기초과학연구원
Institute for Basic Science

Electroweak phase transition in a model for dark matter and muon g-2 anomaly

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October 11, 2019

4th IBS-MultiDark-IPPP Workshop

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Ref. arXiv:1905.10283 [PRD]

Outline

- Introduction
- Model (inert Higgs doublet + vector-like leptons)
- $(g-2)_\mu$, dark matter
- Strong 1^{st}-order electroweak phase transition (SFOEWPT) and its implication: Z boson decays.
- Summary

Introduction

Drawbacks of the Standard Model (SM)

- Baryon asymmetry of the Universe (BAU), $n_B/s \simeq 10^{-10}$
- Dark matter (DM), etc.

muon g-2

$$\delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$

[Hagiwara et al, 1105.3149]

A model extended with inert Higgs doublet and vector-like leptons can explain DM and $(g\text{-}2)_\mu$.

[L. Calibbi, R. Ziegler, J. Zupan, 1804.00009 (JHEP)]

Q. Is EW baryogengesis (EWBG) compatible with them?

As a first step, we focus on 1st-order EWPT.

Model

Particle content

$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes Z_2$

SM + Vector-like leptons: $E_{i=1-3}: \ (\mathbf{1}, \mathbf{1}, -1, -)$

Inert Higgs doublet: $\eta: \ (\mathbf{1}, \mathbf{2}, 1/2, -)$

[D. Boraha, S. Sadhukhanb, S. Sahooa, PLB771, (2017) 624 (1703.08674)]

[L. Calibbi, R. Ziegler, J. Zupan, 1804.00009 (JHEP)]

New lepton Yukawa interaction

$$-\mathcal{L}_Y \ni y_{ij} \bar{\ell}_{iL} \eta E_{jR} + m_{E_i} \bar{E}_{iL} E_{iR} + \mathrm{h.c.}$$

Higgs potential

$$V_0(\Phi, \eta) = \mu_1^2 \Phi^\dagger \Phi + \mu_2^2 \eta^\dagger \eta + \frac{\lambda_1}{2}(\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 + \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) + \left[\frac{\lambda_5}{2}(\Phi^\dagger \eta)^2 + \mathrm{h.c}\right]$$

Lepton Yukawa int.

Couplings of SM leptons to E and η.

$$
\begin{aligned}
-\mathcal{L}_Y &\ni y_{ij}\bar{\ell}_{iL}\eta E_{jR} + m_{E_i}\bar{E}_{iL}E_{iR} + \text{h.c.} \\
&= \frac{1}{\sqrt{2}}\bar{e}_L y E_R (H + iA) + \bar{\nu}_L y E_R H^+ + m_{E_i}\bar{E}_{iL}E_{iR} + \text{h.c.}
\end{aligned}
$$

where m_E is diagonalized. In this basis, y is the general 3×3 complex matrix

$$
y = \begin{pmatrix} y_{eE_1} & y_{eE_2} & y_{eE_3} \\ \boxed{y_{\mu E_1} \quad y_{\mu E_2} \quad y_{\mu E_3}} & & \\ y_{\tau E_1} & y_{\tau E_2} & y_{\tau E_3} \end{pmatrix}
$$

relevant to muon g-2

As a simple setup, we consider $y_{\mu E} \neq 0$ and others $\simeq 0$.

Higgs potential

tree-level potential w/ Z_2 $\Phi \to \Phi$ and $\eta \to -\eta$

$$V_0(\Phi, \eta) = \mu_1^2 \Phi^\dagger \Phi + \mu_2^2 \eta^\dagger \eta + \frac{\lambda_1}{2}(\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 + \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta)$$
$$+ \lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) + \left[\frac{\lambda_5}{2}(\Phi^\dagger \eta)^2 + \text{h.c}\right]$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \eta = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}.$$

H or A (lightest Z_2 odd particle) can be a dark matter (DM).

In this study, we consider H is DM.

Higgs masses

In the vacuum $v = 246\ \mathrm{GeV}$

$$\begin{aligned} m_h^2 &= \lambda_1 v^2, \\ m_H^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2, \\ m_A^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2, \\ m_{H^\pm}^2 &= \mu_2^2 + \frac{1}{2}\lambda_3 v^2. \end{aligned}$$

- Heavy Higgs masses come from both μ_2^2 and symmetry breaking term (λv^2).
- We may know which part is dominant by measuring Higgs couplings precisely.

Model parameters

Original parameters: $\mu_1^2,\ \mu_2^2,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5.$

Converted parameters: $v,\ \mu_2^2,\ \lambda_2,\ m_h,\ m_H,\ m_A,\ m_{H^\pm},$

At tree level

$$\lambda_1 = \frac{m_h^2}{v^2}, \quad \lambda_3 = \frac{2}{v^2}(m_{H^\pm}^2 - \mu_2^2),$$
$$\lambda_4 = \frac{1}{v^2}(m_H^2 + m_A^2 - 2m_{H^\pm}^2), \quad \lambda_5 = \frac{1}{v^2}(m_H^2 - m_A^2).$$

In our study, H is DM, and $m_H \simeq m_h/2$ is taken.

DM physics point of view, $\mu_2^2 \longrightarrow \lambda_L \equiv \lambda_3 + \lambda_4 + \lambda_5$

Also, $m_A = m_{H+}$ ($\lambda_4 = \lambda_5$) to avoid ρ-parameter constraint.

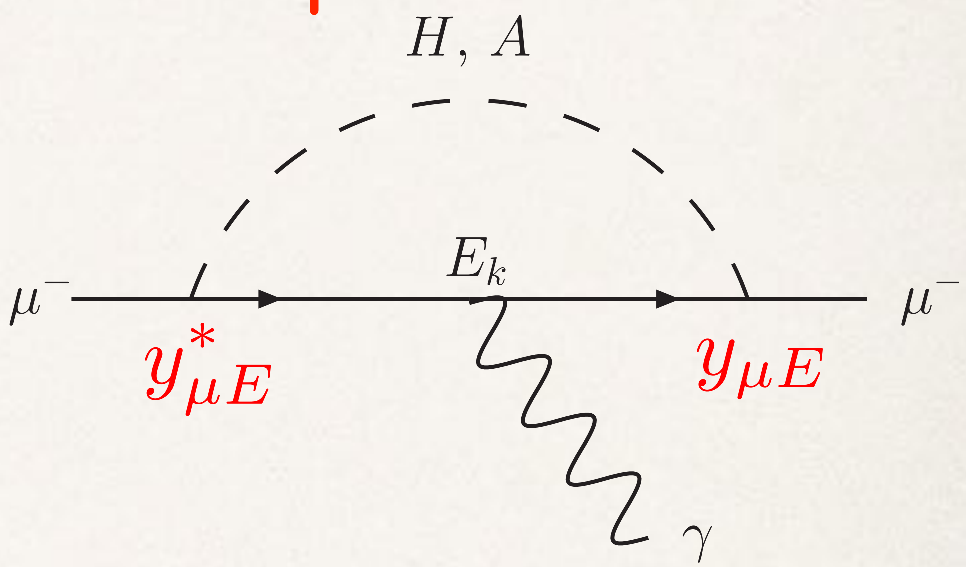
muon g-2
&
Dark Matter

muon g-2

New particles contribute to $(g-2)_\mu$ at 1-loop.

$$\delta a_\mu = \sum_{\phi=H,A} \sum_{i=1-3} \frac{|y_{\mu E_i}|^2}{32\pi^2} S_1(r_{E_i\mu}, r_{\phi\mu}),$$

$$r_{E_i\mu} = m_{E_i}^2/m_\mu^2,\ r_{\phi\mu} = m_\phi^2/m_\mu^2$$



$$\text{For } m_{E_i} = m_\phi \equiv M \gg m_\mu, \quad S_1 = \frac{m_\mu^2}{12M^2} + \mathcal{O}\left(\frac{m_\mu^4}{M^4}\right)$$

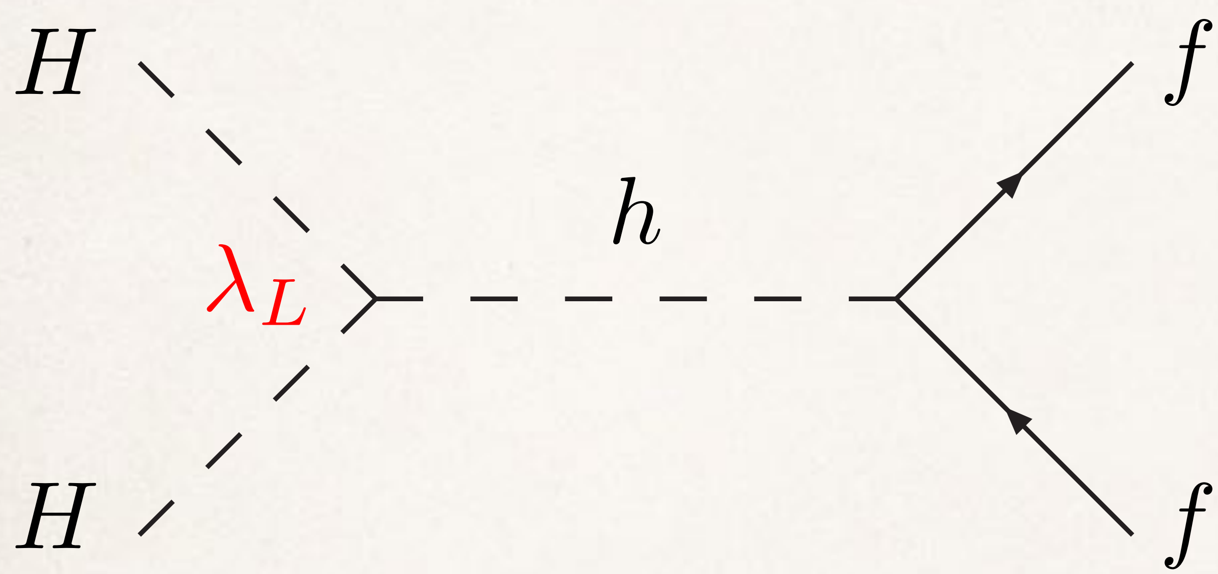
$$\boxed{\delta a_\mu \simeq \frac{1}{32\pi^2}\frac{m_\mu^2}{2M^2}|y_{\mu E}|^2 = (1.77\times 10^{-9})\left(\frac{100\ \text{GeV}}{M}\right)^2 \left|\frac{y_{\mu E}}{1.0}\right|^2}$$

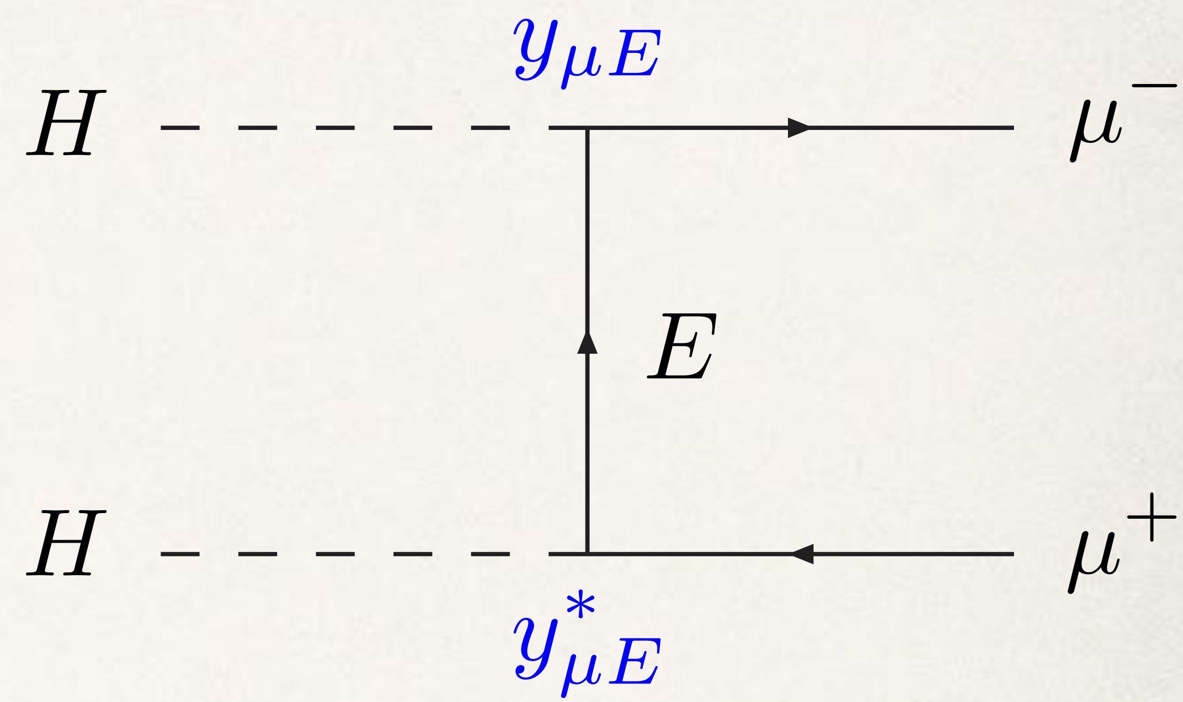
Exp. value: $\delta a_\mu = a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0)\times 10^{-10}$

Hagiwara et al, 1105.3149.

DM relic abundance

For $m_H < m_W$





$$\boxed{\sigma v_{\rm rel} = \frac{N_C^f}{16\pi}\frac{\lambda_L^2 m_f^2 \beta_f^3}{(s-m_h^2)^2 + m_h^2\Gamma_h^2} + \frac{|y_{\mu E}|^4}{60\pi m_H^2}\frac{v_{\rm rel}^4}{(1+r_E)^4}}$$

where $\beta_f = \sqrt{1 - \frac{4m_f^2}{s}}$ $\quad r_E = m_E^2/m_H^2$

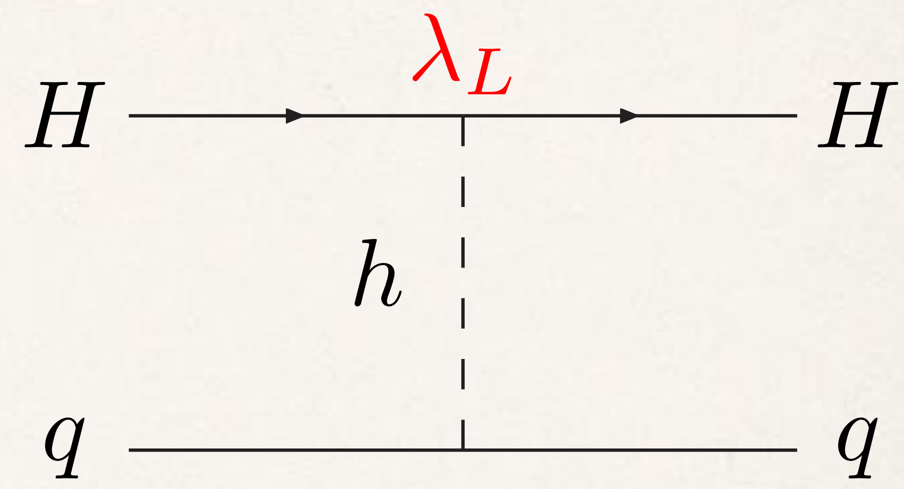
- $m_H \simeq m_h/2$ can give the right amount of DM relic density.
- 2nd diagram would be important if $y_{\mu E} > O(1)$.

