Electroweak phase transition in a complex singlet extension of the Standard Model with degenerate scalars

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arXiv: 2105.11830

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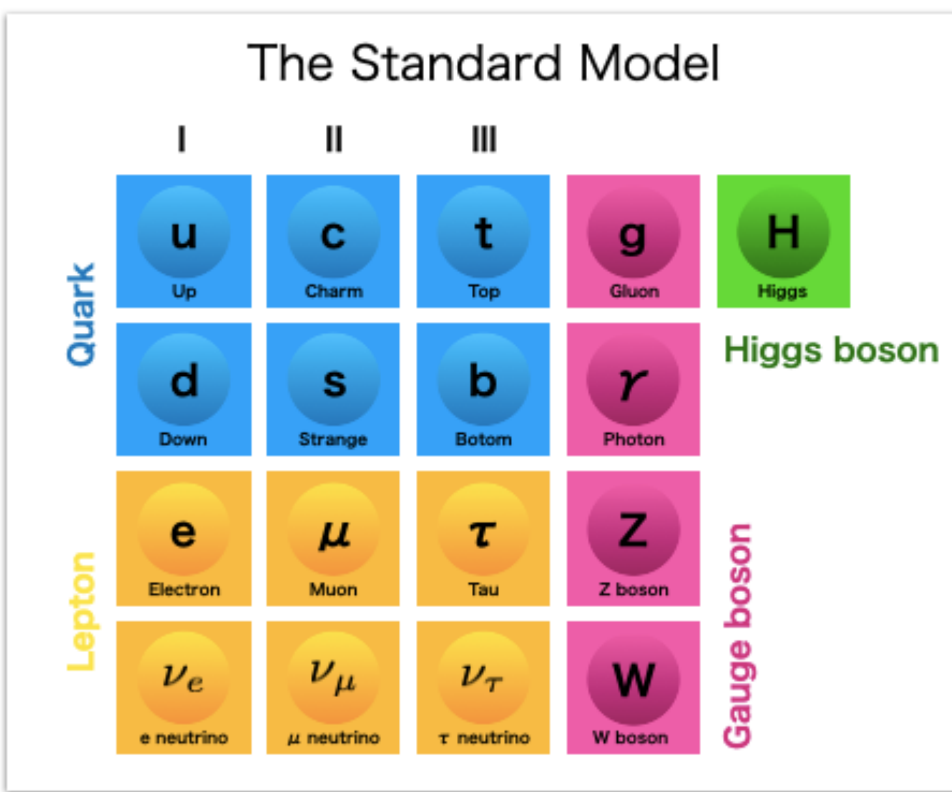
Back ground: Baryon Asymmetry

Baryon asymmetry: imbalance in particles and antiparticles in the observable universe

Sakharov conditions

1. Baryon number violation
   → Sphaleron
2. C symmetry and CP symmetry violation
   → Chiral gauge interaction, CKM matrix
3. Interaction out of thermal equilibrium
   → Strong 1st order phase transition

Electroweak baryogenesis



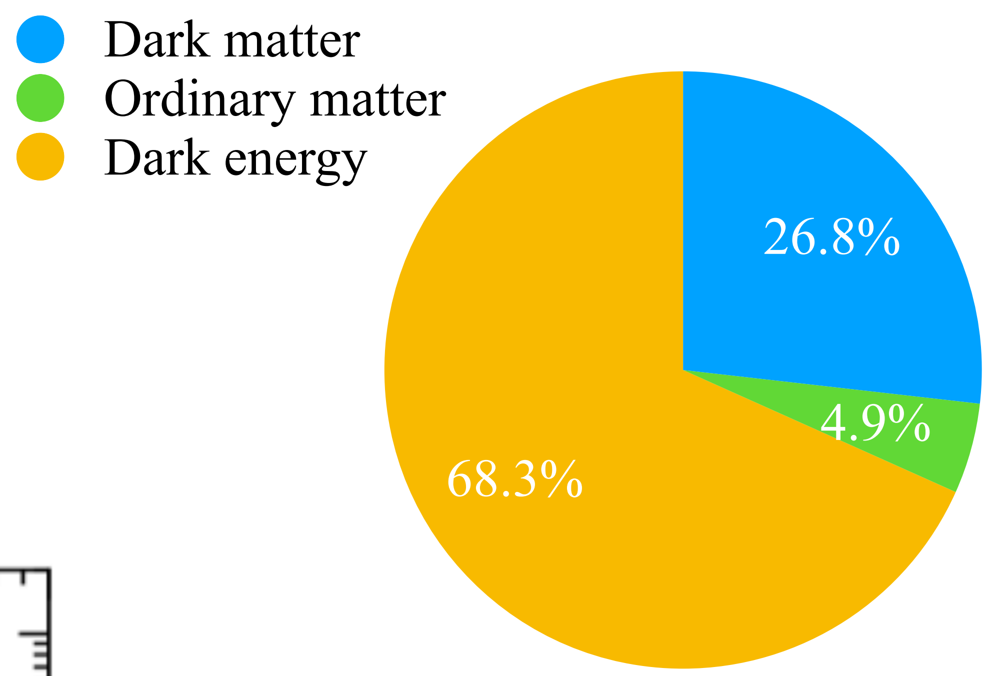
The parameters of the SM do not satisfy Sakharov conditions.

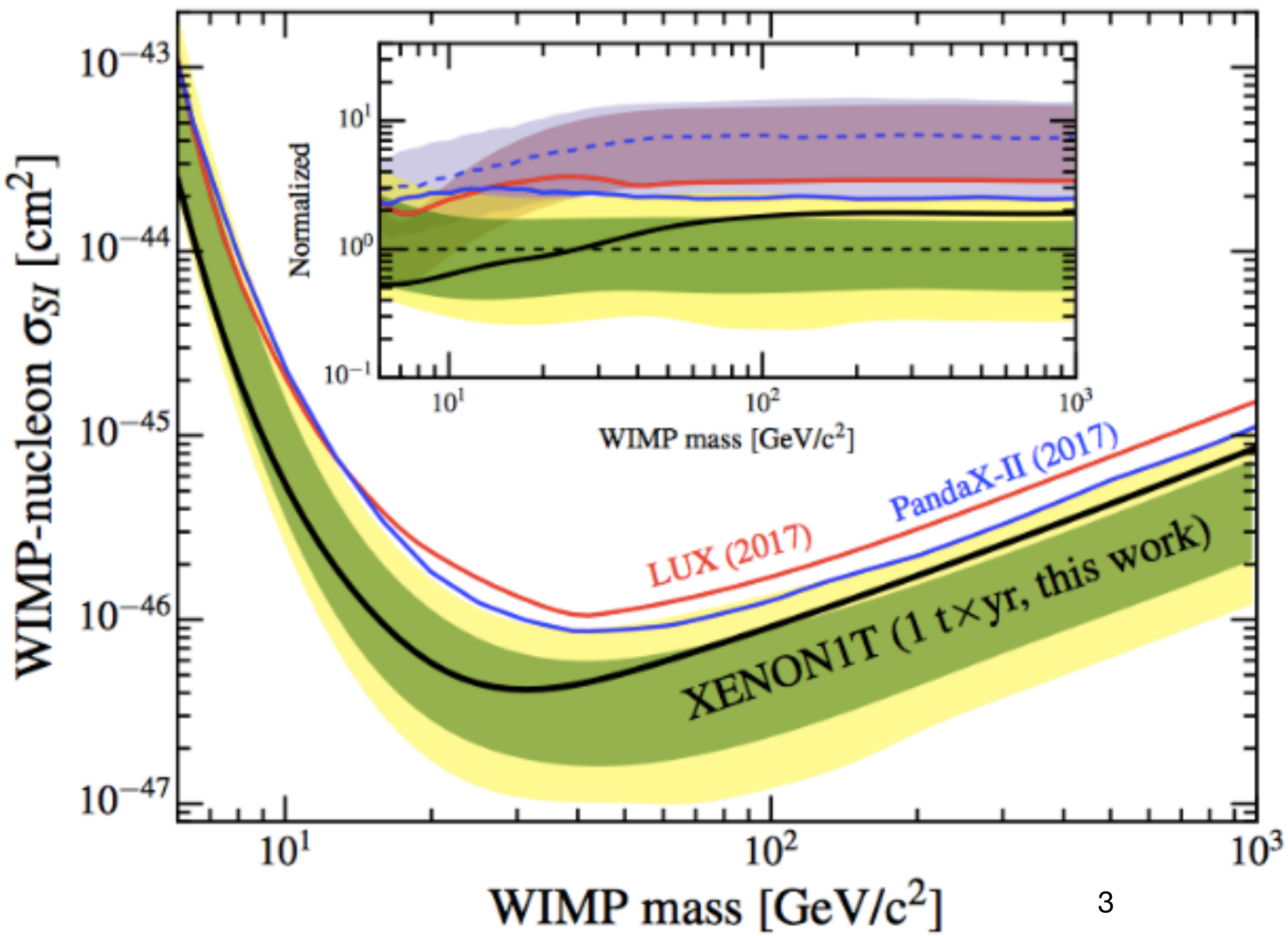
⇒ **We need to extend the SM !**

Back ground: Dark matter

The nature of dark matter

1, massive
2, no electric charge
3, stable





Strict restriction is imposed on the models including DM.

XENON Collaboration [arXiv:1805.12562]

Outline

- Back ground
- CxSM model definition
- Degenerate-scalar scenario
- EWPT in the degenerate-scalar scenario
- Numerical results
- Conclusion

CxSM Model Definition

Complex singlet extension of the SM (CxSM) Barger etal, arXiv:0811.0393

$$V_0 = \underline{\frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4} + \underline{\left(a_1 S + \frac{b_1}{4} S^2 + \text{ c.c. } \right)}$$

<u>Global U(1)</u> and <u>soft breaking terms</u> (minimal set of S.B. operators to realize pNG DM)

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad S = (v_S + s + i\chi)/\sqrt{2}$$

DM (DM stability ↔ CP sym.)

Mass eigenstates

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Mass eigenvalues

$$\Lambda^2 \equiv \frac{d_2}{2} v_S^2 - \sqrt{2} \frac{a_1}{2v_S}$$

$\boxed{h_1, h_2}$

$$m^2_{h_1,h_2} = \frac{1}{2} \left(\frac{\lambda}{2} v^2 + \Lambda^2 \mp \sqrt{\left(\frac{\lambda}{2} v^2 - \Lambda^2 \right)^2 + 4 \left(\frac{\delta_2}{2} v v_S \right)^2} \right)$$

$\boxed{\text{DM}}$

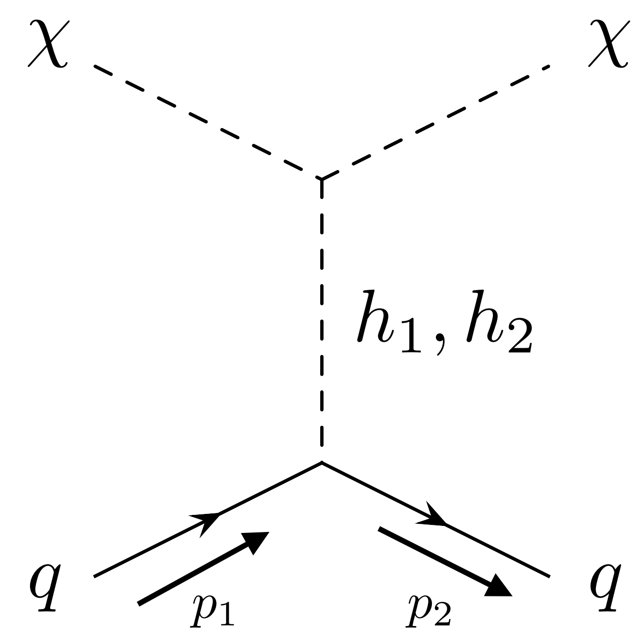
$$m_\chi^2 = -b_1 - \sqrt{2} \frac{a_1}{v_S}$$

