Electroweak baryogenesis as a probe of new physics

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Outline

- Introduction
- Overview of electroweak baryogenesis (EWBG)
- Current status
  - EWBG in SUSY models
  - EWBG in non-SUSY models
- Summary

Higgs and cosmology

❒ Higgs boson was discovered.

$$m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})\ \text{GeV}, \quad (\text{ATLAS})$$
$$m_H = 125.03 \pm 0.30 \left[{}^{+0.26}_{-0.27}(\text{stat}) {}^{+0.13}_{-0.15}(\text{syst}) \right]\ \text{GeV}, \quad (\text{CMS})$$

❒ What is the implication of Higgs physics for cosmology?

- cosmic baryon asymmetry $\Leftrightarrow$ EW baryogenesis
- dark matter $\Leftrightarrow$ inert Higgs, Higgs portal etc.
- inflation $\Leftrightarrow$ Higgs inflation.
- etc

We discuss EW baryogenesis in connection with Higgs physics.

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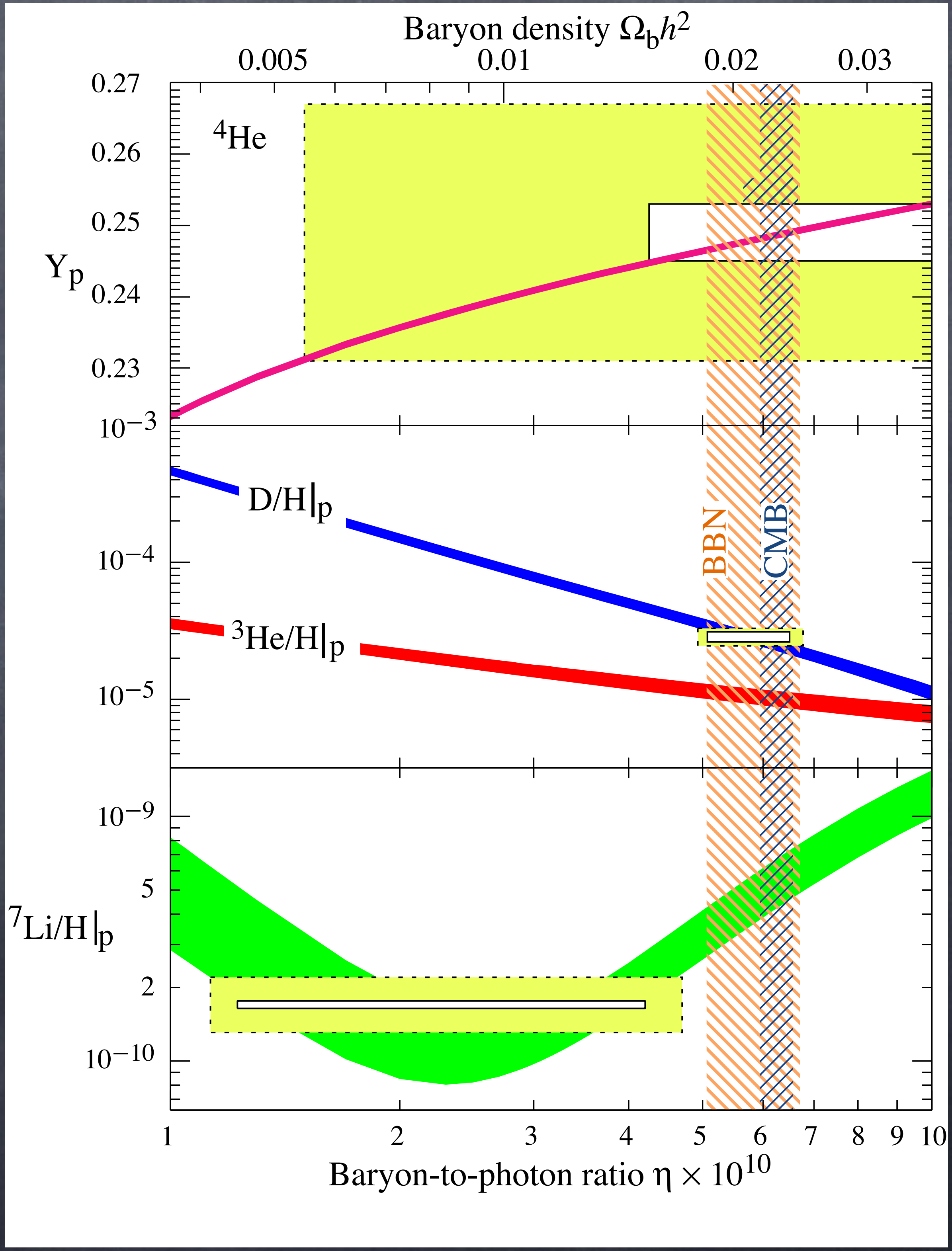
Baryon Asymmetry of the Universe (BAU)

❒ Our Universe is baryon-asymmetric.

$$\eta^{\rm CMB} = \frac{n_B}{n_\gamma} = 6.23(17) \times 10^{-10}, \quad [\rm CMB],$$
$$\eta^{\rm BBN} = \frac{n_B}{n_\gamma} = (5.1 - 6.5) \times 10^{-10}, \quad [\rm BBN].$$

❒ If the BAU is generated before T≃O(1) MeV, the light element abundances (D,^{3}He,^{4}He,^{7}Li) can be explained by the standard Big-Bang cosmology.



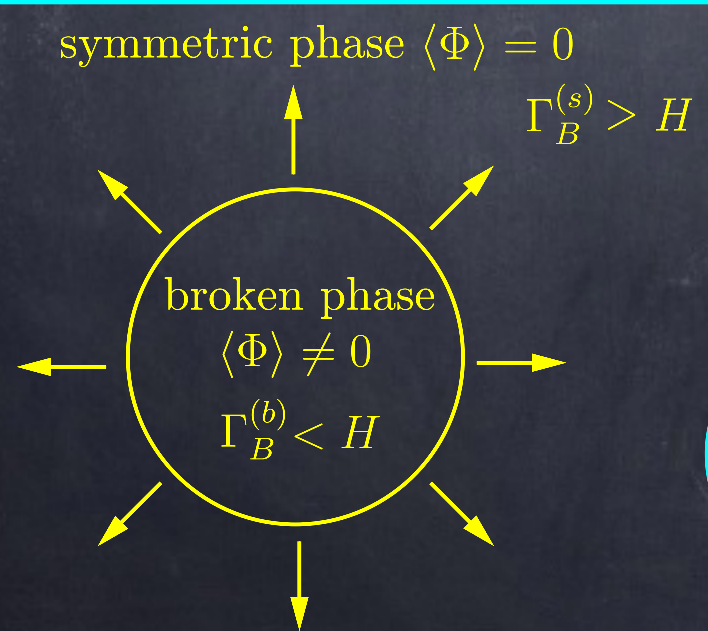
Baryogenesis = generate right η

Electroweak baryogenesis

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

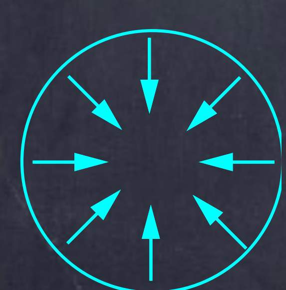
Sakharov's criteria

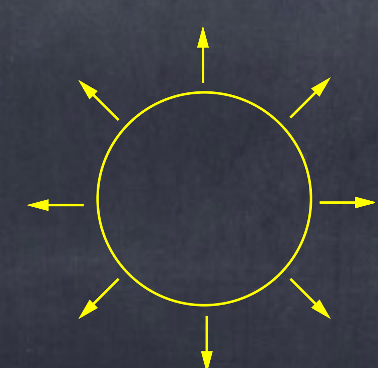
- B violation: anomalous process $0 \leftrightarrow \sum_{i=1,2,3} (3q_L^i + l_L^i)$ (LH fermions)
- C violation: chiral gauge interaction
- CP violation: Kobayashi-Maskawa (KM) phase and other complex phases in the beyond the SM
- Out of equilibrium: 1st-order EW phase transition (EWPT) with expanding bubble walls

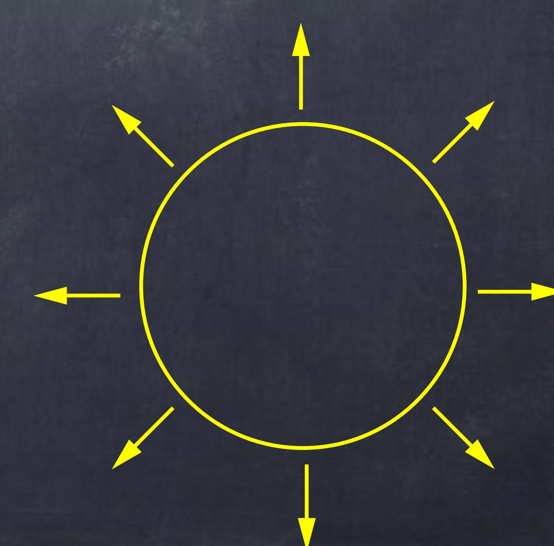


average bubble radius $\mathcal{O}(10^{-6})$ m

[Carrington, Kapusta, PRD47, ('93) 5304]

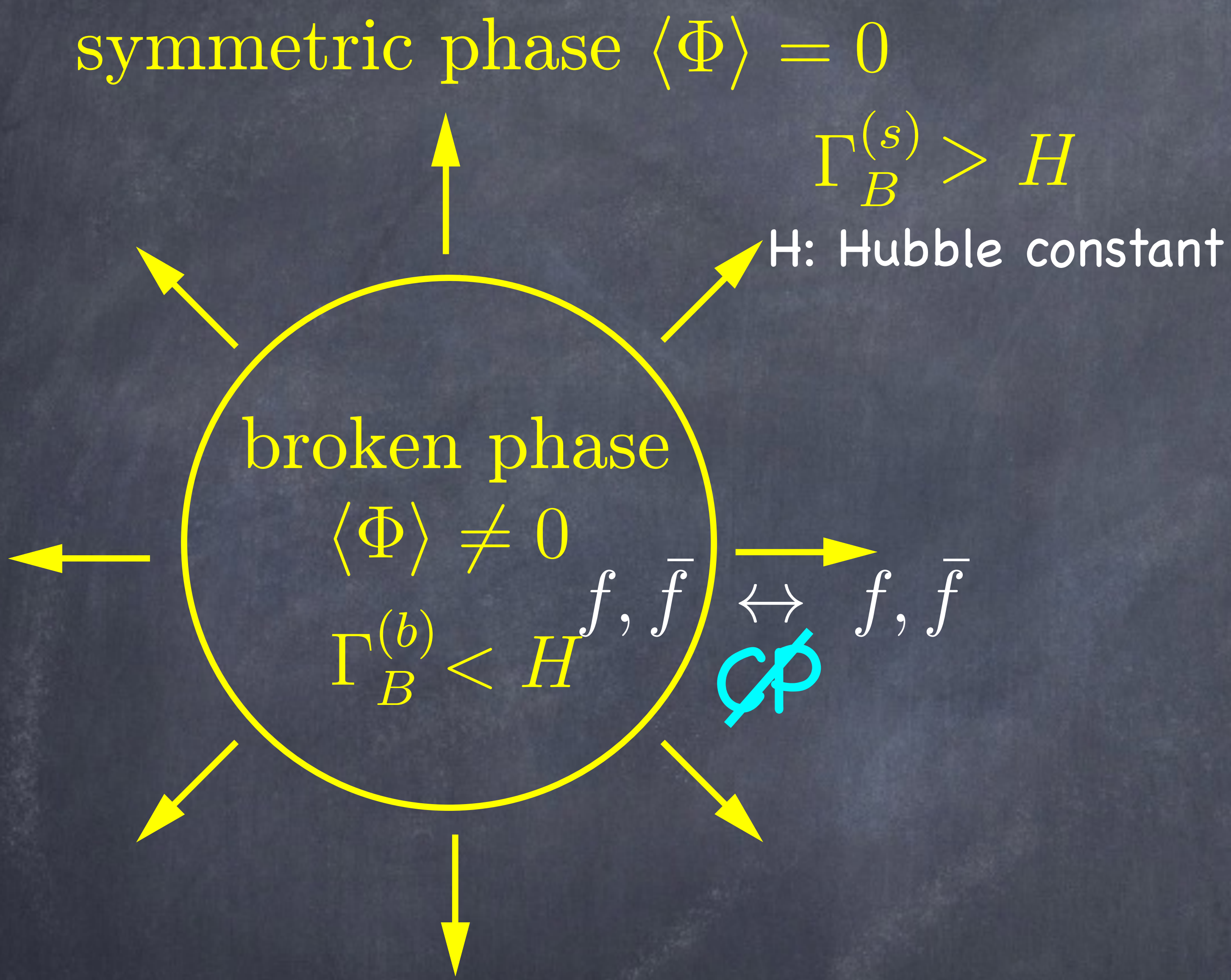






❒ BAU can arise by the growing bubbles.

