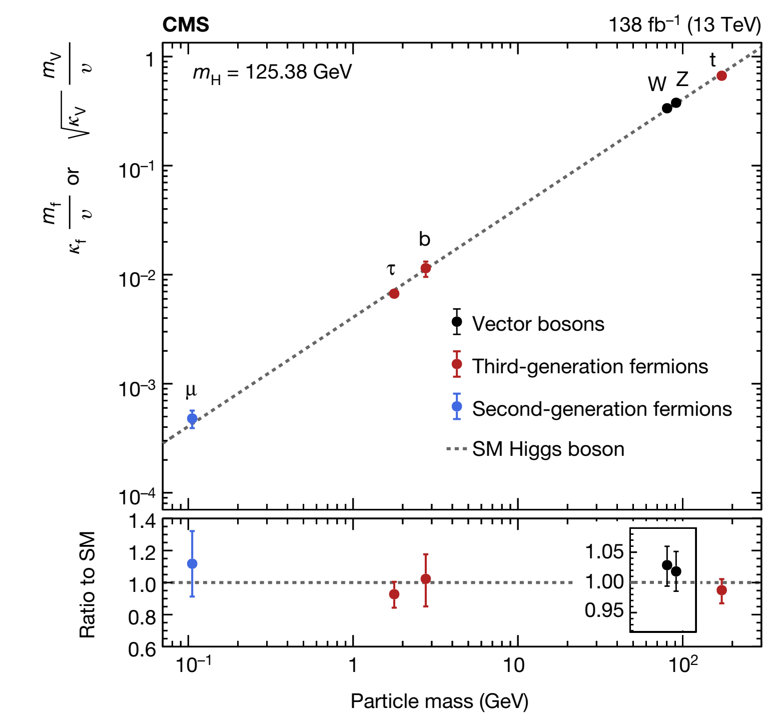

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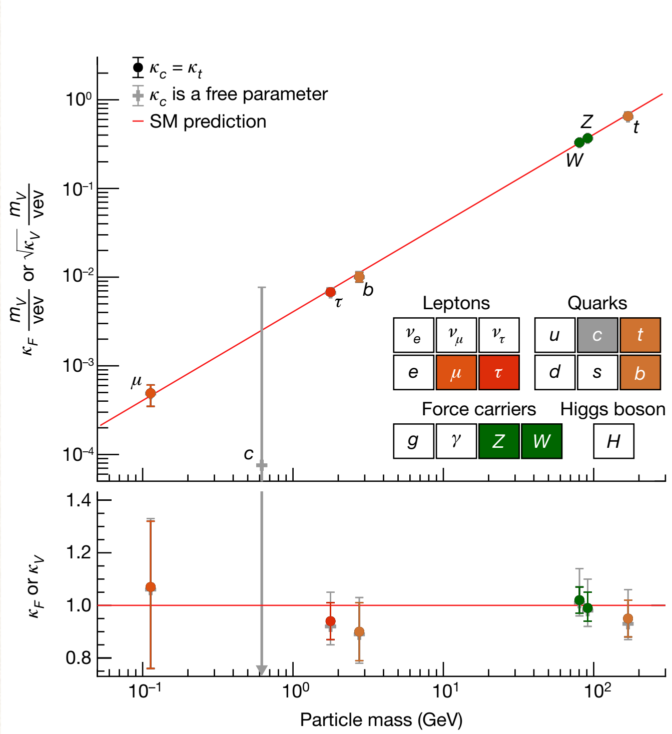

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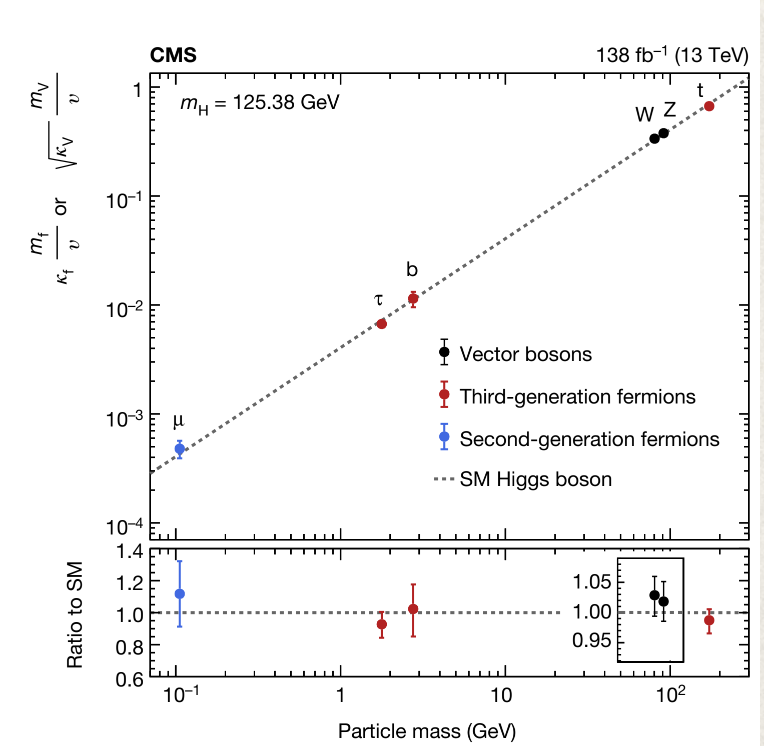

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Precision measurements are necessary to access "min".

Pheno. consequences of $v_C/T_C \gtrsim 1$

~ alignment limit in 2HDM: hVV, hff=SM-like ~

Extra Higgs masses $m^2_{\phi=H,A,H^\pm} = M^2 + \lambda_{h\phi\phi} v^2, \quad M^2 = m_3^2/(\sin\beta\cos\beta)$

Internal structure is essential!	$M^2 \ll \lambda_{h\phi\phi} v^2$	$M^2 \gtrsim \lambda_{h\phi\phi} v^2$
loop properties	non-decoupling	decoupling
1^{st}-order EWPT	$v_C/T_C \gtrsim 1$	$v_C/T_C < 1$
h -> 2 gammas [I.Ginzburg, M.Krawczyk, P.Osland, hep-ph/0211371]	$0.9 \lesssim \mu_{\gamma\gamma} < 1$	$\mu_{\gamma\gamma} \simeq 1$
hhh coupling [S.Kanemura, Y.Okada, E.S., PLB606 (2005) 361]	$\kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} \gtrsim 1.1$	$\kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} \simeq 1$

$A \to ZH, \; H \to ZA, \; H \to hh$ G.C.Dorsch et al, 1405.4437 (PRL); Basler et al 1612.04086 (JHEP); J. Bernon et al, 1712.08430 (JHEP), etc

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Towards Higgs precision era

- Higgs date is getting more and more precise.
- Refinement of $v_C/T_C \gtrsim 1$ is necessary.

Theoretical uncertainties

$$v_C/T_C \gtrsim 1$$

- gauge-dependence
- renormalization scale dependence
- More proper temperature is nucleation temperature T_N.

Lattice studies

[K. Kainulainen et al, 1904.01329 (JHEP); L.Niemi et al, 2005.11332 (PRL), etc]

Perturbative calculation gives useful guidance qualitatively but not quantitatively.

- "1" is a just rough number.
- Depends on sphaleron profiles (model-dependent).

[K. Funakubo, E.S., 2003.13929 (PRD-RC)]

v_C/T_C > (1.1-1.3)

