VANLANG UNIVERSITY

STAI SCIENCE AND TECHNOLOGY ADVANCED INSTITUTE

Towards verification of electroweak baryogenesis

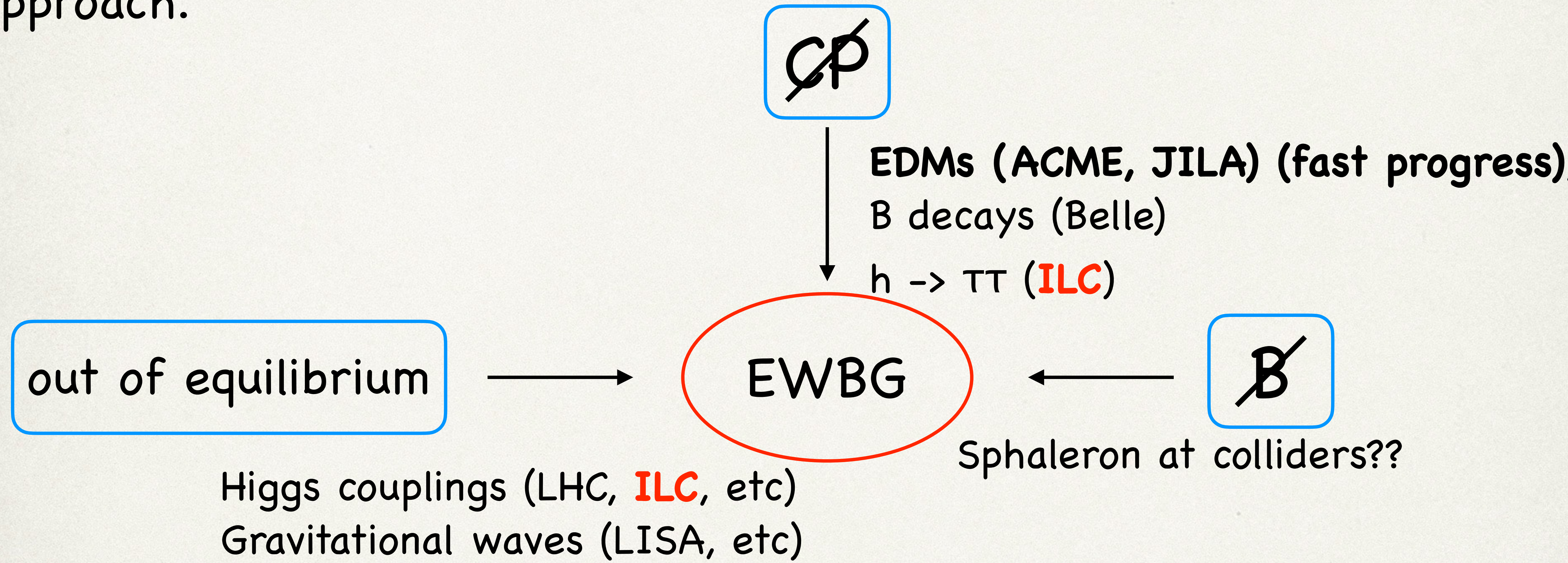
Eibun Senaha (Van Lang U, Vietnam)

October 21, 2024@ILC meeting

Ref. Chikako Idegawa (Sun Yat-Sen U, China), E.S., PLB848 (2024) 138332, (arXiv:2309.09430)

Main concern

Electroweak baryogenesis (EWBG) can be tested using a multifaceted approach.



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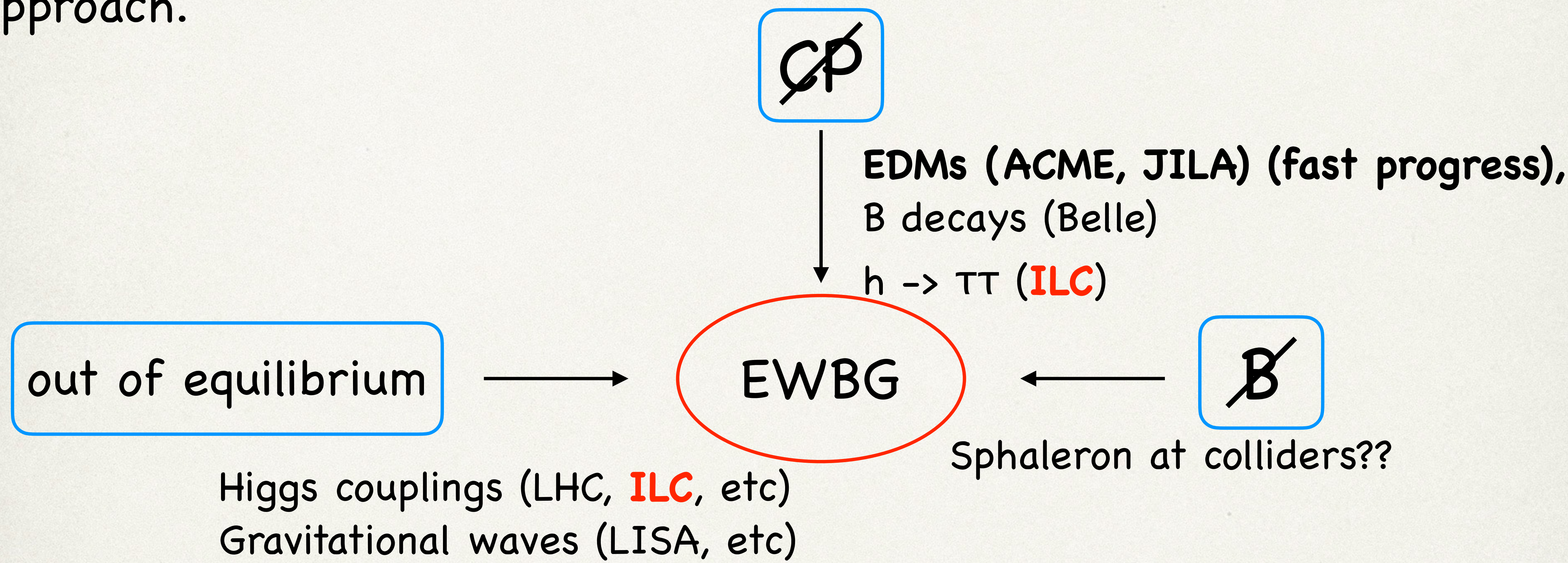

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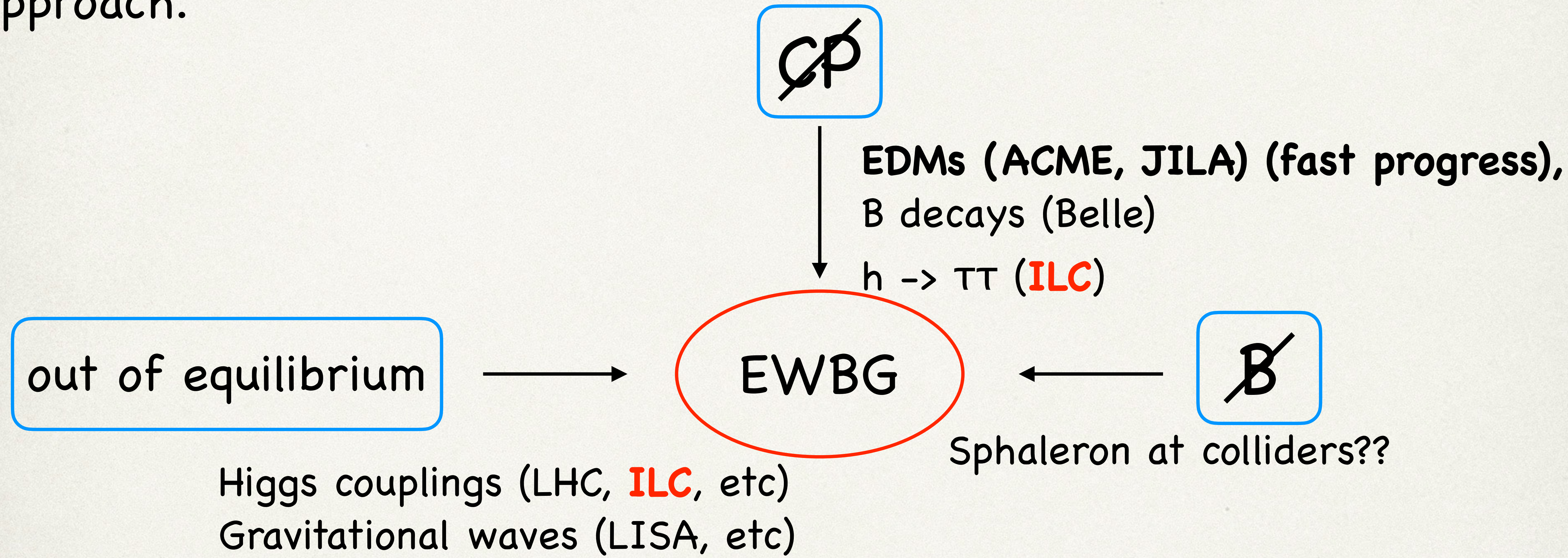

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Q. Is EWBG excluded by the latest electron EDM experiment?

A. No

Outline

- Review of Electroweak Baryogenesis (EWBG)
- EWBG in the complex singlet extension of the SM (cxSM) as a reference case

  C. Idegawa, E.S., PLB848 (2024) 138332, (arXiv:2309.09430)
- Theoretical challenges
- Summary

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)

Many baryogenesis scenarios

[Shaposhnikov, J.Phys.Conf.Ser.171:012005,2009.]

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

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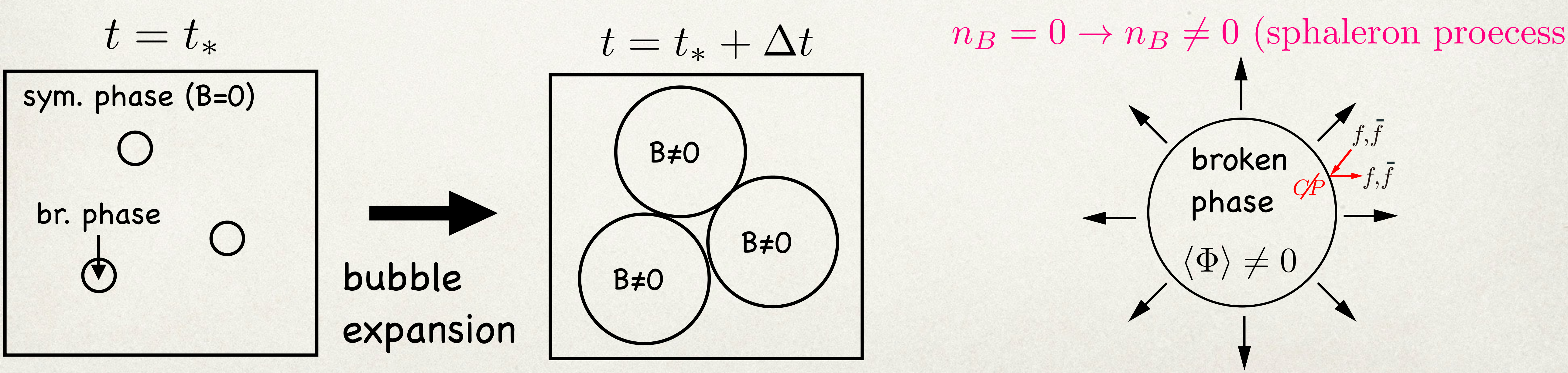
EW baryogenesis (EWBG)

Sakharov's conditions

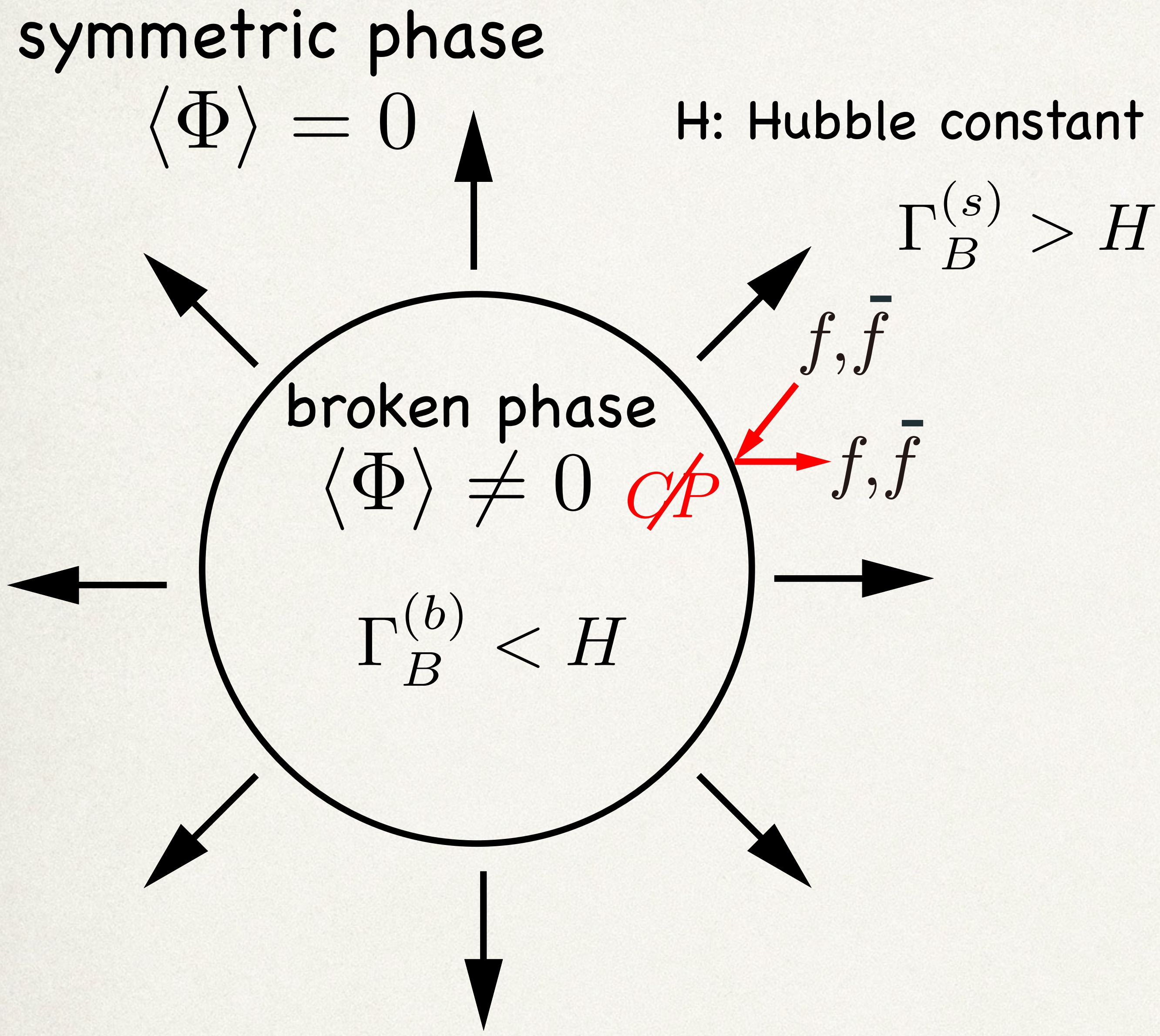
[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

- 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

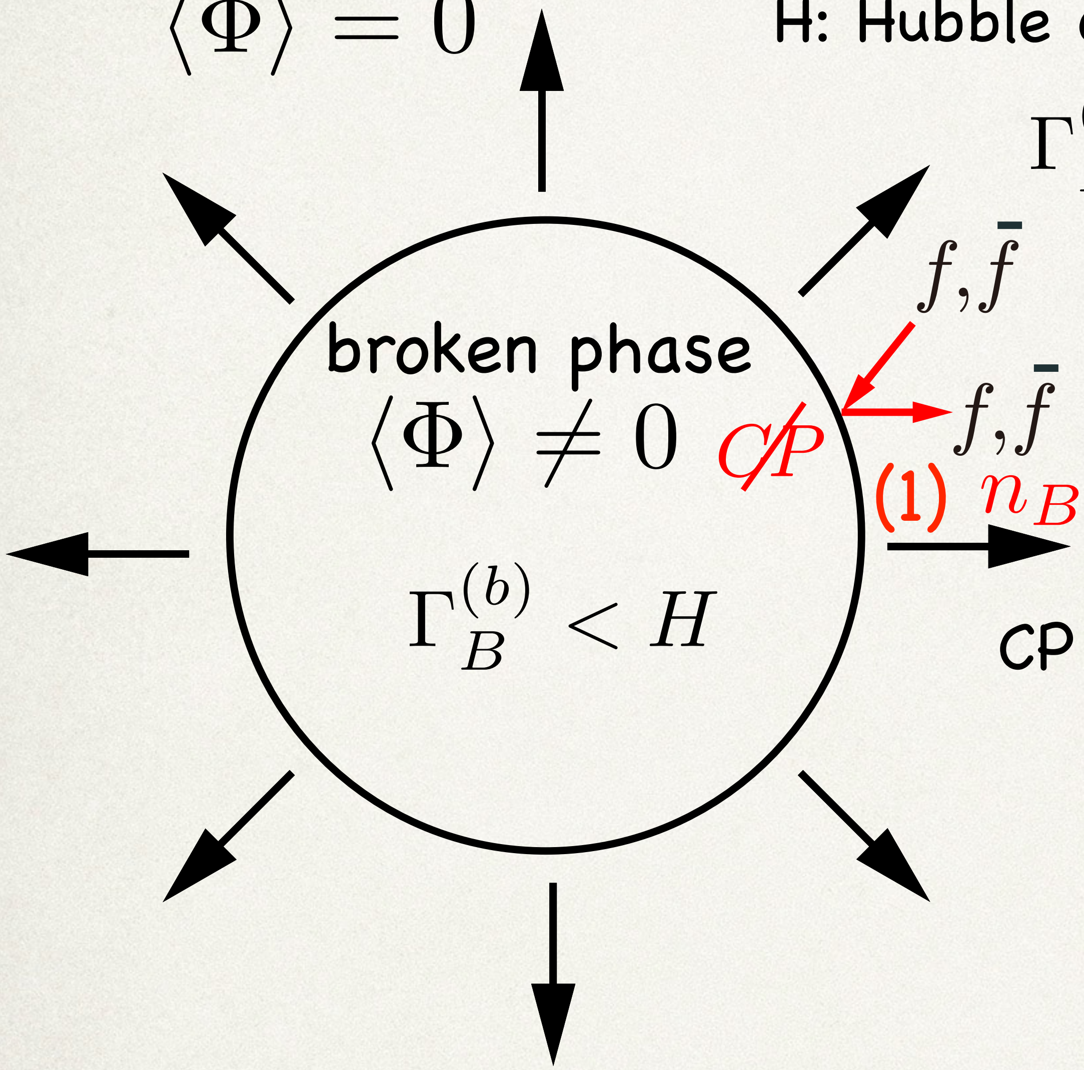


EWBG mechanism

symmetric phase
$\langle \Phi \rangle = 0$

H: Hubble constant

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



(1) $n_B = n_B^L + n_B^R = 0$

$n_B^L \neq 0$, $n_B^R \neq 0$

CP asymmetric but no B asymmetric

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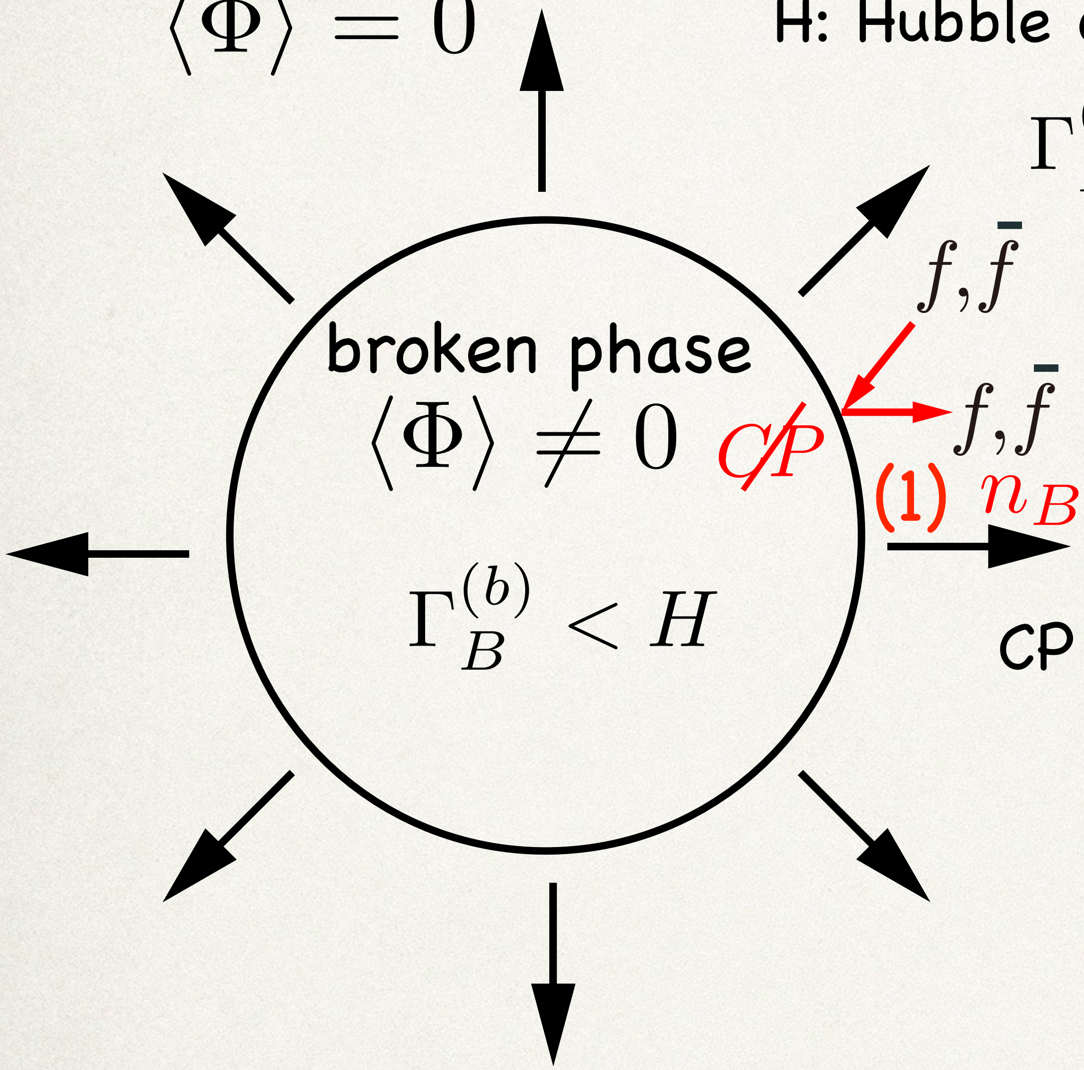

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changed by sphaleron. $t_{\rm wall} < t_{\rm sph}$

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

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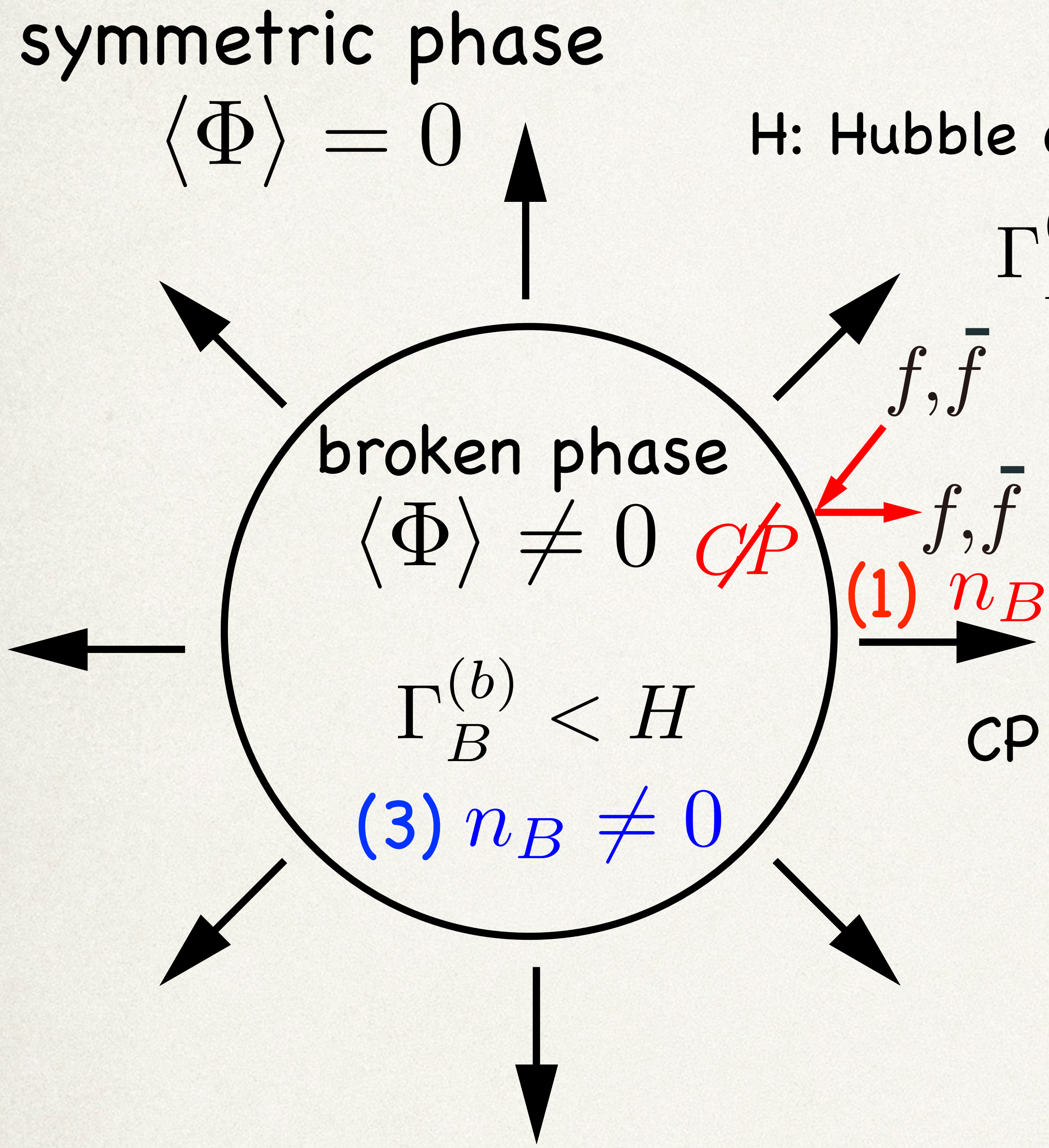

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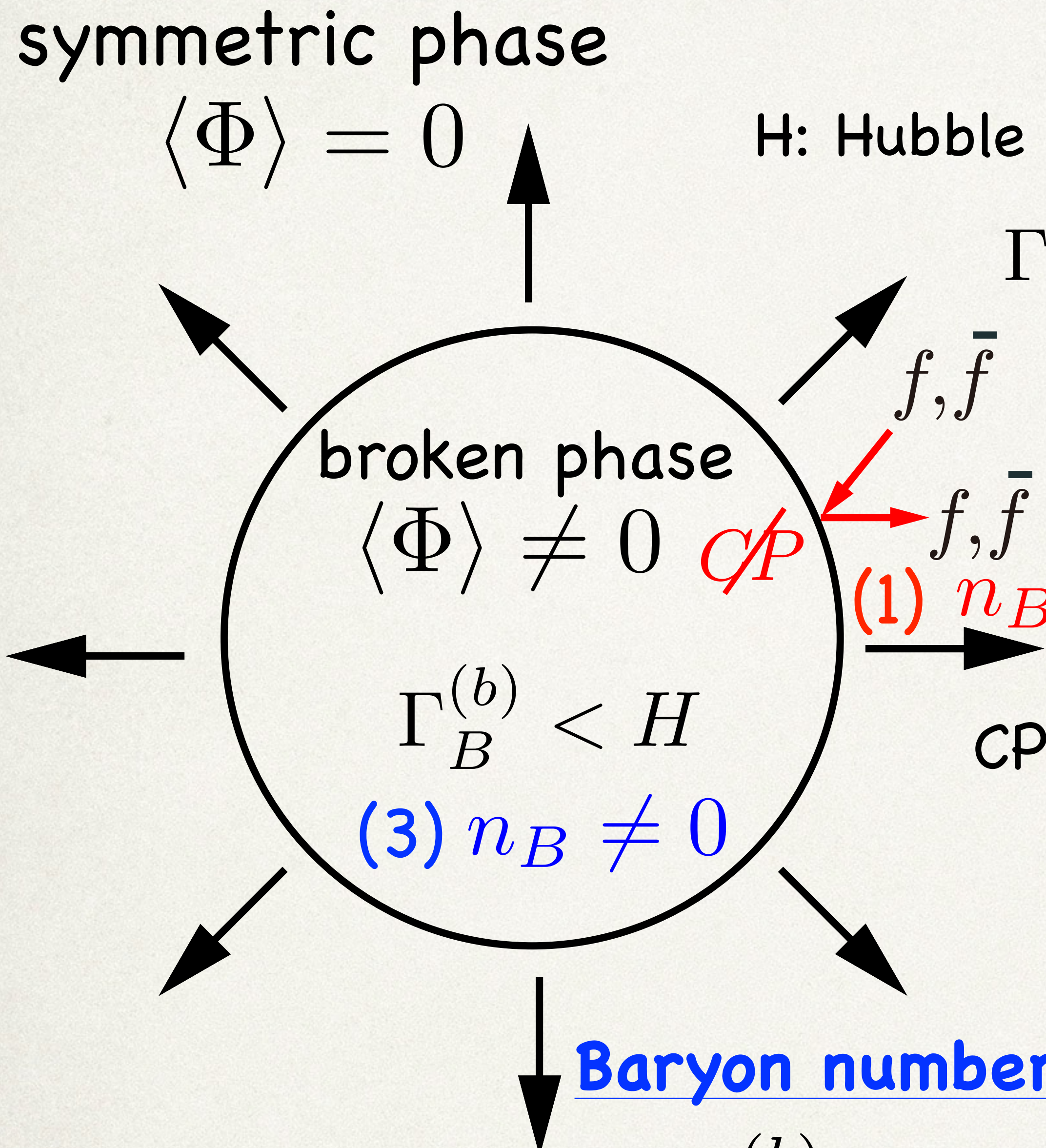

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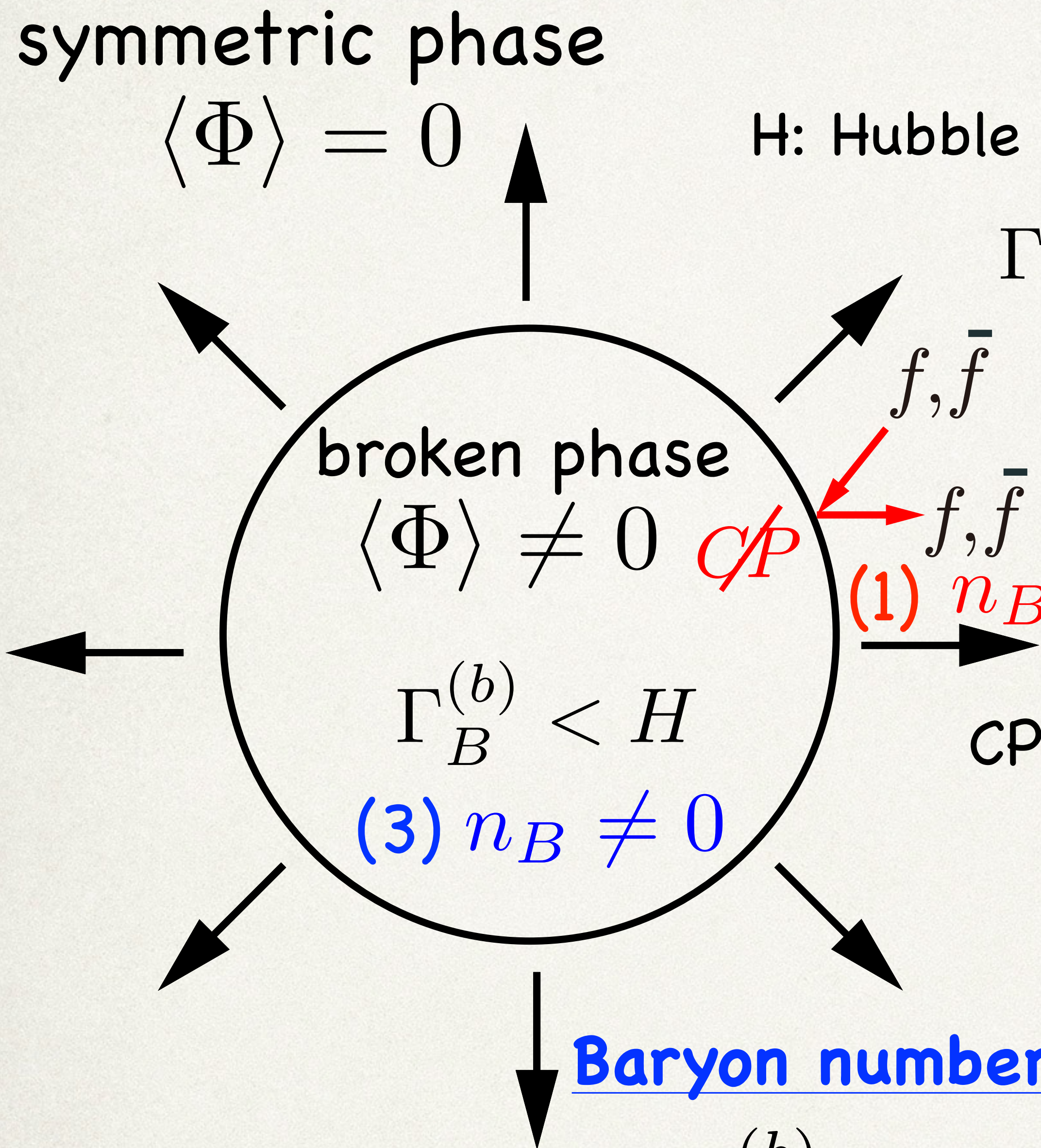
<u>Baryon number preservation condition</u>

