Electroweak Baryogenesis in general 2HDM: update

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Dec 22, 2020 @Webinar of Osaka U

[1] Koichi Funakubo (Saga U) and E.S., 2003.13929.(PRD)

[2] Kaori Fuyuto (LANL), Wei-Shu Hou (Natl Taiwan U) and E.S., 1910.12404 (PRD).

Outline

- Motivation
- Electroweak baryogenesis (EWBG) in general 2HDM

  (1) Improvement of sphaleron decoupling condition

  (2) Update on top-driven EWBG in light of ACME-II

- Summary

Motivation

- SM cannot explain baryon asymmetry of the Universe (BAU), $n_B/n_\gamma \simeq 10^{-10}$.

  (1) no strong 1st-order EW phase transition (EWPT),
  (2) no sufficient CP violation

- 2HDM is a simplest extension that can solve the 2 problems.

(1) Sphaleron decoupling condition is crucial for EWBG tests.

-> We quantify overlooked magnetic mass effects on the condition.

K. Funakubo (Saga U) and E.S., 2003.13929.(PRD)

(2) Size of CP violation is highly constrained by electron electric dipole moment experiment [ACME II (2018)].

-> We revisit top-driven EWBG scenario.

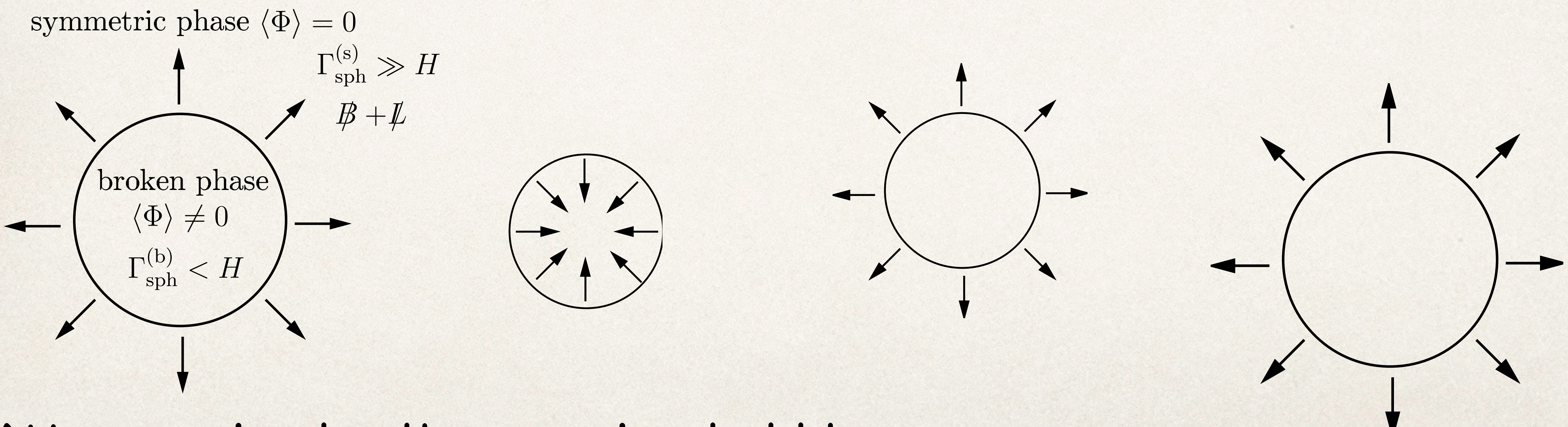
K. Fuyuto (LANL), W.-S. Hou (Natl Taiwan U) and E.S., 1910.12404 (PRD).

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: KM phase 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.

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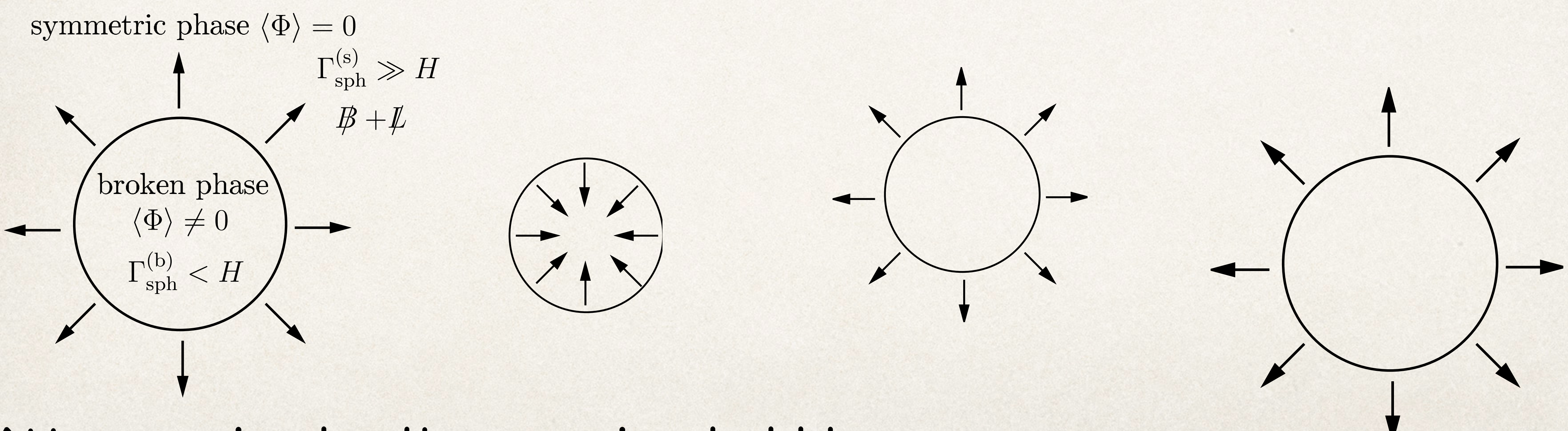
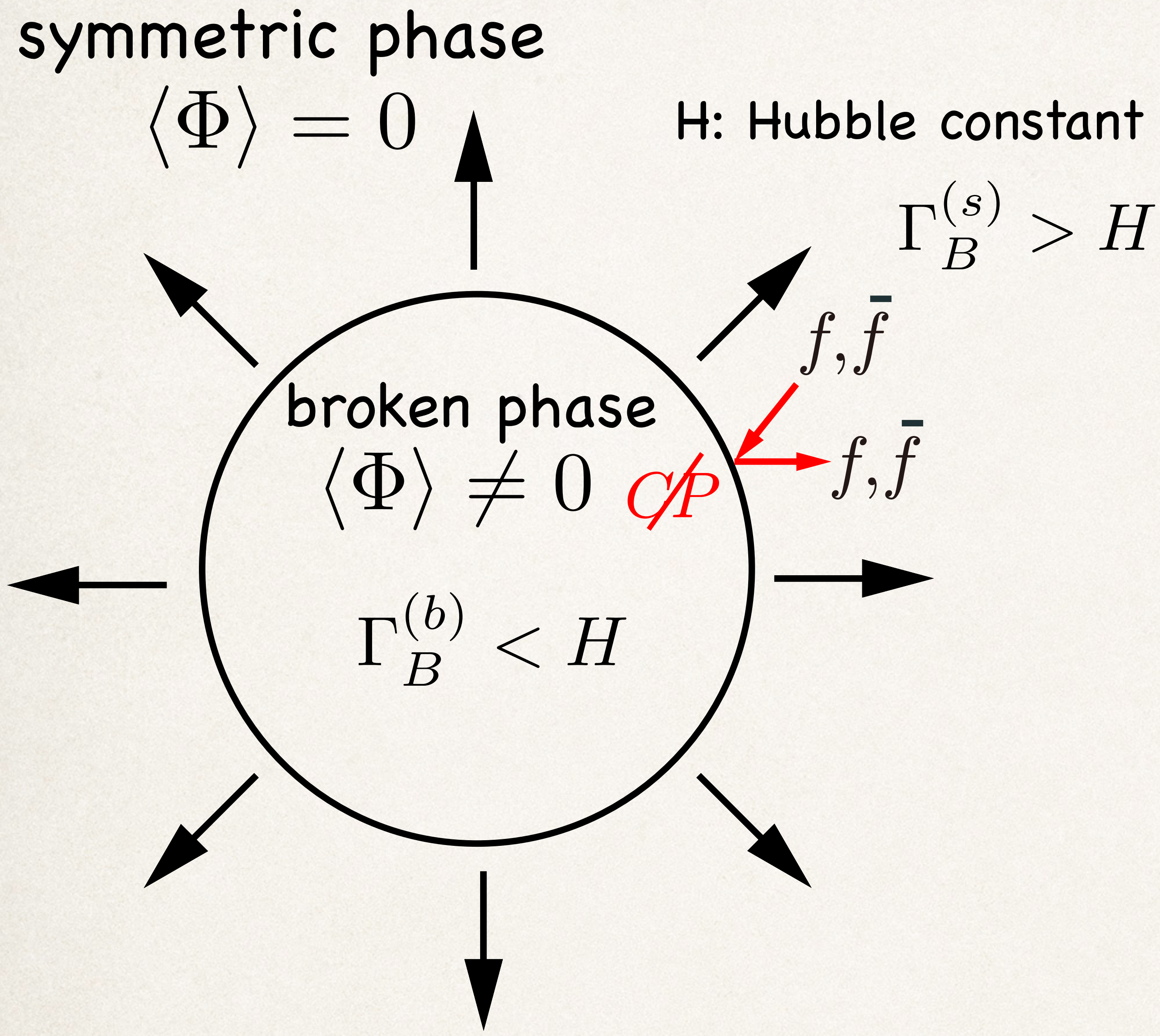
NEW PHYSICS wanted

- CP violation: KM phase 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



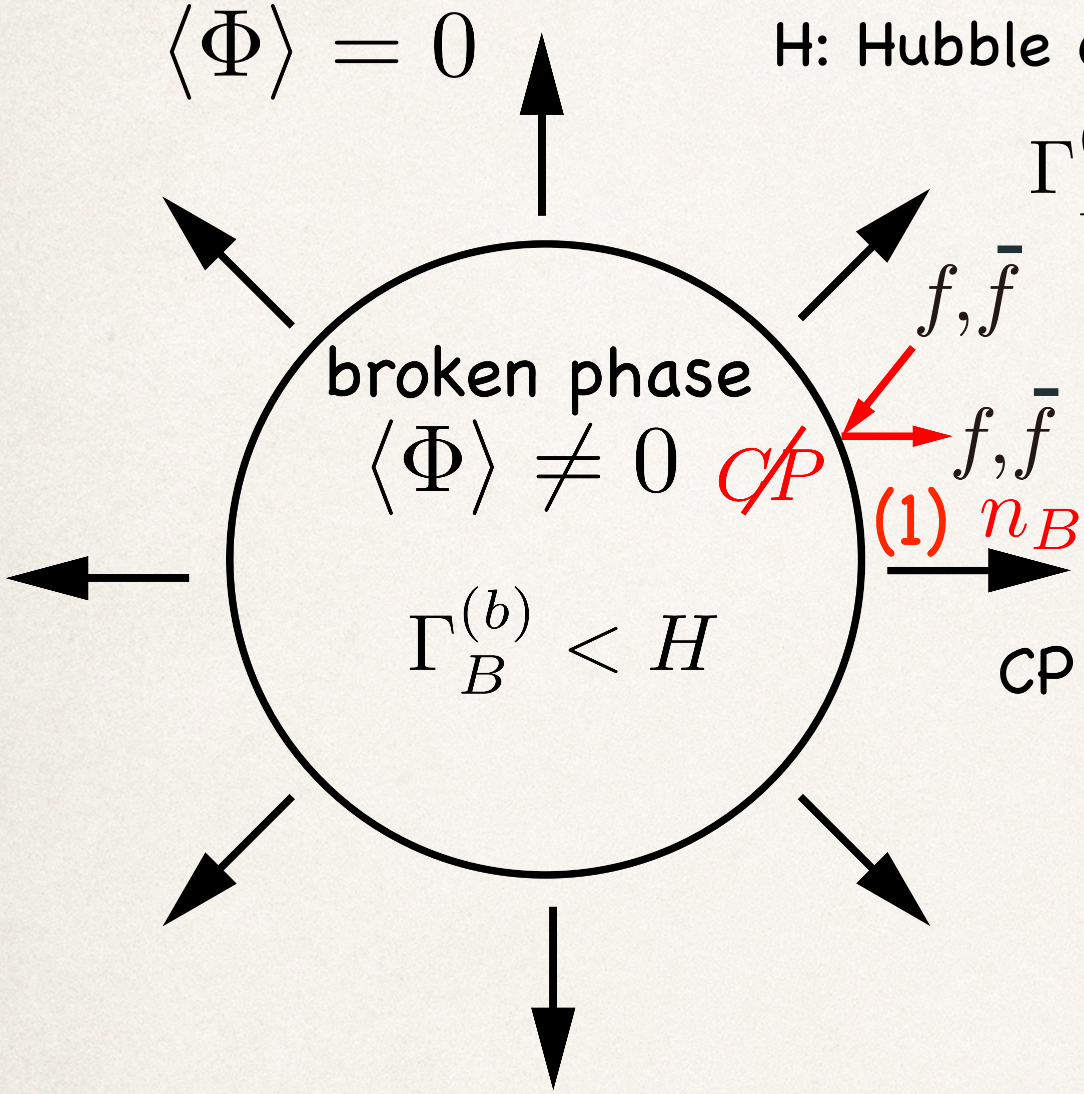
EWBG mechanism

symmetric phase

$\langle \Phi \rangle = 0$

H: Hubble constant

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



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CP asymmetric but no B asymmetric

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

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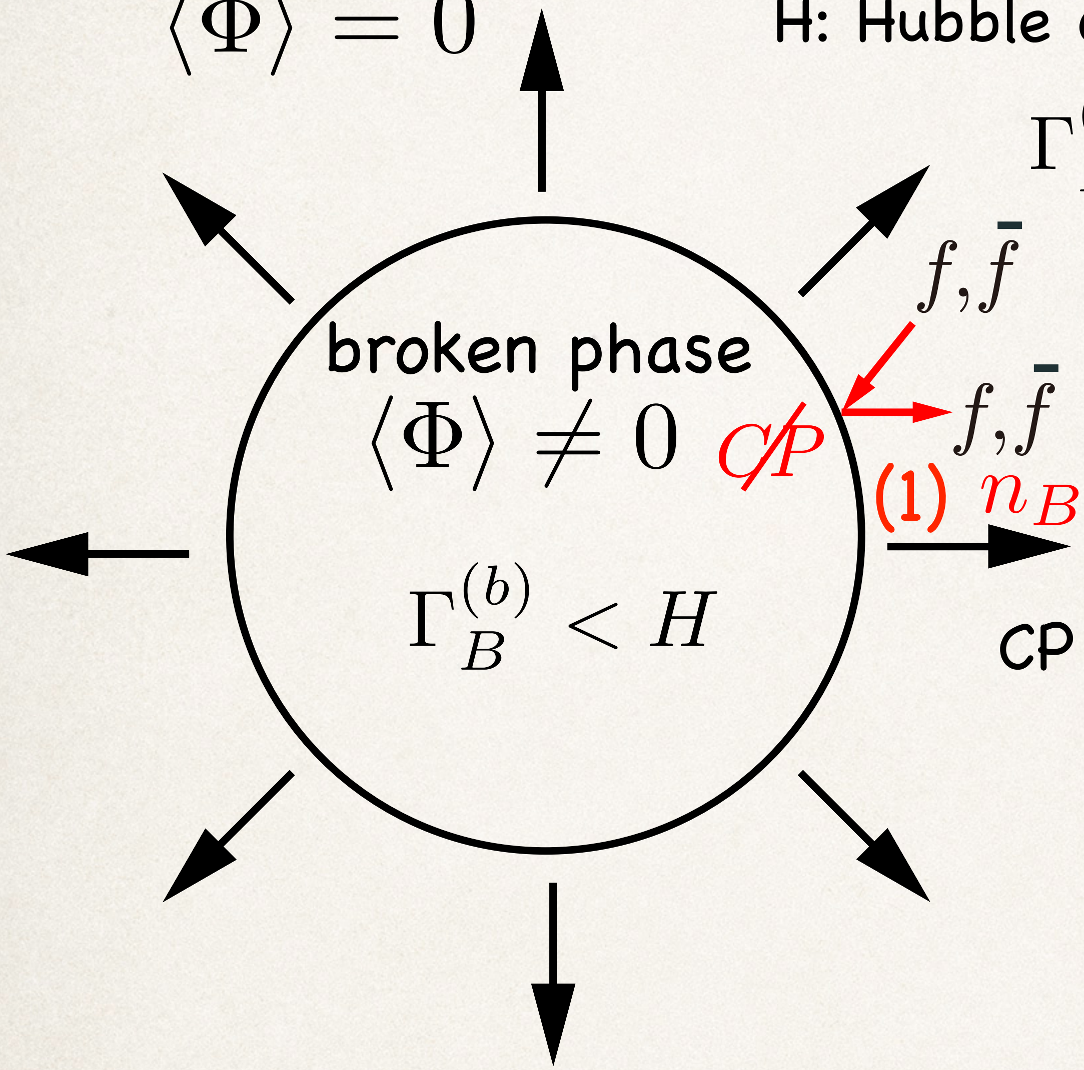
baryogengesis!!



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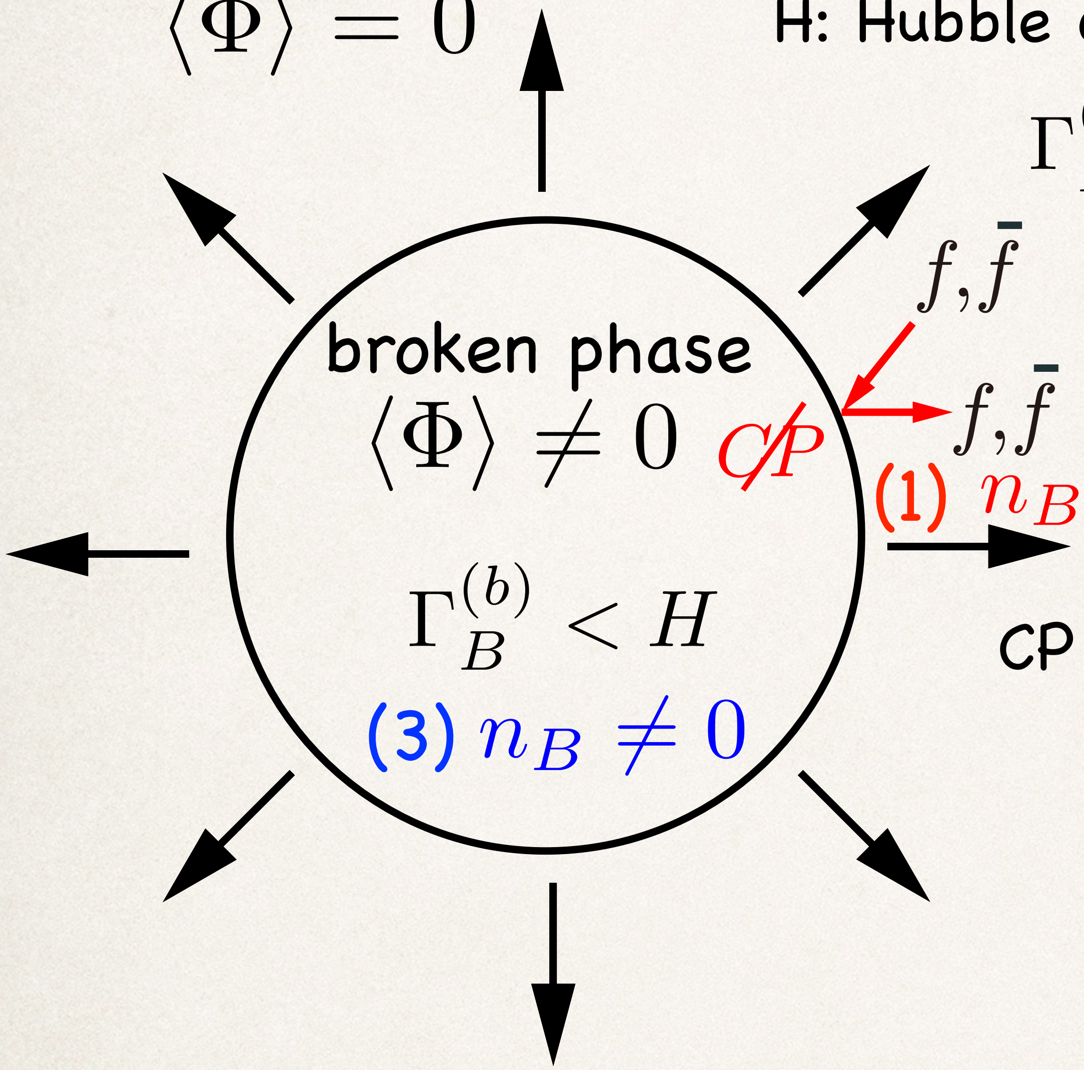