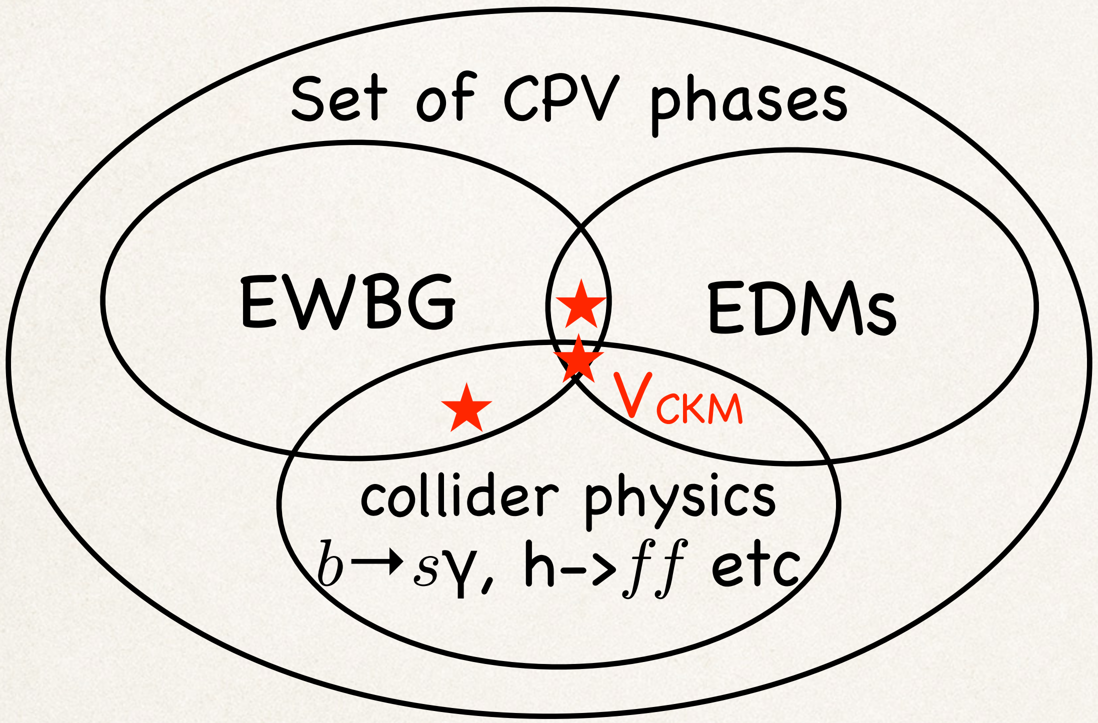
→ precise enough

$$\min < \left|\frac{\delta g}{g^{\rm SM}}\right| < \max$$

← data

EWBG-related CP violation

- CPV in CKM matrix is not sufficient.
- Many CPV sources exist in BSM, and some of them are related to EWBG.



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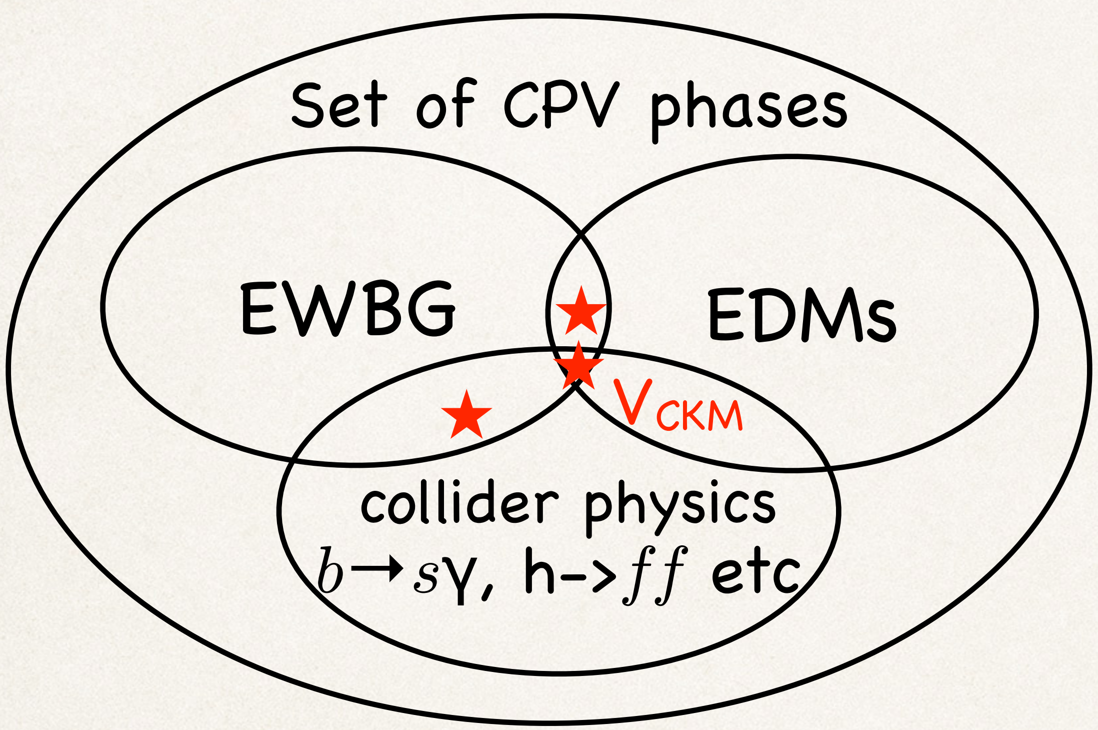

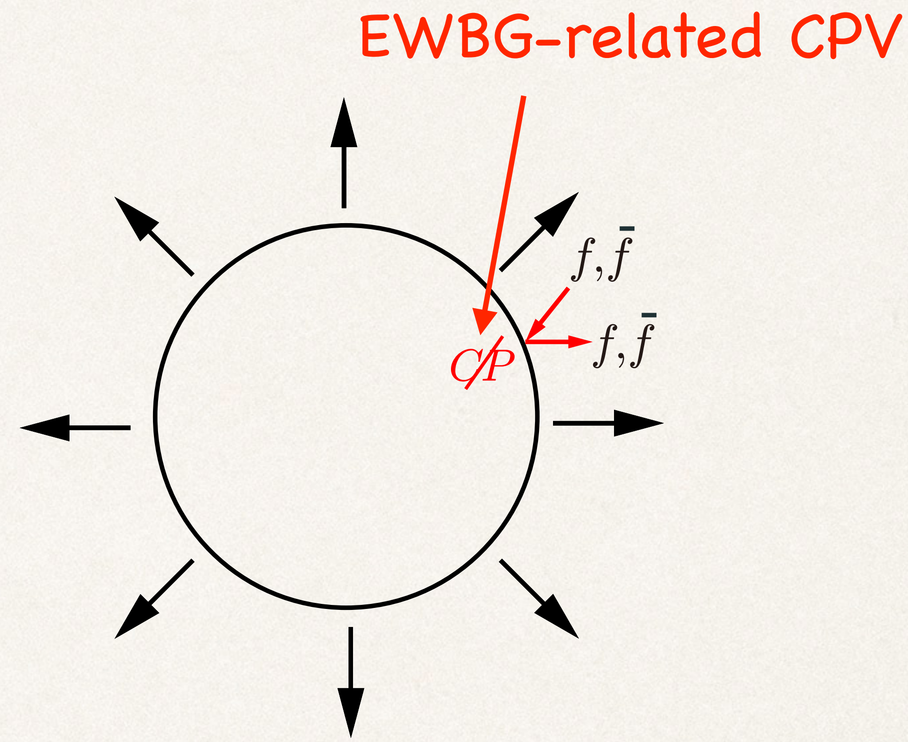

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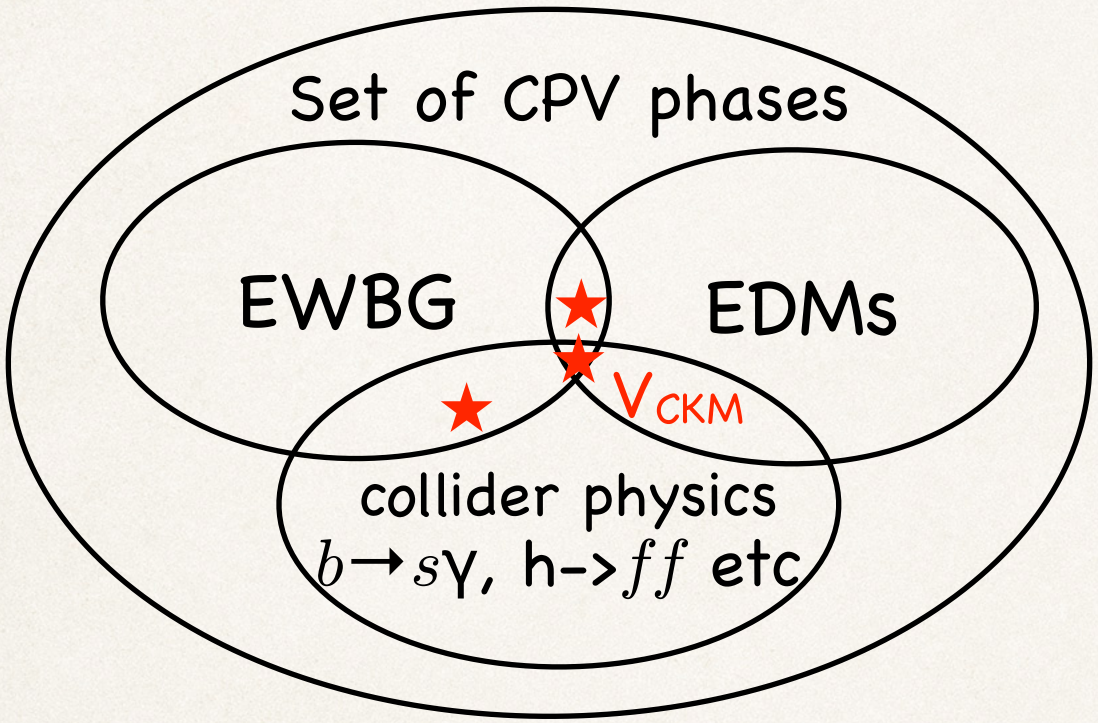