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

EWBG mechanism



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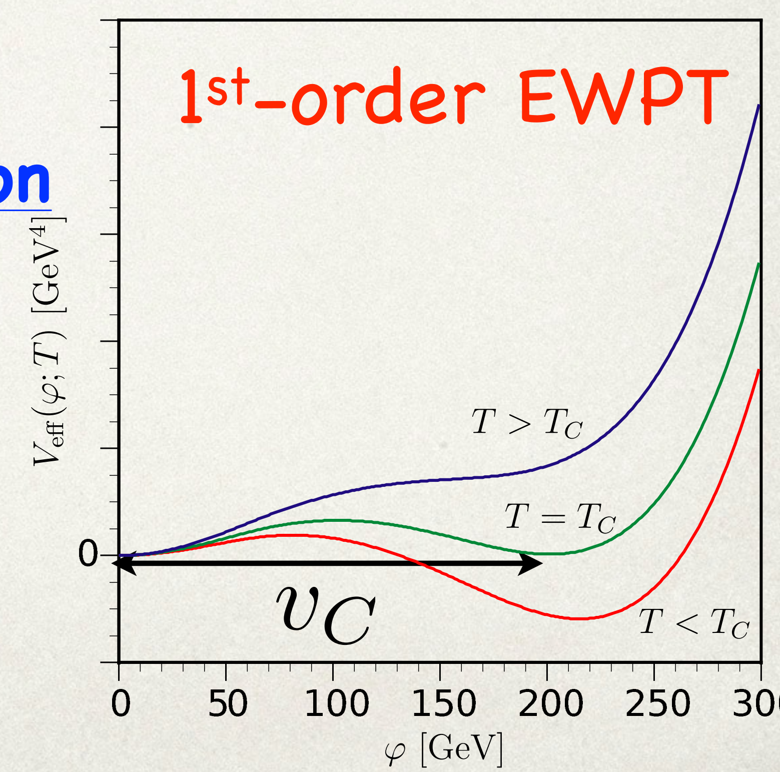
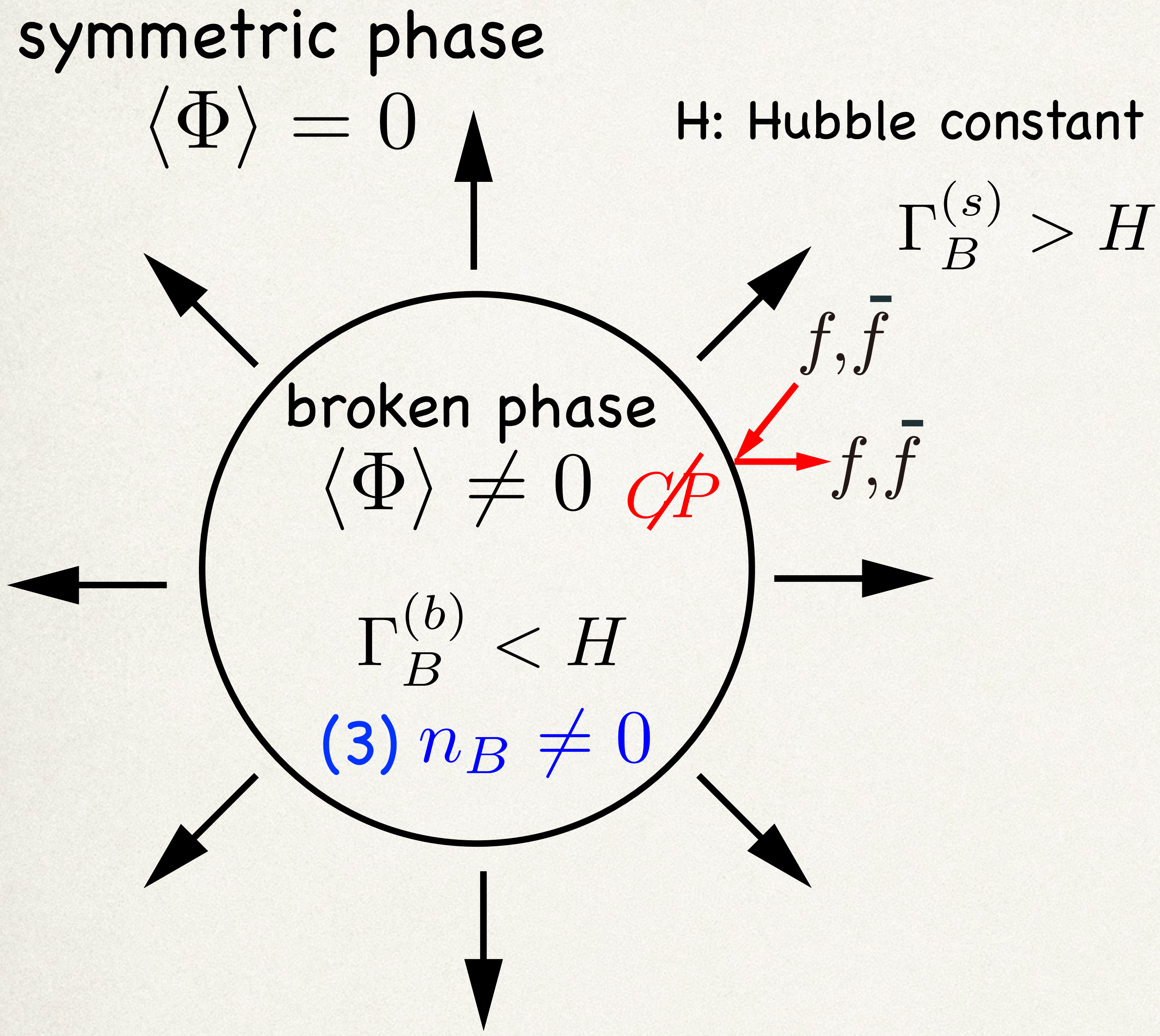
To satisfy Γ_B<H, EWPT has to be strong 1st-order,

$v_C/T_C \gtrsim 1$

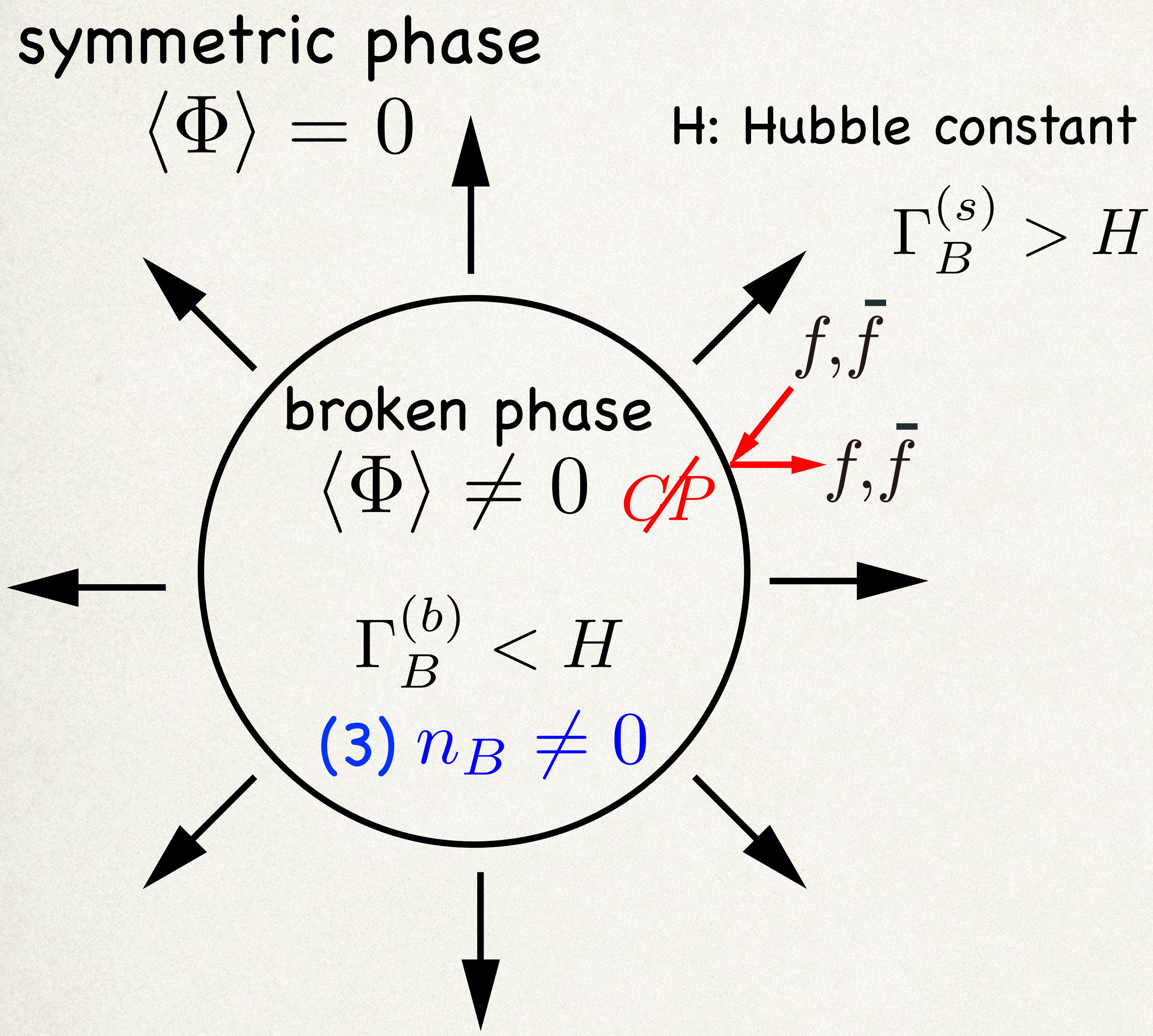


EWBG mechanism



EWBG mechanism

How do we test this scenario?



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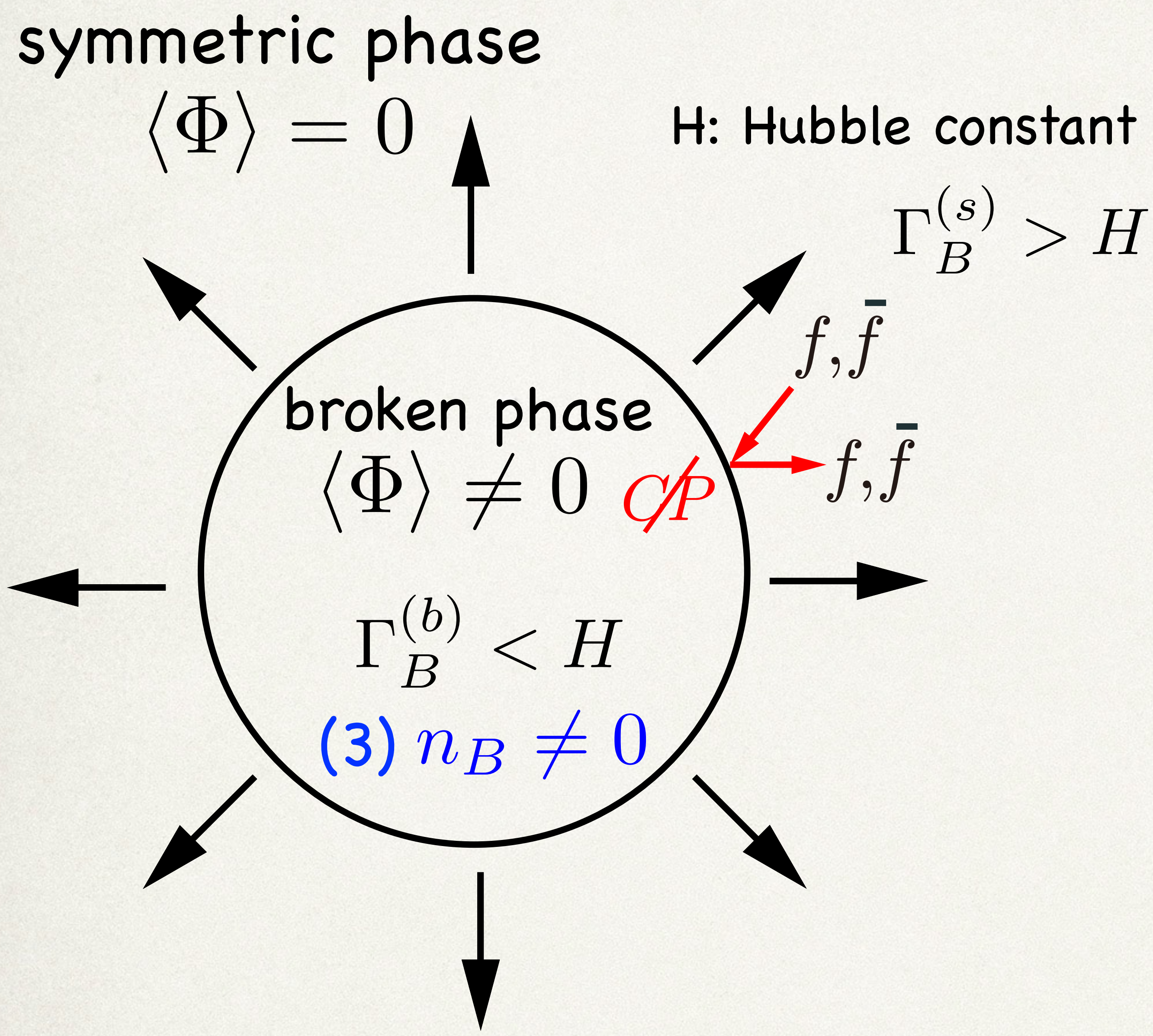

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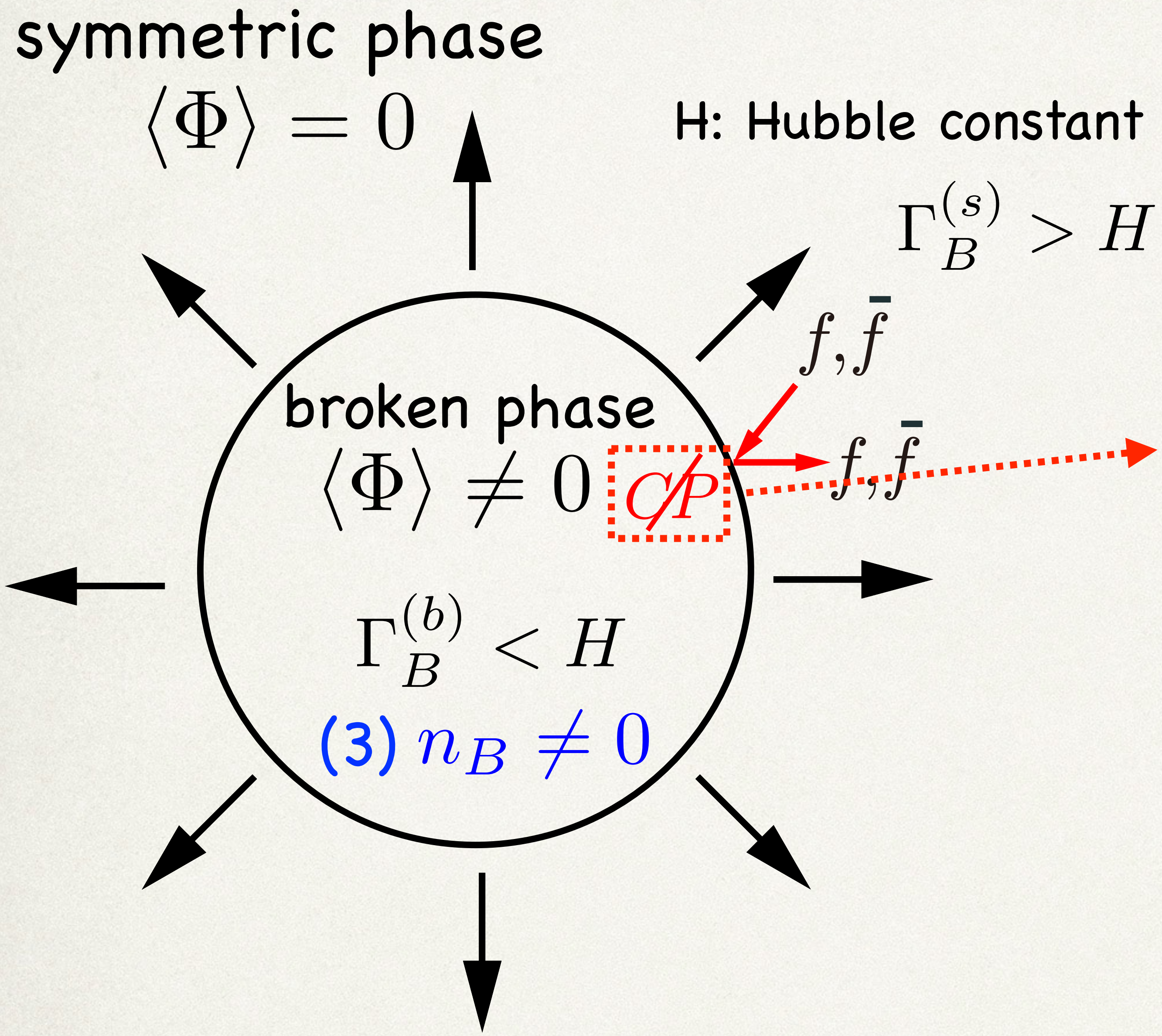

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probe by CPV physics

EDMs, $h \to ff$, $b \to s\gamma$, etc.

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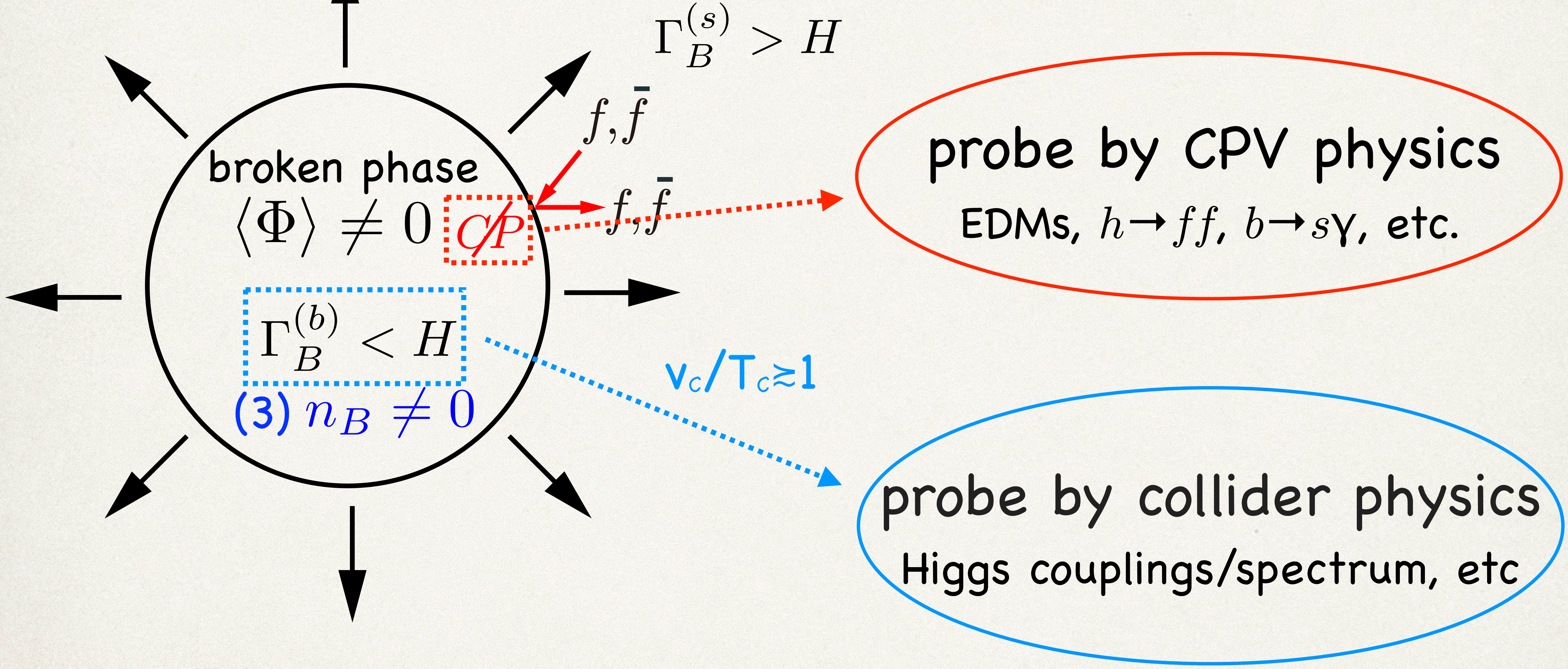

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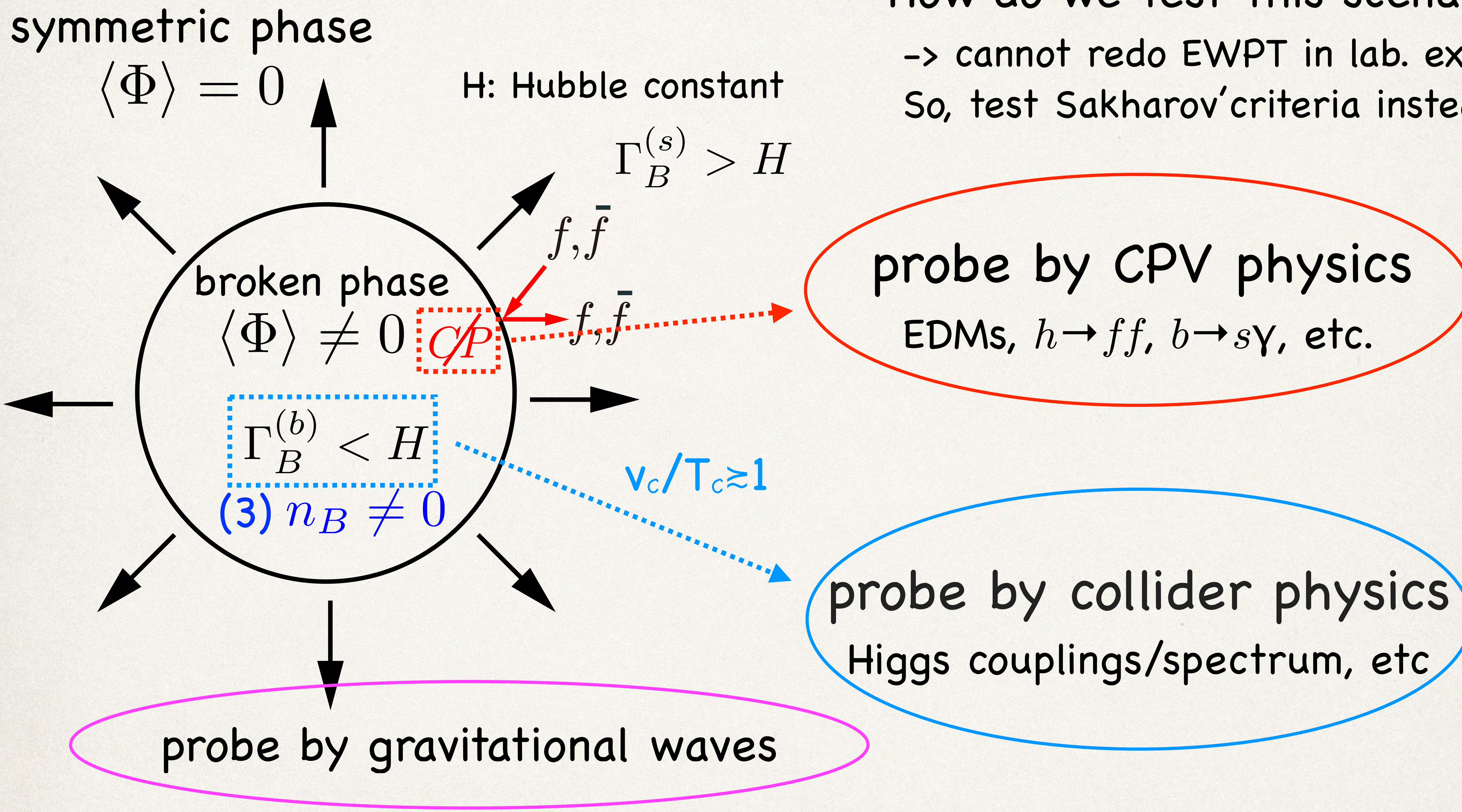

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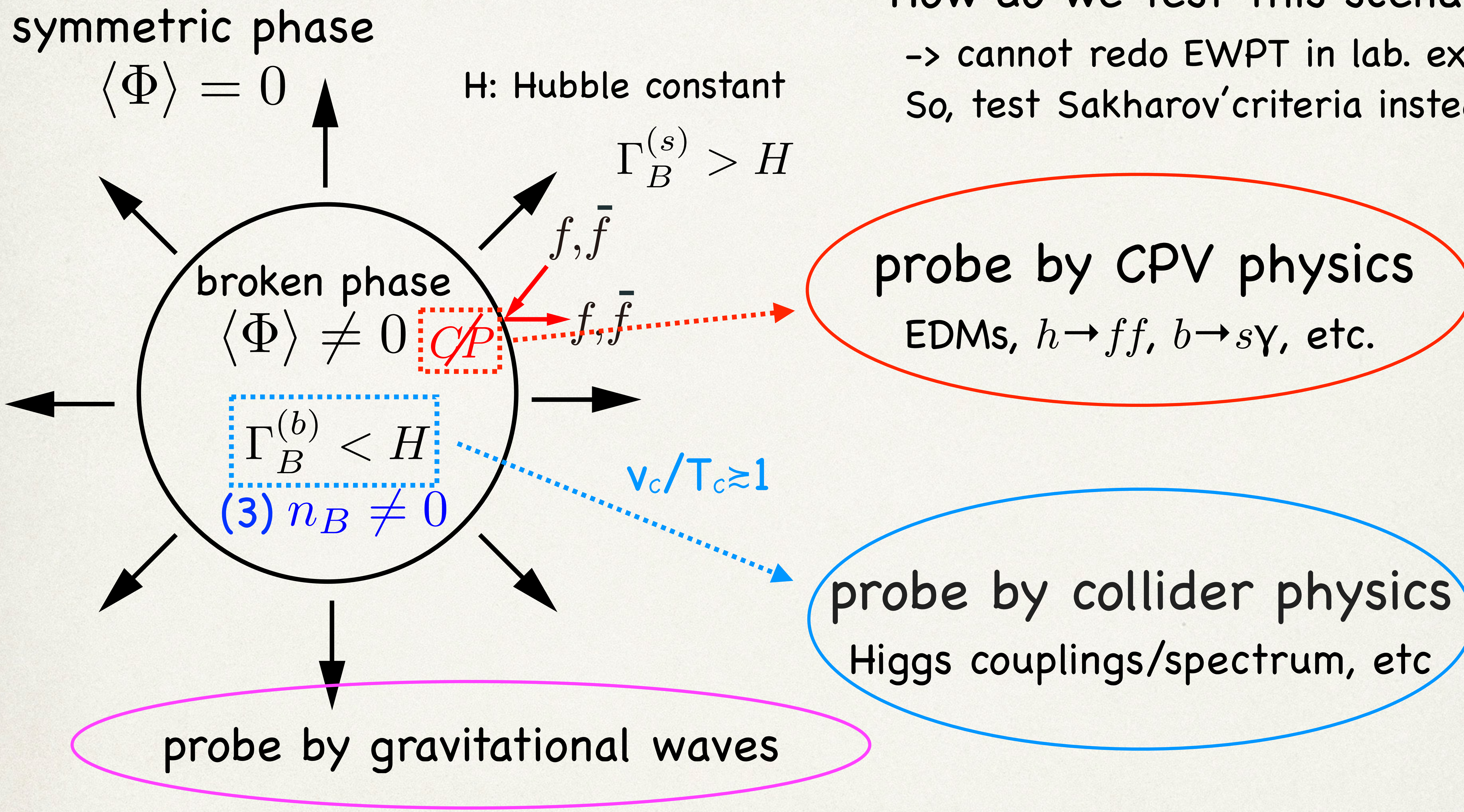

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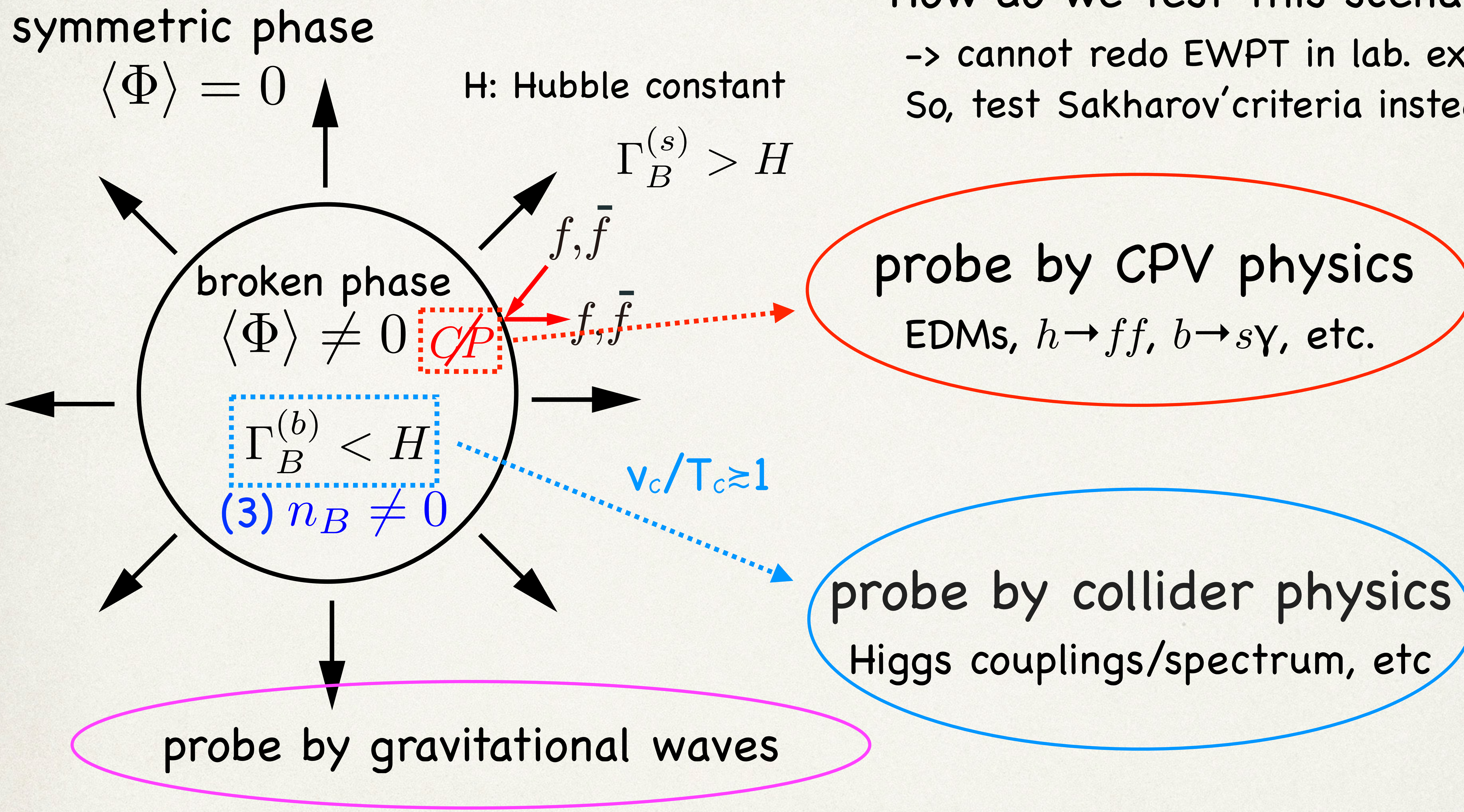

In SM

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

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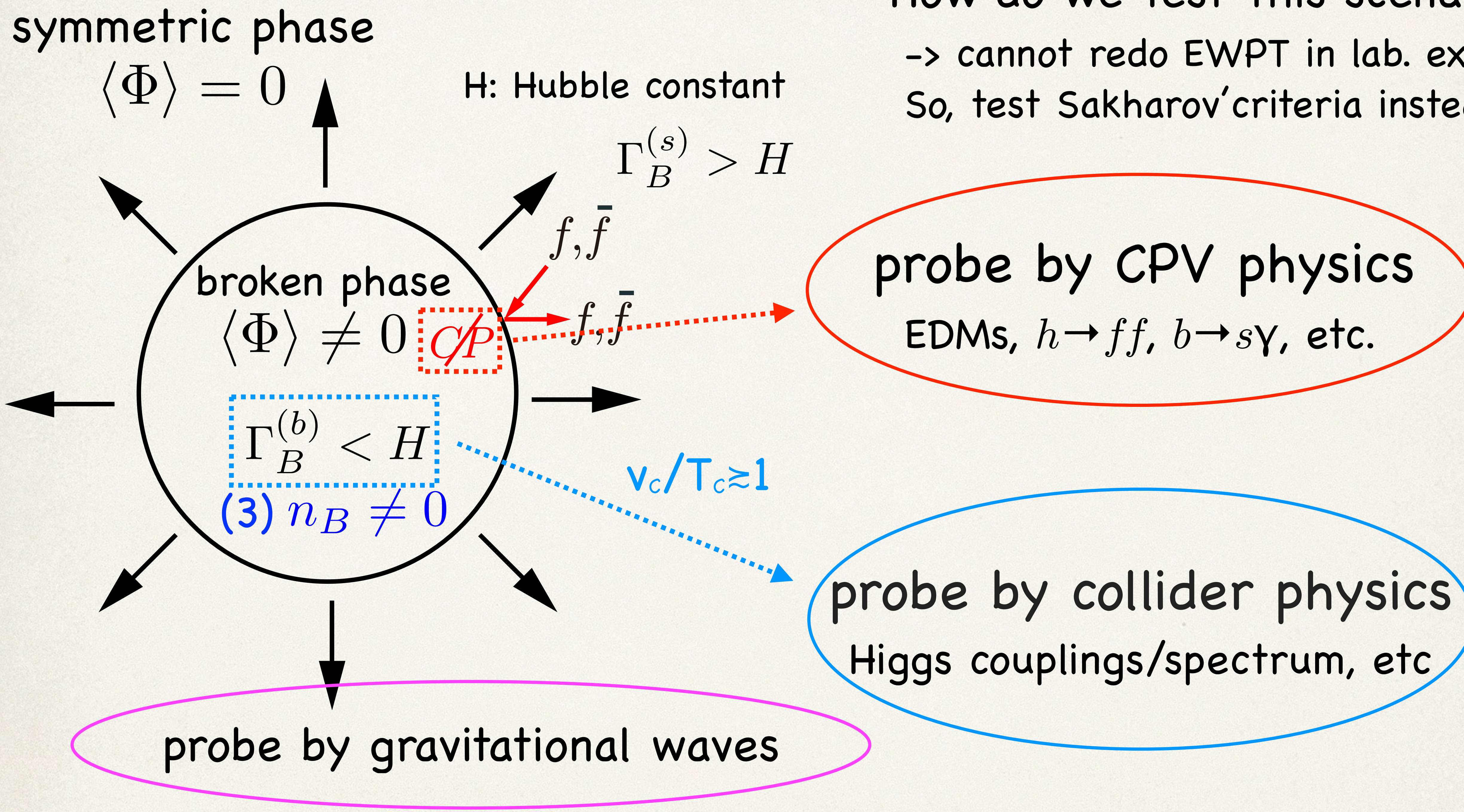

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CPV in CKM is not sufficient.

