Z′-ino-driven electroweak baryogenesis

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Nov 25, 2013. @PASCOS 2013, Taipei, Taiwan

Ref. PRD88,055014 (2013) [arXiv:1308.3389]

Outline

- Introduction
- EWBG in the U(1)′-extended MSSM (UMSSM)
  - strong 1^{st}-order EW phase transition (PT)
  - sphaleron decoupling condition
  - Baryon asymmetry
- Summary

Baryon Asymmetry of the Universe

❒ Our universe is baryon asymmetric. $\frac{n_B}{s} \simeq 10^{-11}$

❒ SM cannot explain the BAU. (CPV & strong 1st PT, X)

New Physics is needed!

❒ EWBG in the MSSM (light stop scenario) is in tension with the LHC data.

- Higgs signal strength is not consistent with the data.

-> viable window is getting closing.

Extensions of the MSSM

- Next-to-MSSM (NMSSM),
- U(1)'-MSSM (UMSSM),
- Triplet-MSSM (TMSSM), etc.

In this talk, we discuss a possibility of the EWBG in the UMSSM.

U(1)'-extended MSSM (UMSSM)

D.Suematsu et al, Int.J.Mod.Phys.A10 ('95) 4521.
M.Cvetic et al, PRD56:2861 ('97)

superpotential: $W_{\rm UMSSM} \ni \epsilon_{ij}\lambda S H_u^i H_d^j$

2 Higgs doublets (H_d, H_u) + 1 Higgs singlet (S)

Higgs potential $V_0 = V_F + V_D + V_{\rm soft}$,

$$V_F = |\lambda|^2\{|\epsilon_{ij}\Phi_d^i\Phi_u^j|^2 + |S|^2(\Phi_d^\dagger\Phi_d + \Phi_u^\dagger\Phi_u)\},$$

$$V_D = \frac{g_2^2+g_1^2}{8}(\Phi_d^\dagger\Phi_d - \Phi_u^\dagger\Phi_u)^2 + \frac{g_2^2}{2}(\Phi_d^\dagger\Phi_u)(\Phi_u^\dagger\Phi_d)$$
$$+\frac{g_1'^2}{2}(Q_{H_d}\Phi_d^\dagger\Phi_d + Q_{H_u}\Phi_u^\dagger\Phi_u + Q_S|S|^2)^2,$$

$$V_{\rm soft} = m_1^2\Phi_d^\dagger\Phi_d + m_2^2\Phi_u^\dagger\Phi_u + m_S^2|S|^2 - (\epsilon_{ij}\lambda A_\lambda S\Phi_d^i\Phi_u^j + {\rm h.c.}).$$

Q's: U(1)' charges, $Q_{Hd} + Q_{Hu} + Q_S = 0$. $g_1' = \sqrt{5/3}g_1$

$$\Phi_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + ia_d) \\ \phi_d^- \end{pmatrix}, \quad \Phi_u = e^{i\theta}\begin{pmatrix} \phi_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u + ia_u) \end{pmatrix},$$

$$S = \frac{1}{\sqrt{2}}(v_S + h_S + ia_S).$$

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$$+\frac{g_1'^2}{2}(Q_{H_d}\Phi_d^\dagger\Phi_d + Q_{H_u}\Phi_u^\dagger\Phi_u + Q_S|S|^2)^2,$$ U(1)′-D term

$$V_{\rm soft} = m_1^2\Phi_d^\dagger\Phi_d + m_2^2\Phi_u^\dagger\Phi_u + m_S^2|S|^2 - (\epsilon_{ij}\lambda A_\lambda S\Phi_d^i\Phi_u^j + {\rm h.c.}).$$

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Tadpole (minimization) conditions

$$\frac{1}{v_d}\left\langle\frac{\partial V_0}{\partial h_d}\right\rangle = m_1^2 + \frac{g_2^2+g_1^2}{8}(v_d^2 - v_u^2) - R_\lambda \frac{v_u v_S}{v_d} + \frac{|\lambda|^2}{2}(v_u^2 + v_S^2) + \frac{g_1'^2}{2} Q_{H_d}\Delta = 0,$$

$$\frac{1}{v_u}\left\langle\frac{\partial V_0}{\partial h_u}\right\rangle = m_2^2 - \frac{g_2^2+g_1^2}{8}(v_d^2 - v_u^2) - R_\lambda \frac{v_d v_S}{v_u} + \frac{|\lambda|^2}{2}(v_d^2 + v_S^2) + \frac{g_1'^2}{2} Q_{H_u}\Delta = 0,$$

$$\frac{1}{v_S}\left\langle\frac{\partial V_0}{\partial h_S}\right\rangle = m_S^2 - R_\lambda \frac{v_d v_u}{v_S} + \frac{|\lambda|^2}{2}(v_d^2 + v_u^2) + \frac{g_1'^2}{2} Q_S\Delta = 0,$$

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$$\frac{1}{v_S}\left\langle\frac{\partial V_0}{\partial a_S}\right\rangle = I_\lambda \frac{v_d v_u}{v_S} = 0,$$

where $v_d = v_u = v_S \neq 0$ is assumed.

$$\Delta = Q_{H_d} v_d^2 + Q_{H_u} v_u^2 + Q_S v_S^2,$$

$$R_\lambda = \frac{\mathrm{Re}(\lambda A_\lambda e^{i\theta})}{\sqrt{2}} = \frac{|\lambda A_\lambda|}{\sqrt{2}}\cos(\delta_{A_\lambda} + \delta_\lambda + \theta) \equiv \frac{|\lambda A_\lambda|}{\sqrt{2}}\cos(\delta_{A_\lambda} + \delta'_\lambda),$$

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$I_\lambda = 0.$ CP is conserved at the tree level.

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CP is conserved at the tree level.

Higgs boson masses

At the tree level, the lightest Higgs mass is bounded as

$$m_{H_1}^2 \leq m_Z^2 \cos^2 2\beta + \frac{|\lambda|^2}{2} v^2 \sin^2 2\beta + g_1'^2 v^2 (Q_{H_d} \cos^2 \beta + Q_{H_u} \sin^2 \beta)^2.$$

CP-even Higgs:

In the limit $Q_{H_d} = Q_{H_u} \equiv Q$, $\tan\beta = 1$, one gets

$$m_{H_{1,2}}^2 = \frac{1}{2}\Big[m_S^2 + |\lambda|^2 v^2 + 6 g_1'^2 Q^2 v_S^2$$

$$\mp \sqrt{\{m_S^2 + 2g_1'^2 Q^2 (3v_S^2 - v^2)\}^2 + 4v^2 \{R_\lambda - (|\lambda|^2 - 2g_1'^2 Q^2) v_S\}^2}\Big],$$

$$m_{H_3}^2 = m_Z^2 - \frac{|\lambda|^2}{2} v^2 + 2R_\lambda v_S,$$

CP-odd Higgs: $$m_A^2 = \frac{2R_\lambda v_S}{\sin 2\beta}\left(1 + \frac{v^2}{4v_S^2} \sin^2 2\beta\right)$$

charged Higgs: $$m_{H^\pm}^2 = m_W^2 + \frac{2R_\lambda}{\sin 2\beta} v_S - \frac{|\lambda|^2}{2} v^2.$$

Heavy Higgs boson masses are controlled by R_λ (A_λ).

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Vacuum structures

Tree-level effective potential

$$V_0(\varphi_d, \varphi_u, \vartheta, \varphi_S) = \frac{1}{2}m_1^2\varphi_d^2 + \frac{1}{2}m_2^2\varphi_u^2 + \frac{1}{2}m_S^2\varphi_S^2 - R_\lambda\varphi_d\varphi_u\varphi_S + \frac{g_2^2+g_1^2}{32}(\varphi_d^2-\varphi_u^2)^2$$
$$+ \frac{|\lambda|^2}{4}(\varphi_d^2\varphi_u^2 + \varphi_d^2\varphi_S^2 + \varphi_u^2\varphi_S^2) + \frac{g_1'^2}{8}(Q_{H_d}\varphi_d^2 + Q_{H_u}\varphi_u^2 + Q_S\varphi_S^2)^2.$$

various vacua:

$$\mathrm{EW}: v = 246\ \mathrm{GeV},\ v_S \neq 0; \quad \mathrm{I}: v = 0,\ v_S \neq 0;$$
$$\mathrm{II}: v \neq 0,\ v_S = 0; \quad \mathrm{SYM}: v = v_S = 0.$$

Energy of EW vacuum is

$$V_0^{(\mathrm{EW})}(v_d, v_u, \theta, v_S) = -\frac{g_2^2+g_1^2}{32}(v_d^2-v_u^2)^2 + \frac{1}{2}R_\lambda v_d v_u v_S - \frac{|\lambda|^2}{4}(v_d^2v_u^2 + v_d^2v_S^2 + v_u^2v_S^2) - \frac{g_1'^2}{8}\Delta^2,$$

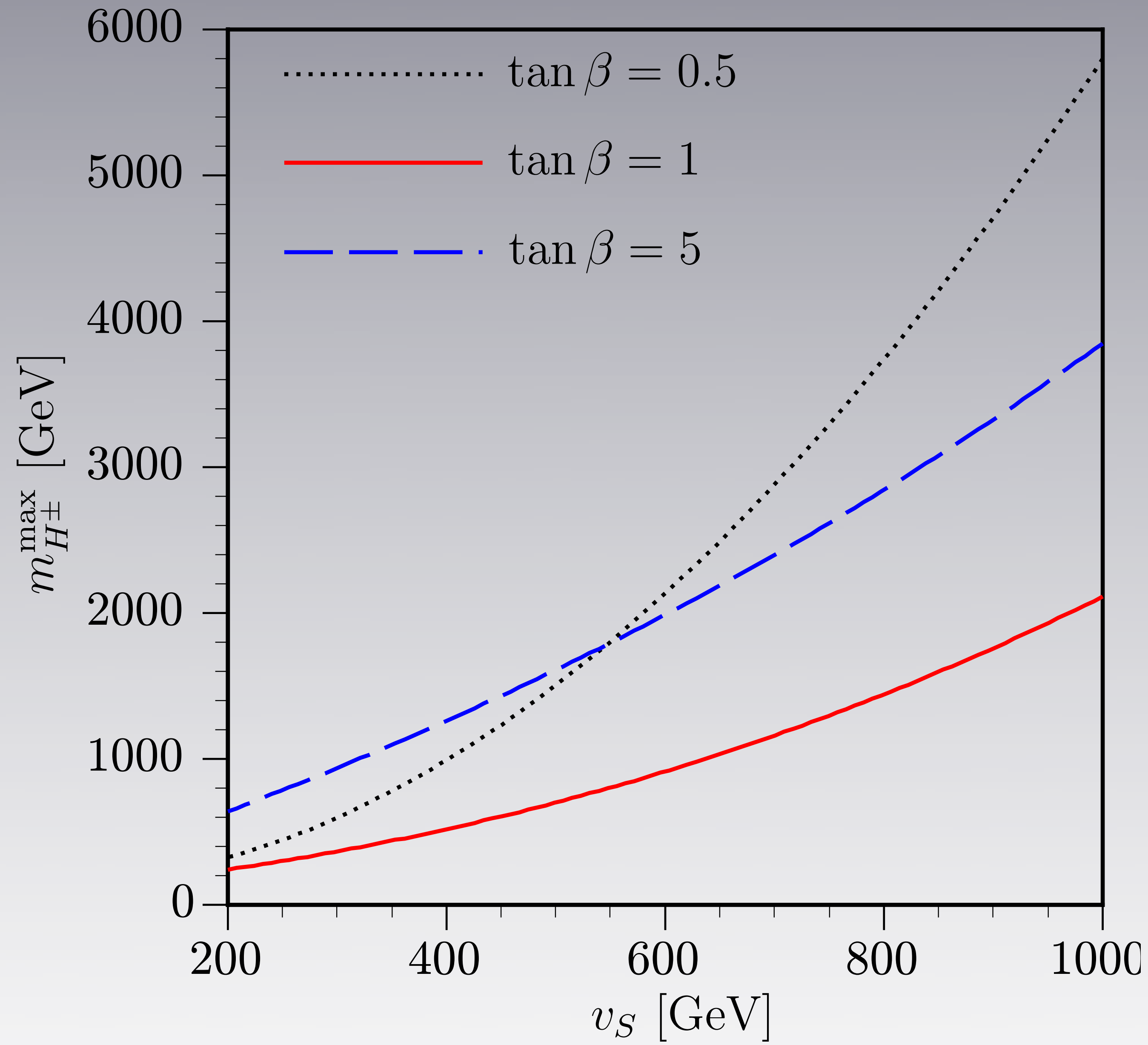
We require $V_0(\boldsymbol{\varphi} = \boldsymbol{v}_{\mathrm{EW}}) < V_0(\boldsymbol{\varphi} \neq \boldsymbol{v}_{\mathrm{EW}}),$