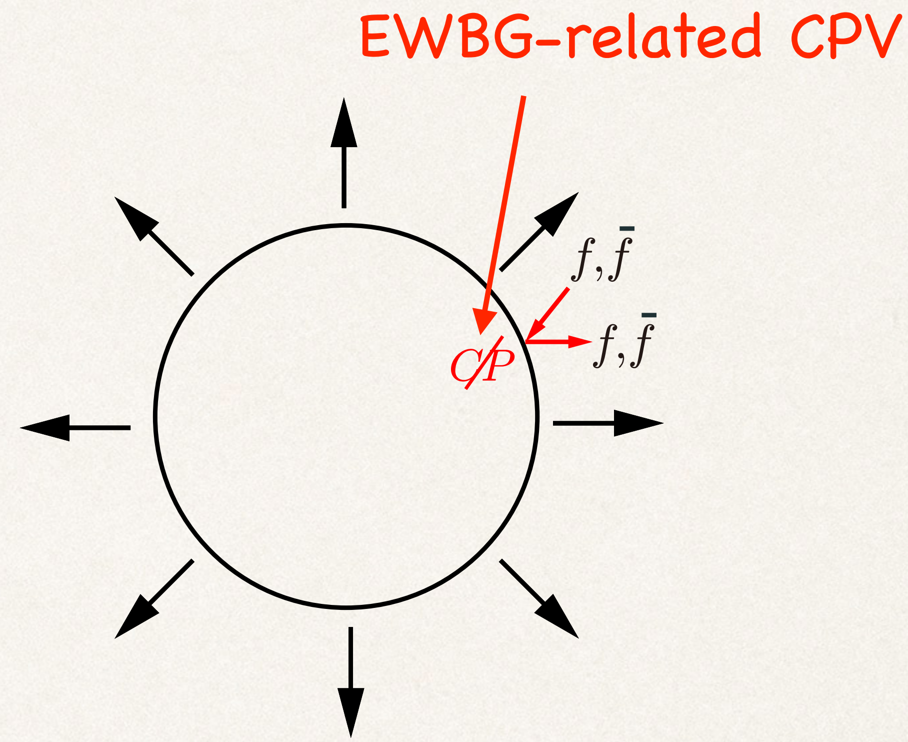

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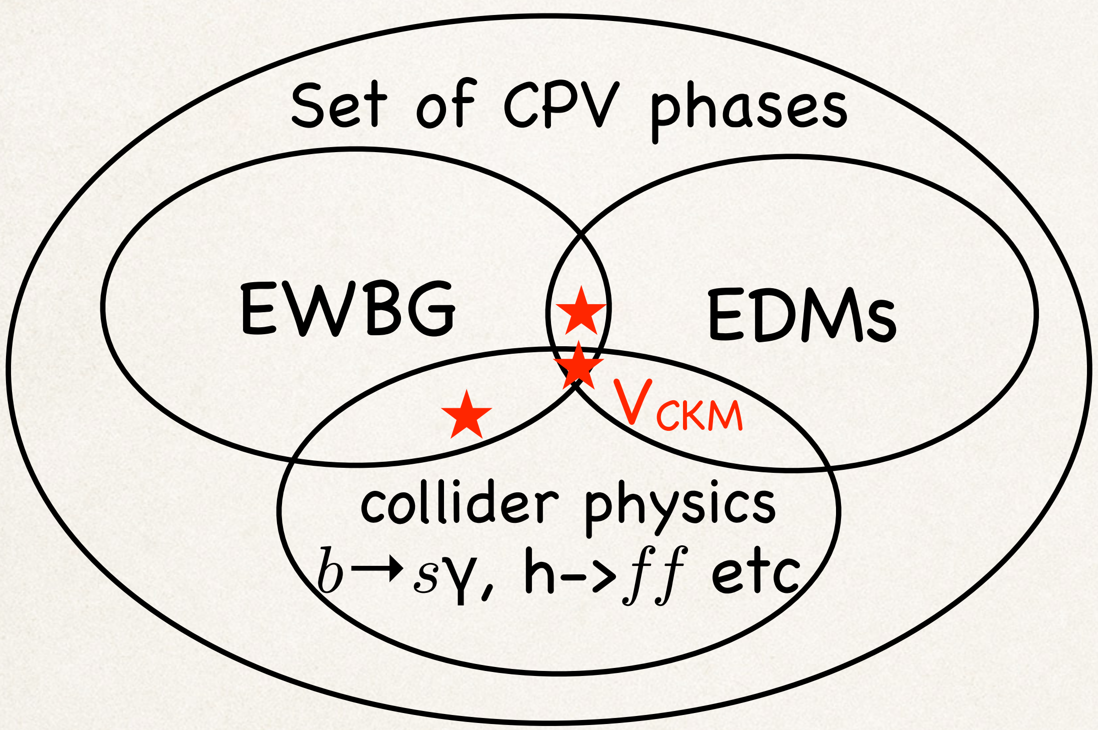