EW Baryogenesis mechanism



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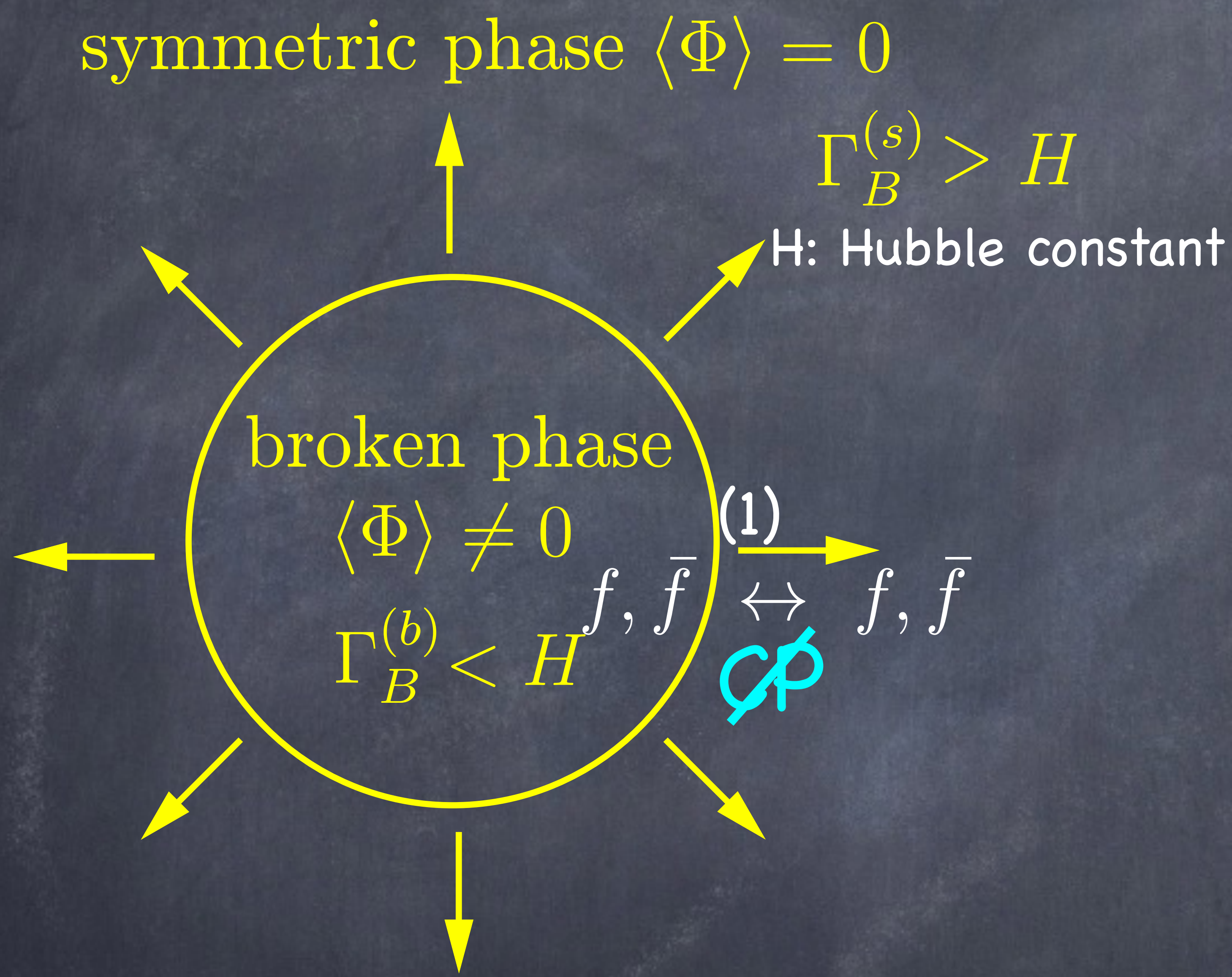

(1) Asymmetries arise (∵ CPV) but no BAU.

$$n_B = \underbrace{n_b^L - n_{\bar{b}}^L}_{\neq 0} + \underbrace{n_b^R - n_{\bar{b}}^R}_{\neq 0} = 0$$

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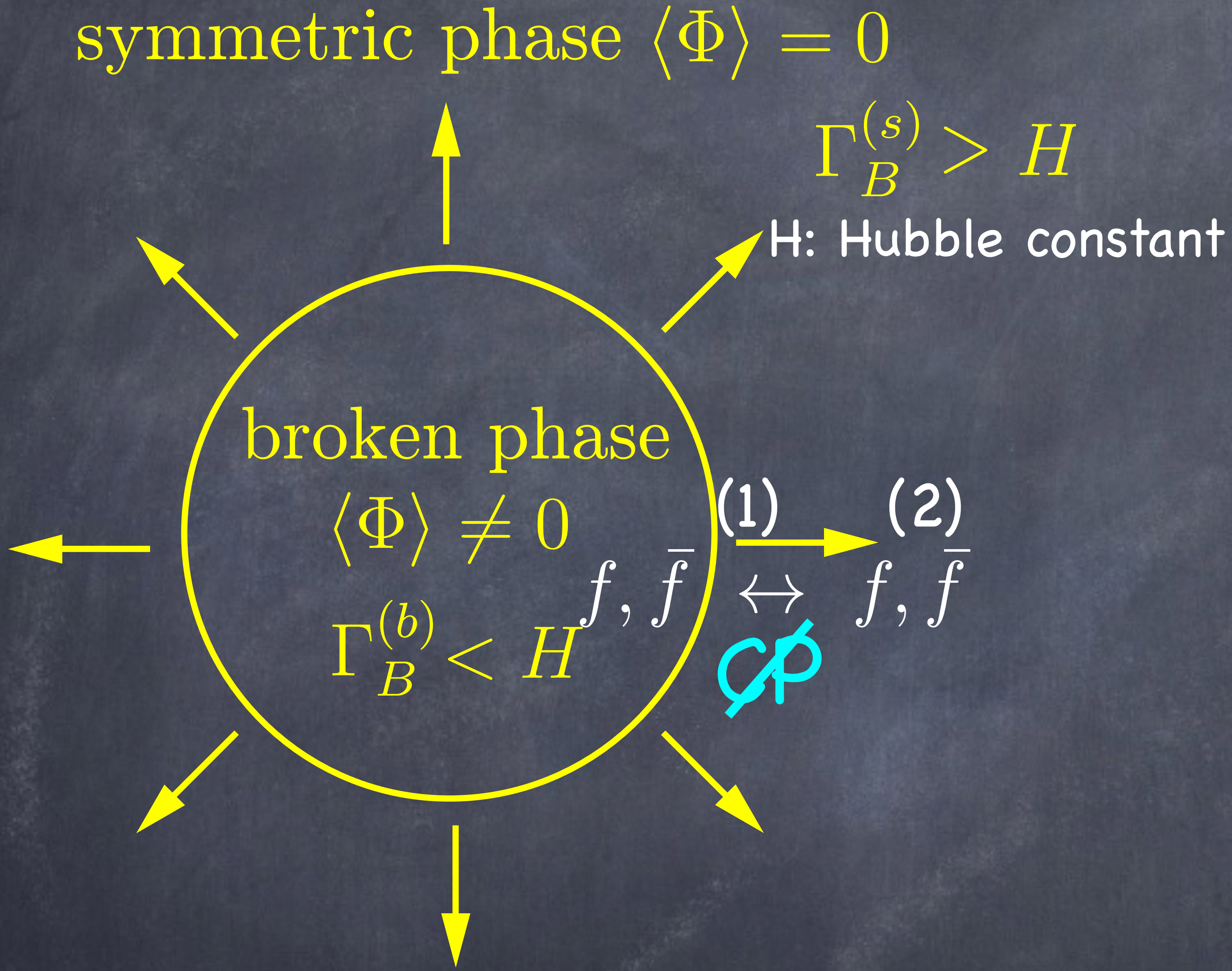

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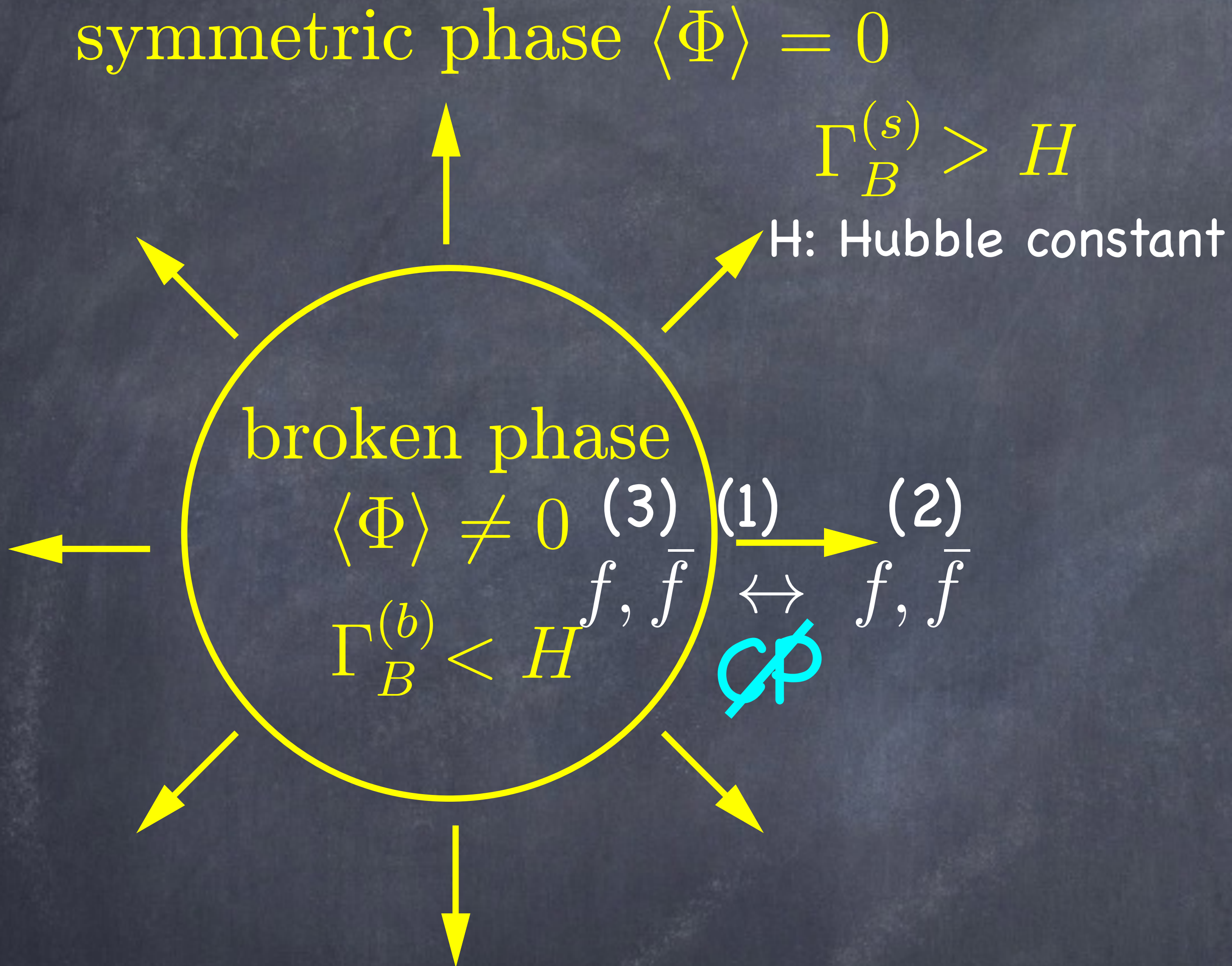

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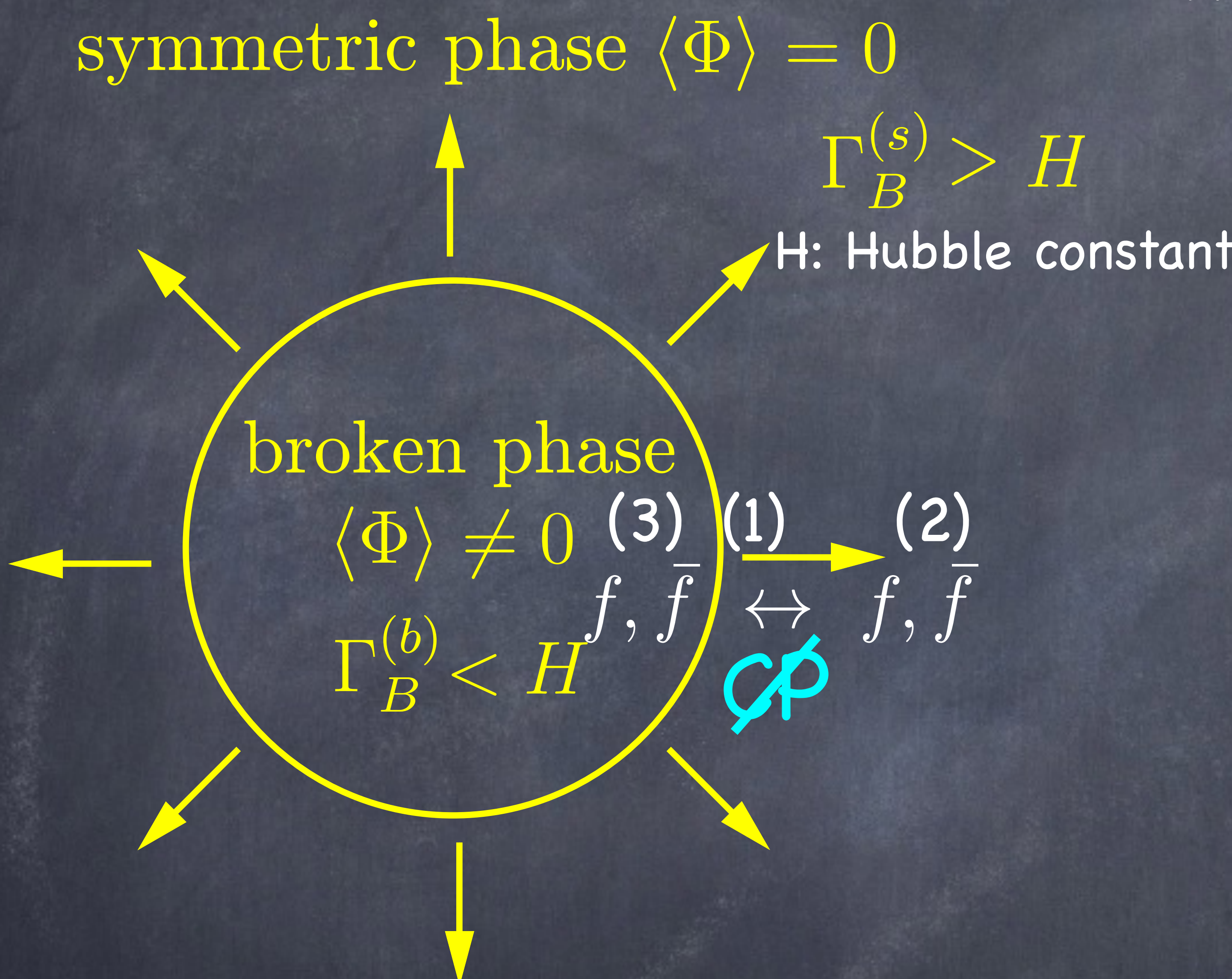