$V_0^{(\mathrm{EW})}(v_d, v_u, \theta, v_S) < 0$ gives an upper bound on $m_{H^\pm}$

$$m_{H^\pm}^2 < m_W^2 + m_Z^2\cot^2 2\beta + \frac{2|\lambda|^2 v_S^2}{\sin^2 2\beta} + \frac{g_1'^2\Delta^2}{v^2\sin^2 2\beta} \equiv (m_{H^\pm}^{\max})^2.$$

$m_{H^\pm}^{\max}$

$|\lambda| = 0.8,\ Q_{H_d} = -0.5,\ Q_{H_u} = Q_{H_d}/\tan^2\beta$



- Smallest $m_{H^\pm}^{\max}$ is realized for $\tan\beta = 1$.
- In this case, $m_{H^\pm} \lesssim 1$ TeV for $v_S \lesssim 640$ GeV.

Neutral gauge boson masses

$$\mathcal{M}^2_{ZZ'} = \begin{pmatrix} \frac{1}{4}(g_2^2+g_1^2)v^2 & \frac{g_1'}{2}\sqrt{g_2^2+g_1^2}(Q_{H_d}v_d^2 - Q_{H_u}v_u^2) \\ \frac{g_1'}{2}\sqrt{g_2^2+g_1^2}(Q_{H_d}v_d^2 - Q_{H_u}v_u^2) & g_1'^2(Q_{H_d}^2 v_d^2 + Q_{H_u}^2 v_u^2 + Q_S^2 v_S^2) \end{pmatrix}.$$

From EW precision tests, $\alpha_{ZZ'} < \mathcal{O}(10^{-3}) \quad \Longrightarrow \quad \tan\beta = \sqrt{\frac{|Q_{H_d}|}{|Q_{H_u}|}}.$

Z′ boson mass: $$m^2_{Z'} = g_1'^2(Q_{H_d}^2 v_d^2 + Q_{H_u}^2 v_u^2 + Q_S^2 v_S^2).$$

Input parameters

tree level: λ $\to$ $m_{H_1} = 126$ GeV, A_λ $\to$ $m_{H^\pm}$, $\tan\beta$ $\to$ $\sqrt{\frac{Q_{H_d}}{Q_{H_u}}}$, v_S $\to$ $m_{Z'}$, Q_{H_d}, Q_{H_u}: $Q_{H_d} = Q_{H_u} = -0.5$

$(Q_S = -Q_{H_d} - Q_{H_d} = 1)$

1-loop level: stop loop

$$m_{\tilde{q}} = m_{\tilde{t}_R} = 1.5 \text{ TeV}, \; A_t = m_{\tilde{q}} + |\mu_{\text{eff}}|/\tan\beta, \; (\mu_{\text{eff}} = \lambda v_S/\sqrt{2}).$$

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Input parameters

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Input parameters

tree level: λ, A_λ, $\tan\beta$, v_S, Q_{H_d}, Q_{H_u}

$\lambda \downarrow$ $m_{H_1} = 126$ GeV

$A_\lambda \downarrow$ $m_{H^\pm} = 550$ GeV

$\tan\beta \downarrow$ $\sqrt{\frac{Q_{H_d}}{Q_{H_u}}} = 1$

$v_S \downarrow$ $m_{Z'}$

$Q_{H_d} = Q_{H_u} = -0.5$

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Electroweak phase transition

Effective potential:

$$V_{\rm eff}(\varphi_d, \varphi_u, \varphi_S; T) = V_0 + V_1 + V_1^T$$

$$V_1 = \sum_i \frac{c_i \bar{m}_i^4}{64\pi^2}\left(\ln\frac{\bar{m}_i^2}{\bar{\mu}^2} - \frac{3}{2}\right),$$

$$V_1^T = \frac{T^4}{2\pi^2}\left[\sum_{i=\text{bosons}} c_i I_B\left(\frac{\bar{m}_i^2}{T^2}\right) + \sum_{i=\text{fermions}} c_i I_F\left(\frac{\bar{m}_i^2}{T^2}\right)\right],$$

$$I_{B,F}(a^2) = \int_0^\infty dx\ x^2 \ln\left(1 \mp e^{-\sqrt{x^2+a^2}}\right).$$

- ❒ gauge bosons, top/bottom, stop/sbottom loops are taken into account.
- ❒ T_C and Higgs VEVs at T_C are determined by $V_{\rm eff}$.

Sphaleron decoupling

After the EWPT, the sphaleron process has to be decoupled.

B-changing rate in the broken phase < Hubble constant

$$\Gamma_B^{(b)}(T) \simeq (\text{prefactor})e^{-E_{\rm sph}/T} < H(T) \simeq 1.66\sqrt{g_*}T^2/m_{\rm P}$$

g_* massless dof, 106.75 (SM) $m_{\rm P}$ Planck mass ≃ 1.22×10^{19} GeV

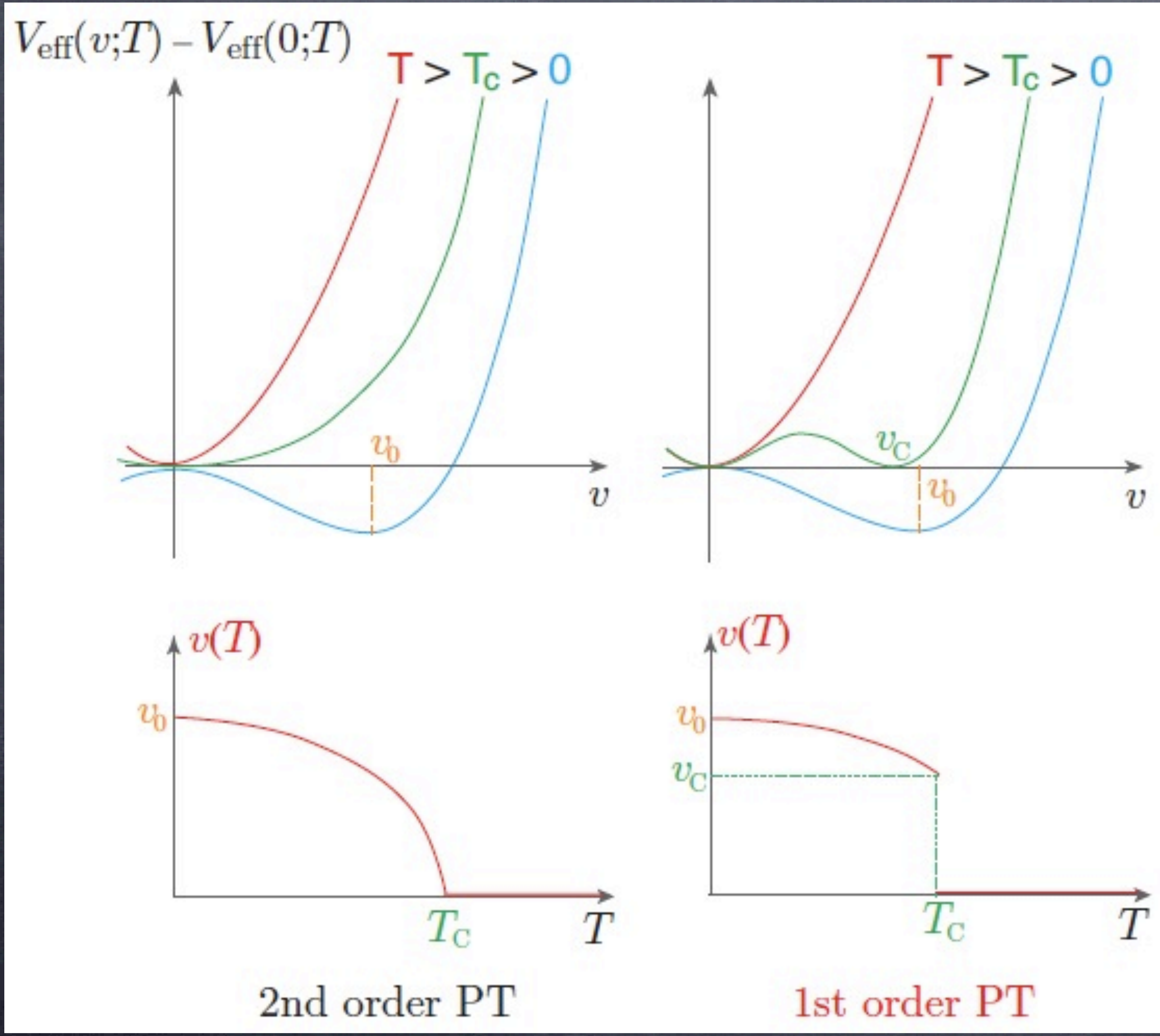
$E_{\rm sph} = 4\pi v\mathcal{E}/g_2$ (g_2: SU(2) gauge coupling),

$$\frac{v}{T} > \frac{g_2}{4\pi\mathcal{E}}\left[42.97 + \text{log corrections}\right] \equiv \zeta_{\rm sph}$$

- sphaleron energy gives the dominant effect.
- log corrections are subleading. (typically 10% correction)

1^{st} and 2^{nd} order EWPTs

This is what the 1^{st}- and 2^{nd}-order PTs look like.