New particles we need

Without any detailed calculation, we know that

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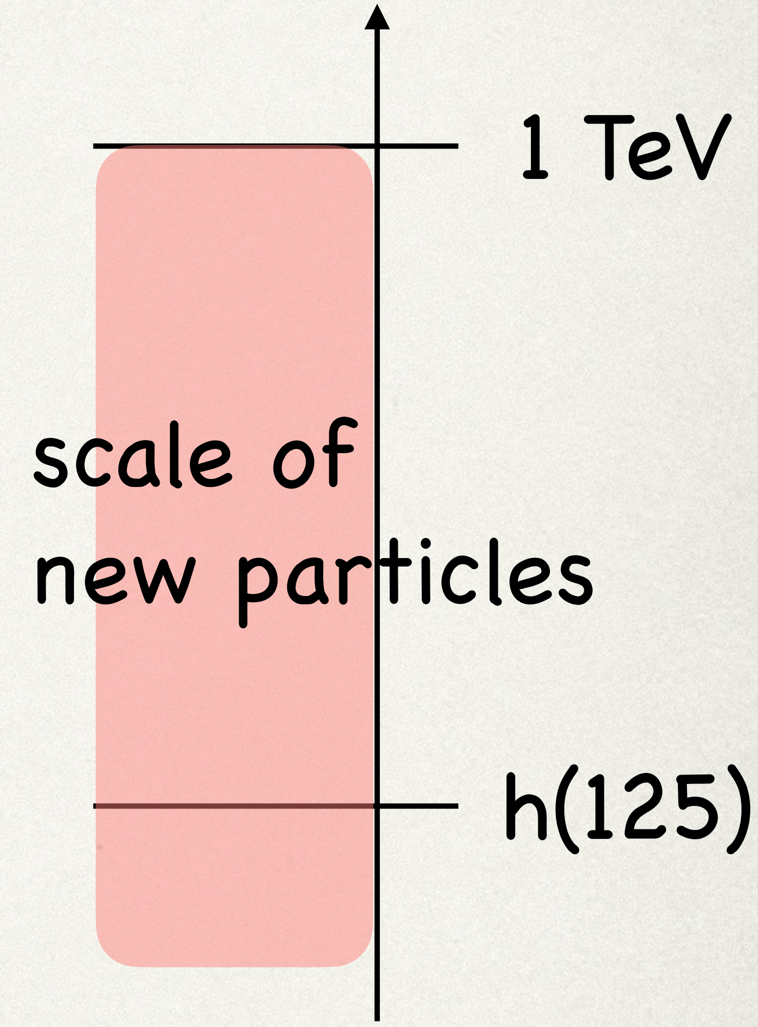
(1) Mass scale

New particles must not be too heavy compared to EWPT temperature O(100) GeV.

Otherwise, new particles would receive strong Boltzmann suppression ($e^{-M/T}$).



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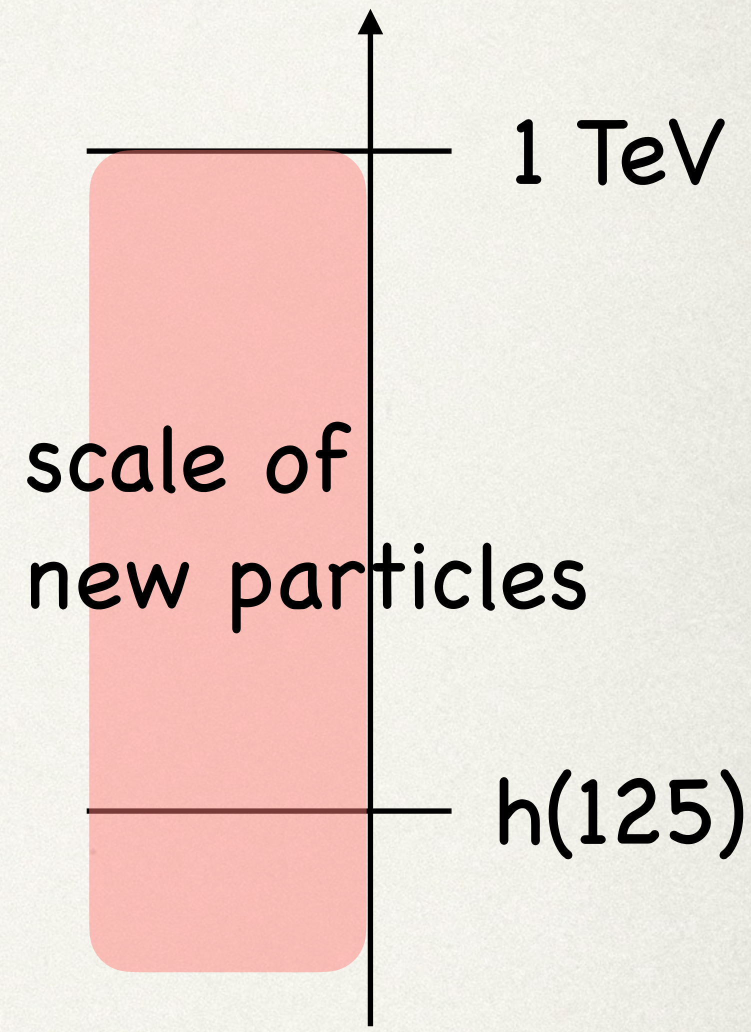
Otherwise, Higgs potential would hardly change, so EWPT cannot be strong 1st order.



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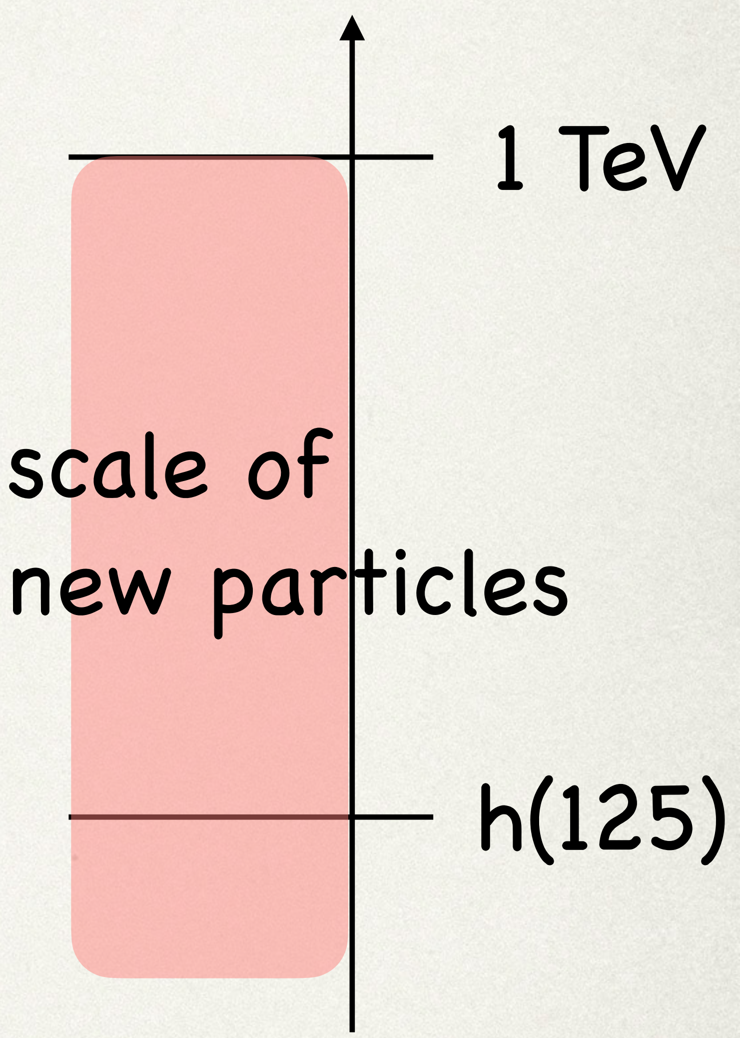

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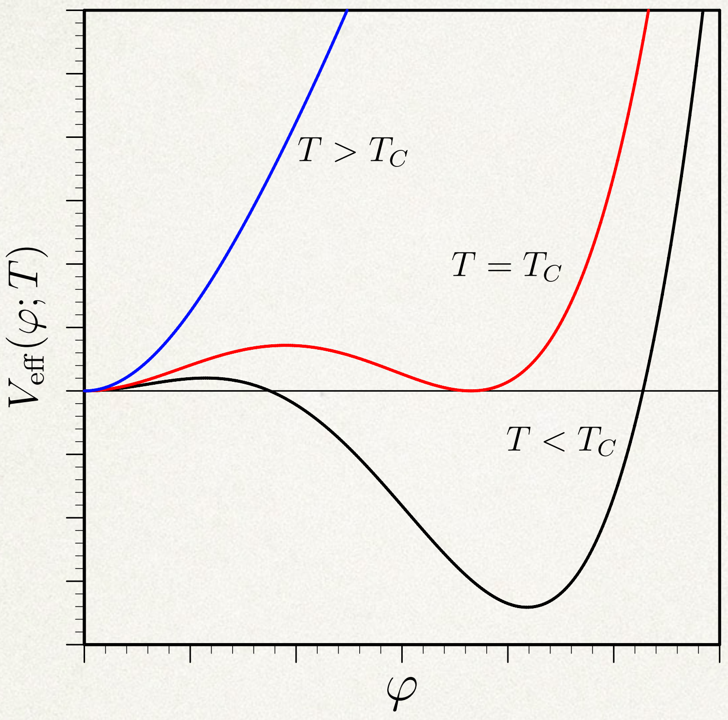
* Effective Field Theory (EFT) framework cannot fully handle the EWBG problem.
-> analysis should be done on a case-by-case basis.

Realization of strong 1st-order EWPT

1st order PT = discontinuity in the 1st-derivative of the free energy (V_{eff}).



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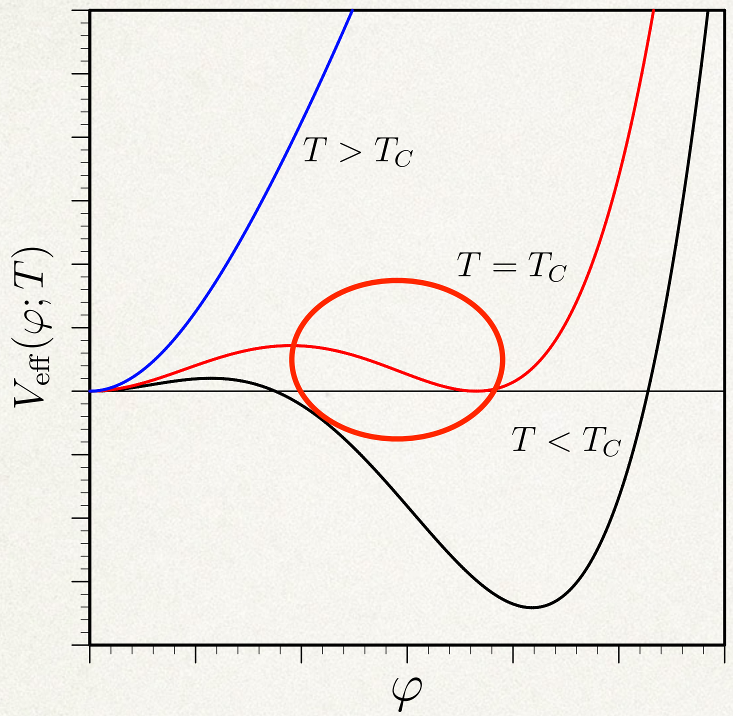

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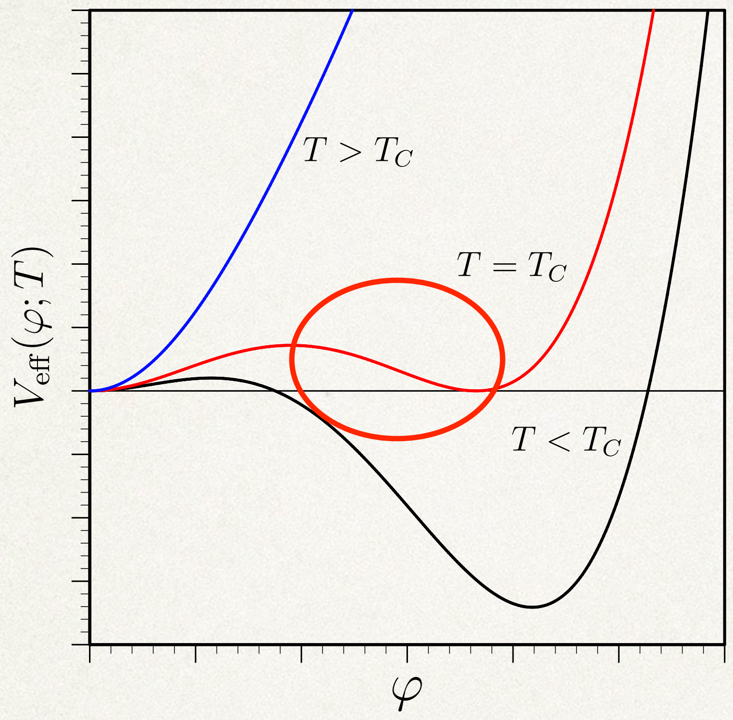

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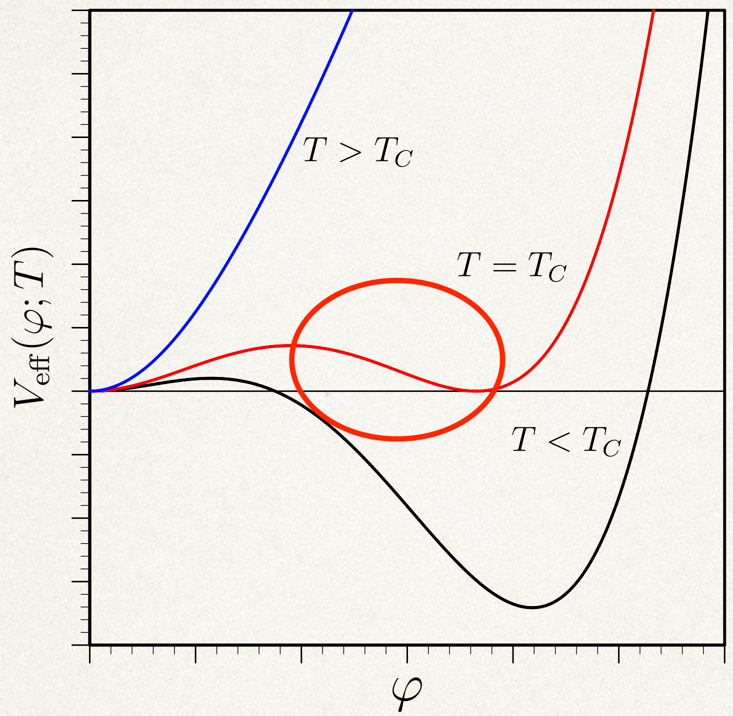

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SM + singlet scalar, etc.

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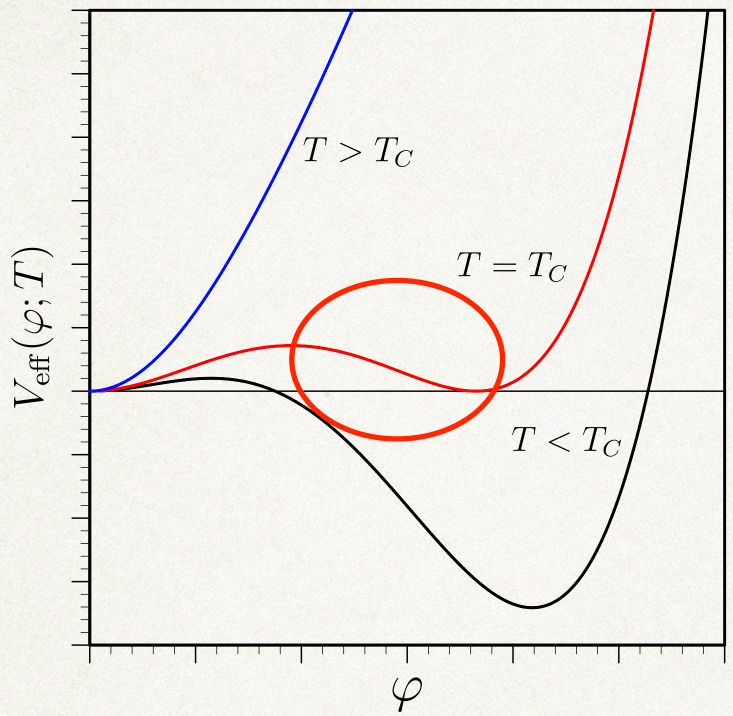

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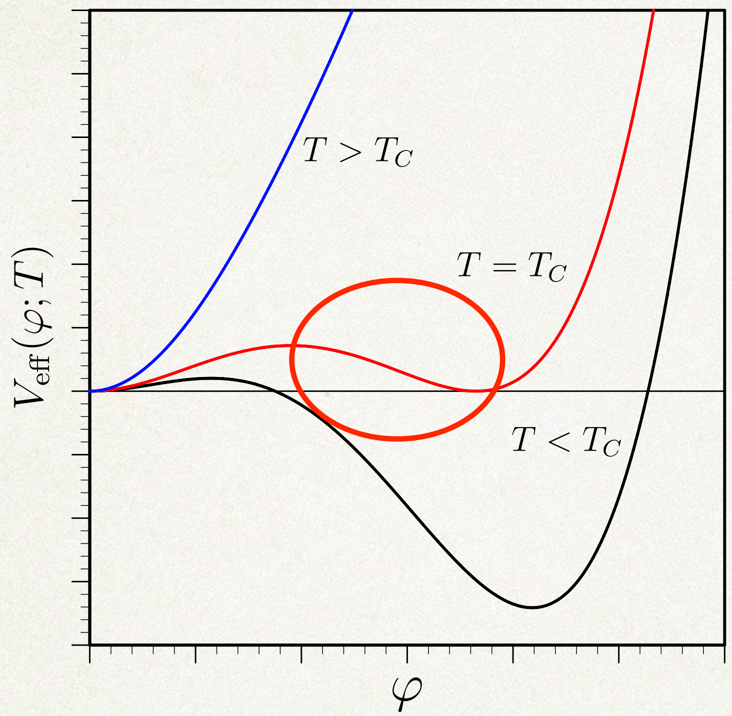

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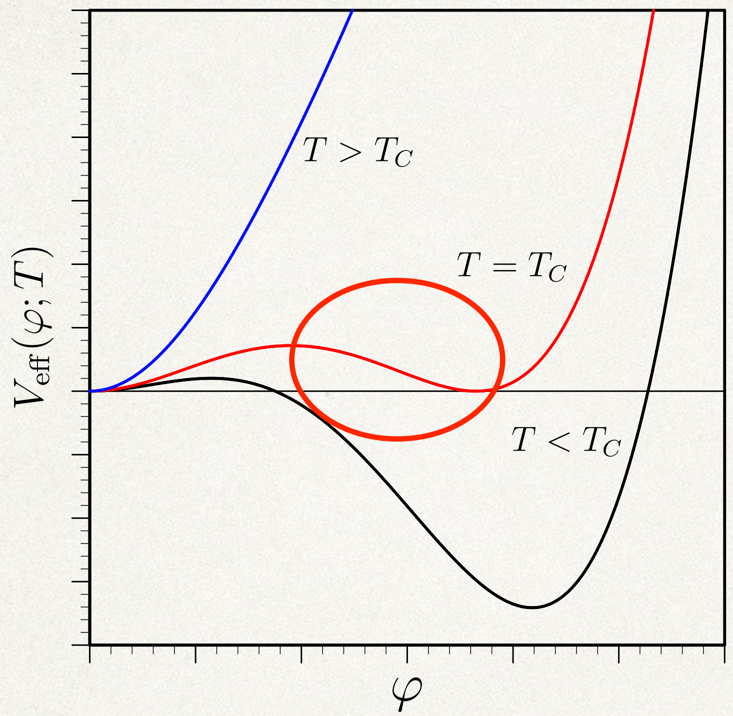

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New physics we need:

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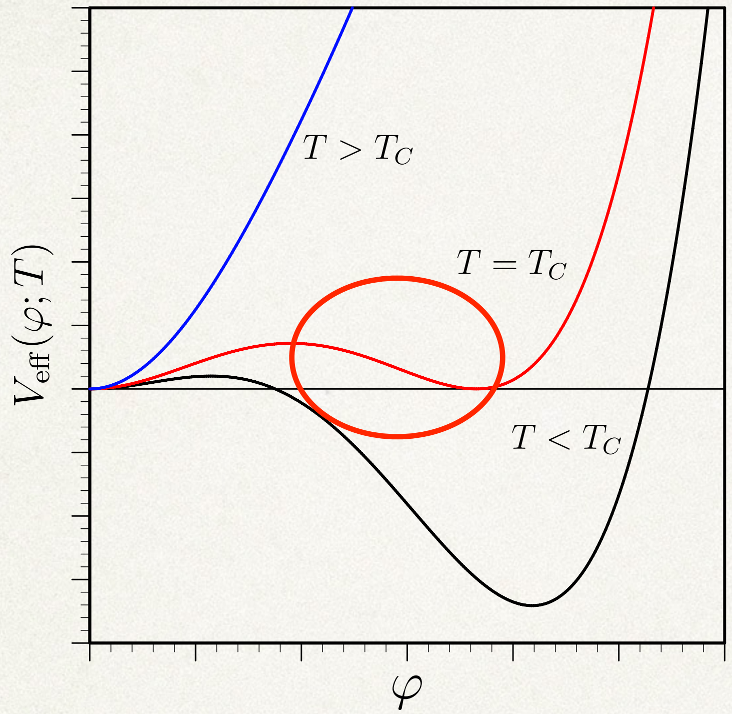

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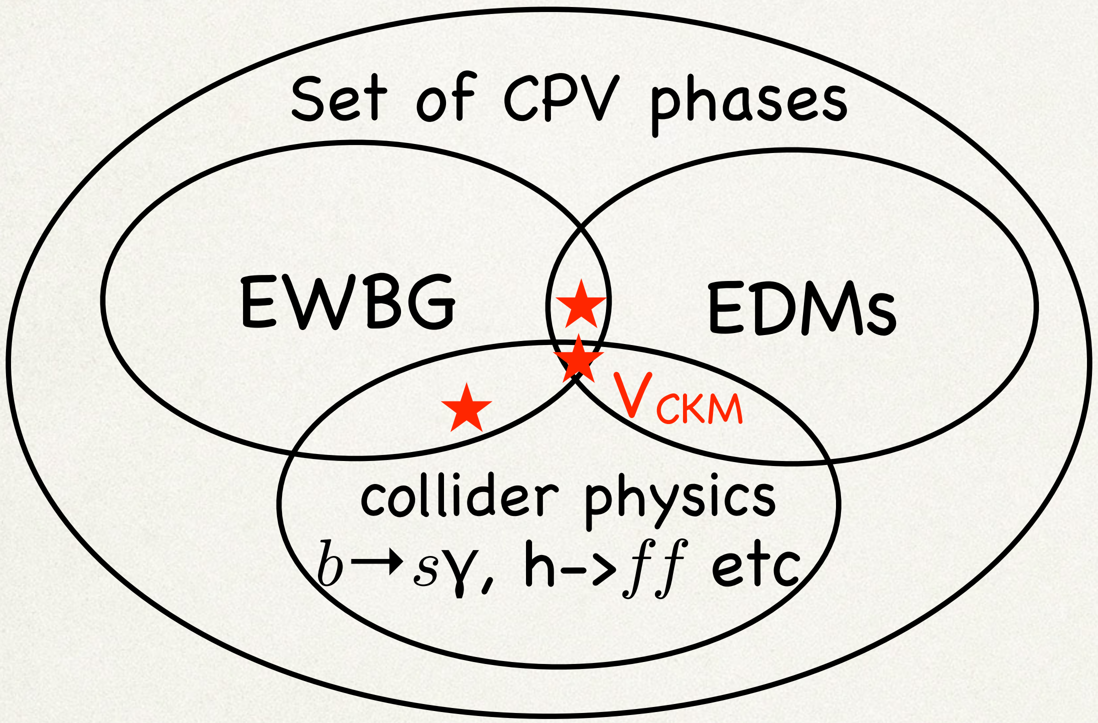
2HDM, etc

New physics we need:

new scalars or new gauge bosons that couple to h(125)

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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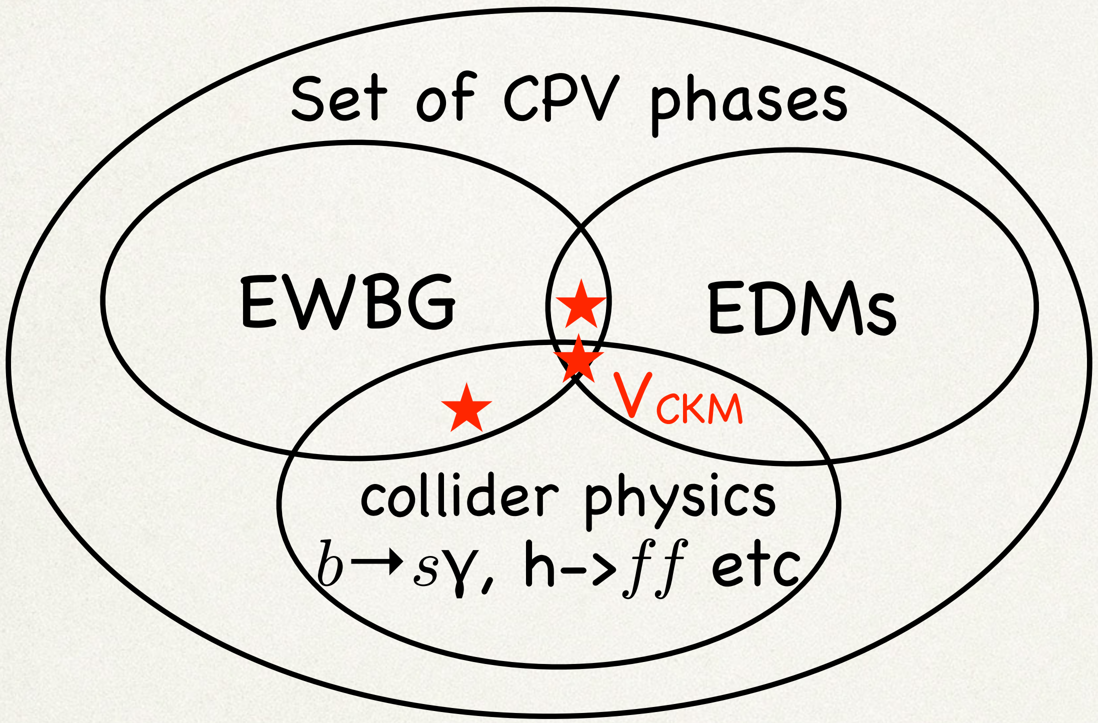

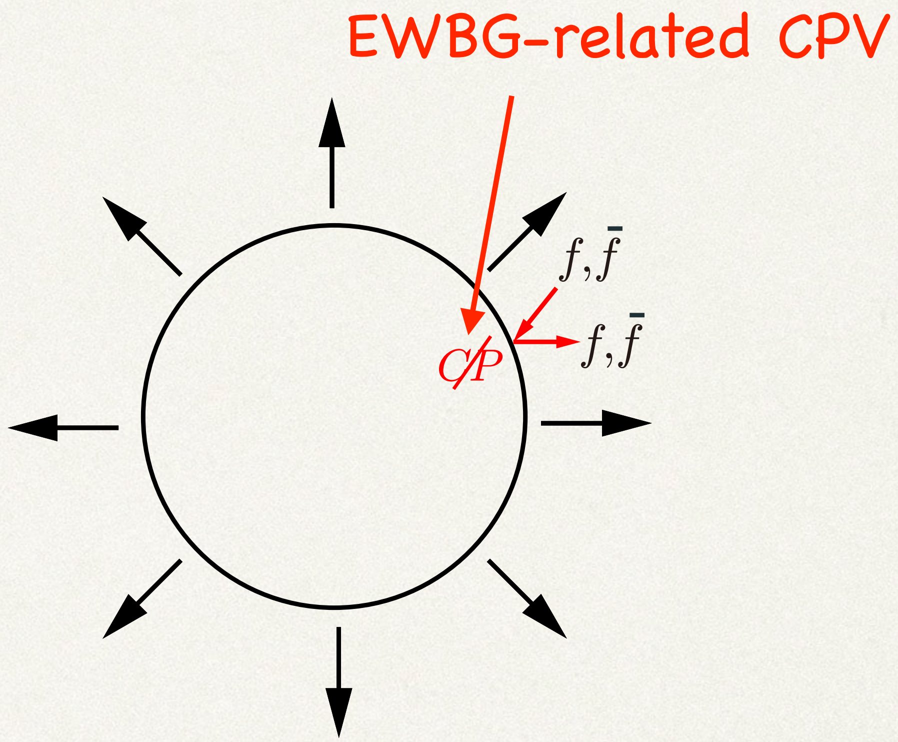

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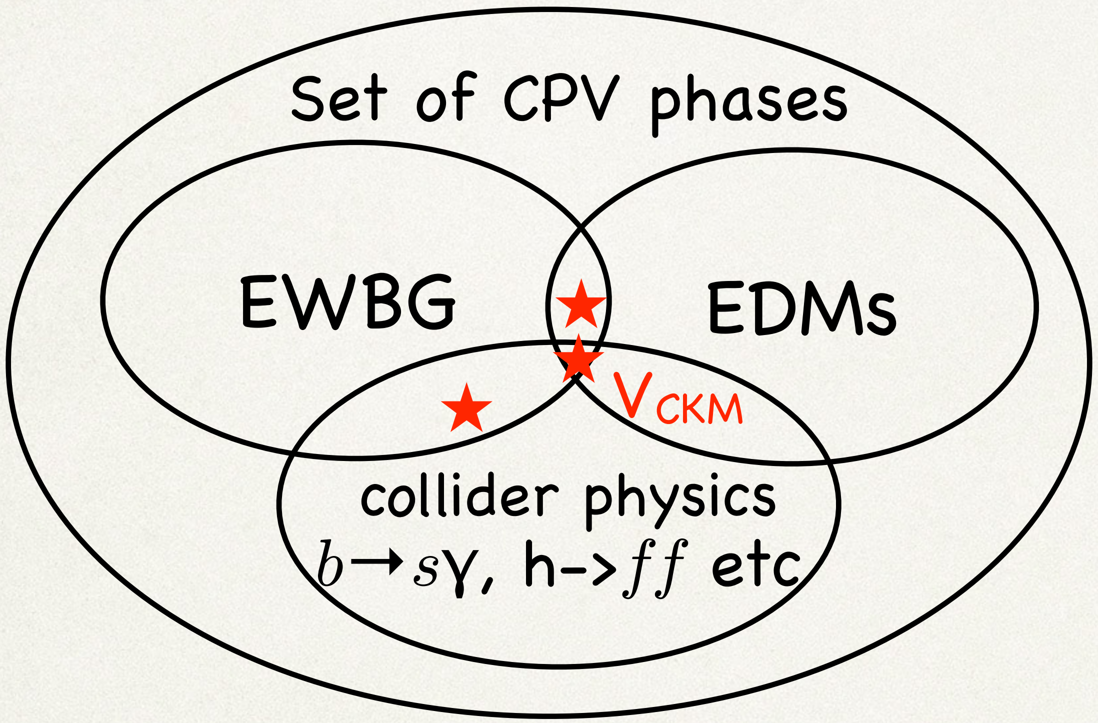

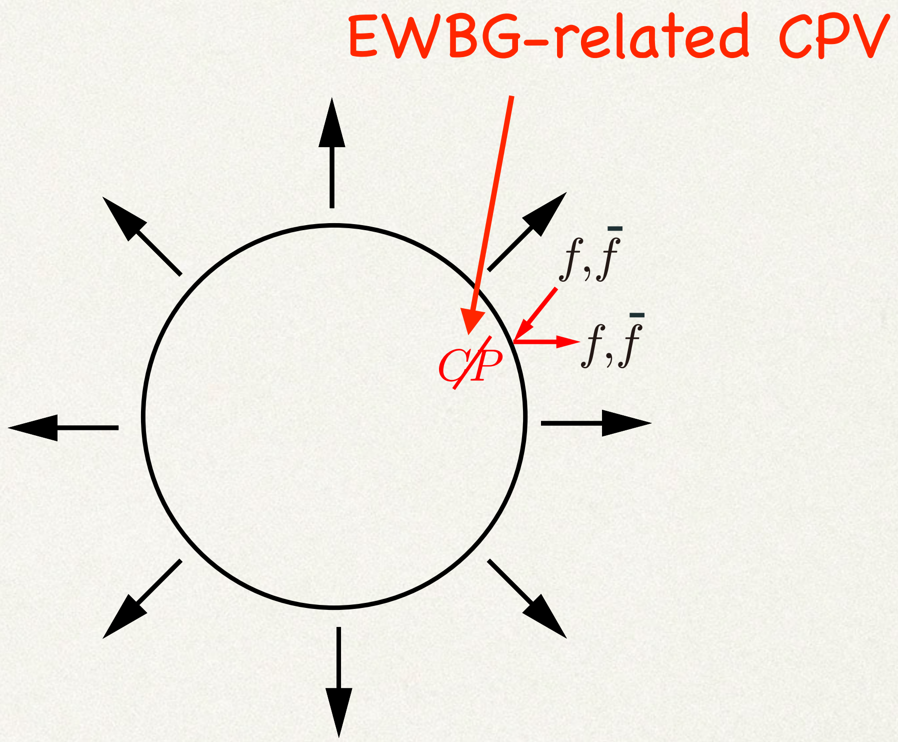

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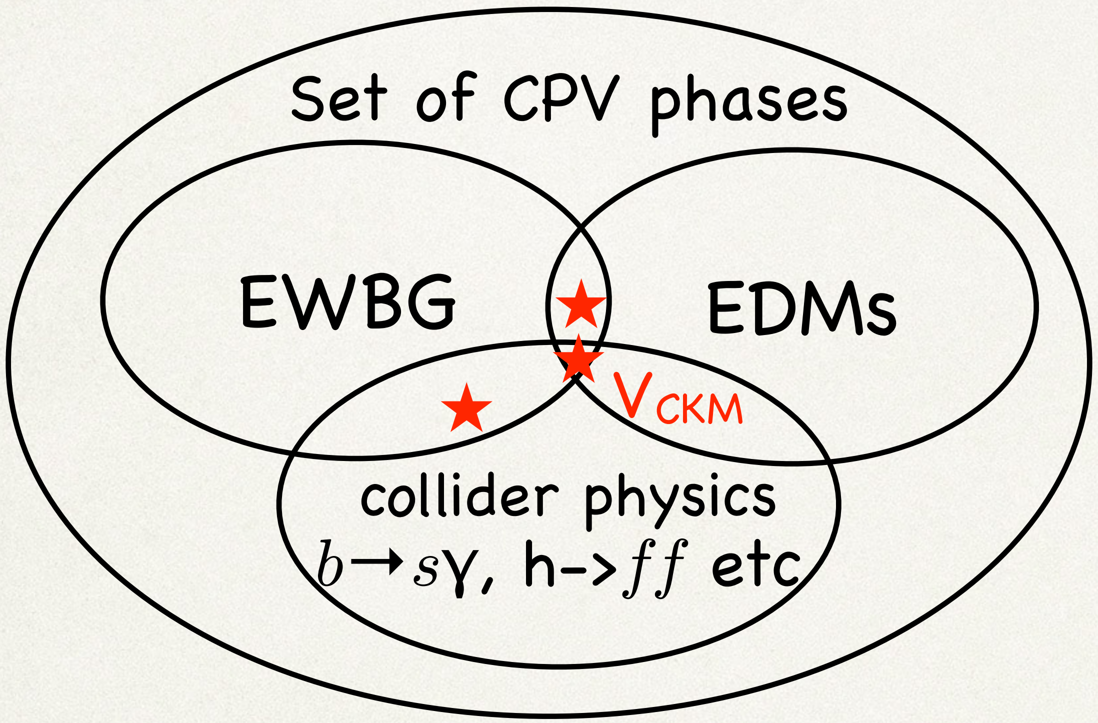