Degenerate-Scalar Scenario

Abe, Cho, Mawatari arXiv:2101.04887

$$i\mathcal{M}_{h_1} = -i\frac{m_f}{vv_S}\frac{m_{h_1}^2 + \frac{\sqrt{2}a_1}{v_S}}{t - m_{h_1}^2}\sin\alpha\cos\alpha\ \bar{u}(p_3)u(p_1),$$

$$i\mathcal{M}_{h_2} = +i\frac{m_f}{vv_S}\frac{m_{h_2}^2 + \frac{\sqrt{2}a_1}{v_S}}{t - m_{h_2}^2}\sin\alpha\cos\alpha\ \bar{u}(p_3)u(p_1),$$



$$i\left(\mathcal{M}_{h_1} + \mathcal{M}_{h_2}\right) = i\frac{m_f}{vv_S}\left(-\frac{m_{h_1}^2 + \frac{\sqrt{2}a_1}{v_S}}{t - m_{h_1}^2} + \frac{m_{h_2}^2 + \frac{\sqrt{2}a_1}{v_S}}{t - m_{h_2}^2}\right)\sin\alpha\cos\alpha\bar{u}\left(p_3\right)u\left(p_1\right)$$

$$\simeq i\frac{m_f}{vv_S}\sin\alpha\cos\alpha\bar{u}\left(p_3\right)u\left(p_1\right)$$

$$\times\left\{\left(\frac{\sqrt{2}a_1}{v_S} + t\right)\left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right) + \frac{\sqrt{2}a_1}{v_S}t\left(\frac{1}{m_{h_1}^4} - \frac{1}{m_{h_2}^4}\right)\right\}\ @\ t\rightarrow 0$$

$$\simeq i\frac{m_f}{vv_S}\sin\alpha\cos\alpha\bar{u}\left(p_3\right)u\left(p_1\right)\frac{\sqrt{2}a_1}{v_S}\left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right)$$

$$\simeq 0\ (m_{h1} \sim m_{h2})$$

EWPT in the degenerate-scalar scenario

Strong 1st order phase transition (SFOEWPT) → $\dfrac{v_c}{T_c} \gtrsim 1$

T_C : critical temperature
v_C : higgs vev at T_C

[Two calculation schemes on the scalar potential (**gauge independent**)]

HT potential $V^{\mathrm{HT}}(\varphi,\varphi_S;T) = V_0(\varphi,\varphi_S) + \frac{1}{2}\left(\Sigma_H \varphi^2 + \Sigma_S \varphi_S^2\right) T^2$

PRM scheme $\dfrac{\partial V_{\mathrm{eff}}(\varphi,\xi)}{\partial \xi} = -C(\varphi,\xi)\dfrac{\partial V_{\mathrm{eff}}(\varphi,\xi)}{\partial \varphi}$ M. J. Ramsey-Musolf, JHEP 07 (2011), 029.

$$V_0\left(0, v_{S,\text{ tree}}^{\text{sym}}\right) + V_1\left(0, v_{S,\text{ tree}}^{\text{sym}};T\right) = V_0\left(v_{\text{tree}}, v_{S,\text{ tree}}\right) + V_1\left(v_{\text{tree}}, v_{S,\text{ tree}};T\right)$$

v_C, v_{SC} and v_{SC}^{sym} are determined by the use of V^{HT}

[Two resummation methods in evaluating one-loop effective potential (**gauge dependent**)]

$$V_{\mathrm{eff}}(\varphi,\varphi_S;T) = V_0(\varphi,\varphi_S;T) + \sum_i n_i \left[V_{\mathrm{CW}}\left(\bar{m}_i^2\right) + \frac{T^4}{2\pi^2} I_{B,F}\left(\frac{\bar{m}_i^2}{T^2}\right)\right]$$

Parwani scheme Replace $\bar{m}^2$ with thermally corrected field depending masses $\bar{M}^2$

AE scheme $V_{\mathrm{daisy}}(\varphi,\varphi_S;T) = \sum\limits_{\substack{i=h_{1,2},\chi \\ W_L, Z_L, \gamma_L}} -n_i \dfrac{T}{12\pi}\left[\left(\bar{M}_i^2\right)^{3/2} - \left(\bar{m}_i^2\right)^{3/2}\right]$

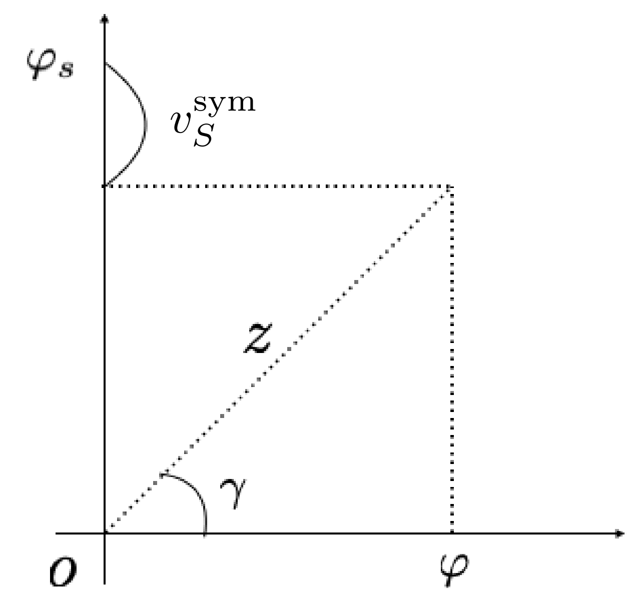
EWPT in the degenerate-scalar scenario

	Gauge independence	Renormalized V_{CW}	One loop contribution
HT potential	○		×
PRM scheme	○	×	○
Parwani scheme	×	○	○
AE scheme	×	○	○

EWPT in the degenerate-scalar scenario

Parametrize the two scalar fields using radial coordinates as

$$\varphi = z\cos\gamma, \varphi_S = z\sin\gamma + v_S^{\mathrm{sym}}$$



HT potential

$$V^{\mathrm{HT}}(\varphi,\varphi_S;T) = V_0(\varphi,\varphi_S) + \frac{1}{2}\left(\Sigma_H\varphi^2 + \Sigma_S\varphi_S^2\right)T^2$$

$$\to \quad V^{\mathrm{HT}}(z,\gamma;T) = c_0 + c_1 z + (c_2 + c_2' T^2)z^2 - c_3 z^3 + c_4 z^4$$

In the case of first-order EWPT

$$T_C \simeq \sqrt{\frac{1}{2\Sigma_H}\left(-m^2 - \frac{(v_{SC}^{\mathrm{sym}})^2}{2}\delta_2\right)},$$

$$v_C \simeq \sqrt{\frac{2\delta_2 (v_{SC}^{\mathrm{sym}})^2}{\lambda}\left(1 - \frac{v_{SC}}{v_{SC}^{\mathrm{sym}}}\right)}$$

$$v_C = \lim_{T\nearrow T_C} v(T)$$

$$v_{SC} = \lim_{T\nearrow T_C} v_S(T)$$

$$v_{SC}^{\mathrm{sym}} = \lim_{T\searrow T_C} v_S(T)$$

Condition of SFOEWPT

$$\frac{v_c}{T_c} \gtrsim 1$$

EWPT in the degenerate-scalar scenario

Tree level potential $V_0 = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(a_1 S + \frac{b_1}{4}S^2 + \text{ c.c.}\right)$

$$\boxed{T_C \simeq \sqrt{\frac{1}{2\Sigma_H}\left(-m^2 - \frac{(v_{SC}^{\text{sym}})^2}{2}\delta_2\right)}},$$

$$v_C \simeq \sqrt{\frac{2\delta_2 \left(v_{SC}^{\text{sym}}\right)^2}{\lambda}\left(1 - \frac{v_{SC}}{v_{SC}^{\text{sym}}}\right)}$$

Condition of SFOEWPT

$$\frac{v_c}{T_c} \gtrsim 1$$

$\boxed{\text{About } T_C}$ $T_C \to$ small, $\delta_2 \to$ positive and sizable

$$\delta_2 = \frac{2}{v v_S}\left(m_{h_1}^2 - m_{h_2}^2\right)\sin\alpha\cos\alpha$$

$v_S \to$ small, $\alpha \to$ the maximal mixing $\frac{\pi}{4}$

EWPT in the degenerate-scalar scenario

$$V_0 = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(a_1 S + \frac{b_1}{4}S^2 + \text{ c.c.}\right)$$

$$T_C \simeq \sqrt{\frac{1}{2\Sigma_H}\left(-m^2 - \frac{(v_{SC}^{\text{sym}})^2}{2}\delta_2\right)},$$

$$v_C \simeq \sqrt{\frac{2\delta_2 \boxed{(v_{SC}^{\text{sym}})^2}}{\lambda}\boxed{\left(1 - \frac{v_{SC}}{v_{SC}^{\text{sym}}}\right)}}$$

Condition of SFOEWPT

$$\frac{v_c}{T_c} \gtrsim 1$$

About v_C

$v_C \to$ large with an amplification factor $\boxed{(v_{SC}^{\text{sym}})^2\left(1 - v_{SC}/v_{SC}^{\text{sym}}\right)}$

$$(v_{SC}^{\text{sym}})^3 + Av_{SC}^{\text{sym}} + B = 0$$

$$A = 2\left(b_1 + b_2 + 2\Sigma_S\right)/d_2$$

$$B = 4\sqrt{2}a_1/d_2$$

v_{SC}^{sym} is scaled by $1/\sqrt{d_2}$ $\qquad \therefore d_2 \to$ small

$$d_2 = \frac{2}{v_S^2}\left[m_{h_1}^2 + (m_{h_2}^2 - m_{h_1}^2)\cos^2\alpha + \frac{\sqrt{2}a_1}{v_S}\right] \simeq \frac{2}{v_S^2}\left[m_{h_1}^2 + \frac{\sqrt{2}a_1}{v_S}\right] \qquad a_1 < 0$$

(1) large δ_2 with a positive sign i.e., $|\alpha| \simeq \dfrac{\pi}{4}$ and $v_S < 1$ GeV

(2) small d_2 i.e., $a_1 < 0$ with its moderate absolute value

EWPT in the degenerate-scalar scenario

Other conditions imposed on the parameters

- The energy difference between the electroweak vacuum prescribed by (v, v_S) and the local vacuum on the φ_S axis specified by $(0, v_S^{\mathrm{sym}})$

$$
\begin{aligned}
\Delta E =& V_0\left(0, v_S^{\mathrm{sym}}\right) - V_0\left(v, v_S\right) \\
=& \sqrt{2} a_1\left(v_S^{\mathrm{sym}} - v_S\right) + \frac{1}{4}\left(b_1 + b_2\right)\left(\left(v_S^{\mathrm{sym}}\right)^2 - v_S^2\right) + \frac{d_2}{16}\left(\left(v_S^{\mathrm{sym}}\right)^4 - v_S^4\right) \\
& - \frac{m^2}{4} v^2 - \frac{\lambda}{16} v^4 - \frac{\delta_2}{8} v^2 v_S^2
\end{aligned}
$$

ΔE could be negative for $\delta_2 \gg 1$ and $d_2 \ll 1$.

$\Downarrow$

δ_2 and d_2 have the upper and lower bound respectively.

- Bounded from below $\quad \lambda > 0, d_2 > 0, \lambda d_2 > \delta_2^2$

- Vacuum stability $\quad \lambda\left(d_2 + \frac{2\sqrt{2}\left|a_1\right|}{v_S^3}\right) > \delta_2^2$

- Conditions from perturbation Theory $\quad \lambda \leqq \frac{16}{3}\pi, d_2 \leqq \frac{16}{3}\pi$