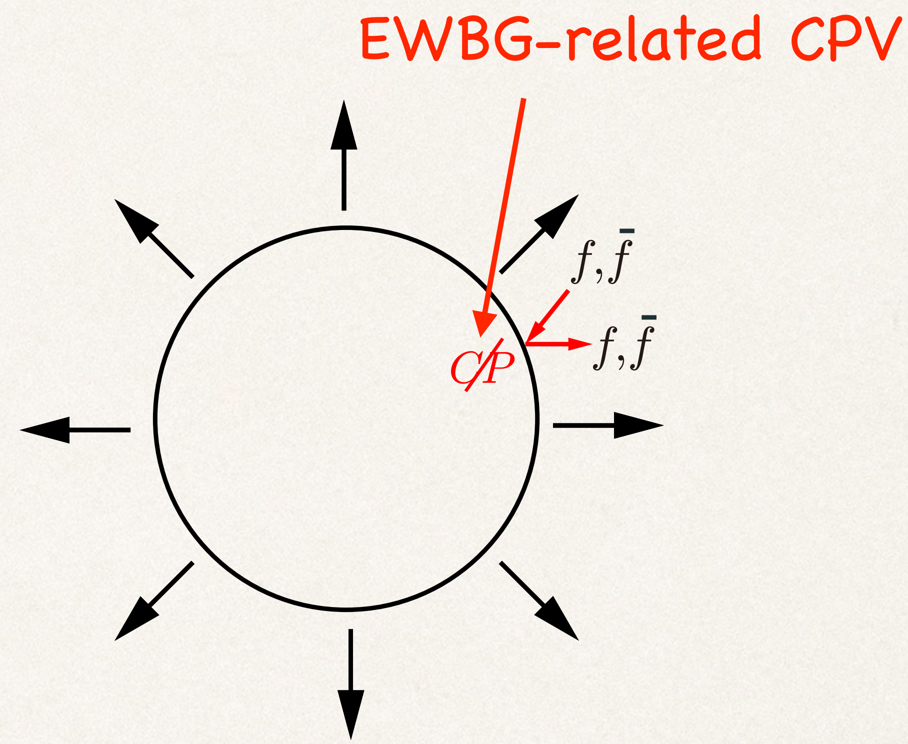

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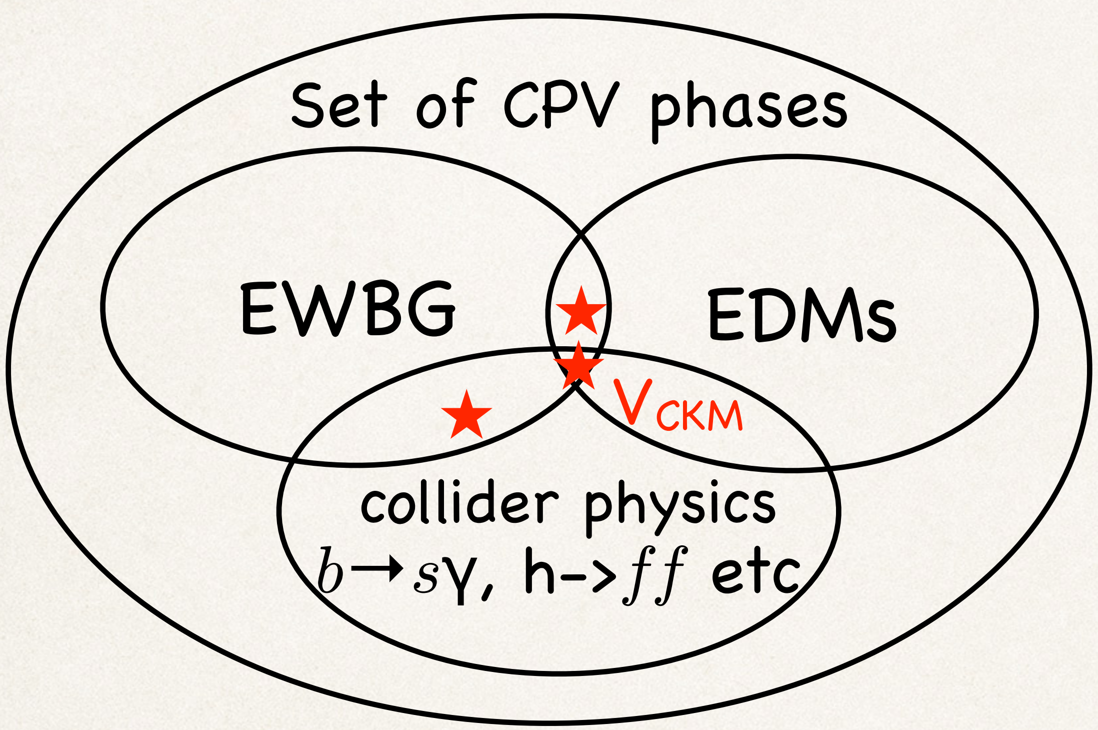

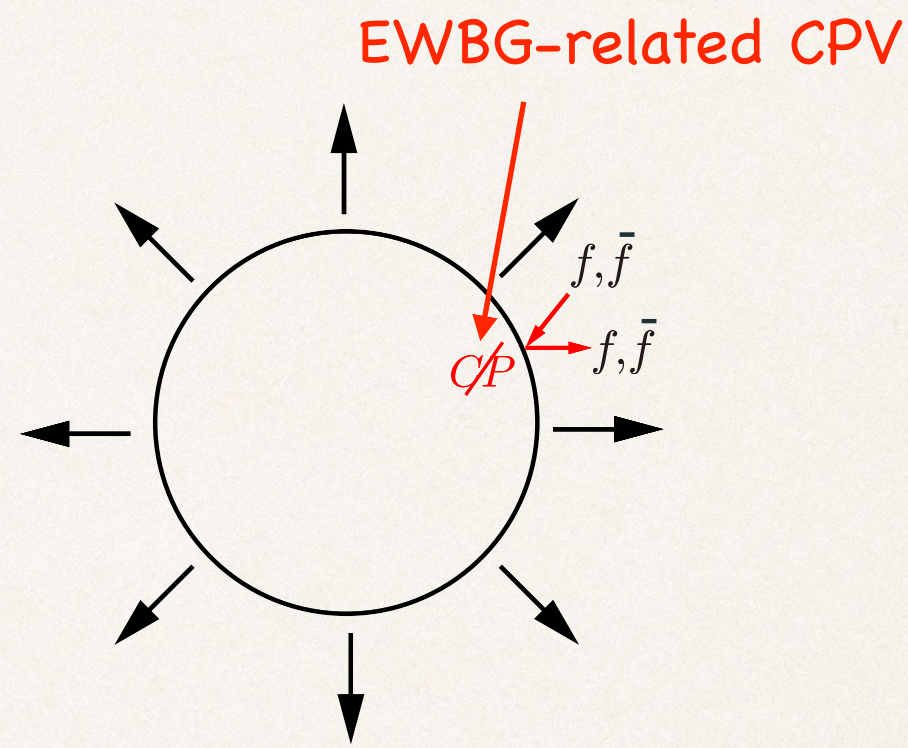

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(1) Yukawa interactions, (2) Higgs self interactions.

EWBG after ACME-II

CP-violating Higgs-fermion coupling

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

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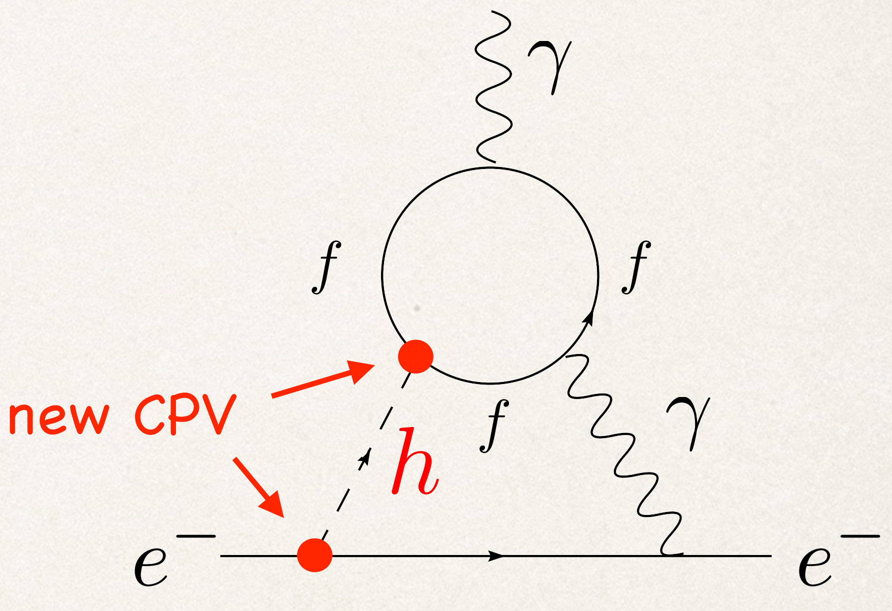

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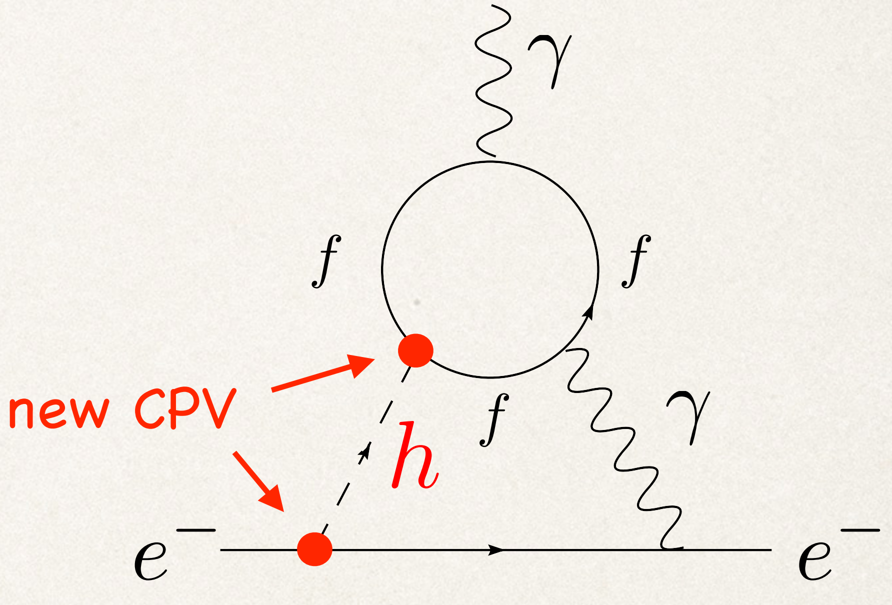


Most EWBG scenarios are now in danger. -> needs suppression mechanism (cancellation)

EWBG after ACME-II

CP-violating Higgs-fermion coupling

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

$\Psi_{\rm CP} = 0 \;\; \to \;\; h$ is pure CP-even

$\Psi_{\rm CP} = \pi/2 \;\; \to \;\; h$ is pure CP-odd <- excluded by LHC

1212.6639 (CMS), 1307.1432 (ATLAS)

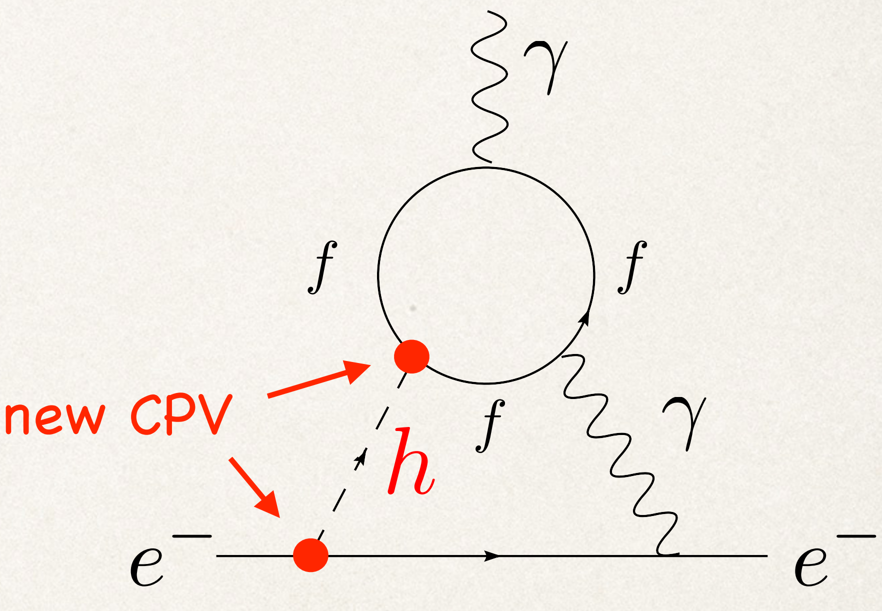
However, h(125) can still be a CP mixture state.