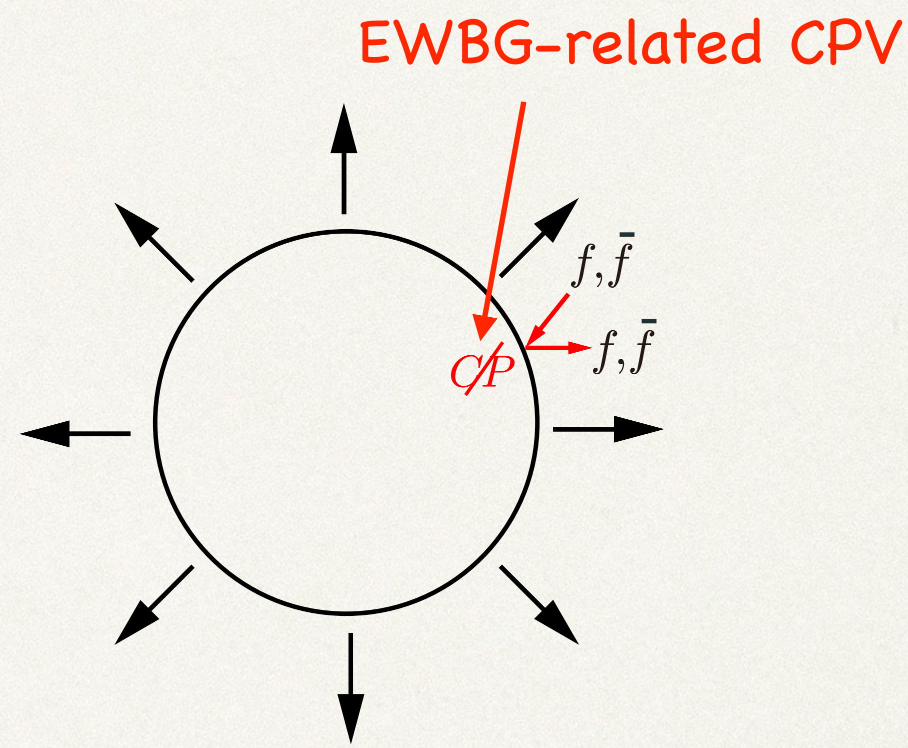

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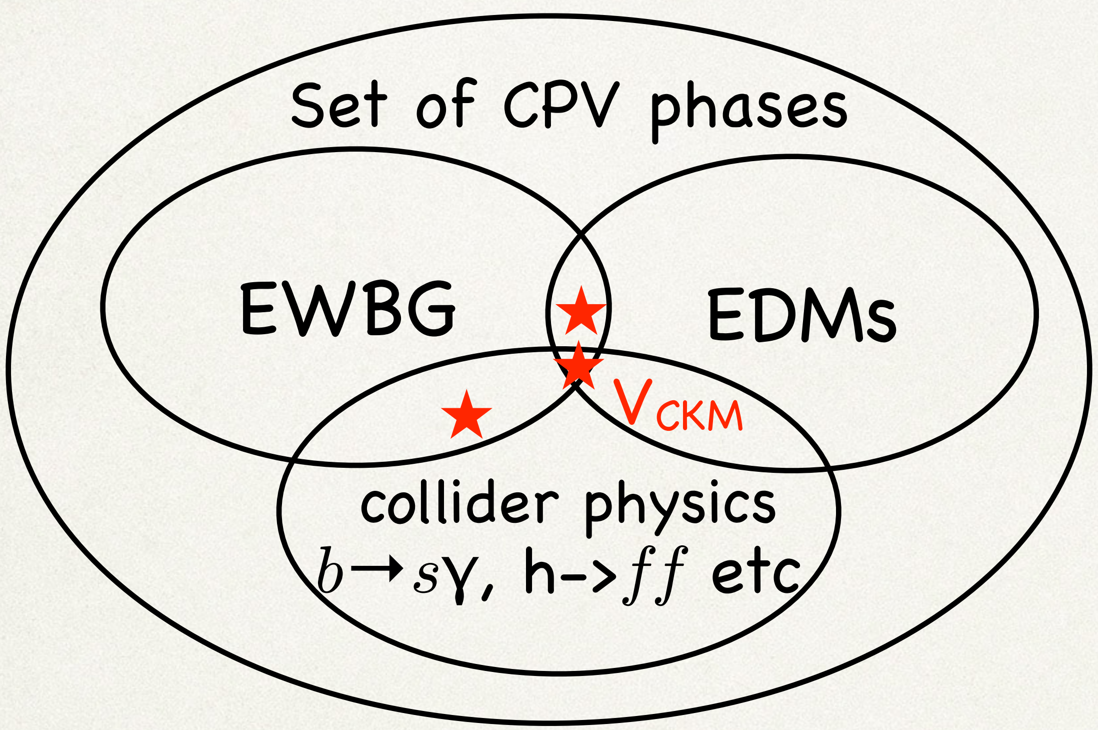

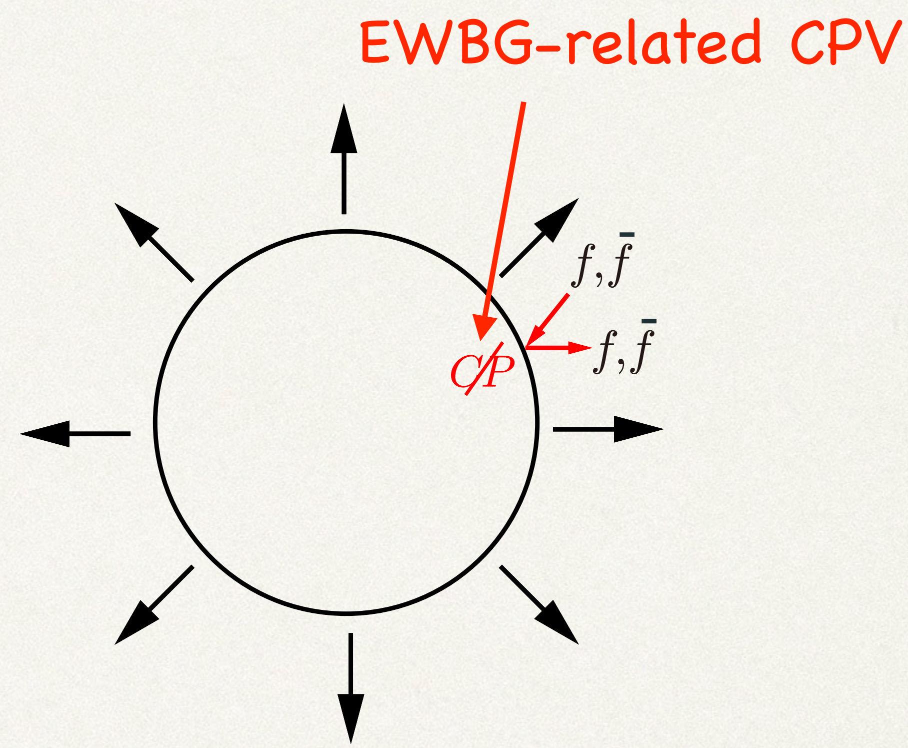

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EWBG after LHC-Run2

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Higgs sector = SM-like

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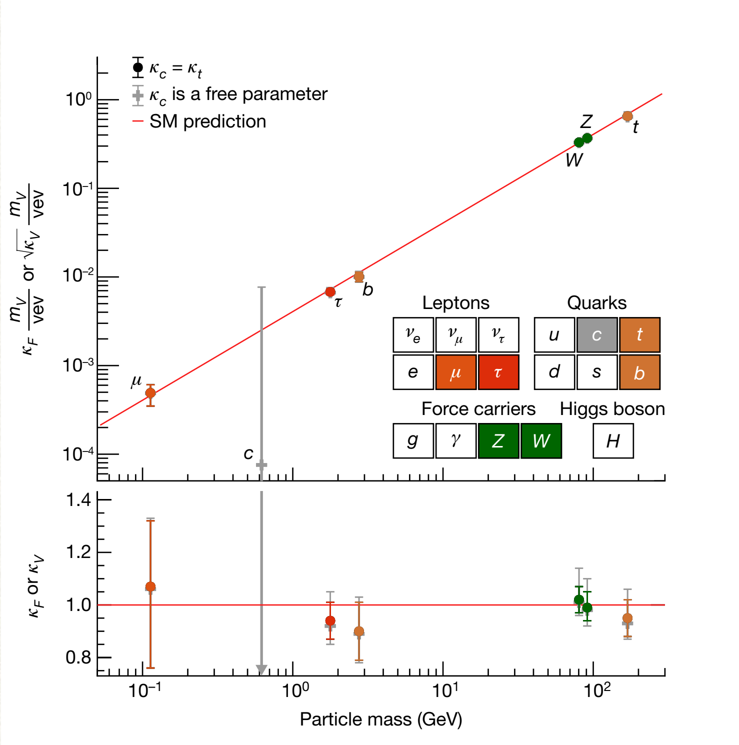
What is SM-like Higgs sector compatible with EWBG?

Nature 607, 52-59 (2022)



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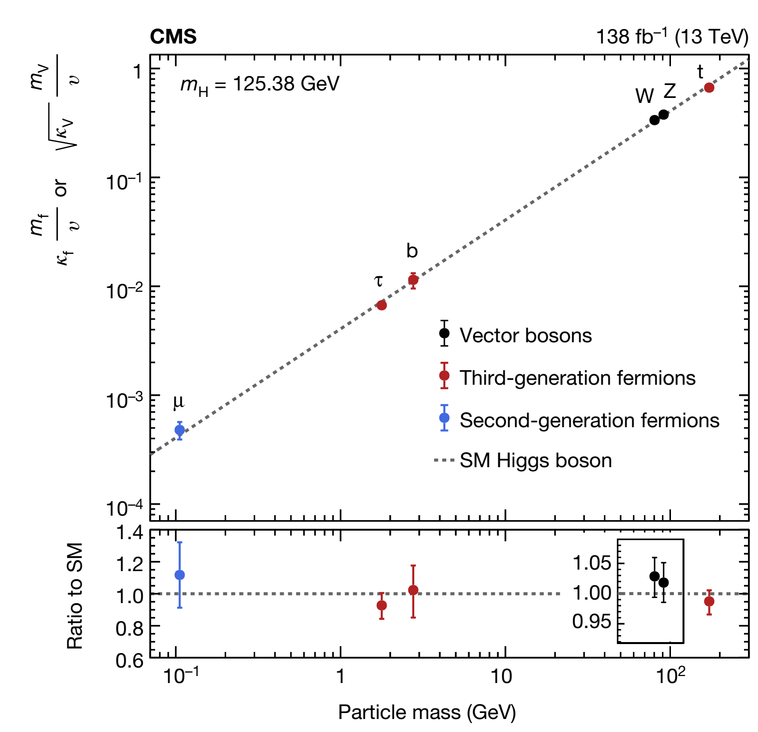

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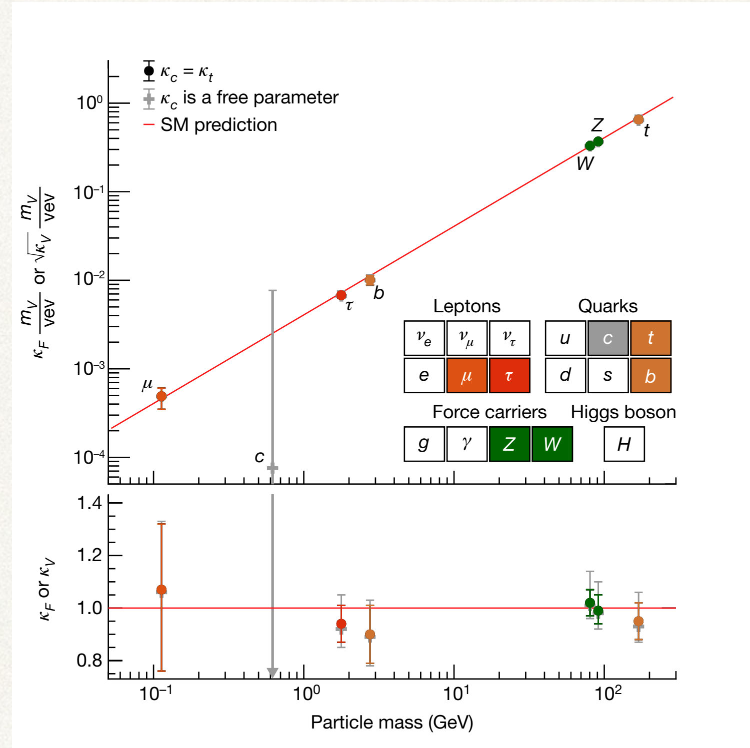

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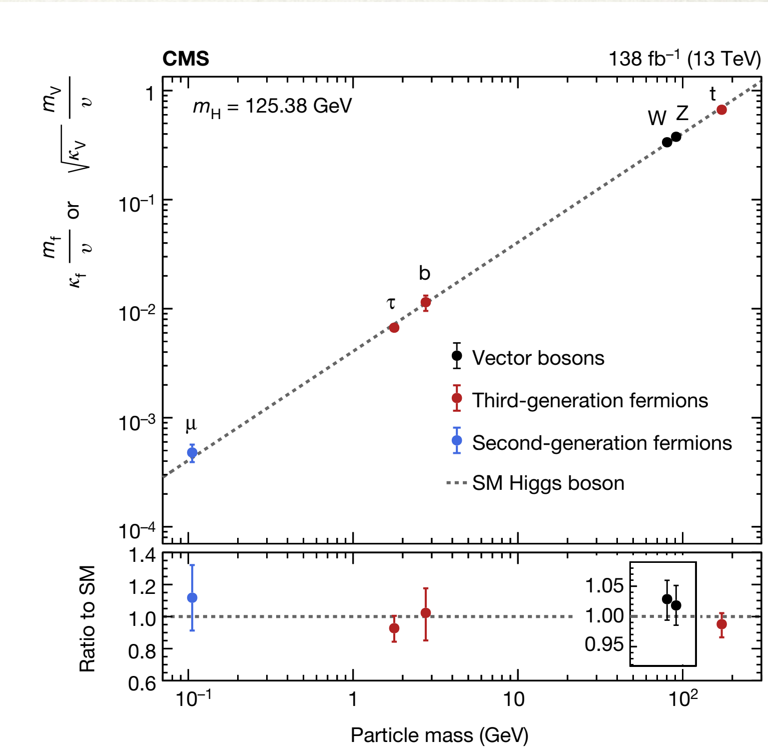

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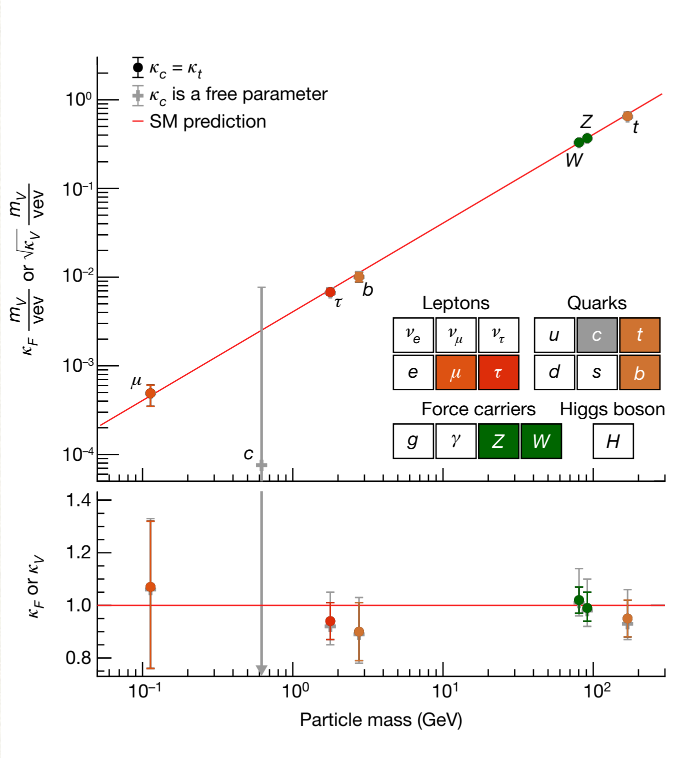

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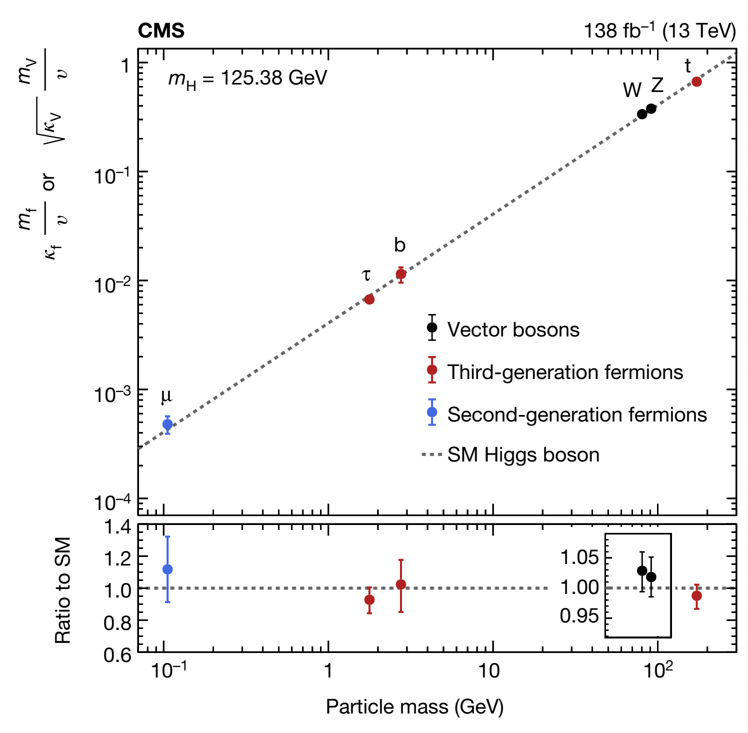

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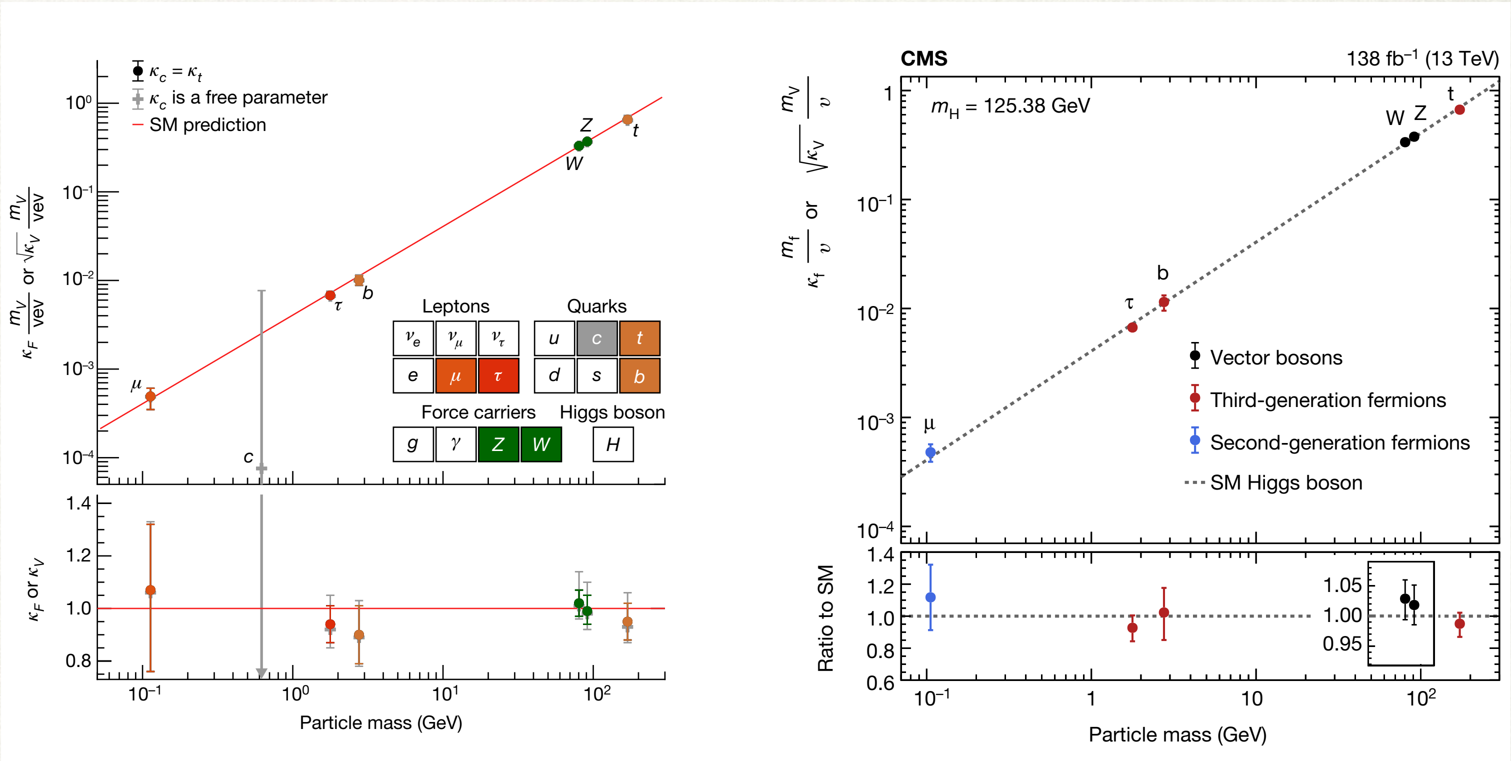

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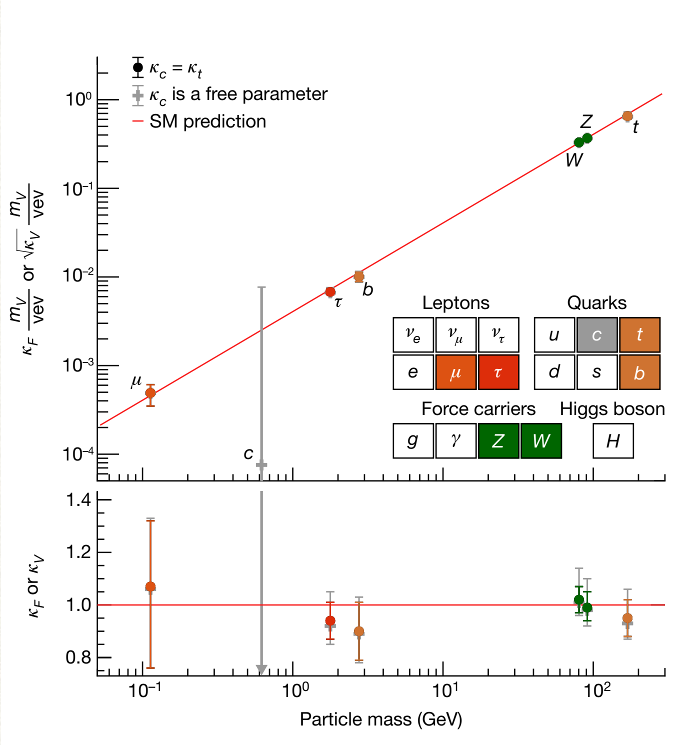

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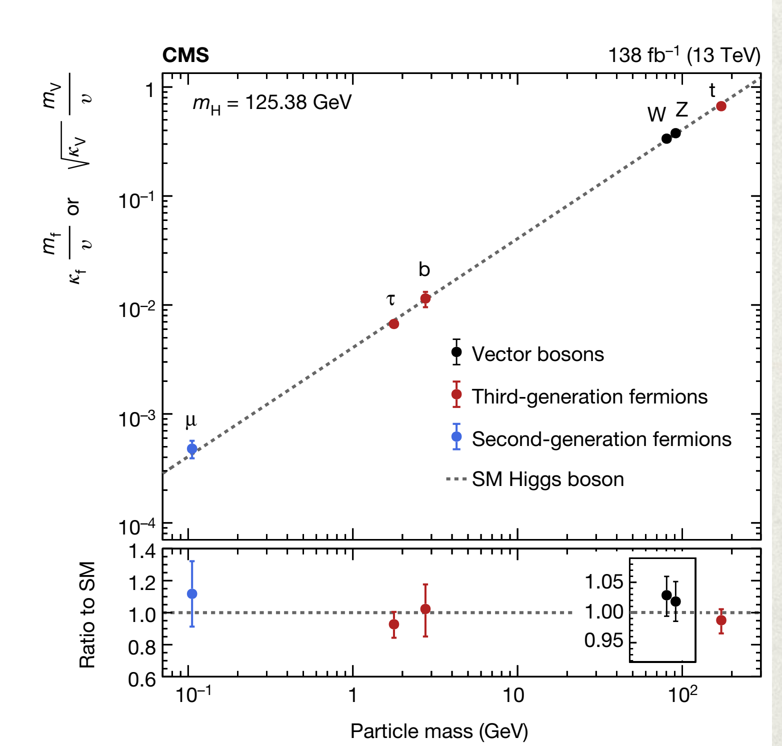

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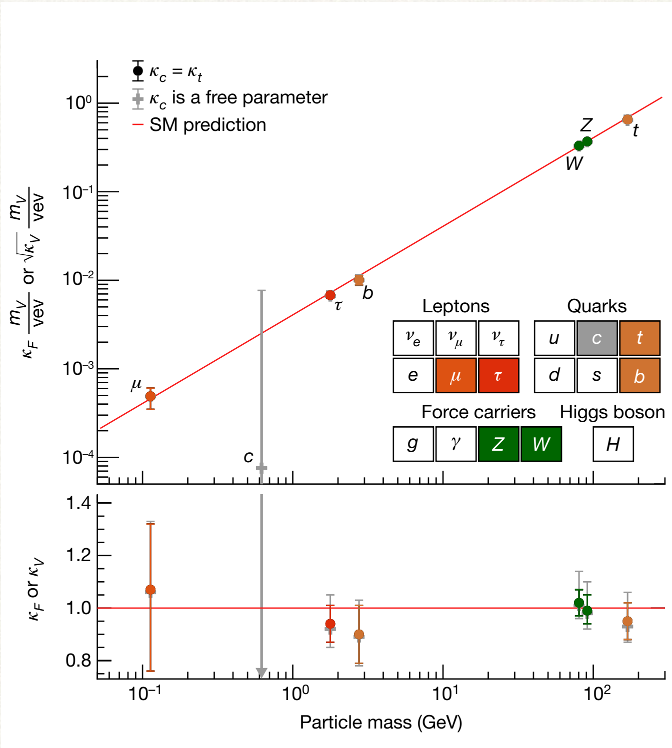

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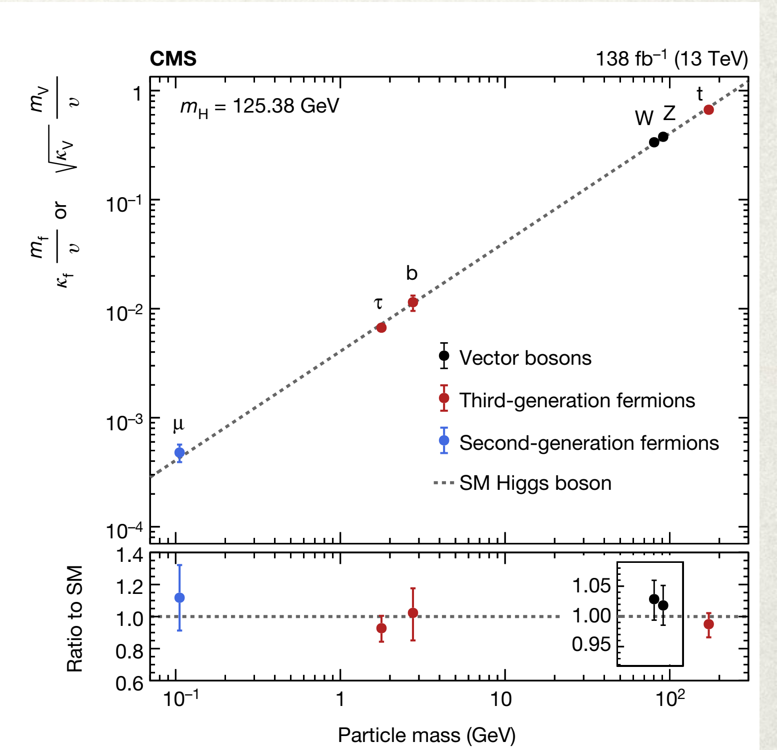

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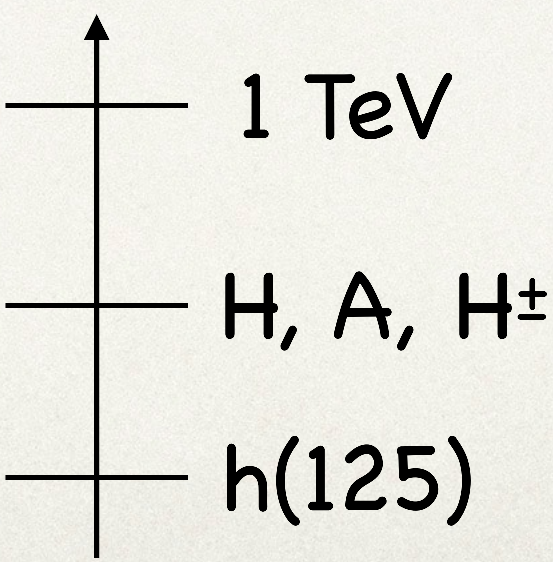

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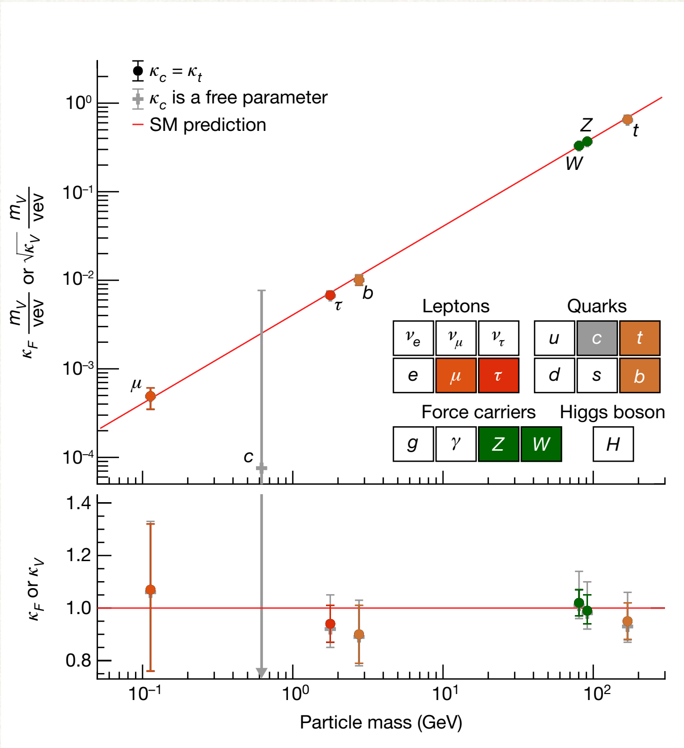

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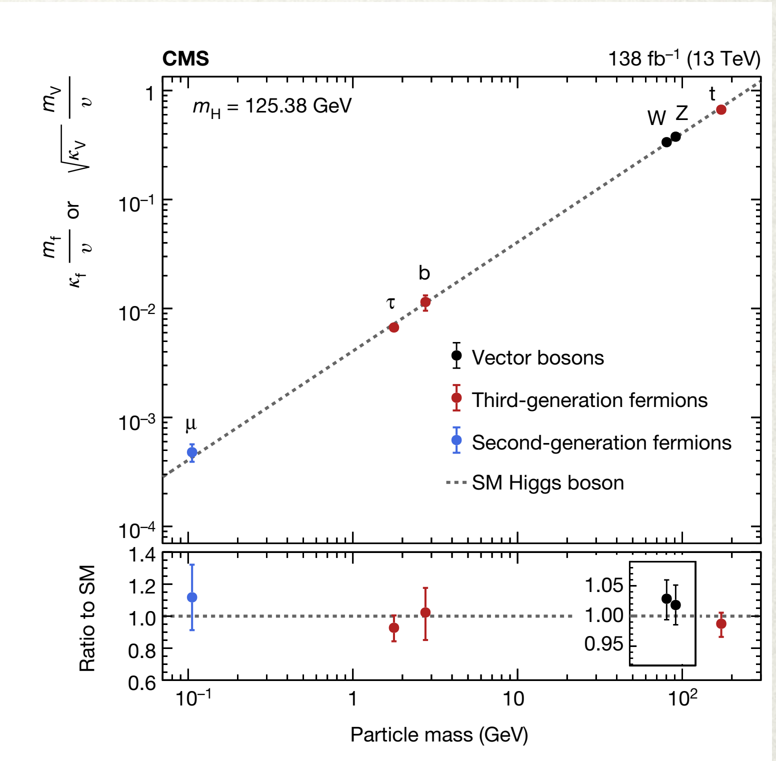

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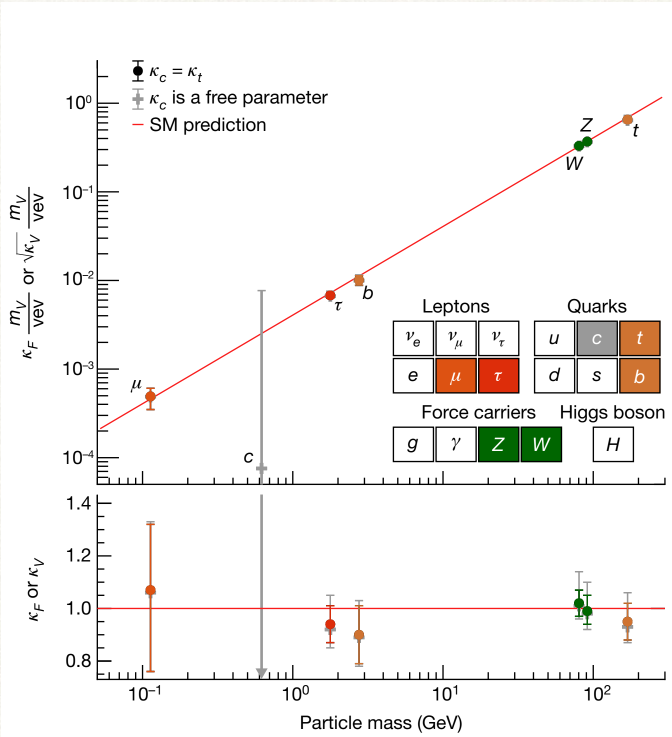