Numerical results

Two benchmark points

the varying parameter

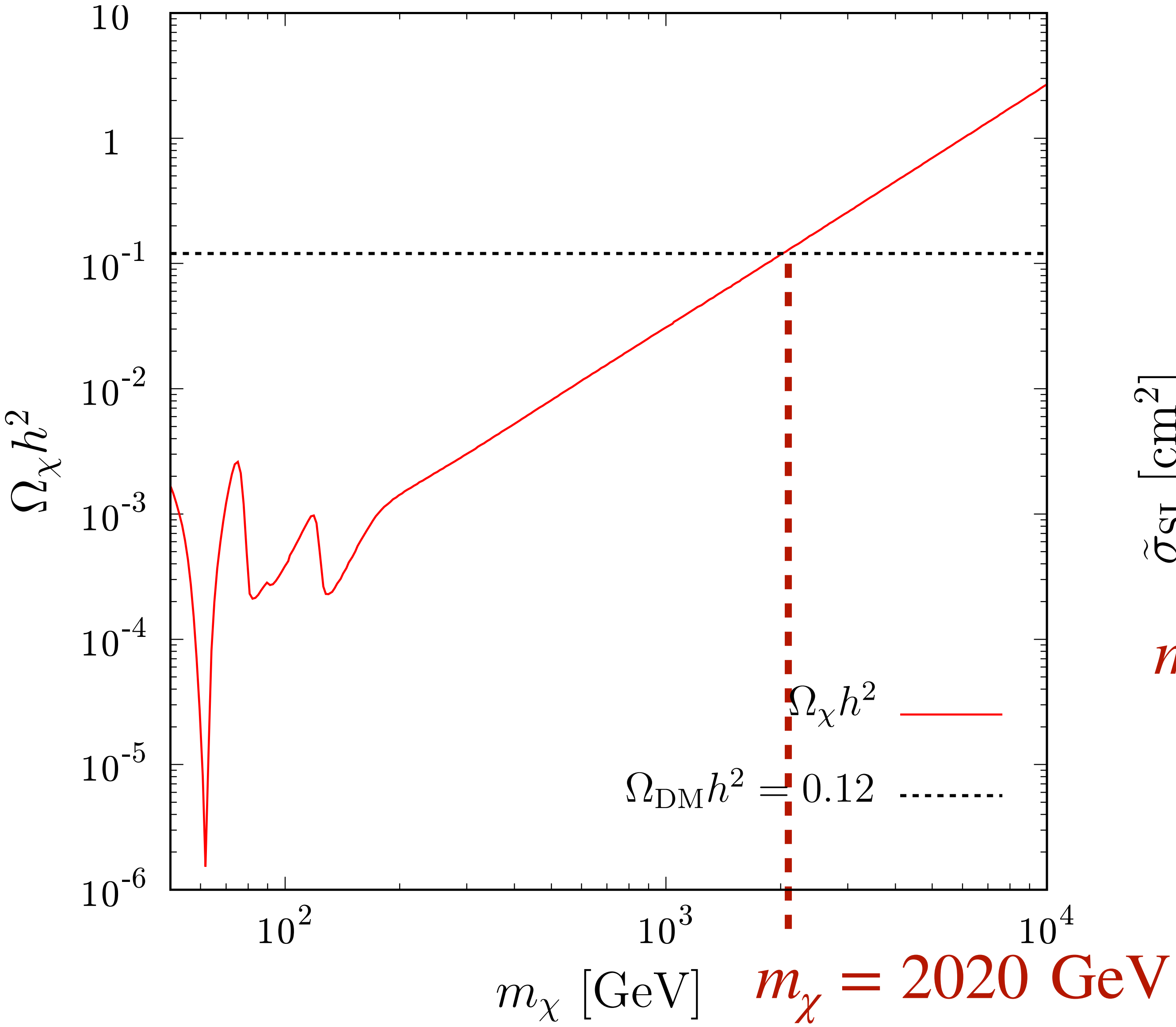
Inputs	v [GeV]	m_{h_1} [GeV]	m_{h_2} [GeV]	α [rad]	a_1 [GeV^3]	v_S [GeV]	m_χ [GeV]
BP1	246.22	125	124	$\pi/4$	-6576.17	0.6	62.5
BP2	246.22	125	126	$-\pi/4$	-6682.25	0.6	62.5

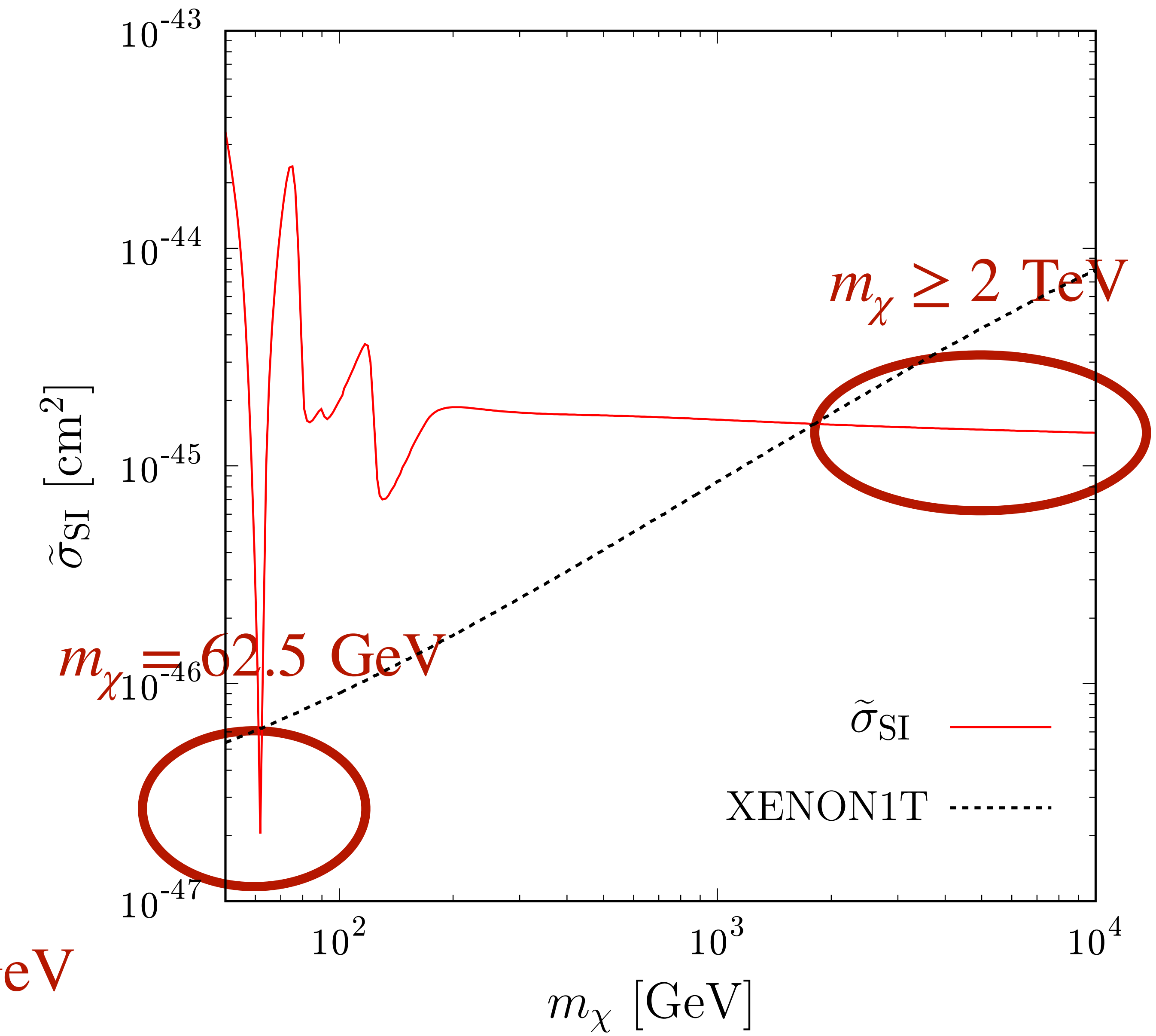
Outputs	m^2 [GeV^2]	b_1 [GeV^2]	b_2 [GeV^2]	λ	a_1 [GeV^3]	d_2	δ_2
BP1	$-(124.5)^2$	$-(107.7)^2$	$-(178.0)^2$	0.511	-6576.17	1.77	1.69
BP2	$-(125.5)^2$	$-(108.8)^2$	$-(178.4)^2$	0.520	-6682.25	1.70	1.59

Calculate the DM relic density $\Omega_\chi h^2$ and SI cross section with the nucleons σ_{SI} in BP1.

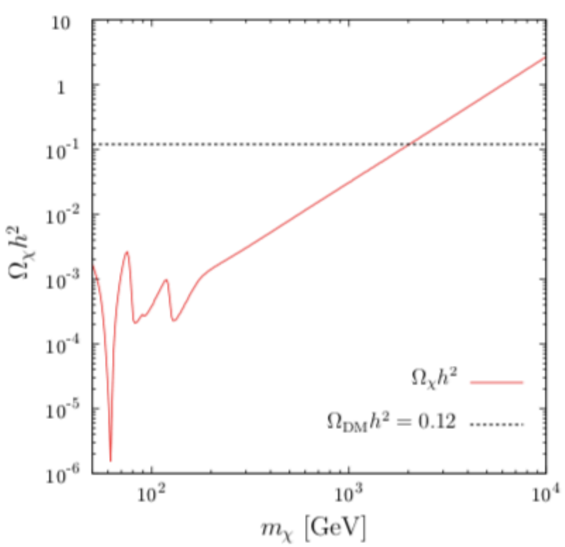
(For the moment, m_χ is treated as the varying parameter.)

Numerical results

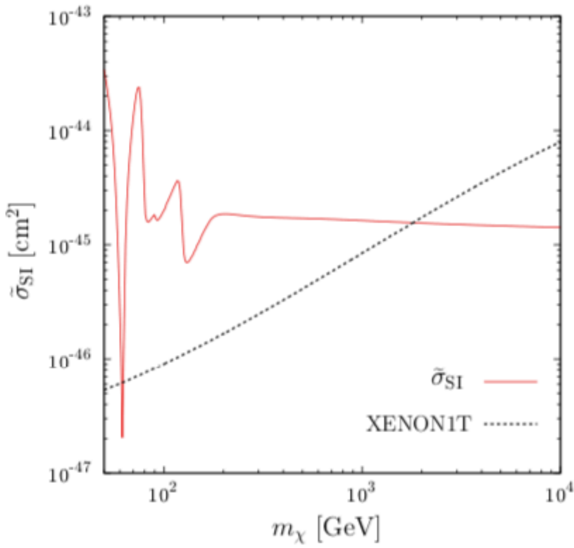




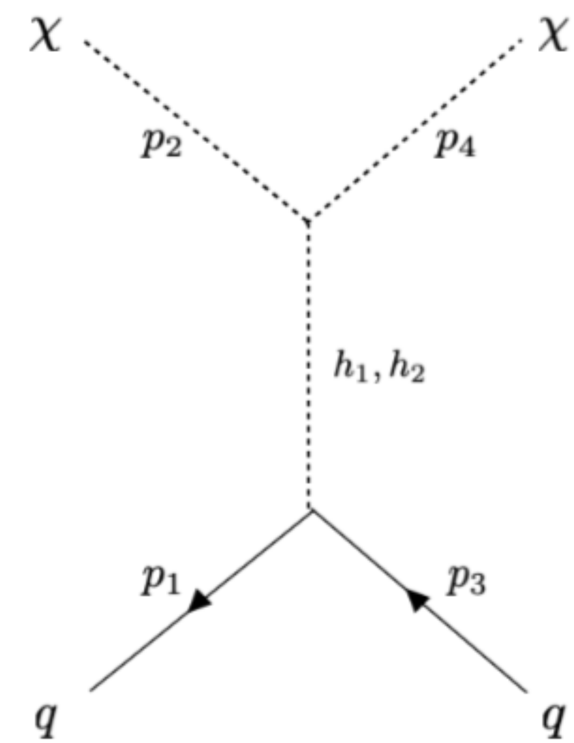
Numerical results



DM relic density $\Omega_\chi h^2$



SI scattering cross section $\sigma_{\rm SI}$



The scattering of dark matter χ and quark q

$$\sigma_{\rm SI} \propto \sin^2\alpha\cos^2\alpha\left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right)^2 \frac{a_1^2}{v_S^4} = \frac{\delta_2^2 v^2}{4 m_{h_1}^4 m_{h_2}^4}\frac{a_1^2}{v_S^2}$$

$$\delta_2 = \frac{2}{v v_S}\left(m_{h_1}^2 - m_{h_2}^2\right)\sin\alpha\cos\alpha$$

Strong 1st EWPT

$\delta_2 \rightarrow$ large

$v_S \rightarrow$ small

(less than 1 GeV)

The core of the cancellation mechanism in the degenerate-scalar scenario:

The suppression of δ_2 owing to $m_{h_1} \simeq m_{h_2}$ with moderate values of v_S.

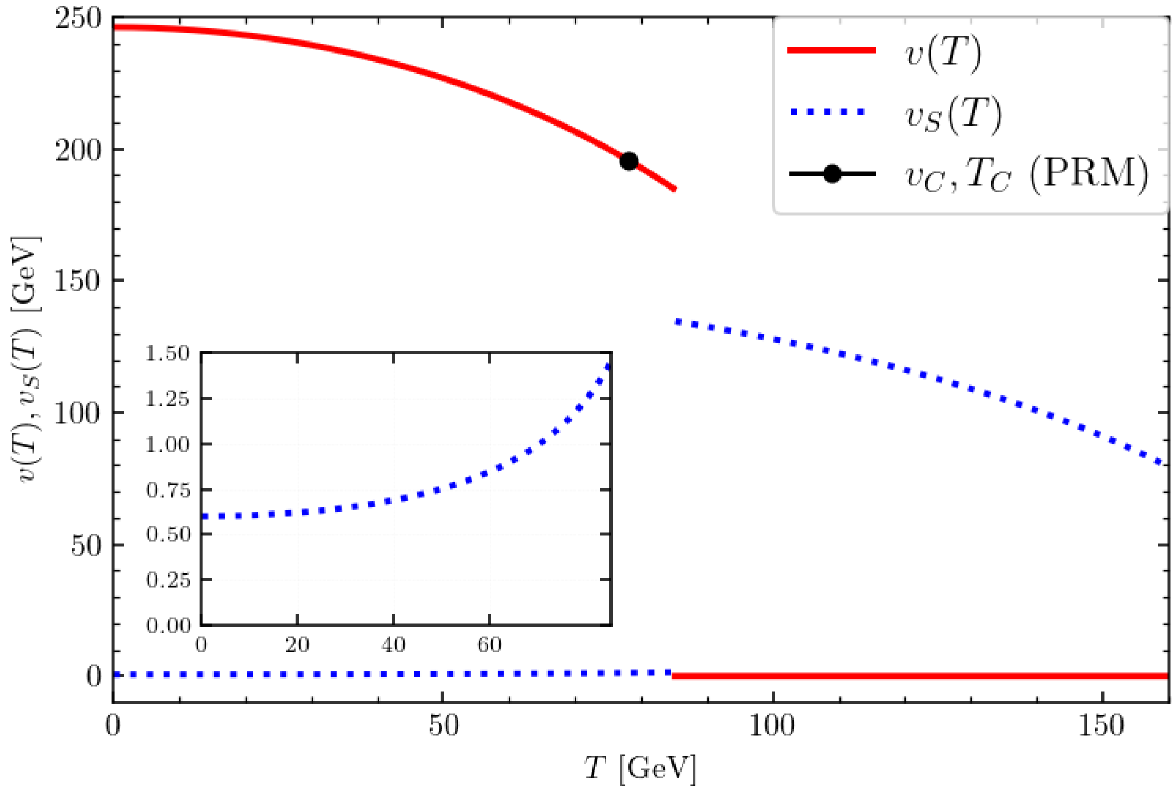
The conditions for the strong 1st EWPT is incompatible with the suppression mechanism.