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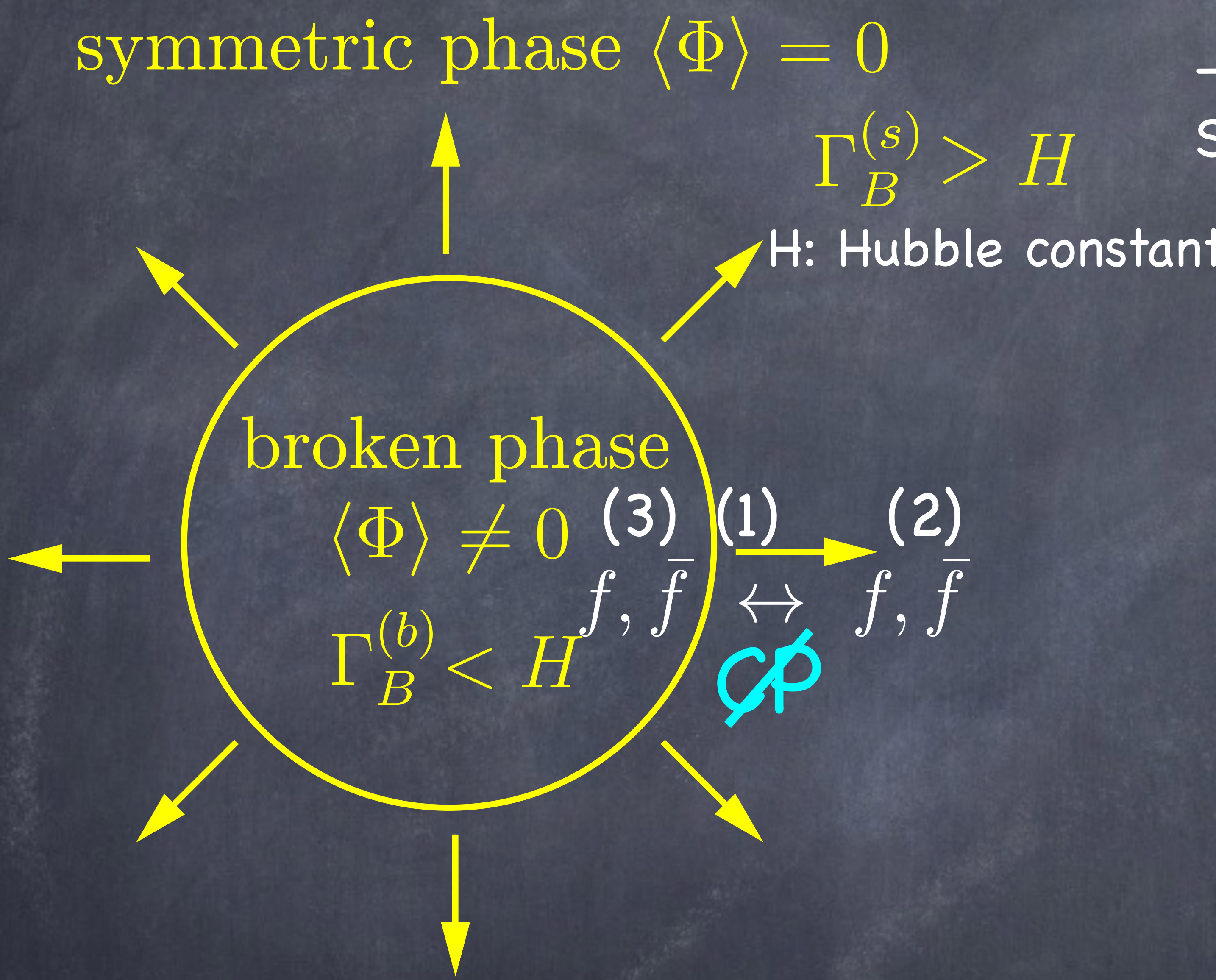

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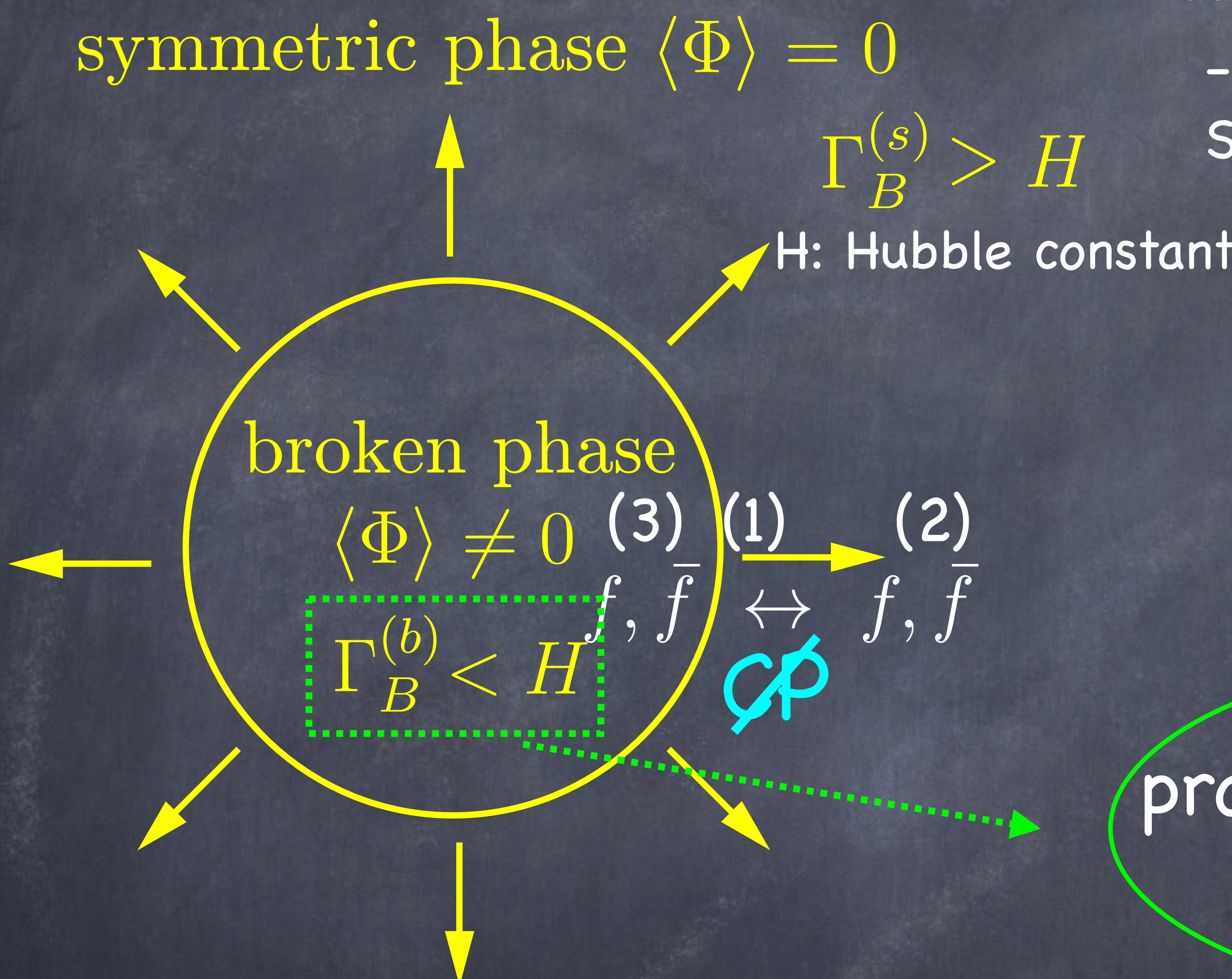

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Higgs physics etc

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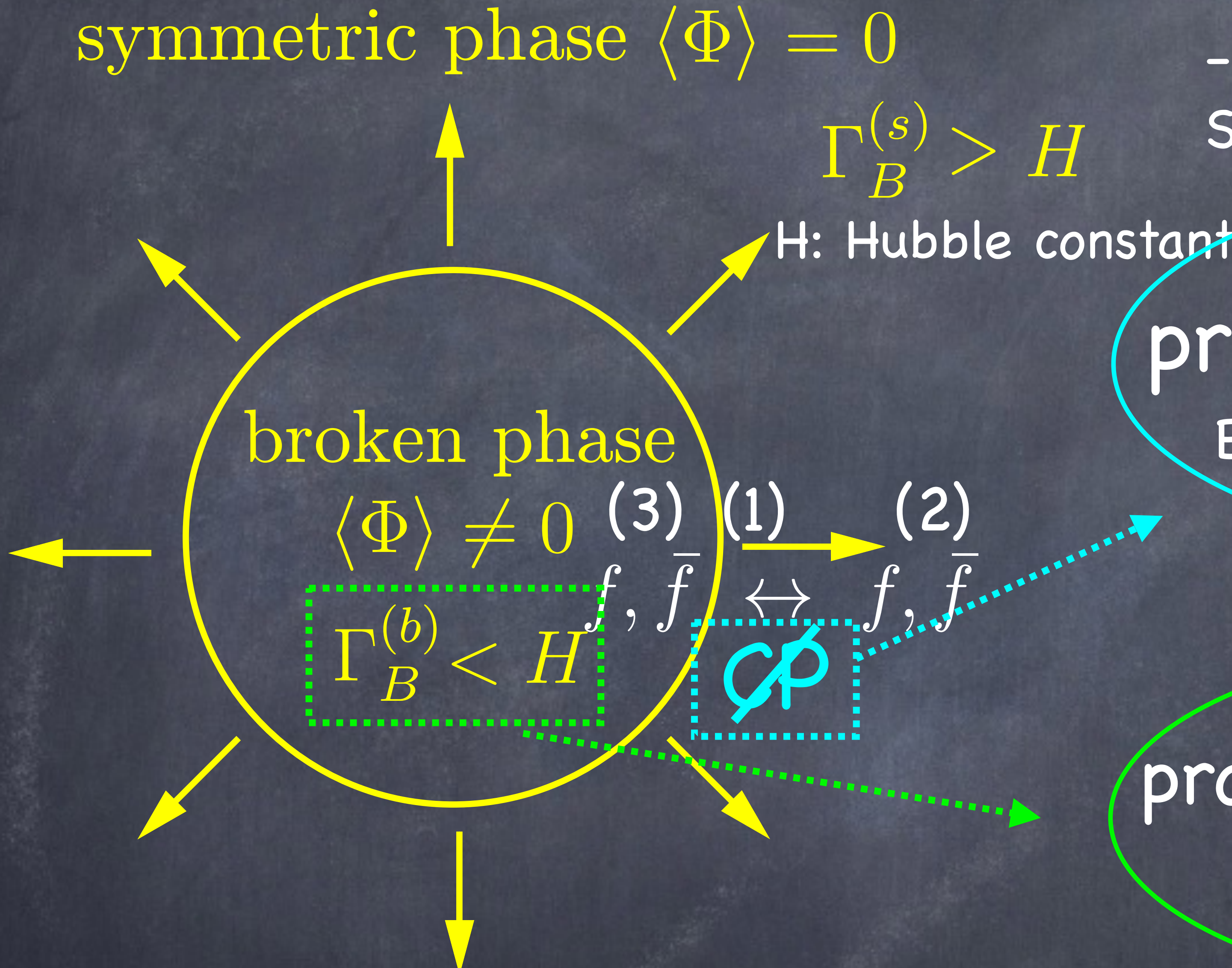

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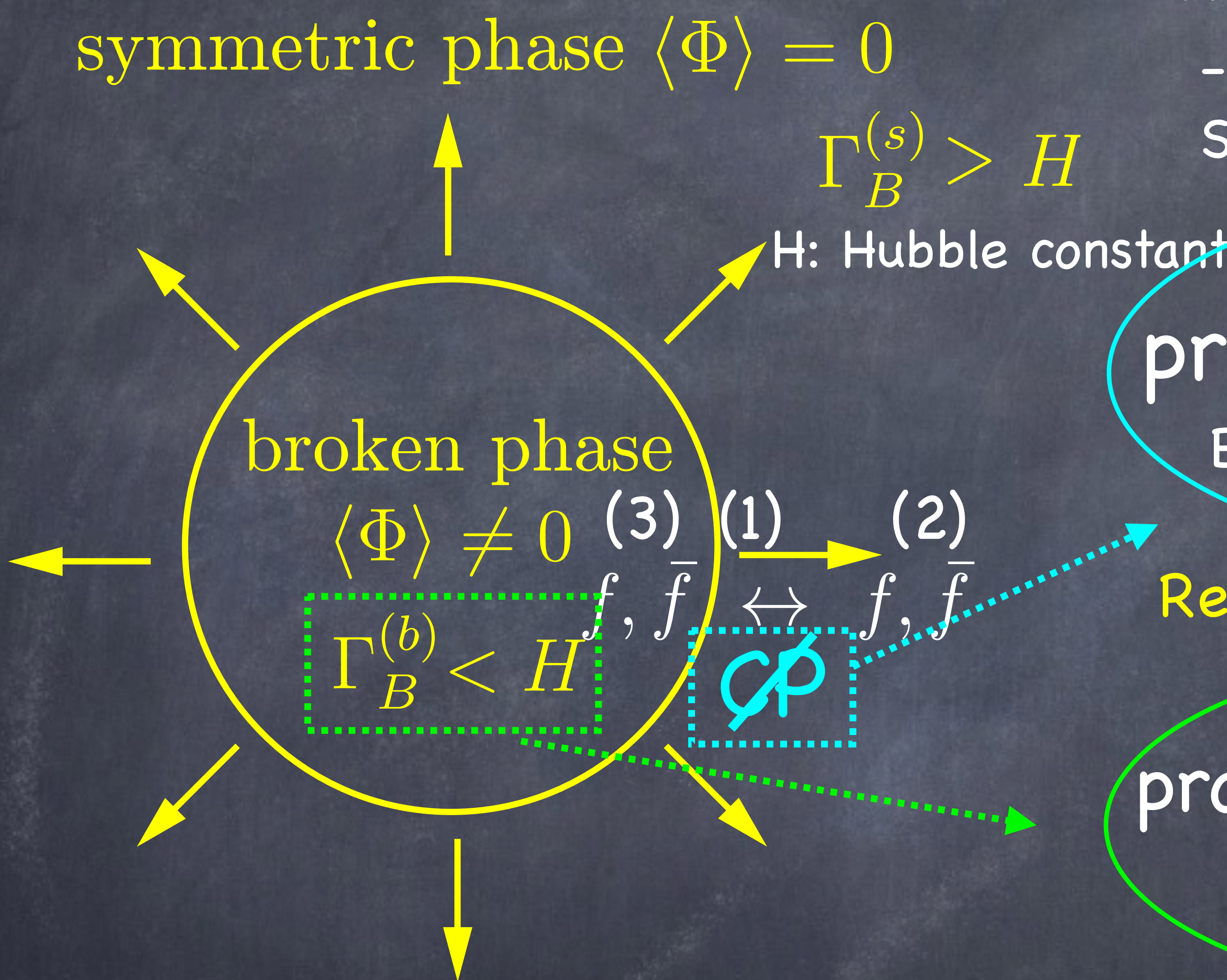