Electric Dipole Moment (EDM)

electron EDM receives the strongest bound:

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

[ACME, Nature 562,355(2018)] (ACME-II)



Most EWBG scenarios are now in danger. -> needs suppression mechanism (cancellation)

*Models that have only 1 CPV phase -> no cancellation mechanism.

e.g., Z_2-2HDMs (type I, II, etc)

EDM cancellation in general 2HDM

K. Fuyuto, W.-S. Hou, E.S., 1705.05034 (PLB); 1910.12404 [PRD-RC]

No Z_2 symmetry -> extra Yukawa couplings exist ($\rho_{ij} \in \mathbb{C}$)

Extra top Yukawa coupling ρ_{tt} is responsible for baryogenesis

$$\mathrm{Re}\rho_{ee} = -r\left(\frac{\lambda_e}{\lambda_t}\right)\mathrm{Re}\rho_{tt},$$

$$\mathrm{Im}\rho_{ee} = -r\left(\frac{\lambda_e}{\lambda_t}\right)\mathrm{Im}\rho_{tt}$$

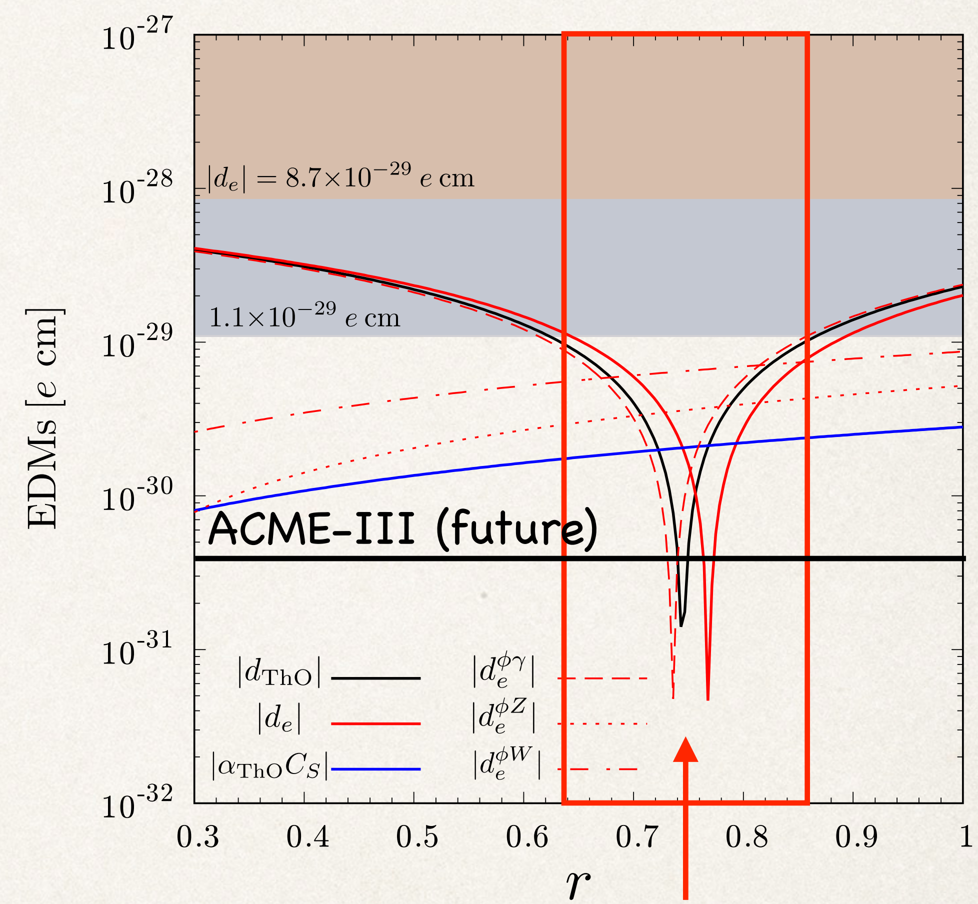
required by EWBG
$|\rho_{tt}|>O(0.01\text{-}1)$

$|\rho_{ee}/\rho_{tt}|$ is SM like if r=O(1).

- cancellation occurs at r=O(1)

- Collider probes of CPV Higgs Yukawa couplings play a complementary role.

$m_H = m_A = m_{H^\pm} = 500$ GeV, $c_{\beta-\alpha} = 0.1$



cancellation region

$\kappa_t = 0.83^{+0.30}_{-0.46}$, $\Psi_{\mathrm{CP}} = 11^{\circ}{}^{+55^{\circ}}_{-77^{\circ}}$ ATLAS ATLAS-CONF-2022-016

$\kappa_t \cos\Psi_{\mathrm{CP}} \in (0.86, 1.26)$, $\kappa_t \sin\Psi_{\mathrm{CP}} \in (-1.07, 1.07)$, CMS 2208.02686

top-driven EWBG is still viable!

Summary and Outlook

- No EWBG possibility in SM and MSSM.

strong 1^{st}-order EWPT → constraints on sub-TeV new particle spectrum

$v_C/T_C \gtrsim 1$ → min < deviations from SM in Higgs couplings < max

model dependent (min) — constraint by experiments (max)

EWBG-related CPV ⟶ electron EDM, $h \to ff$, $b \to s\gamma$, etc

Now LHC, ACME, Belle are probing EWBG possible regions.

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Future

2022 — 2029 — 2030 — 2037 — 2040

LHC Run3

HL-LHC

SuperKEKB

LISA

+ lepton colliders (ILC, CEPC, CLIC, FCC-ee, C^3, etc)

+ EDM experiments: electron (ACME, JILA, etc), proton (IBS-CAPP, BNL, etc)

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Future

2022	2029	2030	2037	2040

LHC Run3 (around 2022) · HL-LHC (2029 to after 2037) · SuperKEKB (around 2022) · LISA (from 2037, continuing past 2040)

\+ lepton colliders (ILC, CEPC, CLIC, FCC-ee, C^3, etc)

\+ EDM experiments: electron (ACME, JILA, etc), proton (IBS-CAPP, BNL, etc)

- EWBG verification keeps going on, and most scenarios would be tested by future experiments if theoretical uncertainties are under control.

Backup

2 Higgs doublet model (2HDM)

Higgs potential

$$V_0(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.})$$
$$+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+ \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left\{\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right\}(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right],$$

$$m_3^2, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C}$$

Higgs fields

$$\Phi_i(x) = \begin{pmatrix} \phi_i^+(x) \\ \frac{1}{\sqrt{2}}\Big(v_i + h_i(x) + i a_i(x)\Big) \end{pmatrix}, \quad i = 1, 2.$$

Parameters

In softly-broken Z_2-2HDMs: 8 parameters = $\{m_{1,-3}, \lambda_{1\text{-}5}, \lambda_6=\lambda_7=0\}$

$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ M^2 = m_3^2/(\sin\beta\cos\beta)$ * if CP is conserved.

$\tan\beta = v_2/v_1,\ \ (v = \sqrt{v_1^2+v_2^2} \simeq 246\ \text{GeV})$

α: mixing angle between h and H

Yukawa interactions in g2HDM

general (no Z_2 sym.)