DM constraints

Spin-independent cross section

$$\sigma_{\rm SI} \simeq \frac{\lambda_L^2 f^2}{4\pi}\left(\frac{m_N^2}{m_H m_h^2}\right)^2$$

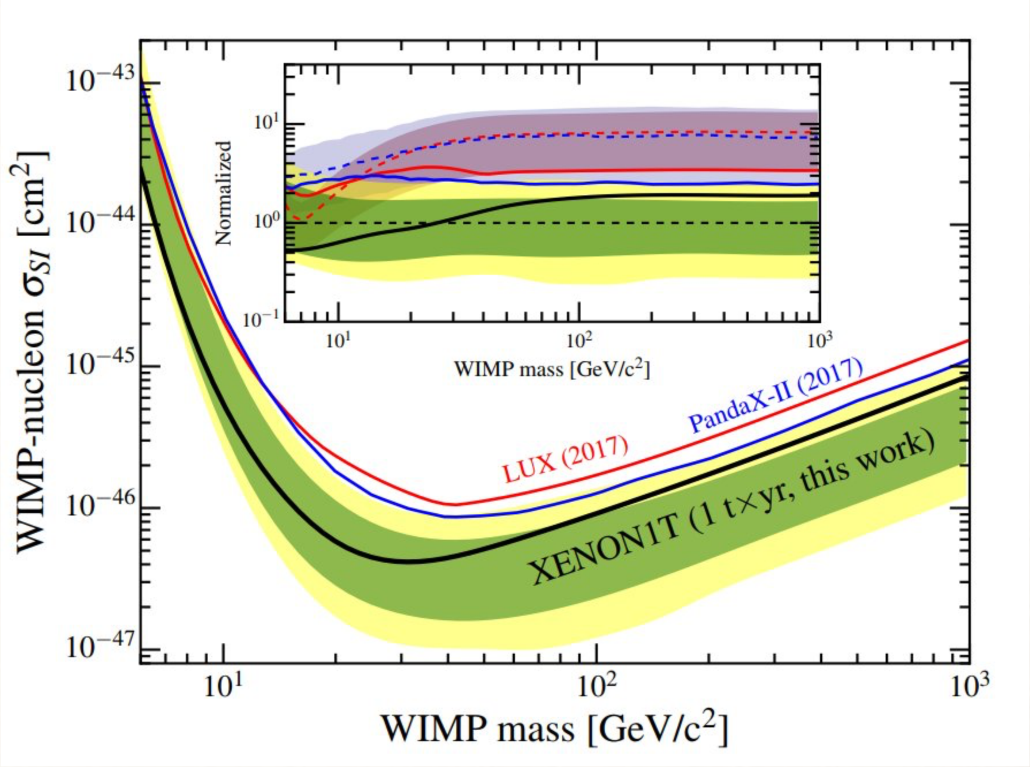
with $f \simeq 0.3$



From the DM direct search,

$$\lambda_L \lesssim \mathcal{O}(10^{-3})$$

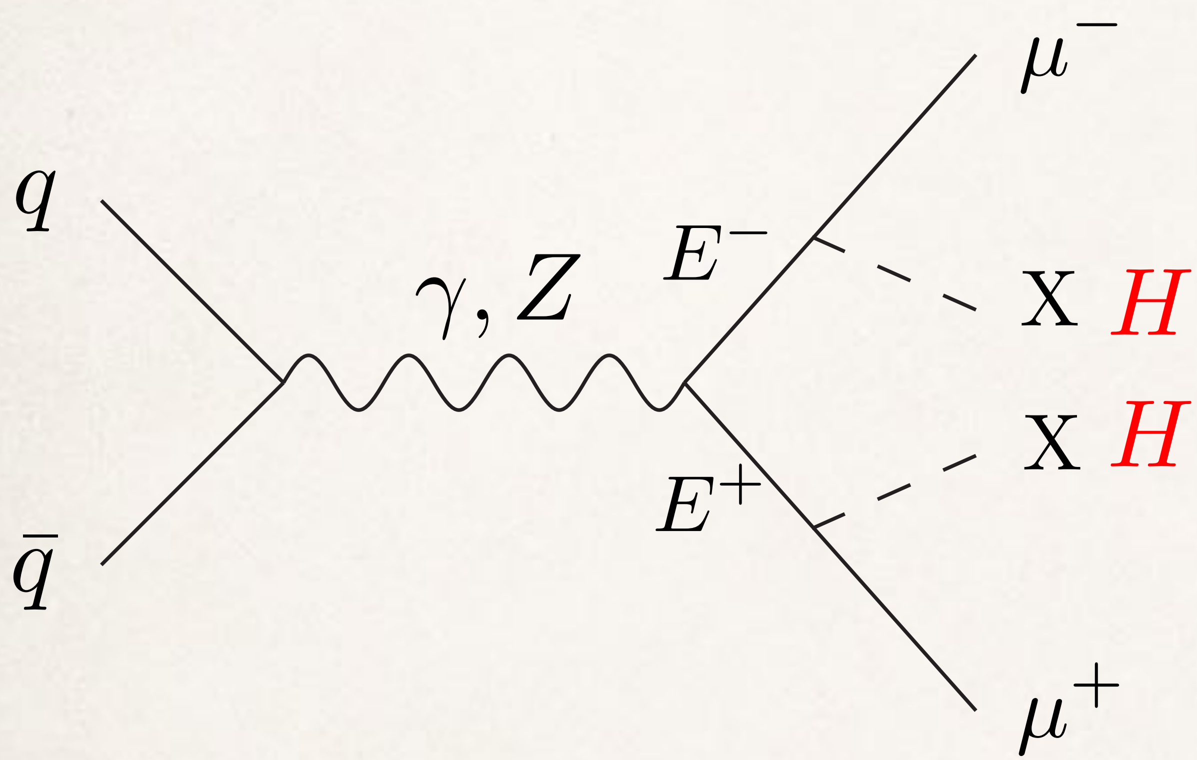
$$\longrightarrow \boxed{\begin{aligned} m_H^2 &= \mu_2^2 + \frac{\lambda_L}{2}v^2 \simeq \mu_2^2, \\ m_A^2 &= \mu_2^2 + \frac{\lambda_3}{2}v^2 \simeq m_H^2 + \frac{\lambda_3}{2}v^2. \end{aligned}}$$

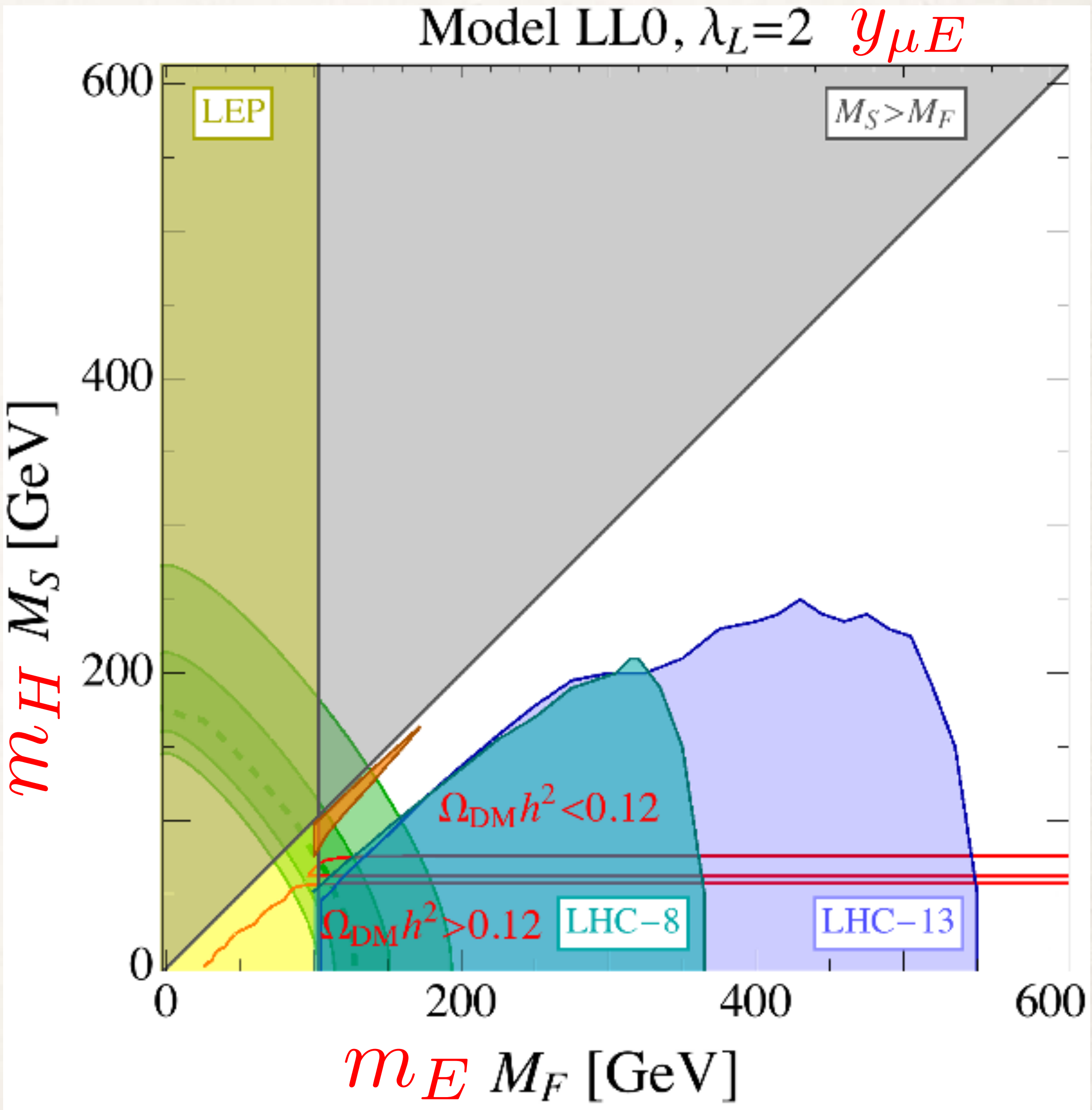


λ_3(>0) controls the mass splitting between H and A.

LHC constraint

Lorenzo Calibbi, Robert Ziegler, Jure Zupan, 1804.00009 (JHEP)





105 GeV < m_E < 125GeV

Is this parameter consistent with SFOEWPT?

LHC constraint

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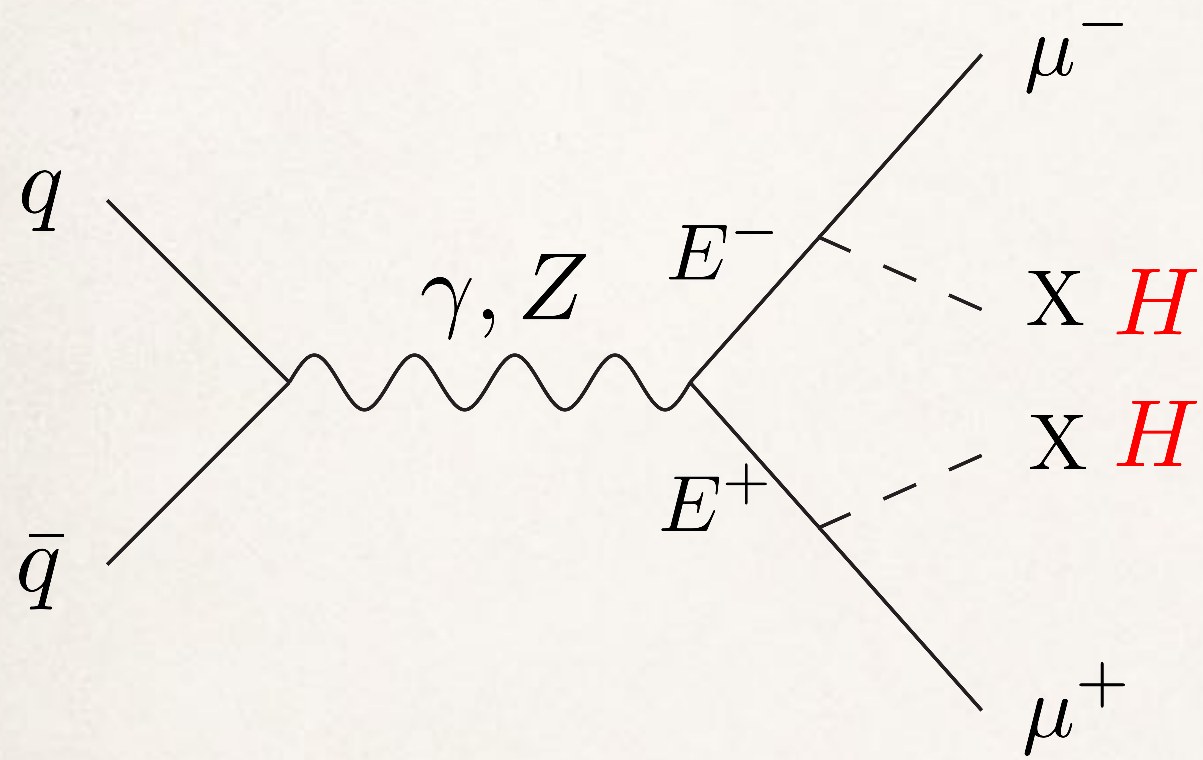
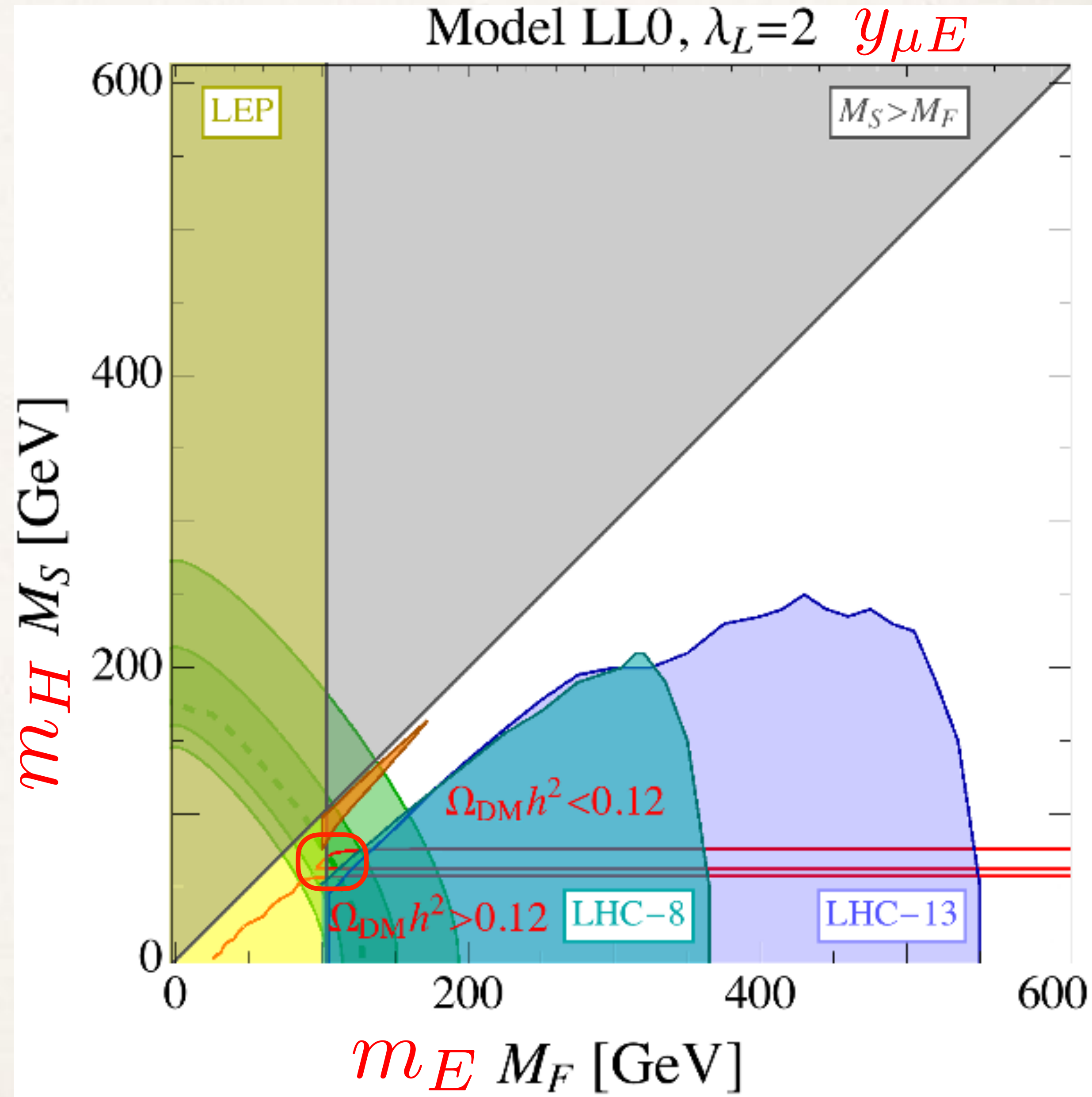