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probe by CPV physics

Electric Dipole Moment etc

Relevant particles are light (<1TeV)

probe by collider physics

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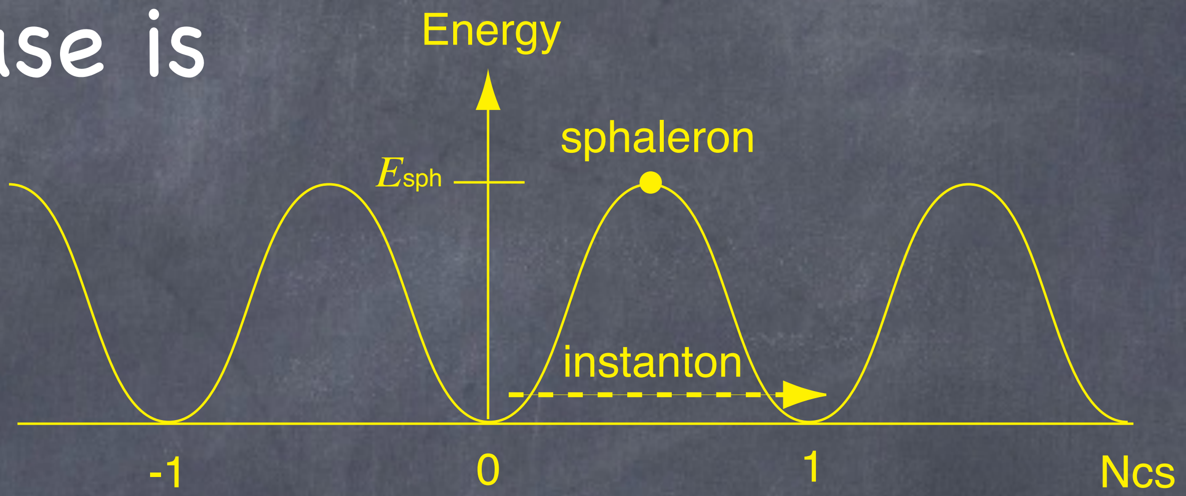
$$\Gamma_B^{(b)} < H$$

B-changing rate in the broken phase is

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



$E_{\rm sph}$ is proportional to the Higgs VEV

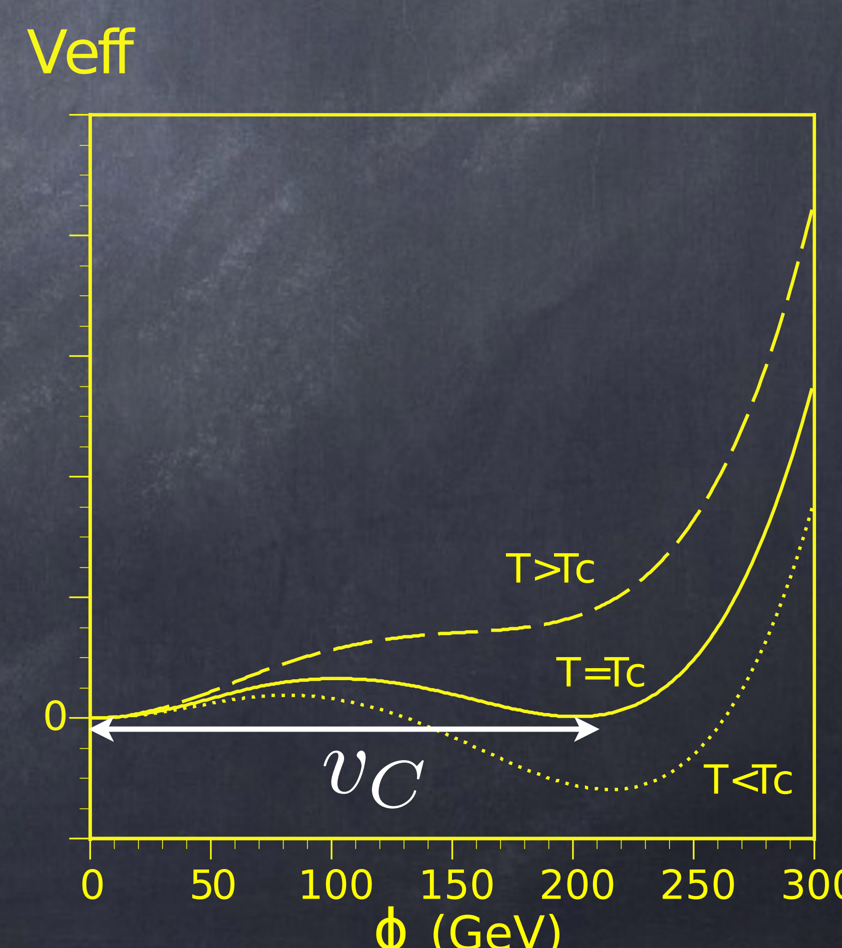
$$E_{\rm sph} \propto v$$

<u>what we need is</u>

large Higgs VEV after the EWPT

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

$$\Gamma_B^{(b)}(T_C) < H(T_C) \rightarrow \frac{v_C}{T_C} > \zeta_{\rm sph}(T_C)$$



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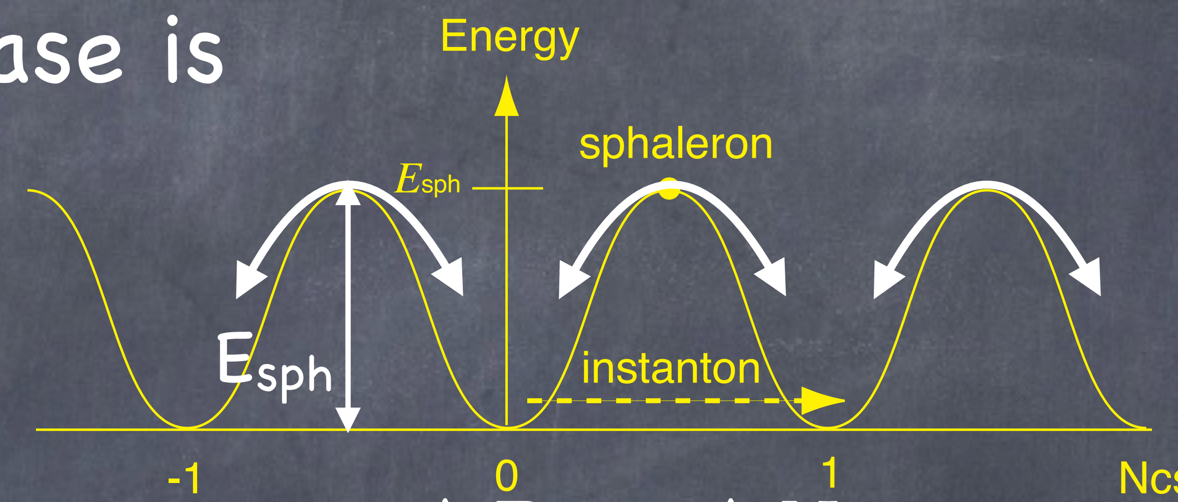

$$\Delta B = 3\Delta N_{\rm CS}$$

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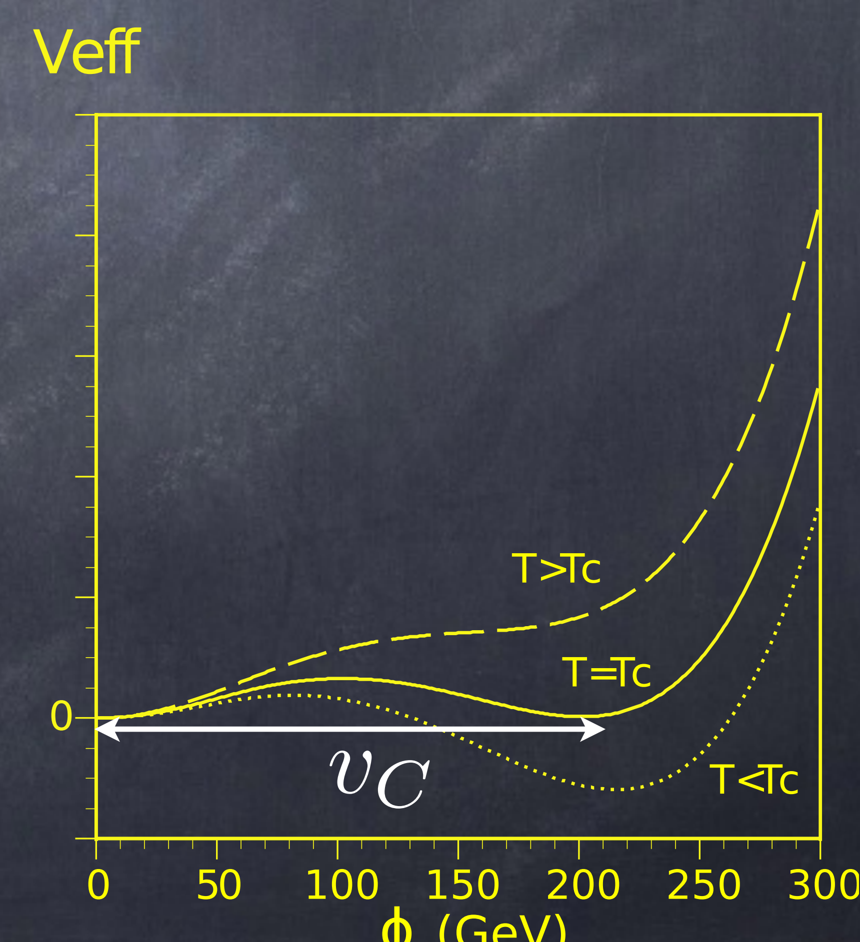

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$E_{\rm sph} = 4\pi v\mathcal{E}/g_2$ (g_2: SU(2) gauge coupling),

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

- dominant effect = sphaleron energy.
- sphaleron energy depends on the Higgs mass etc.

[F.R.Klinkhamer and N.S.Manton, PRD30, 2212 (1984)]

SM case

$$0 < m_h < 1\ \text{TeV},$$
$$1.54 < \mathcal{E} < 2.44,$$
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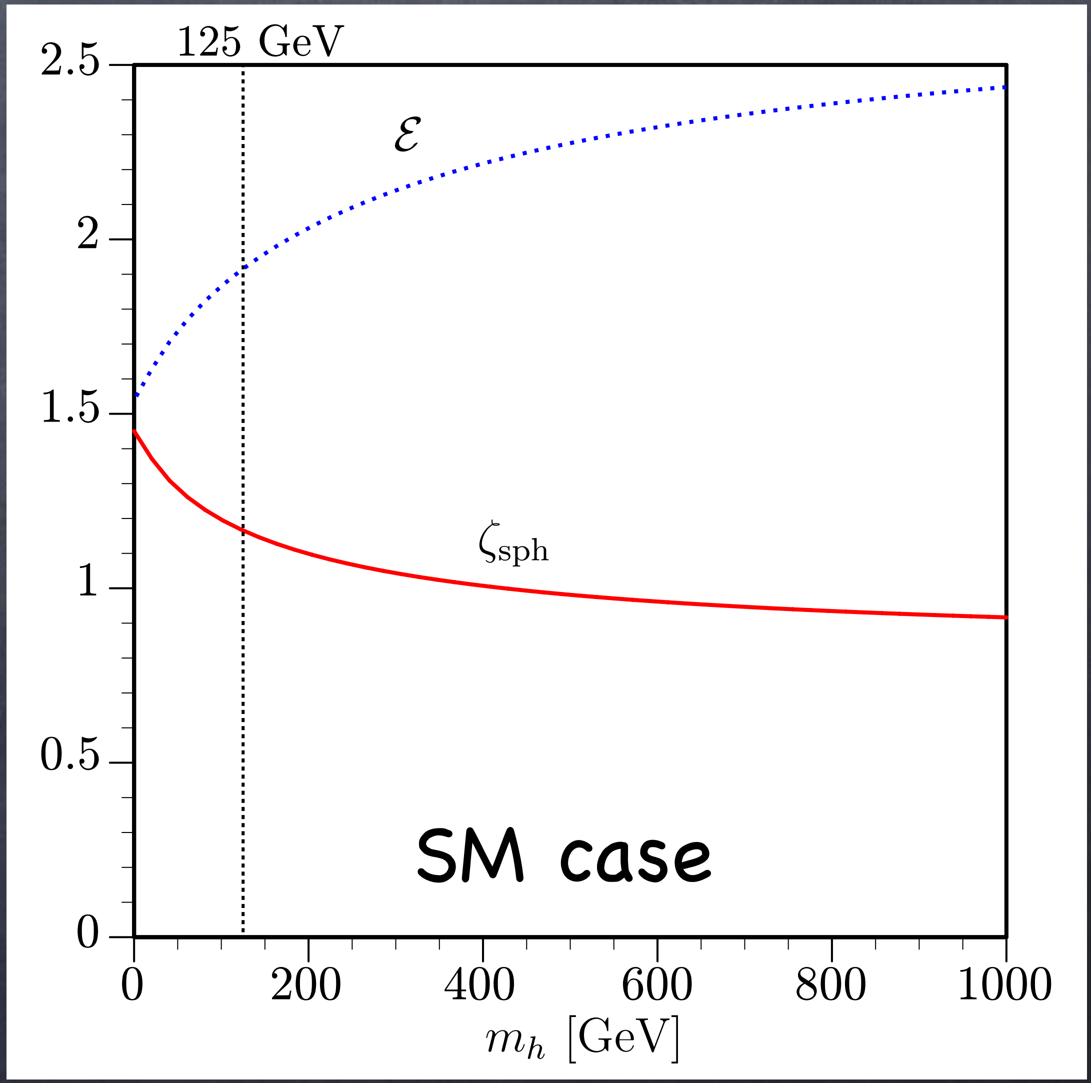