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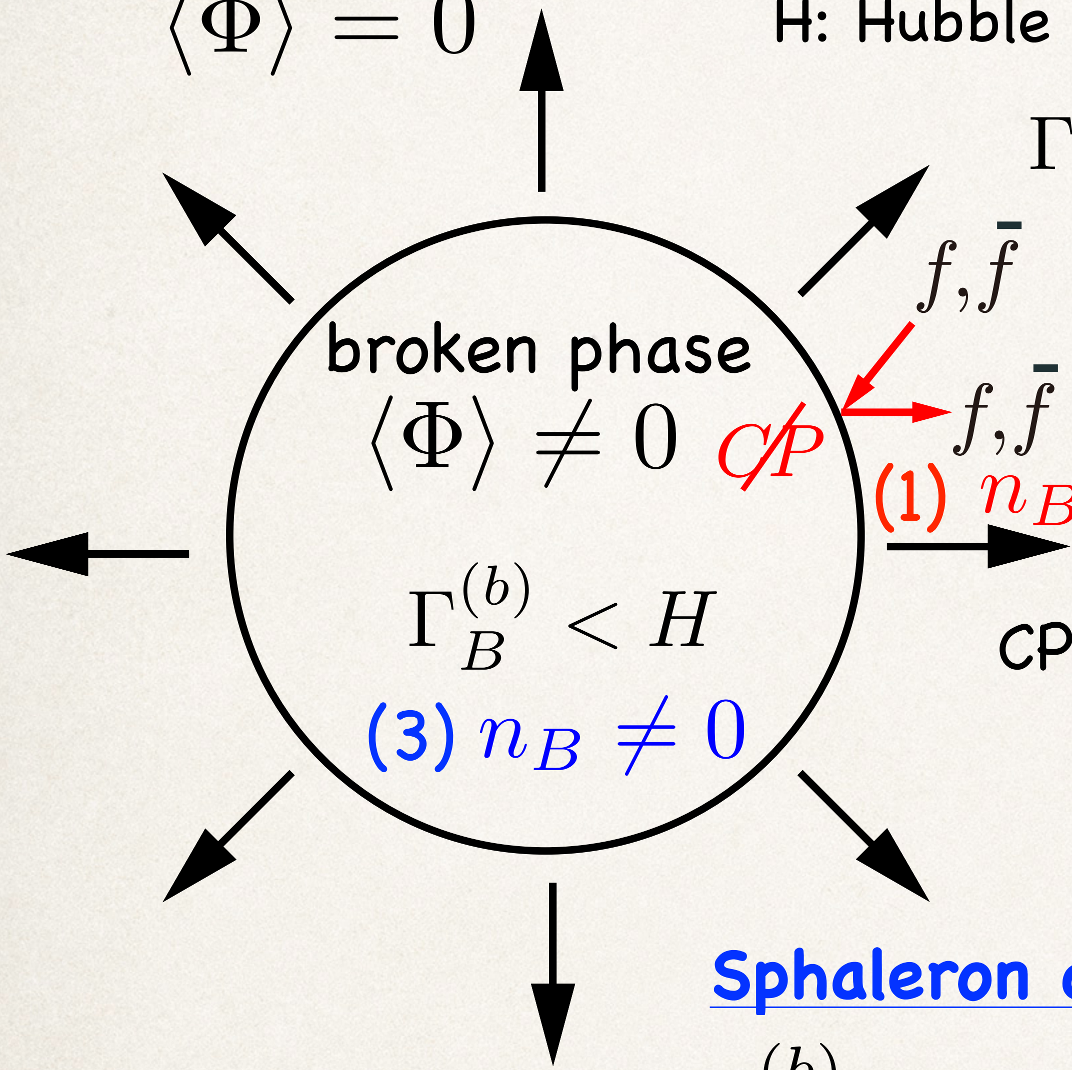

broken phase

$\langle \Phi \rangle \neq 0$ $\cancel{CP}$

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

(3) $n_B \neq 0$

Sphaleron decoupling condition

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

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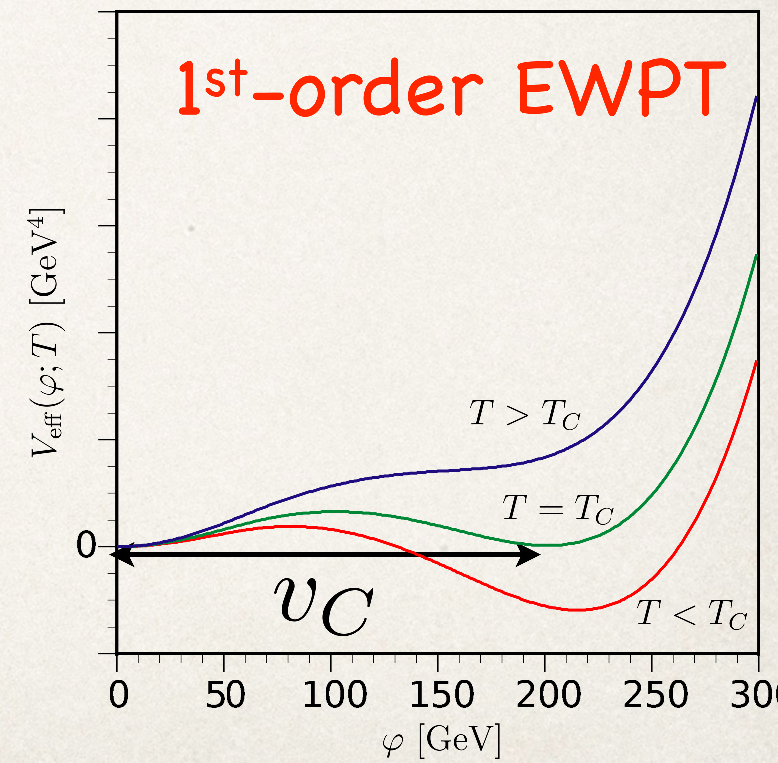

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$$\rightarrow \boxed{1 \lesssim \frac{v_C}{T_C}}$$

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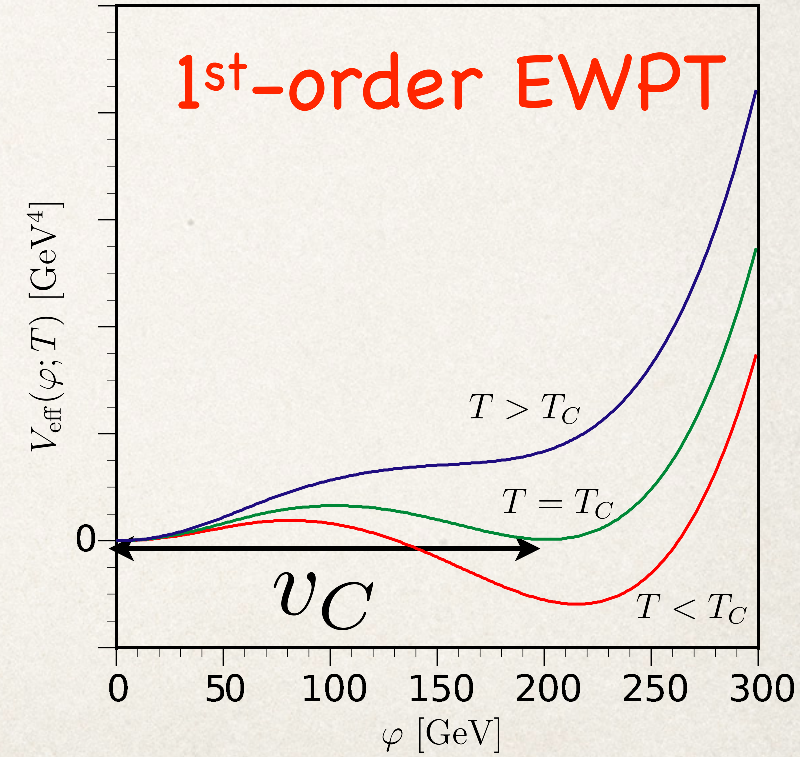
$$\to \boxed{1 \lesssim \frac{v_C}{T_C}} \to \min < \left| \frac{\delta g}{g^{\rm SM}} \right| < \max$$

$\to$ particle spectrum



EWBG mechanism

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

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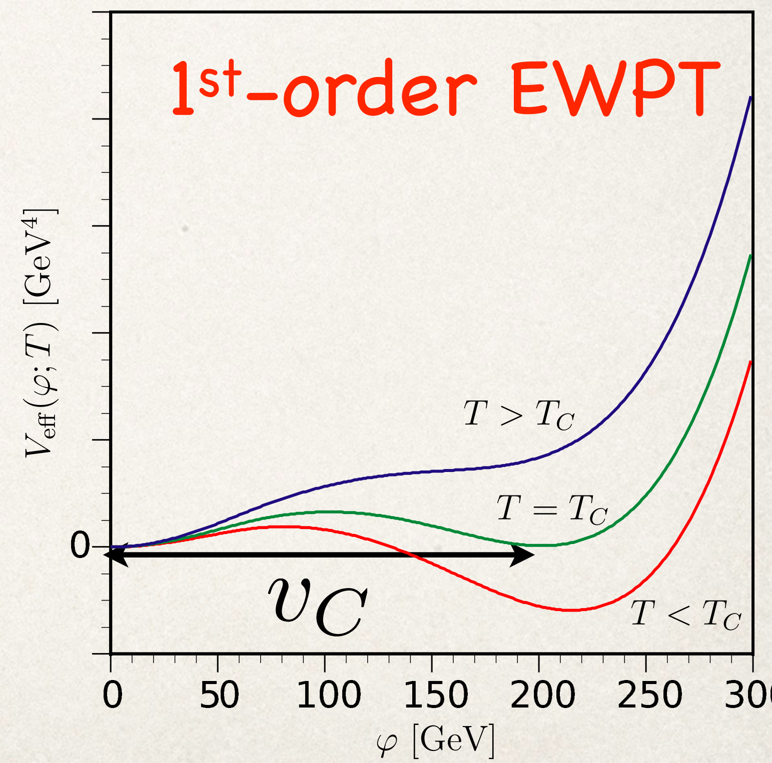

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model-dependent

$$\longrightarrow \boxed{1 \lesssim \frac{v_C}{T_C}} \longrightarrow \min < \left| \frac{\delta g}{g^{\rm SM}} \right| < \max$$

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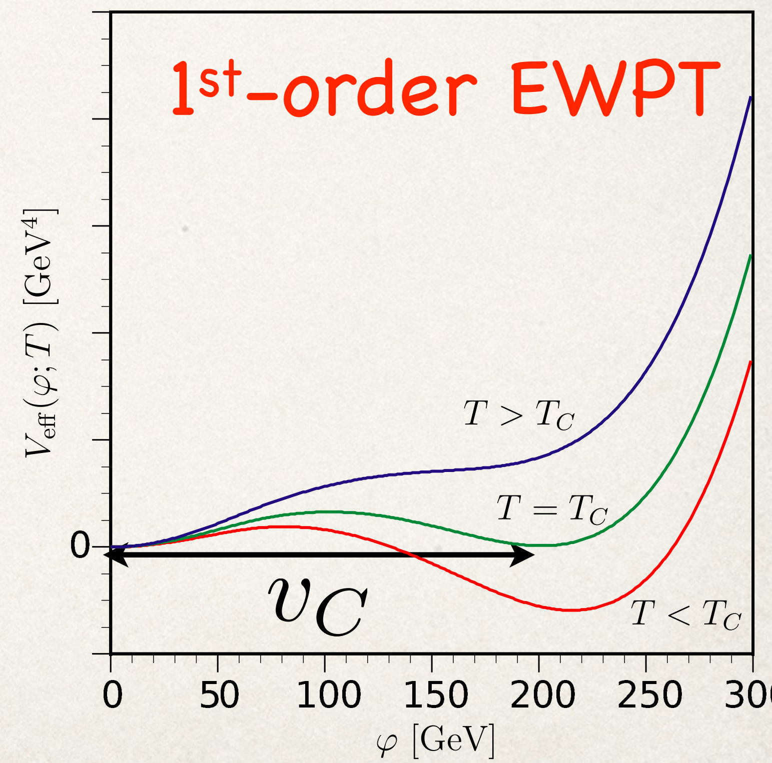
particle spectrum ← constrained by exp. data



Today's topics

1. "Magnetic mass effect on sphaleron energy",
Koichi Funakubo and E.S., 2003.13929 (PRD).

Improvement of sphaleron decoupling condition $$\frac{v_C}{T_C} \gtrsim 1$$

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2. "Cancellation mechanism for the electron electric dipole moment connected with the baryon asymmetry of the Universe",
Kaori Fuyuto, Wei-shu Hou and E.S., 1910.12404 (PRD).

Cancellation mechanism for electron EDM in general 2HDM.

Sphaleron decoupling condition

To avoid washout of BAU, the sphaleron process must be suppressed after EWPT.

Hubble constant

1.22×10^{19} GeV

$$\Gamma_B^{(b)} = \frac{13\cdot 3}{4\cdot 8\pi^2}\frac{\omega_-}{\alpha_W^3}\kappa\mathcal{N}_{\rm tr}\mathcal{N}_{\rm rot}e^{-E_{\rm sph}/T} < \boxed{H(T)} \simeq 1.66\sqrt{g_*(T)}T^2/m_{\rm P}$$

dof of relativistic particles

ω_-: negative mode $\quad \mathcal{N}_{\rm tr}$: translational zero modes,

κ: nonzero modes $\quad \mathcal{N}_{\rm rot}$: rotational zero modes.

Parametrizing $E_{\rm sph} = 4\pi v\mathcal{E}_{\rm sph}/g$,

$$\frac{v}{T} > \frac{g}{4\pi\mathcal{E}_{\rm sph}}\left[44.35 + \ln(\kappa\mathcal{N}_{\rm tr}\mathcal{N}_{\rm rot}) + \ln\left(\frac{\omega_-}{m_W}\right) - \frac{1}{2}\ln\left(\frac{g_*}{106.75}\right) - 2\ln\left(\frac{T}{100\ \text{GeV}}\right)\right] \equiv \zeta_{\rm sph}(T)$$

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leading $\quad$ next-to-leading ~1% (SM) $\quad$ < 1%

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Sphaleron in the SM

~ w/o U(1)$_Y$ ~

$$\mathcal{L}_{\text{gauge+Higgs}} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + (D_\mu\Phi)^\dagger D^\mu\Phi - V(\Phi),$$

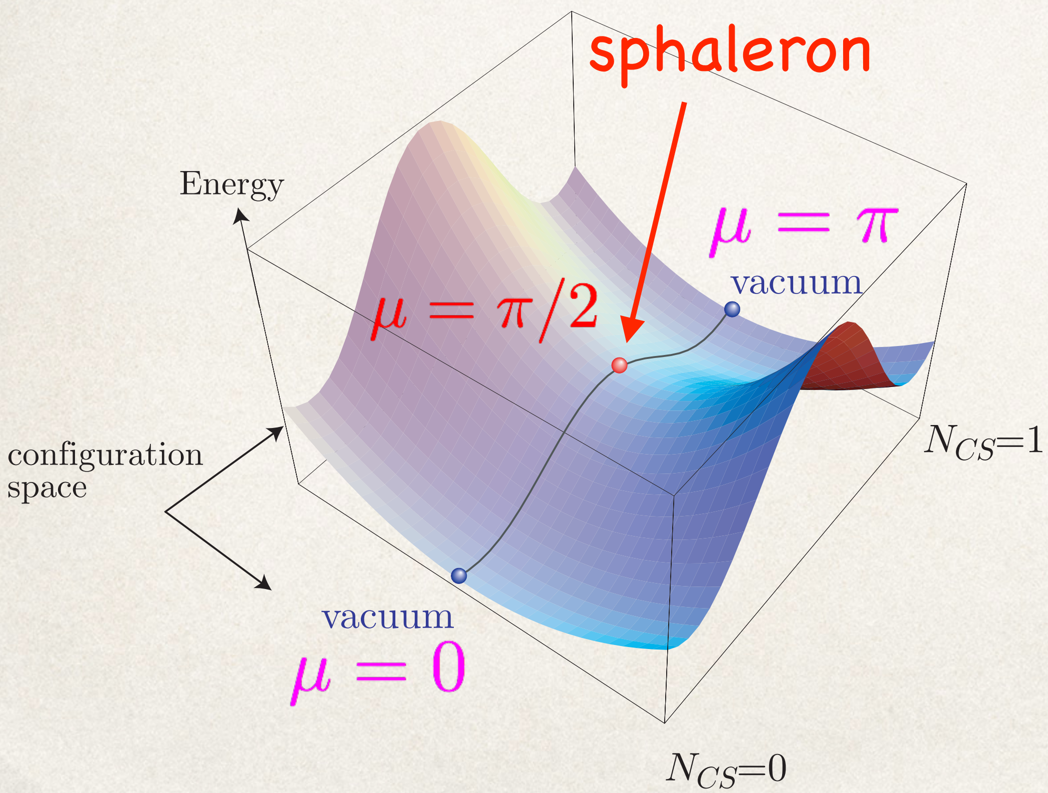
$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g\epsilon^{abc}A^b_\mu A^c_\nu,$$

$$D_\mu\Phi = \left(\partial_\mu + igA^a_\mu\frac{\tau^a}{2}\right), \qquad V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2.$$

How do we find a saddle point configuration?

-> use of a noncontractible loop.

[N.S. Manton, PRD28 ('83) 2019]



$$\mu \in [0, \pi]$$

In the limit of $r = |\boldsymbol{x}| = \infty$,

$$A^\infty_i(\mu, \boldsymbol{x}) = -\frac{i}{g}\partial_i U(\mu,\theta,\phi)U^{-1}(\mu,\theta,\phi),$$

$$\Phi^\infty(\mu, \boldsymbol{x}) = U(\mu,\theta,\phi)\begin{pmatrix} 0 \\ v/\sqrt{2}\end{pmatrix}$$

Manton's ansatz

[N.S. Manton, PRD28 ('83) 2019]

$$A_i(\mu, r, \theta, \phi) = -\frac{i}{g}\boxed{f(r)}\partial_i U(\mu, \theta, \phi) U^{-1}(\mu, \theta, \phi),$$

$$\Phi(\mu, r, \theta, \phi) = \frac{v}{\sqrt{2}}\left[(1-\boxed{h(r)})\begin{pmatrix} 0 \\ e^{-i\mu}\cos\mu \end{pmatrix} + \boxed{h(r)}U(\mu, \theta, \phi)\begin{pmatrix} 0 \\ 1 \end{pmatrix}\right].$$

$\mu = \pi/2 \quad \Rightarrow \quad$ saddle point configuration (sphaleron)

$\mu = 0, \pi \quad \Rightarrow \quad$ vacuum configuration

Changing the variable $r = \sqrt{\boldsymbol{x}^2}$ to ξ, one gets

Energy functional $\left(\mu = \frac{\pi}{2}\right)$ $\quad A_0 = 0$

$$E_{\text{sph}} = \frac{4\pi v}{g}\int_0^\infty d\xi \left[4\left(\frac{df}{d\xi}\right)^2 + \frac{8}{\xi^2}(f-f^2)^2 + \frac{\xi^2}{2}\left(\frac{dh}{d\xi}\right)^2 + h^2(1-f)^2 + \frac{\lambda}{4g^2}\xi^2(h^2-1)^2\right]$$

$$= \frac{4\pi v}{g}\mathcal{E}_{\text{sph}},$$

input: $\frac{\lambda}{g^2} \simeq 0.3$ (SM)