[From K. Funakubo's slide]

❒ order parameter = Higgs VEV

❒ EWBG requires "1^{st}-order" PT

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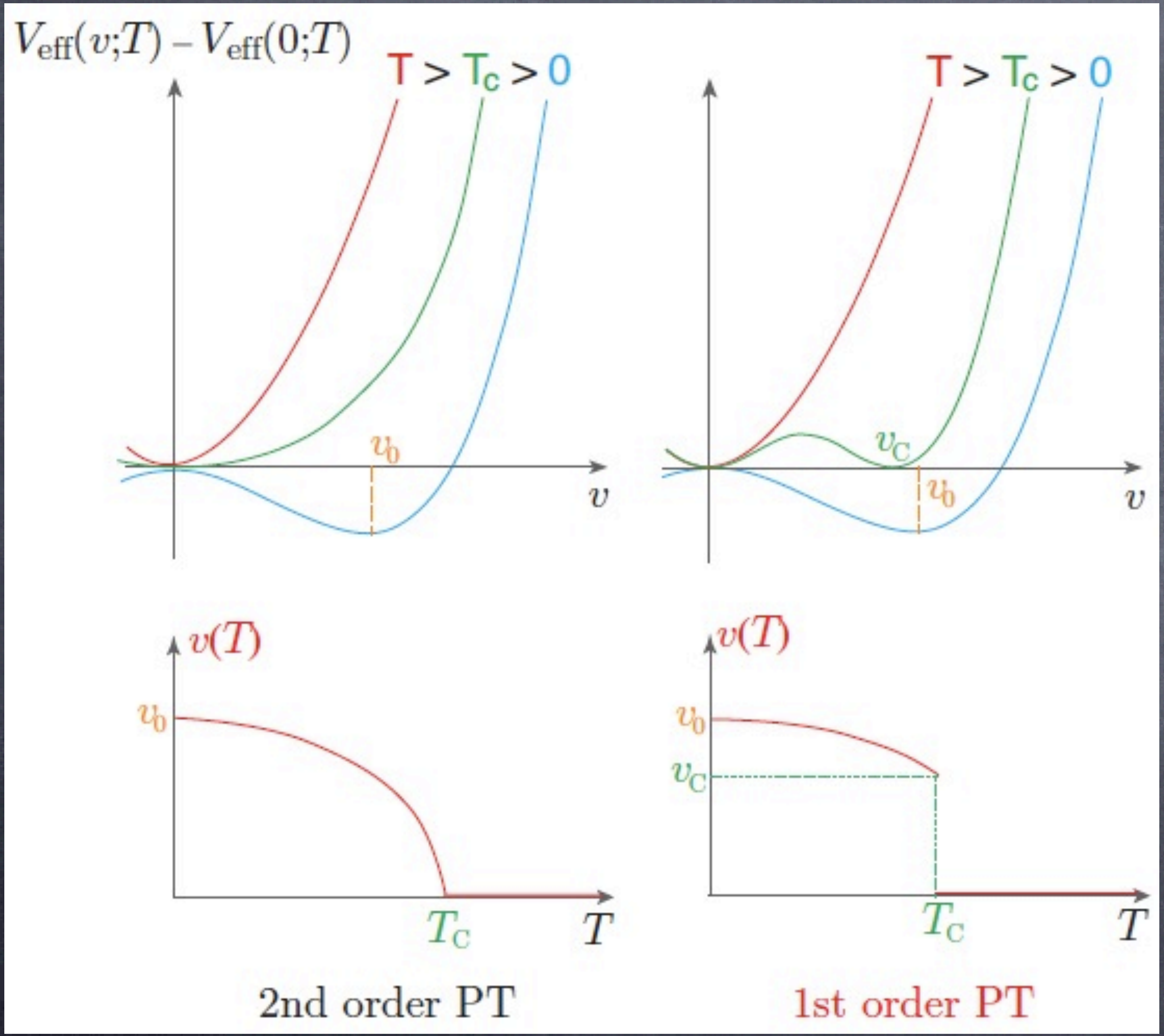

[From K. Funakubo's slide]

- ❒ order parameter = Higgs VEV
- ❒ EWBG requires "1^{st}-order" PT
- ❒ A negative contributions is necessary.

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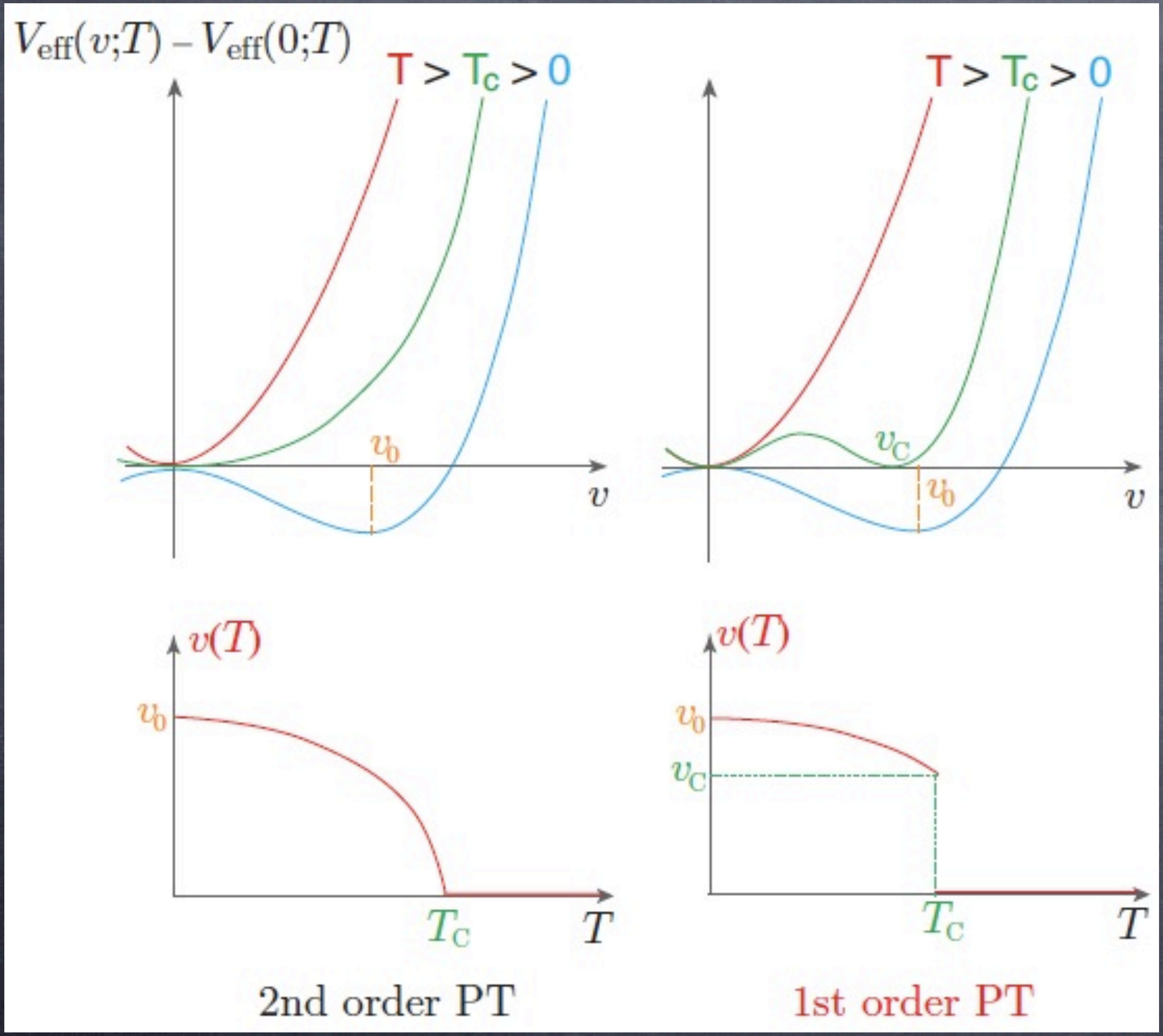

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e.g.

Bosonic thermal loop

$$V_1^{(\mathrm{boson})} \ni -|\mathrm{const}| \cdot |m(v)|^3 T$$

1^{st}-order EWPT

Let us consider the $g_1'=0$ case,

$$V_{\rm eff}(\varphi;T)=\frac{1}{2}M^2(T)\varphi^2+\frac{1}{2}m_S^2\varphi_S^2-\tilde{R}_\lambda\varphi^2\varphi_S+\frac{|\lambda|^2}{4}\varphi^2\varphi_S^2+\frac{\tilde{\lambda}^2}{4}\varphi^4,$$

where

$$M^2(T)=m_1^2\cos^2\beta+m_2^2\sin^2\beta+\mathcal{G}T^2,$$

$$\tilde{R}_\lambda=R_\lambda\sin\beta\cos\beta,\quad \tilde{\lambda}^2=\frac{g_2^2+g_1^2}{8}\cos^2 2\beta+\frac{|\lambda|^2}{4}\sin^2 2\beta,$$

After eliminating φ_S using the minimization condition w.r.t. φ_S, one gets

$$V_{\rm eff}(\varphi;T)=\frac{1}{2}M^2(T)\varphi^2-\frac{\tilde{R}_\lambda^2\varphi^4}{2(m_S^2+|\lambda|^2\varphi^2/2)}+\frac{\tilde{\lambda}^2}{4}\varphi^4$$

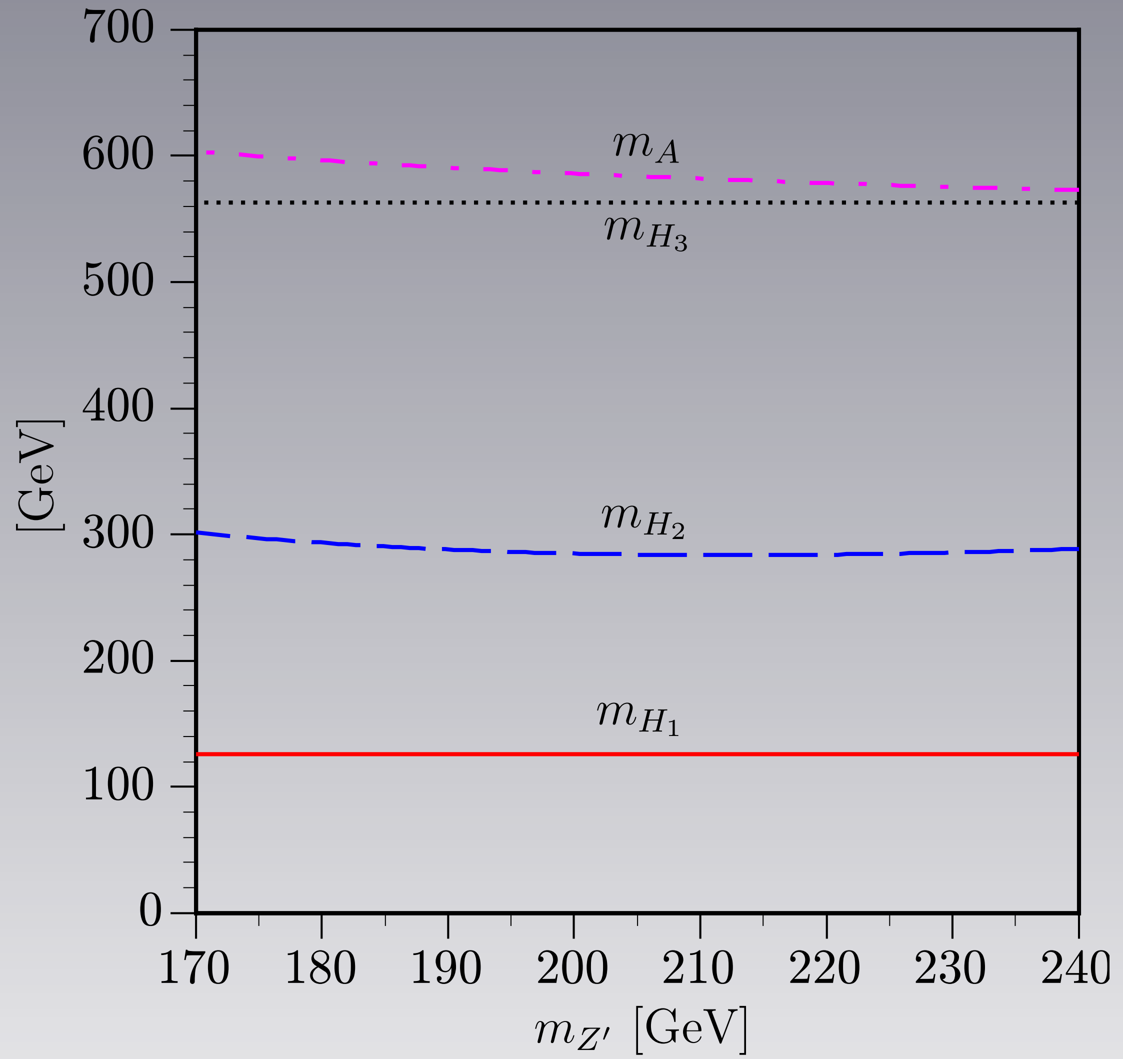
$$\simeq\frac{1}{2}M^2(T)\varphi^2+\frac{1}{4}\left(\tilde{\lambda}^2-\frac{2\tilde{R}_\lambda^2}{m_S^2}\right)\varphi^4+\frac{|\lambda|^2\tilde{R}_\lambda^2}{4m_S^4}\varphi^6.$$