105 GeV < m_E < 125GeV

Is this parameter consistent with SFOEWPT?

EW Phase transition

EW baryogenesis (EWBG)

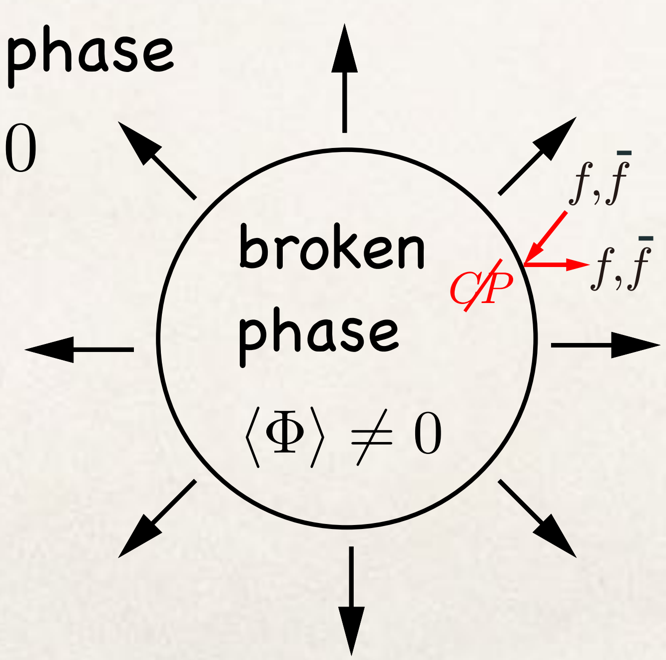
Sakharov's conditions

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

- B violation: anomalous (sphaleron) process
- 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

symmetric phase

$\langle \Phi \rangle = 0$



$n_B = 0 \to n_B \neq 0$ (sphaleron proecess)

baryogengesis occurs outside bubbles!

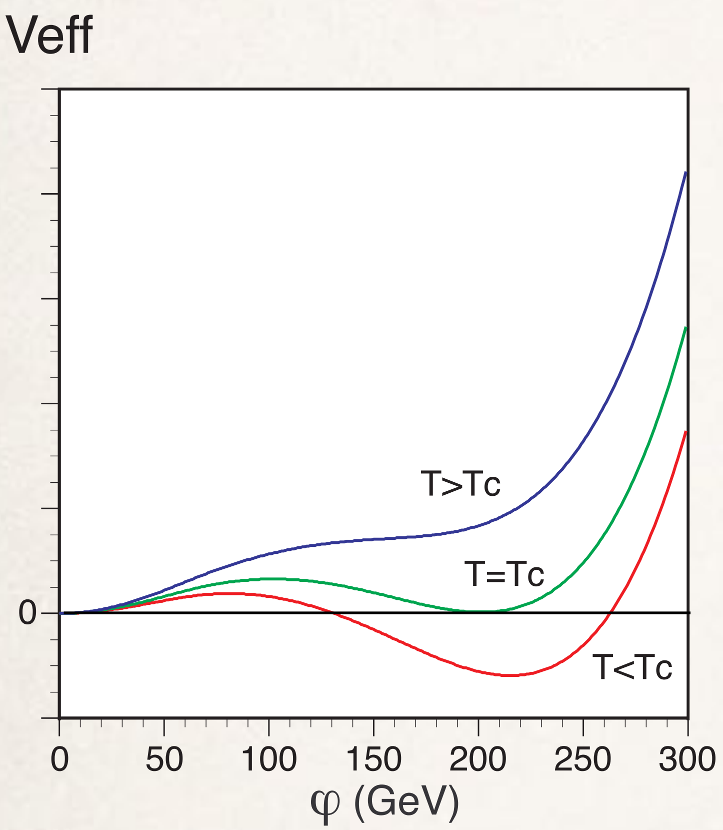
B-preservation condition

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

1st-order EWPT!!

1^{st}-order phase transition

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



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

Extra Higgs loops can enhance E.

$$\bar{m}_\phi^2 = \mu_2^2 + \frac{1}{2}\bar{\lambda}_{h\phi\phi}\varphi^2$$

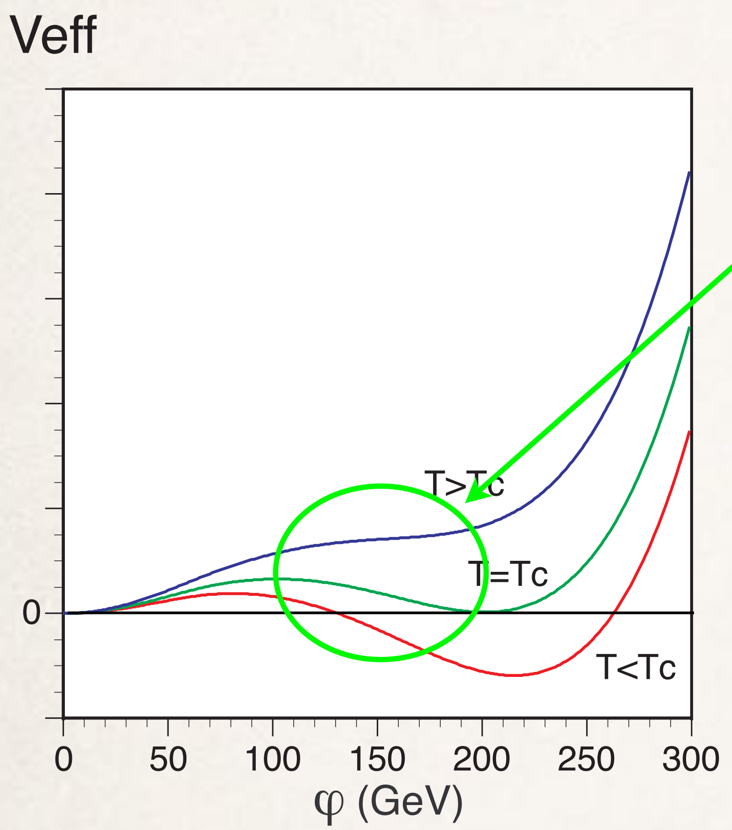
At 1-loop

$$V_{\rm eff} \ni \begin{cases} -(\bar{\lambda}_{h\phi\phi}/2)^{3/2} T \left(1 + \dfrac{\mu_2^2}{\bar{\lambda}_{h\phi\phi}\varphi^2/2}\right)^{3/2} \varphi^3 & \text{for} \quad \mu_2^2 \ll \bar{\lambda}_{h\phi\phi}\varphi^2/2, \\ -(\mu_2^2)^{3/2} T \left(1 + \dfrac{\bar{\lambda}_{h\phi\phi}\varphi^2}{\mu_2^2}\right)^{3/2} & \text{for} \quad \mu_2^2 \gg \bar{\lambda}_{h\phi\phi}\varphi^2/2. \end{cases}$$

In our model, the former implies λ_3 has to be big. $\longrightarrow$ $\boxed{m_H \ll m_A}$

1^{st}-order phase transition

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



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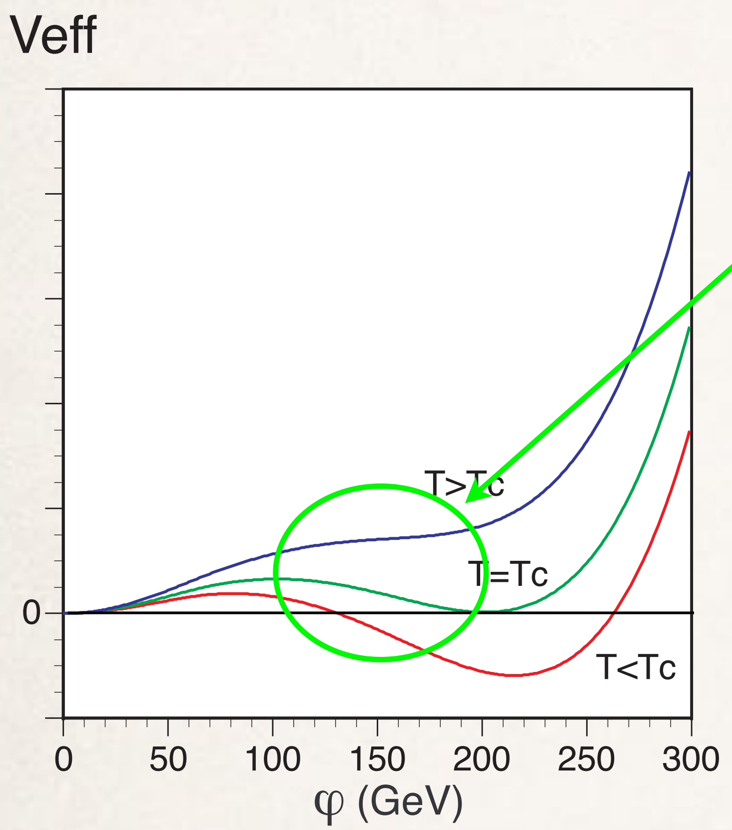
1^{st}-order phase transition

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



$$\textcolor{blue}{v_C} = \frac{2\textcolor{red}{E}T_C}{\lambda_{T_C}} \quad \Rightarrow \quad \frac{\textcolor{blue}{v_C}}{T_C} = \frac{2\textcolor{red}{E}}{\lambda_{T_C}} \gtrsim 1$$

Extra Higgs loops can enhance E.

$$\bar{m}_\phi^2 = \mu_2^2 + \frac{1}{2}\bar{\lambda}_{h\phi\phi}\varphi^2$$

At 1-loop

$$V_{\rm eff} \ni \begin{cases} -(\bar{\lambda}_{h\phi\phi}/2)^{3/2}T\left(1 + \dfrac{\mu_2^2}{\bar{\lambda}_{h\phi\phi}\varphi^2/2}\right)^{3/2} \textcolor{red}{\varphi^3} & \text{for} \quad \mu_2^2 \ll \bar{\lambda}_{h\phi\phi}\varphi^2/2, \\ -(\mu_2^2)^{3/2}T\left(1 + \dfrac{\bar{\lambda}_{h\phi\phi}\varphi^2}{\mu_2^2}\right)^{3/2} & \text{for} \quad \mu_2^2 \gg \bar{\lambda}_{h\phi\phi}\varphi^2/2. \end{cases}$$

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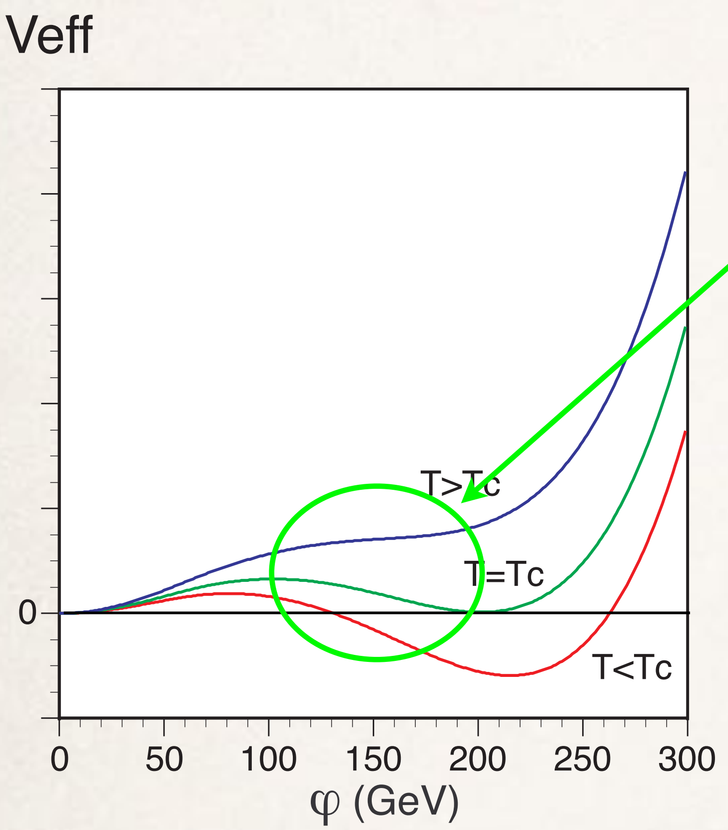

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$$\bar{m}_\phi^2 = \mu_2^2 + \frac{1}{2}\bar{\lambda}_{h\phi\phi}\varphi^2$$