Sphaleron energy

Equations of motion for the sphaleron

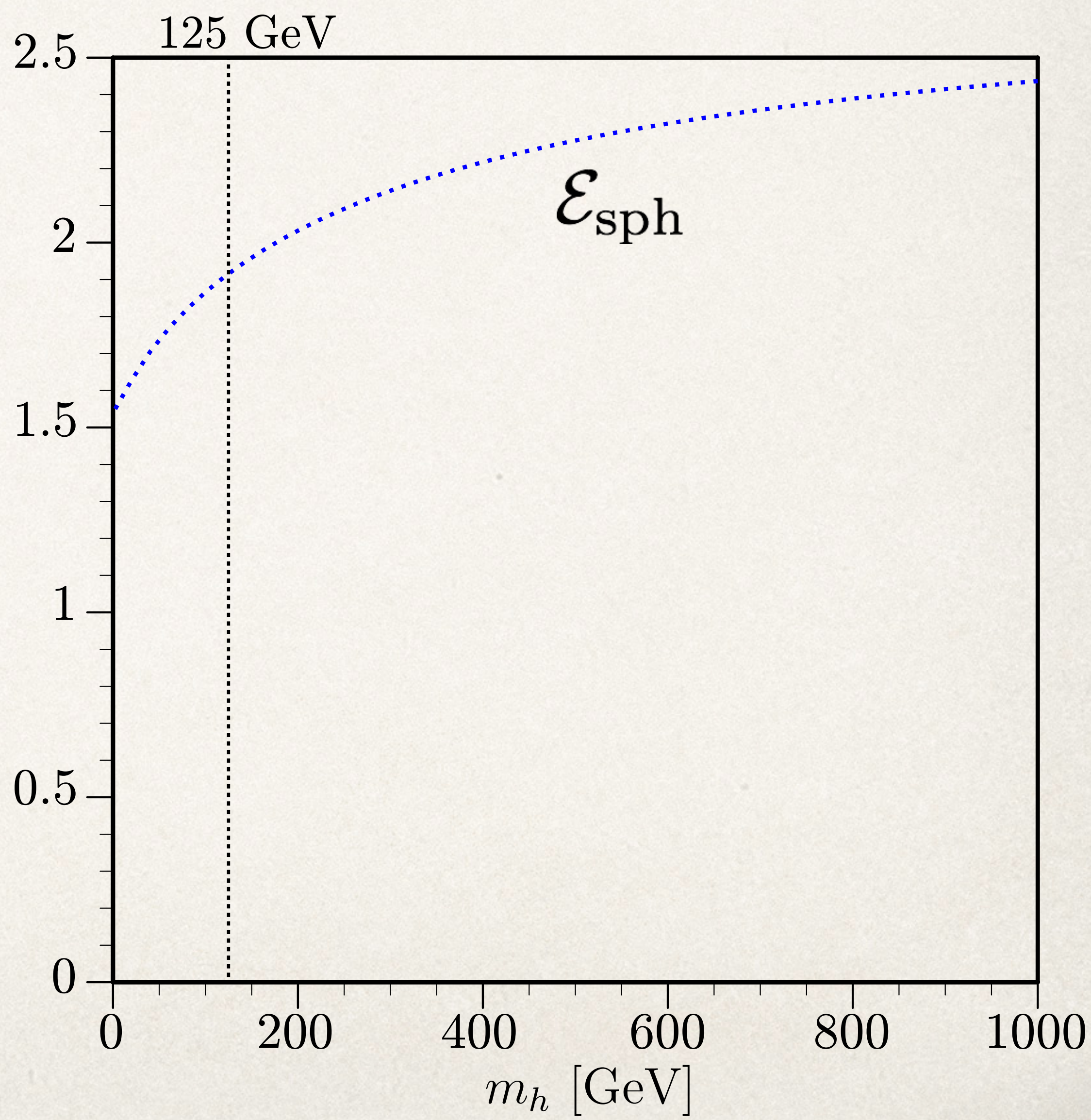
$$\frac{d^2}{d\xi^2}f(\xi) = \frac{2}{\xi^2}f(\xi)(1-f(\xi))(1-2f(\xi)) - \frac{1}{4}h^2(\xi)(1-f(\xi)),$$
$$\frac{d}{d\xi}\left(\xi^2\frac{dh(\xi)}{d\xi}\right) = 2h(\xi)(1-f(\xi))^2 + \frac{\lambda}{g^2}(h^2(\xi)-1)h(\xi)$$

with the boundary conditions:

$$\lim_{\xi\to 0} f(\xi) = 0, \quad \lim_{\xi\to 0} h(\xi) = 0,$$
$$\lim_{\xi\to\infty} f(\xi) = 1, \quad \lim_{\xi\to\infty} h(\xi) = 1.$$

For $m_h = 125$ GeV,

$$\boxed{\begin{array}{l}\mathcal{E}_{\rm sph} = 1.92,\\ (E_{\rm sph} = 9.08\ \mathrm{TeV})\end{array}}$$



Higher-order corrections

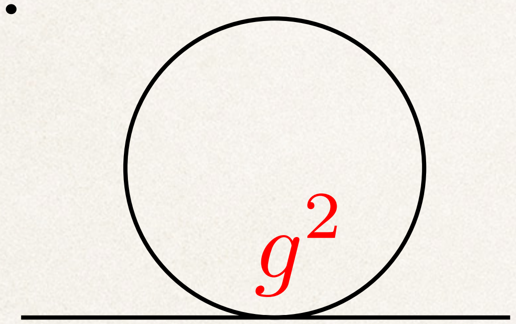
T=0: $V_1^{T=0} = \sum_i \frac{\bar{m}_i^4}{64\pi^2}\left(\ln \frac{\bar{m}_i^2}{\bar{\mu}^2} - c_i\right)$

T>0: $V_1^{T\neq 0} = \sum_i \frac{T^4}{2\pi^2} I_{B,F}\left(\frac{\bar{m}_i^2}{T^2}\right), \quad I_{B,F}(a^2) = \int_0^\infty dx\ x^2 \ln\left[1 \mp e^{-\sqrt{x^2+a^2}}\right].$

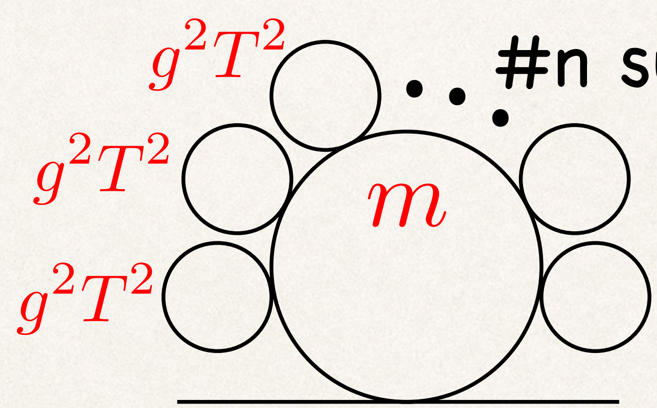
Hard thermal loops

Perturbative expansion breaks down at high T.

e.g.



$\sim g^2T^2$



$\sim \frac{g^4T^3}{m}\left(\frac{g^2T^2}{m^2}\right)^{n-1}$

Resummed Lagrangian

[Parwani (92), Buchmüller et al (93) etc.]

$$\mathcal{L} = \underbrace{\boxed{(\mathcal{L}_R - \Delta m^2(T)\Psi^2)}}_{\text{new 0th-order part}} + \underbrace{\boxed{(\mathcal{L}_{\rm CT} + \Delta m^2(T)\Psi^2)}}_{\text{new counterterm}}$$

Ψ: scalars, gauge bosons

$\Delta m^2(T)$: thermal masses

We evaluate sphaleron energy using the resummed Lagrangian.

Magnetic mass corrections to E_{sph}

$$\mathcal{L}_{\rm eff}^{(2)} = \mathrm{Tr}\big[A^\mu \Pi_{\mu\nu} A^\nu\big] = \frac{1}{2} A^{a\mu}\Pi_{\mu\nu}A^{a\nu},$$

At T>0, Lorentz sym. is broken by thermal bath specified by u^μ.

$u^\mu \;=\; (1, \mathbf{0})$ in the rest frame of thermal bath

Polarization tensor: $\{g_{\mu\nu}, p_\mu p_\nu, u_\mu u_\nu, p_\mu u_\nu + p_\nu u_\nu\}$

$$\Pi_{\mu\nu}(p^0,\boldsymbol{p}) = \Pi_L(p^0,\boldsymbol{p})L_{\mu\nu}(p) + \Pi_T(p^0,\boldsymbol{p})T_{\mu\nu}(p) + \Pi_G(p^0,\boldsymbol{p})G_{\mu\nu}(p) + \Pi_S(p^0,\boldsymbol{p})S_{\mu\nu}(p),$$

$$L_{\mu\nu}(p) = \frac{u_\mu^T u_\nu^T}{(u^T)^2}, \quad T_{\mu\nu}(p) = g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} - L_{\mu\nu}(p),$$

$$G_{\mu\nu}(p) = \frac{p_\mu p_\nu}{p^2}, \quad S_{\mu\nu}(p) = \frac{p_\mu u_\nu^T + p_\nu u_\mu^T}{\sqrt{(p\cdot u)^2 - p^2}}.$$

$$u_\mu^T = u_\mu - (p\cdot u)p_\mu/p^2$$

$$u_\mu^T p^\mu = 0$$

Static limit $\quad p^0 = 0,\ \boldsymbol{p} \to 0$ with $\partial_i A_i = 0$ (sphaleron ansatz)

$$\mathcal{L}_{\rm eff}^{(2)} = \frac{1}{2}m_L^2(T)(A_0^a)^2 - \frac{1}{2}m_T^2(T)(A_i^a)^2, \qquad m_{L,T}^2 = \lim_{p^0=0,\boldsymbol{p}\to 0} \Pi_{L,T}(p^0,\boldsymbol{p})$$

electric mass magnetic mass

$$A_0 = 0 \quad \Rightarrow \quad \Delta E_{\rm sph} = \frac{m_T^2}{2}\int d^3\boldsymbol{x}\ A_i^a A_i^a.$$

but, gauge inv. is unclear.

Magnetic mass corrections to E_{sph}

Gauge-inv. dim.2 operator [D. Zwanziger, Nucl. Phys. B 345, 461 (1990)]

$$\int d^4x\ A^2_{\min} = \min_{\{U\}} \int d^4x\ \mathrm{Tr}[(A^U_\mu)^2] \simeq \int d^4x \left[F_{\mu\nu} \frac{1}{D^2} F^{\mu\nu} + \cdots \right]$$

$$A^U_\mu = U A_\mu U^{-1} + \frac{i}{g}(\partial_\mu U) U^{-1}$$

expressed by infinite series of non-local gauge-inv. terms.

It is known that $\int d^4x\ A^2_{\min} = \int d^4x\ \mathrm{Tr}[A_\mu A^\mu]$ if $\partial_\mu A^\mu = 0$

Since the sphaleron ansatz satisfies this condition, one has the same mass form as the previous case.

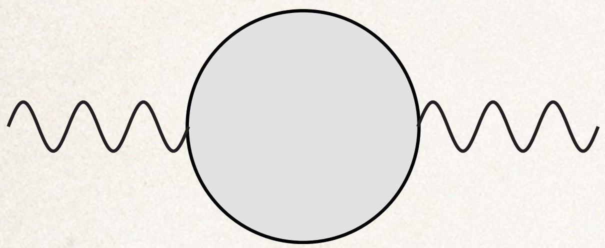
$$\boxed{\Delta E_{\mathrm{sph}} = \frac{m_T^2}{2} \int d^3\boldsymbol{x}\ A^a_i A^a_i .}$$

We regard this as the magnetic mass correction to E_{sph}.

Magnetic mass

In SU(2) gauge Higgs model,

Espinosa, et al, PLB314, 206 (1993);
Buchmuller, et al, AP234, 260 (1994).



$$\Rightarrow \quad m_T^2 = \frac{g^2 T}{3\pi} m_T + \mathcal{O}(v) \qquad m_T = c g^2 T, \quad c = \frac{1}{3\pi} \simeq 0.11$$

1-loop gap eq. at high T. but, this is gauge dependent.

Other studies show that

methods	Refs.	c
gauge-inv. 1-loop gap eq.	Buchmuller, Philipsen, hep-ph/9411334	0.28
〃	Alexanian, Nair, hep-ph/9504256	0.38
〃	Patkos, Petreczky, Szep, hep-ph/9711263	0.35
Lattice	Heller, Karsch, Rank, hep-lat/9710033	0.46

Since there is no robust result, we regard c as the varying parameter.

Sphaleron energy ~ SM w/o U(1)$_Y$ ~

Energy functional

$$E_{\rm sph} = \frac{4\pi v}{g}\int_0^\infty d\xi \left[4f'^2 + \frac{8}{\xi^2}(f-f^2)^2 + \frac{\xi^2}{2}h'^2 + (h^2+r_m^2)(1-f)^2 + \frac{\xi^2 V_0(h)}{g^2v^4}\right] \equiv \frac{4\pi v}{g}\mathcal{E}_{\rm sph}$$

where $\xi = gvr,\ r_m = \dfrac{m_T}{m_W}\quad V_0(h) = \lambda v^4(h^2-1)^2/4$

EOMs

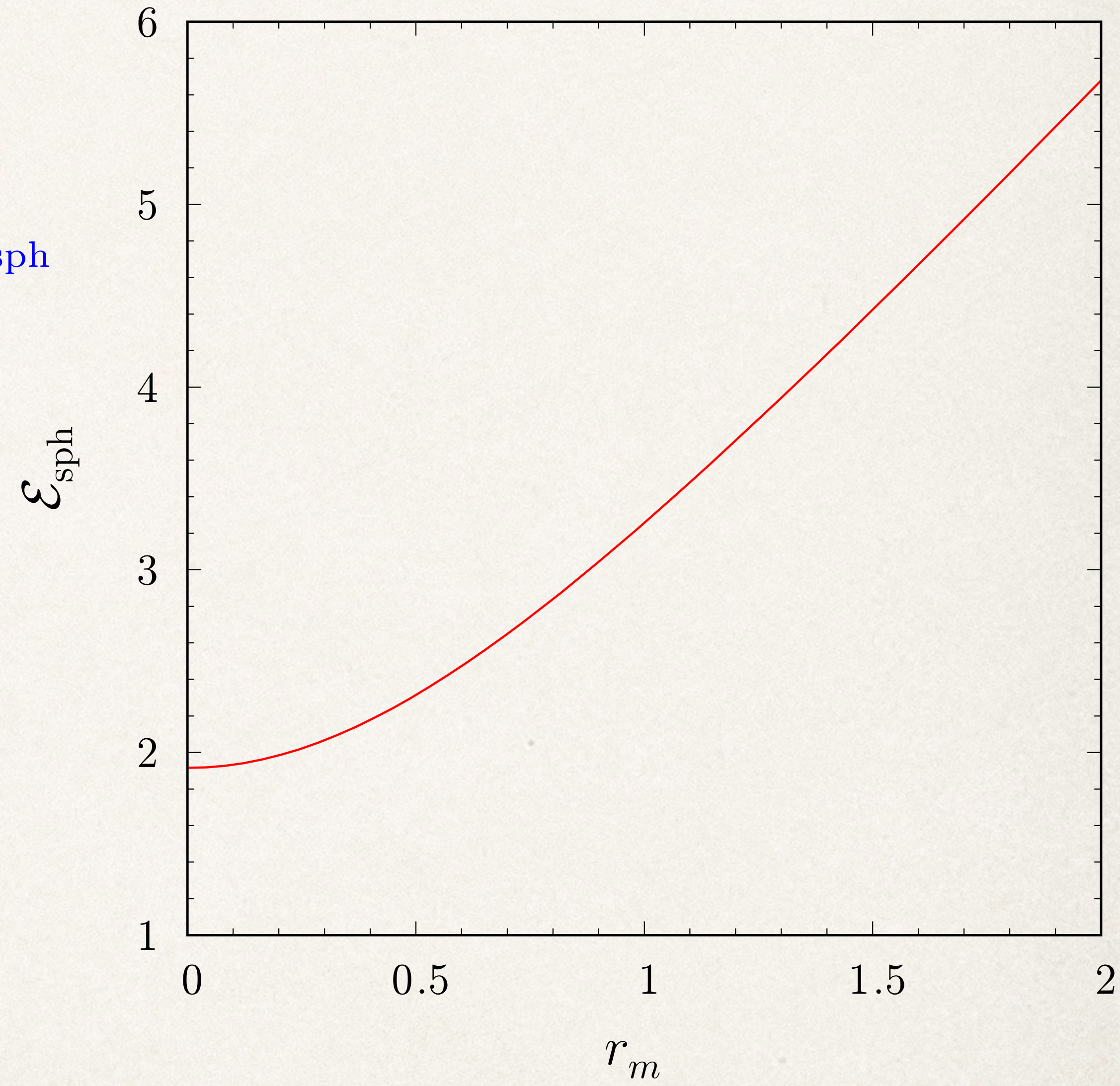
$$\frac{d^2 f}{d\xi^2} = \frac{2}{\xi^2}(f-f^2)(1-2f) - \frac{1}{4}(h^2+r_m^2)(1-f),$$

$$\frac{d^2 h}{d\xi^2} = -\frac{2}{\xi}\frac{dh}{d\xi} + \frac{2}{\xi^2}h(1-f)^2 + \frac{1}{g^2v^4}\frac{\partial V_0}{\partial h},$$

w/ b.c.

$$\lim_{\xi\to 0} f(\xi) = 0,\quad \lim_{\xi\to 0} h(\xi) = 0,$$

$$\lim_{\xi\to\infty} f(\xi) = 1,\quad \lim_{\xi\to\infty} h(\xi) = 1.$$



Sphaleron energy gets larger as m_T increases.

w/o any symmetry, e.g. Z_2

General 2 Higgs doublet model (g2HDM)

Particle content: SM + Φ_2 $\longleftarrow$ 2nd Higgs doublet

Yukawa int.

$$\mathcal{L}_Y = \bar{q}_L(Y_1^{(d)}\Phi_1 + Y_2^{(d)}\Phi_2)d_R + \bar{q}_L(Y_1^{(u)}\tilde{\Phi}_1 + Y_2^{(u)}\tilde{\Phi}_2)u_R + \bar{l}_L(Y_1^{(e)}\Phi_1 + Y_2^{(e)}\Phi_2)e_R + \text{h.c.} \qquad \tilde{\Phi}_{1,2} = i\tau^2\Phi_{1,2}^*$$

Higgs potential:

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

Assumption: CP is **NOT** violated by the Higgs potential and VEVs.

inputs: $\sin(\beta-\alpha)$, $\tan\beta$, m_H, m_A, $m_{H^\pm}$, $M^2 = \frac{m_3^2}{\sin\beta\cos\beta}$, $\lambda_{6,7}$

$v = 246$ GeV, $m_h = 125$ GeV.

EW Phase Transition (EWPT)

EWPT is studied in the SM-like limit. $\sin(\beta-\alpha)=\tan\beta=1$

$$V_{\rm eff}(\varphi;T)=V_0(\varphi)+V_1(\varphi;T),$$

where

$$V_0(\varphi)=-\frac{\mu^2}{2}\varphi^2+\frac{\lambda_{\rm eff}}{4}\varphi^4,$$

$$V_1(\varphi;T)=\sum_{\substack{i=h,H,A,H^\pm,G^0,G^\pm\\ W^\pm_{L,T},Z_{L,T},\gamma_{L,T},t,b}} n_i\left[\frac{\bar{m}_i^4}{64\pi^2}\left(\ln\frac{\bar{m}_i^2}{\bar{\mu}^2}-c_i\right)+\frac{T^4}{2\pi^2}I_{B,F}\left(\frac{\bar{m}_i^2}{T^2}\right)\right]$$

with $\quad I_{B,F}(a^2)=\int_0^\infty dx\; x^2\log\left(1\mp e^{-\sqrt{x^2+a^2}}\right),\quad a^2=m^2/T^2$

$\bar{m}_i^2$ are the thermally-corrected field dependent masses. (Parwani scheme)

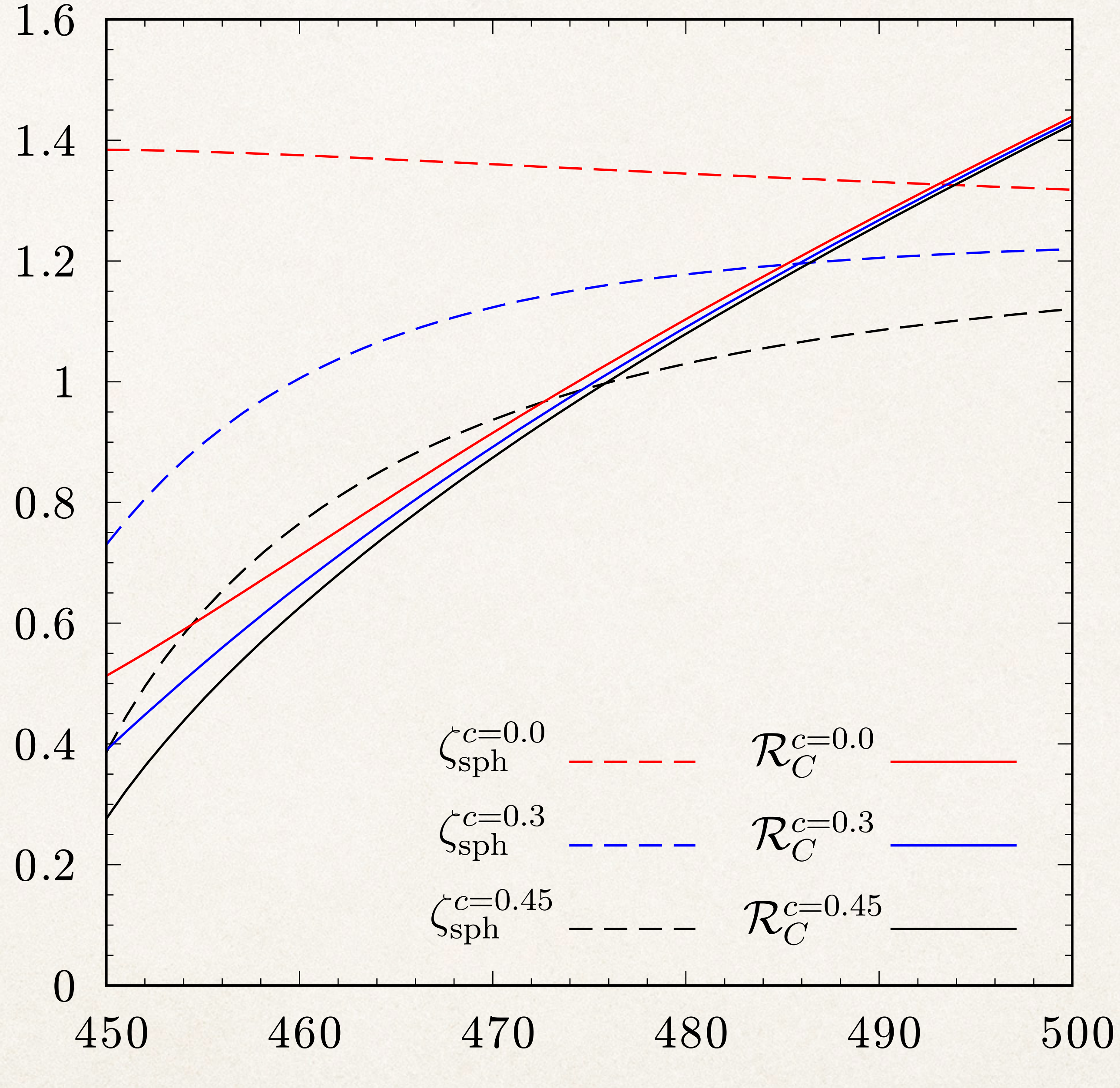
Using this potential, we evaluate $v_C/T_C(\equiv R_C)$ and $\zeta_{sph}(T_C)$.