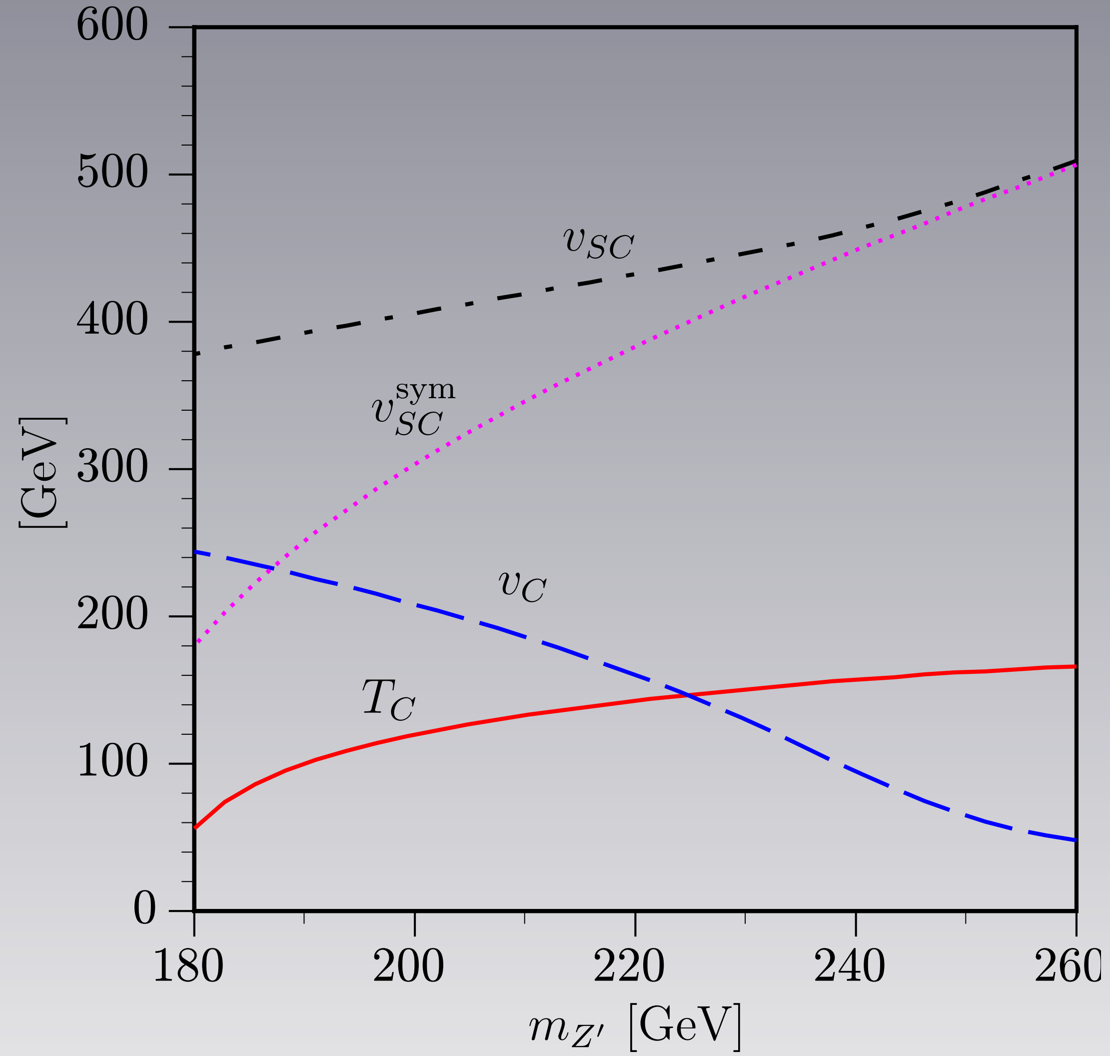
1^{st}-order PT may be realized if $\tilde{\lambda}<\sqrt{\frac{2}{m_S^2}}|\tilde{R}_\lambda|$ $v_C/T_C\nearrow$ if $A_\lambda\nearrow$ and/or $v_S\searrow$

T_C and Higgs VEVs

T_C: T at which V_{eff} has degenerate minima.

$$v_C = \lim_{T\uparrow T_C}\sqrt{v_d^2(T_C)+v_u^2(T_C)},\quad v_{SC} = \lim_{T\uparrow T_C} v_S(T_C),\quad v_{SC}^{\text{sym}} = \lim_{T\downarrow T_C} v_S(T_C).$$





- ❒ In the light Z′ (small v_S) region, the EWPT can be strong 1st order due to the doublet-singlet Higgs mixing effects.
- ❒ Such a Z′ must be leptophobic to be phenomenologically viable.

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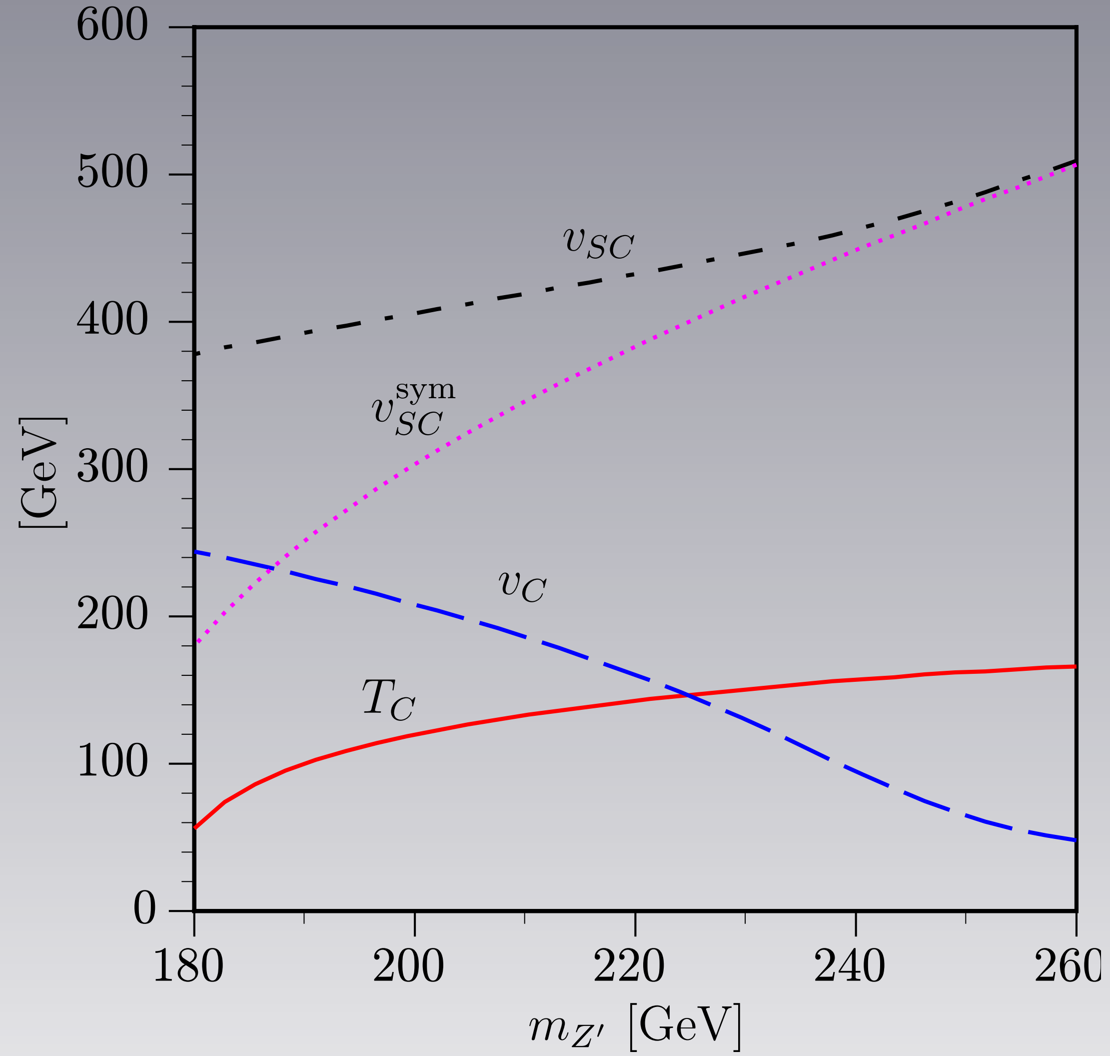

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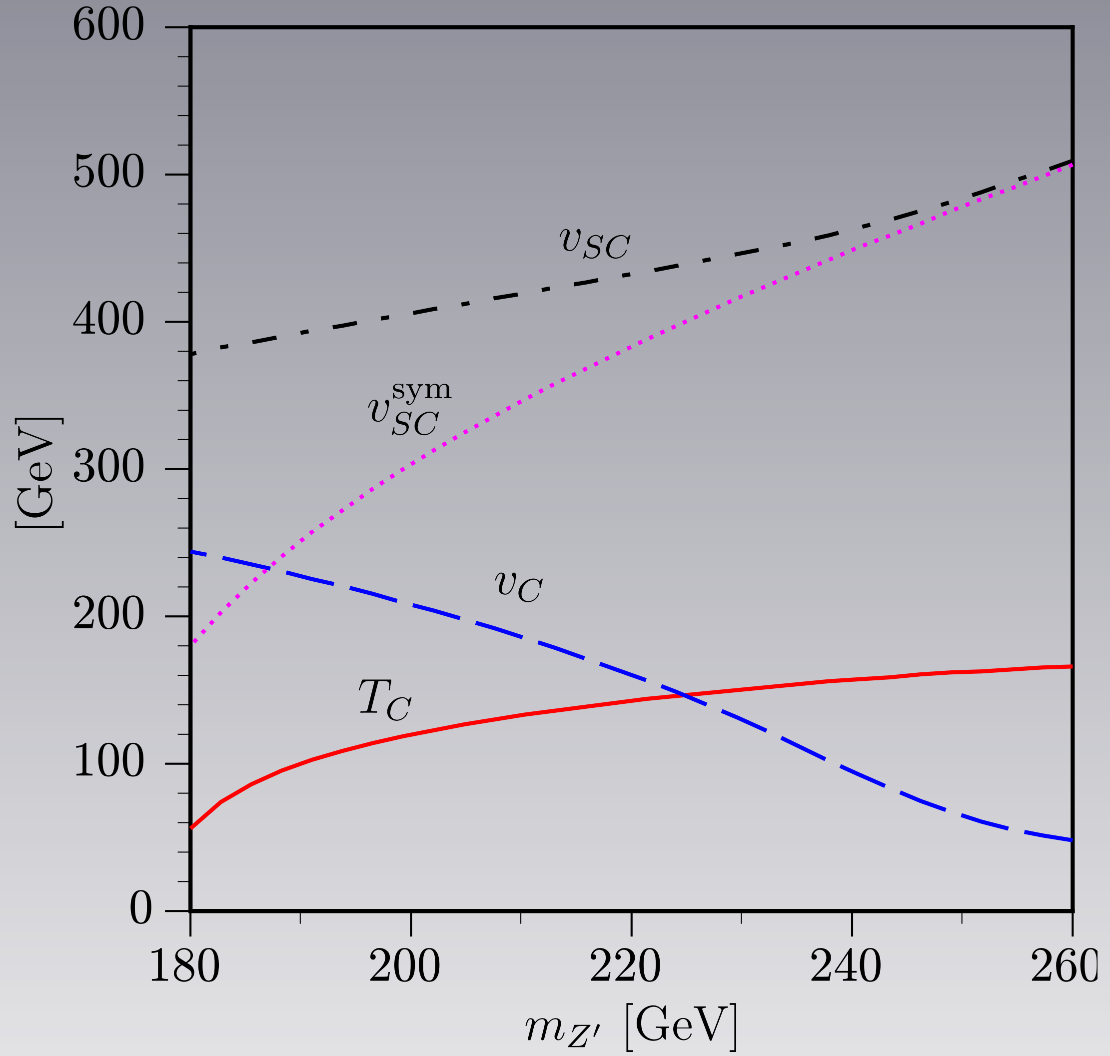