At 1-loop

non-decoupling

$$V_{\rm eff} \ni \begin{cases} -(\bar{\lambda}_{h\phi\phi}/2)^{3/2} T \left(1 + \dfrac{\mu_2^2}{\bar{\lambda}_{h\phi\phi}\varphi^2/2}\right)^{3/2} \varphi^3 & \text{for} \quad \mu_2^2 \ll \bar{\lambda}_{h\phi\phi}\varphi^2/2, \\ -(\mu_2^2)^{3/2} T \left(1 + \dfrac{\bar{\lambda}_{h\phi\phi}\varphi^2}{\mu_2^2}\right)^{3/2} & \text{for} \quad \mu_2^2 \gg \bar{\lambda}_{h\phi\phi}\varphi^2/2. \end{cases}$$

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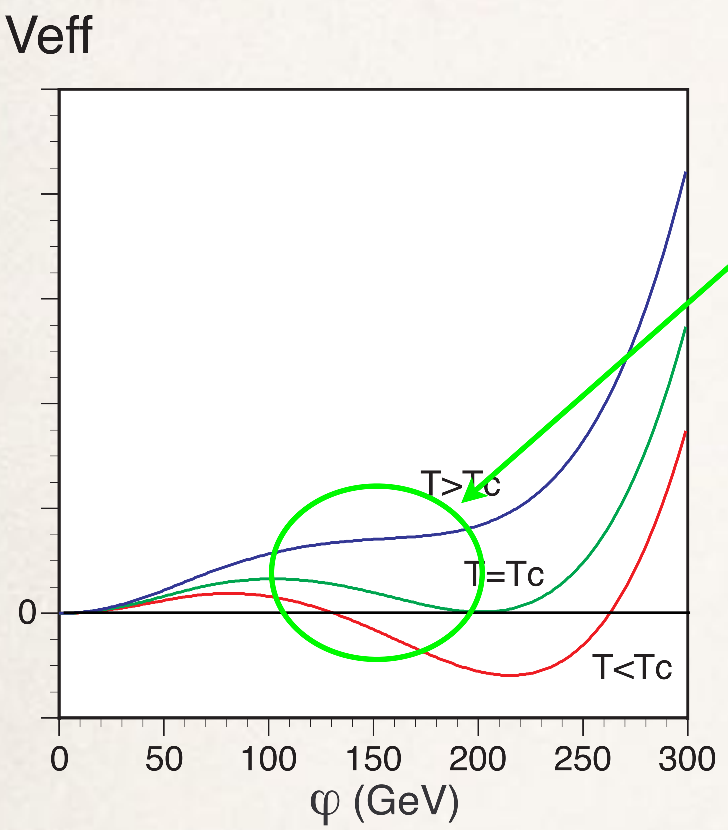
1st-order phase transition

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



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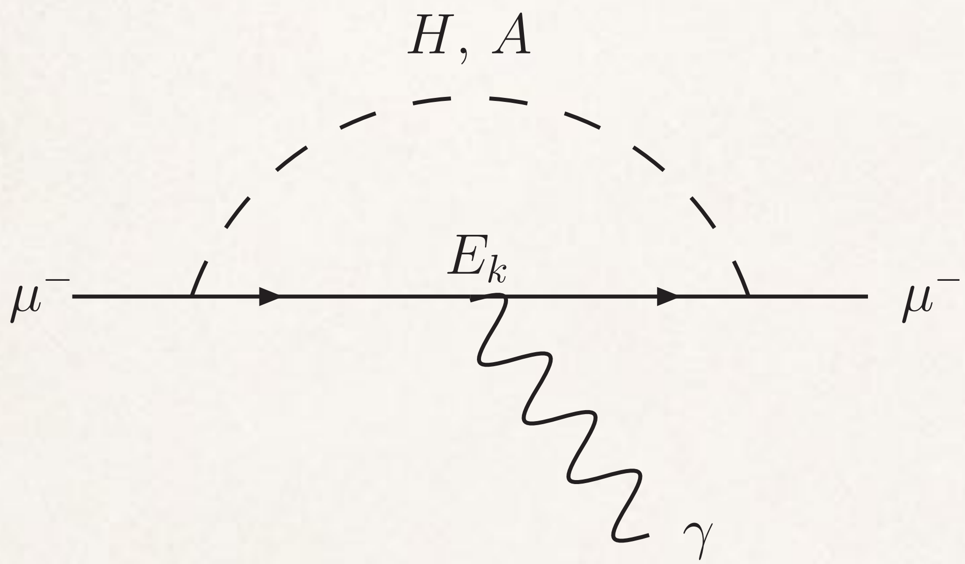
decoupling

In our model, the former implies λ_3 has to be big. $\longrightarrow$ $\boxed{m_H \ll m_A}$

Phenomenological Consequences

$(g-2)_\mu$ vs. $Z \to \mu^+\mu^-$

Without any calculations, we know Z -> $\mu^+\mu^-$ must deviate from the SM prediction in the $(g-2)_\mu$-favored region.



$\longrightarrow$ $(g-2)_\mu$

$(g-2)_\mu$ vs. $Z \to \mu^+\mu^-$

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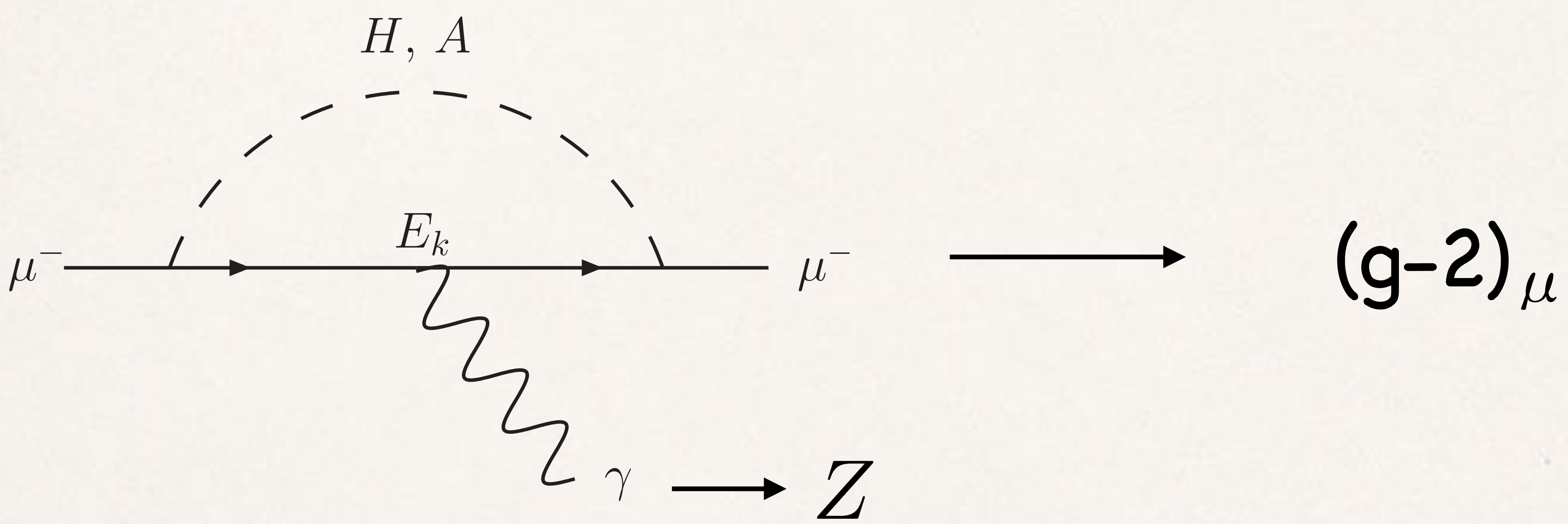

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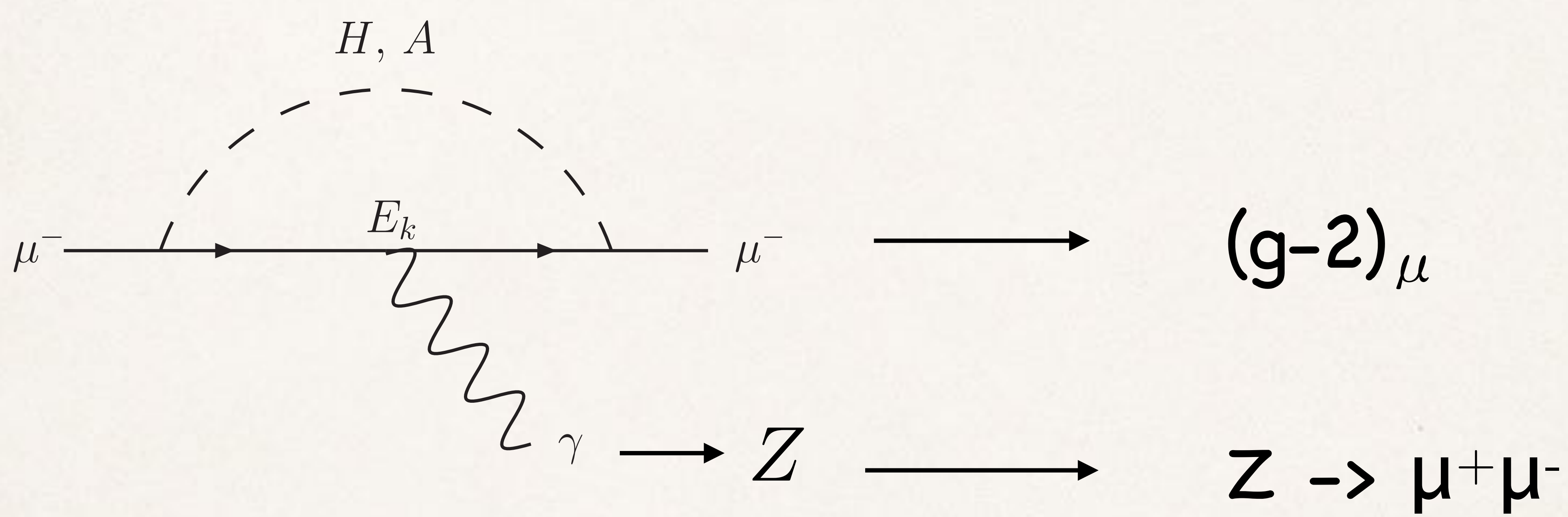

$(g\text{-}2)_\mu$ vs. $Z \to \mu^+\mu^-$

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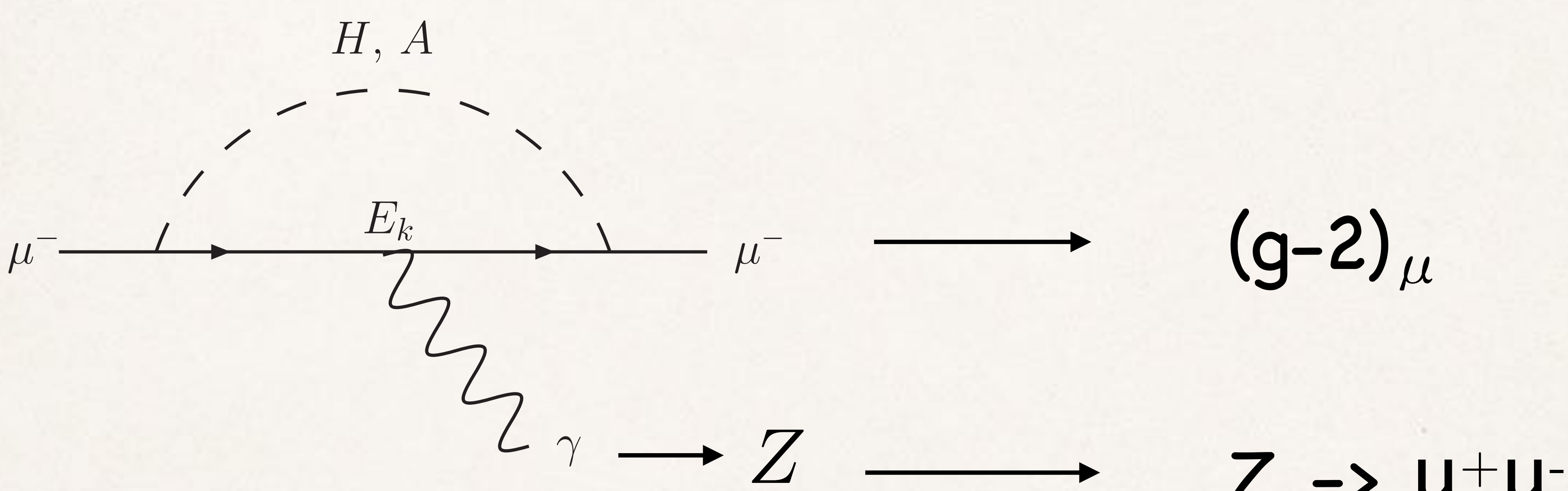
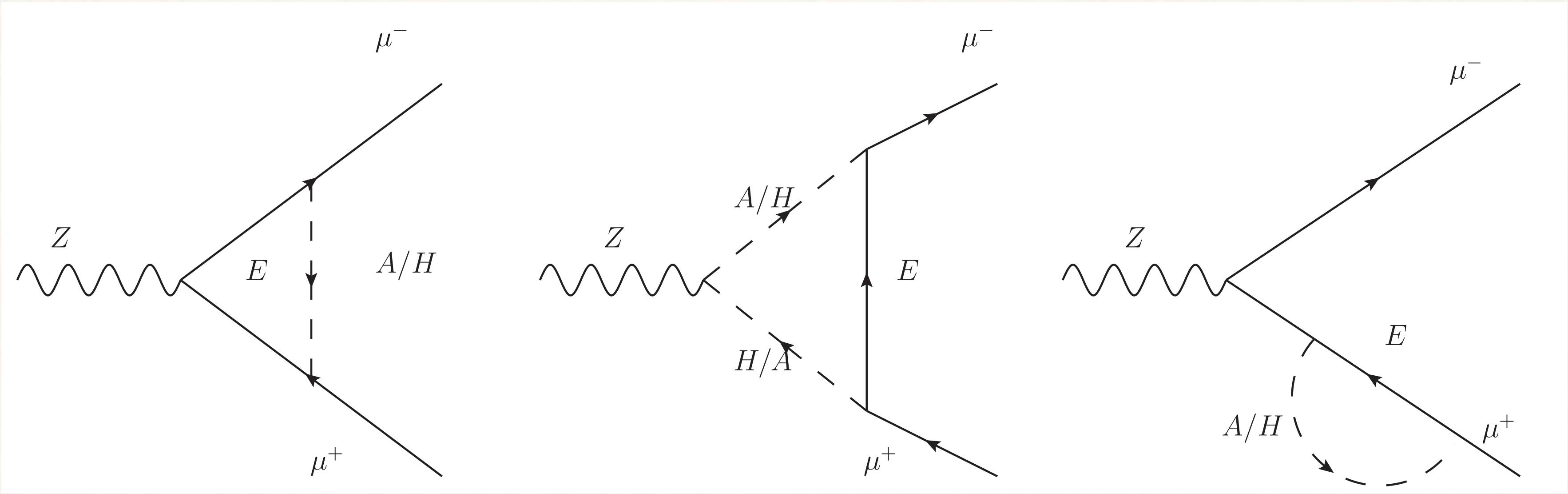


We consider the Z decay in the case of $m_H \ll m_A$.