$v_C/T_C > \zeta_{sph}(T_C)$ region

$s_{\beta-\alpha} = t_\beta = 1,\ M = \sqrt{m_3^2/s_\beta c_\beta} = 300$ GeV, $\lambda_{6,7} = 0.$

$v_C/T_C > \zeta_C \rightarrow \Gamma_{sph} < H$

$m_T = cg^2T$



$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

sphaleron decoupling region can be expanded due to the magnetic mass effect.

$v_C/T_C > \zeta_{sph}(T_C)$ region

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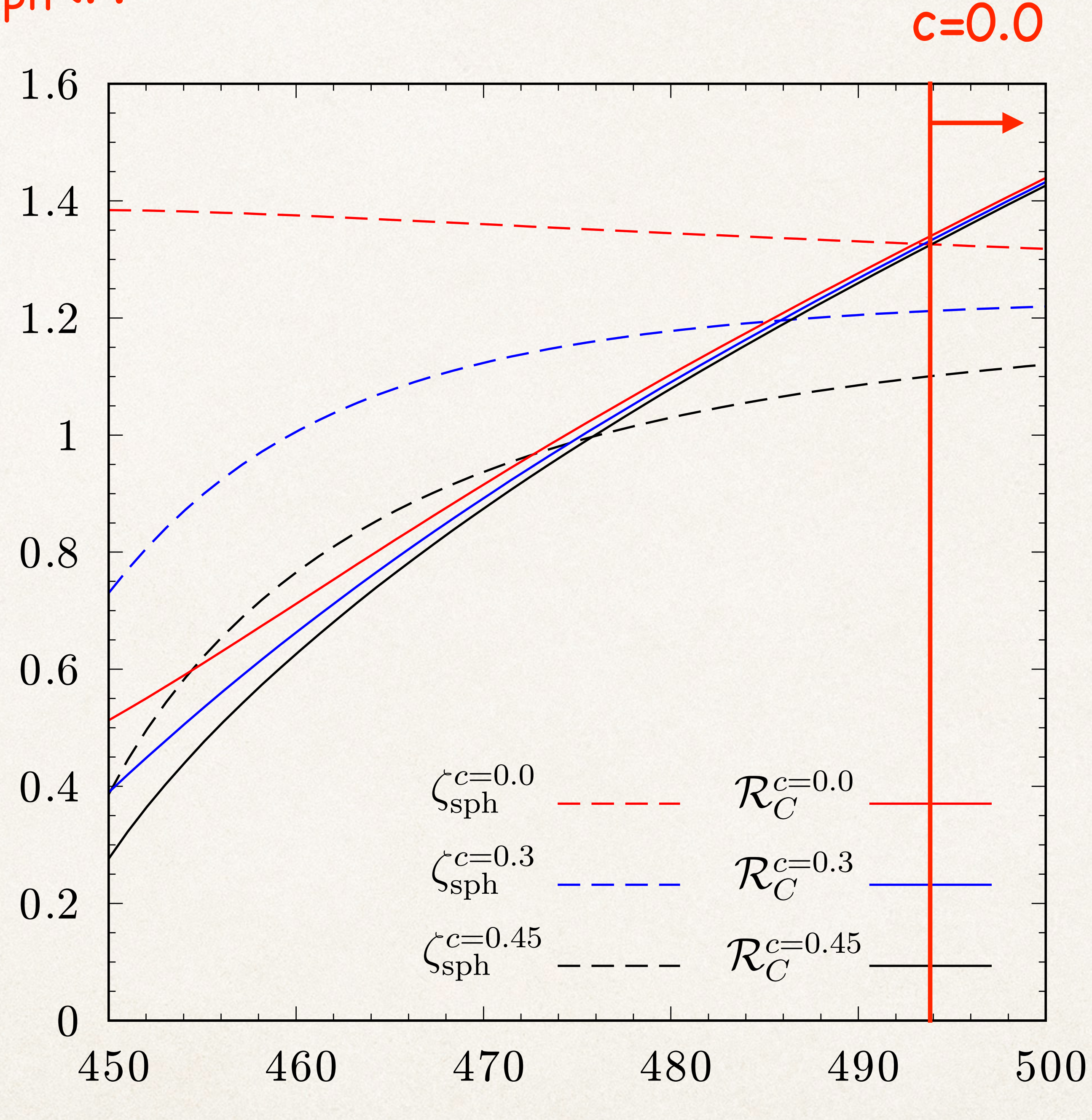

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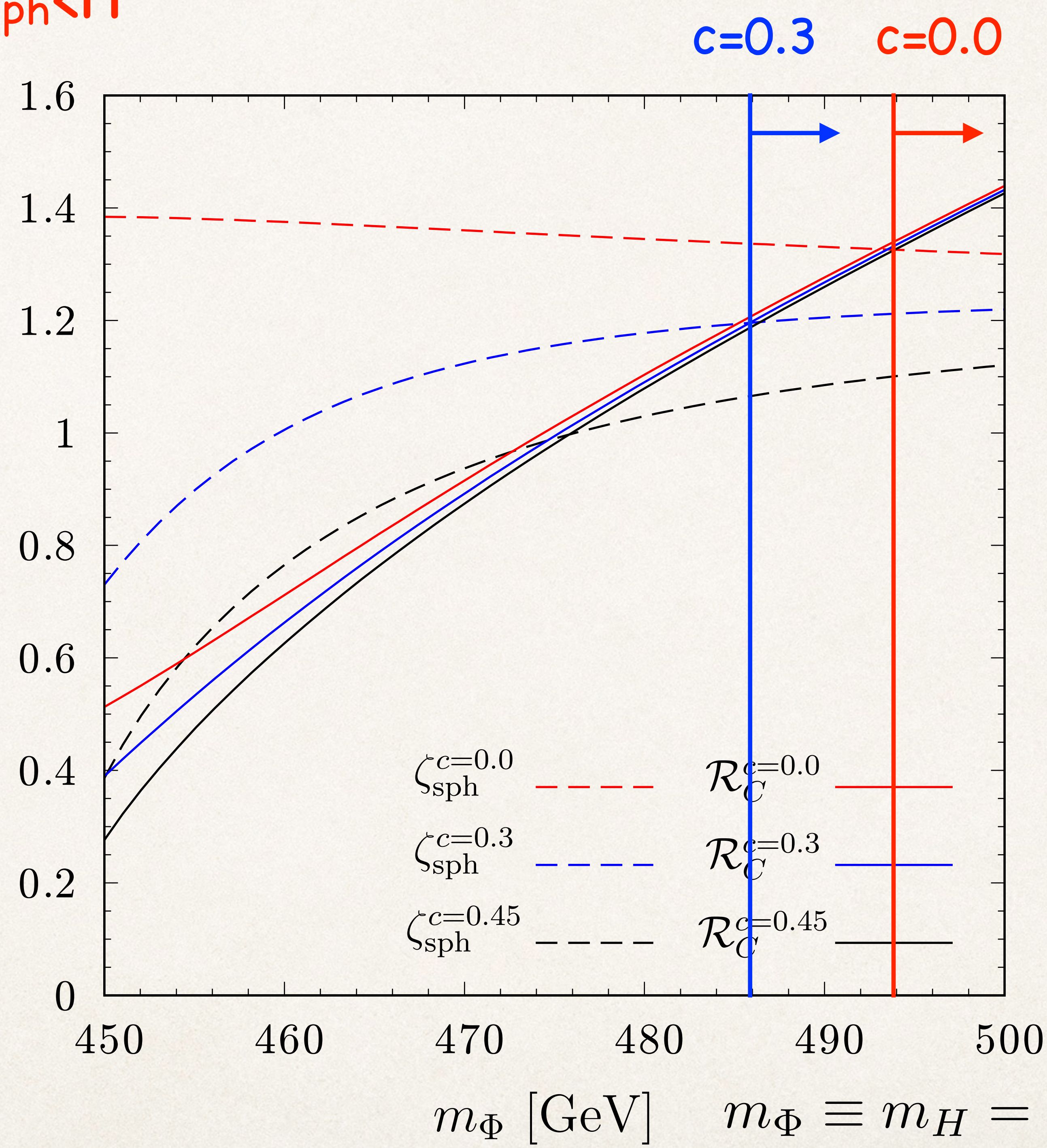

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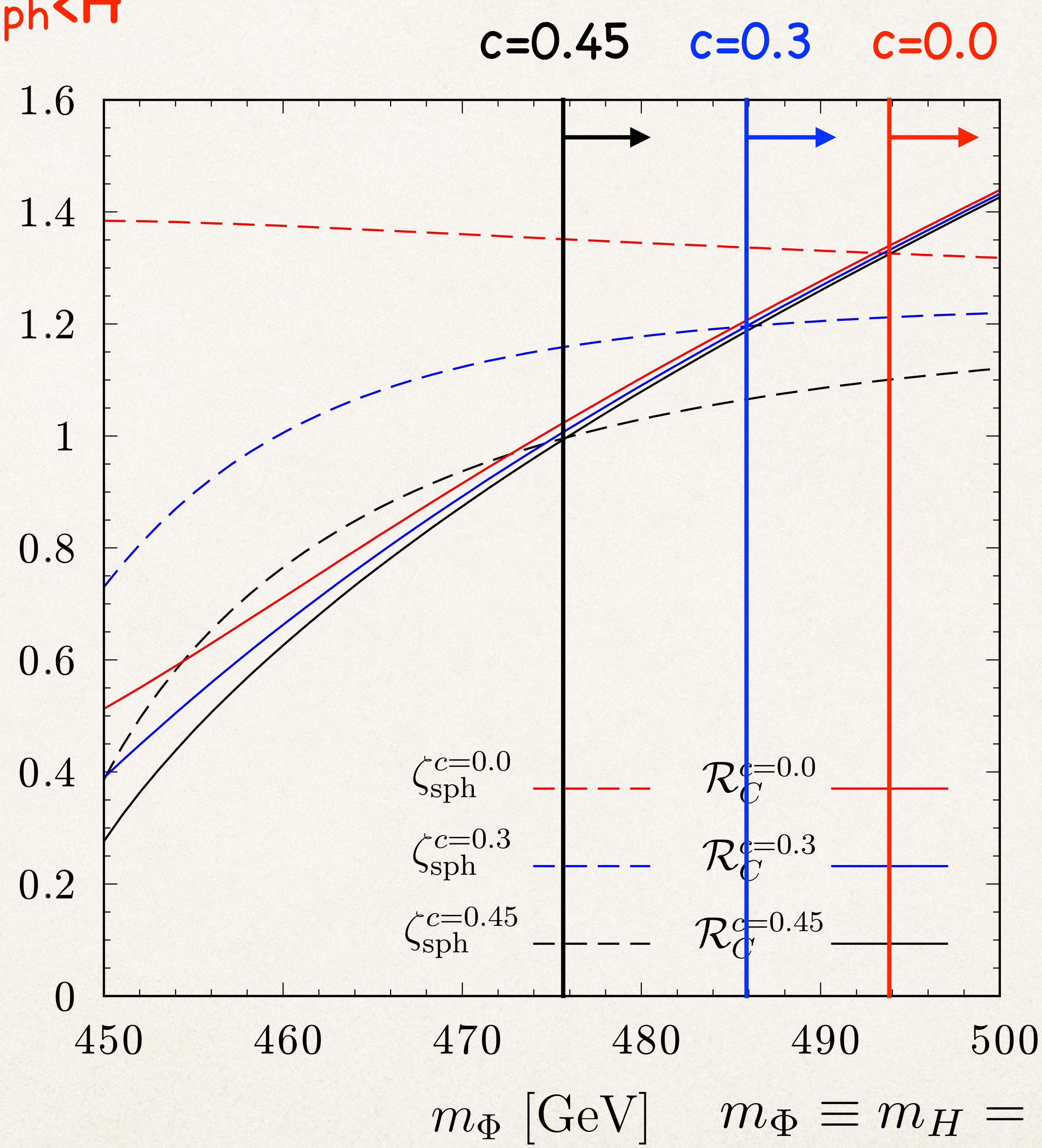

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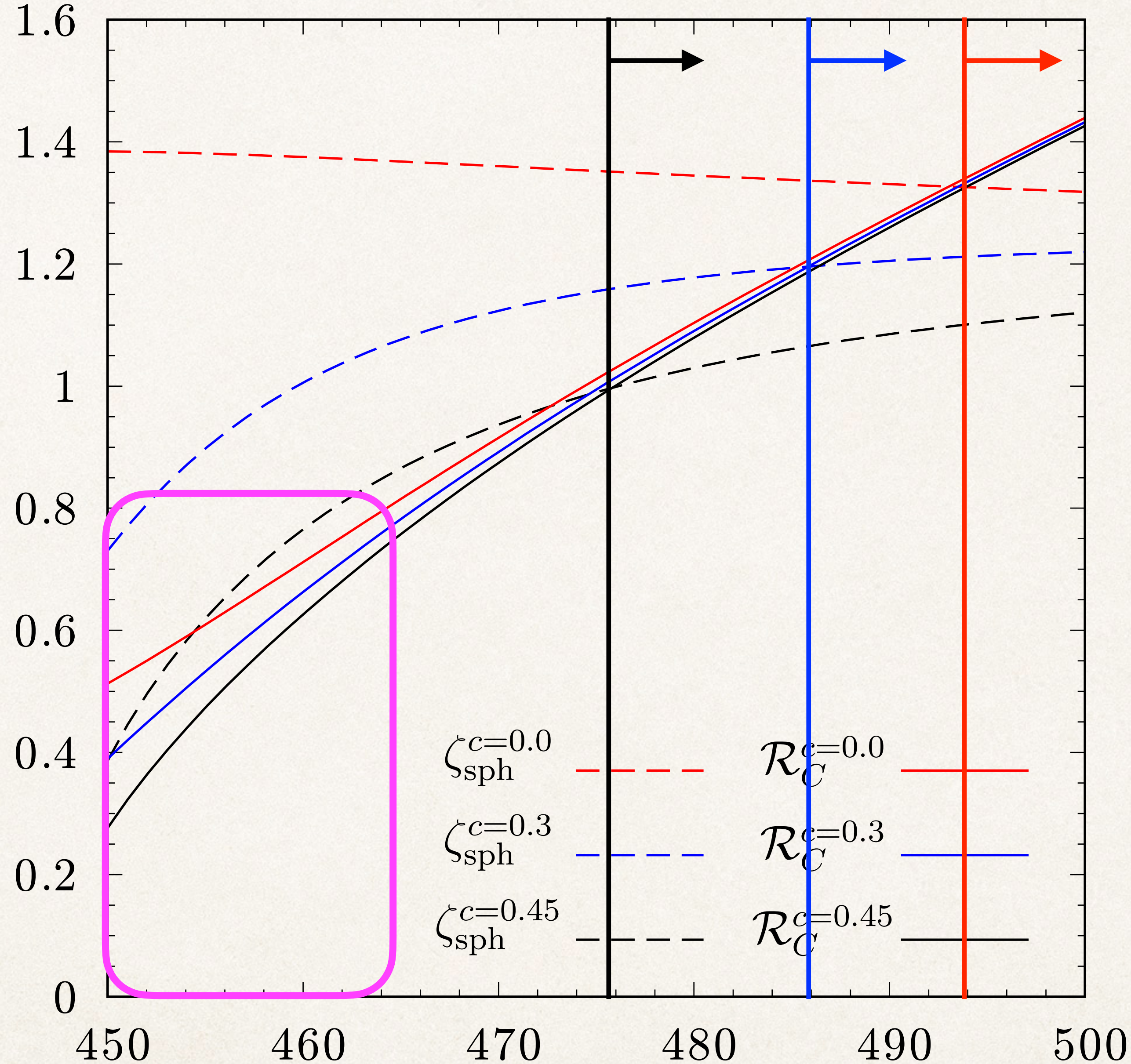
c=0.45 c=0.3 c=0.0

$m_T = cg^2T$



m_Φ [GeV] $m_\Phi \equiv m_H = m_A = m_{H^\pm}$

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Today's topics

1. "Magnetic mass effect on sphaleron energy",
   Koichi Funakubo and E.S., 2003.13929.

Improvement of sphaleron decoupling condition $\dfrac{v_C}{T_C} \gtrsim 1$

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2. "Cancellation mechanism for the electron electric dipole moment connected with the baryon asymmetry of the Universe",
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Cancellation mechanism for electron EDM in general 2HDM.