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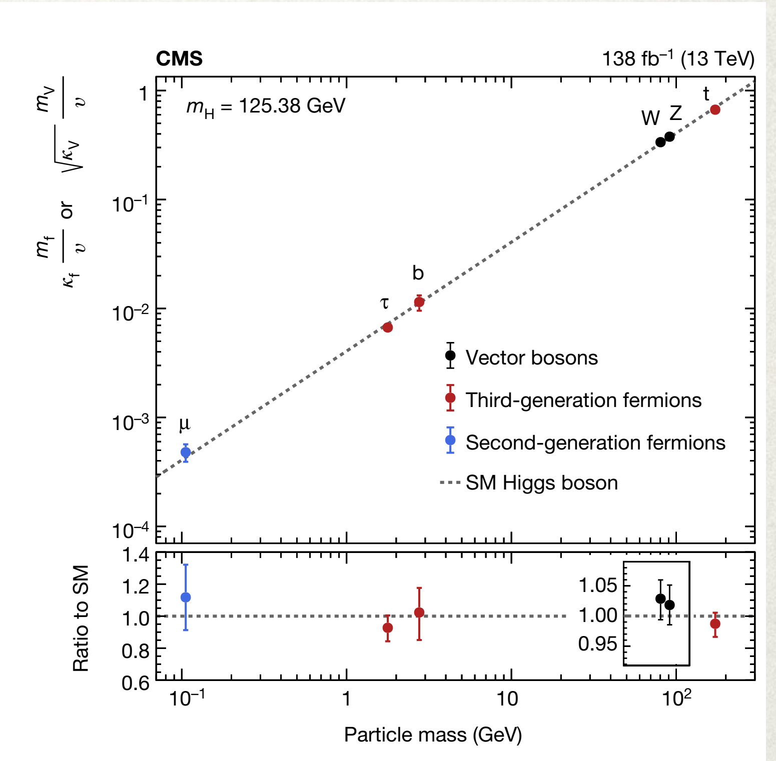

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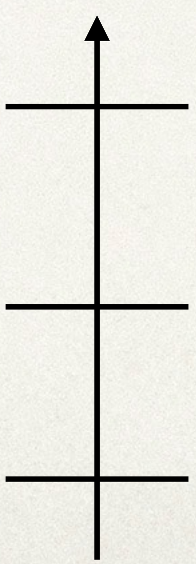

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[G.C.Dorsch, S.J.Huber, K.Mimasu, J.M.No, 1405.4437(PRL)]

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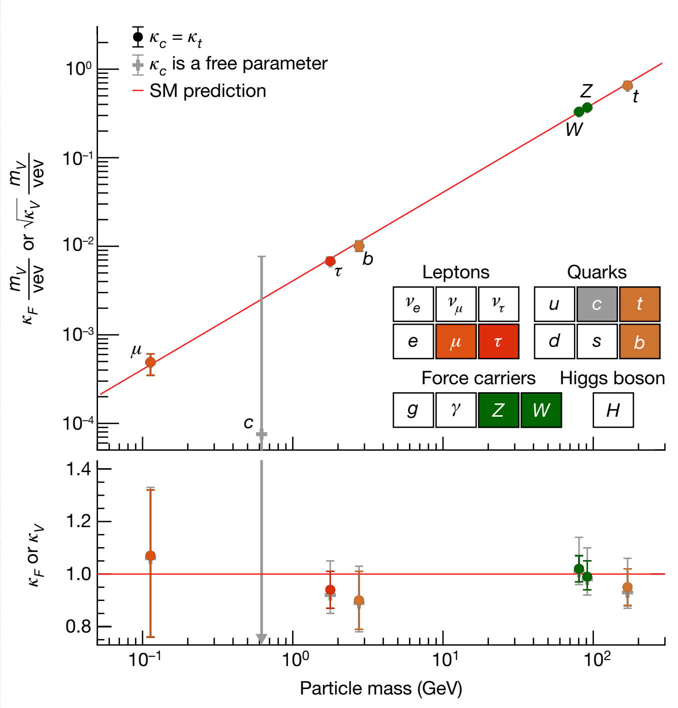

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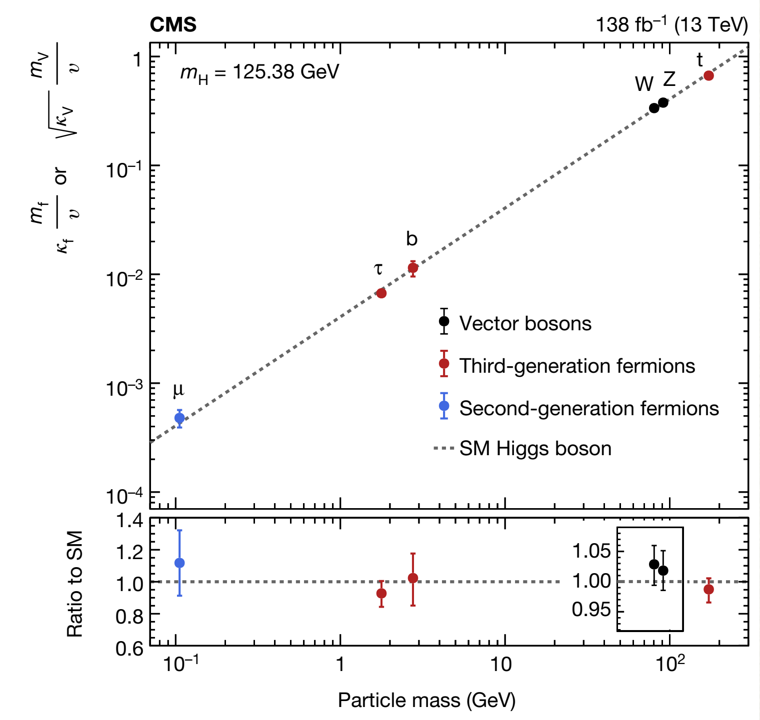

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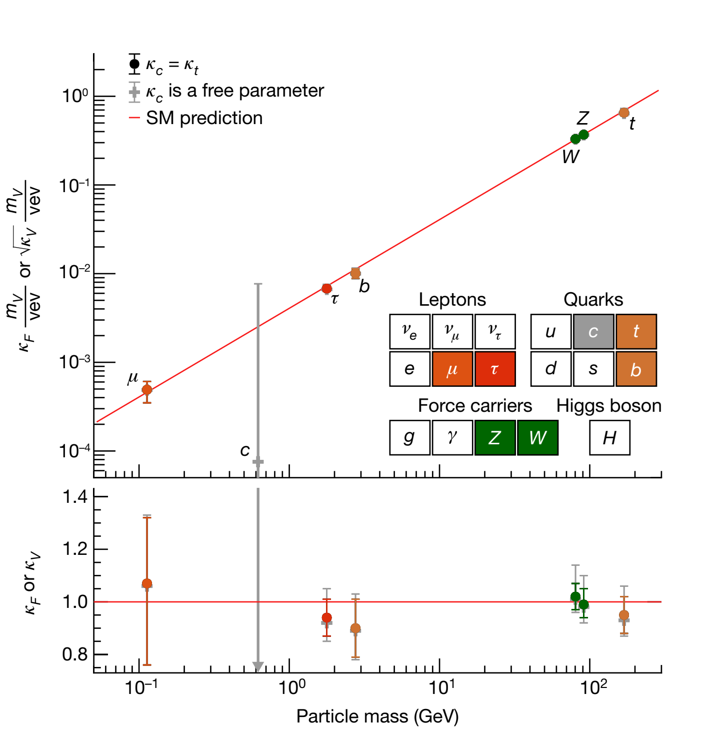

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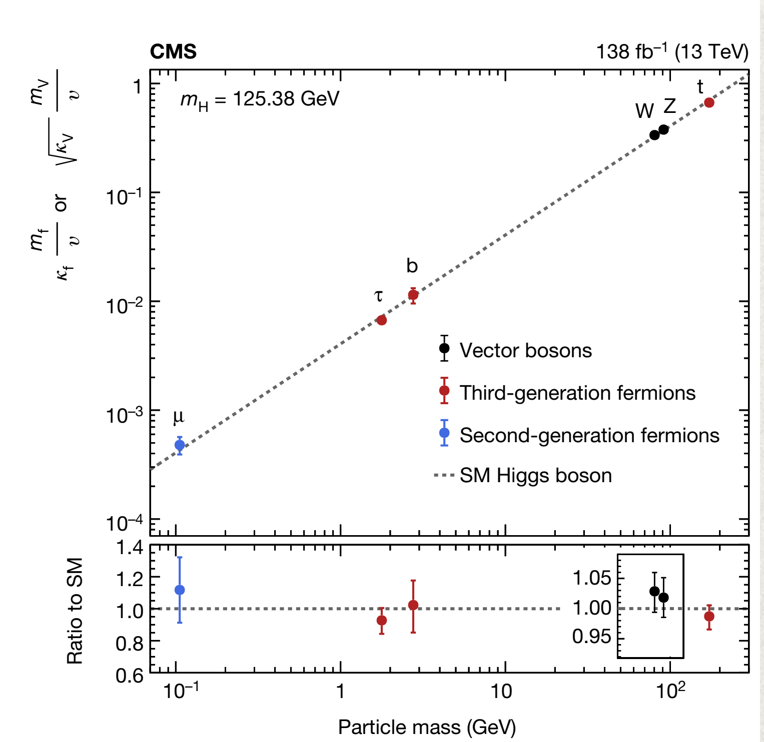

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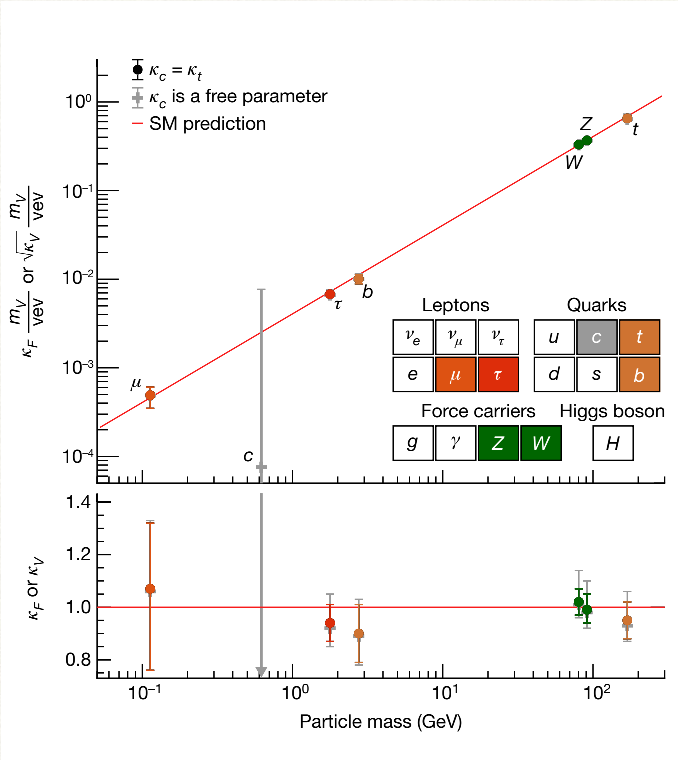

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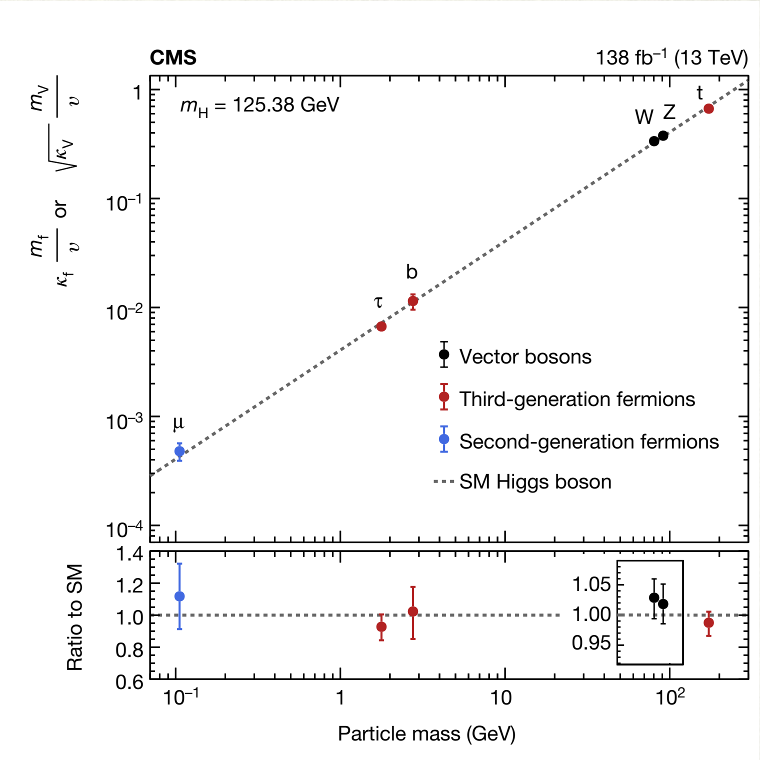

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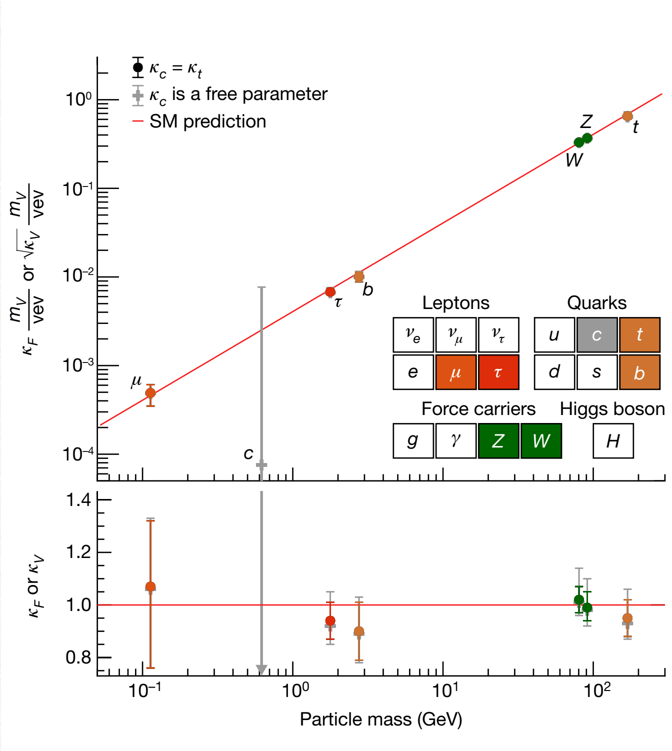

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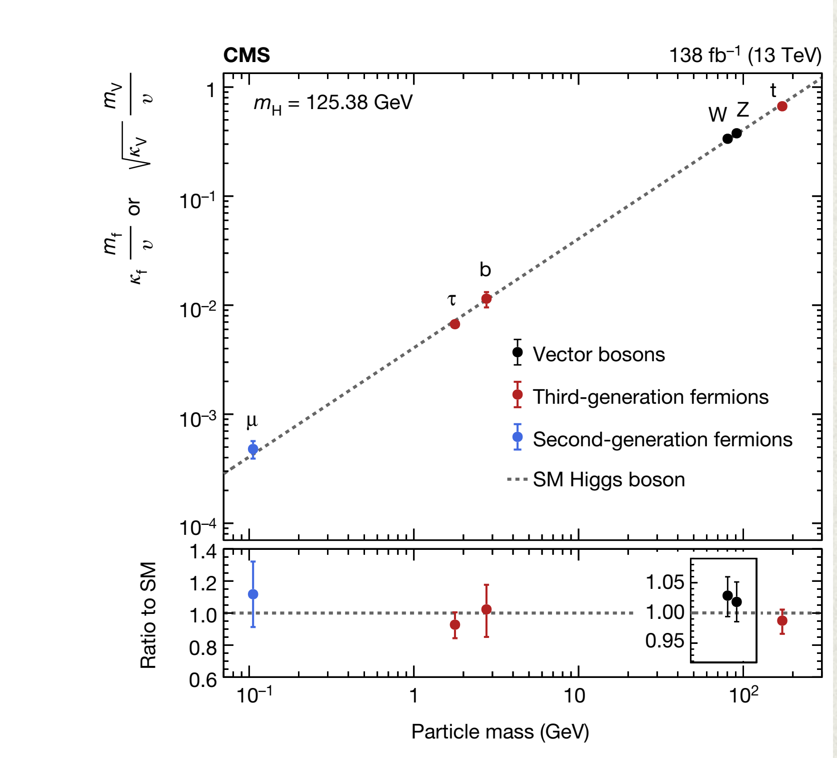

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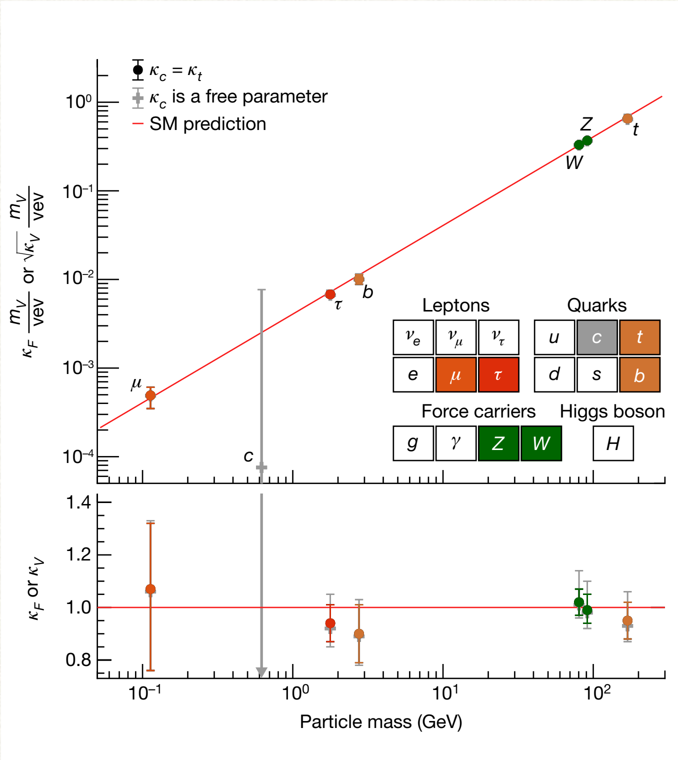

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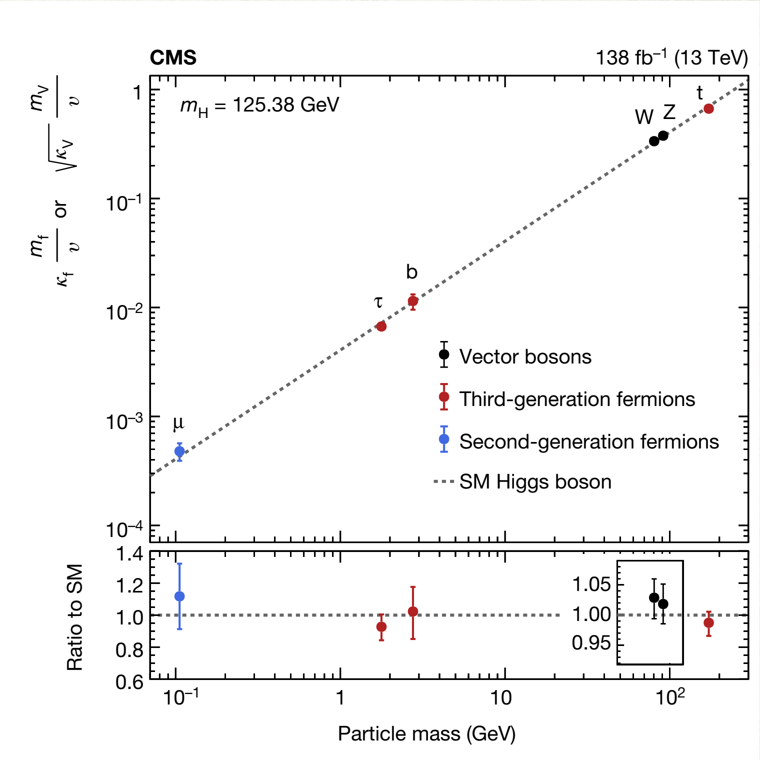

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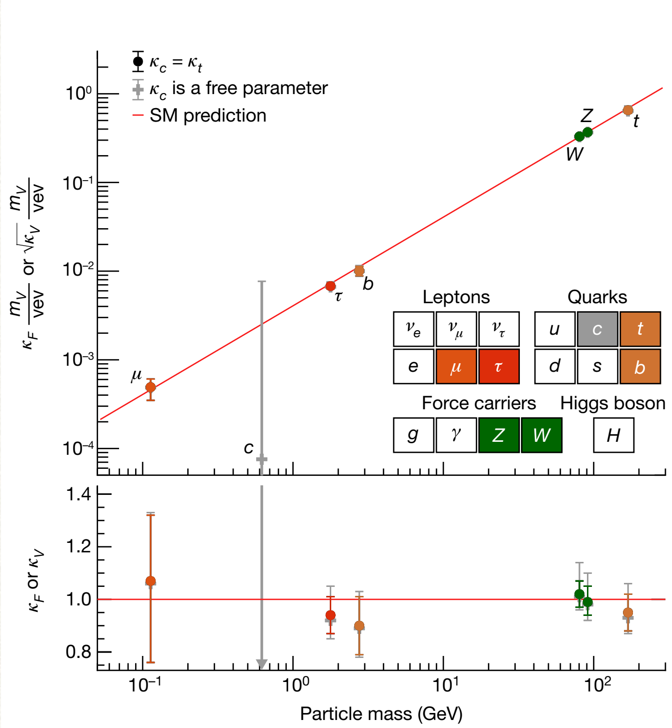

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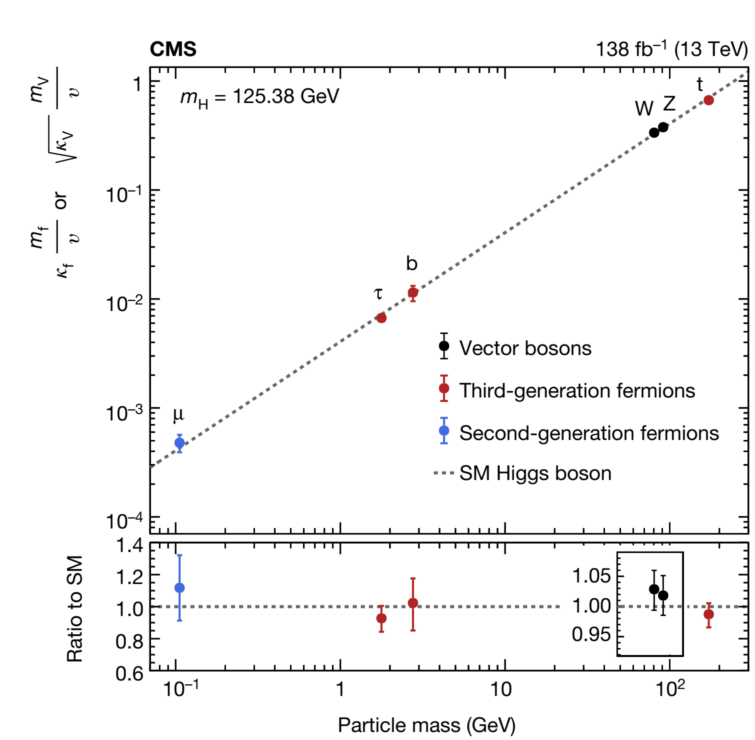

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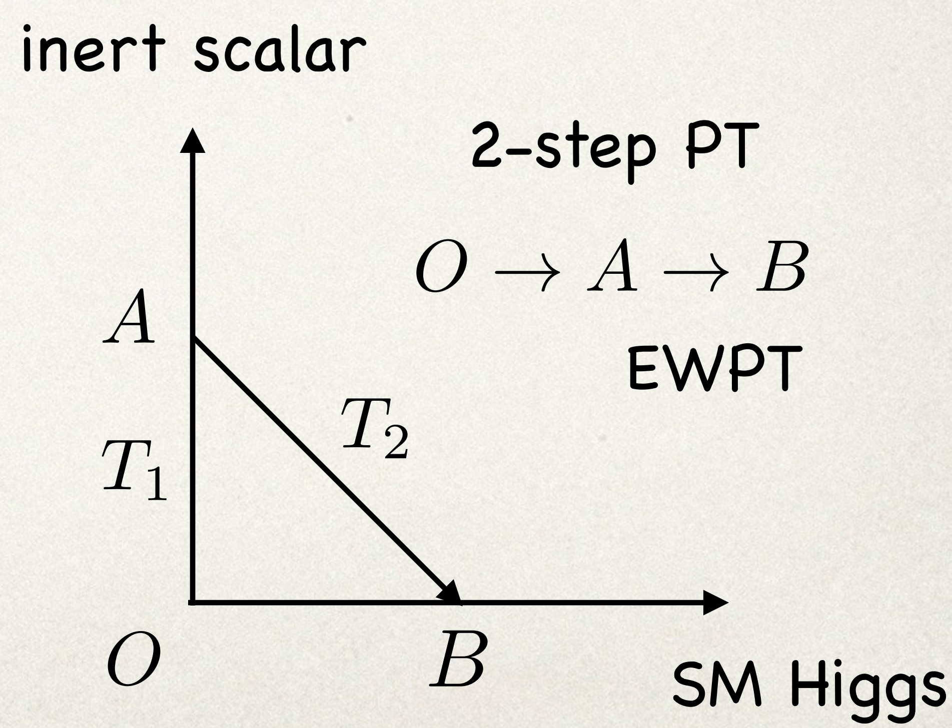

2-step PT

$O \to A \to B$

EWPT

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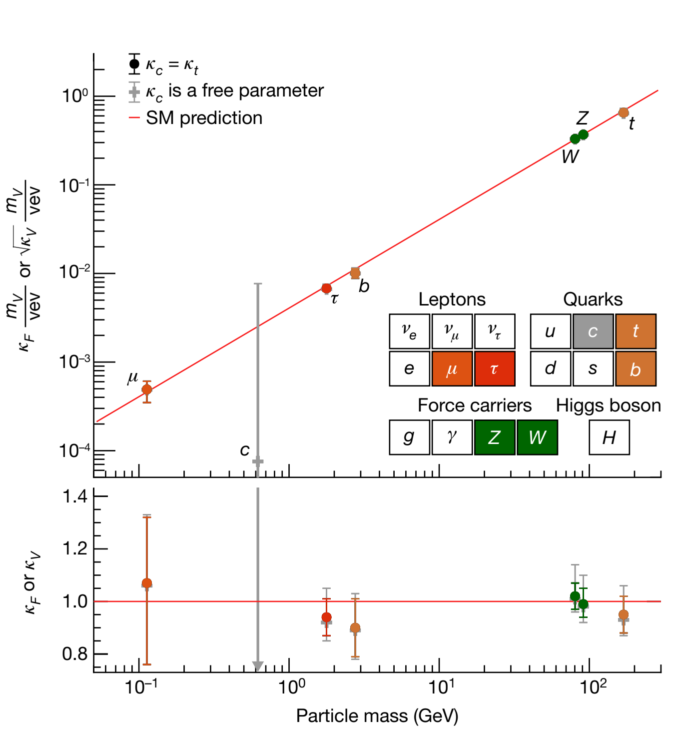

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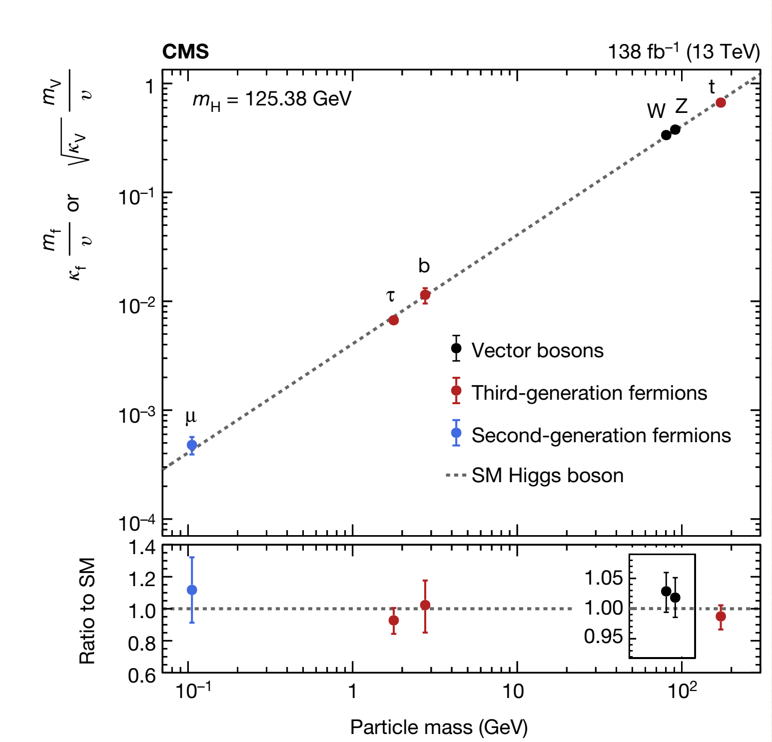

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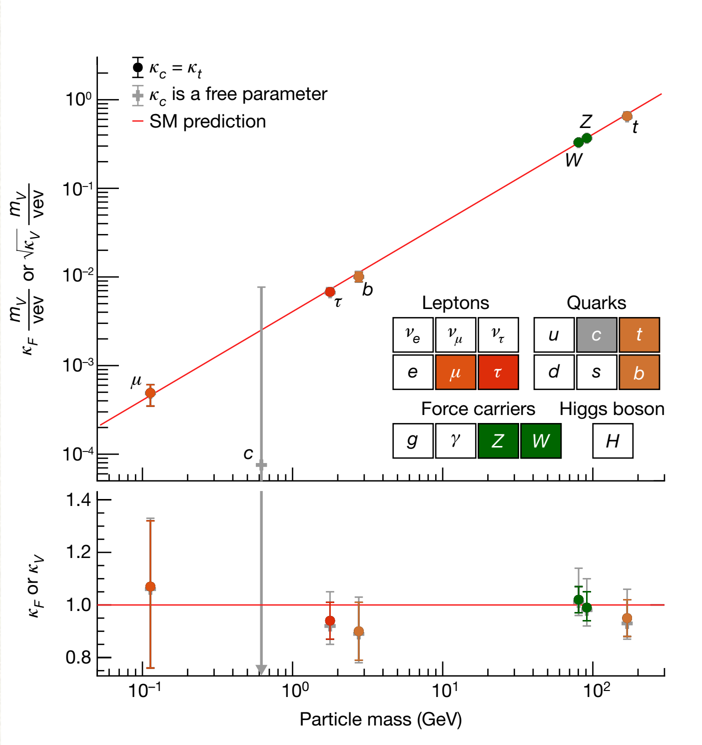

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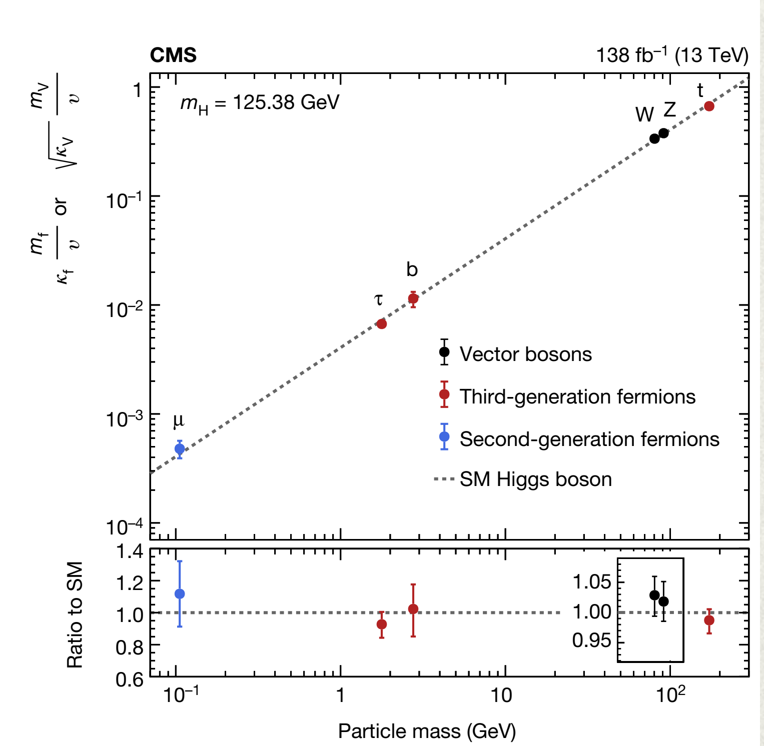

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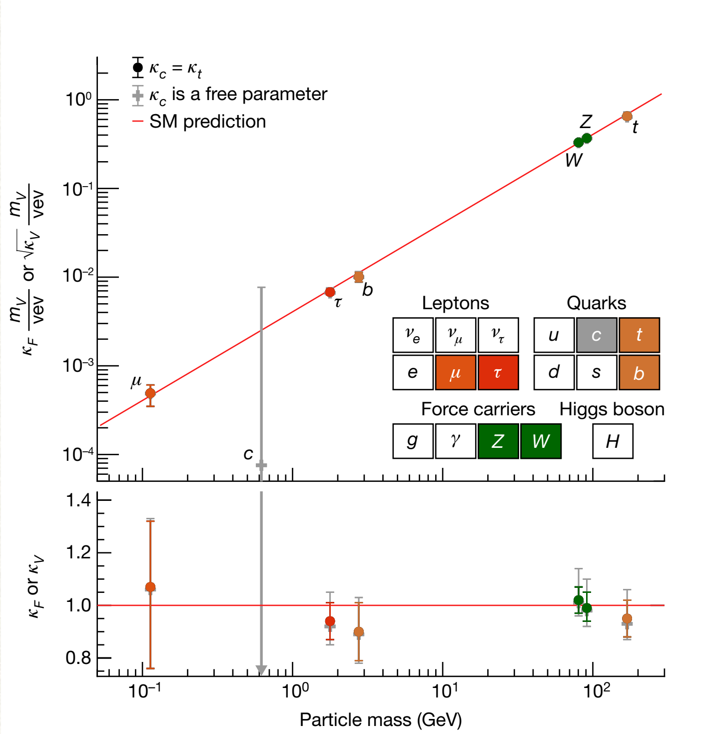

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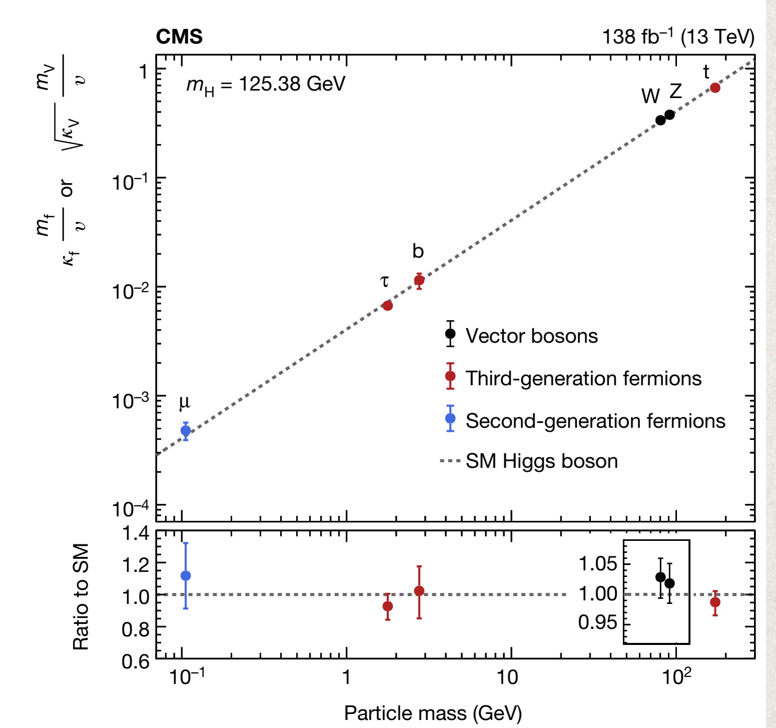

(3) Degenerate scalar scenarios

E.g. SM + a complex scalar

$$m_{h_1} \simeq m_{h_2} \simeq 125 \text{ GeV}$$

- Signal strengths are SM like

$$\sigma_{gg\to h_i \to VV^*} \underset{m_{h_1}\simeq m_{h_2}}{\simeq} \sigma^{\rm SM}_{gg\to h}\left[\sum_i \frac{\kappa_{if}^2\kappa_{iV}^2}{\Gamma_{h_i}}\right]\Gamma^{\rm SM}_{h\to VV^*}$$

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For the probe of this scenario at ILC, see, e.g., S. Abe, G.-C. Cho, and K. Mawatari, PRD104, 035023 (2021).