$Z \to \mu^+\mu^-$



$$\mathcal{L} = -g_Z Z_\mu \bar{f}\gamma^\mu \left[g^L_{Z\bar{f}f} P_L + g^R_{Z\bar{f}f} P_R\right] f, \qquad g_Z = g_2/c_W$$

$$\Gamma(Z \to \ell^+\ell^-) = \frac{m_Z}{24\pi} g_Z^2 \left[|g^L_{Z\bar{\ell}\ell}|^2 + |g^R_{Z\bar{\ell}\ell}|^2\right],$$

Dividing the SM and NP parts, $g^{L,R}_{Z\bar{\ell}\ell} = g^{L,R,\mathrm{SM}}_{Z\bar{\ell}\ell} + \Delta g^{L,R}_{Z\bar{\ell}\ell}$

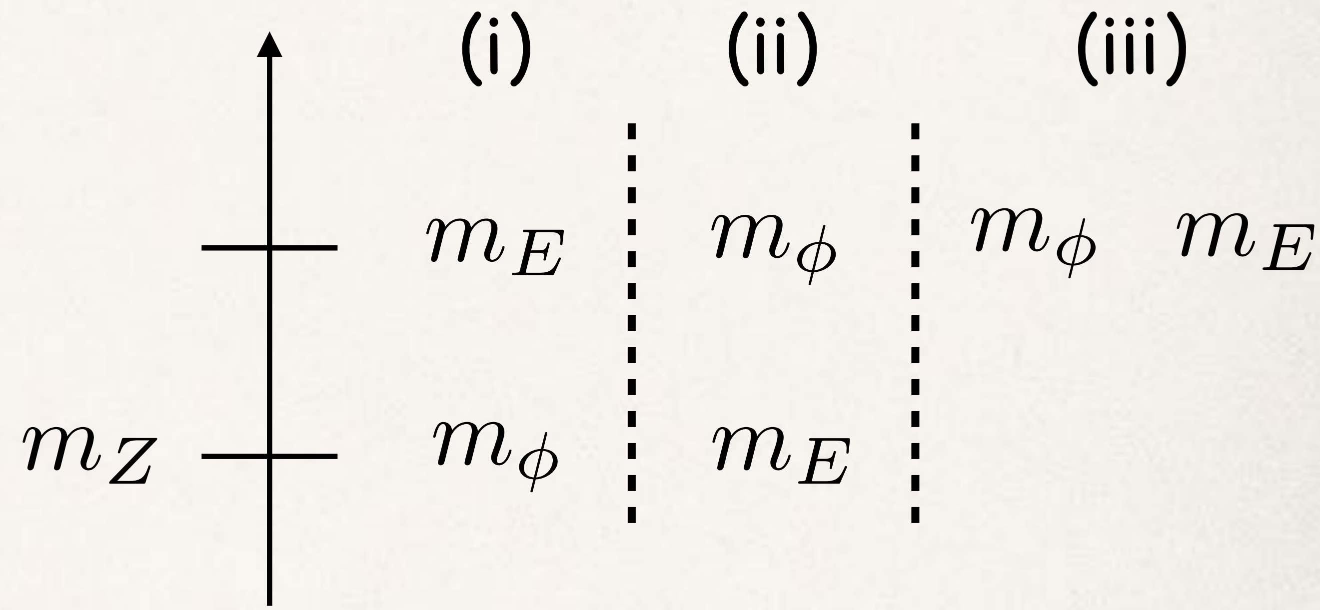
$$\Delta g^L_{Z\bar{\mu}\mu} = \frac{3|y_{\mu E}|^2}{32\pi^2}\left[\tilde{F}_3(m_E, m_H, m_A) + \sum_{\phi=H,A}\left\{\left(-\frac{1}{2} + s_W^2\right) F_2(m_E, m_\phi) + s_W^2 F_3(m_E, m_\phi)\right\}\right],$$

$$\Delta g^R_{Z\bar{\mu}\mu} = 0.$$

$Z \to \mu^+\mu^-$

Limiting cases:

3 cases



Case of $m_\phi = m_H = m_A$

$$\Delta g^L_{Z\bar{\mu}\mu} \to 0 \quad \text{for}$$

Case of $m_E, m_H \ll m_A$

(mass splitting between neutral scalars)

$$\Delta g^L_{Z\bar{\mu}\mu} \to \text{log enhancement of } \ln(m_A^2/m_H^2)$$

$$\longrightarrow \quad \Delta\Gamma(Z \to \mu^+\mu^-) \simeq \frac{m_Z^2 g_Z^2 |y_{\mu E}|^2}{128\pi^3}\left(-\frac{1}{2} + s_W^2\right)\left[C + \frac{1}{4}\ln\frac{m_A^2}{m_H^2}\right]$$

non-log terms $\quad m_A^2 - m_H^2 \simeq \frac{\lambda_3}{2} v^2$

- log enhancement is known in Z->bb in 2HDM [Haber, Logan, hep-ph/9909335(PRD)].
- This is also emphasized in lepton-specific 2HDM [E. Chun, J. Kim, JHEP07(2016)110]

Lepton flavor non-universality

- this scenario is severely constraint by

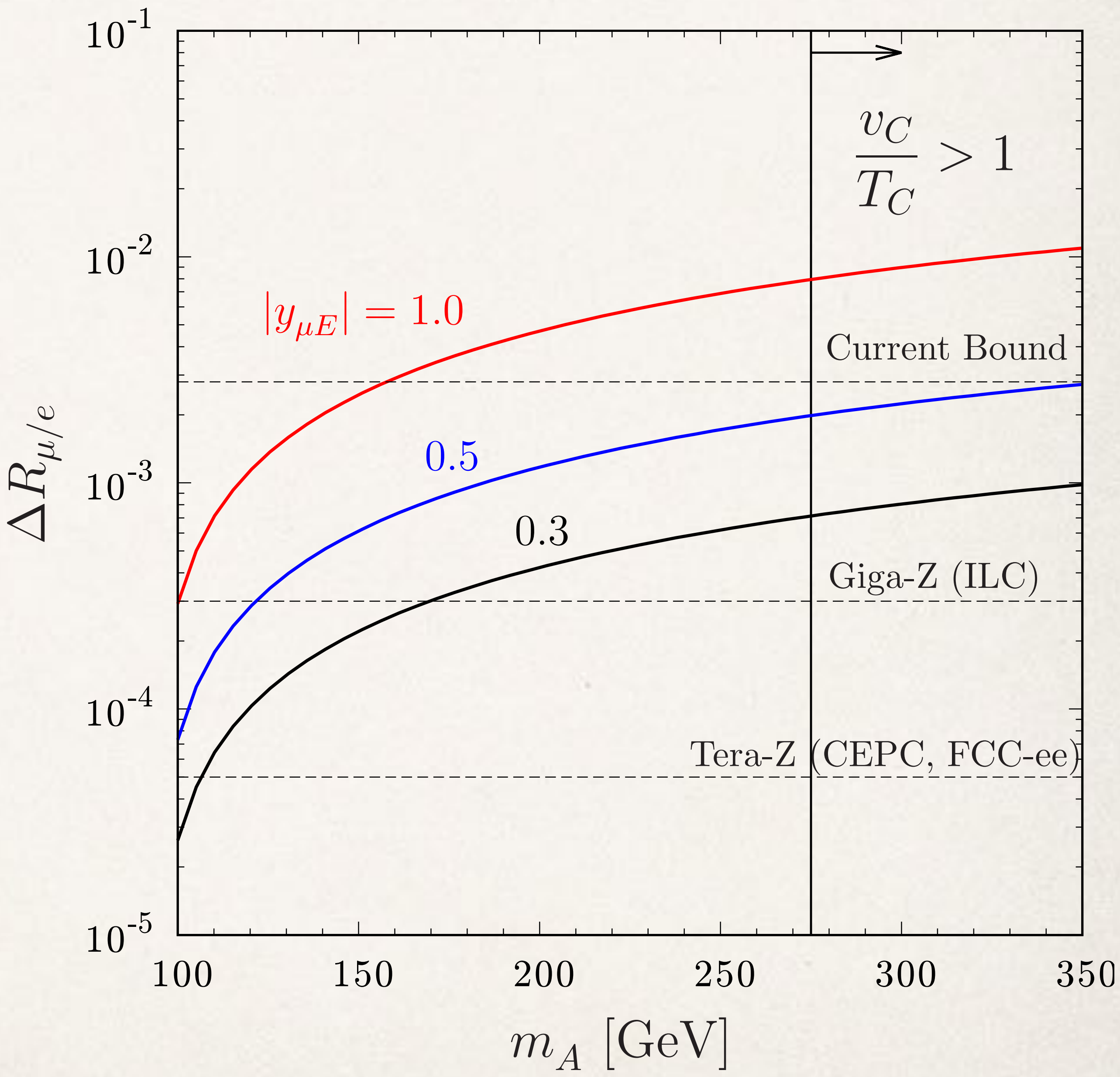
$$R_{\mu/e} = \frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)}$$

- $\Delta R_{\mu/e}$ is enhanced as m_A increases. $\because$ $\ln(m_A/m_H)$

- SFOEWPT region is 275 GeV $\lesssim m_A \lesssim$ 350 GeV

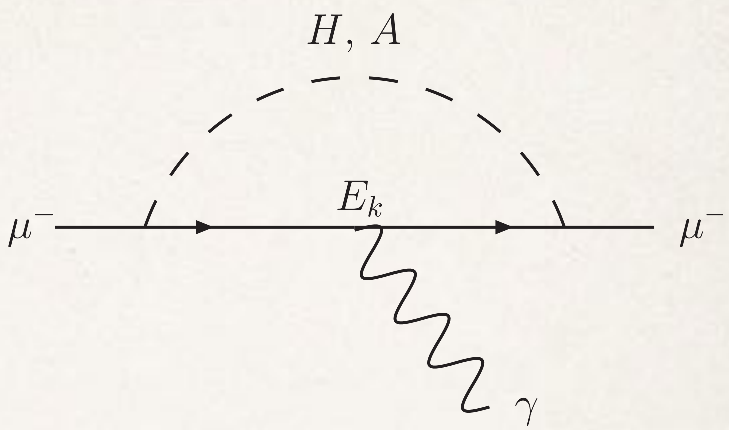
$\longrightarrow$ $y_{\mu E} \lesssim 0.5$.

For $m_H \simeq 63$ GeV, $m_E = 120$ GeV



Giga/Tera-Z experiments can test this scenario.

muon g-2

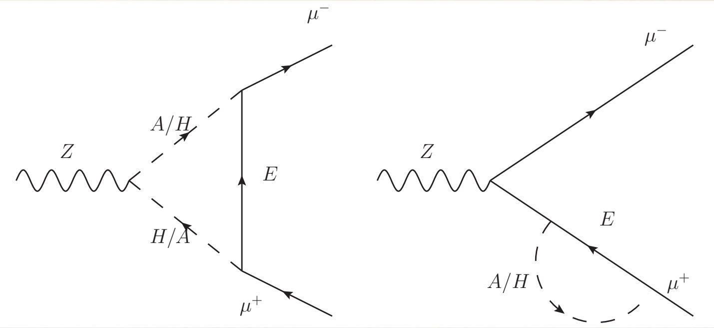


For $m_H \ll m_A$, one finds

$$\delta a_\mu \simeq \frac{3|y_{\mu E}|^2}{32\pi^2}\left[\frac{m_\mu^2}{12m_H^2} + \frac{m_\mu^2}{m_A^2}\left\{\frac{1}{3} + \frac{m_E^2}{m_A^2}\left(\frac{11}{6} + \ln\frac{m_E^2}{m_A^2}\right)\right\}\right]$$
$$\simeq \frac{|y_{\mu E}|^2}{32\pi^2}\frac{m_\mu^2}{4m_H^2}.$$

- Effects of A is simply decoupled. (no log-enhancement).

cf. Z->$\mu^+\mu^-$, log enhancement comes from



However, no such diagrams in $(g\text{-}2)_\mu$.

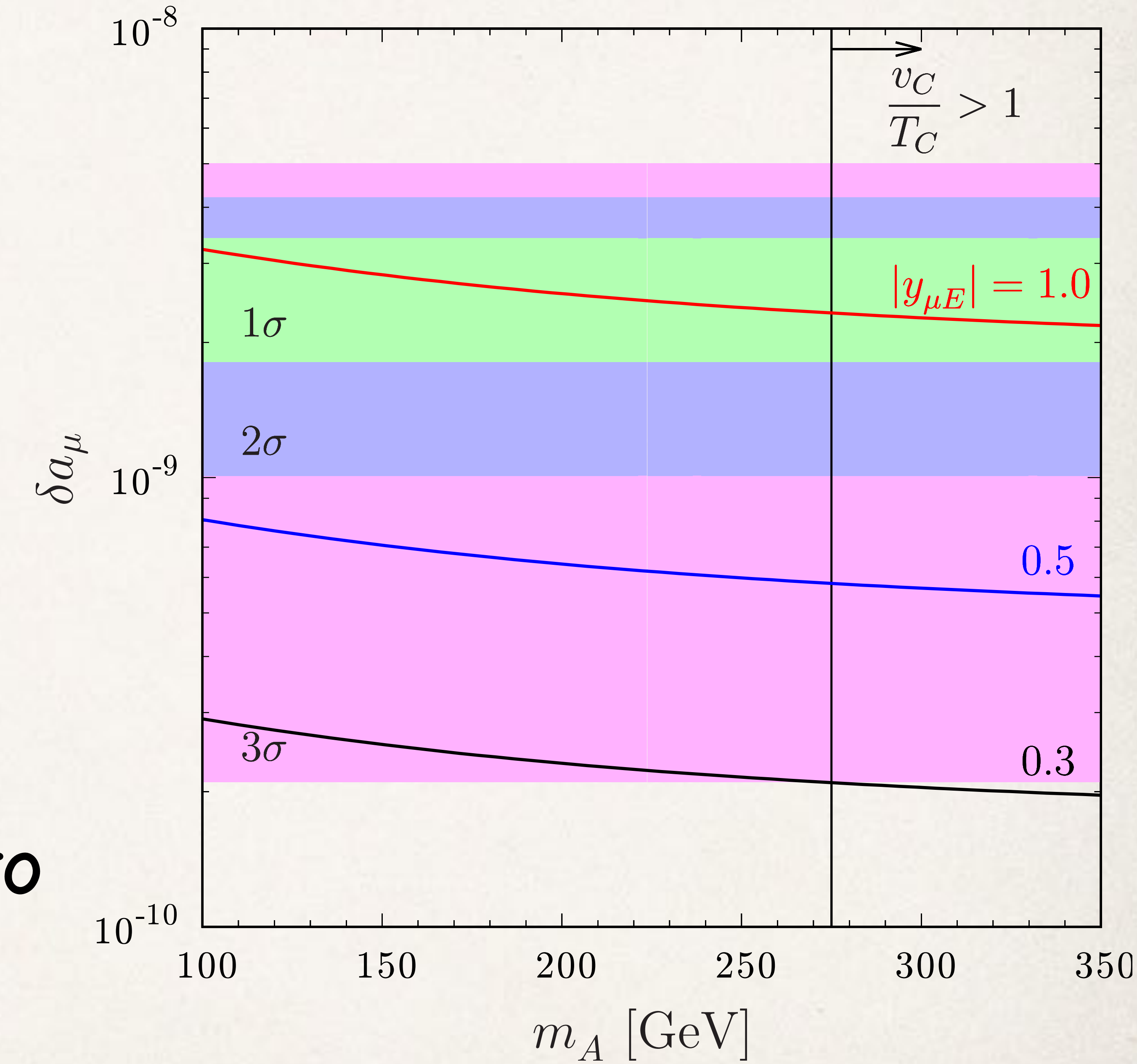
muon g-2

For $m_H \simeq 63$ GeV, $m_E = 120$ GeV

- very sensitive to $y_{\mu E}$

- $(g\text{-}2)_\mu$ can be explained at $1\,\sigma$ level if $y_{\mu E} \simeq 1.0$.