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Yukawa interactions in g2HDM

Up-type Yukawa couplings:

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

$$\tilde{\Phi}_{1,2} = i\tau^2\Phi^*_{1,2}$$

In the mass eigenbasis

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

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125 GeV Higgs

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EWBG-related CP violation

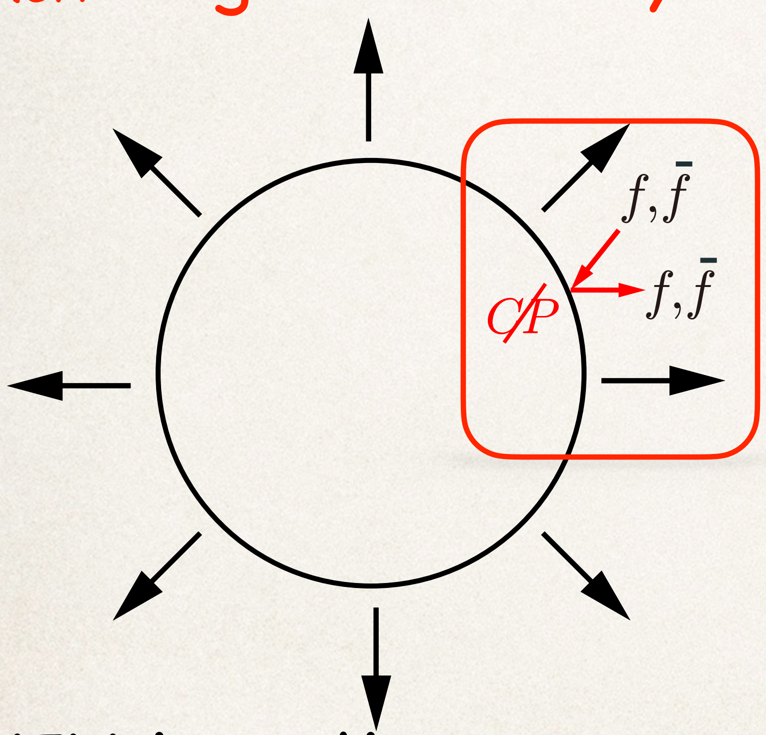
for a review, see A. Riotto, hep-ph/9807454

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

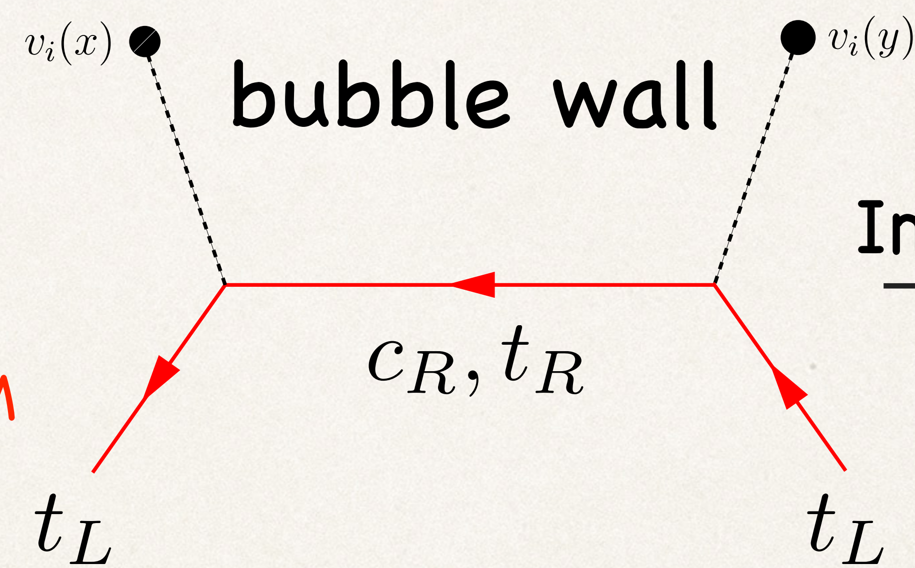
$$D_Q n_B''(\bar{z}) - v_w n_B'(\bar{z}) - \theta(-\bar{z})\mathcal{R} n_B(\bar{z}) = \theta(-\bar{z})\frac{3}{2}\Gamma_B^{(\mathrm{sym})} n_{\mathrm{left}}(\bar{z})$$

diffusion const. wall velocity back reaction sph. rate

n_{left} is generated by scatterings btw particles and bubbles.



e.g. g2HDM



Im part $\longrightarrow$ $S_{t_L}^{\mathrm{CPV}}$

VEV insertion approx.

$$S_{t_L}^{\mathrm{CPV}} = C_{\mathrm{BAU}} \mathrm{Im}\Big[(Y_1)_{tj}(Y_2)^*_{tj}\Big] v^2 \Delta\beta \quad j = c, t$$

loop function

$\longrightarrow$ $n_{\mathrm{left}} \propto S_{t_L}$ $\downarrow$ n_B

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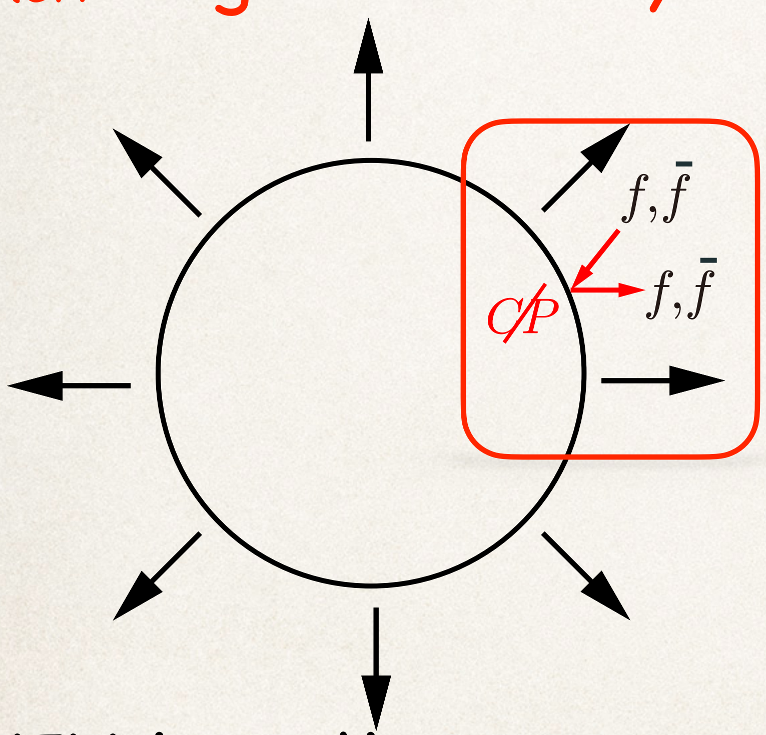

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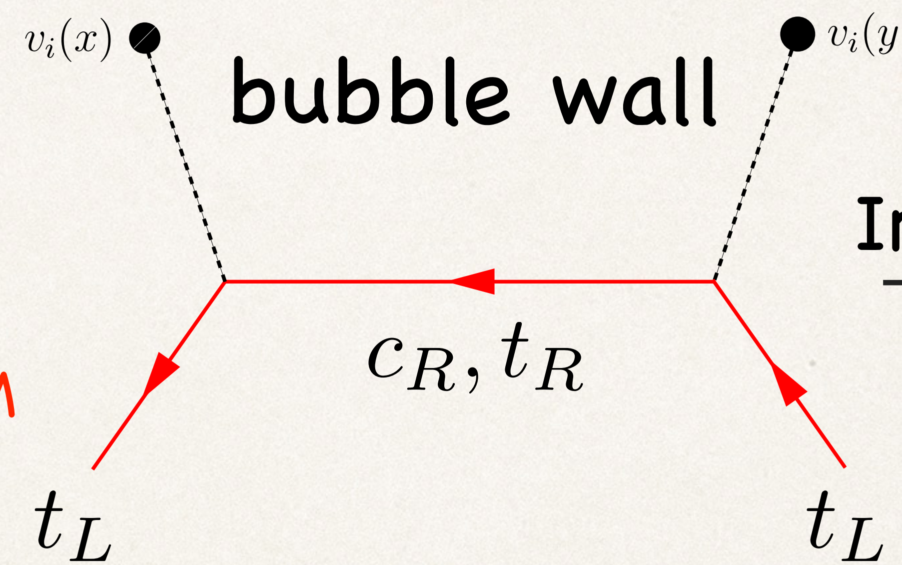

$\xrightarrow{\text{Im part}}$ $S_{t_L}^{\mathrm{CPV}}$

VEV insertion approx.

BAU-related CPV

$$\boxed{S_{t_L}^{\mathrm{CPV}} = \underset{\substack{\uparrow \\ \text{loop function}}}{C_{\mathrm{BAU}}} \boxed{\mathrm{Im}\left[(Y_1)_{tj}(Y_2)^*_{tj}\right]_{j=c,t}} v^2 \Delta\beta} \longrightarrow n_{\mathrm{left}} \propto S_{t_L}$$

$$\downarrow$$

$$n_B$$

BAU-related CPV at T=0

$$V_L^{u\dagger}(Y_1 c_\beta + Y_2 s_\beta)V_R^u = \mathrm{diag}(\lambda_u, \lambda_c, \lambda_t) \equiv Y_{\mathrm{diag}},$$

$$V_L^{u\dagger}(-Y_1 s_\beta + Y_2 c_\beta)V_R^u = \rho \;=\; \begin{pmatrix} \rho_{uu} & \rho_{uc} & \rho_{ut} \\ \rho_{cu} & \rho_{cc} & \rho_{ct} \\ \rho_{tu} & \rho_{tc} & \rho_{tt} \end{pmatrix}$$

t-c case

$$\longrightarrow \quad \mathrm{Im}\Big[(Y_1)_{tc}(Y_2)^*_{tc}\Big] = \mathrm{Im}\Big[(V_L^u Y_{\mathrm{diag}} V_R^{u\dagger})_{32}(V_L^u \rho V_R^{u\dagger})_{32}\Big]$$

Simplified case: Guo et al, 1609.09849 [PRD].

$$Y_{i=1,2} = \begin{pmatrix} (Y_i)_{uu} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & (Y_i)_{tc} & (Y_i)_{tt} \end{pmatrix}, \quad \tan\beta = 1, \quad (Y_1)_{tt} = (Y_2)_{tt}$$

$$\longrightarrow \quad \mathrm{Im}\Big[(Y_1)_{tc}(Y_2)^*_{tc}\Big] = -\lambda_t \mathrm{Im}(\rho_{tt}), \quad \rho_{ct} = 0, \quad m_c = 0.$$

ρ_{tt} is the contributor to the BAU!!

BAU-related CPV at T=0

$$V_L^{u\dagger}(Y_1 c_\beta + Y_2 s_\beta)V_R^u = \mathrm{diag}(\lambda_u, \lambda_c, \lambda_t) \equiv Y_{\mathrm{diag}},$$
$$V_L^{u\dagger}(-Y_1 s_\beta + Y_2 c_\beta)V_R^u = \rho \; = \begin{pmatrix} \rho_{uu} & \rho_{uc} & \rho_{ut} \\ \rho_{cu} & \rho_{cc} & \rho_{ct} \\ \rho_{tu} & \rho_{tc} & \rho_{tt} \end{pmatrix}$$

t-c case

$$\longrightarrow \quad \mathrm{Im}\Big[(Y_1)_{tc}(Y_2)^*_{tc}\Big] = \mathrm{Im}\Big[(V_L^u Y_{\mathrm{diag}} V_R^{u\dagger})_{32}(V_L^u \rho V_R^{u\dagger})_{32}\Big]$$

Simplified case: Guo et al, 1609.09849 [PRD].

$$Y_{i=1,2} = \begin{pmatrix} (Y_i)_{uu} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & (Y_i)_{tc} & (Y_i)_{tt} \end{pmatrix}, \quad \tan\beta = 1, \quad (Y_1)_{tt} = (Y_2)_{tt}$$

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ρ_{tt} is the contributor to the BAU!!

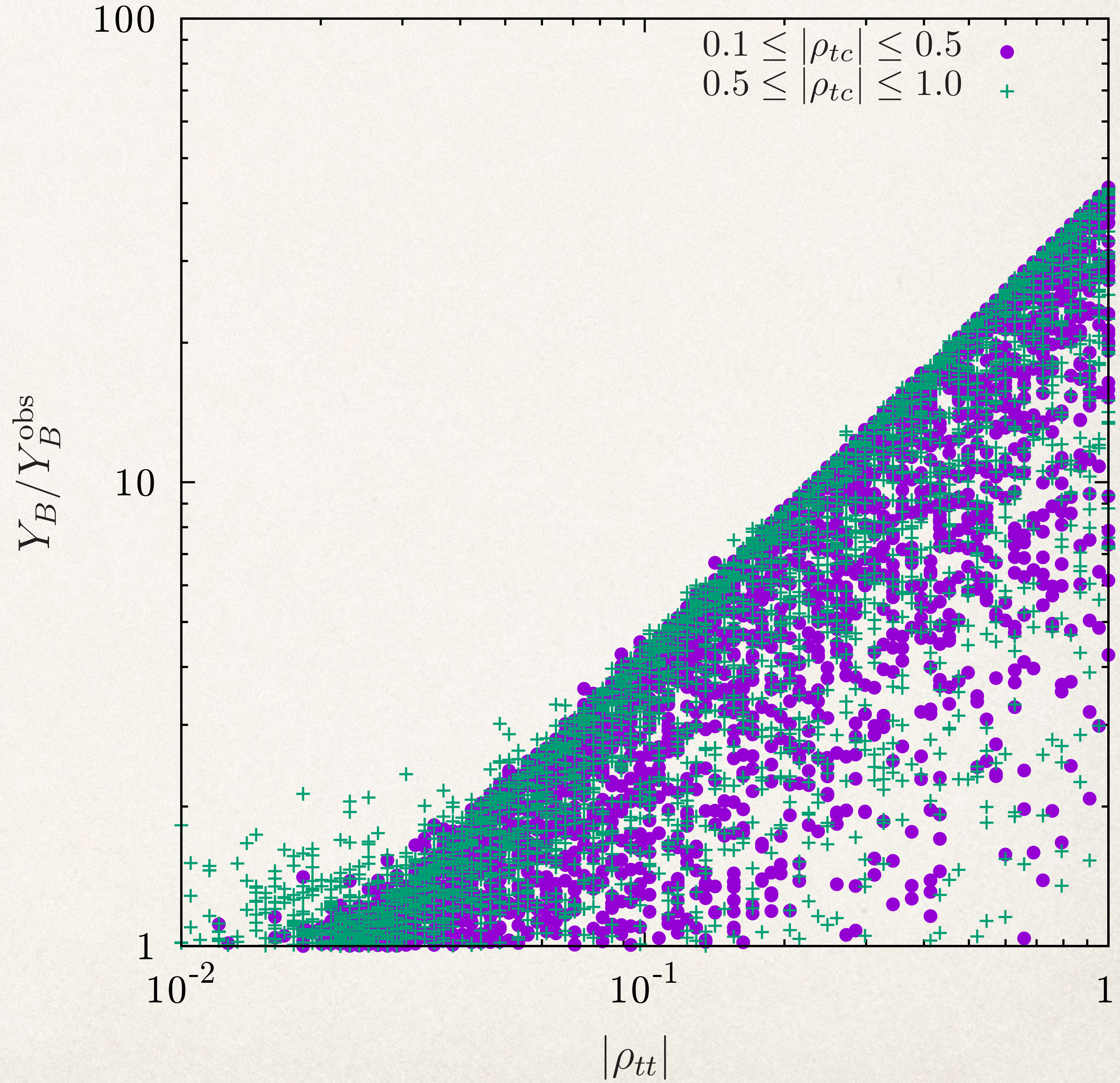
Ramdom scan

$T_C = 119.2$ GeV	$v_C = 176.7$ GeV	$v_w = 0.4$	$\Delta\beta = 0.015$	$D_q = 8.9/T$	$D_H = 101.9/T$
$m_{t_L} = 0.59T$	$m_{t_R} = 0.62T$	$m_{c_R} = 0.50T$	$\Gamma_{q_{L,R}} = 0.22T$	$\Gamma_B^{(s)} = 120\alpha_W^5 T$	$\Gamma_{ss} = 16\alpha_s^4 T$

- Yukawa couplings ($Y_{1,2}$) are randomly scanned.

- Leading effect on Y_B: ρ_{tt}

- Subleading effect: ρ_{tc}



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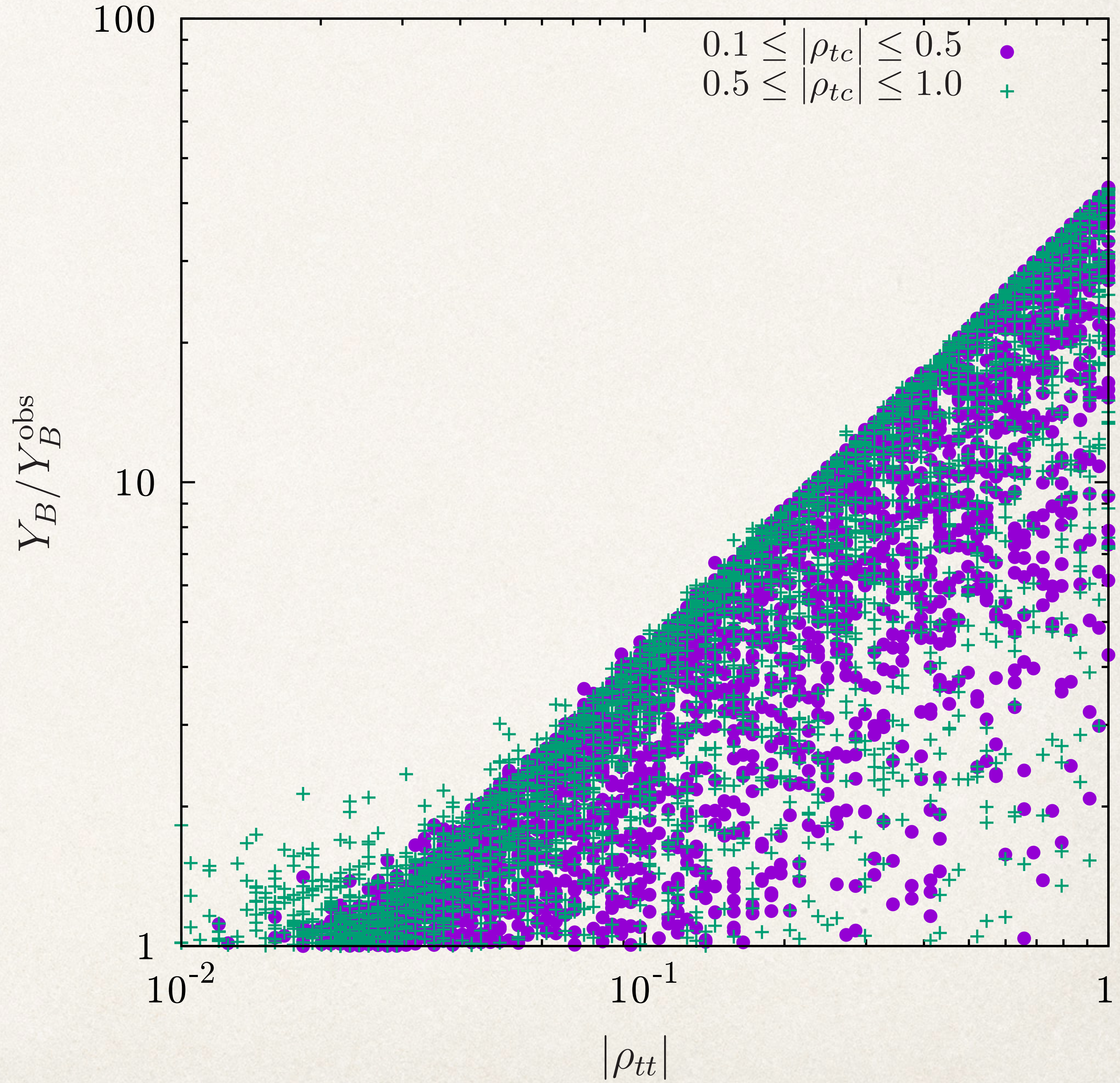
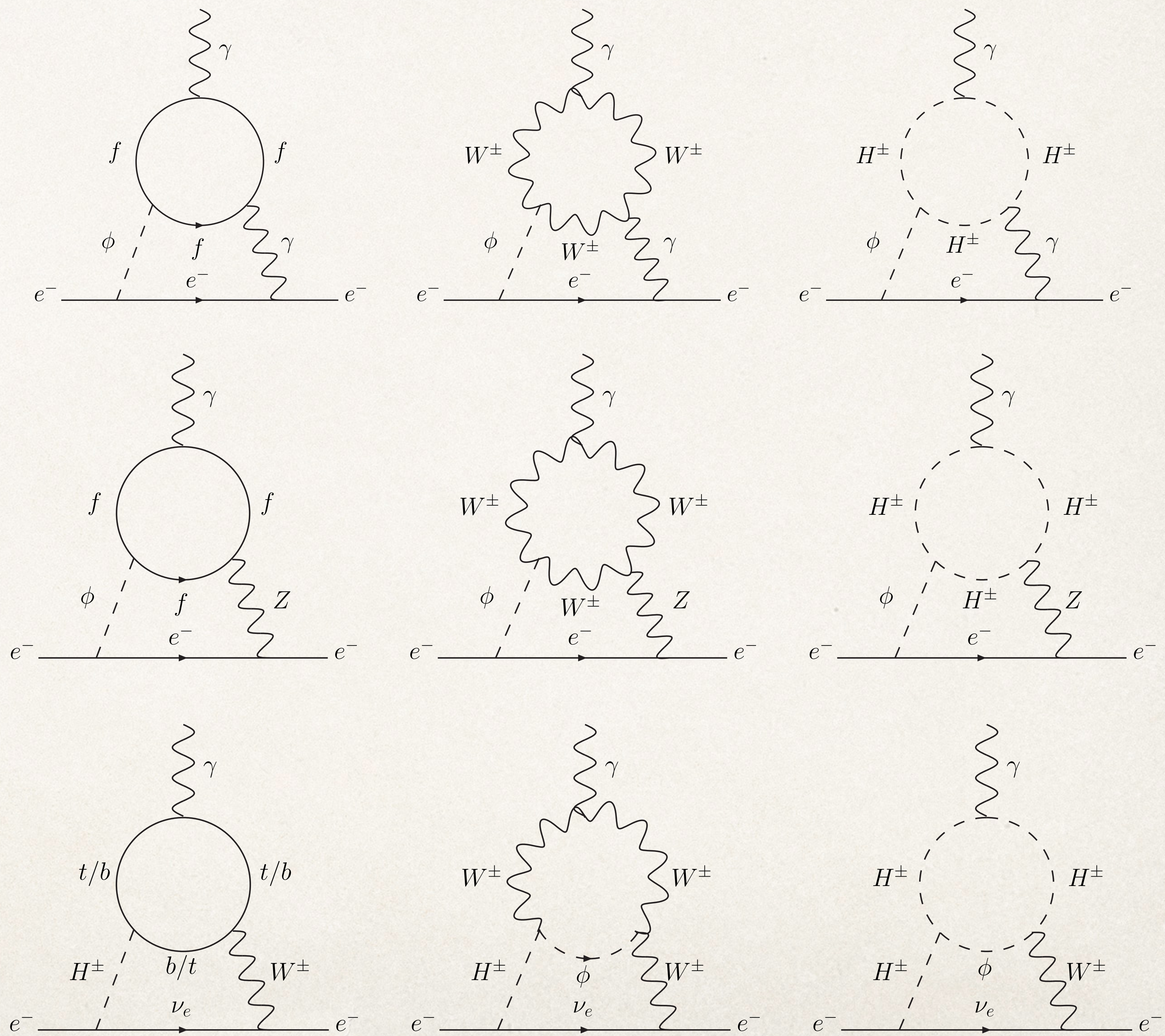


However, ρ_{tt} is highly constrained by eEDM.

electron EDM constraint

Dominant eEDM contributions come from 2-loop diagrams.