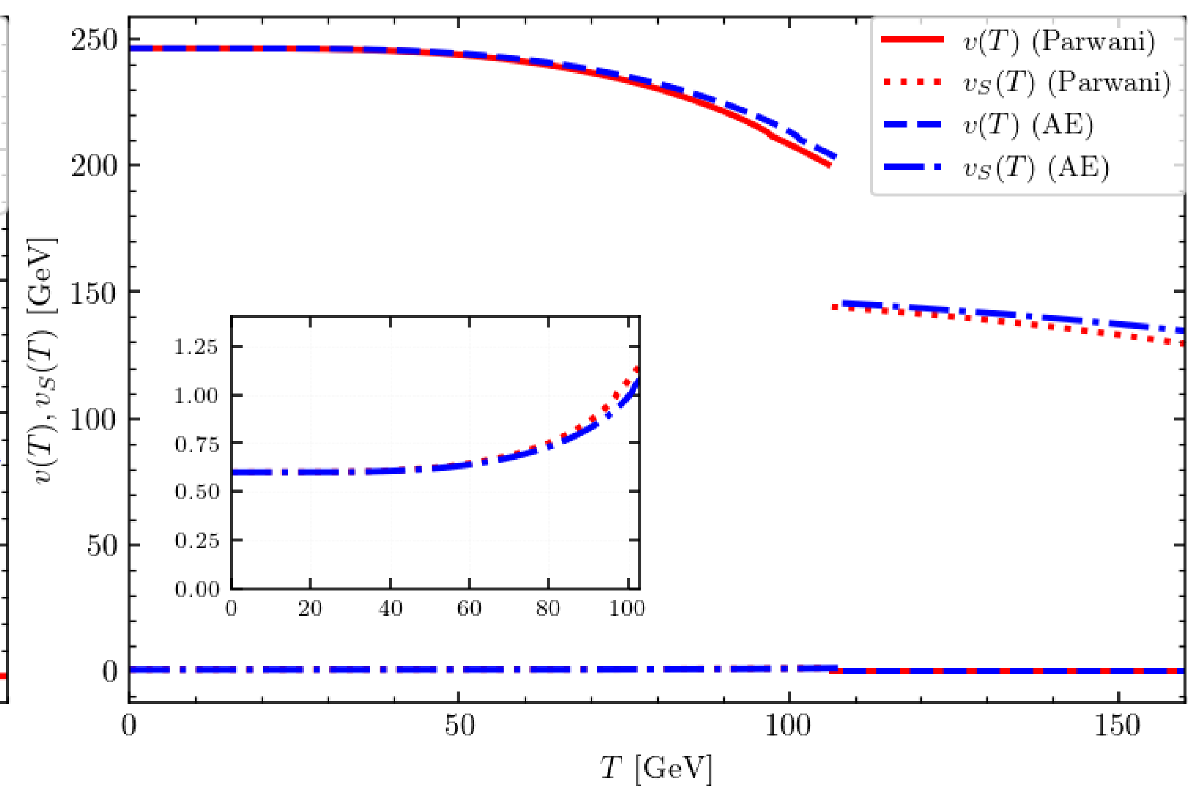
Numerical results

HT/PRM

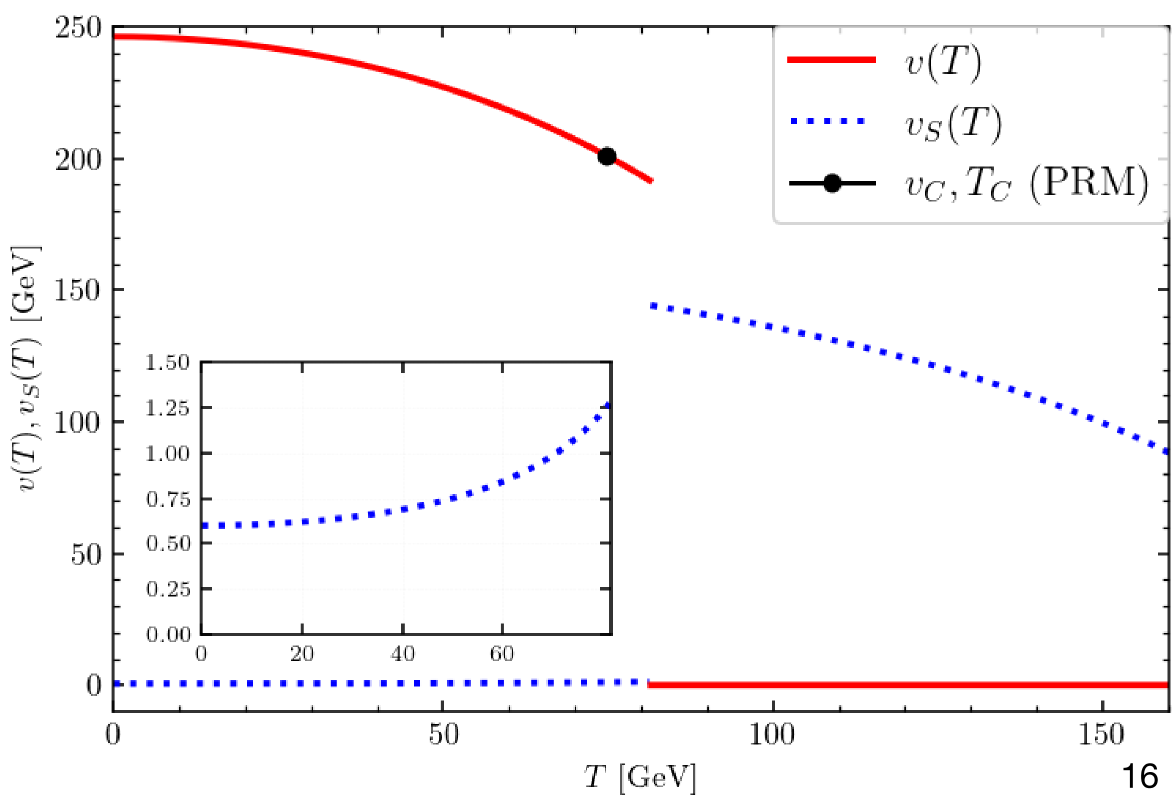
Parwani/AE

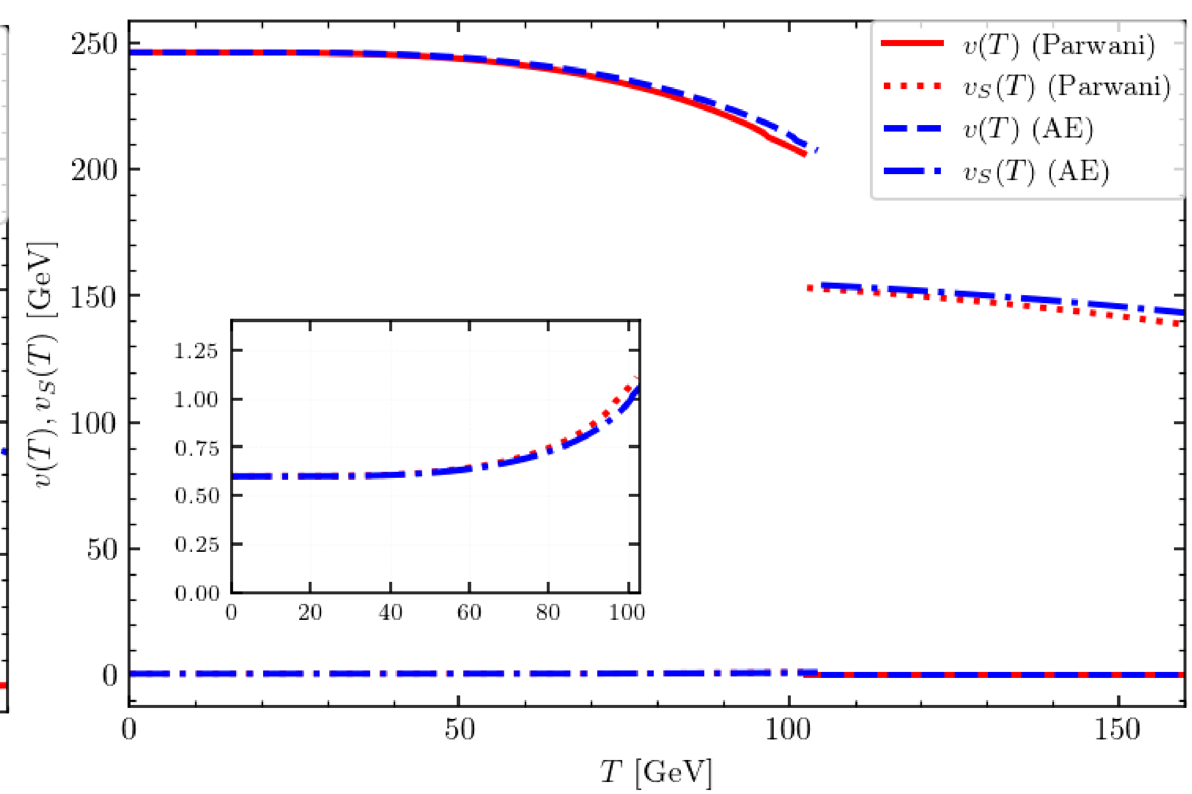
BP1





BP2

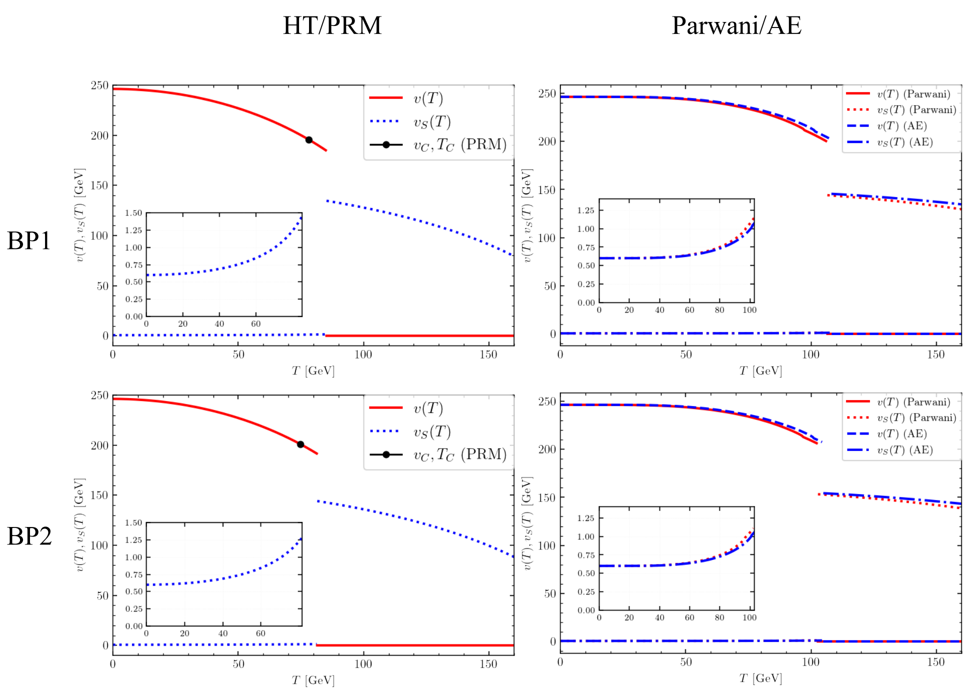




Numerical results

Condition of SFOEWPT

$$\frac{v_c}{T_c} \gtrsim 1$$



Ex) BP1

	BP1			
Scheme	HT	PRM	Parwani	AE
v_C/T_C	$\frac{184.4}{85.3} = 2.2$	$\frac{195.6}{78.2} = 2.5$	$\frac{201.5}{106.8} = 1.9$	$\frac{202.7}{107.8} = 1.9$
v_{SC} [GeV]	1.5	1.2	1.2	1.2
v_{SC}^{sym} [GeV]	134.6	137.3	144.8	145.3

Strong 1st PT !