Up-type Yukawa couplings:

$$-\mathcal{L}_Y = \bar{q}_{iL}(Y_{1ij}\tilde{\Phi}_1 + Y_{2ij}\tilde{\Phi}_2)q_{jR} + \text{h.c.} \qquad \tilde{\Phi}_{1,2} = i\tau^2\Phi^*_{1,2}$$

In the mass eigenbasis

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{\lambda_i\delta_{ij}}{\sqrt{2}}s_{\beta-\alpha} + \frac{\rho_{ij}}{\sqrt{2}}c_{\beta-\alpha}\right]u_{jR}h + \bar{u}_{iL}\left[\frac{\lambda_i\delta_{ij}}{\sqrt{2}}c_{\beta-\alpha} - \frac{\rho_{ij}}{\sqrt{2}}s_{\beta-\alpha}\right]u_{jR}H - \frac{i}{\sqrt{2}}\bar{u}_{iL}\rho_{ij}\bar{u}_{jR}A + \text{h.c.}$$

125 GeV Higgs

CP-even

CP-odd

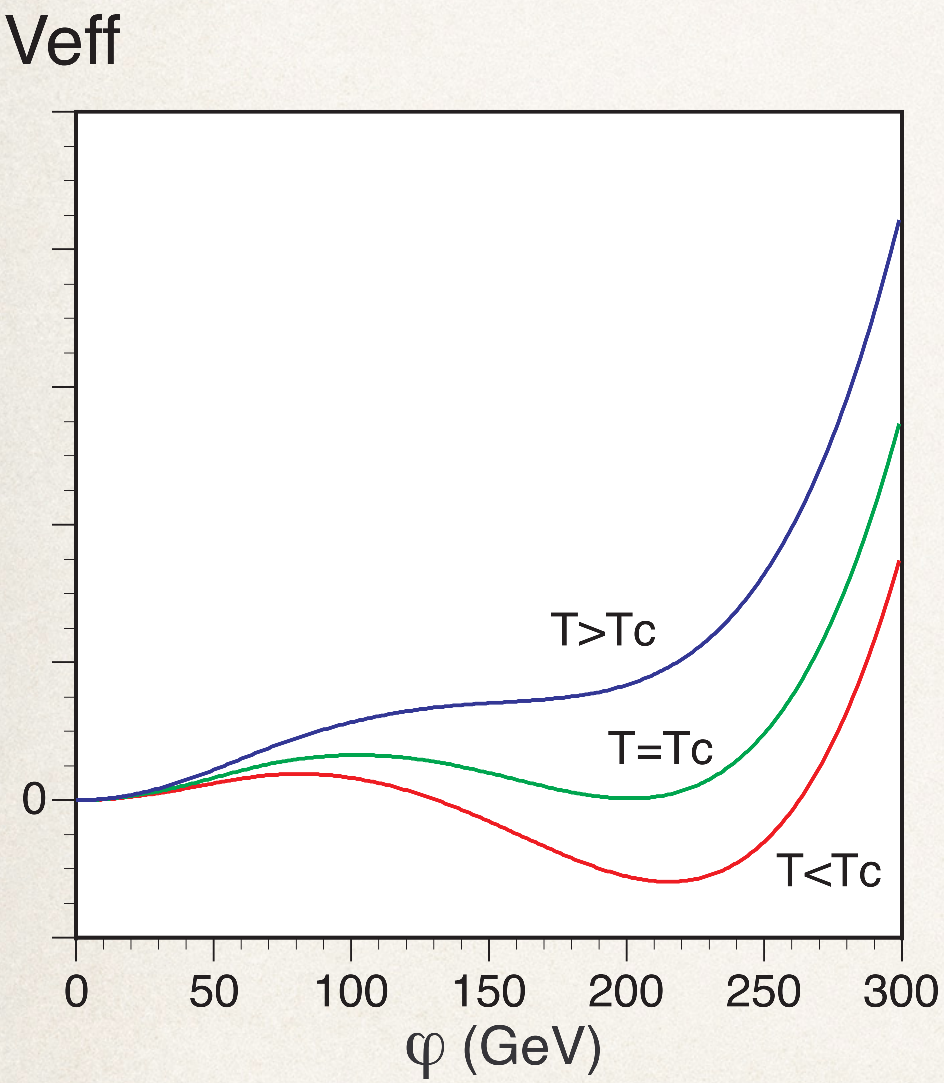
$\lambda_i = \sqrt{2}m_{f_i}/v$, ρ_{ij}: 3×3 complex matrices

- Unlike Z_2-2HDM, no tanβ dependence.
- ρ_{ij} are generally complex. $\rho_{ij} \in \mathbb{C} \Rightarrow$ CPV $\Rightarrow$ Baryogenesis!!
- EWBG by ρ_{tt} (t-EWBG), ρ_{bb} (b-EWBG), $\rho_{\tau\tau}$ (τ-EWBG), etc.

1st-order phase transition

- Thermal potential driven 1st-order PT -

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



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

e.g., 2HDM

Heavy Higgs loops can enhance E.

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

non-decoupling

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

decoupling

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

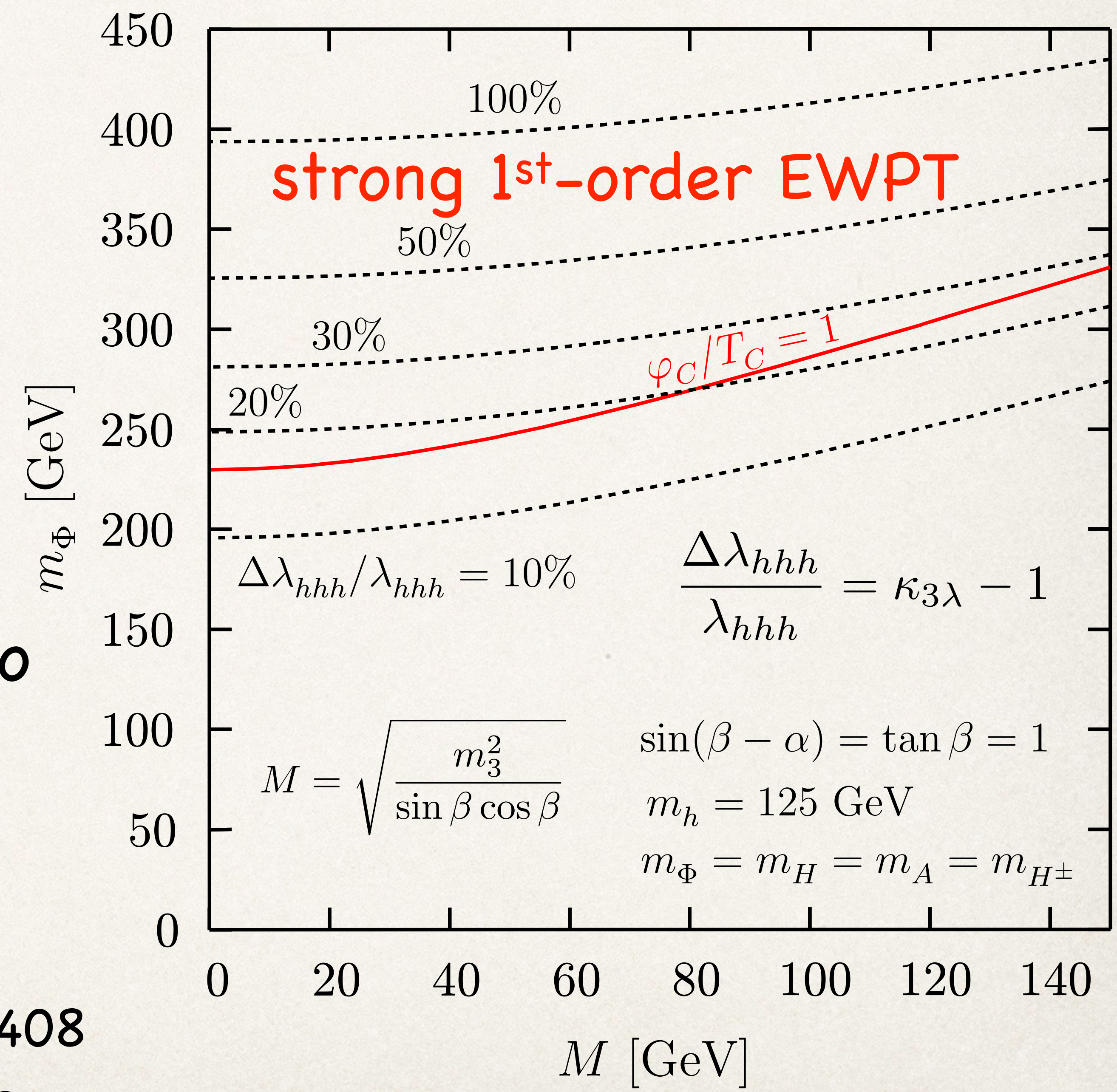
λ_{hhh}-EWPT correlation in 2HDM

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

- Strong 1st-order EWPT leads to large deviation in λ_{hhh}.

- Non-decoupling loop effect is the origin of the enhancement.