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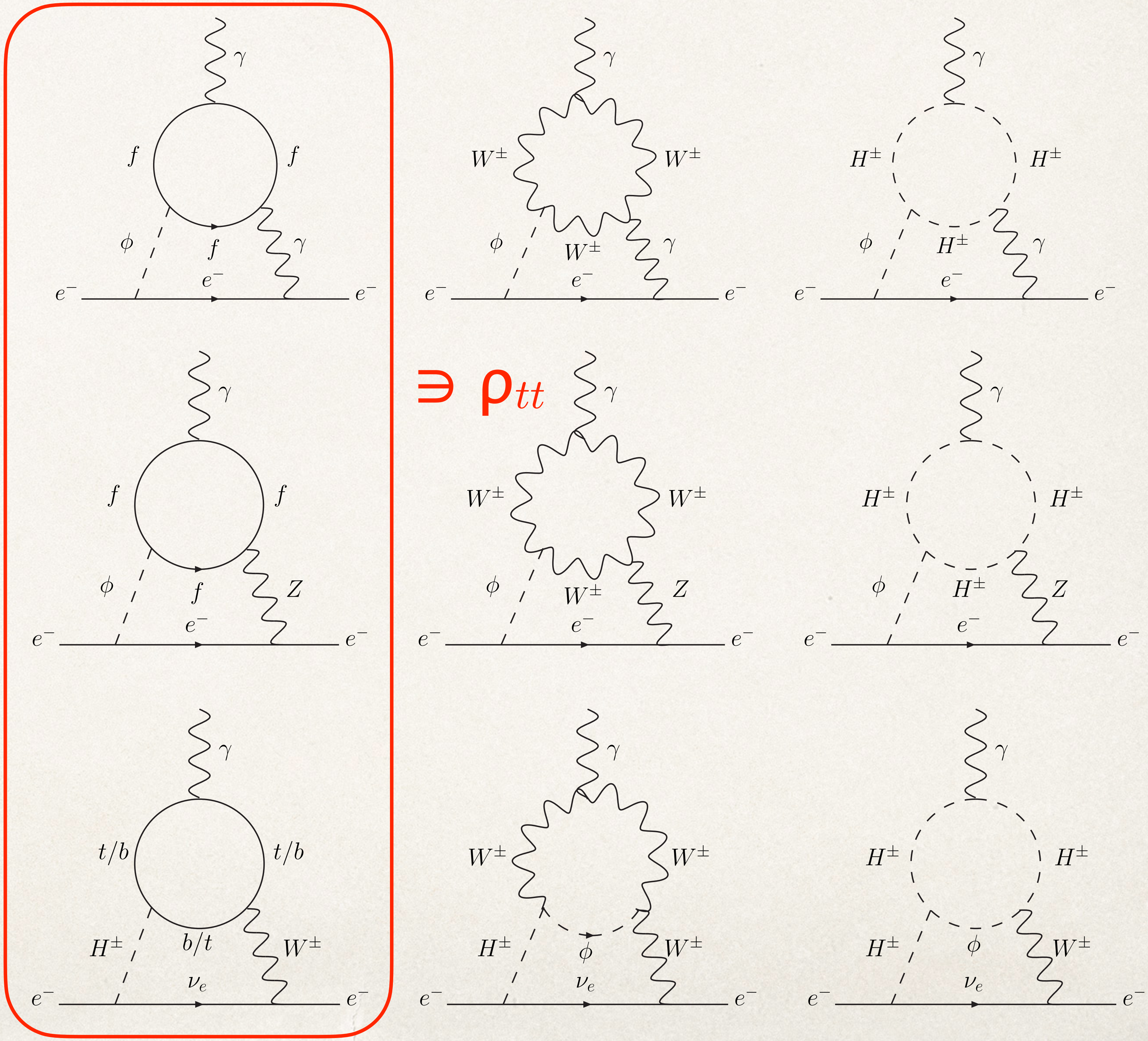
linking to t-EWBG



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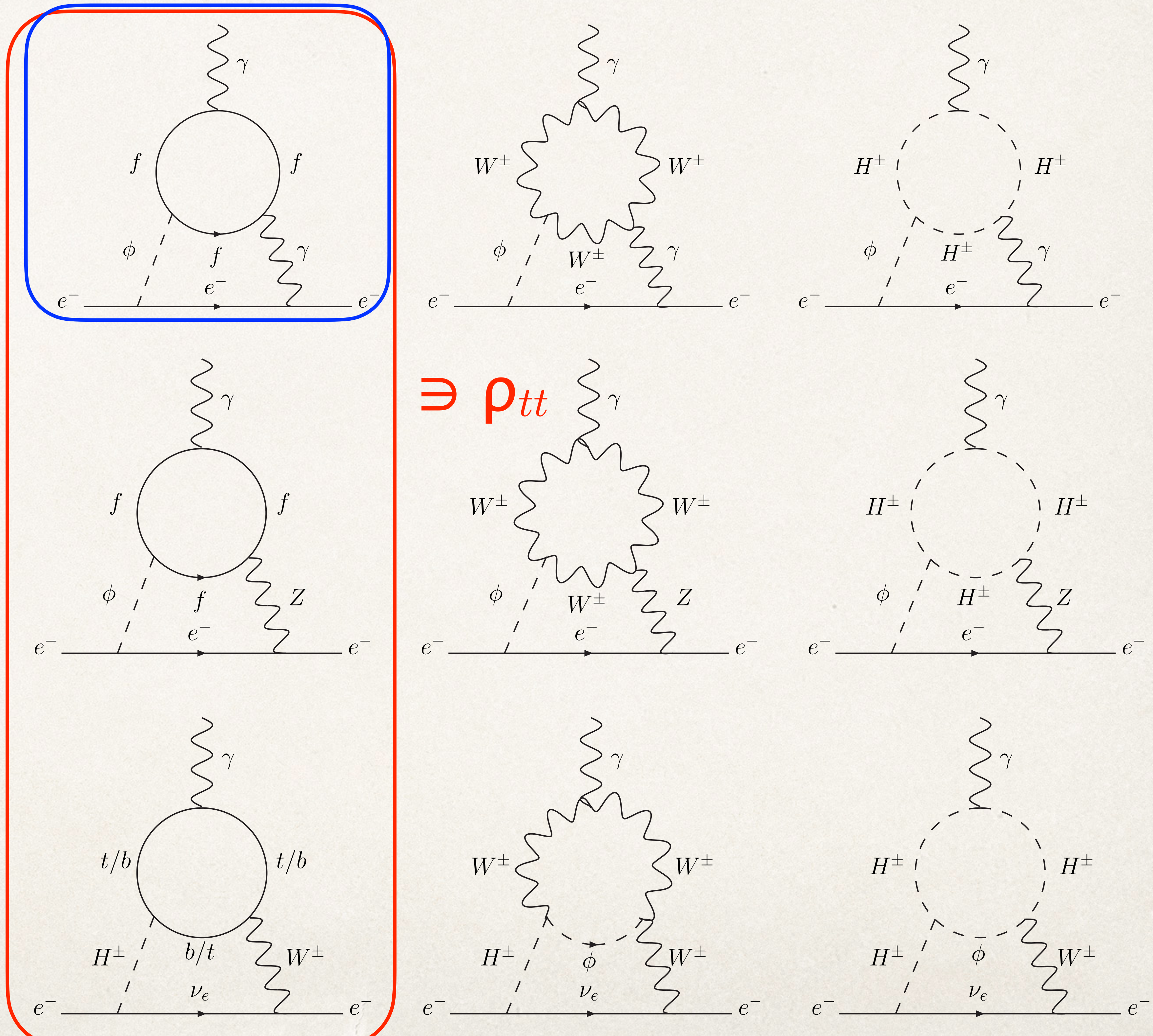
dominant

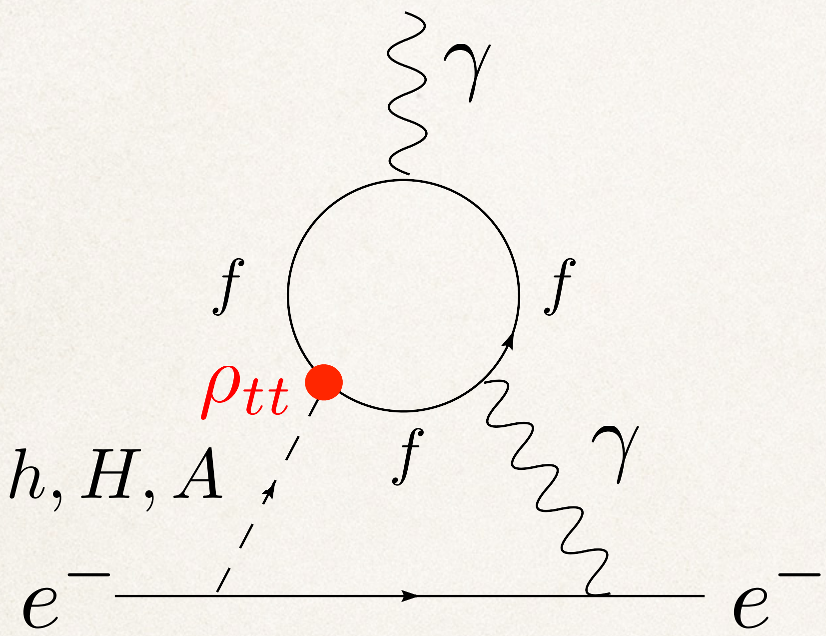
linking to t-EWBG

$\ni \rho_{tt}$



eEDM connected to t-EWBG

eEDM in the t-EWBG scenario is induced by ρ_{tt}.



If $\rho_{tt} \neq 0$ and other $\rho_{ff} = 0$,

$$\frac{(d_e^{\phi\gamma})_t}{e} = \frac{\alpha_{\rm em} s_{2\gamma}}{12\sqrt{2}\pi^3 v}\frac{m_e}{m_t}\boxed{{\rm Im}\rho_{tt}}\Delta g,$$

$$\Delta g = g(\tau_{th}) - g(\tau_{tH}), \quad \tau_{ij} = m_i^2/m_j^2$$

$$g(\tau) = \frac{\tau}{2}\int_0^1 dx \, \frac{1}{x(1-x)-\tau}\ln\left(\frac{x(1-x)}{\tau}\right)$$

eEDM bound: *not found yet

$|d_e| < 1.1 \times 10^{-29}$ e cm (ACME-II) $|d_e| < 8.7 \times 10^{-29}$ e cm (ACME-I)

${\rm Im}\rho_{tt}$ is necessary for EWBG but constrained by eEDM.

t-EWBG

before ACME-II

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

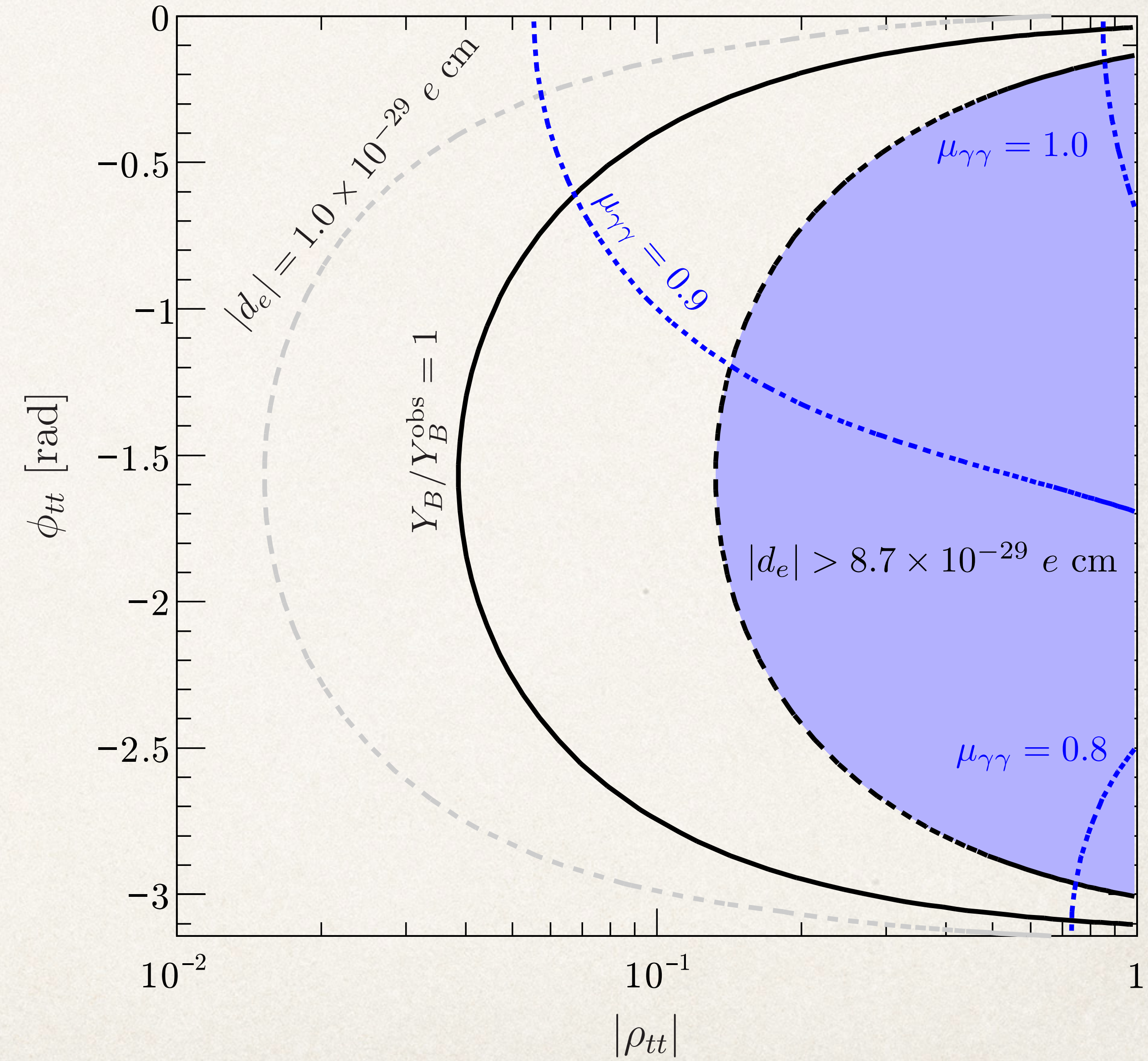
$$\rho_{tt} = |\rho_{tt}| e^{i\phi_{tt}}$$

- Sufficient BAU can be generated if $|\rho_{tt}| \gtrsim 0.04$ with moderate CP phases

- ACME-II has excluded such a parameter space!!

So, is t-EWBG dead?

- This conclusion is made assuming other ρ_{ii}=0.



K. Fuyuto, W.S. Hou, E.S., 1705.05034 [PLB]

t-EWBG

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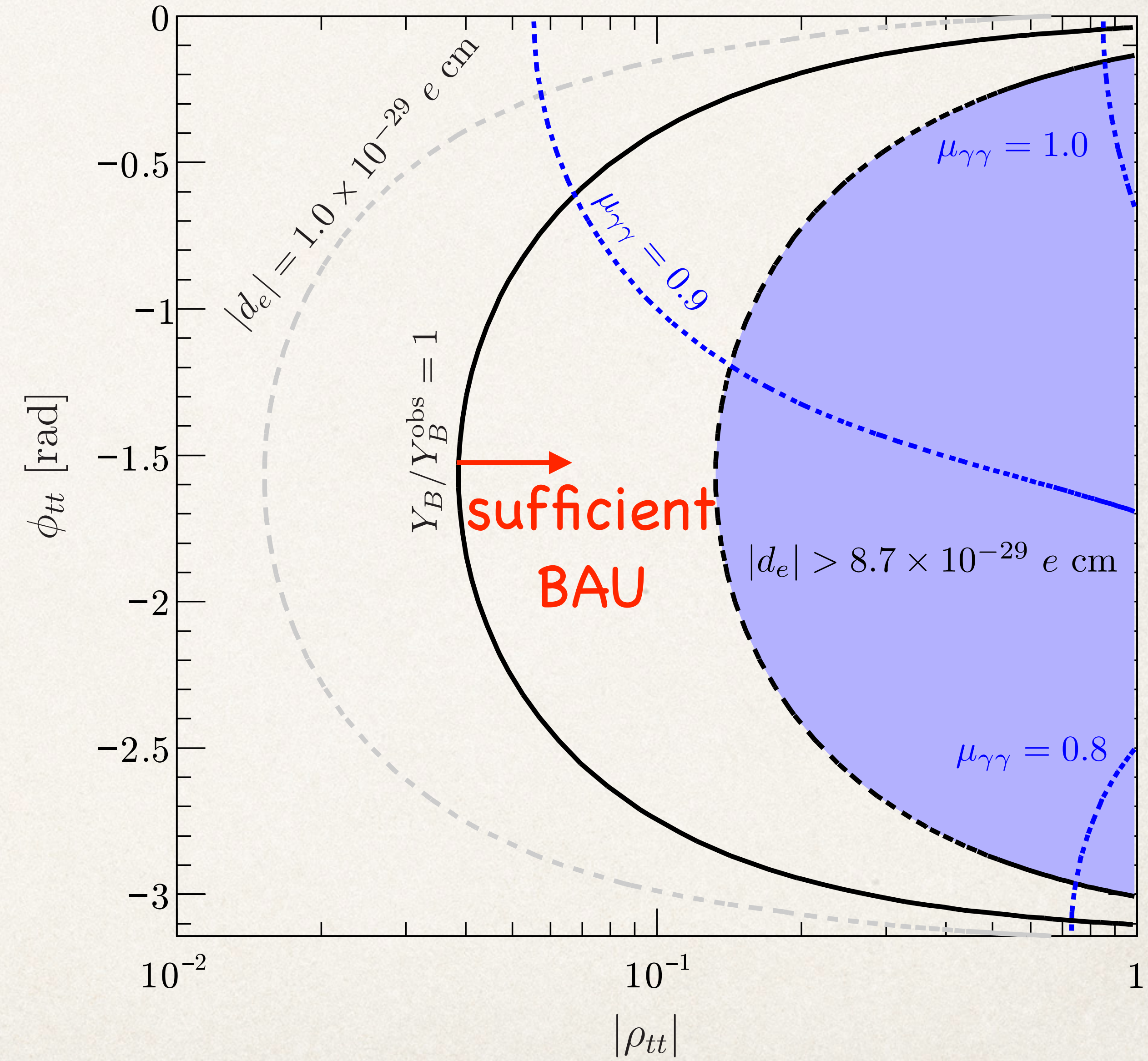