- However, $m_A \lesssim 160$ GeV due to the Z decay constraint.



- No regions that satisfy SFOEWPT & $(g\text{-}2)_\mu$ simultaneously.

Summary

We have studied the model with VL-leptons & inert doublet.

$\Omega_{\rm DM}h^2$ strong 1st-order EWPT	✓ ✓
observables	predictions
$(g-2)_\mu$ $\Gamma(Z\to\mu^+\mu^-)/\Gamma(Z\to e^+e^-)$ $\mu_{\gamma\gamma}$ $\kappa_\lambda=\lambda_{3h}/\lambda_{3h}^{\rm SM}$	outside 2σ region $\simeq 10^{-3}$ probed at Z factory $\simeq 0.9$ $\gtrsim 1.2$

$$m_A \simeq m_{H^\pm} \gtrsim 275\ \mathrm{GeV}$$

ρ parameter

strong 1st-order EWPT

$$m_h = 125\ \mathrm{GeV}$$

105 GeV ≲ m_E ≲ 125 GeV

$$m_H \simeq m_h/2$$

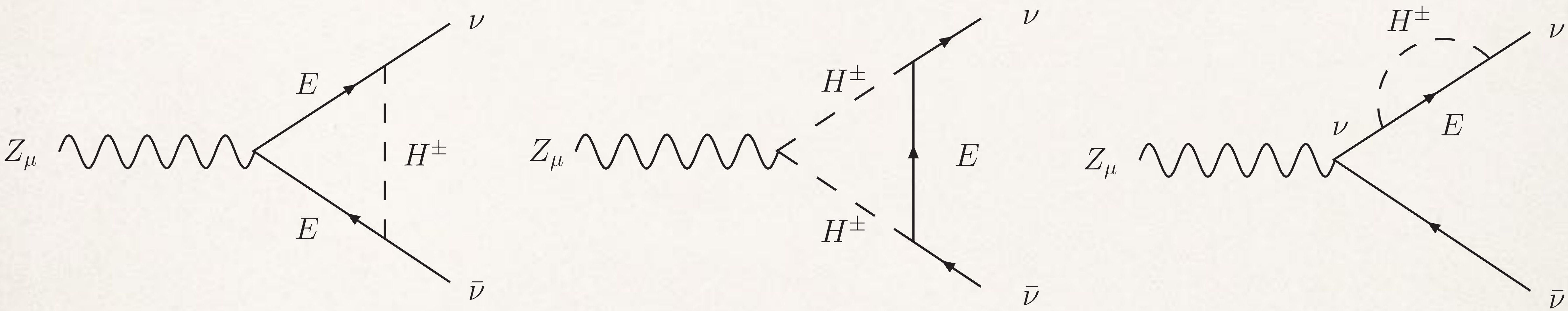
qq->EE->2μ+MET

DM & $(g-2)_\mu$

Backup

$Z \to \nu\nu$

As is $Z \to \mu^+\mu^-$, $Z \to \nu\nu$ is modified.



$$\Delta g^L_{Z\bar{\nu}\nu} = \frac{3|y_{\mu E}|^2}{16\pi^2}\Big[s_W^2 \left\{ F_3(m_E, m_{H^\pm}) + \tilde{F}_3(m_E, m_{H^\pm}, m_{H^\pm}) \right\} + \frac{1}{2}\left\{ F_2(m_E, m_{H^\pm}) - \tilde{F}_3(m_E, m_{H^\pm}, m_{H^\pm}) \right\} \Big],$$

$$\Delta g^R_{Z\bar{\nu}\nu} = 0.$$

In this decay, there is no log-enhancement since no mass splitting between H^+ and H^-.

W-μ-ν vertex

W-μ-ν vertex is also modified.

$\longrightarrow$ lepton flavor non-universality in muon decay

$$\Delta g^L_{W\mu\nu_\mu} = -\frac{3|y_{\mu E}|^2}{32\pi^2}\Big[\tilde{F}_3(m_E, m_{H^\pm}, m_H) + \tilde{F}_3(m_E, m_{H^\pm}, m_A) - \frac{1}{2}\Big\{F_2(m_E, m_H) + F_2(m_E, m_A) + 2F_2(m_E, m_{H^\pm})\Big\}\Big].$$

For $m_H \ll m_{H^+}$

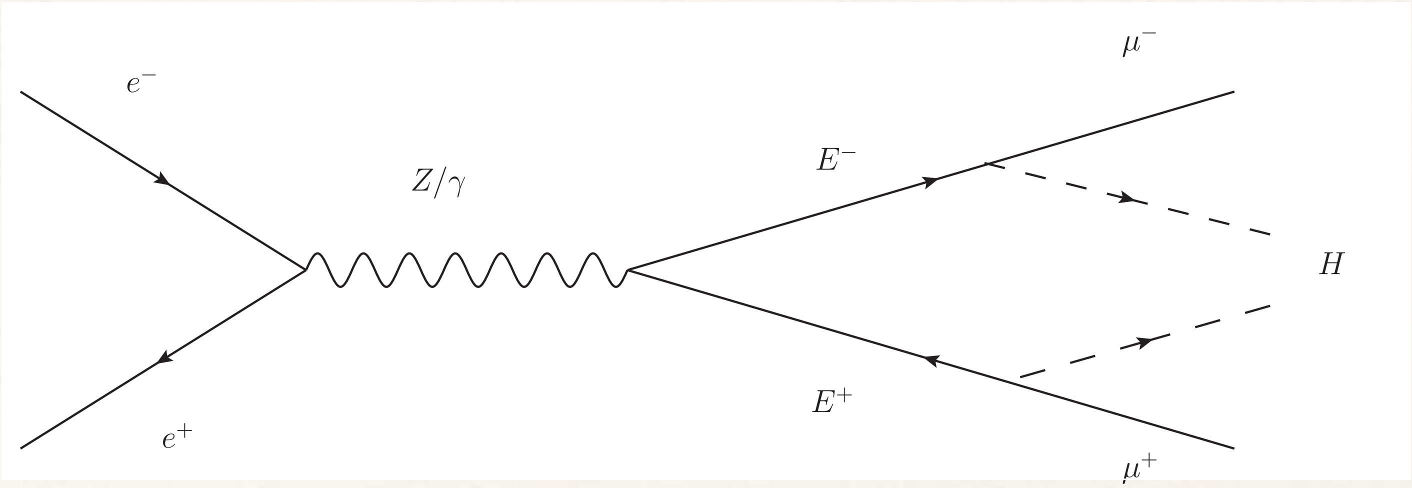
$$\Delta g^L_{W\mu\nu_\mu} \simeq -\frac{3|y_{\mu E}|^2}{32\pi^2}\left[(\text{non-log terms}) + \frac{1}{4}\ln\frac{m^2_{H^\pm}}{m^2_H}\right].$$

This vertex is enhanced by the log correction.

However, $Z \to \mu^+\mu^-$ is more important numerically.

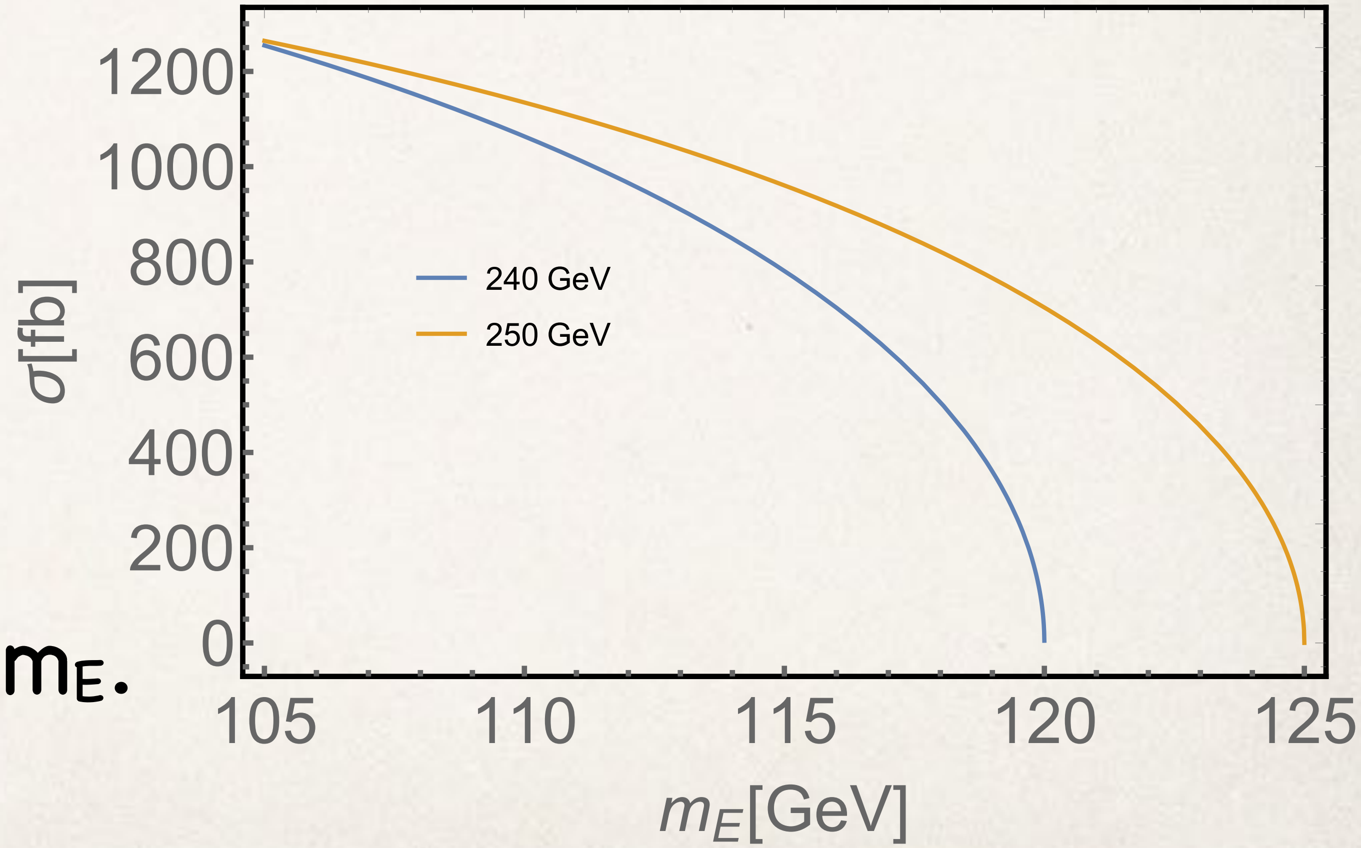
In lepton-specific 2HDM, this correction can be more important.

$e^+e^- \to \gamma/Z \to E^+E^-$



Dominant contribution:

$$\sigma(e^+e^- \to \gamma \to E^+E^-)$$
$$= \frac{4\pi\alpha^2}{3s^2}(s + 2m_E^2)\sqrt{1 - \frac{4m_E^2}{s}}$$



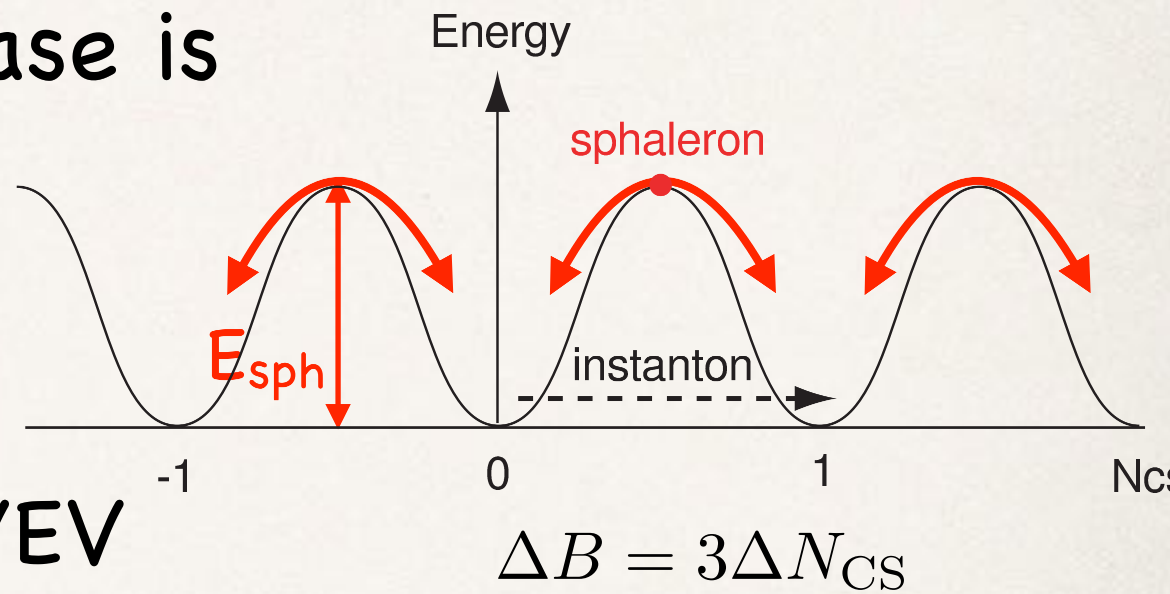
- cross section depends only m_E.

- cross section is O(pb).