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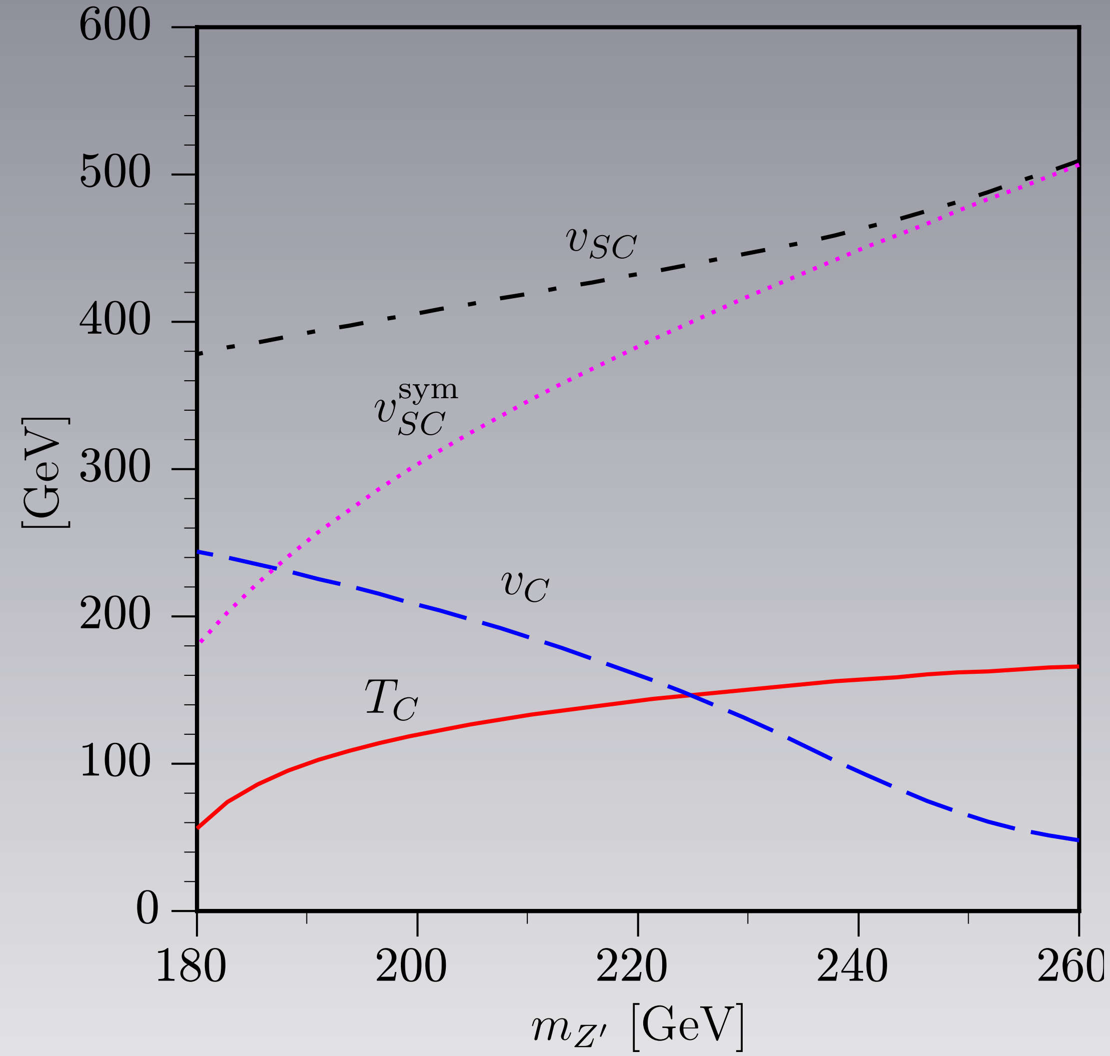

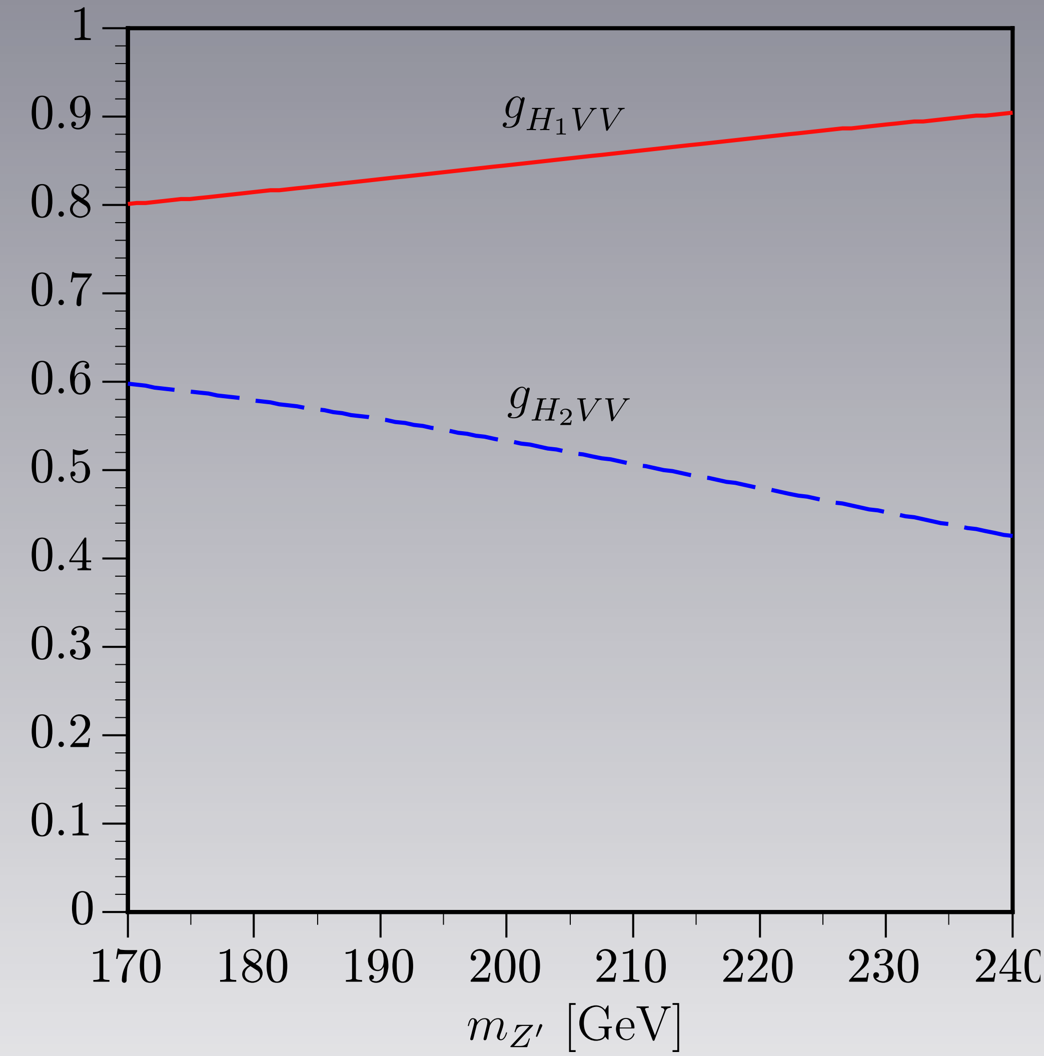

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Experimental constraints on light leptophobic Z′

- Electroweak precision tests (see e.g. Umeda,Cho,Hagiwara, PRD58 (1998) 115008)
-> In our case, no constraint since Z-Z′ mixing is assumed to be small.
- All dijet-mass searches at Tevatron/LHC are limited to M_{jj}>200 GeV.
- Z′ boson (<200 GeV) is constrained by the UA2 experiment.