K. Fuyuto, W.S. Hou, E.S., 1705.05034 [PLB]

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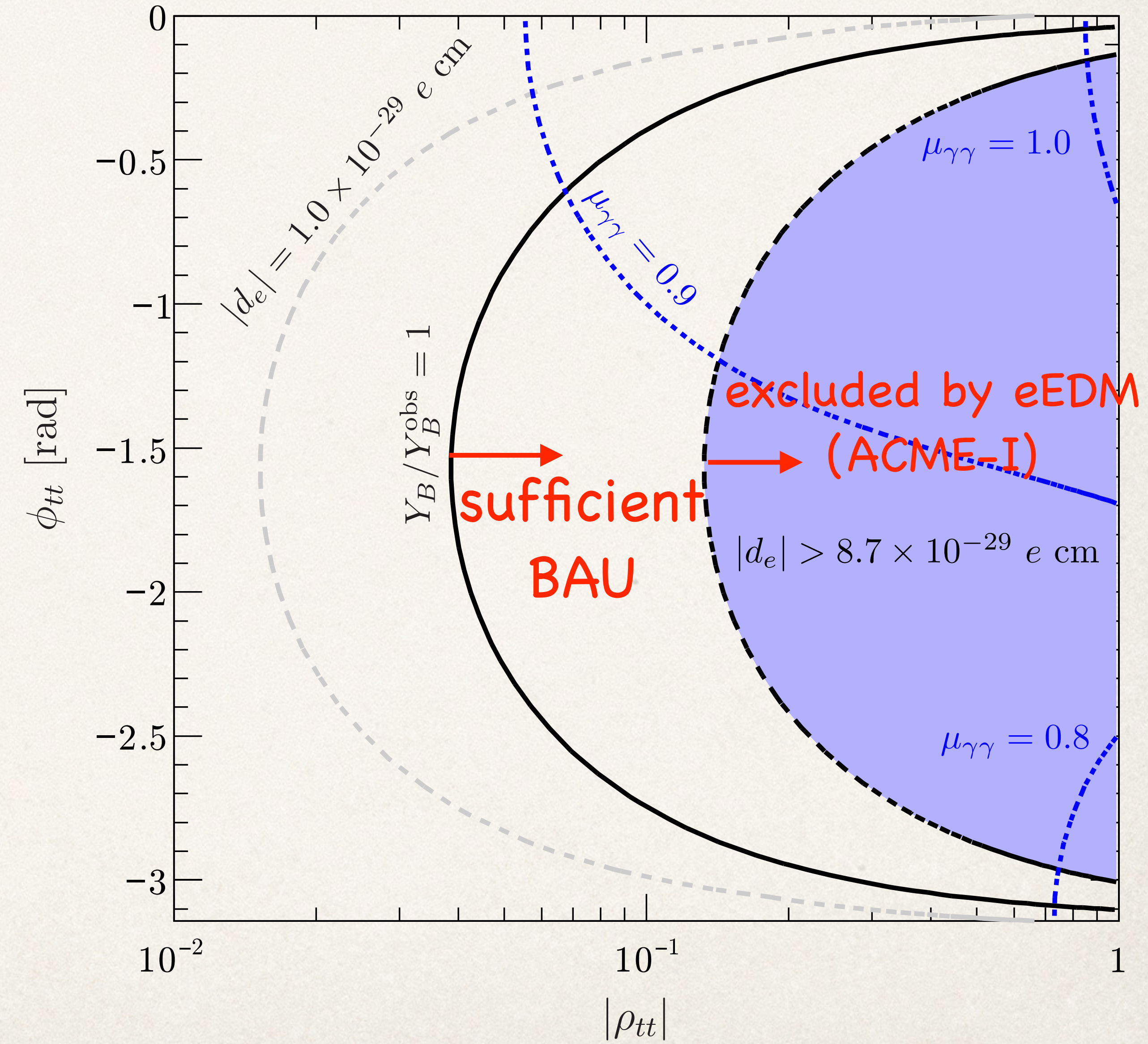

K. Fuyuto, W.S. Hou, E.S., 1705.05034 [PLB]

t-EWBG

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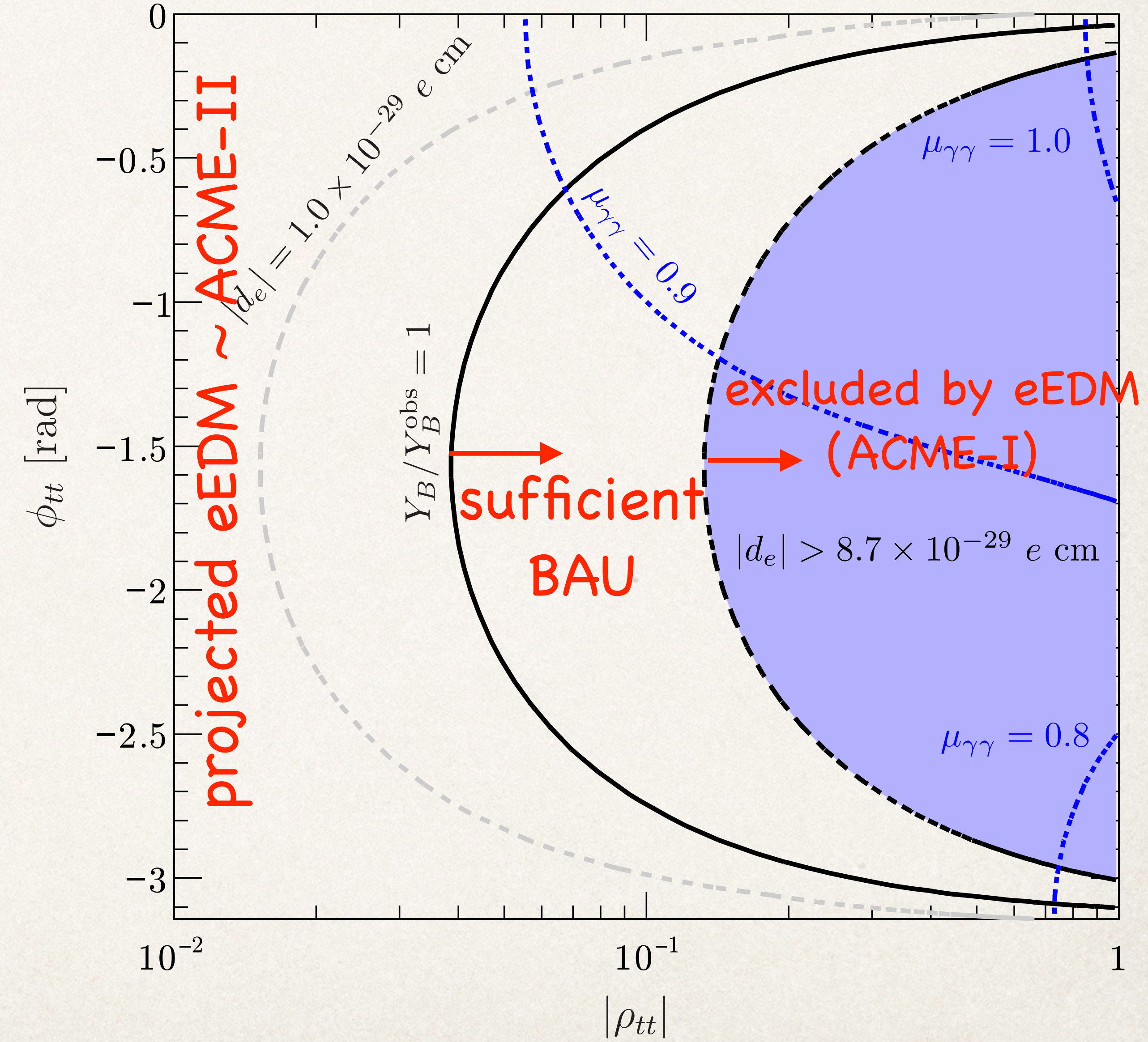


K. Fuyuto, W.S. Hou, E.S., 1705.05034 [PLB]

Importance of ρ_{ee}

K. Fuyuto, W.-S. Hou, E.S., 1910.12404 [PRD]

- ρ_{ee} cannot be exactly zero w/o symmetry or protection mechanism.

- Once there exist 2 complex parameters (ρ_{tt}, ρ_{ee}), cancellation of eEDM is in principle possible.

Classification of cancellation mechanism

Structured cancellation:

SM Yukawa-type hierarchy

$$\boxed{|\rho_{ff}| \approx \lambda_f}$$

λ_f are known

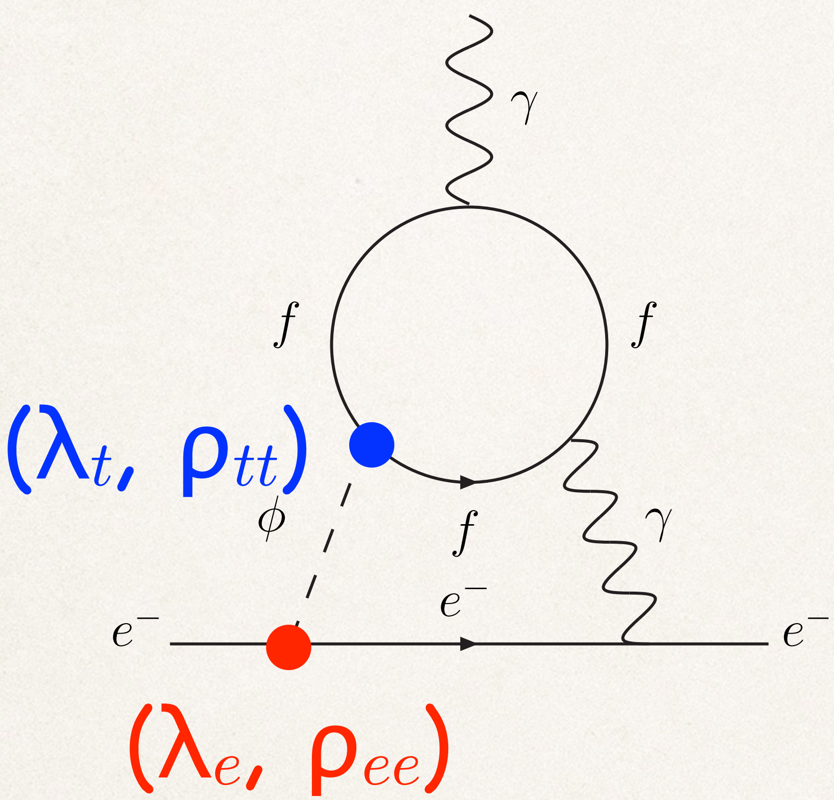
Unstructured cancellation:

Non-SM Yukawa-type hierarchy

$$\boxed{|\rho_{ff}| \not\approx \lambda_f}$$

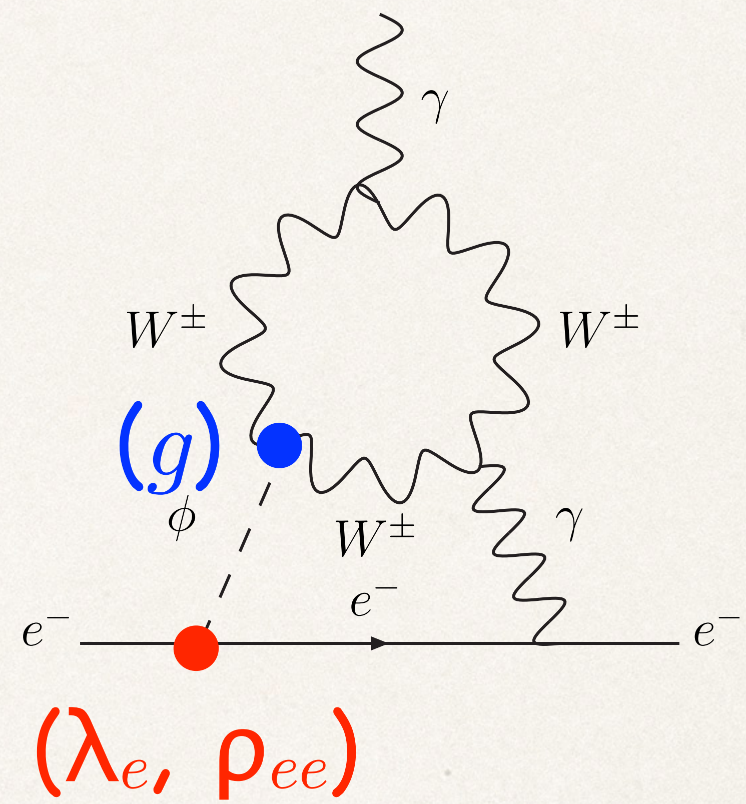
Decomposition

For nonzero ρ_{tt} and ρ_{ee}, the following 2 diagrams are relevant.



→ $\lambda_t\mathrm{Im}(\rho_{ee})$, $\lambda_e\mathrm{Im}(\rho_{tt})$ $\cdots$ (mix)
$\mathrm{Im}(\rho_{ee}\rho_{tt})$ $\cdots$ (extra)

$$(d_e^{\phi\gamma})_t = (d_e^{\phi\gamma})_t^{\mathrm{mix}} + (d_e^{\phi\gamma})_t^{\mathrm{extr}}$$



→ $g\mathrm{Im}(\rho_{ee})$ $\cdots$ (mix)

$$(d_e^{\phi\gamma})_W = (d_e^{\phi\gamma})_W^{\mathrm{mix}}$$

Cancellation mechanism

We consider cancellation mechanism such that

$$(d_e^{\phi\gamma})_t^{\rm mix} + (d_e^{\phi\gamma})_W^{\rm mix} = 0, \qquad (d_e^{\phi\gamma})_t^{\rm extr} = 0.$$

$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\frac{{\rm Im}\rho_{ee}}{{\rm Im}\rho_{tt}} = c \times \frac{\lambda_e}{\lambda_t} \qquad \frac{{\rm Re}\rho_{ee}}{{\rm Re}\rho_{tt}} = -\frac{{\rm Im}\rho_{ee}}{{\rm Im}\rho_{tt}} = -c \times \frac{\lambda_e}{\lambda_t}.$$

$$\longrightarrow \boxed{\left|\frac{\rho_{ee}}{\rho_{tt}}\right| = c \times \frac{\lambda_e}{\lambda_t}}$$ SM Yukawa-type hierarchy

$$c = (16/3)\Delta g/(\Delta\mathcal{J}_W^{\gamma} - (16/3)\Delta f).$$

E.g., c≃0.7 in the EWBG benchmark. (m_H=m_A=m_{H+}=500 GeV)

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SM Yukawa-type hierarchy

$$c = (16/3)\Delta g/(\Delta \mathcal{J}_W^{\gamma} - (16/3)\Delta f).$$

structured cancellation!!

E.g., c≃0.7 in the EWBG benchmark. ($m_H=m_A=m_{H+}=500$ GeV)

d_{ThO} and its details

Let's take absolute values of EDMs to see cancellation behavior

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

where

$$\mathcal{L}_{eN} = -\frac{G_F}{\sqrt{2}} C_S (\bar{N}N)(\bar{e} i\gamma_5 e)$$

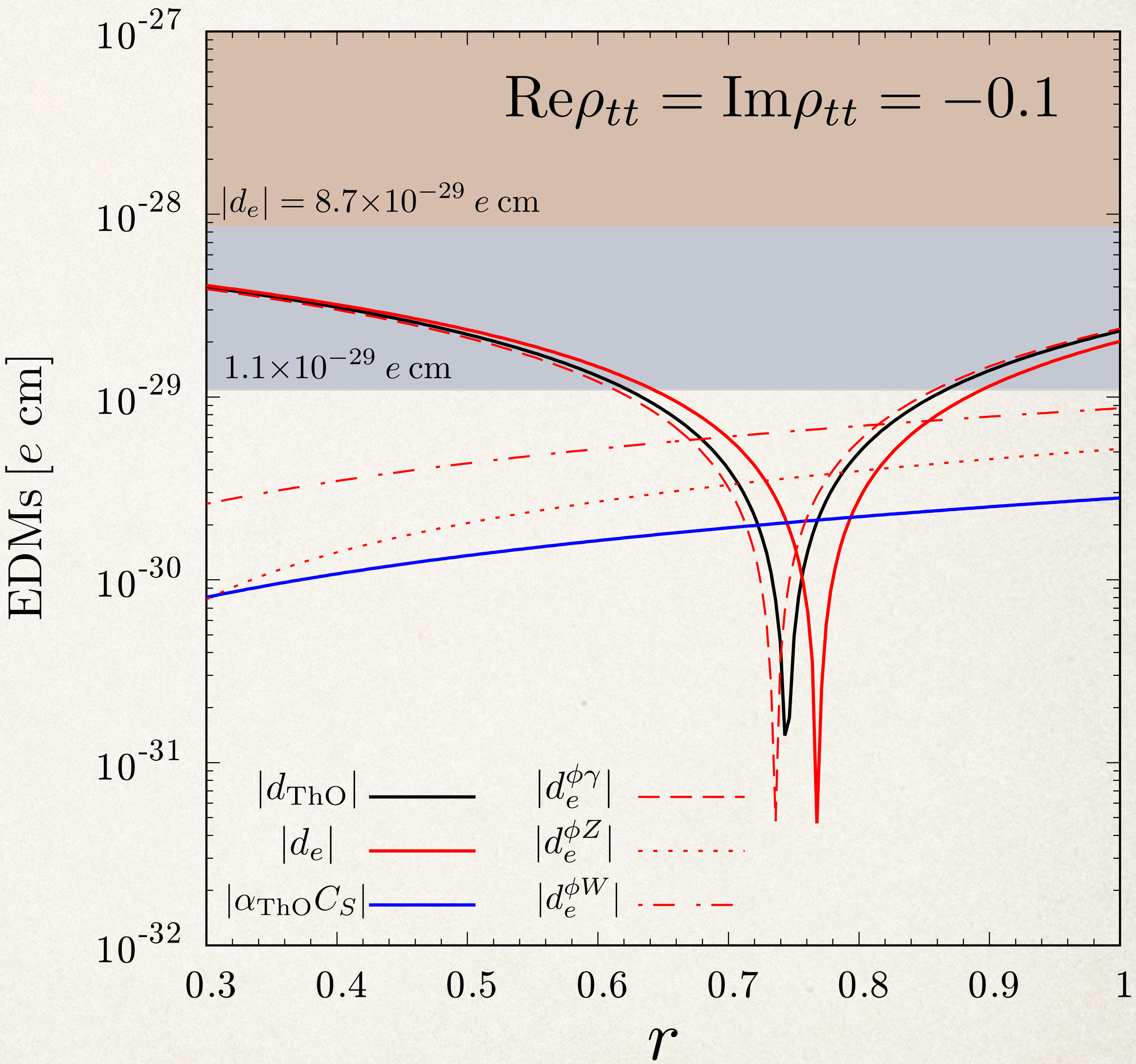
$$\alpha_{\mathrm{ThO}} = 1.5 \times 10^{-20}\ e\ \mathrm{cm}$$

- Strong cancellation happens in $d_e^{\phi\gamma}$ due to $(d_e^{\phi\gamma})_t$ + $(d_e^{\phi\gamma})_W$ ≃ 0.

- $d_e^{\phi W}$ becomes dominant, followed by $d_e^{\phi Z}$.

- Cancellation happens if ρ_{ee}≠0 and r=O(1).

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



$$\mathrm{Re}\rho_{ff} = -r\left(\frac{\lambda_f}{\lambda_t}\right)\mathrm{Re}\rho_{tt},\ \mathrm{Im}\rho_{ff} = r\left(\frac{\lambda_f}{\lambda_t}\right)\mathrm{Im}\rho_{tt}$$

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}.