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

B-changing rate in the broken phase is

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



E_{sph} is proportional to the Higgs VEV

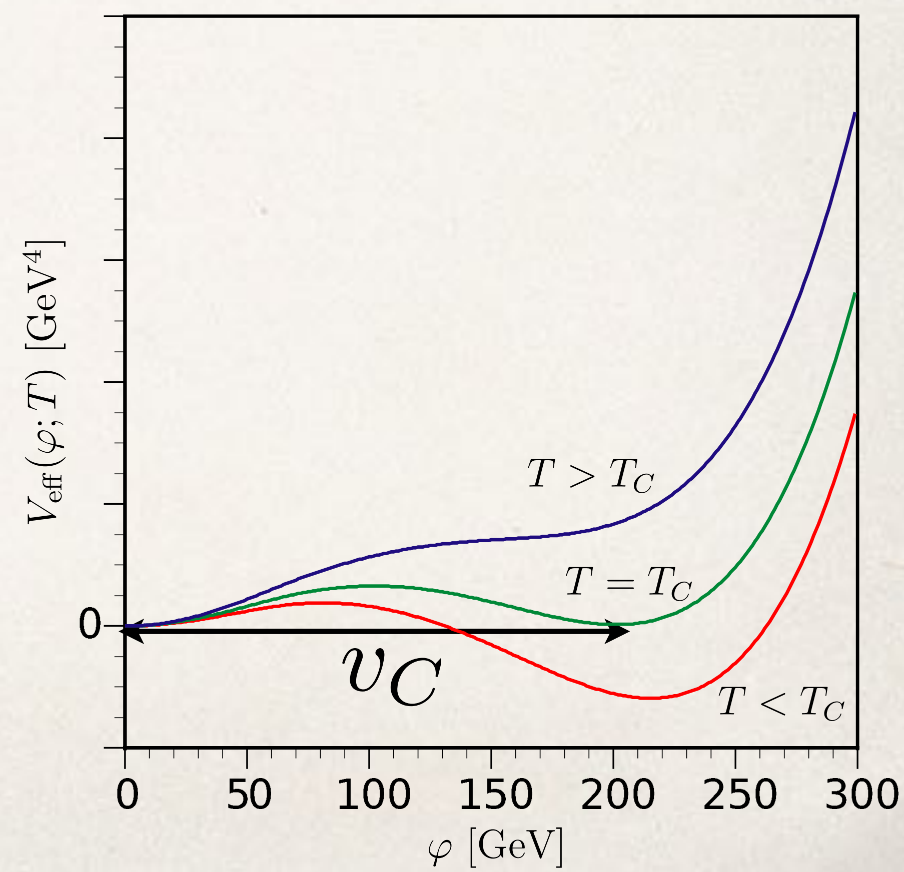
$$\boxed{E_{\text{sph}} \propto v(T)}$$

<u>what we need is</u>

large Higgs VEV after the EWPT

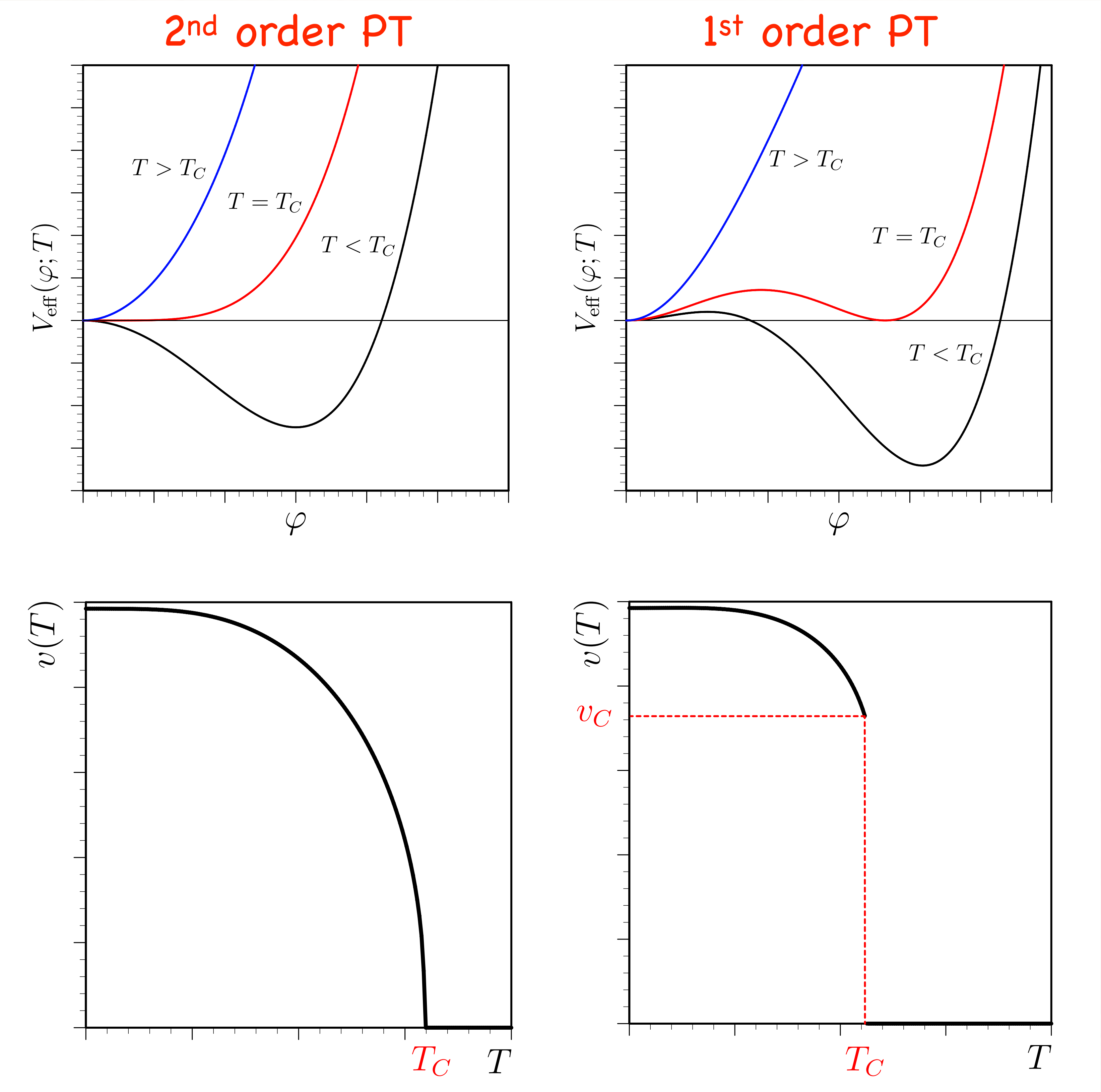
⇒ EWPT has to be "**strong**" 1st order!!

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



How do we get 1st-order EWPT?

1st(2nd) order PT=discontinuities in 1st(2nd) derivatives of free energy (V_{eff})



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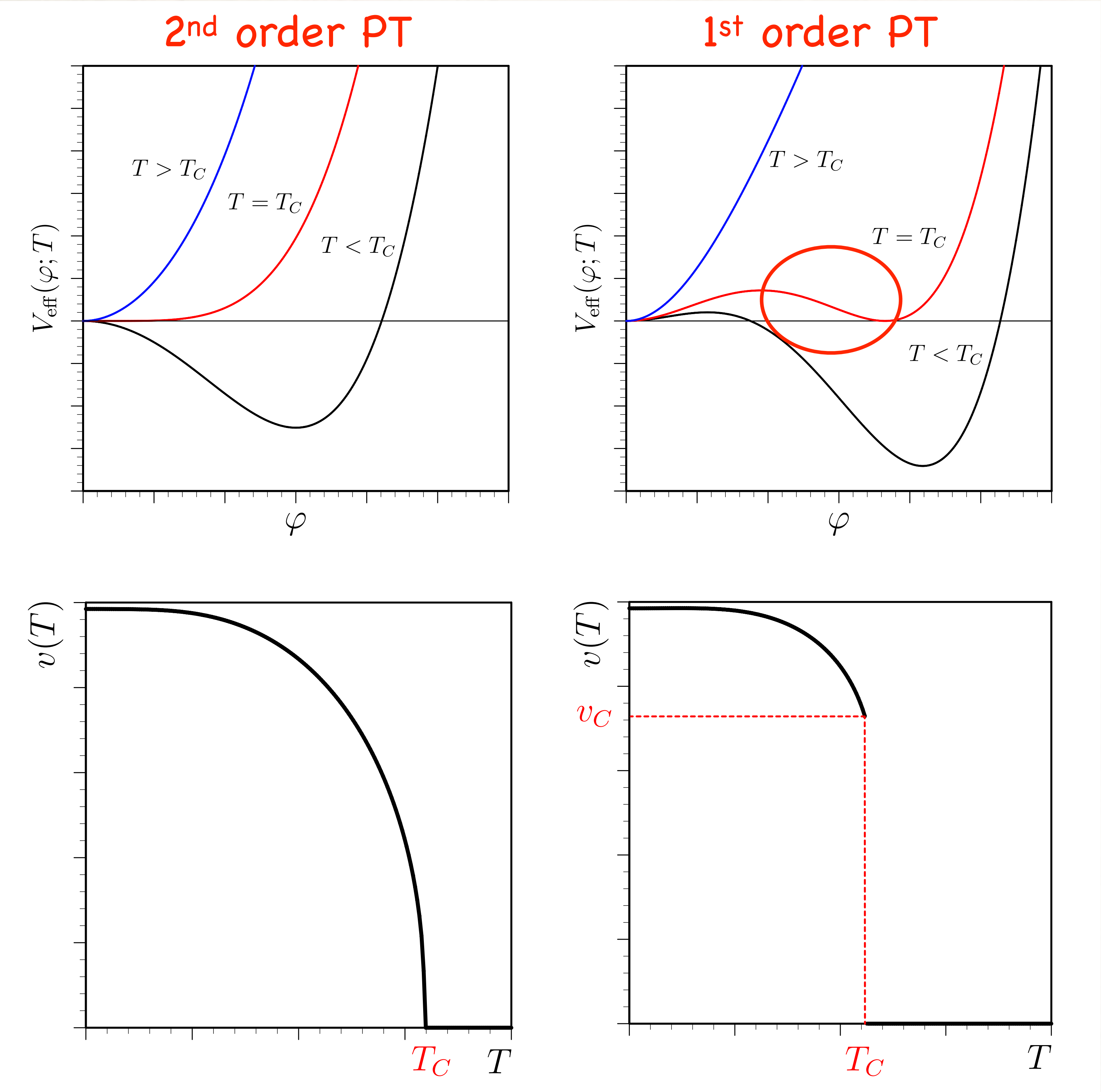

1st-order PT

$\Downarrow$

Negative contributions in V_{eff}.

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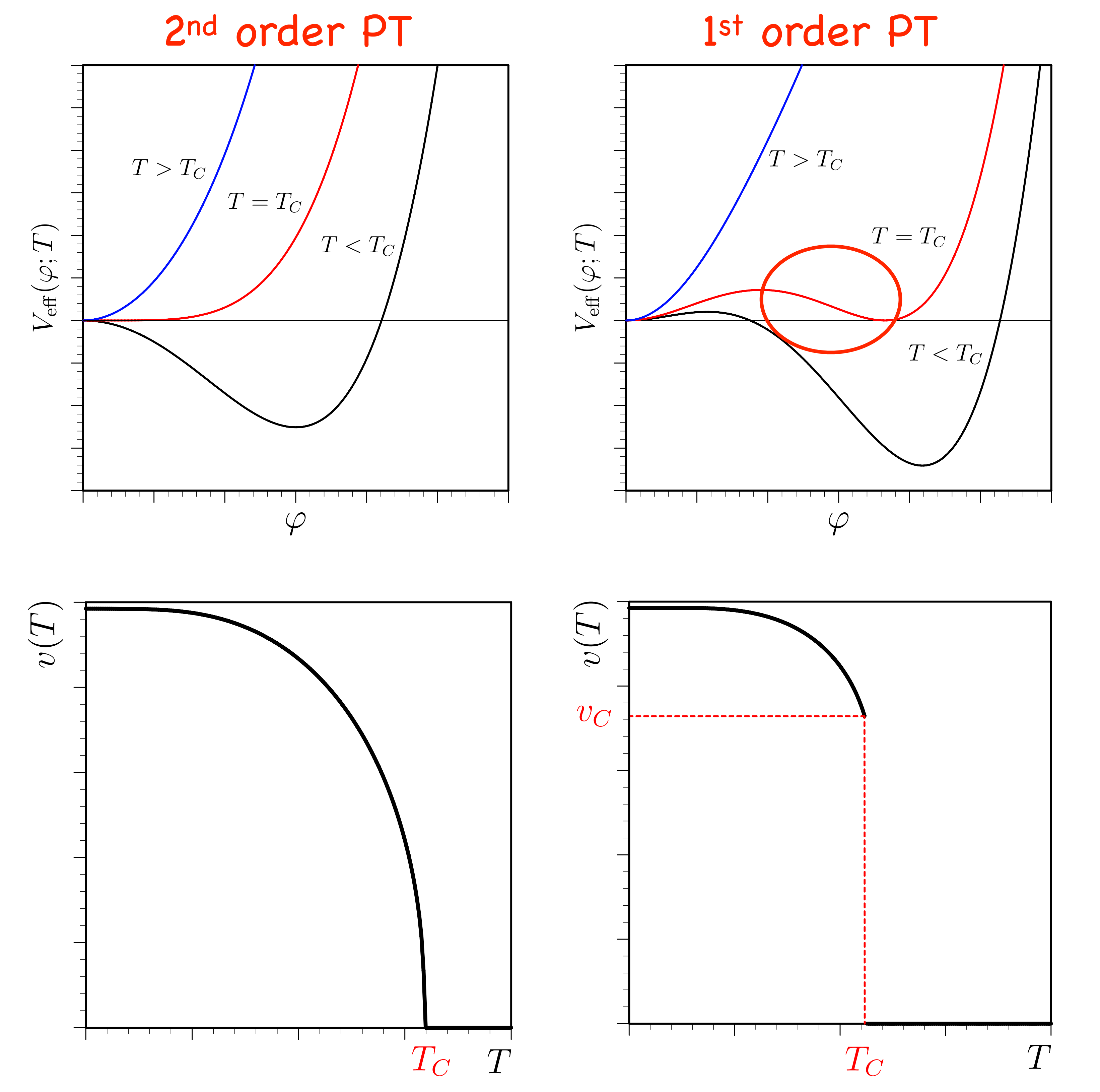

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Negative contributions in V_{eff}.

From where?