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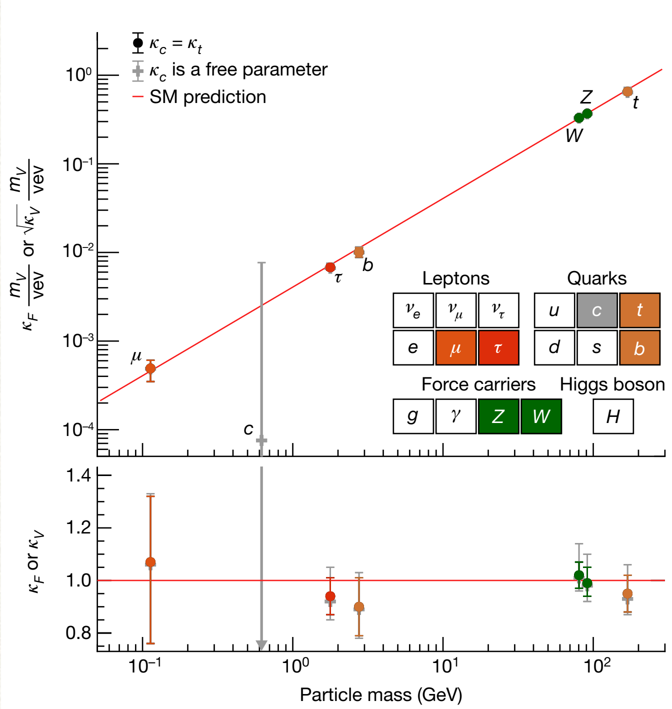

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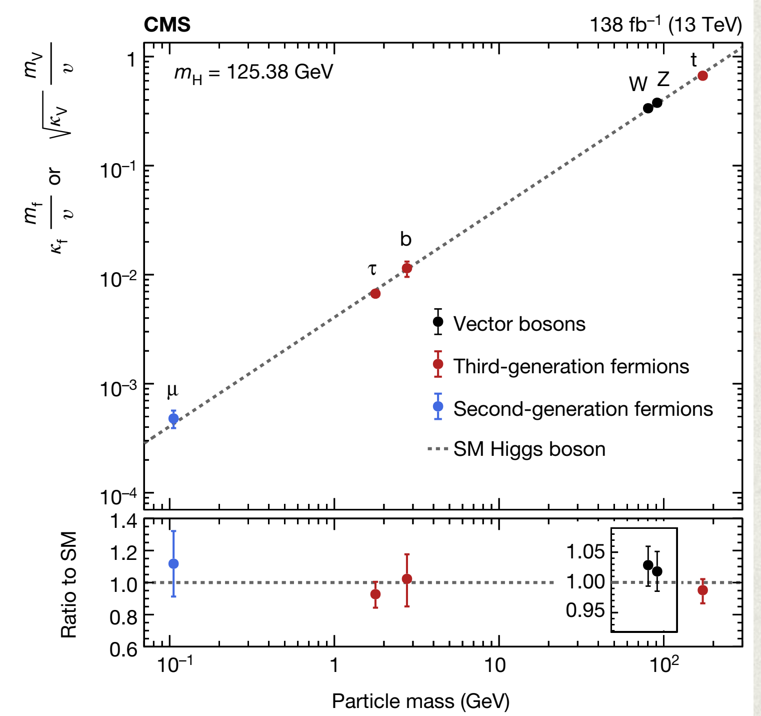

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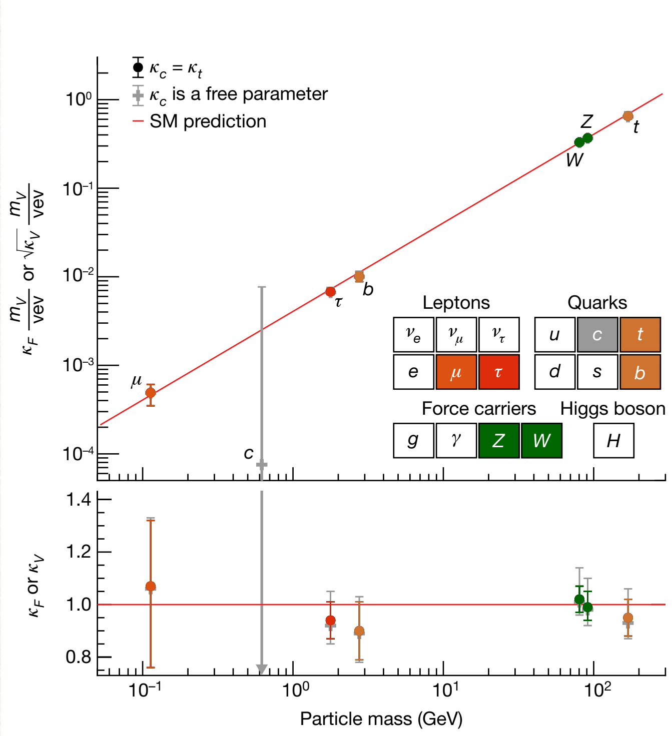

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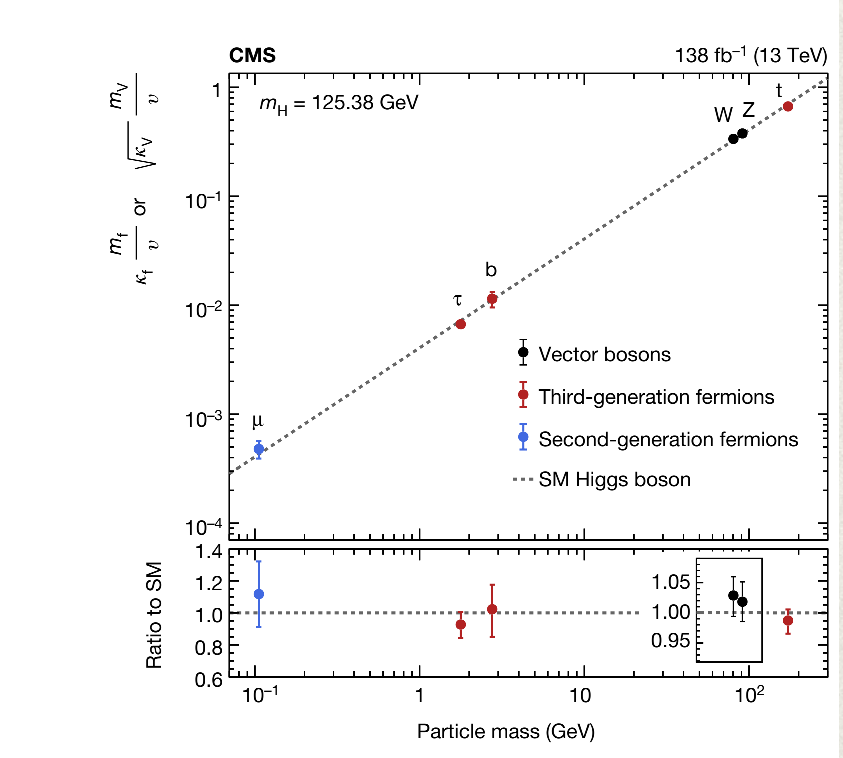

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Nature 607, 52-59 (2022) | Nature 607, 60-68 (2022)

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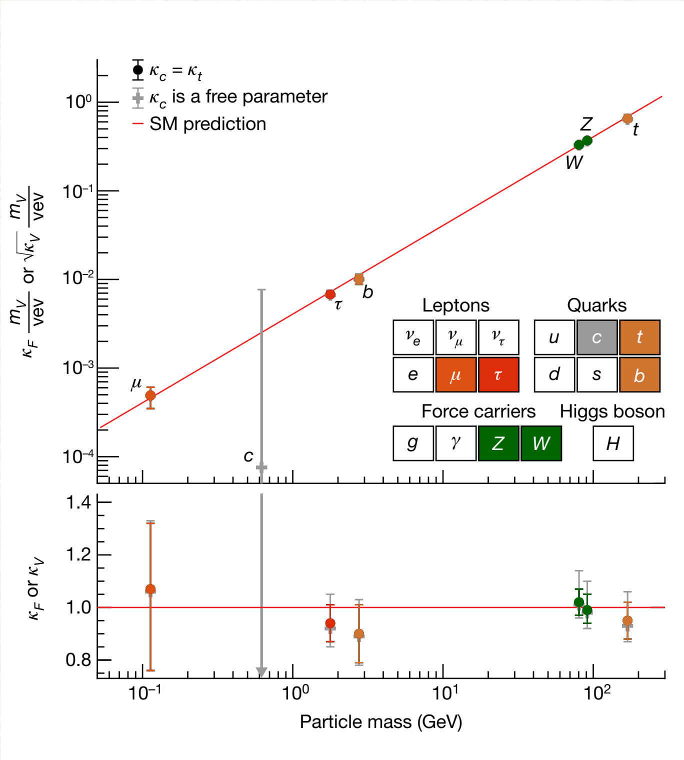

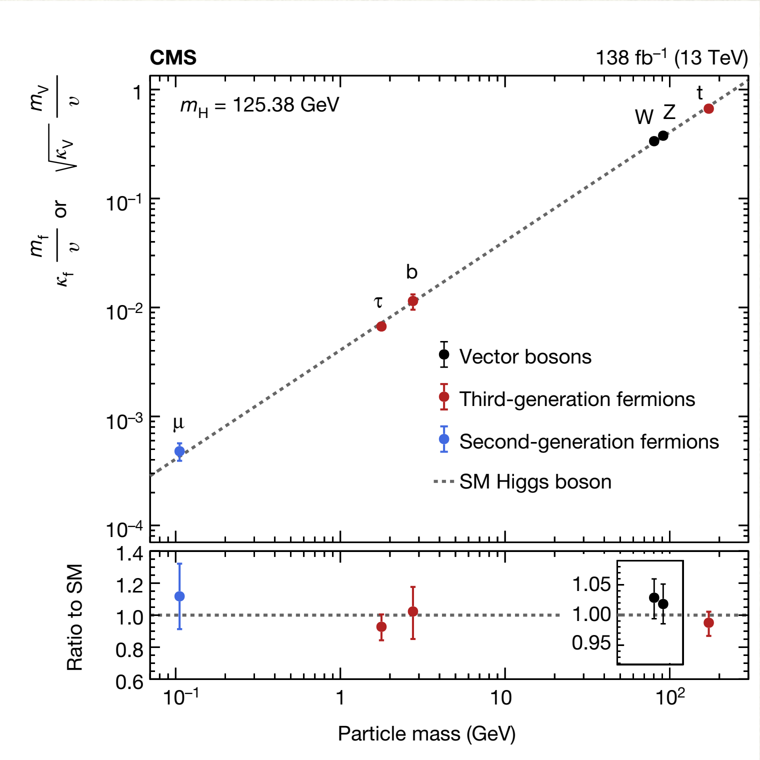

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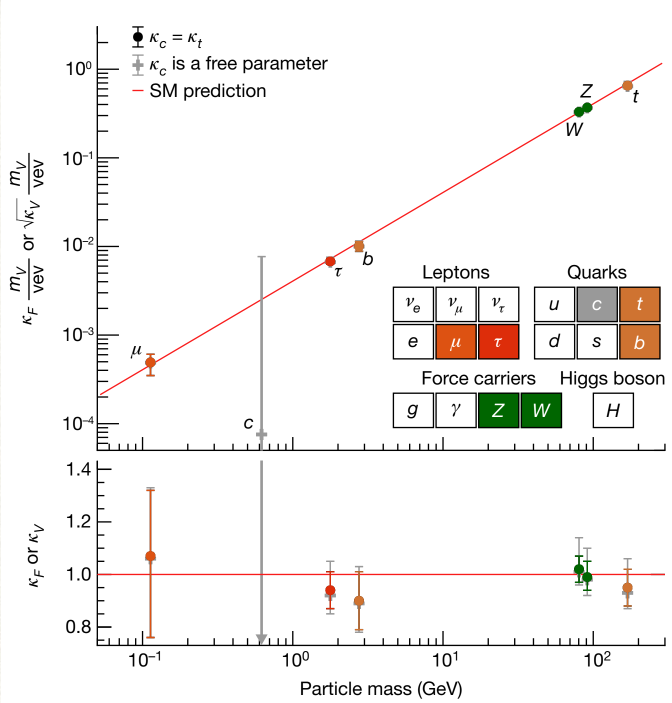

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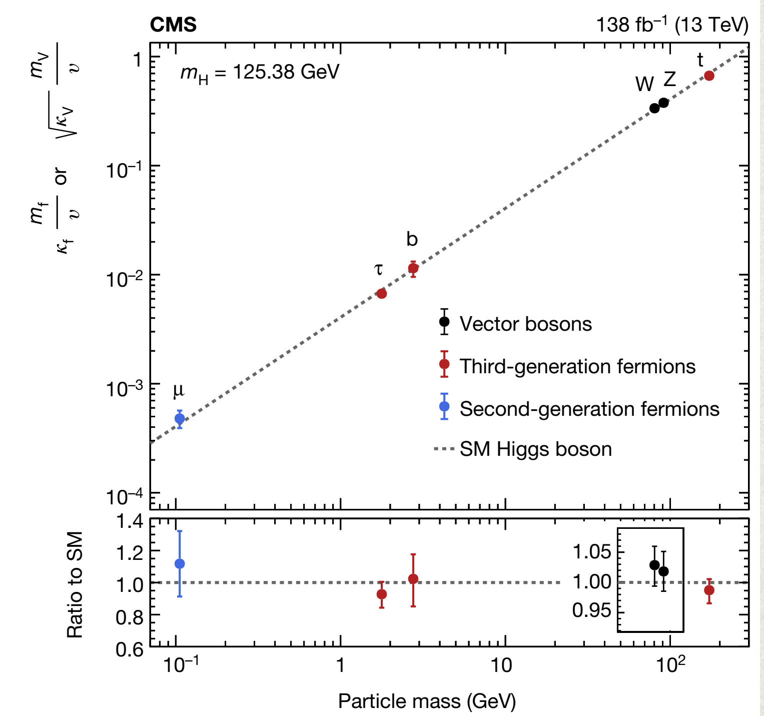

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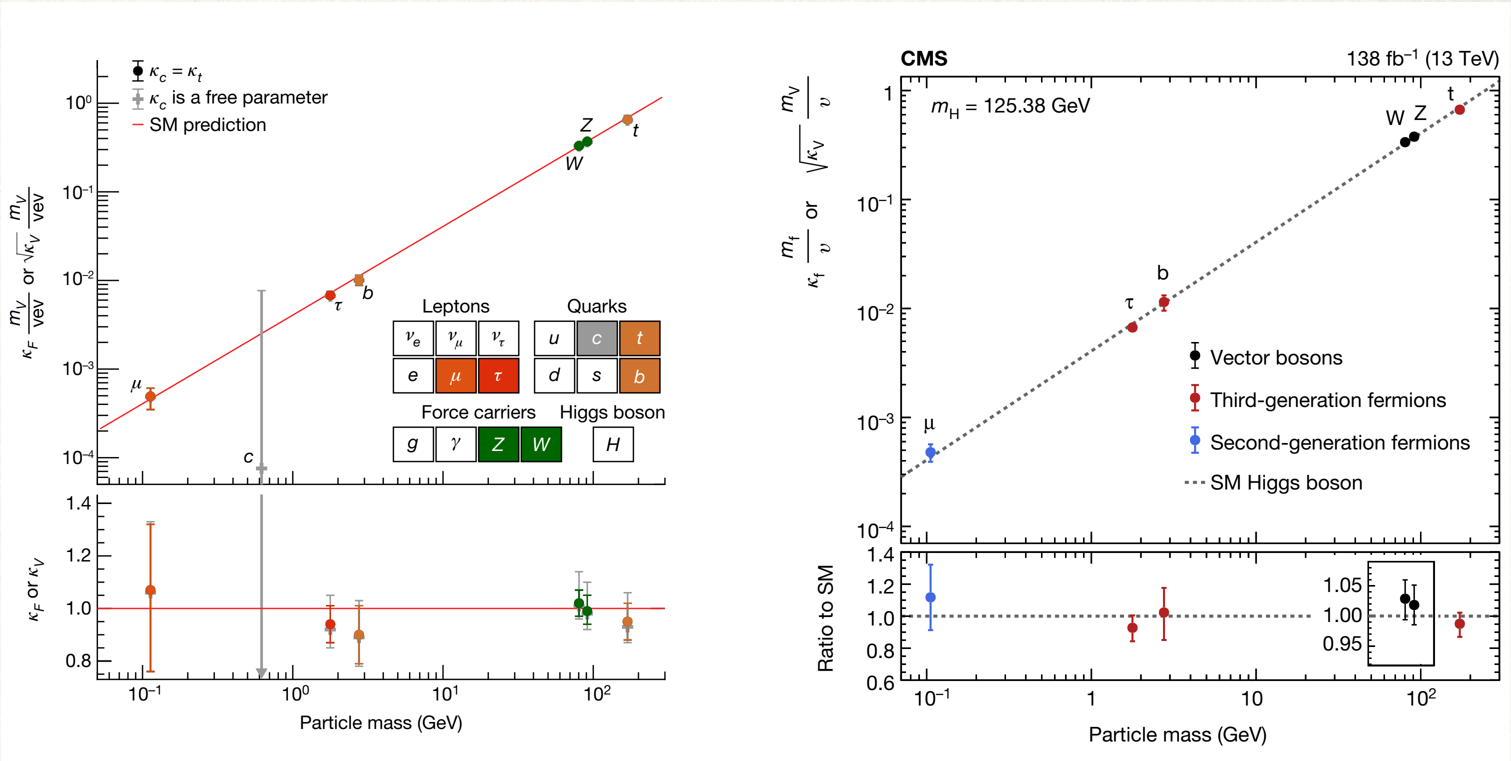

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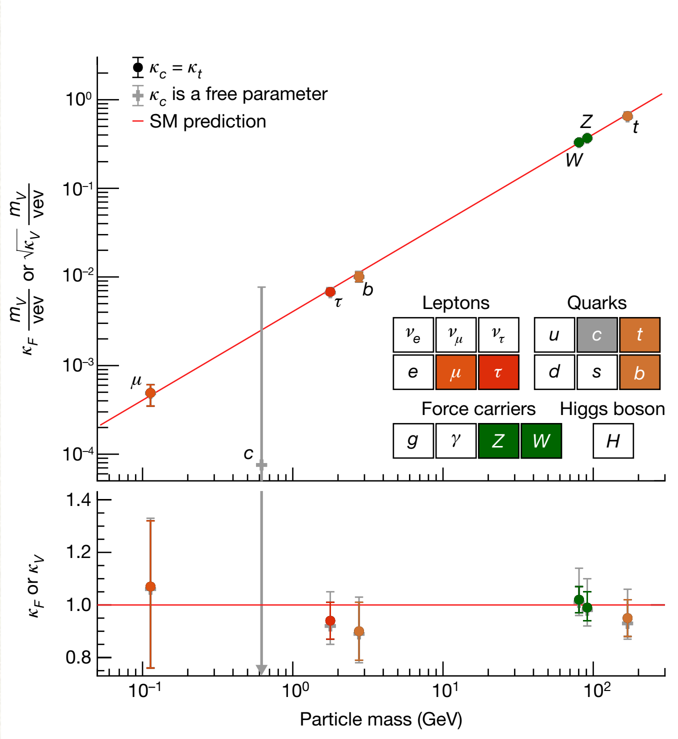

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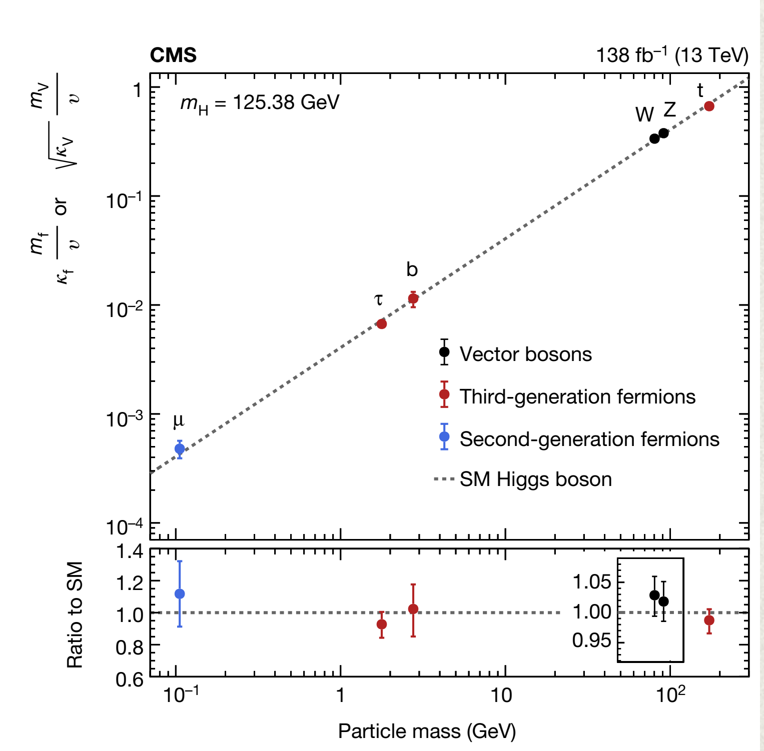

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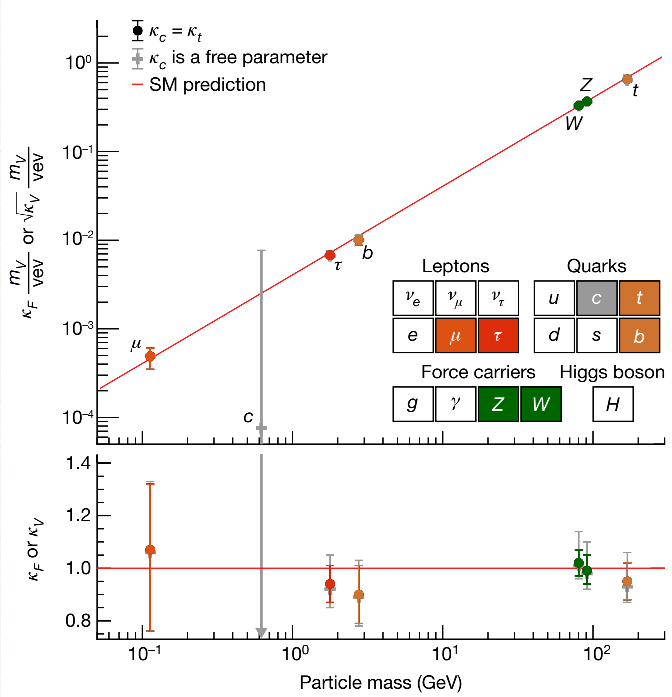

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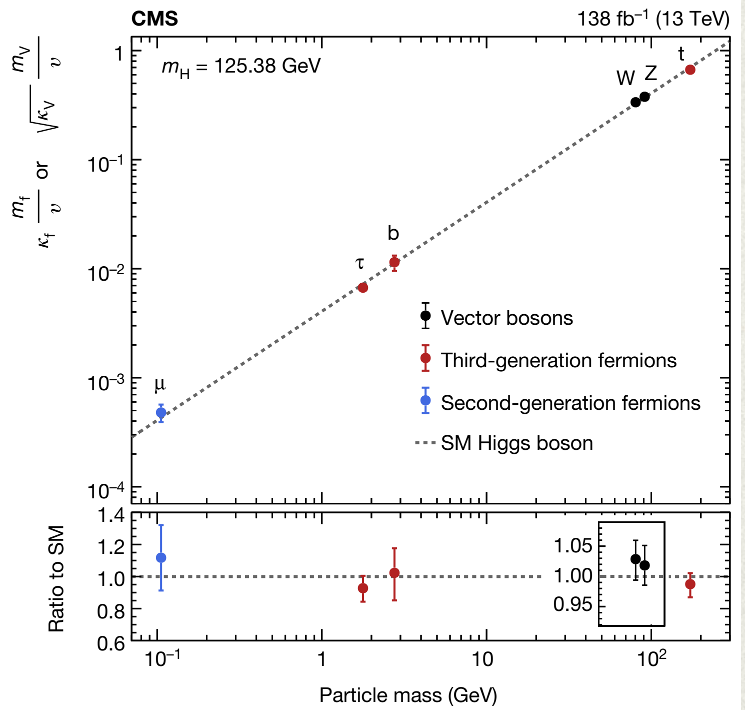

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Precision measurements are necessary to access "min".

EWBG after ACME-II/JILA2022

CP-violating Higgs-fermion coupling

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

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

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

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Electric Dipole Moment (EDM)

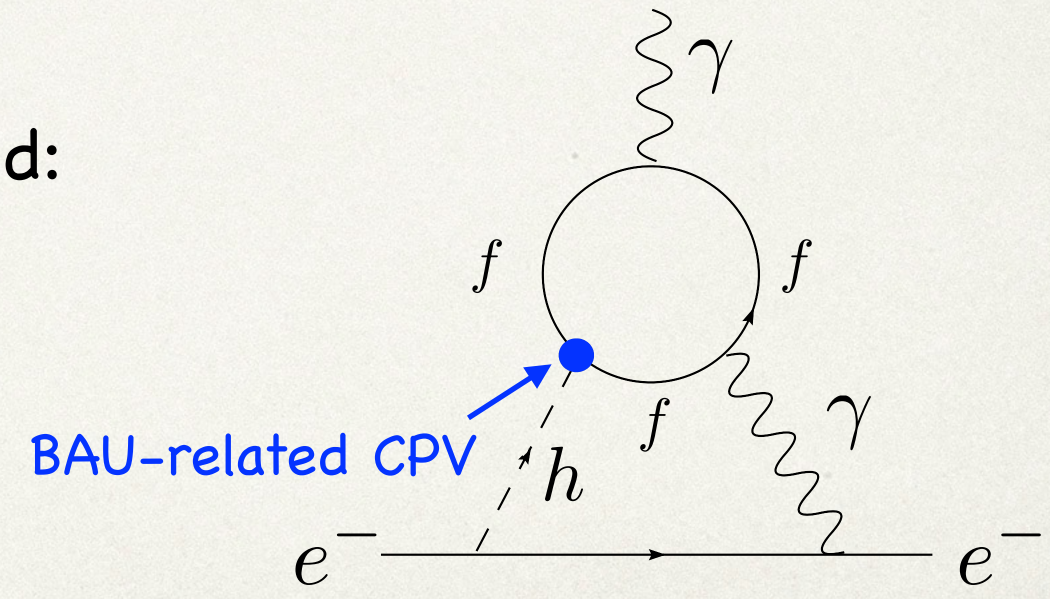
electron EDM receives the strongest bound:

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

ACME, Nature 562, 355 (2018)

$|d_e^{\rm JILA}| < 4.1 \times 10^{-30}\ e$ cm

JILA, Science 381 (2023) 46



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

EWBG-EDM connection

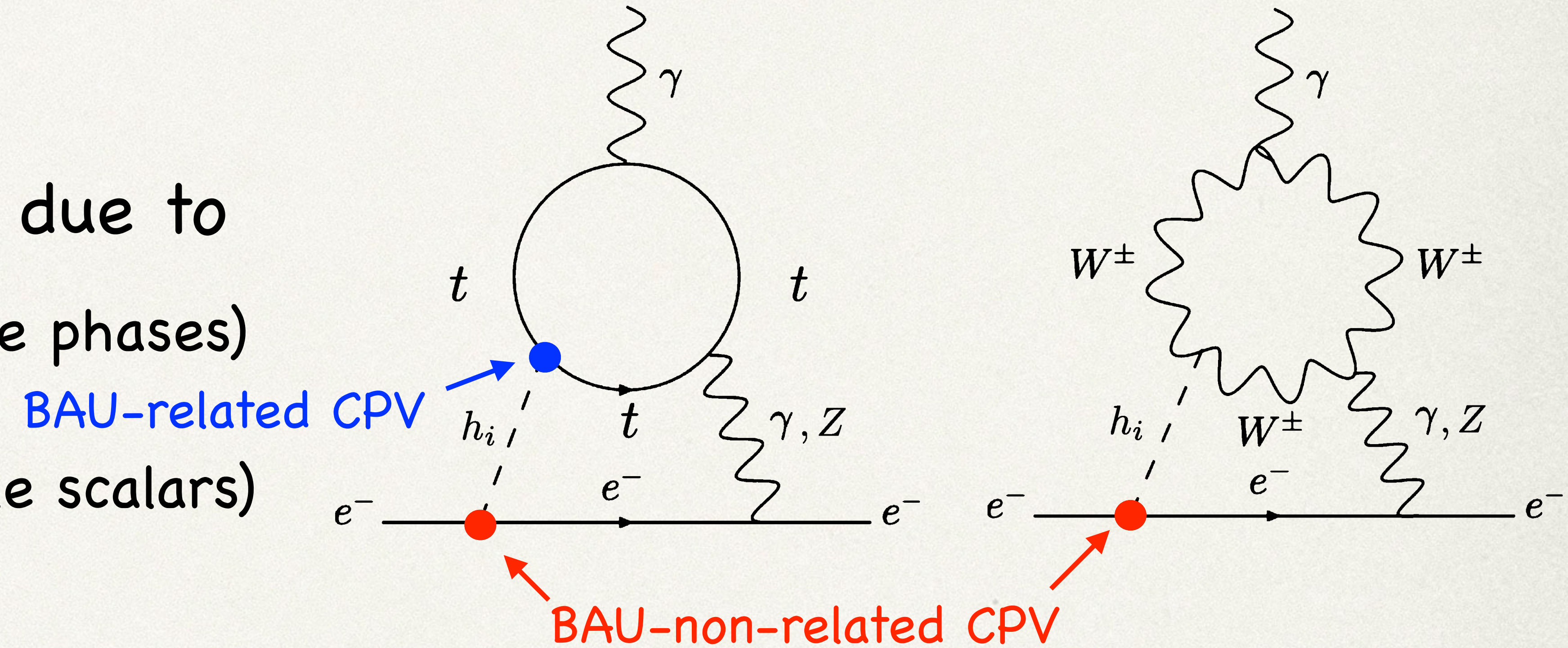
The results of eEDM experiments may suggest the existence of a suppression mechanism if EWBG is true.

Cancellation mechanism

eEDM can be suppressed due to

(1) phase alignments (multiple phases)

(2) mass degeneracy (multiple scalars)



Other possibilities

- Spontaneous CPV (+ tiny explicit CPV) at T>0

  -> At T=0, VEV becomes real, leaving only a tiny explicit CPV.