UA2 bounds on $m_{Z'}$

UA2 Collaborations,NPB400: (1993) 3

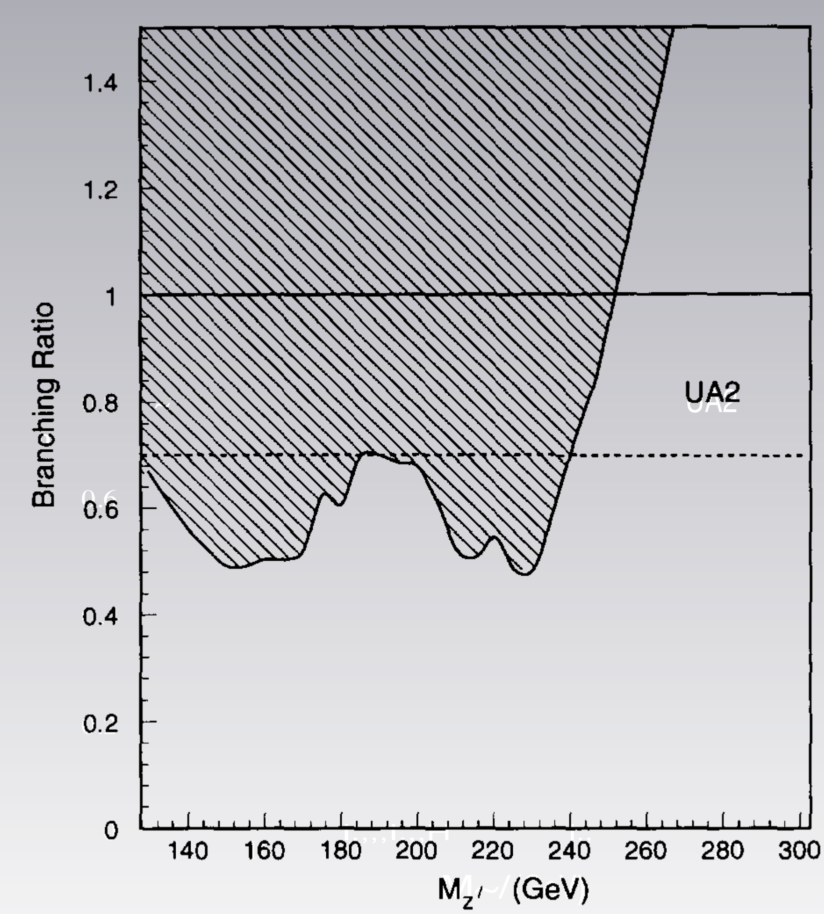
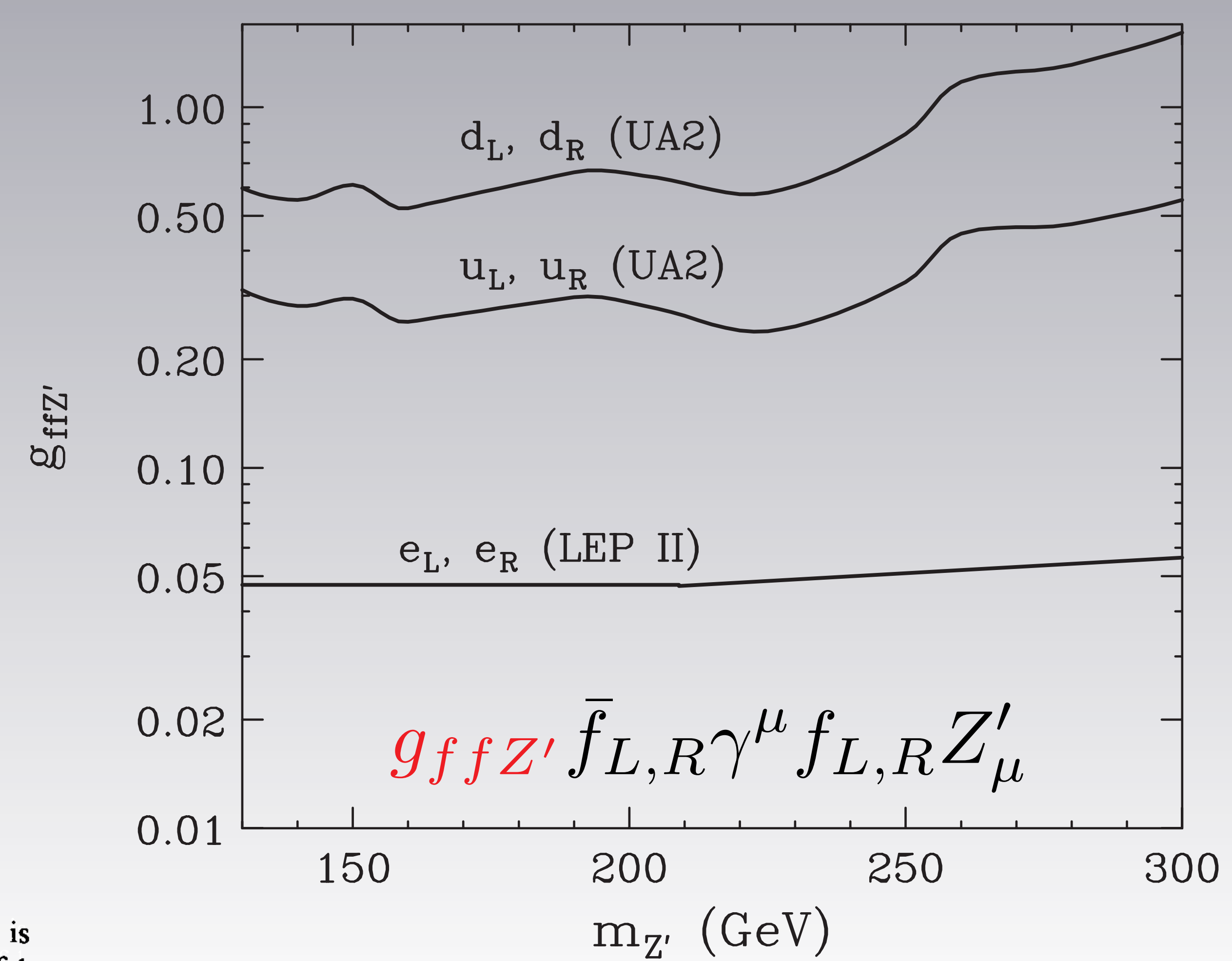


Fig. 5. Excluded region to 90% for Z′ → q̄q, (excluded region is hatched). The branching ratio is given as a fraction of standard model branching ratio. The solid line shows a branching ratio of 1 for Z′ → q̄q whilst the dashed line shows a branching ratio of 0.7.

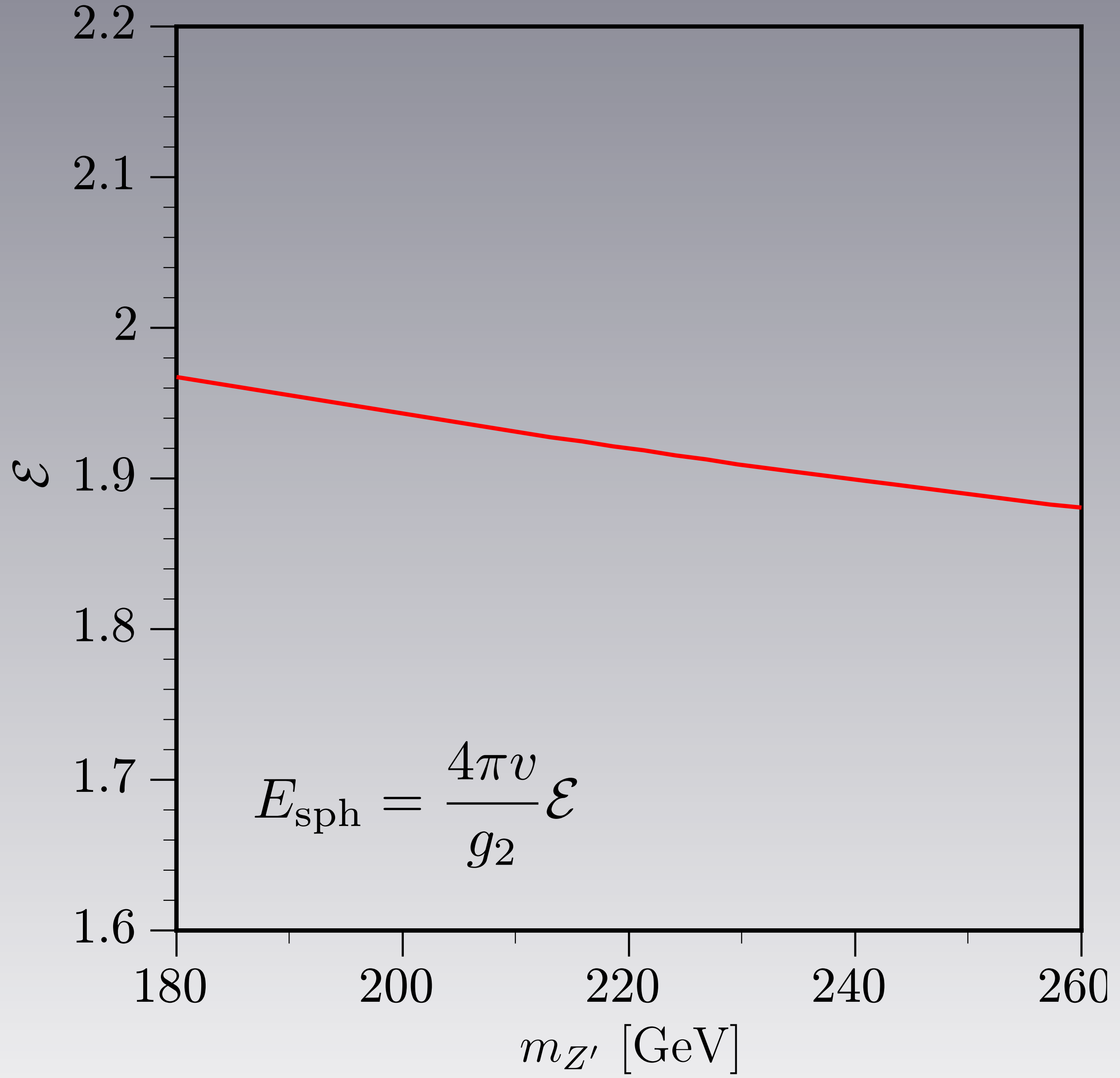
M. Buckley et al,PRD83:115013 (2011)



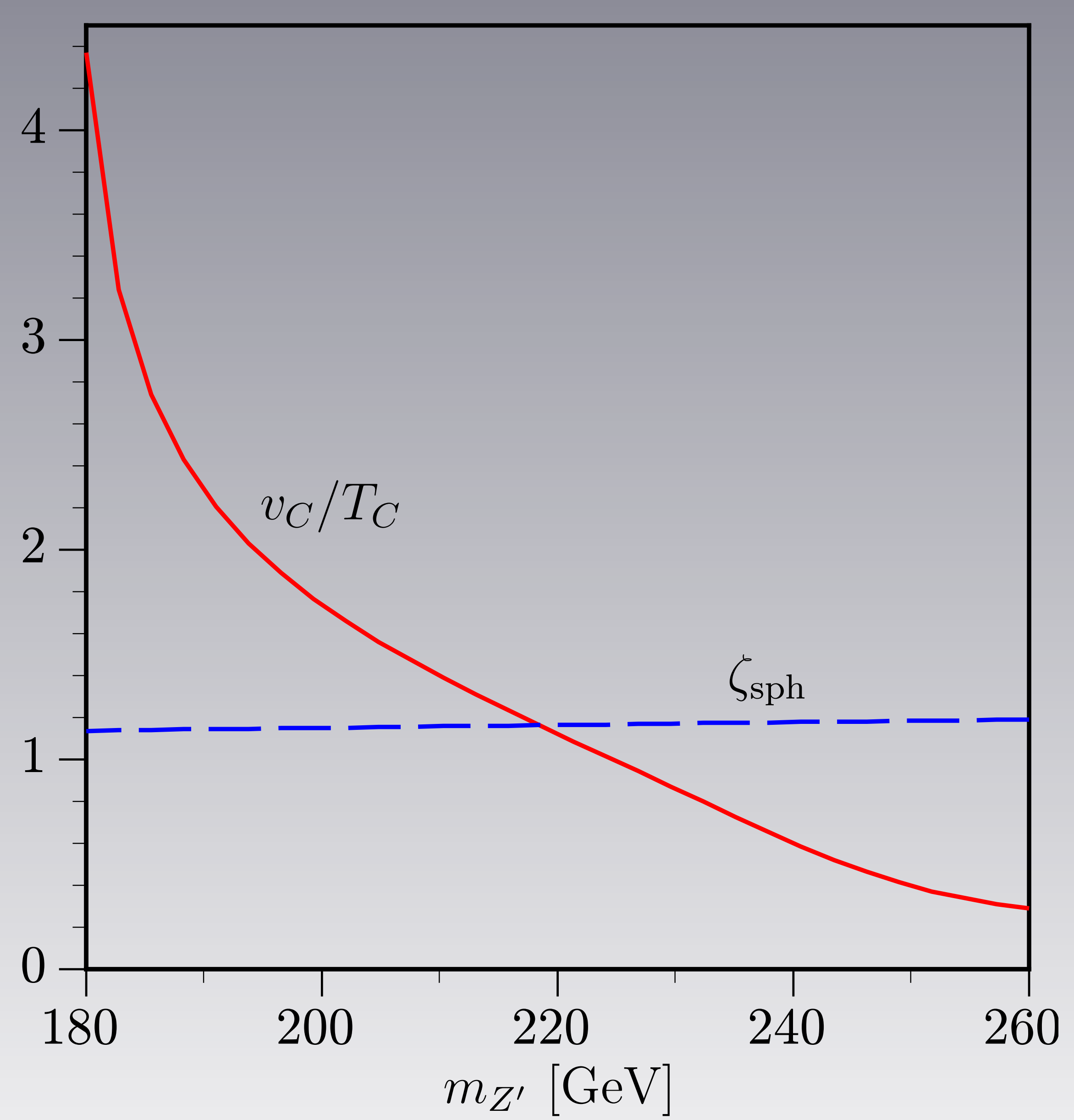
Sphaleron decoupling

For simplicity, we evaluate sphaleron energy at T=0.
Also, $U(1)_Y$ and $U(1)'$ contributions are neglected.