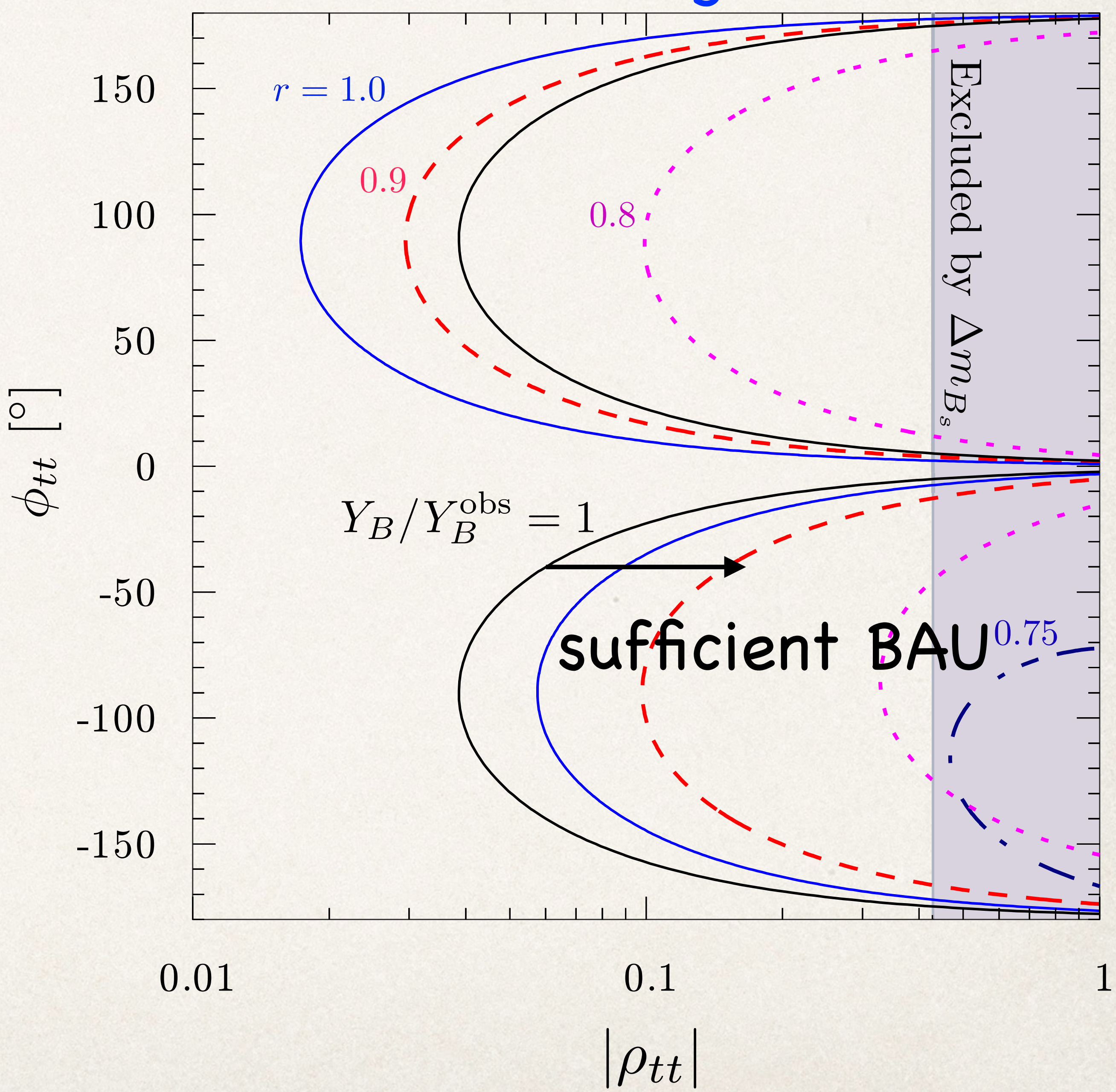
- BAU-favored regions revive!!

- 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}



Summary

1st part of my talk:

- We have studied the sphaleron decoupling condition taking the magnetic mass into account.

- Nonzero magnetic mass can increase the sphaleron energy, which makes the sphaleron decoupling condition more relaxed.

2nd part of my talk:

- We have revisited the t-EWBG scenario in the general 2HDM in light of ACME-II.

- Built-in cancellation mechanism for eEDM exists, which indicates the presence of ρ_{ee} such that $|\rho_{ee}/\rho_{tt}| \sim \lambda_e/\lambda_t$. t-EWBG scenario is still viable.

Backup

1^{st}-order EWPT

$$s_{\beta-\alpha} = t_\beta = 1, m_{H^\pm} = m_A,\ \ M = \sqrt{m_3^2/s_\beta c_\beta} = 300\ \text{GeV}$$

$$\lambda_6 = \lambda_7 = 0$$

- EWBG-viable region

  $v_C/T_C >$ 1.17

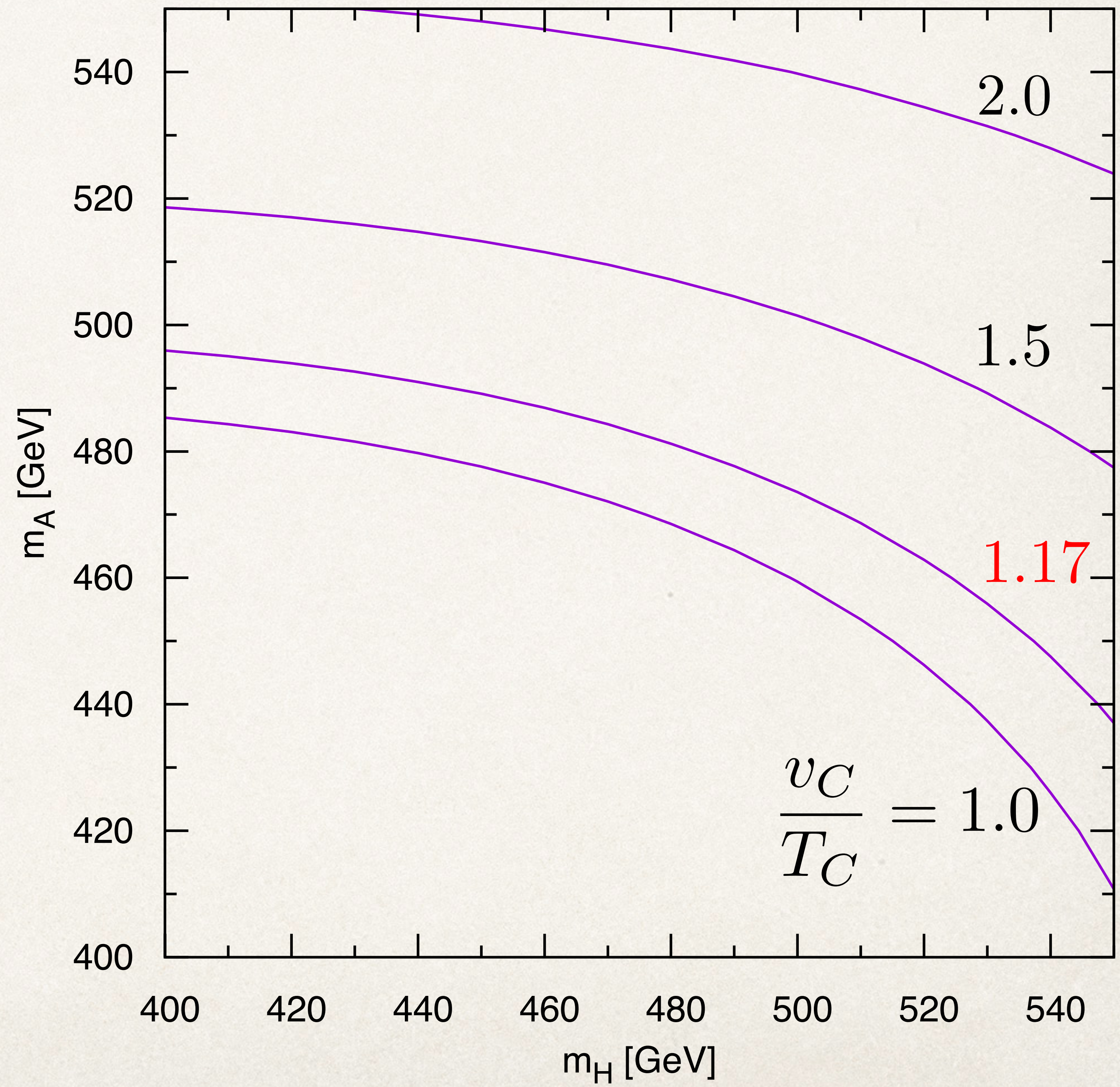
- Heavy Higgs w/ non-decoupling plays a role.

- Too heavy Higgs could violate perturbativity.

Benchmark point:

$$m_H = m_A = m_{H^\pm} = 500\ \text{GeV}$$

$$\frac{v_C}{T_C} = 1.48$$



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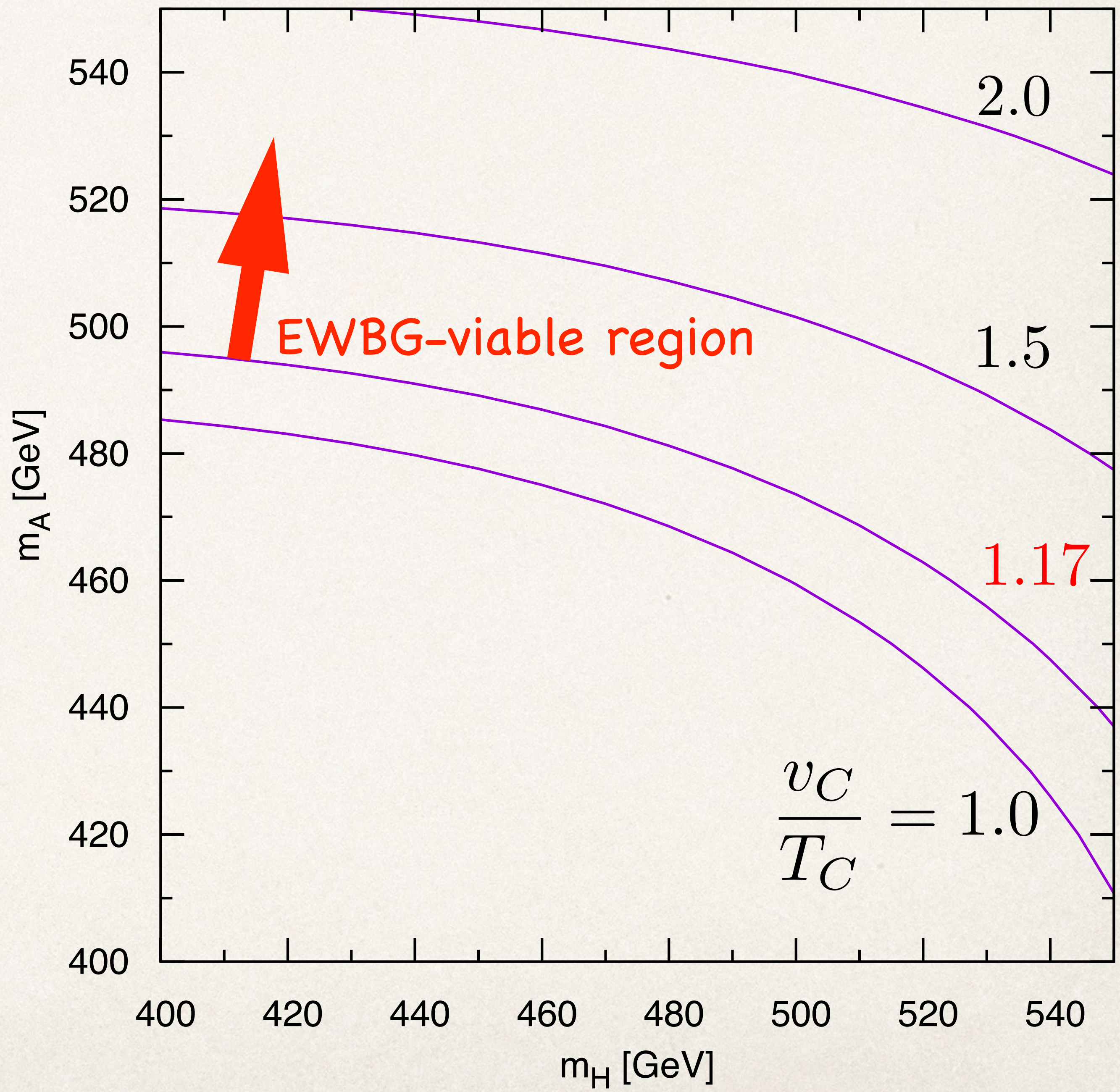

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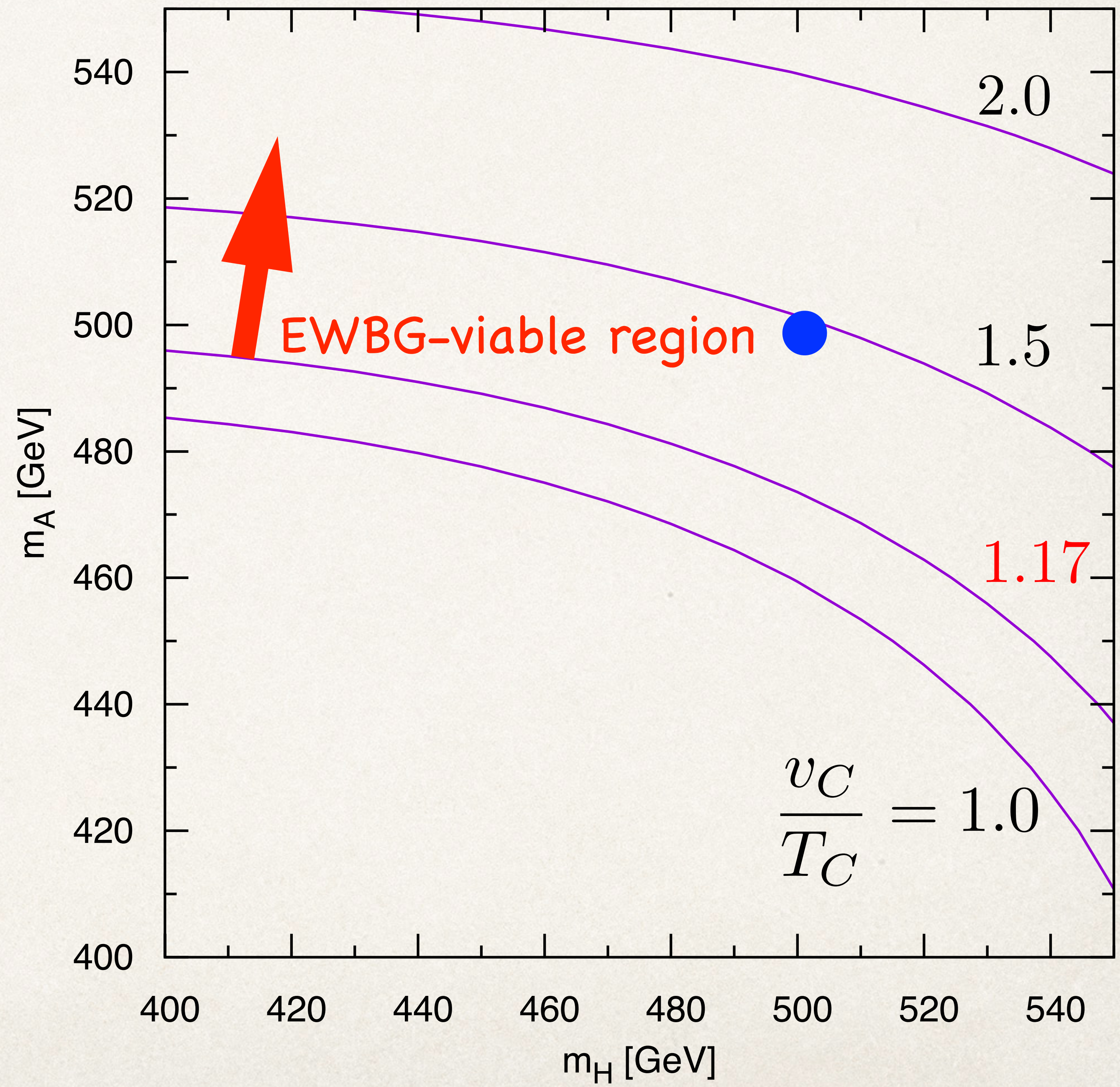

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$$\frac{v_C}{T_C} = 1.48$$

Case of $(d_e^{\phi\gamma})_t^{\rm extr} \neq 0$

We could consider another cancellation case:

$$(d_e^{H\gamma})_t^{\rm (mix)} + (d_e^{H\gamma})_t^{\rm (extr)} + (d_e^{H\gamma})_W^{\rm (mix)} = 0.$$

Taking Reρ_{ee}=0 for illustration, one has

$$\frac{{\rm Im}\rho_{ee}}{{\rm Im}\rho_{tt}} \simeq \frac{(16/3)\Delta g}{\Delta\mathcal{J}_W^\gamma - (16/3)\Delta f + \epsilon}\frac{\lambda_e}{\lambda_t} \equiv c' \times \frac{\lambda_e}{\lambda_t},$$

where $$s_{2\gamma}\lambda_t\,\epsilon = -(16/3){\rm Re}\rho_{tt}\left[f(\tau_{tA}) + g(\tau_{tA})\right].$$

- c'>>1 if the denominator becomes small. -> $d_{\rm ThO}$ gets enhanced by other diagrams, which can be excluded.

- |c'|>0.3 in experimentally allowed Reρ_{tt}.

CP violation at 1-loop

$$O^T \mathcal{M}_N'^2 O = \mathrm{diag}(m_{H_1}^2, m_{H_2}^2, m_{H_3}^2)$$

$$\mathcal{M}_N'^2 \simeq \begin{pmatrix} m_h^2 & 0 & -\frac{3}{4\pi^2}\lambda_t \mathrm{Im}\rho_{tt} m_t^2 \\ 0 & m_H^2 & -\frac{3}{4\pi^2}\mathrm{Re}\rho_{tt}\mathrm{Im}\rho_{tt} m_t^2 \\ -\frac{3}{4\pi^2}\lambda_t \mathrm{Im}\rho_{tt} m_t^2 & -\frac{3}{4\pi^2}\mathrm{Re}\rho_{tt}\mathrm{Im}\rho_{tt} m_t^2 & m_A^2 \end{pmatrix}$$

$$\tan 2\theta_{13} = \frac{2(\mathcal{M}_N'^2)_{13}}{m_h^2 - m_A^2}. \longrightarrow \theta_{13} \simeq 9.6 \times 10^{-3}$$ for m_A= 500 GeV, Imρ_{tt}=1.

$$\tan 2\theta_{23} = \frac{2(\mathcal{M}_N'^2)_{23}}{m_H^2 - m_A^2} = \infty \quad \theta_{23} = \pi/4$$ for m_H=m_A= 500 GeV, $(\mathcal{M}_N'^2)_{23} \neq 0$

For the top-loop Barr-Zee diagram, one of the relevant parts takes the form

$$\sum_i O_{2i} O_{3i} f(\tau_{tH_i}) = O_{21} \underbrace{O_{31}}_{\ll 1} f(\tau_{tH_1}) + (\underbrace{O_{22}O_{32} + O_{23}O_{33}}_{\ll 1\ \because\ \text{orthogonality of } O}) f(\tau_{tH_2}) \ll 1,$$

Therefore, 1-loop CPV effects are rather minor.

C_S comes into play

ACME experiment measures EDM of ThO.

$$d_{\rm ThO} = d_e + \alpha_{\rm ThO} C_S \qquad \mathcal{L}_{eN} = -\frac{G_F}{\sqrt{2}} C_S (\bar{N}N)(\bar{e} i\gamma_5 e)$$

$$\alpha_{\rm ThO} = 1.5 \times 10^{-20}\ e\ {\rm cm}$$

Once the cancellation happens in d_e, C_S contribution could comes into play.

$\longrightarrow$ $|d_e| < 1.1 \times 10^{-29}\ e\ {\rm cm}$ is not applicable. $C_S=0$

We have to use

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

[ACME, Nature 562,355(2018)]

From now on, we consider $d_{\rm ThO}$ taking C_S into account.

C_S contribution

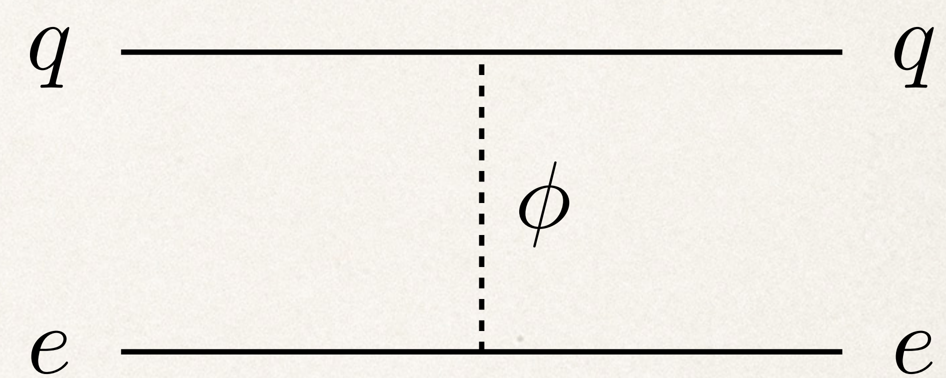
CP-violating Higgs couplings to fermions

$$\mathcal{L}_{\phi\bar{f}f} = -\phi\bar{f}\left(g^S_{\phi\bar{f}f} + i\gamma_5 g^P_{\phi\bar{f}f}\right)f$$

C_S arises from 4 fermion operators as

$$\mathcal{L}^{\rm CPV}_{4f} = \sum_q C_{qe}(\bar{q}q)(\bar{e}i\gamma_5 e)$$

$$C_{qe} = \sum_{\phi=h,H,A} \frac{g^S_{\phi\bar{q}q}g^P_{\phi\bar{e}e}}{m^2_\phi}.$$



We use

$$C_S = -2v^2\left[6.3(C_{ue}+C_{de}) + C_{se}\frac{41\ \text{MeV}}{m_s} + C_{ce}\frac{79\ \text{MeV}}{m_c} + 6.2\times10^{-2}\left(\frac{C_{be}}{m_b}+\frac{C_{te}}{m_t}\right)\right]$$

The sign of C_S depends on ρ_{qq} (q=u,d,s,c,b)