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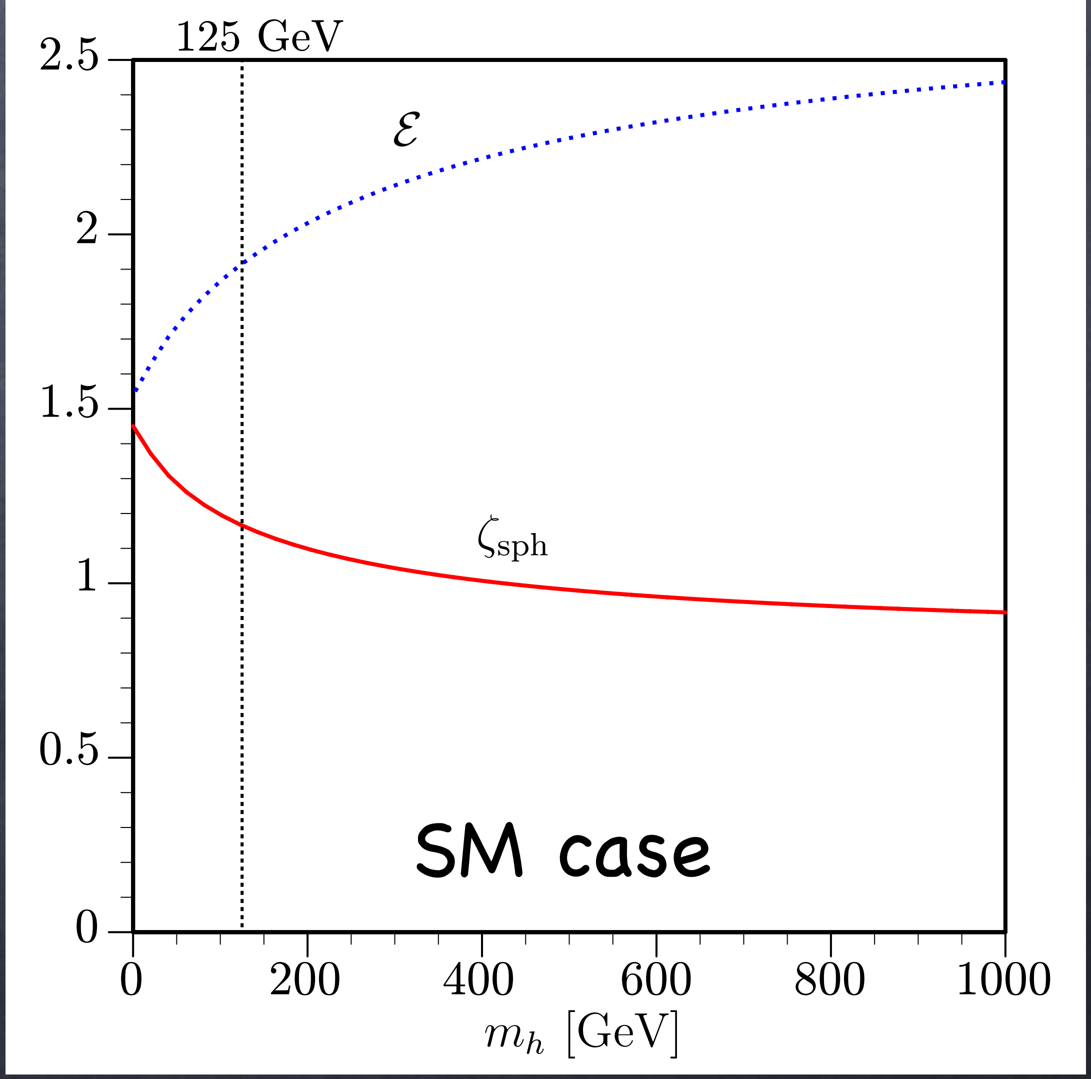

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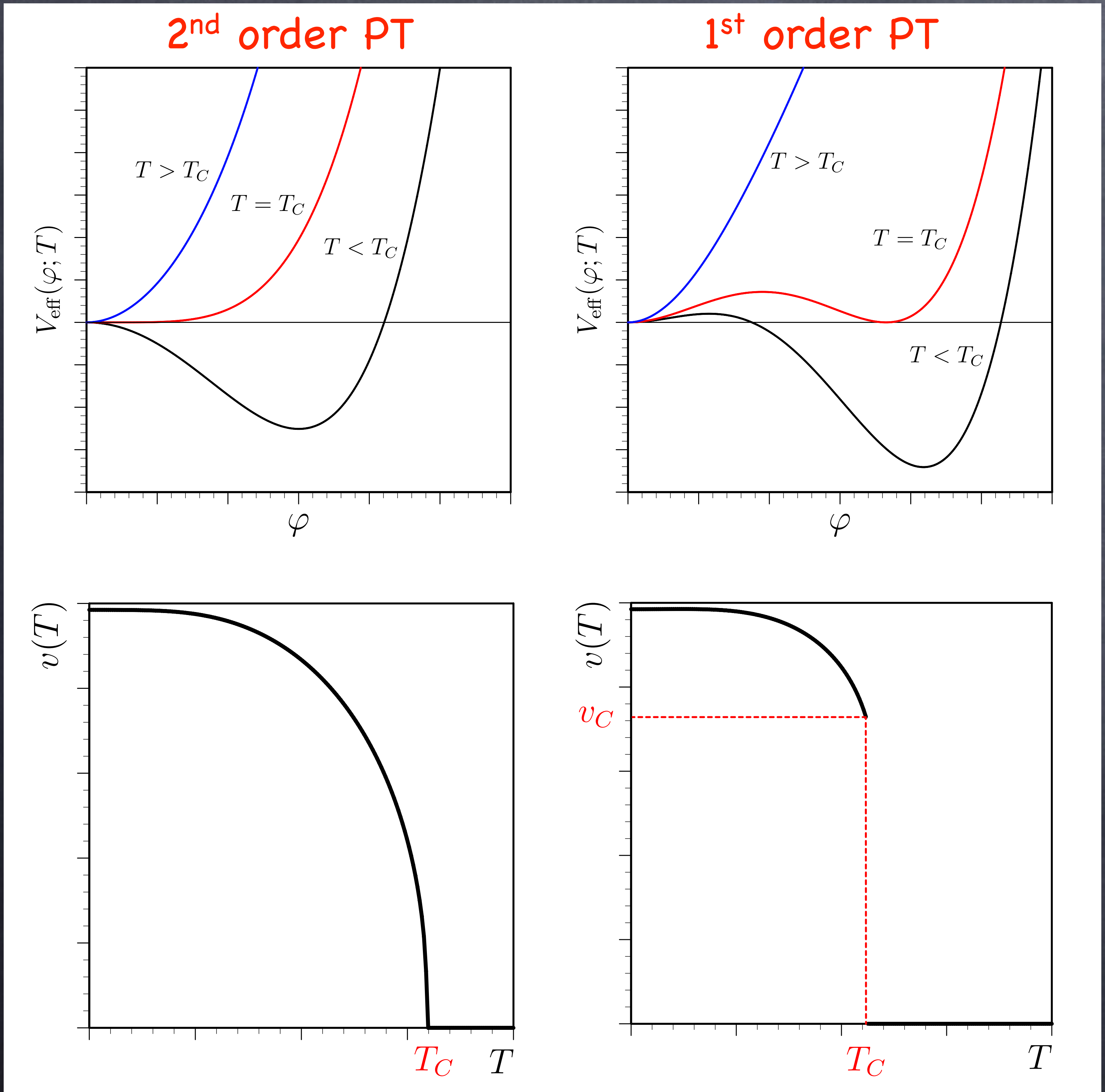
$$m_h = 125\ \text{GeV} \rightarrow \frac{v}{T} > \zeta_{\rm sph} = 1.16$$

How do we get 1st-order EWPT?

1st(2nd) order PT = discontinuities in 1st(2nd) derivatives of free energy



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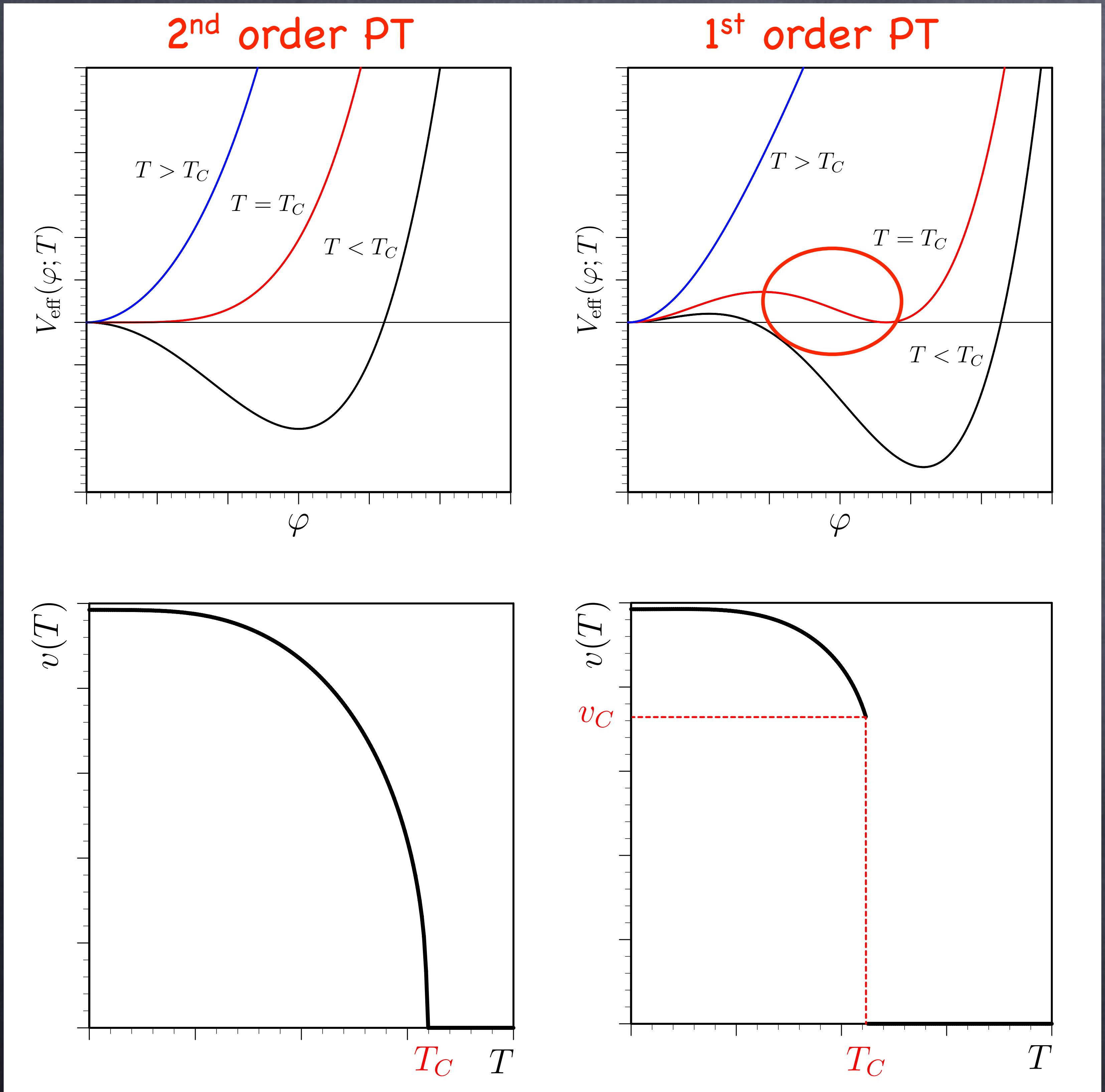

1st-order PT

$\Downarrow$

Negative contributions in V_{eff}.