The consequences found in BP1 all apply to BP2 as well.

Strong first-order EWPT in the degenerate-scalar scenario is possible in the both cases $m_{h_1} > m_{h_2}$ and $m_{h_1} < m_{h_2}$.

Numerical results

The viable DM regions: $m_\chi = 62.5\ \text{GeV}$, $\underline{2\ \text{TeV}}$

When $m_\chi = 2\ \text{TeV}$, one can find the first-order EWPT in the HT, Parwani, and AE schemes while not in the PRM scheme.

$$V_0\left(0, v_{S,\ \text{tree}}^{\text{sym}}\right) + V_1\left(0, v_{S,\ \text{tree}}^{\text{sym}}; T\right) = V_0\left(v_{\text{tree}}, v_{S,\ \text{tree}}\right) + V_1\left(v_{\text{tree}}, v_{S,\ \text{tree}}; T\right)$$

the right-hand side has to be lower than the left-hand side at zero temperature, otherwise, the degeneracy point where T_C is defined would not exist.

Ex) BP1

For $m_\chi \gtrsim 700\ \text{GeV}$, the right-hand side would exceed the left-hand side.

$\rightarrow$ This bound could be relaxed when one includes higher-order corrections.

Summary

We adopted CxSM as a model to explain dark matter, and discussed it from the view point of the strong 1st order phase transition necessary to explain baryon asymmetry.

We analytically showed that the suppression of σ_{SI} driven by the smallness of δ_2, which could be realized by a ratio of the mass difference of two scalars and the singlet VEV v_S, conflicts with one of the necessary conditions for the strong first-order EWPT.

Our numerical analysis also confirms that σ_{SI} is not suppressed by the degenerated scalar masses. Nonetheless, the allowed regions are still present at around $m_\chi = 62.5$ GeV and 2 TeV.

We analyzed EWPT in the viable DM regions by four different calculation schemes: HT, PRM, Parwani and AE, and when $m_\chi = 62.5$ GeV, all the calculations indicate the strong first-order EWPT. When $m_\chi = 2$ TeV, HT, Parwani and AE calculations indicate the strong first-order EWPT.

Back up

CxSM Model Definition

The general scalar potential

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

The minimalization condition

$$-m^2 = \frac{\lambda}{2}v^2 + \frac{\delta_2}{2}v_S^2,$$
$$-b_2 = \frac{\delta_2}{2}v^2 + \frac{d_2}{2}v_S^2 + b_1 + 2\sqrt{2}\frac{a_1}{v_S}$$

Mixing angle α

$$\tan 2\alpha = 2\frac{\frac{\delta_2}{2}vv_S}{\frac{\lambda}{2}v^2 - \Lambda^2}, \quad \cos 2\alpha = \frac{\frac{\lambda}{2}v^2 - \Lambda^2}{m_{h_1}^2 - m_{h_2}^2}$$

$$\Lambda^2 \equiv \frac{d_2}{2}v_S^2 - \sqrt{2}\frac{a_1}{2v_S}$$

Mass eigenvalues

$$m_{h_1,h_2}^2 = \frac{1}{2}\left(\frac{\lambda}{2}v^2 + \Lambda^2 \mp \frac{\frac{\lambda}{2}v^2 - \Lambda^2}{\cos 2\alpha}\right)$$
$$= \frac{1}{2}\left(\frac{\lambda}{2}v^2 + \Lambda^2 \mp \sqrt{\left(\frac{\lambda}{2}v^2 - \Lambda^2\right)^2 + 4\left(\frac{\delta_2}{2}vv_S\right)^2}\right)$$

CxSM Model Definition

Scalar trilinear interactions

$$\mathcal{L}_S = -\frac{1}{2v_S}\left\{\left(m_{h_1}^2 + \frac{\sqrt{2}a_1}{v_S}\right)\sin\alpha\, h_1\chi^2 + \left(m_{h_2}^2 + \frac{\sqrt{2}a_1}{v_S}\right)\cos\alpha\, h_2\chi^2\right\}$$

Yukawa interactions

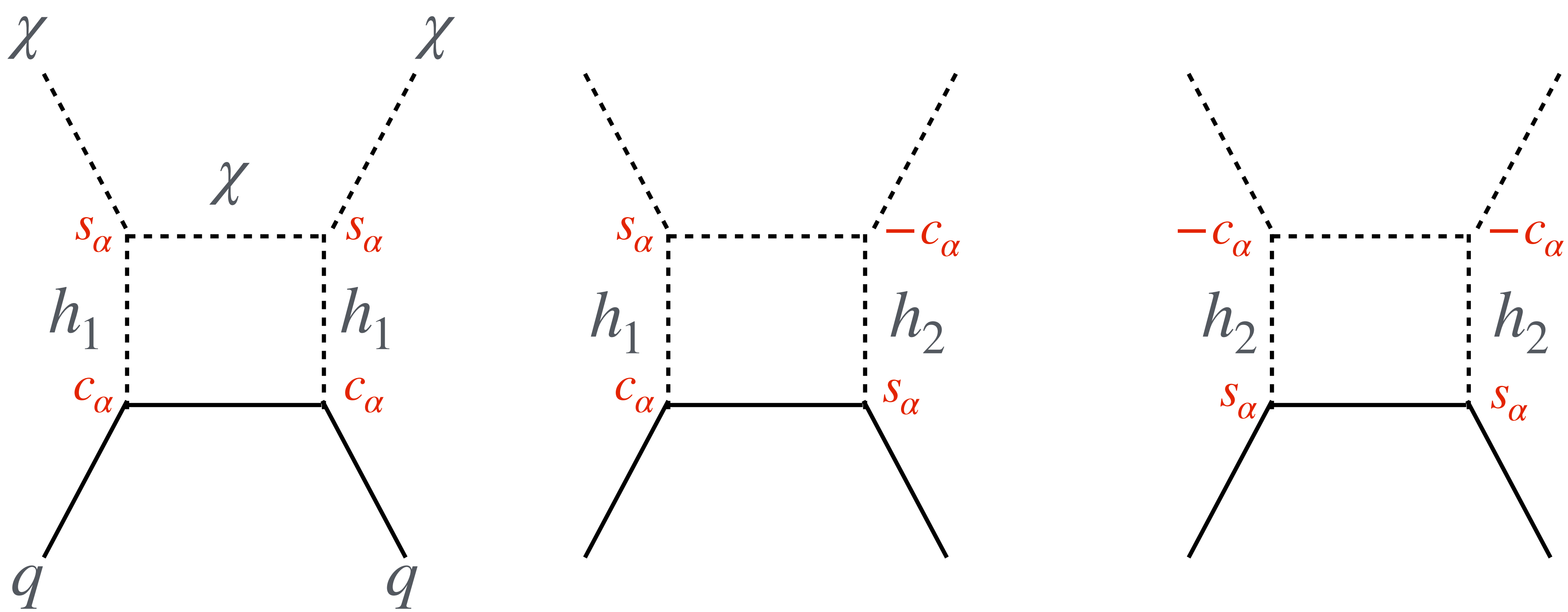
$$\mathcal{L}_Y = -\frac{m_f}{v}\bar{f}f\left(h_1\cos\alpha - h_2\sin\alpha\right)$$

$$\boxed{F(m_{h_1})\cos^2\alpha + F(m_{h_2})\sin^2\alpha \simeq F(m_{h_{\mathsf{SM}}}) \text{ for } m_{h_1} \simeq m_{h_2} \simeq m_{h_{\mathsf{SM}}}}$$

Degenerate-Scalar Scenario

Degenerate scalar scenario@ one-loop Azevedo etal., 1801.06105

$$\sigma_{\chi N}^{\rm NLO} = \sin 2\alpha \left(\frac{\mu_{\chi N} f_N m_N}{m_{h_1} m_{h_2}}\right)^2 \frac{\boxed{m_{h_1}^2 - m_{h_2}^2}}{v^3 v_S^3} \times \text{loop func.} \qquad \propto m_{h_1}^2 - m_{h_2}^2$$



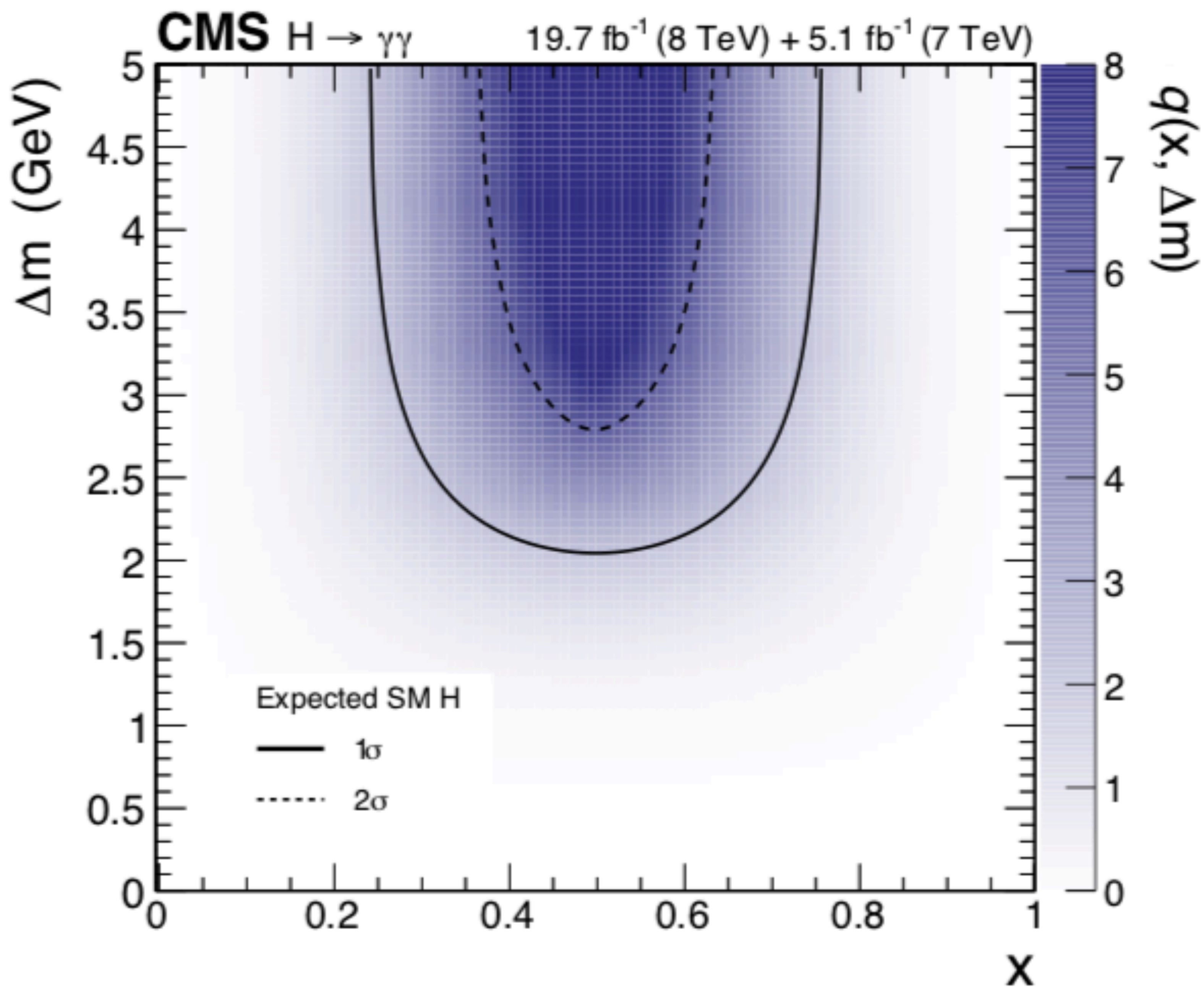
$(s_\alpha c_\alpha)^2 f(m_{h_1}, m_{h_1})$ $\quad -2(s_\alpha c_\alpha)^2 f(m_{h_1}, m_{h_2})$ $\quad (-s_\alpha c_\alpha)^2 f(m_{h_2}, m_{h_2})$

Sum $= (s_\alpha c_\alpha)^2 (f(1,1) - f(1,2)) + (s_\alpha c_\alpha)^2 (f(2,2) - f(2,1))$ –> 0 for $m_{h_1} \sim m_{h_2}$

Degenerate-Scalar Scenario

CMS collaboration, V. Khachatryan et al.,
Eur. Phys. J. C 74 (2014) 3076, [1407.0558].