  E.g., 1807.06987, SM + complex singlet scalar + dim.6 Yukawa op., explicit CPV ≃ $O(10^{-15})$

- CPV comes from dark sectors

  E.g., 1908.04818, SM + extra fermions w/ gauged $U(1)_{lepton}$, eEDM (3-loop) < 10^{-30} e cm

EWBG-B physics connection

BAU-related CPV also show up in B physics

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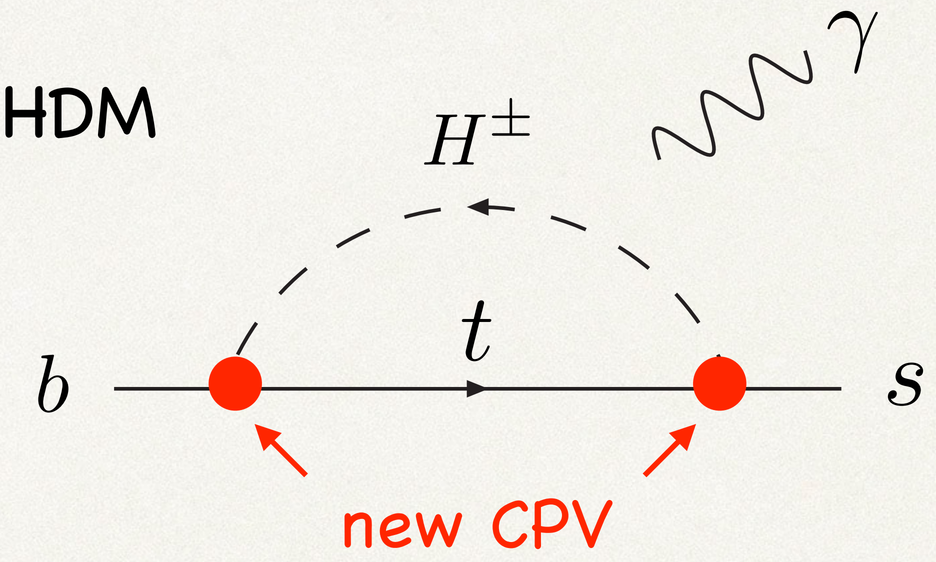
E.g. $b \to s\gamma$ in general 2HDM



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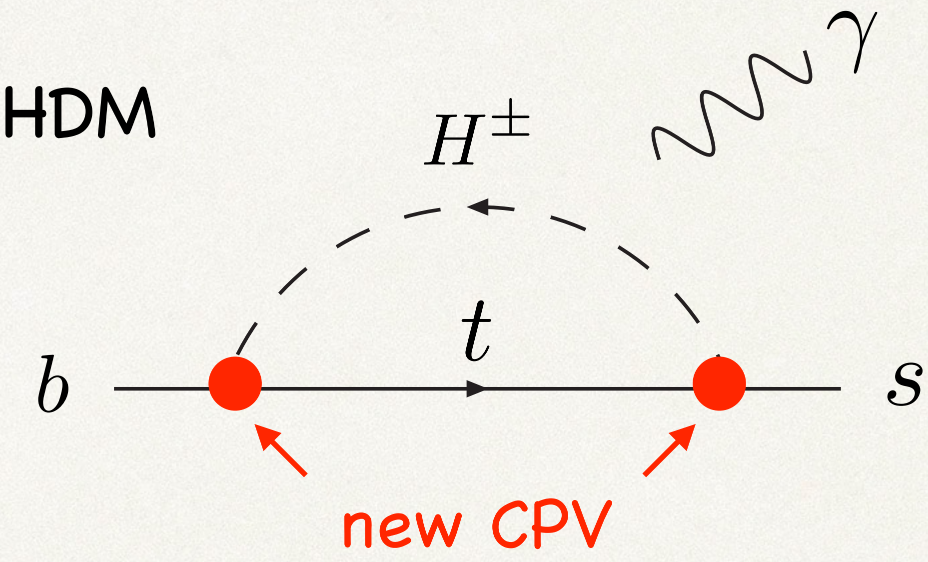

CP asymmetry

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

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

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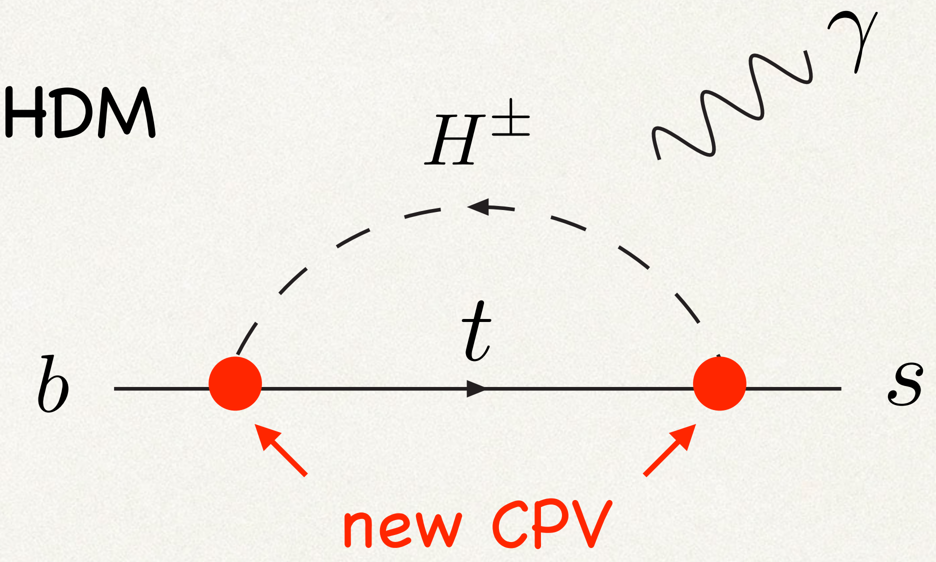

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Experimental constraint

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

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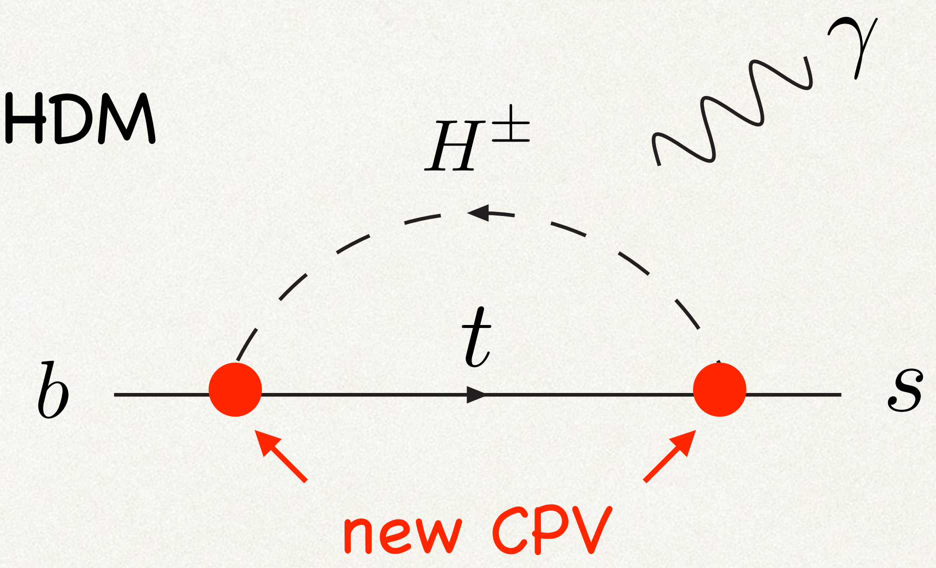

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Some EWBG scenarios can be probed by this $\Delta A_{\rm CP}$ measurement even when eEDM is accidentally suppressed.

Complex singlet extension of the SM (cxSM)

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A complex singlet scalar (S) is added to the SM.

General scalar potential

$$V_0(H,S) = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2}H^\dagger H|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4$$
$$+ \left[\frac{\delta_1}{4}H^\dagger H S + \frac{\delta_3}{4}H^\dagger H S^2 + a_1 S + \frac{b_1}{4}S^2 + \frac{c_1}{6}S^3\right.$$
$$\left. + \frac{c_2}{6}S|S|^2 + \frac{d_1}{8}S^4 + \frac{d_3}{8}S^2|S|^2 + \text{h.c.}\right]$$

Not all terms are necessary to address EWBG.

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A simplified model

$S \to e^{i\alpha}S$ global U(1)

$$V_0(H,S) = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \boxed{\frac{\delta_2}{2}H^\dagger H|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4}$$
$$+ \left[a_1 S + \frac{b_1}{4}S^2 + \text{h.c.}\right] \qquad a_1, b_1 \in \mathbb{C} \qquad \text{1 phys. phase}$$

- a_1 and b_1 are needed to avoid an unwanted Nambu-Goldstone and domain wall.
- Even though a_1 and b_1 can be complex, additional terms are needed to break CP.

Complex singlet extension of the SM (cxSM)

H and S are parametrized as

$$H(x) = \begin{pmatrix} G^+(x) \\ \frac{1}{\sqrt{2}}\left(v + h(x) + iG^0(x)\right) \end{pmatrix}, \quad S(x) = \frac{1}{\sqrt{2}}\boxed{\left(v_S^r + iv_S^i\right.}\left. + s(x) + i\chi(x)\right).$$

complex VEV

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complex VEV

Mass matrix

$$V_0 \ni \frac{1}{2} (h \quad s \quad \chi) \mathcal{M}_S^2 \begin{pmatrix} h \\ s \\ \chi \end{pmatrix}, \qquad \mathcal{M}_S^2 = \begin{pmatrix} \frac{\lambda}{2} v^2 & \frac{\delta_2}{2} v v_S^r & \frac{\delta_2}{2} v v_S^i \\ \frac{\delta_2}{2} v v_S^r & \frac{d_2}{2} v_S^{r2} - \frac{\sqrt{2} a_1^r}{v_S^r} & \frac{d_2}{2} v_S^r v_S^i \\ \frac{\delta_2}{2} v v_S^i & \frac{d_2}{2} v_S^r v_S^i & \frac{d_2}{2} v_S^{i2} + \frac{\sqrt{2} a_1^i}{v_S^i} \end{pmatrix}$$

$$O^T \mathcal{M}_S^2 O = \mathrm{diag}(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2)$$

The h-χ and s-χ mixings are due to the complex parameters in the S sector.

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Higgs couplings

scalar coupling (no pseudoscalar coupling)

$$\mathcal{L}_{h_i\bar{f}f} = -\frac{m_f}{v}\sum_{i=1}^{3}\kappa_{if}\boxed{h_i\bar{f}f,} \quad \mathcal{L}_{h_iVV} = \frac{1}{v}\sum_{i=1}^{3}\kappa_{iV}h_i(m_Z^2 Z_\mu Z^\mu + 2m_W^2 W_\mu^+ W^{-\mu}),$$

$$\kappa_{if} = O_{1i} \text{ and } \kappa_{iV} = O_{1i}$$

- Complex parameters in the S sector do not induce CPV.
- As a 1st step, we consider CPV-dimension 5 operators.

Complex singlet extension of the SM (cxSM)

Dim.5 operators

$$-\mathcal{L}_{h_i\bar{f}f}^{\text{dim.5}} \ni \bar{q}_L\tilde{H}\left(y_t+\frac{c_t}{\Lambda}S\right)t_R+\bar{\ell}_L H\left(y_e+\frac{c_e}{\Lambda}S\right)e_R+\text{h.c.} \qquad c_t, c_e \in \mathbb{C}$$

$$c_f=|c_f|e^{i\phi_f}=c_f^r+ic_f^i,\ f=t,e \qquad \Lambda:\text{cutoff scale}$$

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$$c_f=|c_f|e^{i\phi_f}=c_f^r+ic_f^i,\ f=t,e \qquad \Lambda:\text{cutoff scale}$$

CPV Yukawa interactions

$$\mathcal{L}_{h_i\bar{f}f}=-\sum_{i=1}^{3}h_i\bar{f}\left(g^S_{h_i\bar{f}f}+ig^P_{h_i\bar{f}f}\gamma_5\right)f$$

$$g^S_{h_i\bar{f}f}=\frac{1}{\sqrt{2}}\left[y_fO_{1i}+\frac{v}{\sqrt{2}\Lambda}(c_f^rO_{2i}-c_f^iO_{3i})\right], \quad g^P_{h_i\bar{f}f}=\frac{v}{\sqrt{2}\Lambda}(c_f^rO_{3i}+c_f^iO_{2i})$$

Complex singlet extension of the SM (cxSM)

Dim.5 operators

$$-\mathcal{L}^{\rm dim.5}_{h_i\bar{f}f} \ni \bar{q}_L\tilde{H}\left(y_t + \frac{c_t}{\Lambda}S\right)t_R + \bar{\ell}_L H\left(y_e + \frac{c_e}{\Lambda}S\right)e_R + \text{h.c.} \qquad c_t, c_e \in \mathbb{C}$$

$$c_f = |c_f|e^{i\phi_f} = c_f^r + ic_f^i,\ \ f = t, e \qquad \Lambda : \text{cutoff scale}$$

CPV Yukawa interactions

$$\mathcal{L}_{h_i\bar{f}f} = -\sum_{i=1}^{3} h_i\bar{f}\left(g^S_{h_i\bar{f}f} + ig^P_{h_i\bar{f}f}\gamma_5\right)f$$

$$g^S_{h_i\bar{f}f} = \frac{1}{\sqrt{2}}\left[y_f O_{1i} + \frac{v}{\sqrt{2}\Lambda}(c_f^r O_{2i} - c_f^i O_{3i})\right], \quad g^P_{h_i\bar{f}f} = \frac{v}{\sqrt{2}\Lambda}(c_f^r O_{3i} + c_f^i O_{2i})$$

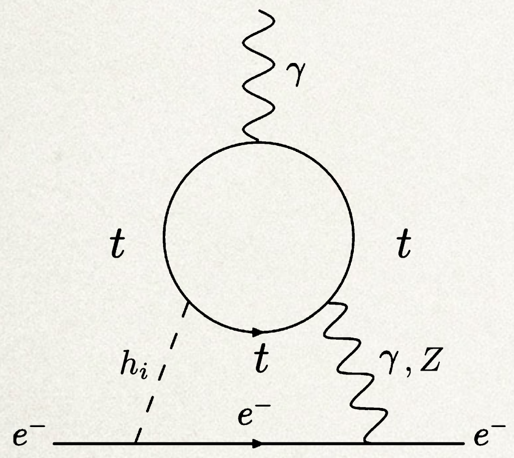
We will consider 2 cases:

1. Both c_t and c_e are real ($c_{t,e} \in \mathbb{R}$)
2. Both c_t and c_e are complex ($c_{t,e} \in \mathbb{C}$)

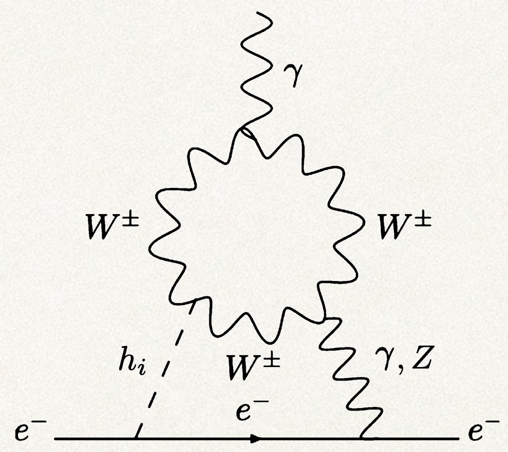
electron EDM

[C. Idegawa, E.S., PLB848 (2024) 138332]

$c_{t,e} \in \mathbb{R}$



$$d_e^t = (d_e^{h\gamma})_t + (d_e^{hZ})_t$$

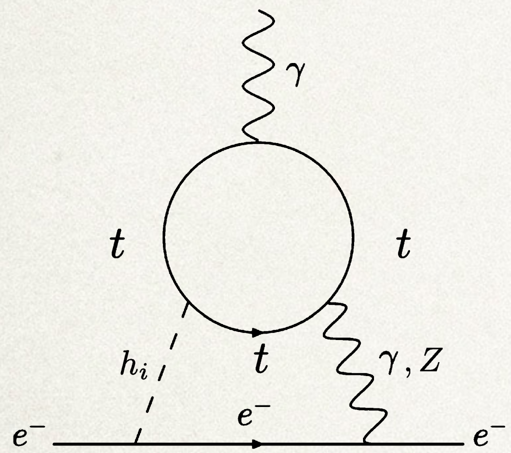


$$d_e^W = (d_e^{h\gamma})_W + (d_e^{hZ})_W$$

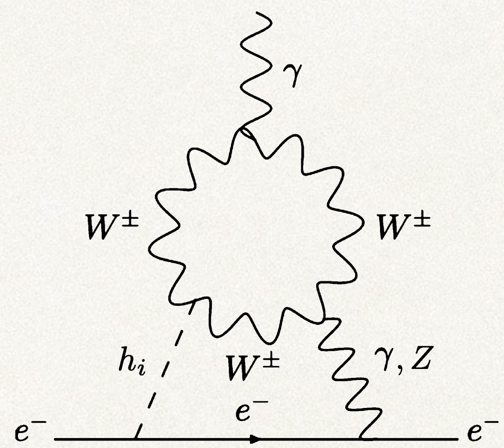
electron EDM

[C. Idegawa, E.S., PLB848 (2024) 138332]

$c_{t,e} \in \mathbb{R}$



$d_e^t = (d_e^{h\gamma})_t + (d_e^{hZ})_t$



$d_e^W = (d_e^{h\gamma})_W + (d_e^{hZ})_W$

$$d_e = d_e^t + d_e^W$$

$$d_e^t \propto \sum_{i=1,2,3} (aO_{1i}O_{3i} + bO_{2i}O_{3i})F(m_{h_i})$$

$$d_e^W \propto \sum_{i=1,2,3} a'O_{1i}O_{3i}G(m_{h_i})$$

electron EDM

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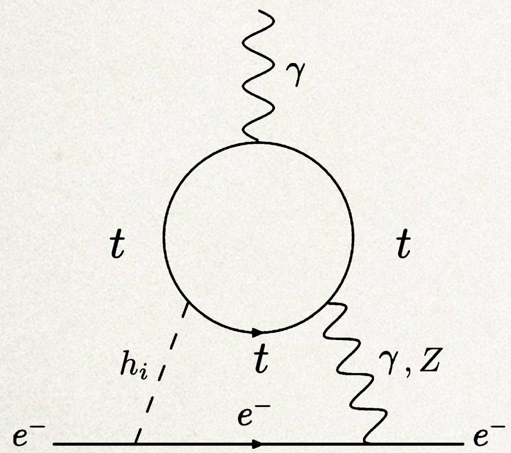

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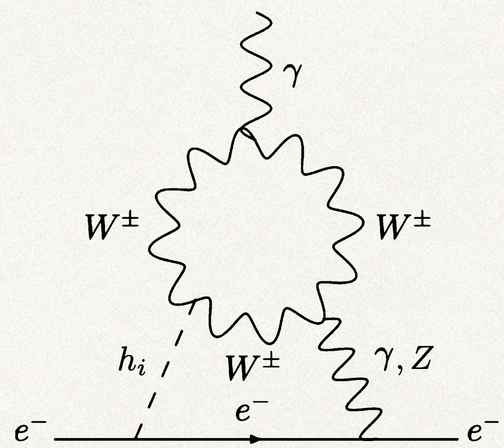

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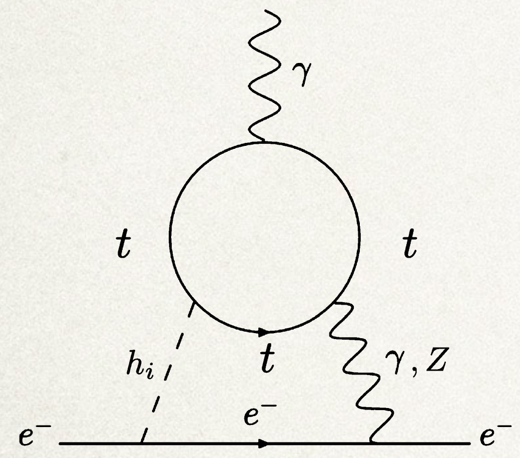
$$d_e^W \propto \sum_{i=1,2,3} a'O_{1i}O_{3i}G(m_{h_i})$$

For $m_{h_1} = m_{h_2} = m_{h_3}$, $d_e^t = 0$ and $d_e^W = 0$. $\because$ Orthogonality of mixing matrix O. $\sum_i O_{\alpha i}O_{\beta i} = \delta_{\alpha\beta}$

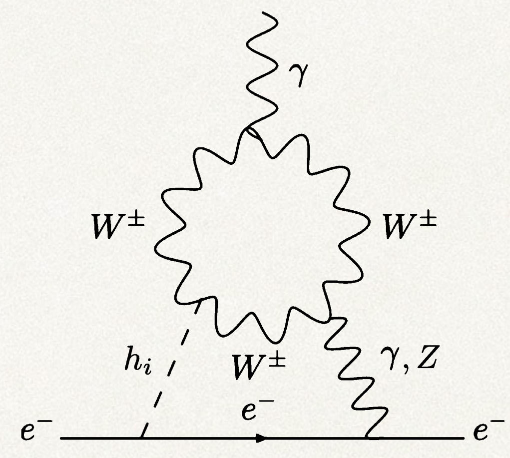
electron EDM

[C. Idegawa, E.S., PLB848 (2024) 138332]

$\underline{c_{t,e} \in \mathbb{R}}$

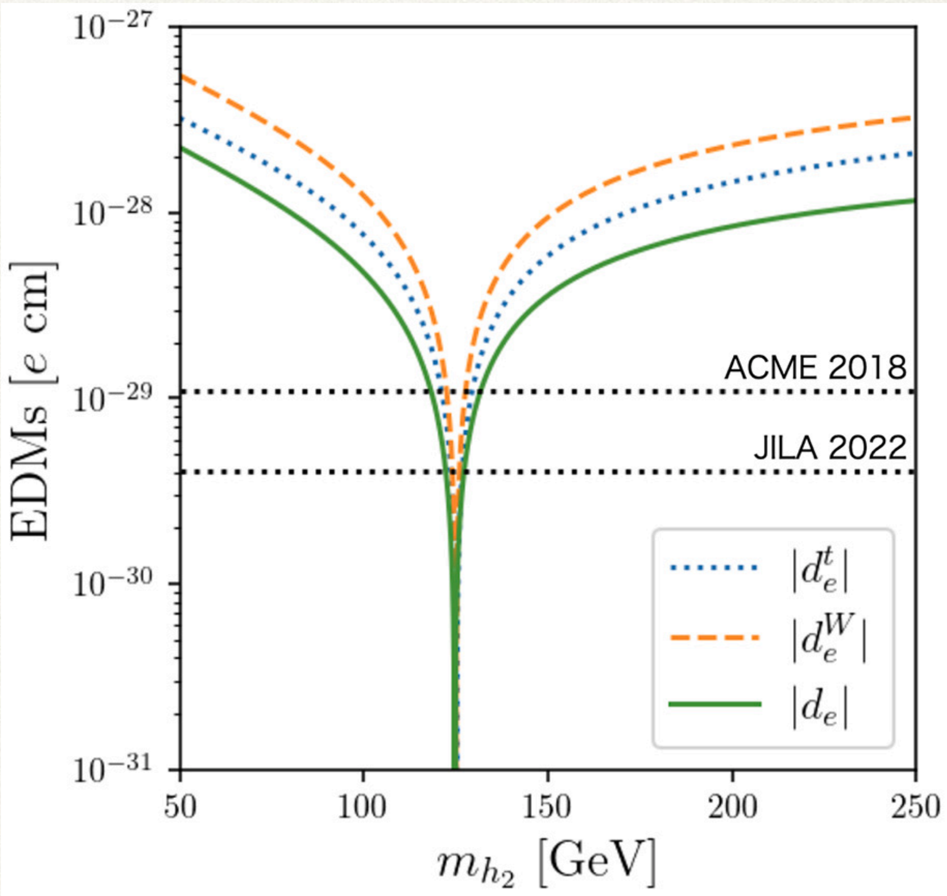


$d_e^t = (d_e^{h\gamma})_t + (d_e^{hZ})_t$



$d_e^W = (d_e^{h\gamma})_W + (d_e^{hZ})_W$

$|c_t| = y_t,\ |c_e| = y_e,\ \phi_t = \phi_e = 0,\ \Lambda = 1.0$ TeV



$$d_e = d_e^t + d_e^W$$

$$d_e^t \propto \sum_{i=1,2,3} (aO_{1i}O_{3i} + bO_{2i}O_{3i})F(m_{h_i})$$

$$d_e^W \propto \sum_{i=1,2,3} a'O_{1i}O_{3i}G(m_{h_i})$$

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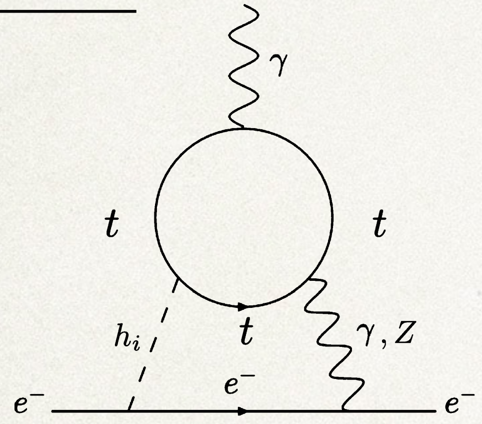
electron EDM

[C. Idegawa, E.S., PLB848 (2024) 138332]

$\underline{c_{t,e} \in \mathbb{C}}$



$$d_e^t \propto \sum_{i=1,2,3} (aO_{1i}O_{3i} + bO_{2i}O_{3i} + cO_{1i}O_{2i} + dO_{2i}O_{2i} + eO_{3i}O_{3i})\bar{F}(m_{h_i})$$

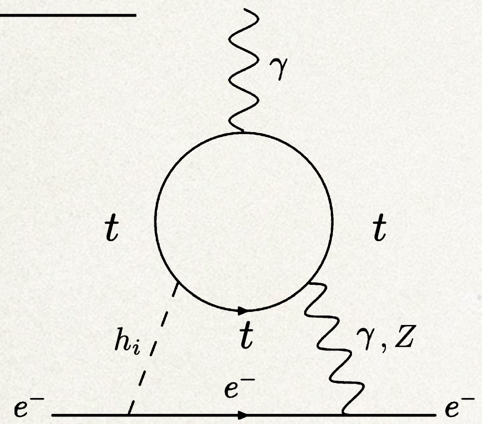
$$\underset{m_{h_i}=m_{h_j}}{\rightarrow} |c_t||c_e| \sin(\phi_t - \phi_e)\bar{F}(m_{h_i})$$

$$\longrightarrow \quad d_e^t = 0 \text{ if } m_{h_i} = m_{h_j} \text{ and } \phi_t = \phi_e \pm n\pi \ (n \in \mathbb{Z})$$

electron EDM

$\underline{c_{t,e} \in \mathbb{C}}$

[C. Idegawa, E.S., PLB848 (2024) 138332]



$$d_e^t \propto \sum_{i=1,2,3} (aO_{1i}O_{3i} + bO_{2i}O_{3i} + cO_{1i}O_{2i} + dO_{2i}O_{2i} + eO_{3i}O_{3i})\bar{F}(m_{h_i})$$

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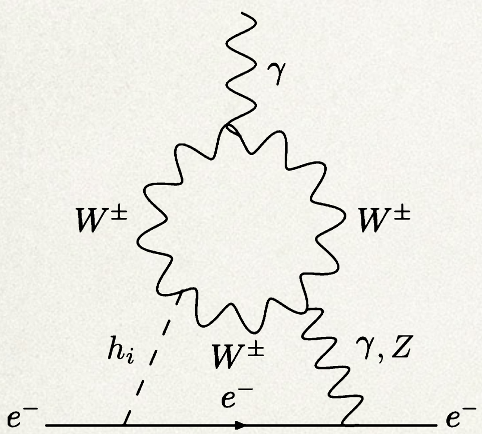


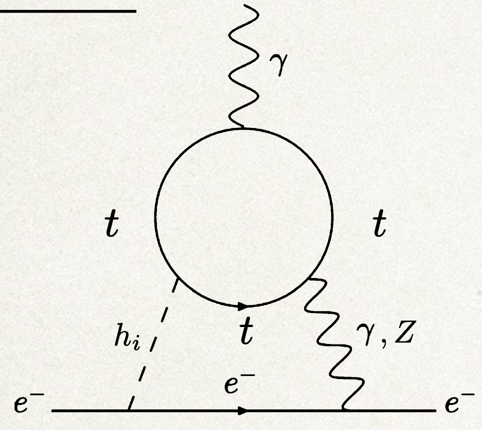
$$d_e^W \propto \sum_{i=1,2,3} (a'O_{1i}O_{3i} + b'O_{1i}O_{2i})G(m_{h_i})$$

$$\longrightarrow \quad d_e^W = 0 \text{ if } m_{h_i} = m_{h_j}$$

electron EDM

[C. Idegawa, E.S., PLB848 (2024) 138332]

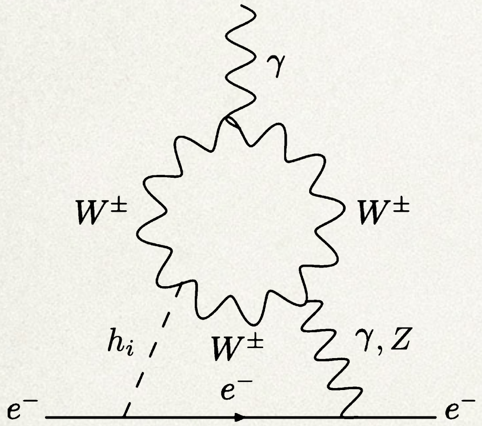
$\underline{c_{t,e} \in \mathbb{C}}$



$$d_e^t \propto \sum_{i=1,2,3} (aO_{1i}O_{3i} + bO_{2i}O_{3i} + cO_{1i}O_{2i} + dO_{2i}O_{2i} + eO_{3i}O_{3i})\bar{F}(m_{h_i})$$

$$\xrightarrow[m_{h_i}=m_{h_j}]{} |c_t||c_e|\sin(\phi_t - \phi_e)\bar{F}(m_{h_i})$$

$$\longrightarrow \quad d_e^t = 0 \text{ if } m_{h_i} = m_{h_j} \text{ and } \phi_t = \phi_e \pm n\pi \ (n \in \mathbb{Z})$$



$$d_e^W \propto \sum_{i=1,2,3} (a'O_{1i}O_{3i} + b'O_{1i}O_{2i})G(m_{h_i})$$

$$\longrightarrow \quad d_e^W = 0 \text{ if } m_{h_i} = m_{h_j}$$

Conditions for eEDM = 0

	d_e^t	d_e^W
$c_{t,e} \in \mathbb{R}$	$m_{h_i} = m_{h_j}$	$m_{h_i} = m_{h_j}$
$c_{t,e} \in \mathbb{C}$	$m_{h_i} = m_{h_j}$ & $\phi_t = \phi_e \pm n\pi$	$m_{h_i} = m_{h_j}$

eEDM can be suppressed by **mass degeneracy** and/or **phase alignment**.

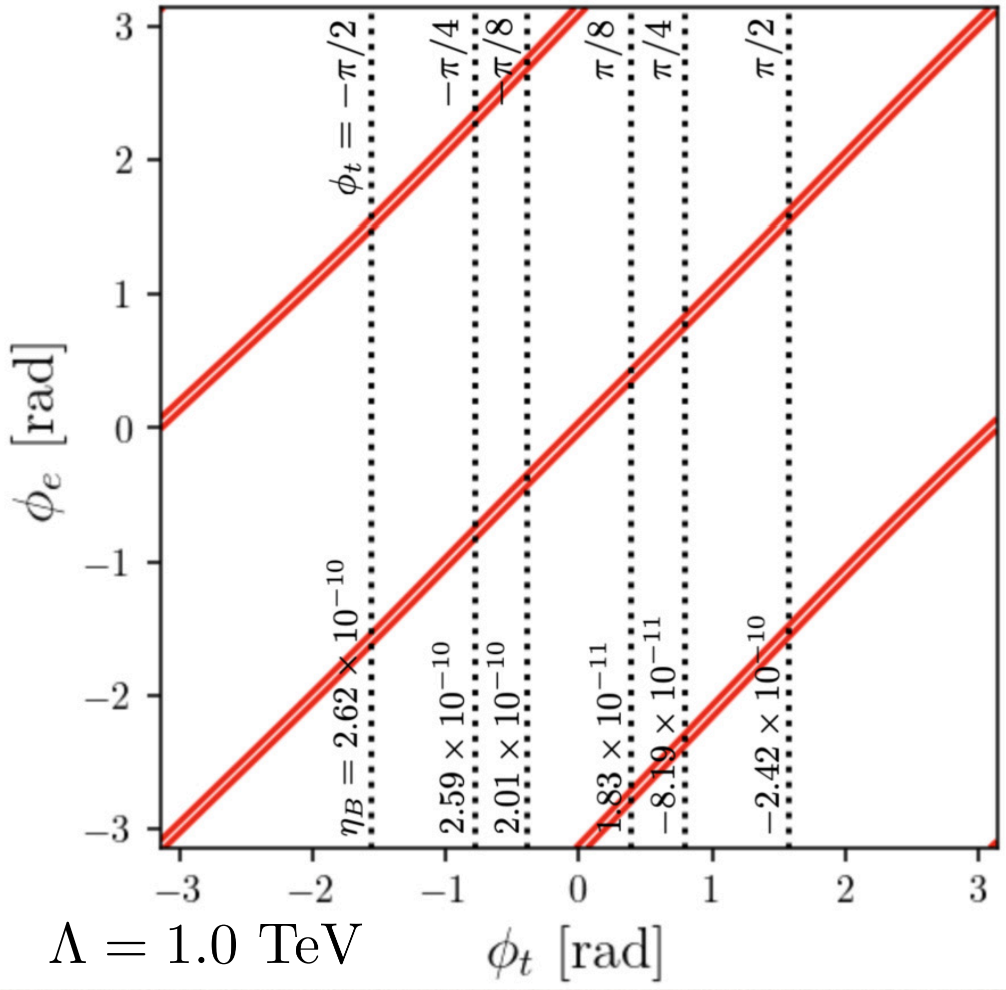
BAU

Inputs and outputs in our benchmark. In this case, $\alpha_3 = 0.464$ radians, and the Higgs coupling modifiers are $\kappa_1 = 0.711$, $\kappa_2 = -0.711$, and $\kappa_3 = 0.0$.

Inputs	v [GeV]	v_S^r [GeV]	v_S^i [GeV]	m_{h_1} [GeV]	m_{h_2} [GeV]	m_{h_3} [GeV]	α_1 [rad]	α_2 [rad]
	246.22	0.6	−0.3	125.0	124.0	124.5	$\pi/4$	0.0
Outputs	m^2	b_2 [GeV^2]	b_1 [GeV^2]	λ	δ_2	d_2	a_1^r [GeV^3]	a_1^i [GeV^3]
	$-(124.5)^2$	$-(121.2)^2$	-7.717×10^{-12}	0.511	1.51	1.111	$-(18.735)^3$	$-(14.870)^3$

$$\eta_B^{\rm BBN} = (5.8 - 6.5) \times 10^{-10}, \quad \eta_B^{\rm CMB} = (6.105 \pm 0.055) \times 10^{-10}$$

within narrow bands $|d_e| < |d_e^{\rm JILA}|$



- JILA constraint is avoidable by the scalar mass degeneracy and phase alignment.

- BAU (based on a WKB method) is somewhat smaller than the observed values.

Q. Can we say that this scenario is excluded because of the deficit of the BAU?

BAU computations

- Semi-classical force mechanism (WKB approximation)

  [Joyce et al, PRL75, 1695 ('95), J. Cline et al, JHEP 07 (2000) 018]

- VEV insertion approximation (VIA)

  [Riotto, hep-ph/9510271, 9712221, 9803357, Lee, Cirigliano, Ramsey-Musolf, hep-ph/0412354]

- BAU(VIA) > BAU(WKB) by up to $O(10^2)$ 2108.03580, 2108.04249

- Non-existence of CPV source by the above VIA calculation 2108.08336, 2206.01120

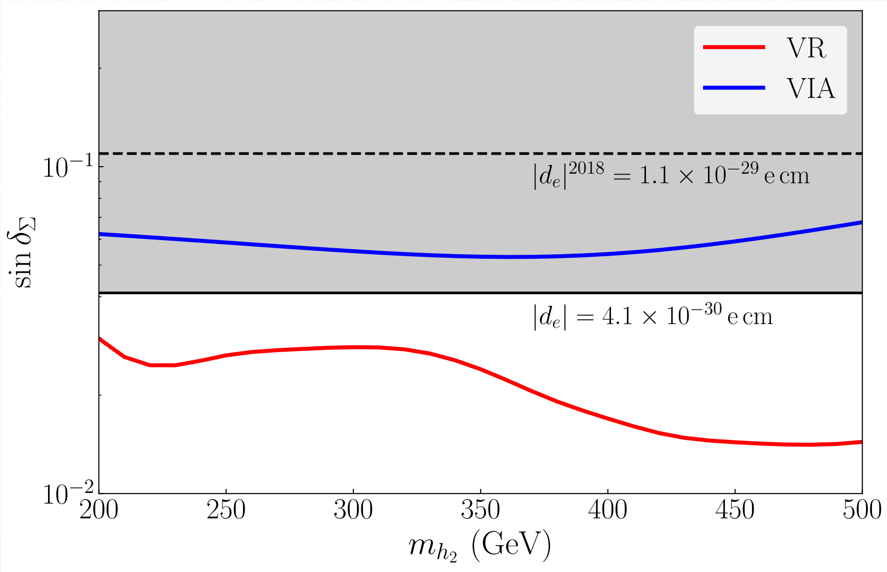
In 2024, a new result came along.