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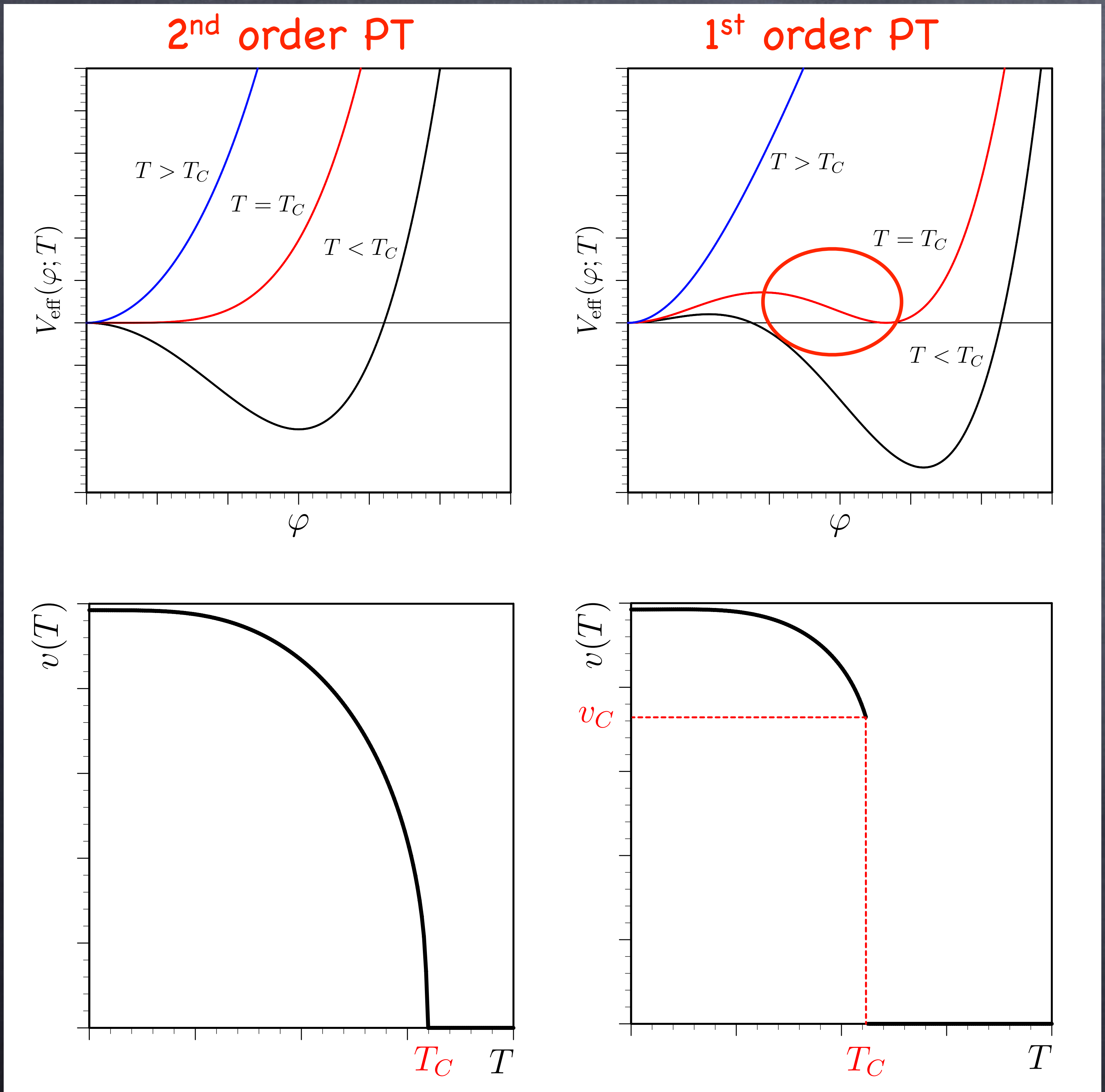

1st-order PT

⇓

Negative contributions in V_{eff}.

From where?

Origins of the negative contributions in $V_{eff.}$

2 representative cases.

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1. Thermal loop driven case

e.g. SM, MSSM. ∋ doublet Higgs

boson loop

$$V_1^{(\mathrm{boson})} = \frac{T}{2} \sum_{n=-\infty}^{\infty} \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \ln\left[(2n\pi T)^2 + \boldsymbol{k}^2 + m^2(\varphi)\right]$$

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Typical signals

Deviations of hgg and/or hγγ and/or hhh couplings

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e.g. rSM, NMSSM. ∋ singlet Higgs

$$V_0 \ni \mu_{HS}\varphi_H^2\varphi_S + \mu_S\varphi_S^3$$

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Typical signals

Deviations of HVV and/or Hff and/or hhh couplings.

What are possible models?

- SM EWBG was excluded. No 1st-order PT for m_h=125 GeV.

$\frac{v_C}{T_C} \gtrsim 1$ not satisfied

SUSY

- ❒ MSSM $W_{\rm MSSM} = f^{(e)} H_d L E + f^{(d)} H_d Q D - f^{(u)} H_u Q U + \mu H_u H_d$
- ❒ Next-to-MSSM (NMSSM) $W_{\rm NMSSM} = W_{\rm MSSM}|_{\mu=0} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$
- ❒ U(1)'-extended-MSSM (UMSSM) $W_{\rm UMSSM} = W_{\rm MSSM}|_{\mu=0} + \lambda S H_u H_d$
- ❒ 4 Higgs doublets+singlets-extended MSSM

$$W = \lambda \Big[H_d \Phi_u \zeta + H_u \Phi_d \eta - H_u \Phi_u \Omega^- - H_d \Phi_d \Omega^+ + n_\Phi \Phi_u \Phi_d + n_\Omega (\Omega^+ \Omega^- - \zeta\eta) \Big]$$
$$- \mu (H_u H_d - n_\Phi n_\Omega) - \mu_\Phi \Phi_u \Phi_d - \mu_\Omega (\Omega^+ \Omega^- - \zeta\eta).$$

[S. Kanemura, T. Shindou, T. Yamada, PRD86, 055023 (2012)]

- ❒ etc.

non-SUSY SM + SU(2) n-plet Higgs, n=1,2,3,...

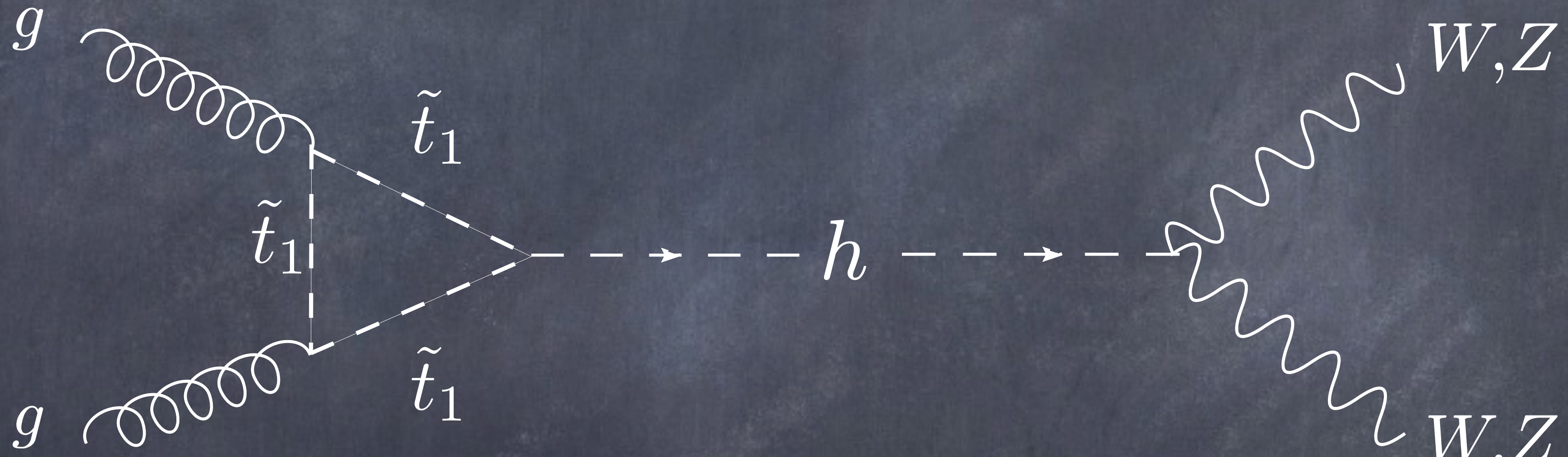
MSSM EWBG

light stop scenario

$$m^2_{\tilde{t}_1}(\varphi) \simeq \frac{y_t^2 \sin^2\beta}{2}\varphi^2 \quad (m^2_{\tilde{q}_L} \gg m^2_{\tilde{t}_R}, |A_t - \mu/\tan\beta|^2 \simeq 0)$$

Strong 1^{st}-order EWPT is driven by the light stop with a mass below 120 GeV. [M. Carena et al, NPB812, (2009) 243].

Prediction: σ(gg -> H -> VV)/ σ(gg -> H -> VV)$_{SM}$ ≃ (2-3)



MSSM EWBG

light stop scenario

$$m^2_{\tilde{t}_1}(\varphi) \simeq \frac{y_t^2 \sin^2\beta}{2}\varphi^2 \quad (m^2_{\tilde{q}_L} \gg m^2_{\tilde{t}_R}, |A_t - \mu/\tan\beta|^2 \simeq 0)$$

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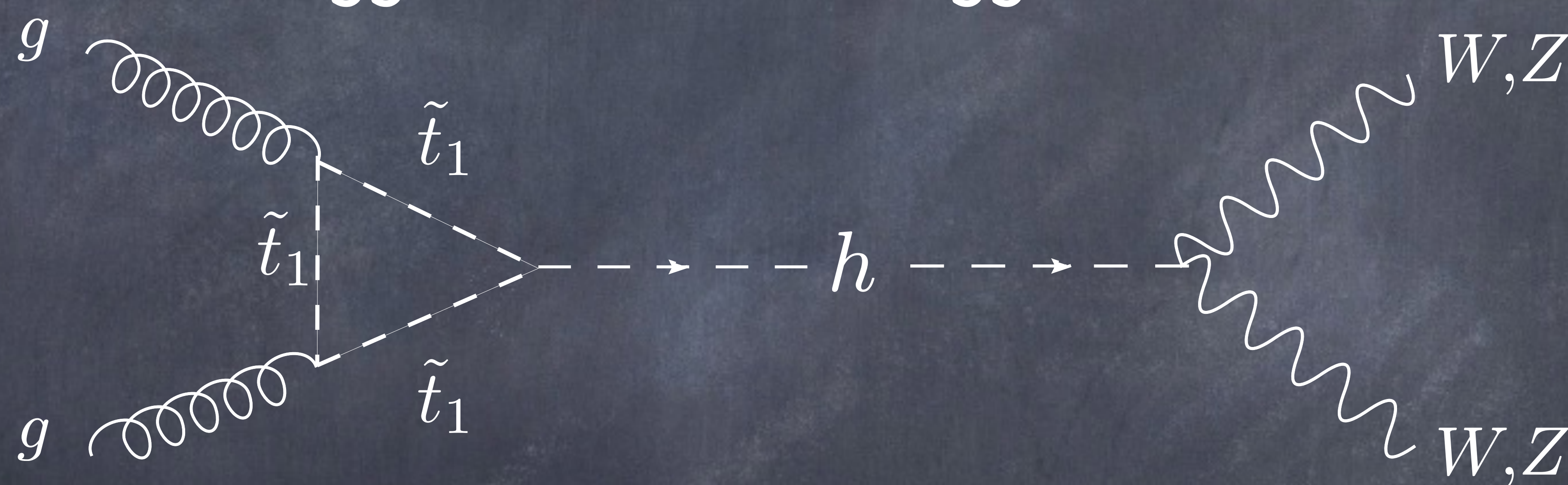

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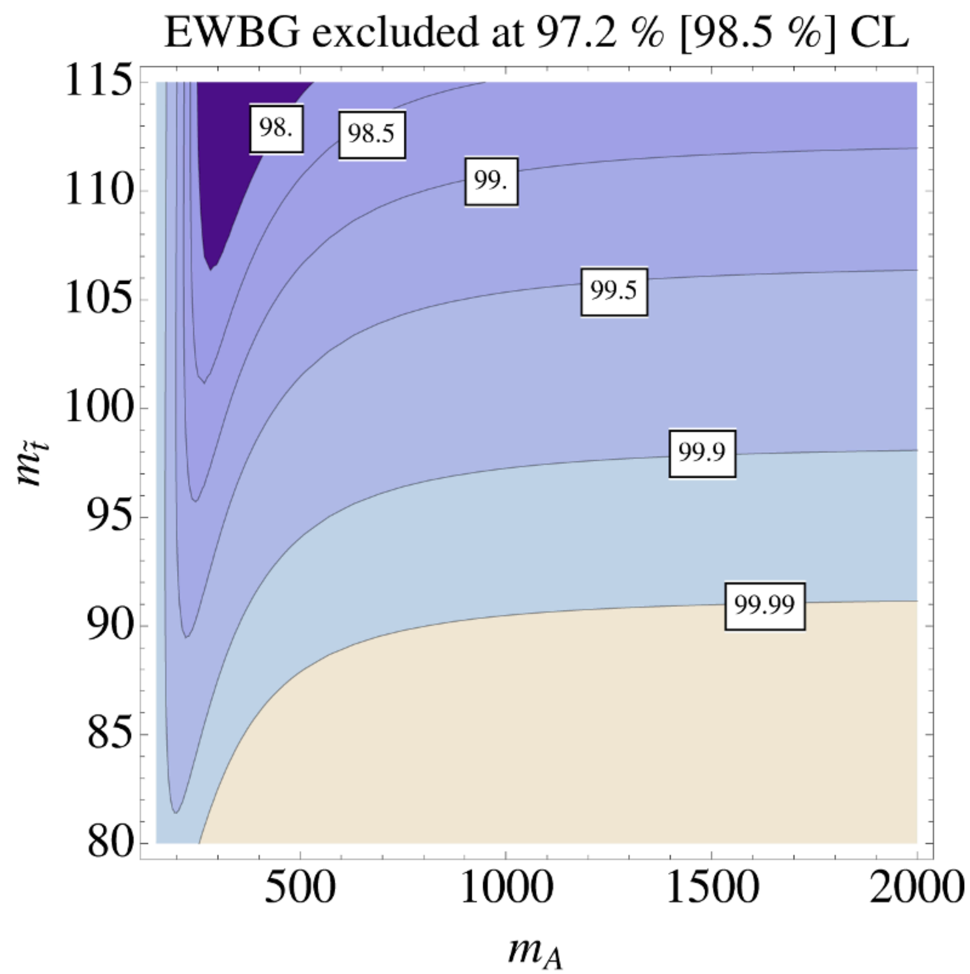