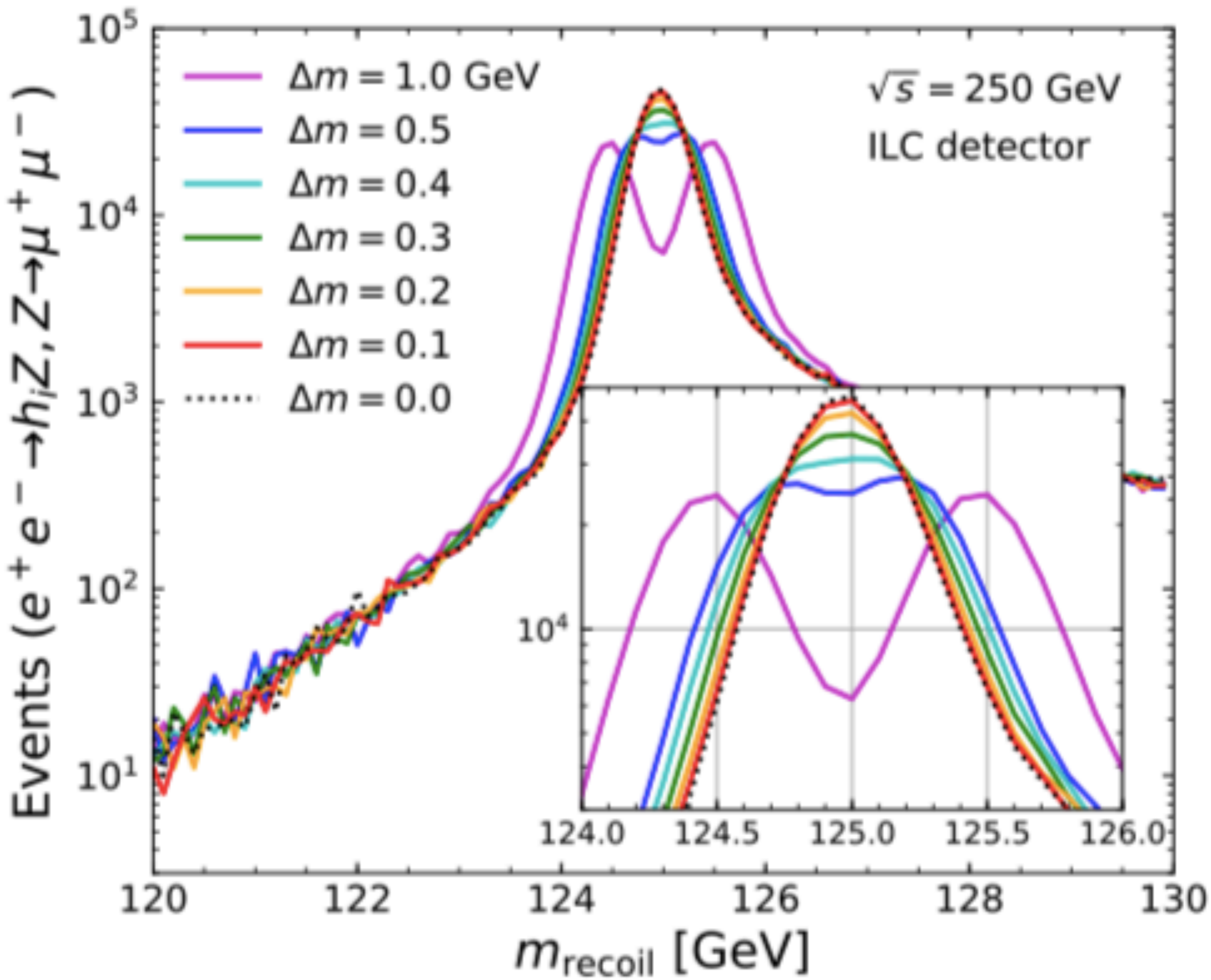
@ LHC



Degenerate-Scalar Scenario

Sachiho Abe , Gi-Chol Cho, Kentarou Mawatari,
arXiv:2101.04887

@ ILC



EWPT in the degenerate-scalar scenario

HT potential $V^{\mathrm{HT}}(\varphi, \varphi_S; T) = V_0(\varphi, \varphi_S) + \frac{1}{2}\left(\Sigma_H \varphi^2 + \Sigma_S \varphi_S^2\right) T^2$ the gauge-invariant thermal masses

$$\Sigma_H = \frac{\lambda}{8} + \frac{\delta_2}{24} + \frac{3g_2^2 + g_1^2}{16} + \frac{y_t^2}{4}, \quad \Sigma_S = \frac{\delta_2 + d_2}{12}$$

PRM scheme $\frac{\partial V_{\mathrm{eff}}(\varphi, \xi)}{\partial \xi} = -C(\varphi, \xi) \frac{\partial V_{\mathrm{eff}}(\varphi, \xi)}{\partial \varphi}$ the Nielsen-Fukuda-Kugo (NFK) identity

One can obtain the NFK identity to given order by expanding each term in the both sides in power of ħ.

$$V_0\left(0, v_{S,\ \mathrm{tree}}^{\mathrm{sym}}\right) + V_1\left(0, v_{S,\ \mathrm{tree}}^{\mathrm{sym}}; T\right) = V_0\left(v_{\mathrm{tree}}, v_{S,\ \mathrm{tree}}\right) + V_1\left(v_{\mathrm{tree}}, v_{S,\ \mathrm{tree}}; T\right)$$

v_C, v_{SC} and v_{SC}^{sym} are determined by the use of V^{HT}

$$V_{\mathrm{eff}}(\varphi, \varphi_S; T) = V_0(\varphi, \varphi_S; T) + \sum_i n_i \left[V_{\mathrm{CW}}\left(\bar{m}_i^2\right) + \frac{T^4}{2\pi^2} I_{B,F}\left(\frac{\bar{m}_i^2}{T^2}\right)\right]$$

$$V_{\mathrm{CW}}\left(\bar{m}_i^2\right) = \frac{\bar{m}_i^4}{64\pi^2}\left(\ln \frac{\bar{m}_i^2}{\bar{\mu}^2} - c_i\right), \quad I_{B,F}\left(a^2\right) = \int_0^\infty dx\, x^2 \ln\left(1 \mp e^{-\sqrt{x^2+a^2}}\right)$$

Parwani scheme Replace $\bar{m}^2$ with thermally corrected field depending masses $\bar{M}^2$

AE scheme $V_{\mathrm{daisy}}(\varphi, \varphi_S; T) = \sum_{\substack{i=h_{1,2}, \chi \\ W_L, Z_L, \gamma_L}} -n_i \frac{T}{12\pi}\left[\left(\bar{M}_i^2\right)^{3/2} - \left(\bar{m}_i^2\right)^{3/2}\right]$

EWPT in the degenerate-scalar scenario

$$V^{\mathrm{HT}}(z,\gamma;T) = c_0 + c_1 z + (c_2 + c_2' T^2) z^2 - c_3 z^3 + c_4 z^4$$

$$c_0 = \sqrt{2} a_1 v_s^A(T) + \frac{1}{4}(b_1 + b_2 + 2\Sigma_S T^2)(v_s^A(T))^2 + \frac{1}{16}(v_s^A(T))^4,$$

$$c_1 = \left(\sqrt{2} a_1 + \frac{1}{2}(b_1 + b_2 + 2\Sigma_S T^2) v_s^A(T) + \frac{1}{4} d_4 (v_s^A(T))^3\right) \sin\gamma,$$

$$c_2 = \frac{1}{4}\left((b_1 + b_2)\sin^2\gamma + m^2 \cos^2\gamma\right) + \frac{1}{8}\left(3 d_2 \sin^2\gamma + \delta_2 \cos^2\gamma\right)(v_s^A(T))^2,$$

$$c_2' = \frac{1}{2}\left(\Sigma_H \cos^2\gamma + \Sigma_S \sin^2\gamma\right),$$

$$c_3 = \frac{1}{4}\sin\gamma\left(d_2 \sin^2\gamma + \delta_2 \cos^2\gamma\right) v_s^A(T),$$

$$c_4 = \frac{1}{16}\left(d_2 \sin^4\gamma + 2\delta_2 \sin^2\gamma\cos^2\gamma + \lambda\cos^4\gamma\right),$$

$$T_C^2 = \frac{1}{2\left(\Sigma_H + \Sigma_S t_{\gamma_C}^2\right)}\left[-m^2 - \frac{\left(v_{SC}^{\mathrm{sym}}\right)^2 \delta_2}{2} - \left\{b_1 + b_2 + \left(\frac{3d_2}{2} - \frac{\left(\delta_2 + d_2 t_{\gamma_C}^2\right)^2}{\lambda + 2\delta_2 t_{\gamma_C}^2 + d_2 t_{\gamma_C}^4}\right)\left(v_{SC}^{\mathrm{sym}}\right)^2\right\} t_{\gamma_C}^2\right],$$

$$v_C = \frac{-2 t_{\gamma_C}\left(v_{SC}^{\mathrm{sym}}\right)^2\left(\delta_2 + d_2 t_{\gamma_C}^2\right)}{\lambda + 2\delta_2 t_{\gamma_C}^2 + d_2 t_{\gamma_C}^4}$$

$$t_{\gamma_C} = \frac{\sin\gamma(T_C)}{\cos\gamma(T_C)} = \frac{v_{SC} - v_{SC}^{\mathrm{sym}}}{v_C},$$

$$v_C = \lim_{T \nearrow T_C} v(T),$$

$$v_{SC} = \lim_{T \nearrow T_C} v_S(T),$$

$$v_{SC}^{\mathrm{sym}} = \lim_{T \searrow T_C} v_S(T)$$

EWPT in the degenerate-scalar scenario

$$\delta_2 = \frac{2}{v v_S}\left(m_{h_1}^2 - m_{h_2}^2\right) \sin\alpha\cos\alpha$$

Invariant under the transformation $m_{h_1}^2 - m_{h_2}^2 \to -(m_{h_1}^2 - m_{h_2}^2)$ and $\alpha \to -\alpha$

$$d_2 = \frac{2}{v_S^2}\left[m_{h_1}^2 + \left(m_{h_2}^2 - m_{h_1}^2\right)\cos^2\alpha + \frac{\sqrt{2}a_1}{v_S}\right] \simeq \frac{2}{v_S^2}\left[m_{h_1}^2 + \frac{\sqrt{2}a_1}{v_S}\right]$$

The sign of $m_{h_1}^2 - m_{h_2}^2$ cannot be compensated by that of α

EWPT in the degenerate-scalar scenario

Phys. Rev. D 93, 065032 (2016)

Local minimum (v, v_S, v_χ)

$\rightarrow$ It might be local min. also in $S = v_S,\ h = v$ subspace

When the coeff. of χ^2 is negative, $V_0(v, v_S, \chi)$ has min.

$$\frac{\delta_2}{8}v^2 + \frac{b_2}{4} + \frac{d_2}{8}v_S^2 - \frac{b_1}{4} < 0$$

$$\frac{m_\chi^2}{2} < 0$$

This inequality does not hold.