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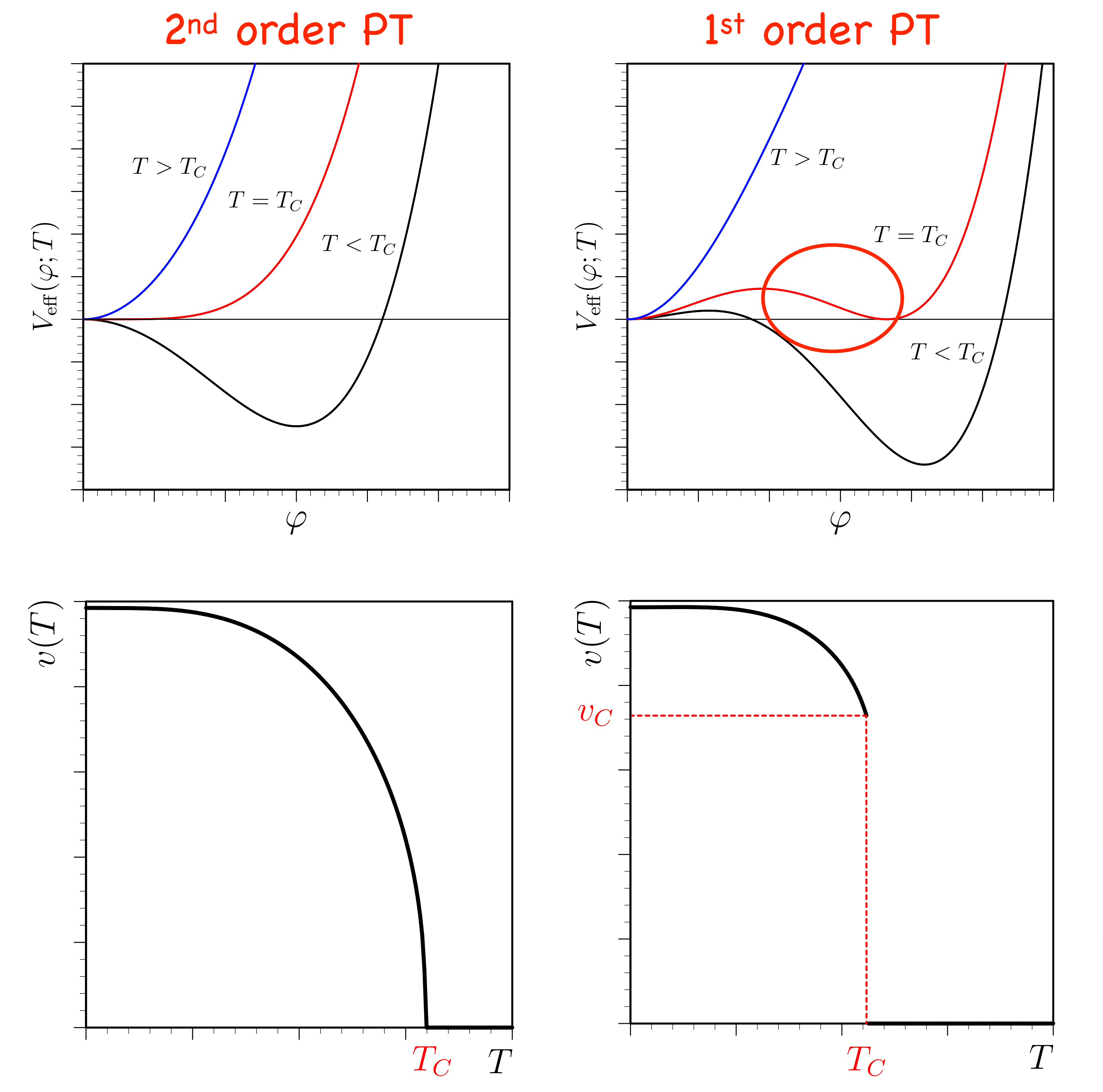


1st-order PT

$\Downarrow$

Negative contributions in V_{eff}.

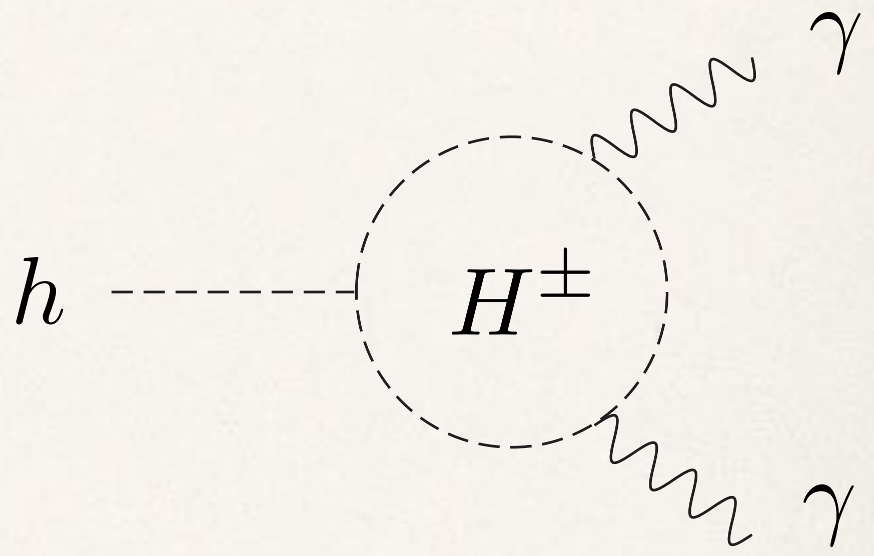
From where?

-> thermal loops of A, $H^{\pm}$ in this model.

h → γγ

Charged Higgs contributes to h-> $\gamma\ \gamma$

$$\mu_{\gamma\gamma} \simeq \left| 1 + \frac{1}{3\mathcal{A}_{\rm SM}} \left(1 - \frac{\mu_2^2}{m_{H^\pm}^2} \right) \right|^2$$



$$\mathcal{A}_{\rm SM} = -6.49 \qquad m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

$\mu_2^2 \ll m_{H^\pm}^2$ is necessary to have strong 1st-order EWPT

-> charged Higgs loop does not decouple in this case.

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

$$\boxed{\mu_{\gamma\gamma} \underset{\mu_2^2 \ll m_{H^\pm}^2}{\simeq} \left| 1 + \frac{1}{3\mathcal{A}_{\rm SM}} \right|^2 \simeq 0.9}$$

h → γγ

Charged Higgs contributes to h-> γ γ

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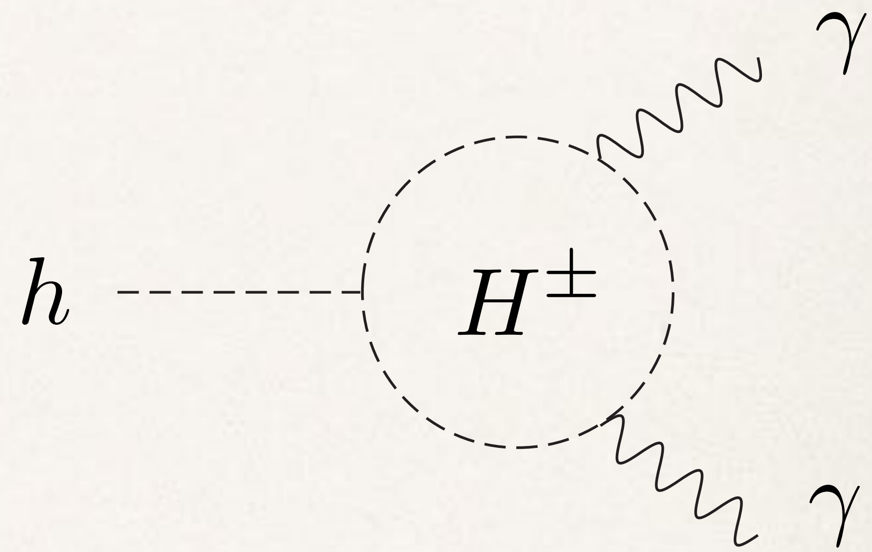

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$h \to \gamma\gamma$

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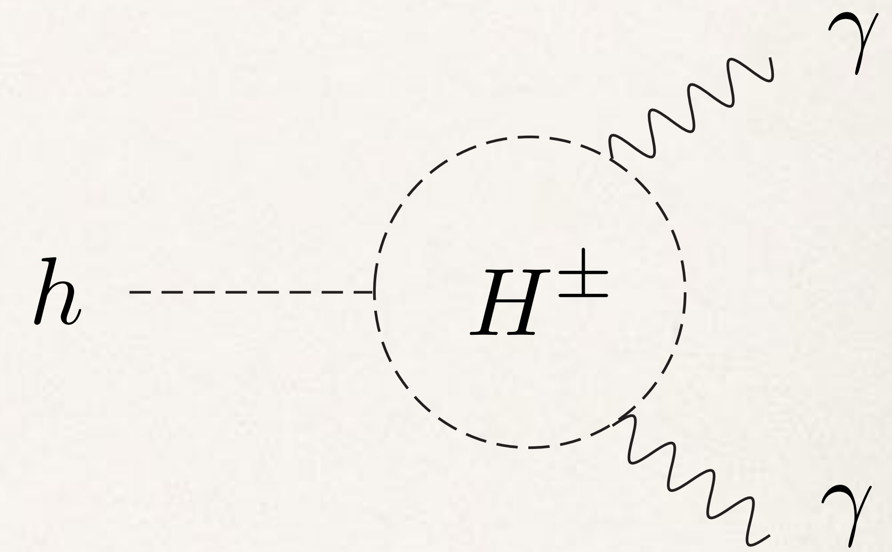

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$$\mu_{\gamma\gamma} = \begin{cases} 1.18^{+0.17}_{-0.14} \ \text{(CMS)} & \text{1804.02716} \\ 0.99^{+0.15}_{-0.14} \ \text{(ATLAS)} & \text{1802.04146} \end{cases}$$

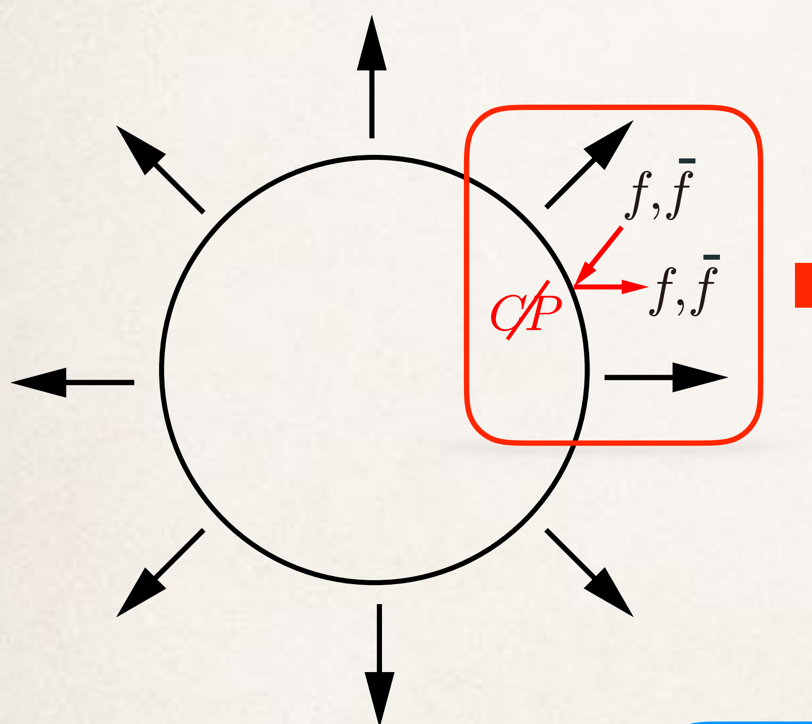
Baryon number density (n_B)

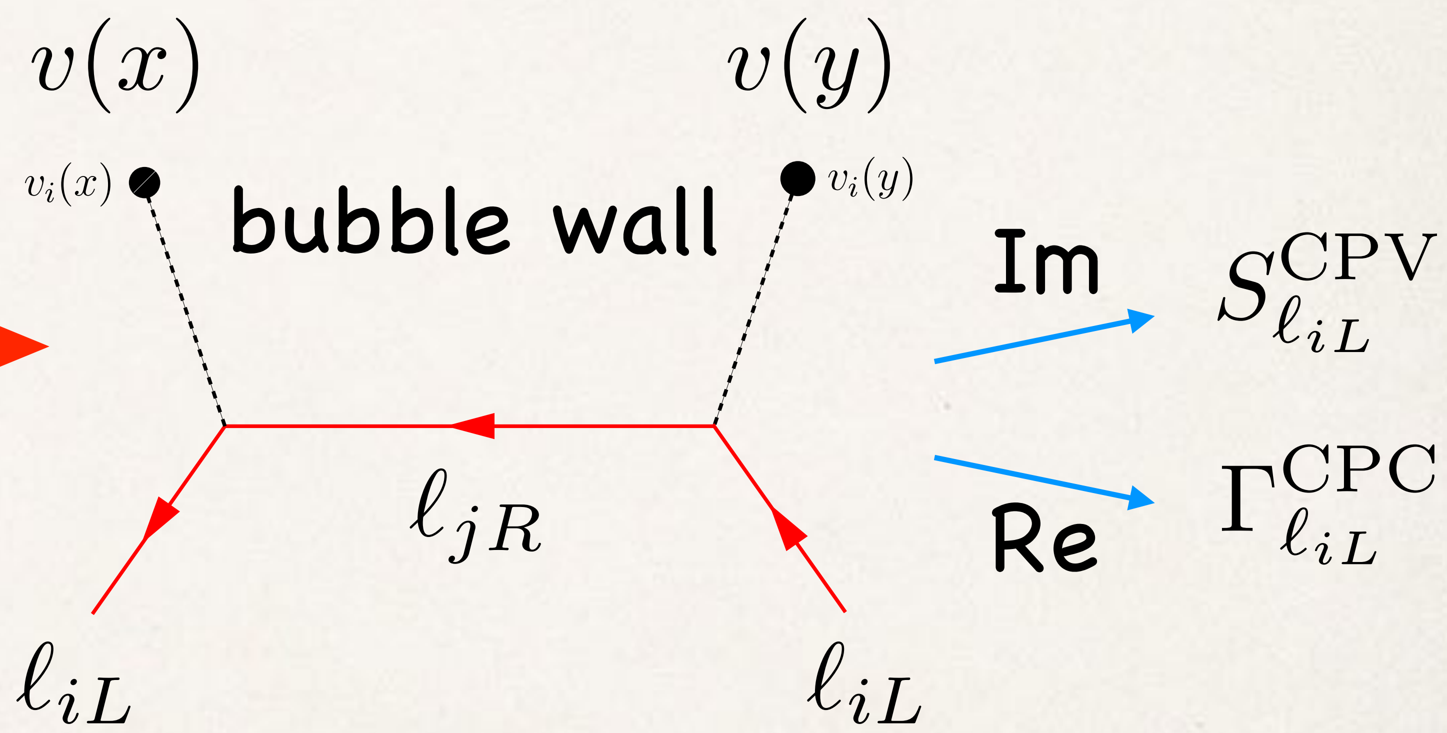
Diffusion eq. for n_B: $\bar{z} < 0$: sym-phase, $\bar{z} > 0$: br-phase

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

diffusion const. wall velocity back reaction sph. rate

n_L is generated by scatterings b/w particles and bubbles.





$$n_B \propto n_L \propto S_{\ell_{iL}}^{\mathrm{CPV}} \Big/ \sqrt{\Gamma_{\ell_{iL}}^{\mathrm{CPC}}}$$

SI DM-nucleon cross section