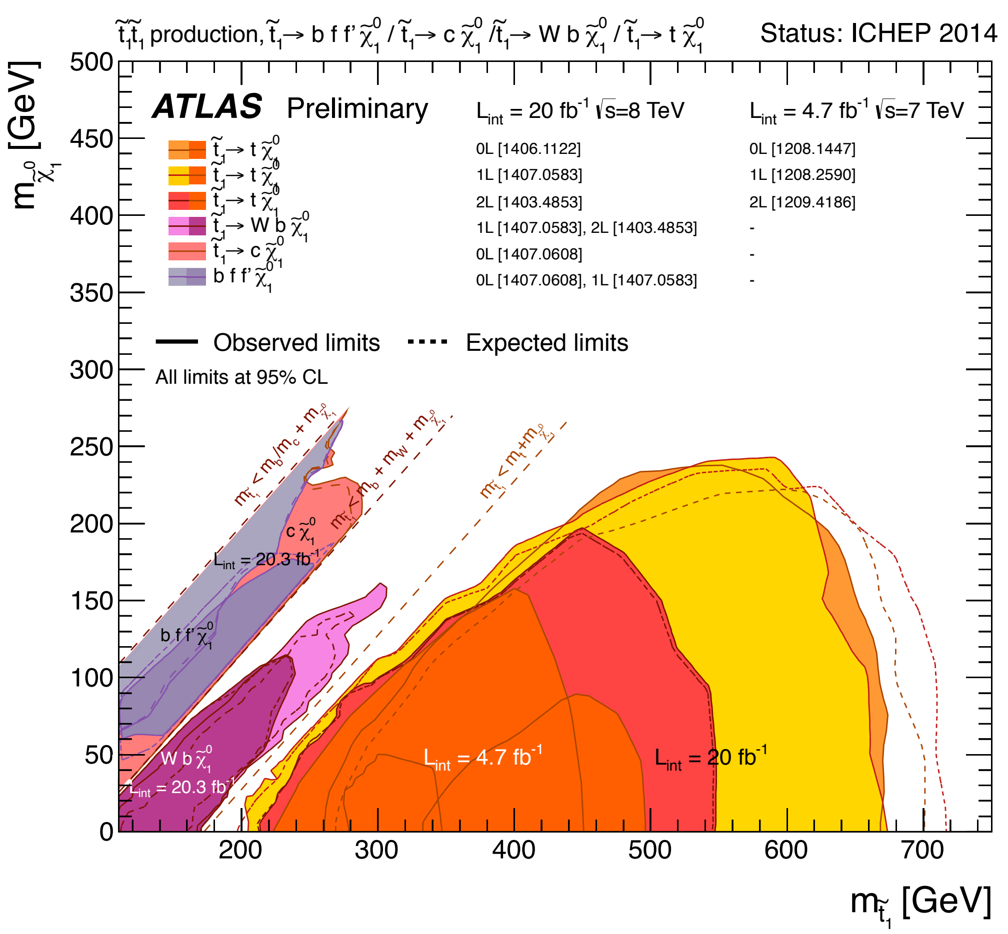

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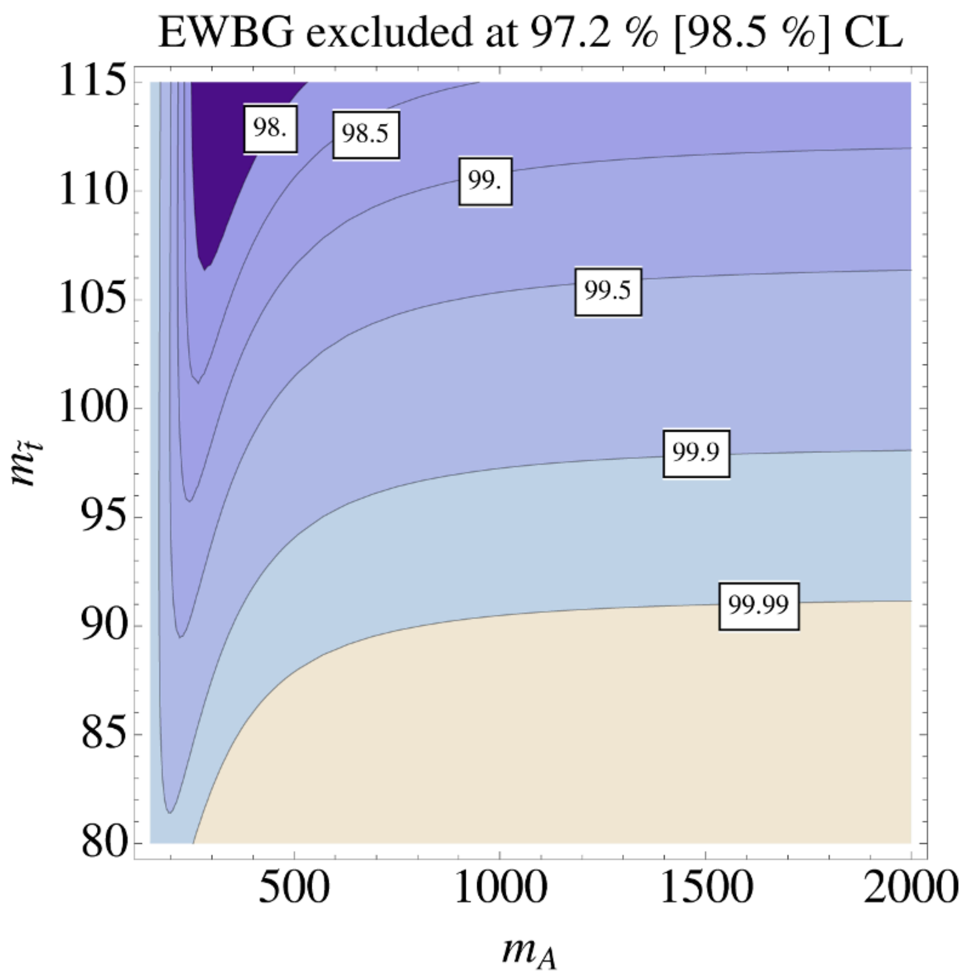

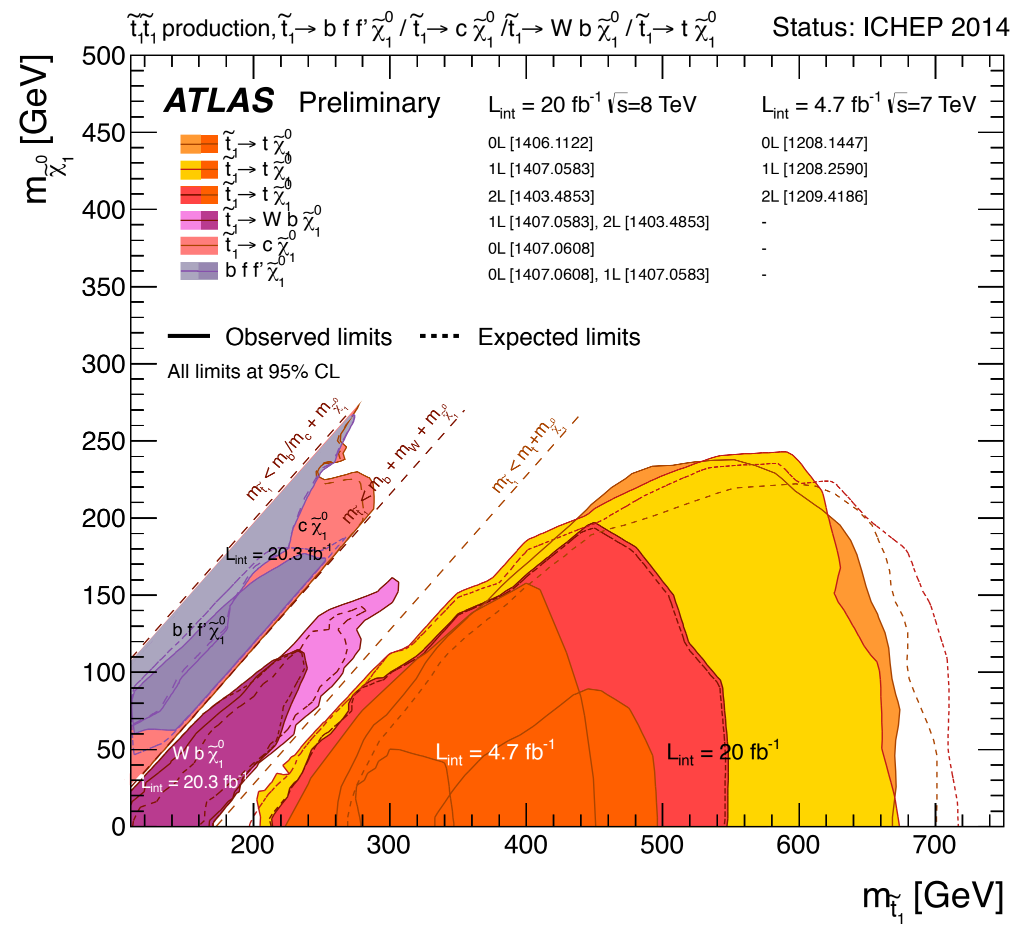

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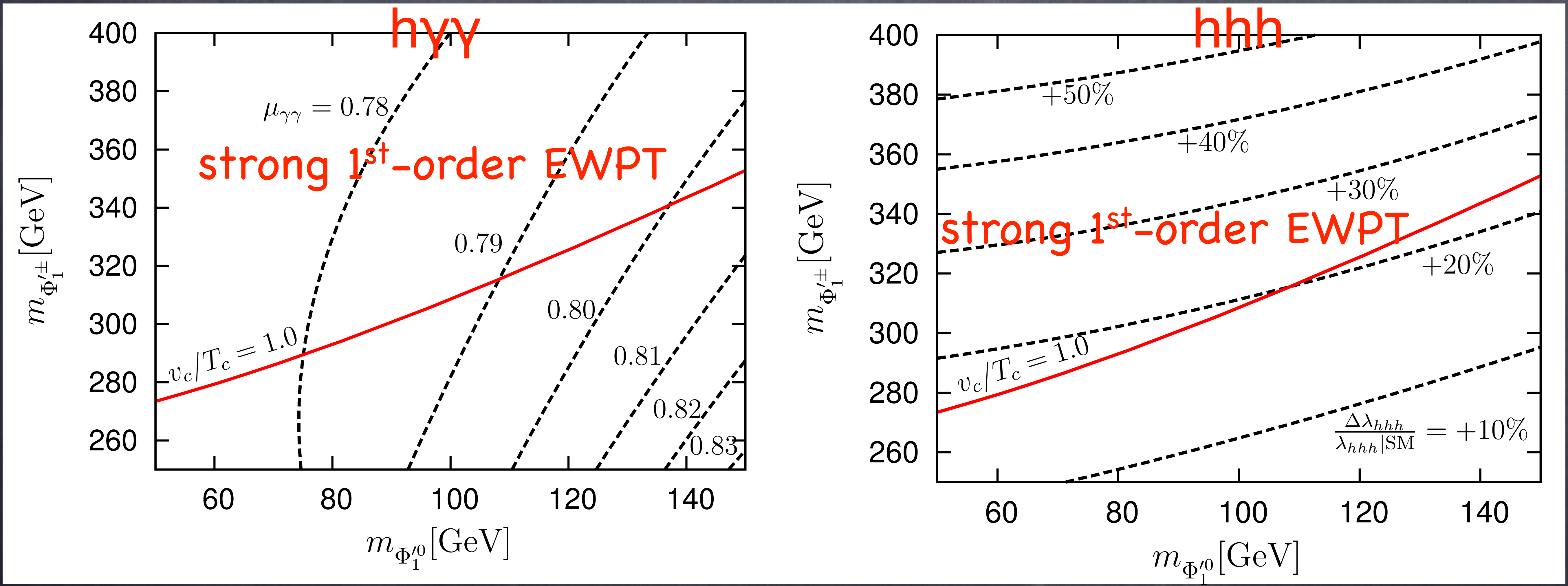
$\frac{v_C}{T_C} \gtrsim 1$ not satisfied

4 Higgs doublets+singlets-extended MSSM

❒ Strong 1st-order EWPT is driven by the charged Higgs bosons.



[S. Kanemura, E.S., T. Shindou, T. Yamada, JHEP05 (2013) 066]

If the EWPT is strong 1st order,

- $\mu_{\gamma\gamma}$ is reduced by more than 20%,
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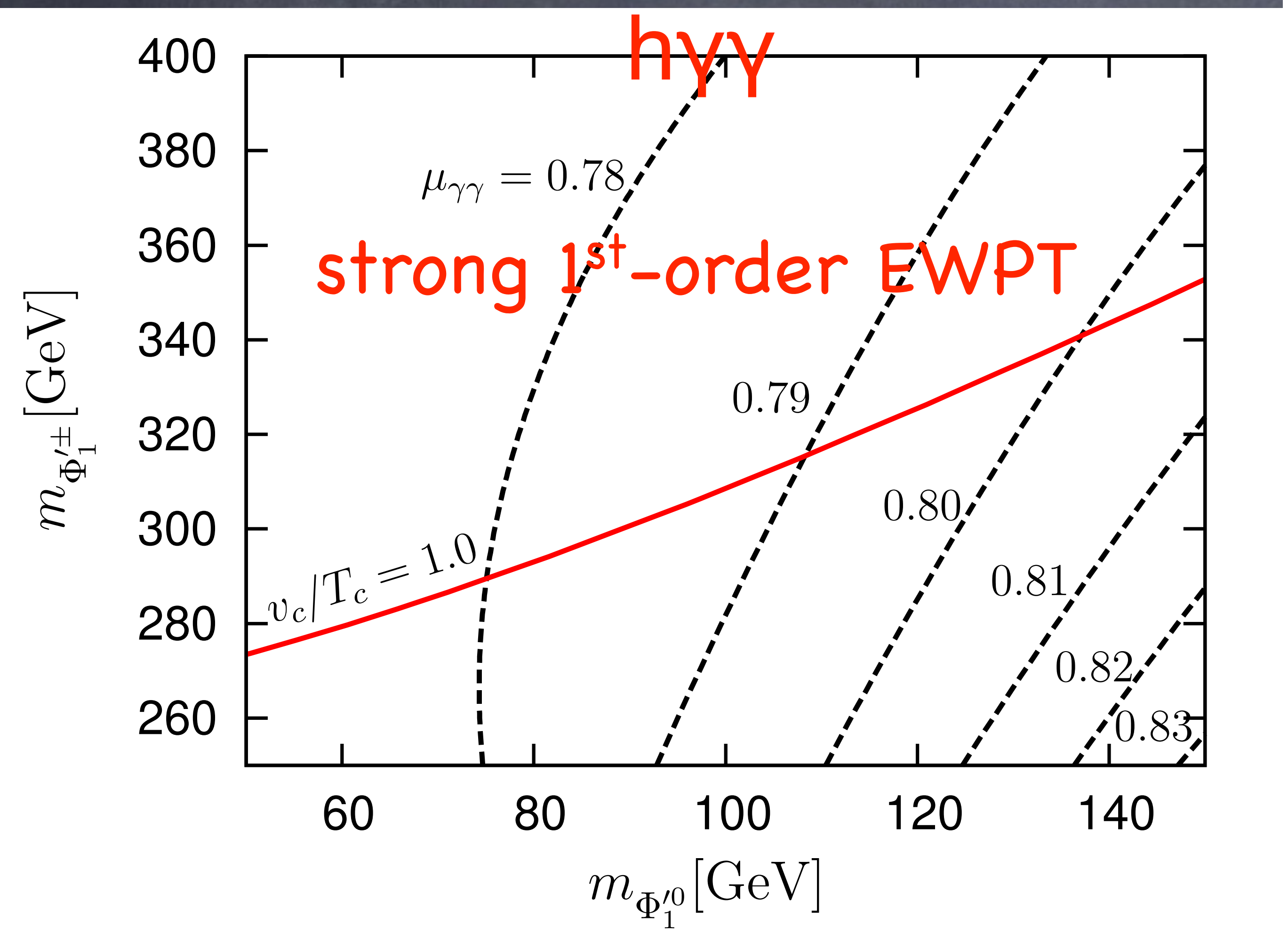

$$\mu_{\gamma\gamma} = 1.17 \pm 0.27 \text{ (ATLAS)}$$

$$\mu_{\gamma\gamma} = 1.14^{+0.26}_{-0.23} \text{ (CMS)}$$

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Non-SUSY models

SM + SU(2) n-plet Higgs, n=1,2,3,...