- VEV Resummation (VR) (with flavor oscillation)

  [Y-Z. Li, M. J. Ramsey-Musolf, J-H. Yu, 2404.19197]

- BAU(VR) > BAU(VIA) by up to around 5.

- Consistent with the JILA experiment.



However, the BAU shown here is still not robust.

Theoretical challenges

EWBG calculation is subject to a lot of uncertainties.

(1) Electroweak phase transition

- Lattice calculations are necessary for quantitative studies.

(2) Bubble walls

- Wall profile (velocity, thickness, etc) is essential for the BAU calculation.

(3) Sphaleron

- Refinement of $\Gamma_B < H$

(4) BAU calculation Closed-time-path formalism

- Consistent treatment of CPV source and its diffusion in a moving bubble wall
- Beyond derivative expansion in a thin wall case

BAU is still order-of-magnitude estimate.

"EWBG possible region" should be interpreted as "BAU can be in the right ballpark value within 1-2 order-of-magnitude theoretical uncertainties".

Lesson from SM EWBG

EWBG in the SM was excluded.

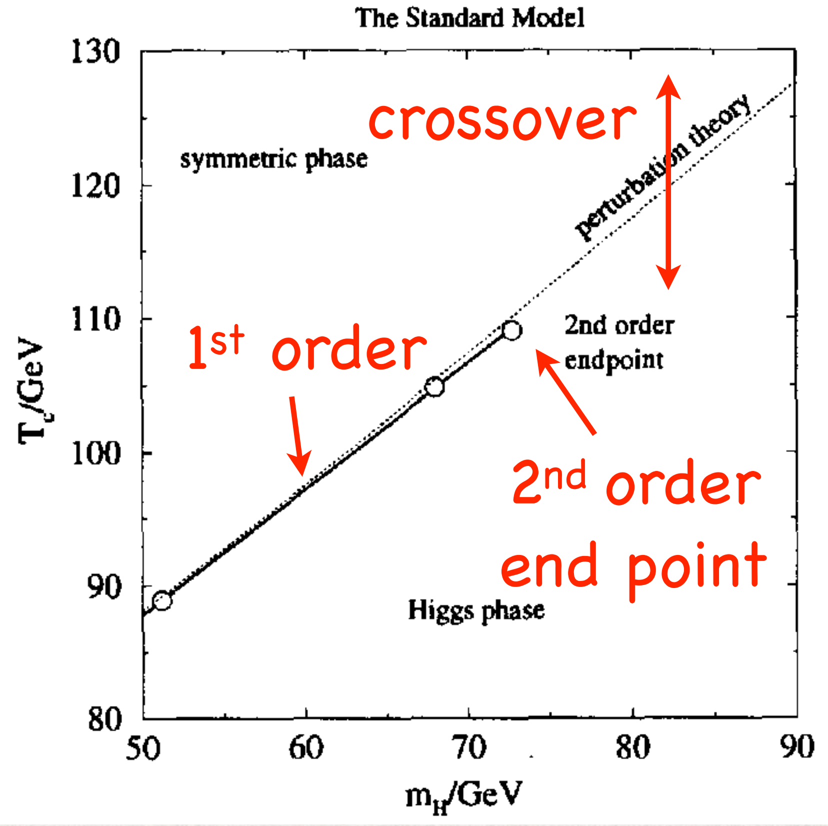
- CP violating effect is too small to generate BAU

[Gavela et al, NPB430,382 ('94); Huet and Sather, PRD51,379 ('95).]

* Even though the BAU is way below the observed value, we still do not know its precise value due to the lack of consistent and robust BAU formulation.

- EWPT is smooth crossover for m_h>73 GeV.

[Kajantie at al, PRL77,2887 ('96); Rummukainen et al, NPB532,283 ('98); Csikor et al, PRL82, 21 ('99); Aoki et al, PRD60,013001 ('99). Laine et al, NPB73,180('99)]



There was no consensus on the viability of EWBG until lattice calculations ruled out the possibility of the 1st-order EWPT.

The importance of Higgs physics is not weakened by the current EDM results.

Summary

- No EWBG possibility in SM and MSSM.

strong 1st-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, JILA, Belle are probing EWBG possible regions.

JILA's result is impressive, but other probes are still necessary.

Future

- Hadron colliders (HL-LHC, etc)
- lepton colliders (ILC, etc)
- EDM experiments: electron (ACME, JILA, etc), proton (IBS-CAPP, BNL, etc)
- Gravitational waves (LISA, TianQin, Taiji, DECIGO, etc)

EWBG verification continues, and most scenarios would be tested by future experiments if theoretical uncertainties are under control.

Backup

Degenerate scalar scenario

S. Abe, G.-C. Cho, and K. Mawatari, PRD104, 035023 (2021).

$m_{h_1} \simeq m_{h_2} \simeq 125\ \mathrm{GeV}$

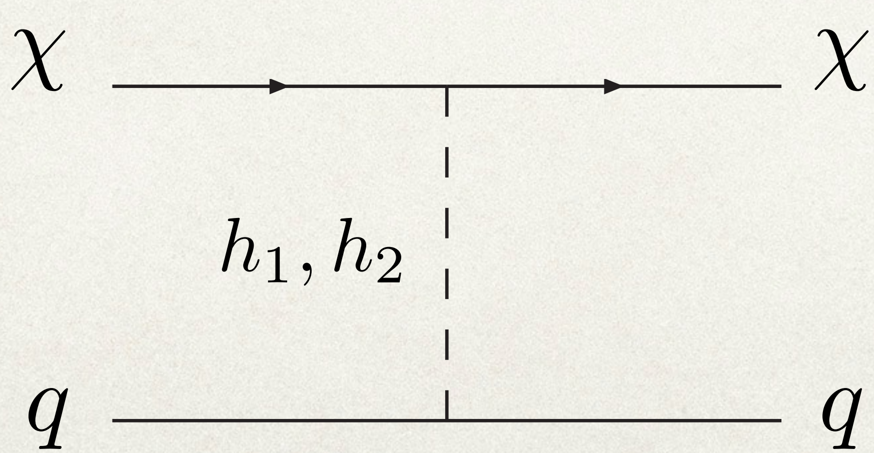
$$\sigma_{gg\to h_i \to VV^*} \underset{m_{h_1}\simeq m_{h_2}}{\simeq} \sigma^{\mathrm{SM}}_{gg\to h}\left[\sum_i \frac{\kappa_{if}^2\kappa_{iV}^2}{\Gamma_{h_i}}\right]\Gamma^{\mathrm{SM}}_{h\to VV^*}$$

$$= \sigma^{\mathrm{SM}}_{gg\to h}\cdot \mathrm{Br}^{\mathrm{SM}}_{h\to VV^*} \quad \left(\Gamma_{h_i} \simeq \kappa_i^2 \Gamma_h^{\mathrm{SM}},\ \sum_i \kappa_i^2 = 1\right)$$

Higgs signal strengths become SM-like.

In this talk, $m_{h_1} \simeq m_{h_2} \simeq m_{h_3}$

*This scenario was investigated in the context of DM physics.



$$\sigma_{\mathrm{SI}} \propto \sin^2\alpha\cos^2\alpha\left(\frac{1}{m_{h_1}^2}-\frac{1}{m_{h_2}^2}\right)^2\frac{a_1^2}{v_S^4}$$

-> 0 for $m_{h1}=m_{h2}$

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
1st-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]	$\kappa_\lambda = \dfrac{\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} \gtrsim 1.1$	$\kappa_\lambda = \dfrac{\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} \simeq 1$

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

*3 degenerate scalars (H, A, H+) could also be consistent with $v_C/T_C > 1$.

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

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[S.Kanemura, Y.Okada, E.S., PLB606 (2005) 361]	$\kappa_\lambda \in \begin{cases} (-0.4, 6.3) \\ (-1.24, 6.49) \end{cases}$	ATLAS 2211.01216 CMS 2207.00043

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

*3 degenerate scalars (H, A, H+) could also be consistent with $v_C/T_C > 1$.

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)]

$v_C/T_C > (1.1\text{–}1.3)$

precise enough → $\mathrm{min} < \left|\frac{\delta g}{g^{\mathrm{SM}}}\right| < \mathrm{max}$ ← data

BSM models

SUSY models

- Minimal Supersymmetric SM (MSSM)

BSM models

SUSY models

- Minimal Supersymmetric SM (MSSM)

    strong 1^{st}-order EWPT

    light stop (< top mass)

BSM models

SUSY models

- Minimal Supersymmetric SM (MSSM)

strong 1^{st}-order EWPT

light stop (< top mass)

CPV

chariginos, neutralinos

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light stop (< top mass)

-> viable window is closed.

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

Yukawa interactions in g2HDM

general (no Z_2 sym.)

Up-type Yukawa couplings:

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

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- EWBG by ρ_{tt} (t-EWBG), ρ_{bb} (b-EWBG), $\rho_{\tau\tau}$ (τ-EWBG), etc.

EDM cancellations in t-EWBG

We reanalyze the eEDM with nonzero ρ_{ee}.

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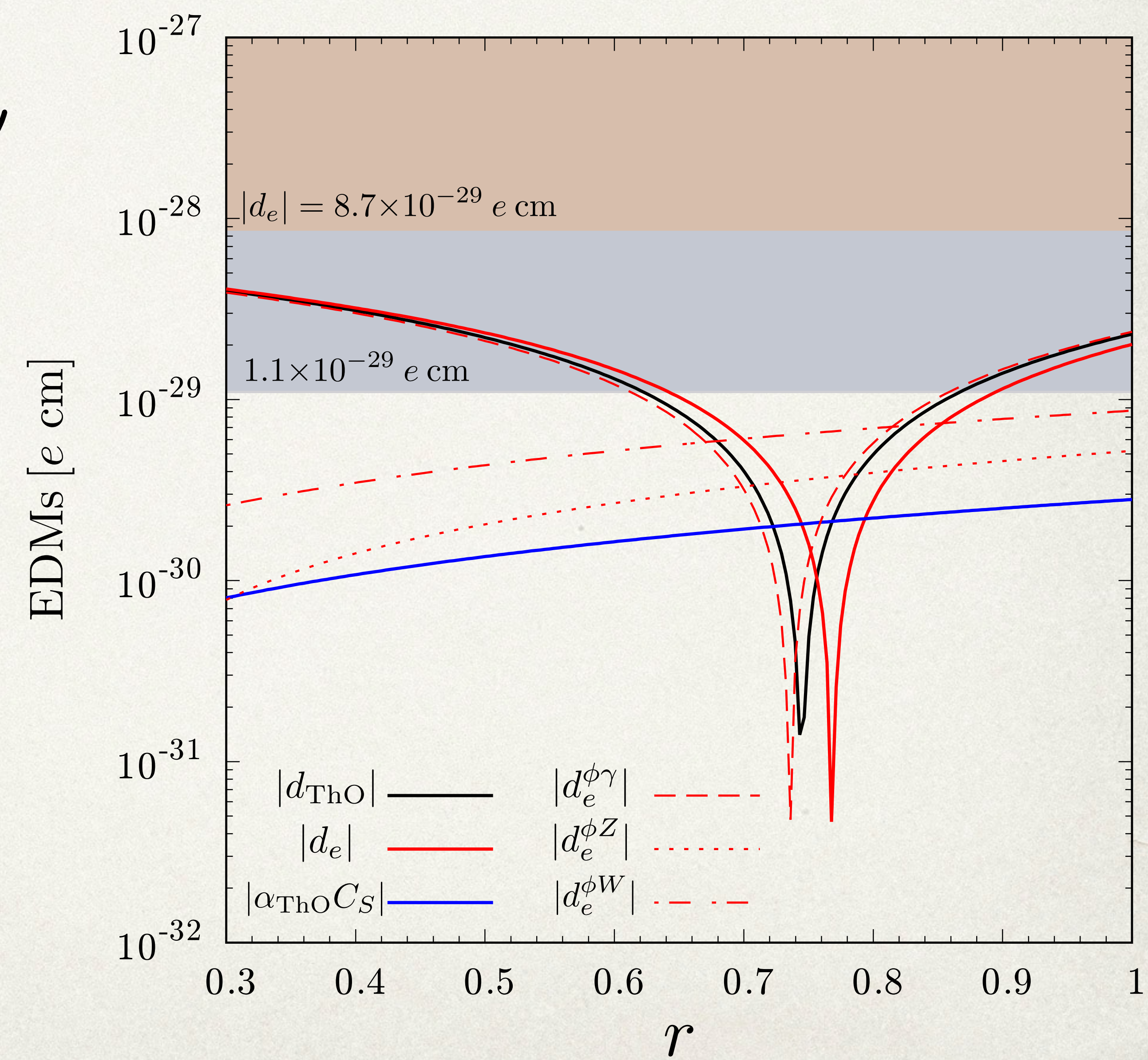

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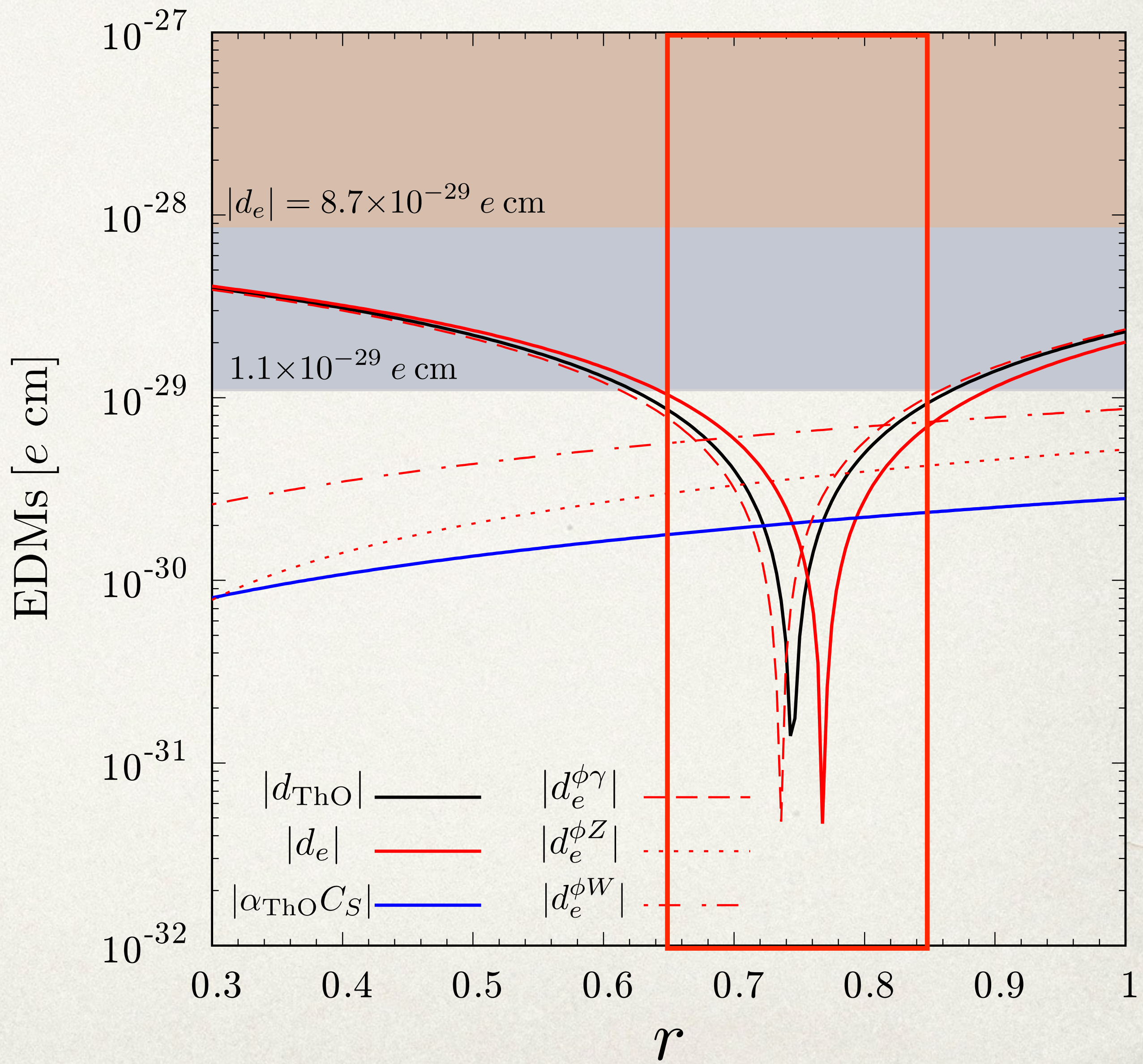

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- cancellation at r=O(1) (structured cancellation)
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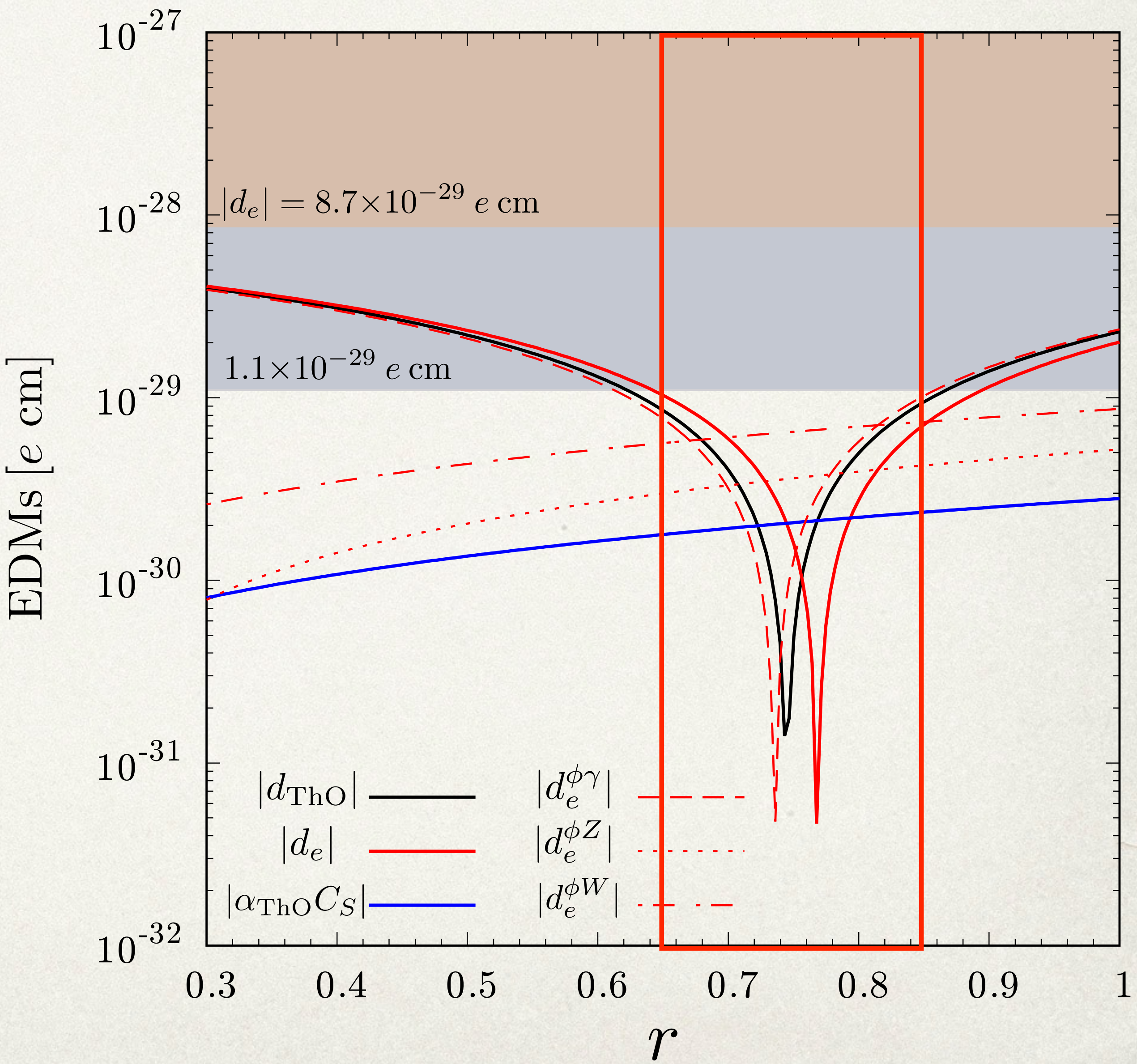

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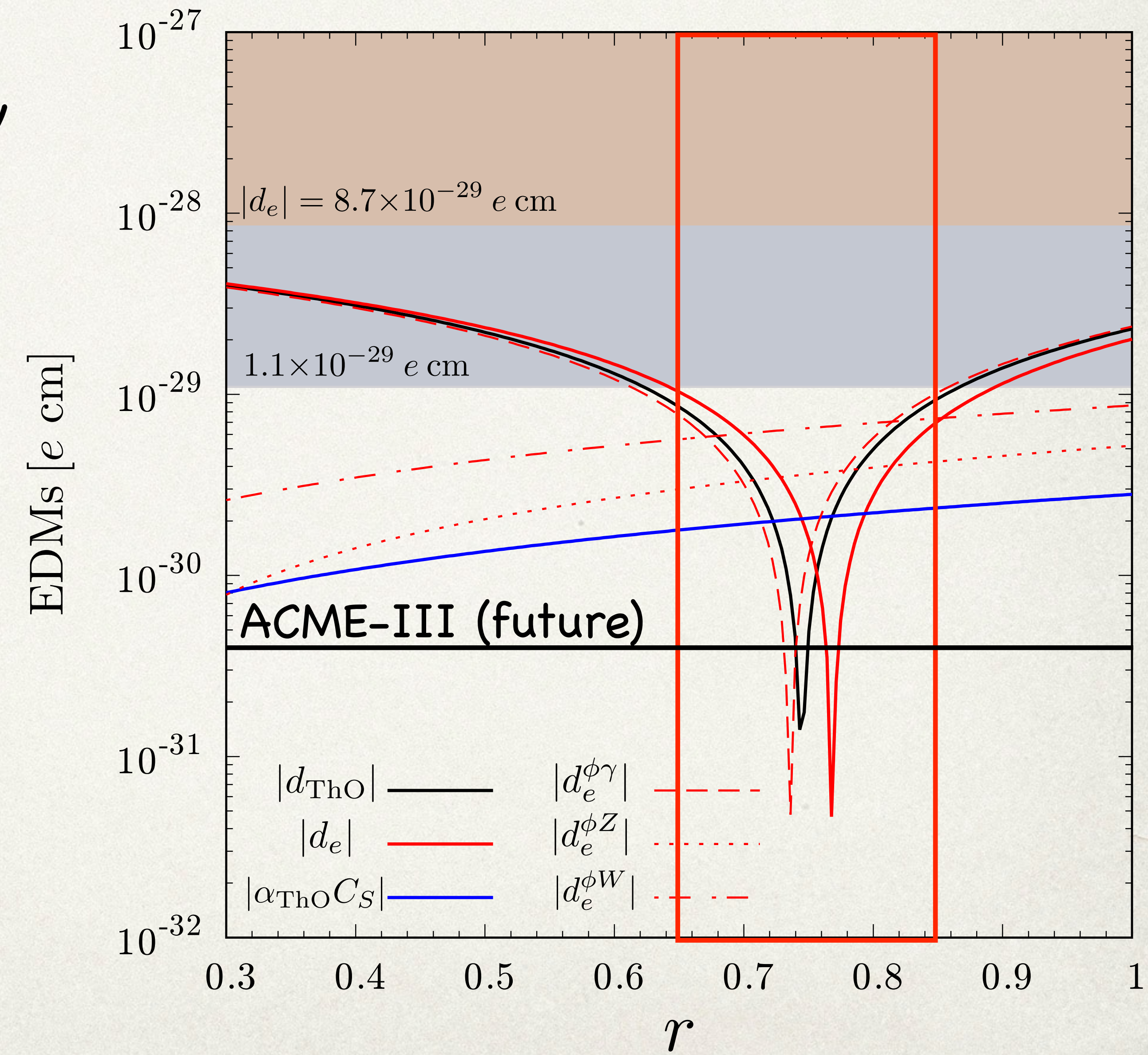

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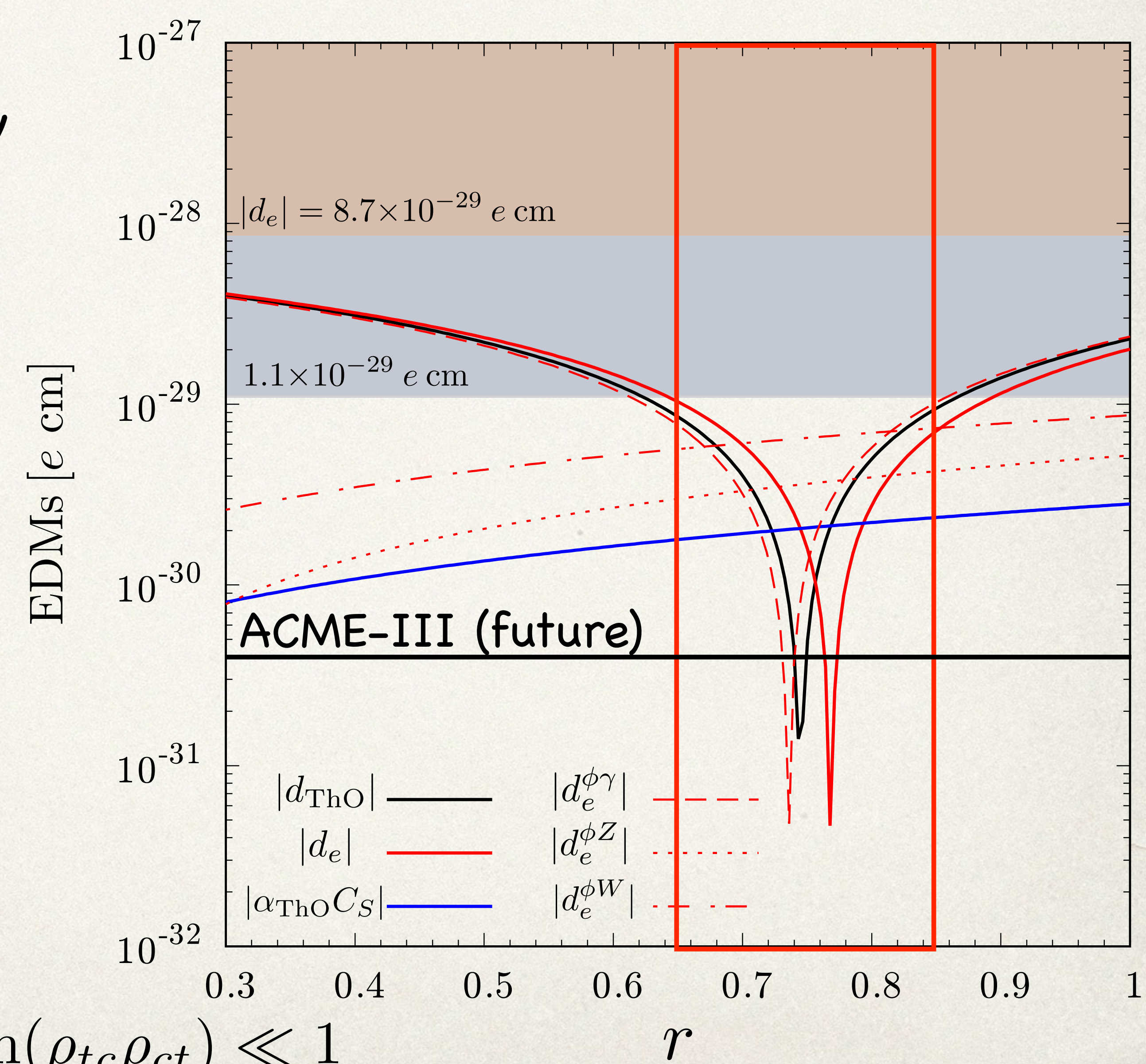
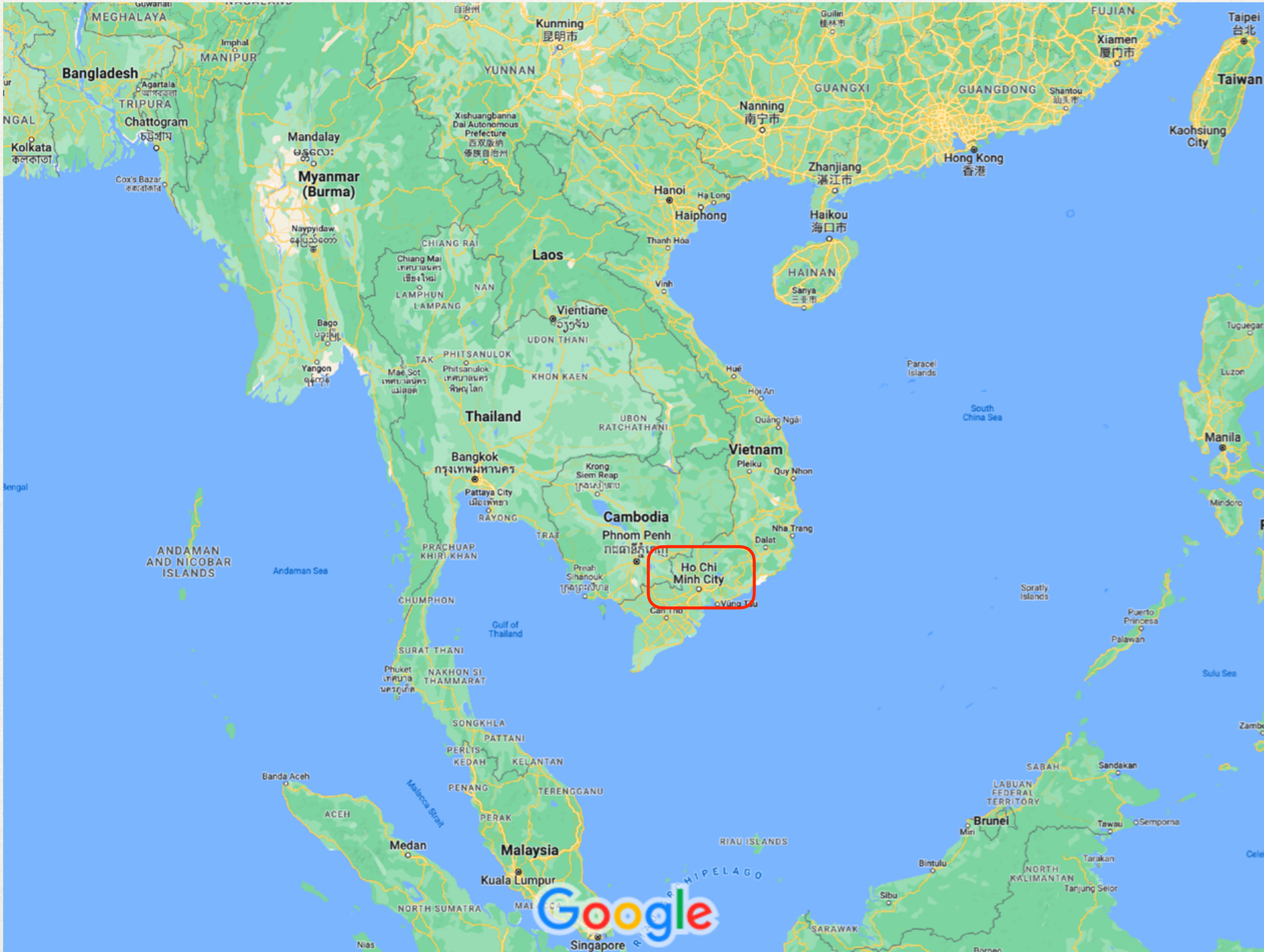


* Much less EDM constraint on tc-EWBG. $\mathrm{Im}(\rho_{tc}\rho_{ct}) \ll 1$

Where is Van Lang Univ.?



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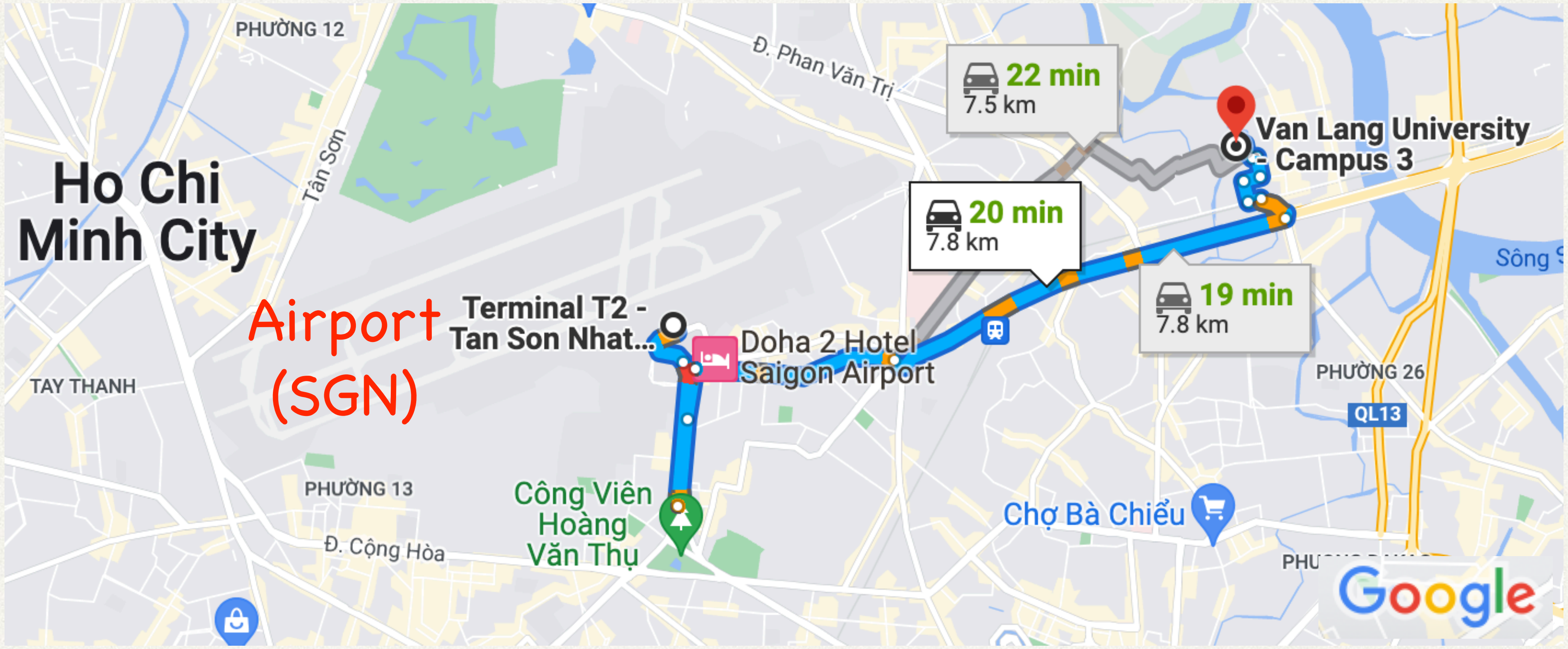

I belong to
Subatomic Physics Research Group in Science and Technology Advanced Institute (STAI) since October in 2021.