sphaleron energy

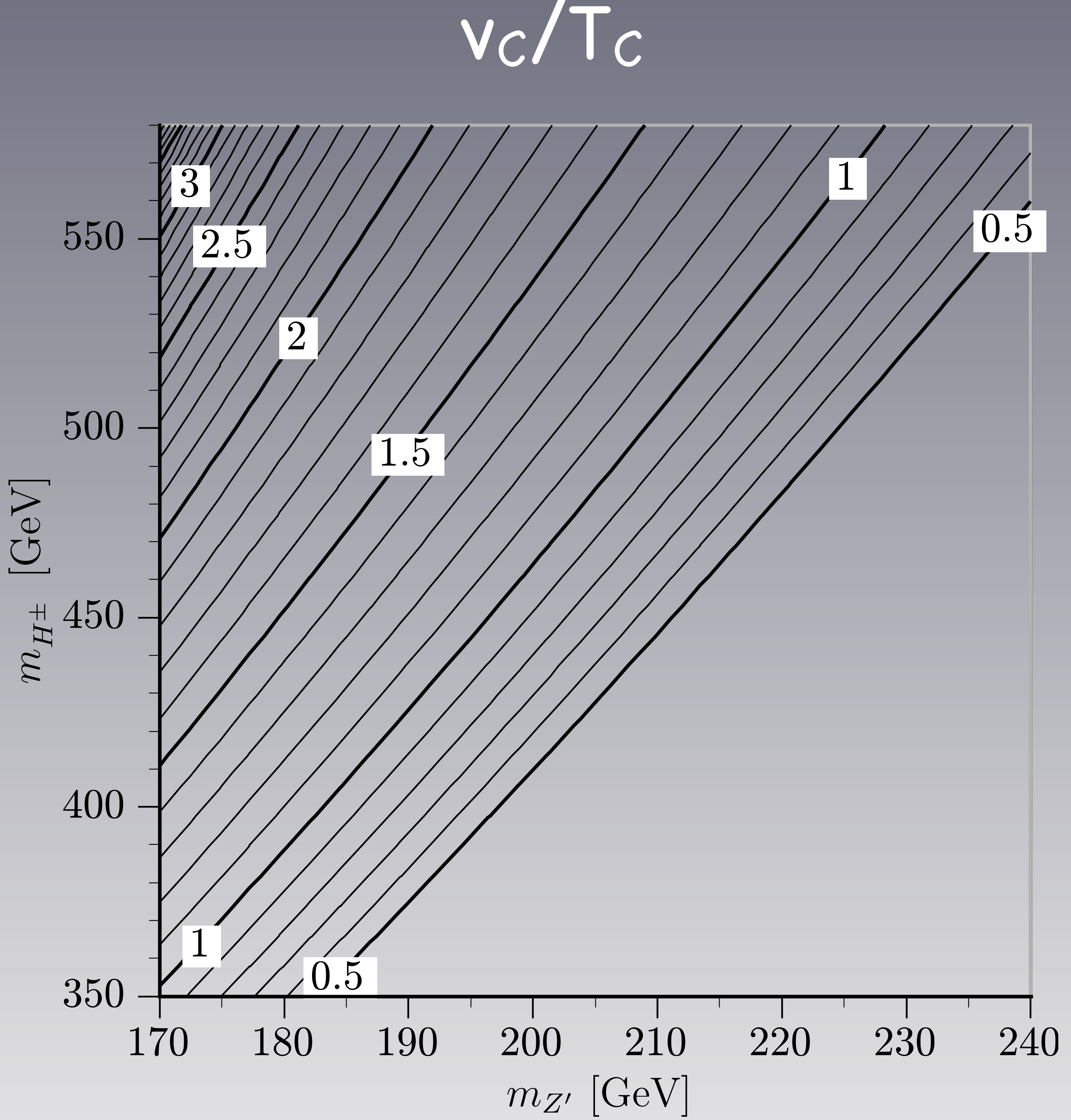


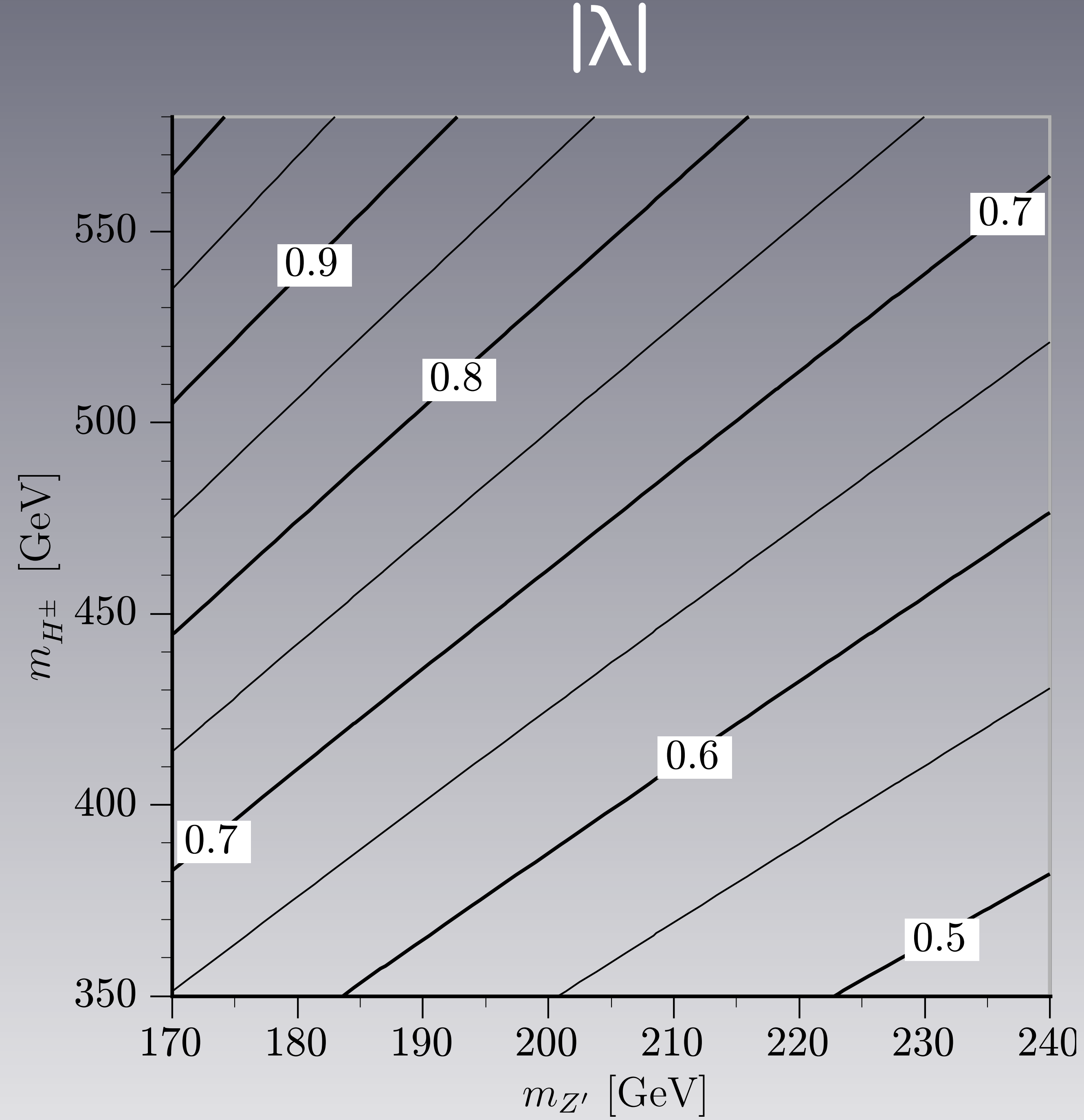
v_C/T_C vs. ζ_{sph}



❒ sphaleron decoupling condition is satisfied for $m_{Z'} \lesssim 220$ GeV.

Scan analysis





- Smaller $m_{H^\pm}$ ($|A_\lambda|$) gives weaker v_C/T_C.
- Strong 1st-order EWPT requires relatively large $|\lambda|$.

BAU

Under the reasonable assumptions, one may get

$$n_B = \frac{3}{2}\Gamma_B^{(s)}\frac{S^{\rm CPV}}{\sqrt{\Gamma}}\frac{L_w\sqrt{\bar{D}}}{v_w^2}r_1$$

$\Gamma_B^{(s)}$: B-changing rate in the symmetric phase

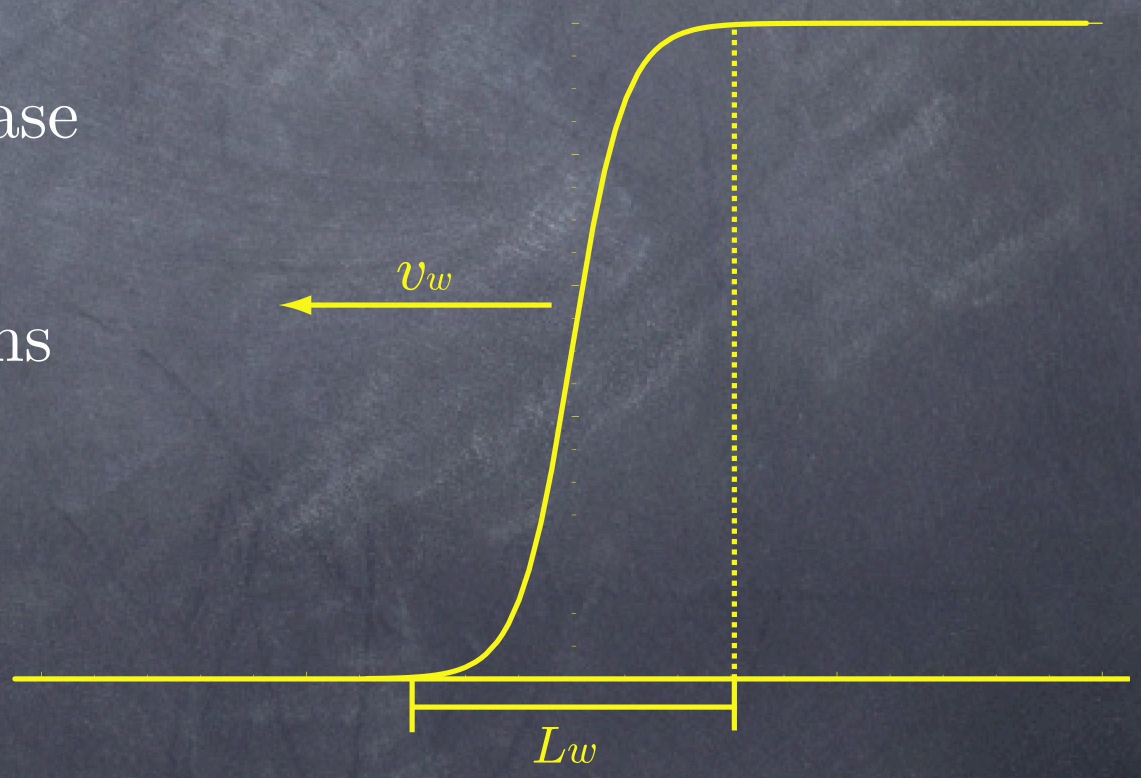
$S^{\rm CPV}$: CP-violating source terms