- Heavy Higgs boson masses have to be sub TeV due to unitarity and/or perturbativity.



current experimental bounds

$$\kappa_{3\lambda} \in \begin{cases} (-11, 17) & \text{(CMS)} \quad 1806.00408 \\ (-8.2, 13.2) & \text{(ATLAS)} \quad 1807.04873 \end{cases}$$

More detailed studies can be bound at Basler et al 1711.04097 (JHEP), Bernon et al, 1712.08430 (JHEP).

Pheno. consequences of $v_c/T_c \gtrsim 1$

~ alignment limit version: hVV, hff=SM-like ~

h -> 2 gammas:

[I.Ginzburg, M.Krawczyk, P.Osland, hep-ph/0211371]

$$\mu_{\gamma\gamma} \simeq \begin{cases} \left|1 + \dfrac{1}{3\mathcal{A}_{\rm SM}}\right|^2 \simeq \boxed{0.9} & \text{for } M^2 \ll \tilde{\lambda}_i v^2, \\ \left|1 + \dfrac{\tilde{\lambda}_i v^2}{3\mathcal{A}_{\rm SM} m_{H^\pm}^2}\right|^2 & \text{for } M^2 \gtrsim \tilde{\lambda}_i v^2. \end{cases} \qquad \mathcal{A}_{\rm SM} = -6.49$$

$$\mu_{\gamma\gamma} = \begin{cases} 1.18^{+0.17}_{-0.14} \ (\text{CMS}) & \text{1804.02716} \\ 0.99^{+0.15}_{-0.14} \ (\text{ATLAS}) & \text{1802.04146} \end{cases}$$

hhh coupling:

[S. Kanemura, S. Kiyoura, Y. Okada, E.S., C.-P. Yuan, PLB558 (2003) 157]

$$\kappa_{3h} = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} \simeq \begin{cases} 1 \boxed{+} \displaystyle\sum_{\Phi=H,A,H^\pm} \frac{c_\Phi}{12\pi^2} \frac{\boxed{m_\Phi^4}}{m_h^2 v^2} & \text{for } M^2 \ll \tilde{\lambda}_i v^2, \\ 1 \boxed{+} \displaystyle\sum_{\Phi=H,A,H^\pm} \frac{c_\Phi}{12\pi^2} \frac{(\tilde{\lambda}_i v^2)^3}{m_h^2 v^2 m_\Phi^2} & \text{for } M^2 \gtrsim \tilde{\lambda}_i v^2. \end{cases} \qquad n_{H,A} = 1 \text{ and } n_{H^\pm} = 2$$

- Correction is positive.
- Power correction!! (*log corrections are absorbed into m_h.)

t-EWBG with $\rho_{ee} \neq 0$

$$d_{\mathrm{ThO}} = d_e + \alpha_{\mathrm{ThO}} C_S$$

- Dangerous diagrams are cancelled by nonzero ρ_{ee}.

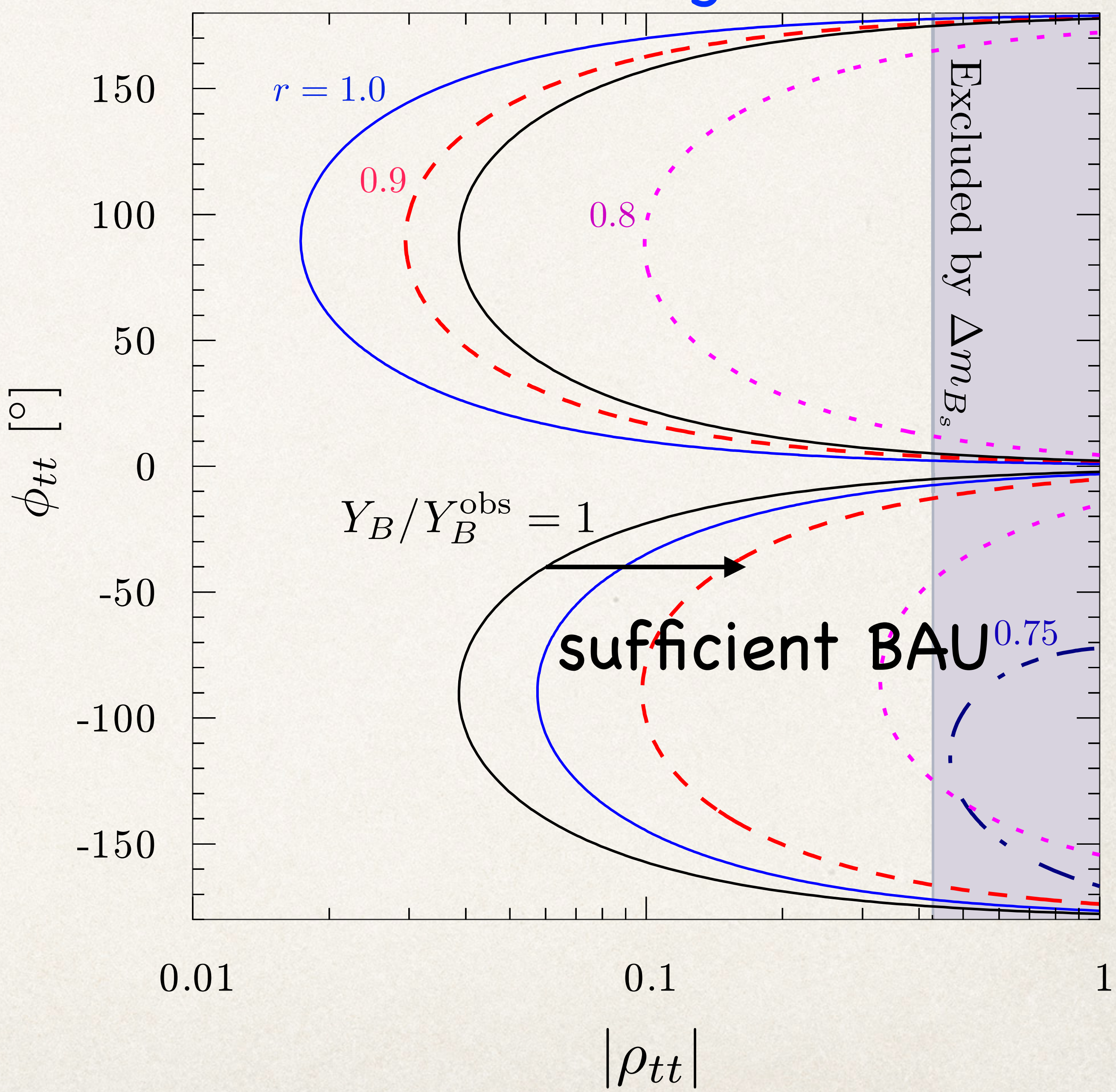
- BAU-favored regions revive!!

- ACME-II may indicate

$$\left|\frac{\rho_{ee}}{\rho_{tt}}\right| \simeq \frac{\lambda_e}{\lambda_t}$$

$$d_{\mathrm{ThO}}^{\mathrm{EXP}} = (4.3 \pm 4.0) \times 10^{-30}\ e\ \mathrm{cm}$$

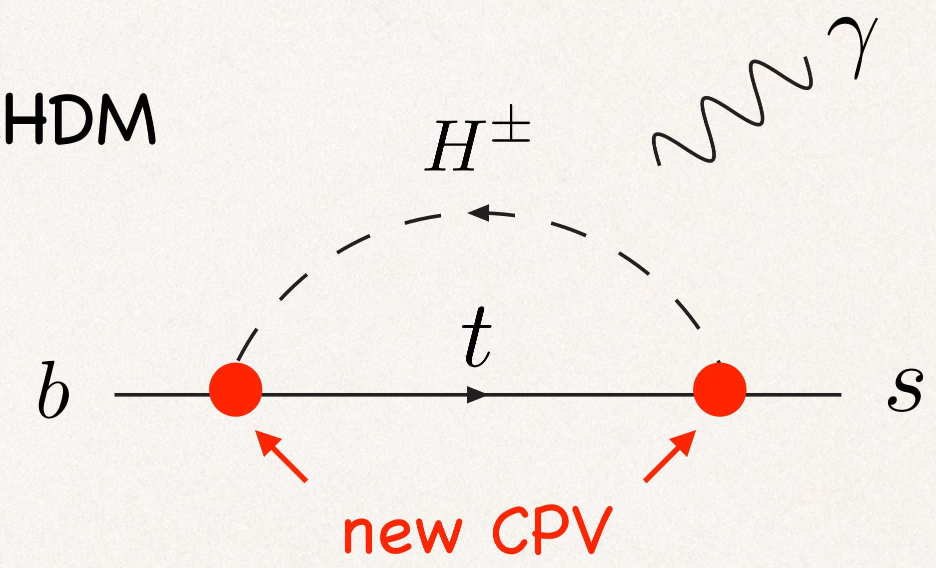
2σ allowed region of d_{ThO}



CPV in b->s+gamma

BAU-related CPV also show up in B physics

E.g. $b \to s\gamma$ in general 2HDM



CP asymmetry

$$\mathcal{A}_{\rm CP} = \frac{\Gamma(\overline{B} \to \overline{X}_s\gamma) - \Gamma(B \to X_s\gamma)}{\Gamma(\overline{B} \to \overline{X}_s\gamma) + \Gamma(B \to X_s\gamma)}$$

$$\Delta\mathcal{A}_{\rm CP} \equiv \mathcal{A}_{B^- \to X_s^- \gamma} - \mathcal{A}_{B^0 \to X_s^0 \gamma}$$