In $T \neq 0$, it is stable at $\chi = 0$ due to thermal contribution

Electroweak baryogenesis

Baryon number violation

→ Sphaleron process

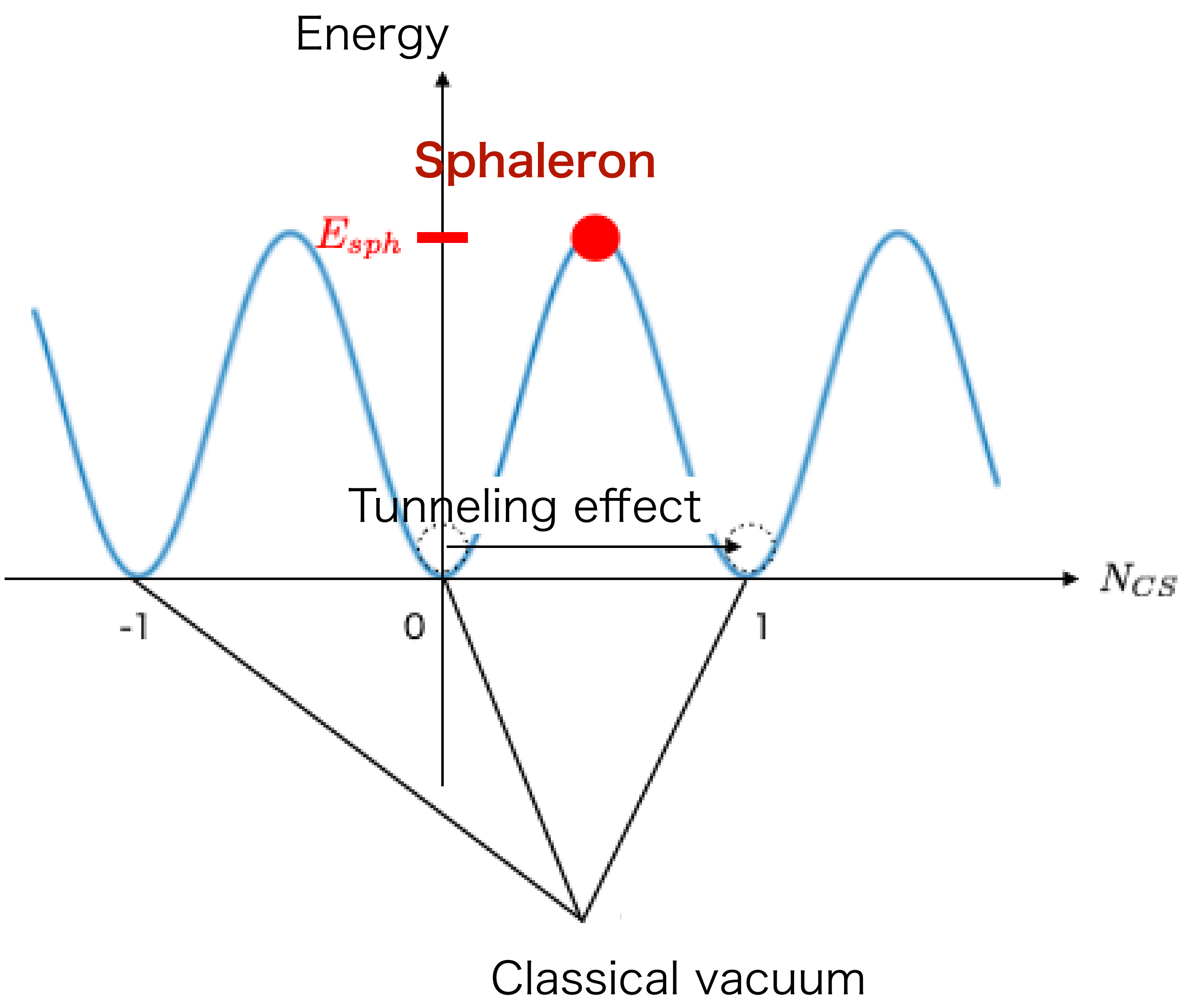
Baryon number

quark : 1/3

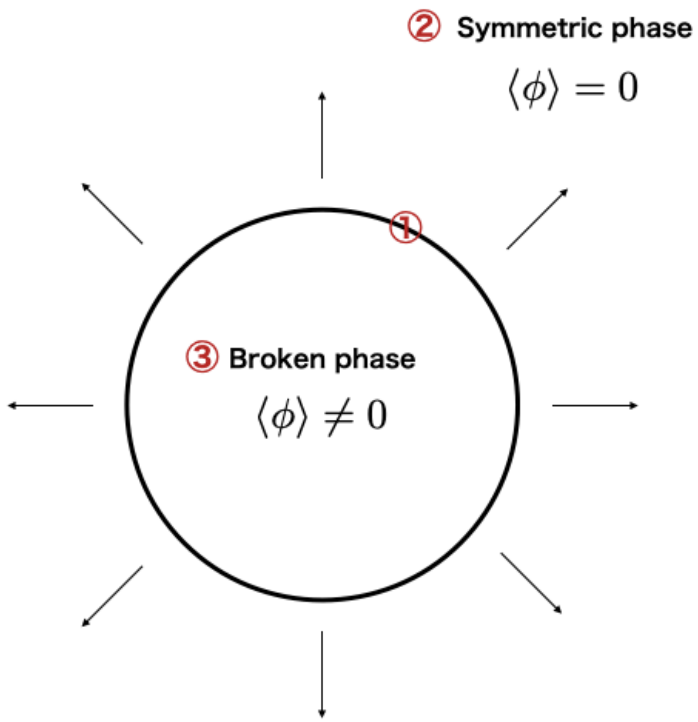
antiquark : -1/3

lepton : 0

boson : 0



Electroweak baryogenesis

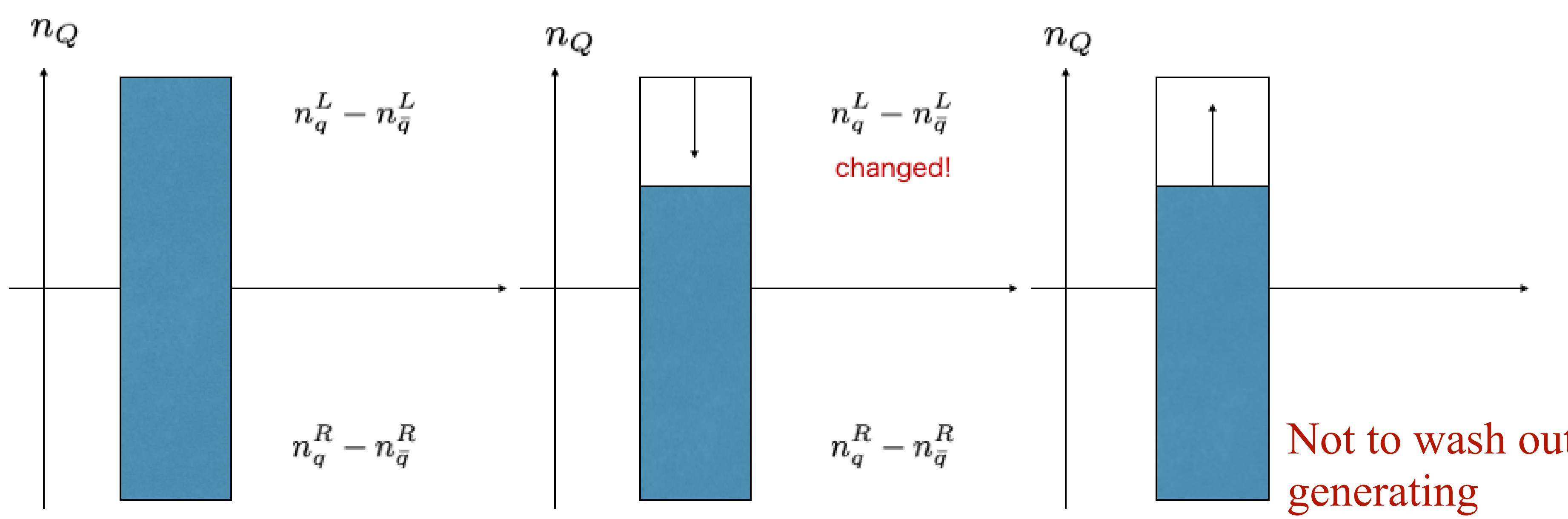


Transmittance, Reflectance

Left-handed quark q^L = Right-handed antiquark $\bar{q}^R$

Left-handed antiquark $\bar{q}^L$ = Right-handed quark q^R

① On the wall ② Symmetric phase ③ Broken phase



Not to wash out generating baryon number

$n_Q \equiv n_q^L - n_{\bar{q}}^L + n_q^R - n_{\bar{q}}^R = 0$

$n_Q \equiv n_q^L - n_{\bar{q}}^L + n_q^R - n_{\bar{q}}^R \neq 0$

baryon number generation

$\boxed{\Gamma_{\rm sph}^{(b)} < H}$ H……Hubble constant

Electroweak baryogenesis

The change rate in the baryon number in the broken phase $\Gamma_B^{(b)}(T)$

To generate baryon number

$\Gamma_B^{(b)}(T)$ must be small

$$\Gamma_B^{(b)}(T) \simeq (\text{ pre }) \frac{\Gamma_{\text{sph}}^{(b)}}{T^3} \simeq (\text{ pre }) e^{-E_{\text{sph}}/T}$$

E_{sph} …… sphaleron energy

Sphaleron rate/time/volume

$$\Gamma_{\text{sph}}^{(b)} \simeq T^4 e^{-E_{\text{sph}}/T}$$

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

Higgs vev must be large

$$\Rightarrow \quad \frac{v_c}{T_c} \gtrsim 1$$

Electroweak baryogenesis

$$\boxed{\Gamma_B^{(b)}(T) < H} \quad \rightarrow \quad \Gamma_B^{(b)}(T) \simeq (\text{ pre })e^{-E_{\mathrm{sph}}/T} < H(T) \simeq 1.66\sqrt{g_*}T^2/m_{\mathrm{P}}$$

g_* ……massless dof

m_{P}……Plank mass

$$E_{\mathrm{sph}} = 4\pi v\mathcal{E}/g_2 \rightarrow$$

g_2 ……SU(2) gauge coupling constant

$$\frac{v}{T} \geq \frac{g_2}{4\pi\mathcal{E}}(42.97 + \mathrm{logcorrections})$$

In the case of the SM

$$m_h = 125\ \mathrm{GeV}, \mathcal{E} = 1.92(T=0) \quad \Rightarrow \quad \frac{v}{T} \geq 1.16$$

EWPT in the SM

M. Quiros, [arXiv:hep-ph/9901312 [hep-ph]]

Effective potential of the SM

$$\Gamma\left[\phi_c\right] = -\int d^4x V_{\text{eff}}\left(\phi_c\right)$$

- tree level potential
- zero-temperature one loop potential (the Coleman Weinberg Potential)
- finite-temperature one loop potential

$$V\left(\phi_c, T\right) = D\left(T^2 - T_o^2\right)\phi_c^2 - ET\phi_c^3 + \frac{\lambda(T)}{4}\phi_c^4$$

$$D = \frac{2m_W^2 + m_Z^2 + 2m_t^2}{8v^2}$$

$$E = \frac{2m_W^3 + m_Z^3}{4\pi v^3}$$

$$T_o^2 = \frac{m_h^2 - 8Bv^2}{4D}$$

$$B = \frac{3}{64\pi^2 v^4}\left(2m_W^4 + m_Z^4 - 4m_t^4\right)$$

$$\lambda(T) = \lambda - \frac{3}{16\pi^2 v^4}\left(2m_W^4 \log\frac{m_W^2}{A_B T^2} + m_Z^4 \log\frac{m_Z^2}{A_B T^2} - 4m_t^4 \log\frac{m_t^2}{A_F T^2}\right)$$