Γ : CP-conserving chirality changing terms

L_w : wall width

$\bar{D}$: diffusion constant

r_1 : numerical factor



Using the CTP formalism, we evaluate $S^{\rm CPV}$ and Γ

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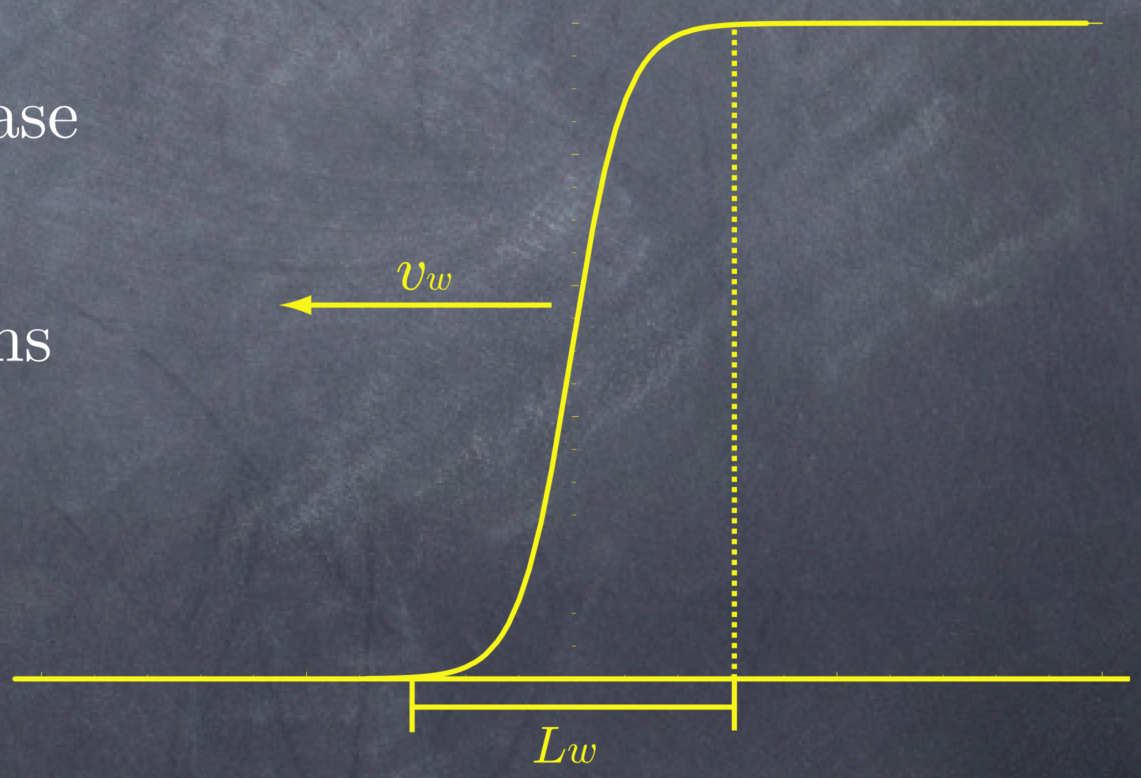
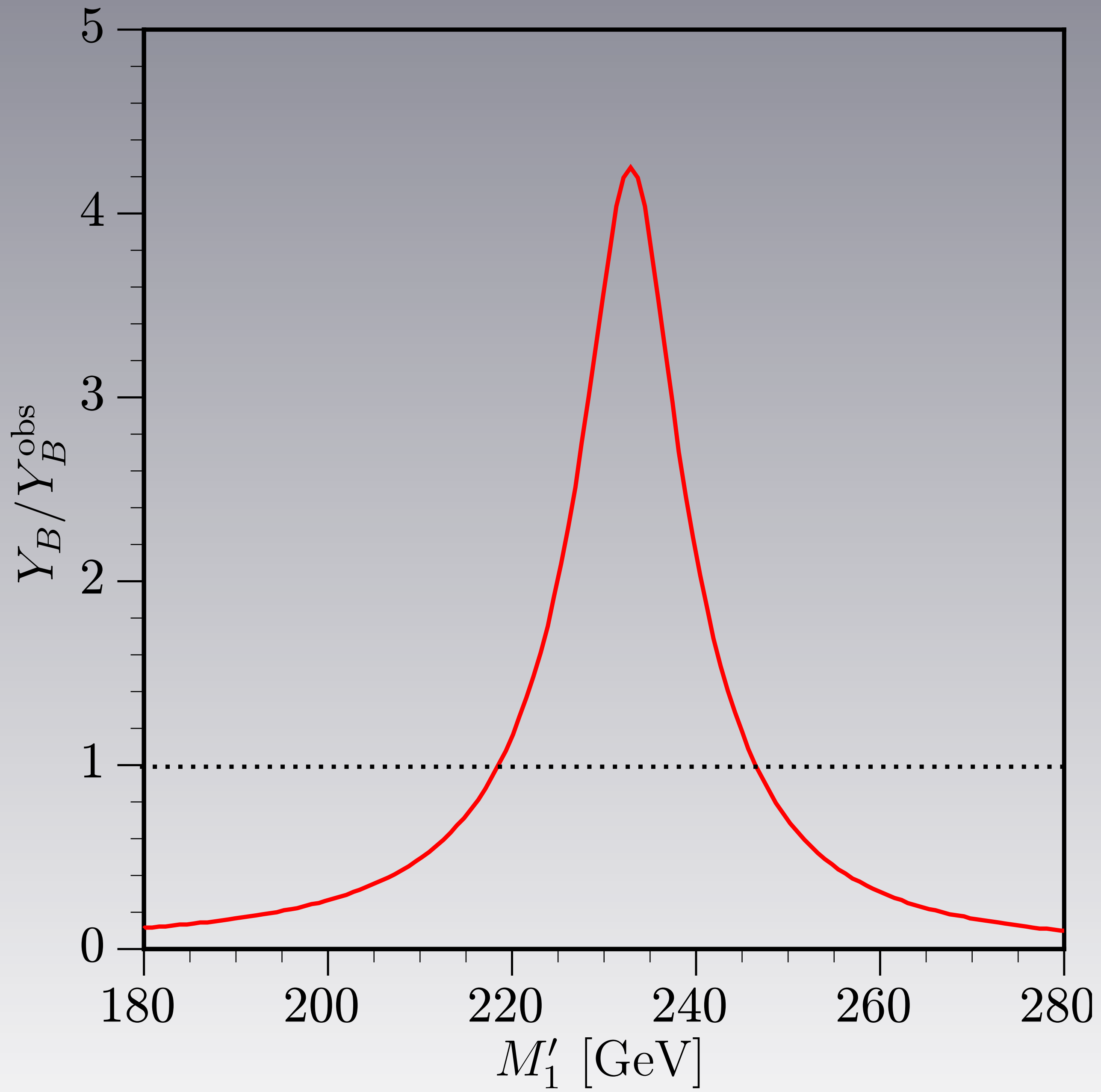


Using the CTP formalism, we evaluate S^{CPV} and Γ

Z′-ino driven EWBG

$\tan\beta = 1,\ m_{H_1} = 126$ GeV, $m_{H^\pm} = 550$ GeV, $m_{Z'} = 200$ GeV,
$Q_{H_d} = Q_{H_u} = -0.5,\ \delta_{M_1'} = \pi/2,\ \delta_\lambda = 0,\ \Delta\beta = 0.01,\ v_w = 0.4.$

$$Y_B = \frac{n_B}{s}$$



❒ If $M'_1 \simeq \mu_{\rm eff}$, BAU can be explained by the Z′-ino effect.

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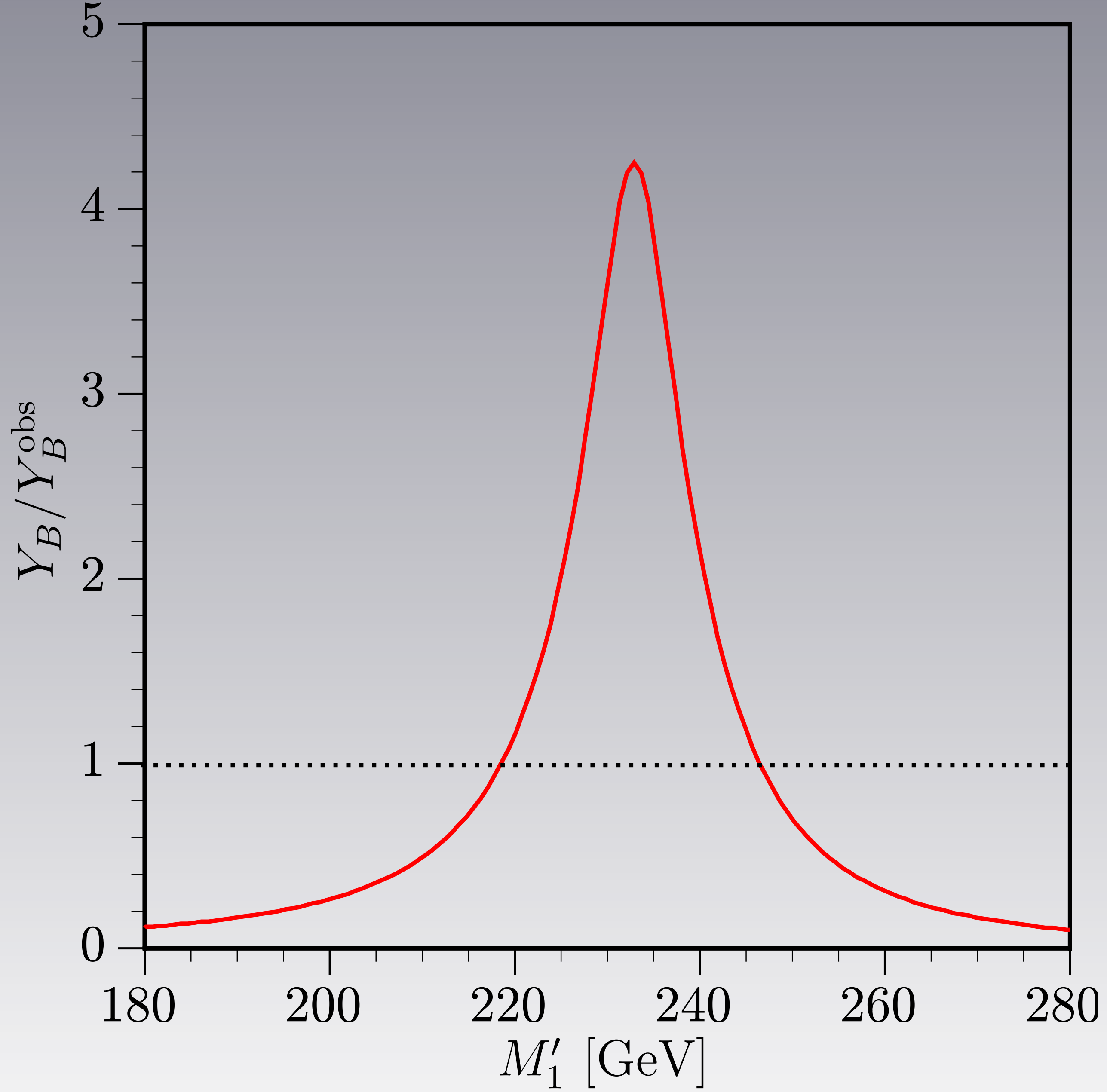

❒ If $M'_1 \simeq \mu_{\rm eff}$, BAU can be explained by the Z′-ino effect.

Summary

❒ We have revisited the possibility of EWBG in the UMSSM in light of m_h=126 GeV.

❒ Doublet-singlet Higgs mixings existing in the tree-level Higgs potential can induce the strong 1^{st}-order EWPT, which leads to

- reduction of the H_1VV coupling
- leptophobic light Z′ boson

❒ Sufficient BAU may be generated by the Z′-ino effects.

outlook

Next step is

- collider phenomenology
- precise knowledge of bubble wall profiles (wall velocity&width)