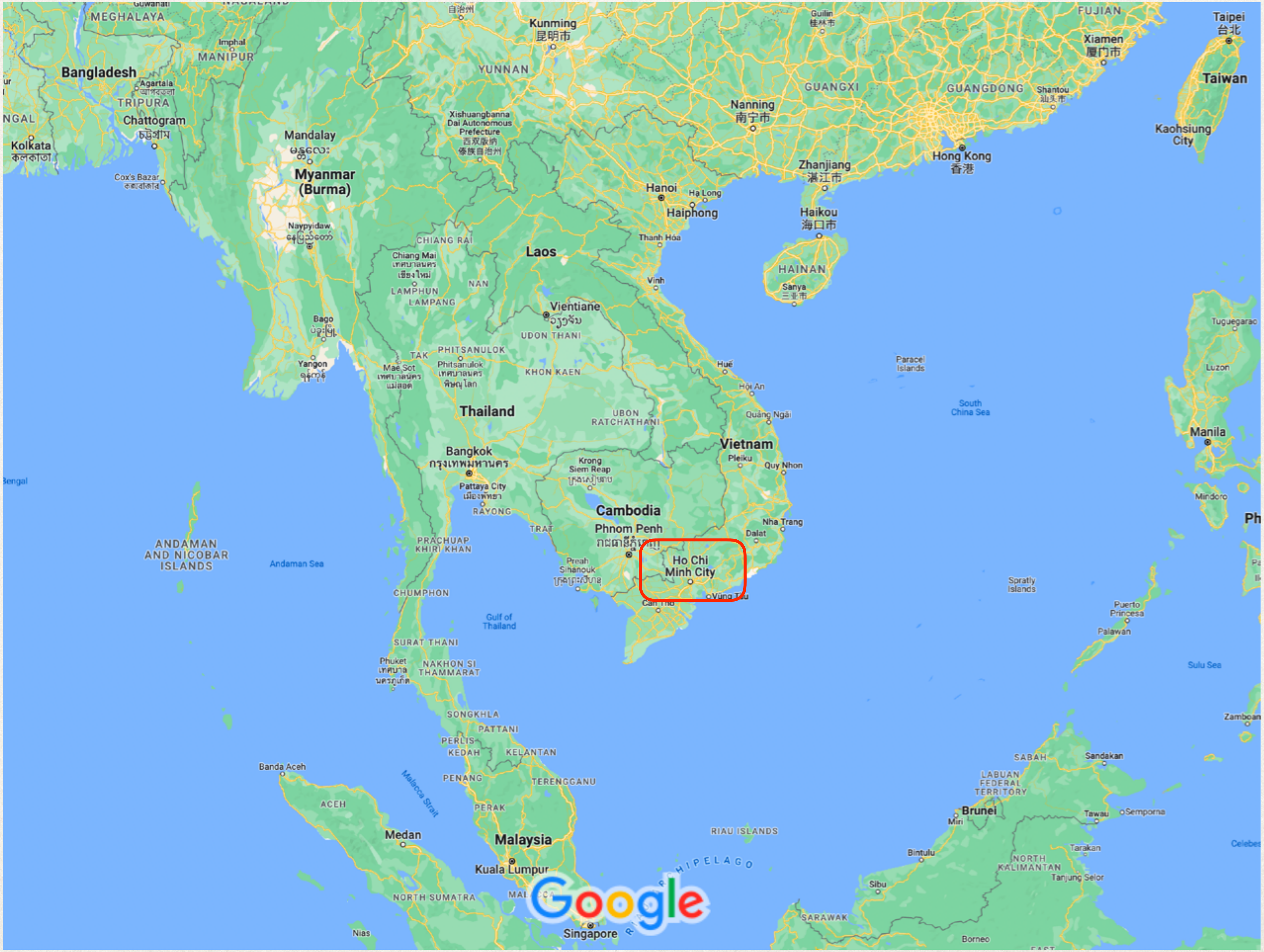
Experimental constraint

$$\Delta\mathcal{A}_{\rm CP}^{\rm EXP} = (+3.69 \pm 2.65 \pm 0.76)\%$$

S. Watanuki, A.Ishikawa et al. [Belle Collaboration], PRD99, 032012 (2019) [1807.04236].

Some EWBG scenarios can be probed by this ΔA_{CP} measurement even when eEDM is accidentally suppressed.

Where is Van Lang Univ.?



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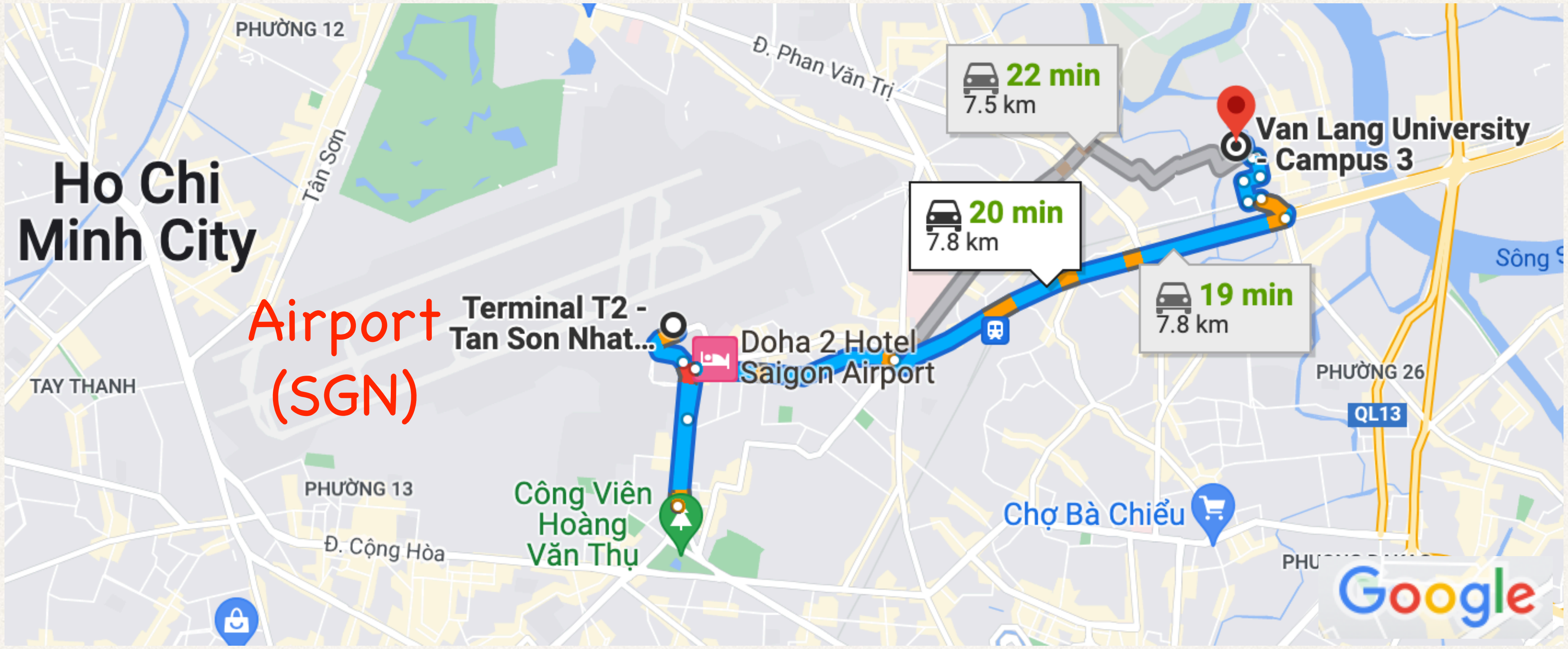

I belong to
Subatomic Physics Research Group in Science and Technology Advanced Institute (STAI) since October in 2021.