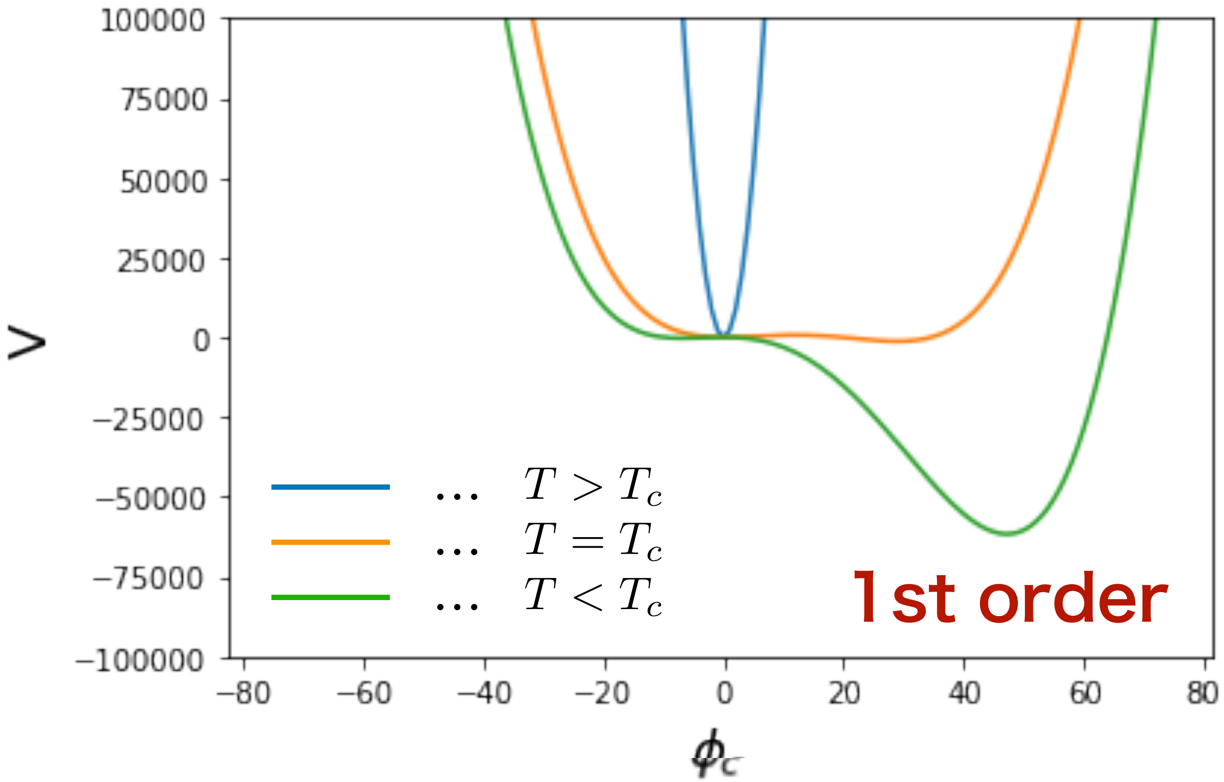
Higgs field

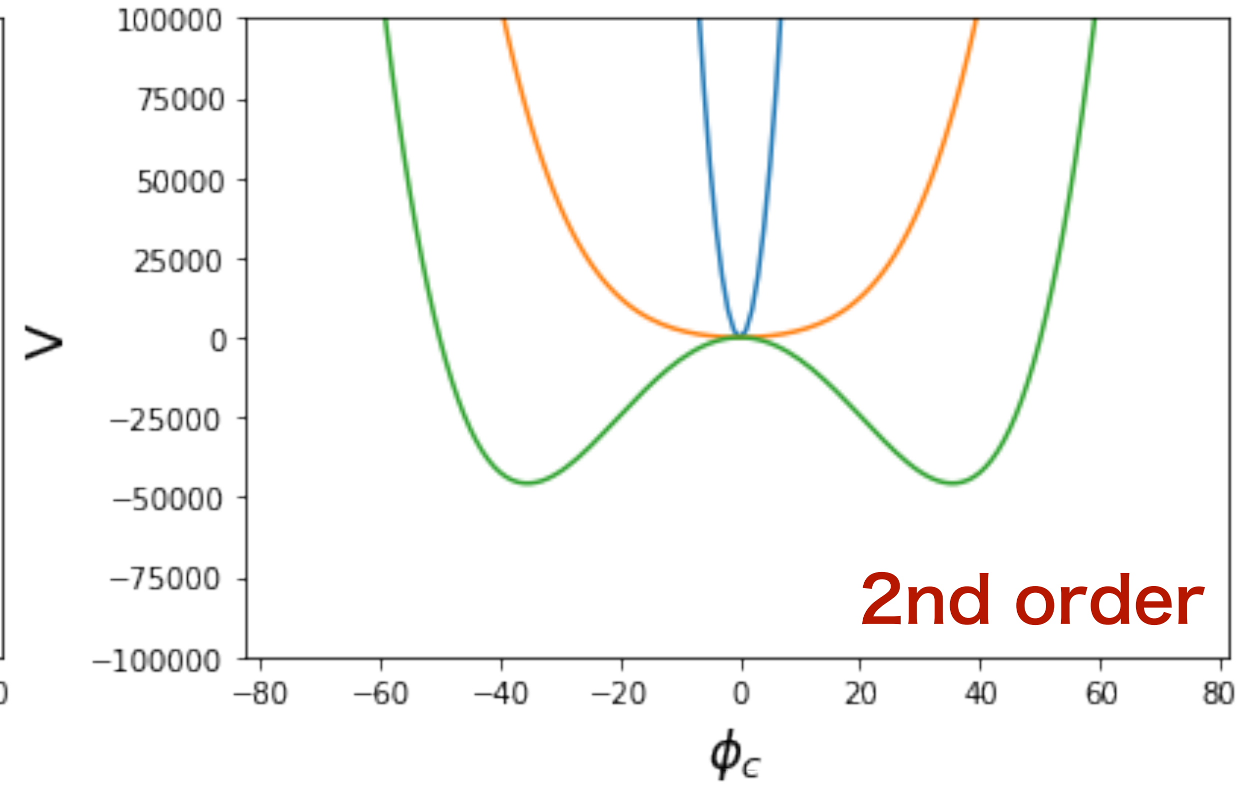
$$H = \begin{pmatrix} \chi_1 + i\chi_2 \\ \frac{\phi_c + h + i\chi_3}{\sqrt{2}} \end{pmatrix}$$

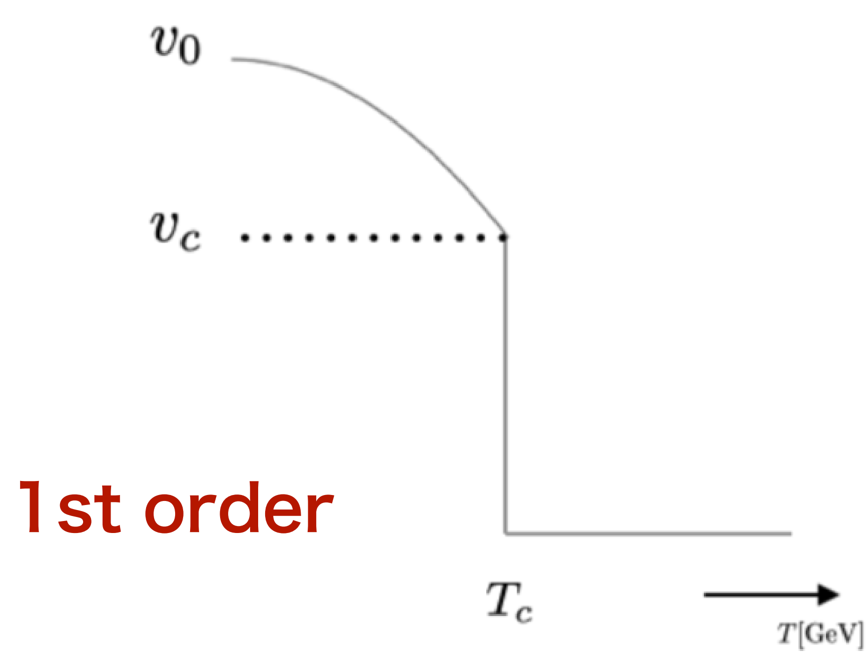
ϕ_c ……real background field

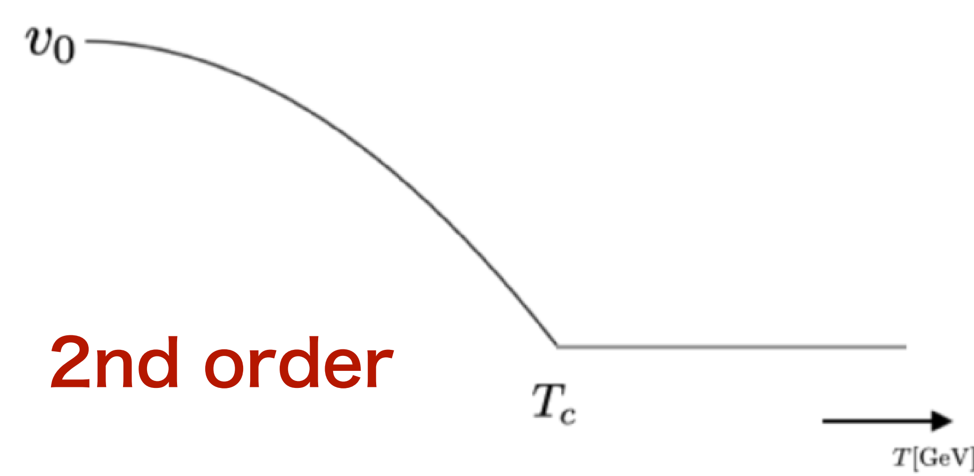
χ_a $(a = 1, 2, 3)$ ……goldstone bosons

EWPT in the SM





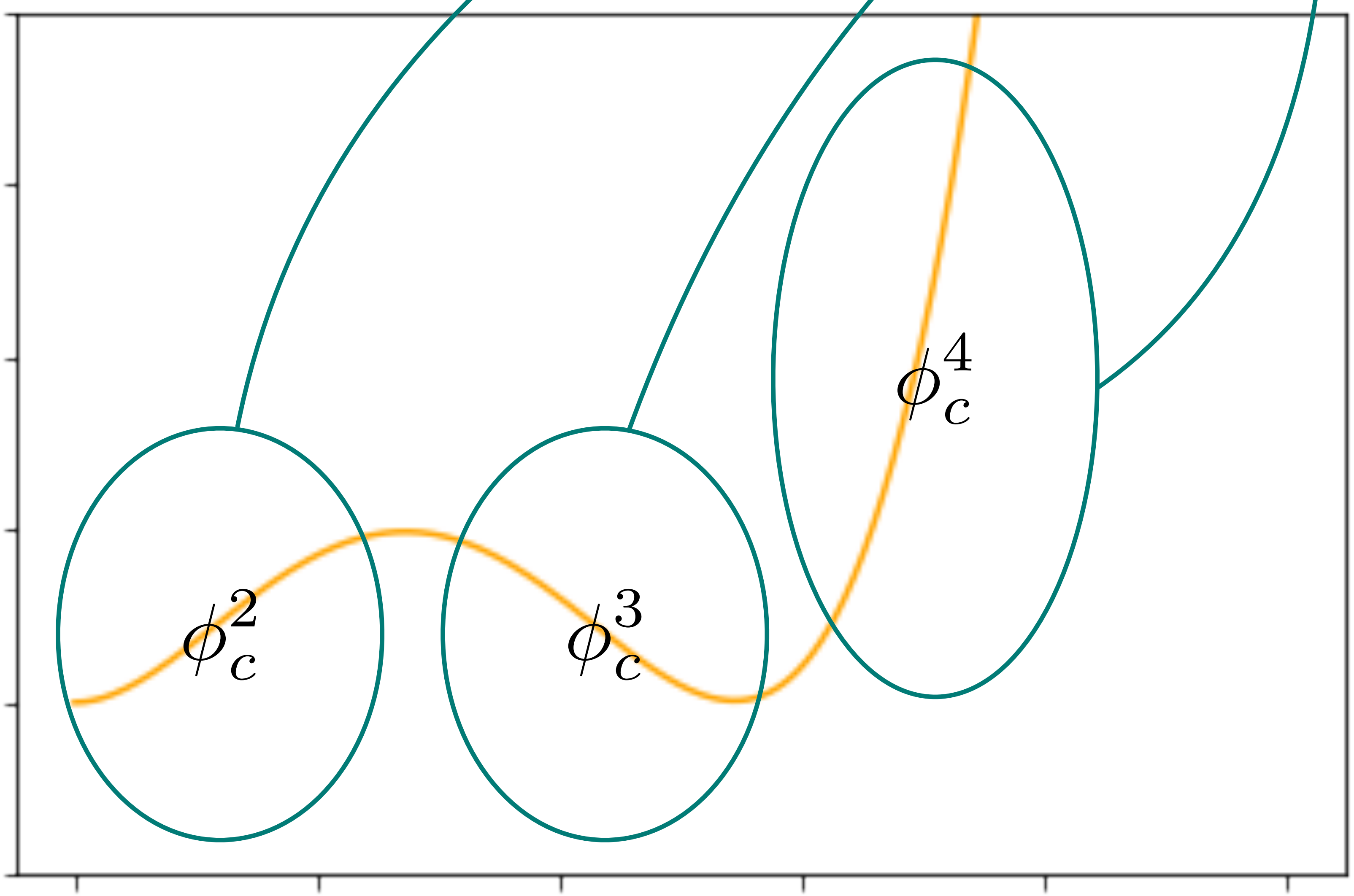




$-ET\phi_c^3$ from finite-temperature boson loop causes a 1st order PT.

EWPT in the SM

$$V\left(\phi_c, T\right) = D\left(T^2 - T_o^2\right)\phi_c^2 - ET\phi_c^3 + \frac{\lambda(T)}{4}\phi_c^4$$



$v(T)$ makes discontinuous transition.
(1st order PT)

A barrier is needed between the origin, and $v(T)$

ϕ_c^3 contributes.

EWPT in the SM

In the SM, SFOEWPT condition

$$\frac{v_c}{T_c} = \frac{2E}{\lambda(T_c)} \gtrsim 1$$

$$m_h \lesssim 64\ \mathrm{GeV}$$

Conflict with observation at LHC → We need to extend the SM!

Numerical results

We use a public code micrOMEGAs to calculate $\Omega_\chi h^2$ and $\sigma_{\rm SI}$.

The value of $\Omega_\chi h^2$ should not exceed the observed value

$$\Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$$

In the case of $m_\chi = 30$ GeV, for instance, the maximum value is $\sigma_{\rm SI} \simeq 4.1 \times 10^{-47}$ cm^2

under the assumption $\Omega_\chi = \Omega_{\rm DM}$.

In cases that $\Omega_\chi < \Omega_{\rm DM}$, we scale $\sigma_{\rm SI}$ as

$$\widetilde{\sigma}_{\rm SI} = \left(\frac{\Omega_\chi}{\Omega_{\rm DM}} \right) \sigma_{\rm SI}$$

Future work

Main topic: About the feasibility of CxSM when CP symmetry is broken.

1. Spontaneous CP violation

$$V_0 = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(a_1 S + \frac{b_1}{4} S^2 + \text{ c.c. } \right)$$

Investigate the feasibility of SFOEWPT

Introduce complex phase

2. Explicit CP violation

Introduce such a dimension-five operator

$$(\text{coeff.})\ \bar{t}_L \gamma_5 t_R S + h.c.$$

There is a phase in the (coeff.) that cannot be removed by the field redifinition,

and it contributes to the baryon number generation.