- Colored particles (squarks) may not play a role in realizing strong 1st-order PT. (due to severe LHC bounds)

- EWPT may be simply described by extended Higgs sector.

[N.B.] CP violation comes from (chargino, neutralino)-sector which would not be relevant in studying EWPT. (bosons are more important than fermions)

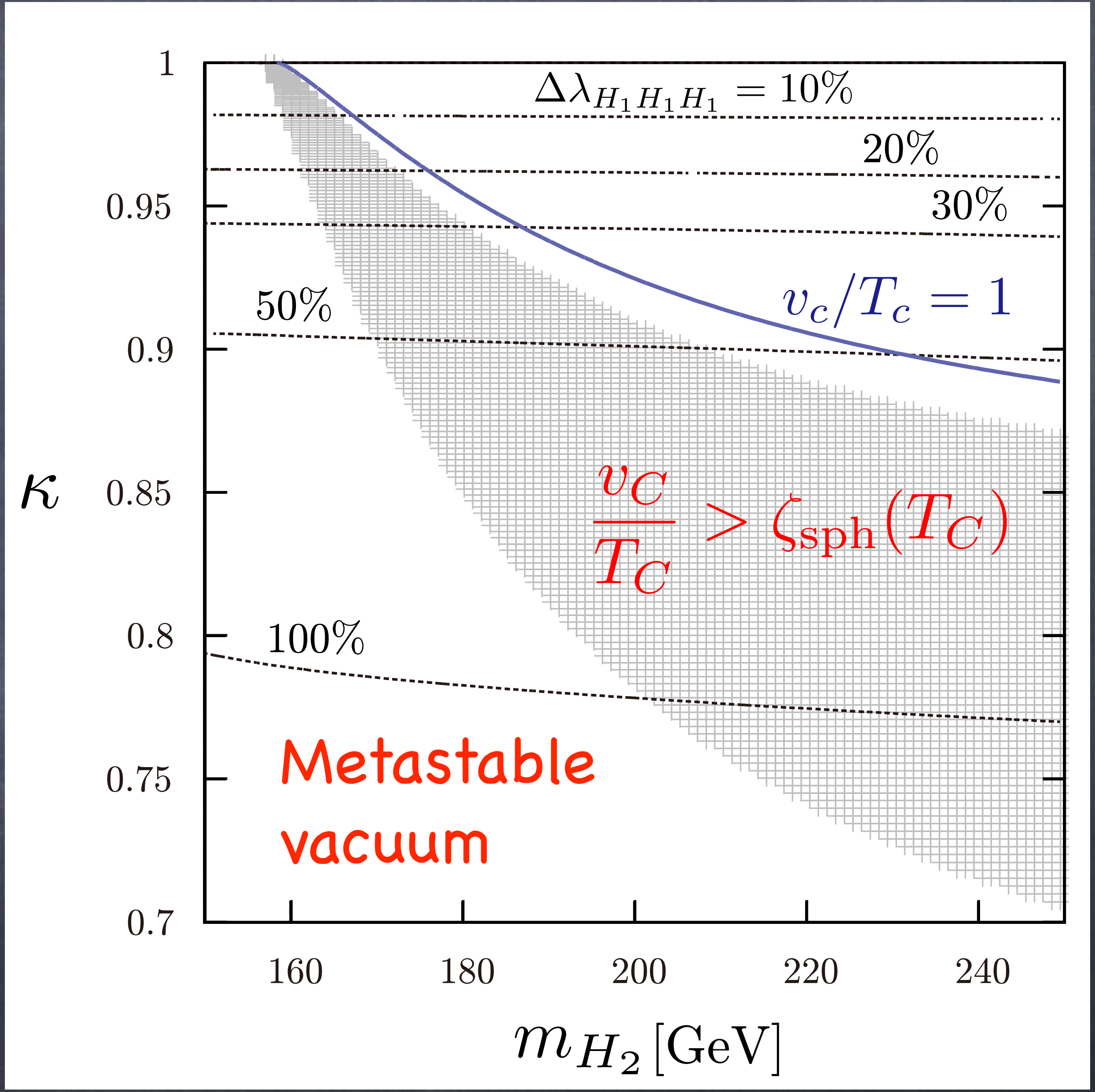
Singlet Higgs extended SM

[Fuyuto, E.S., PRD90, 015015 (2014)]

- real singlet Higgs is added.

$$\kappa = \frac{g_{H_1 VV}}{g_{hVV}^{\rm SM}} = \frac{g_{H_1 ff}}{g_{hff}^{\rm SM}}$$
$$= \cos\alpha$$

- 1st order EWPT is driven by the doublet-singlet Higgs mixing effects.



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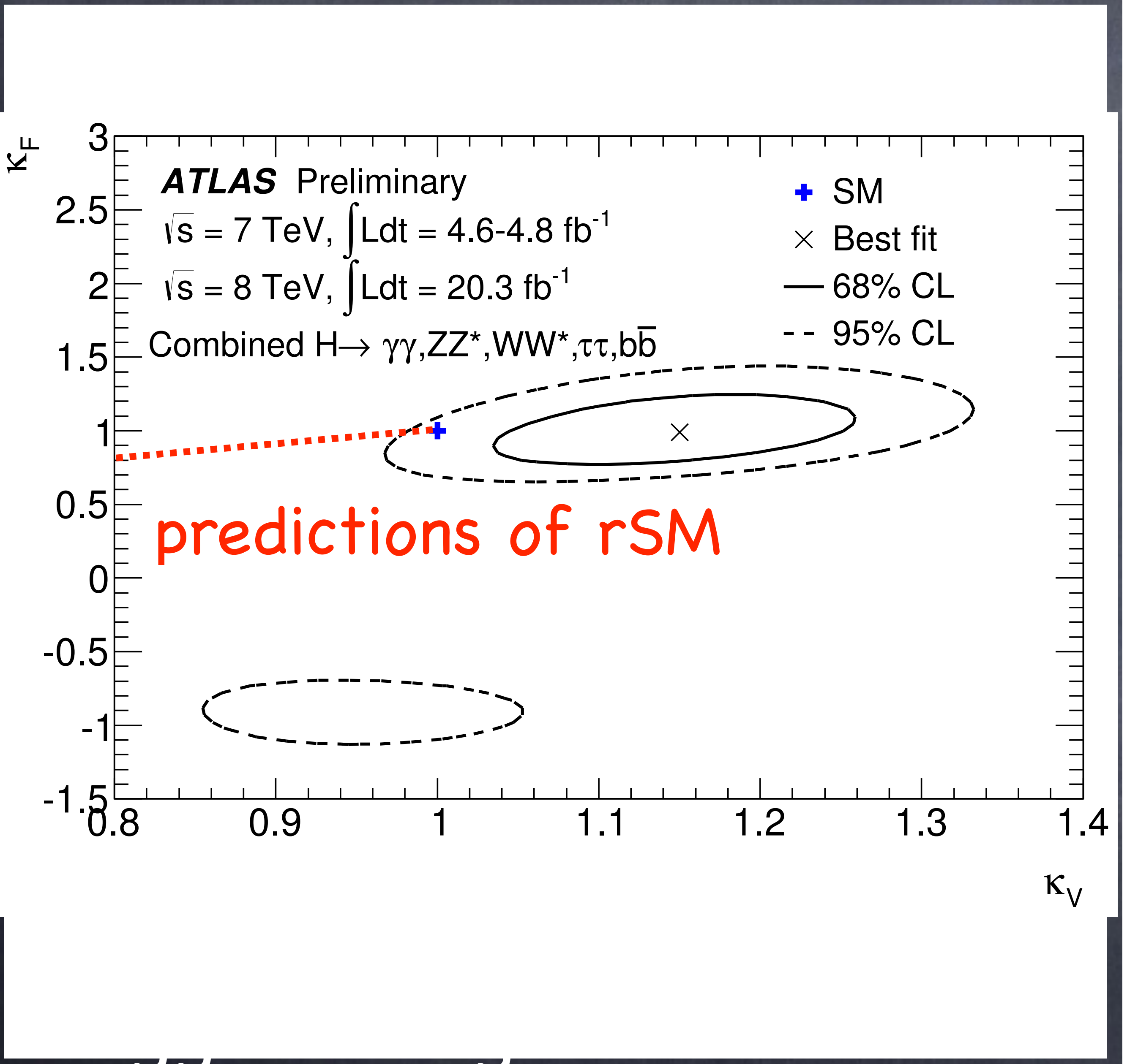

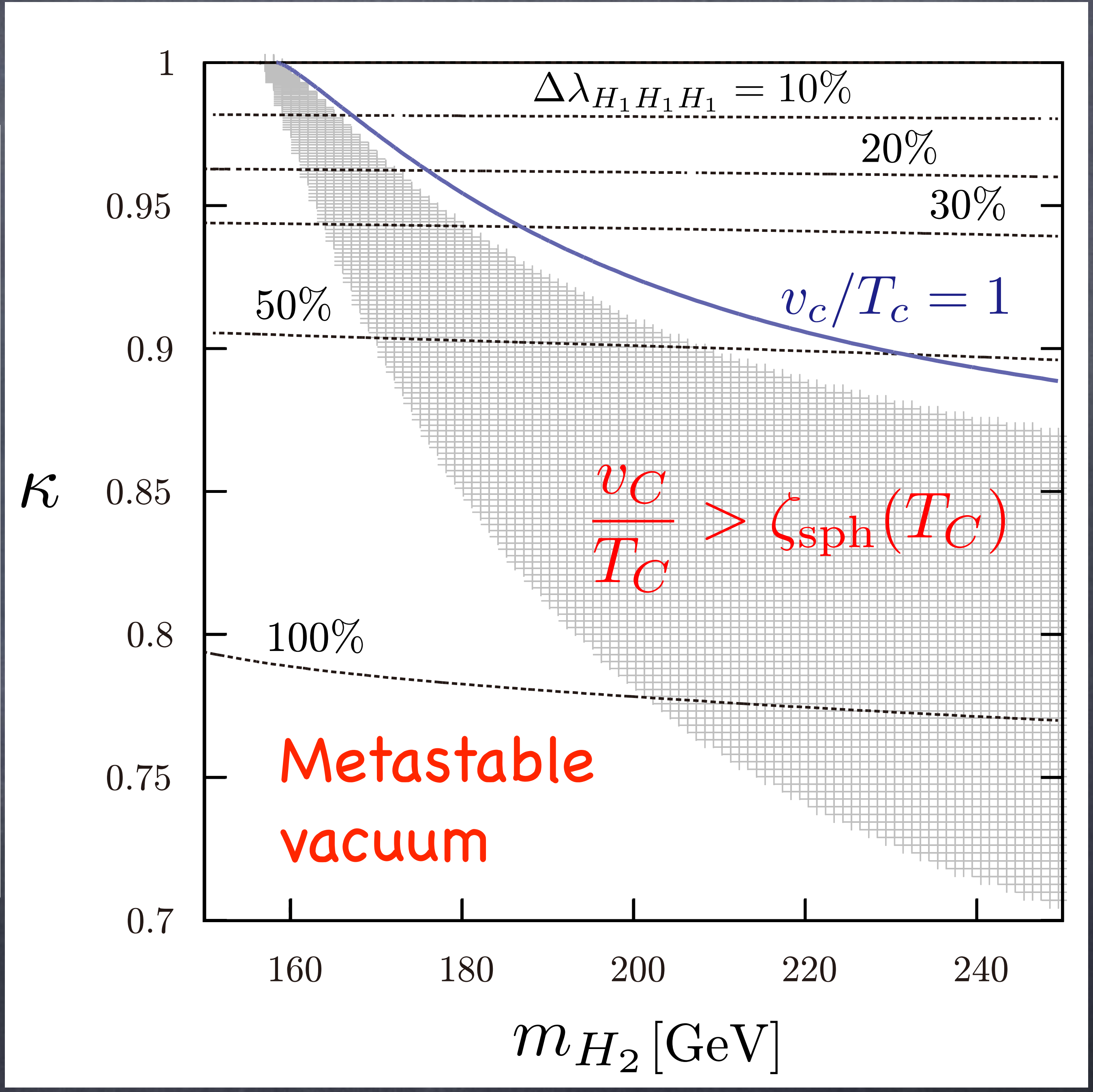

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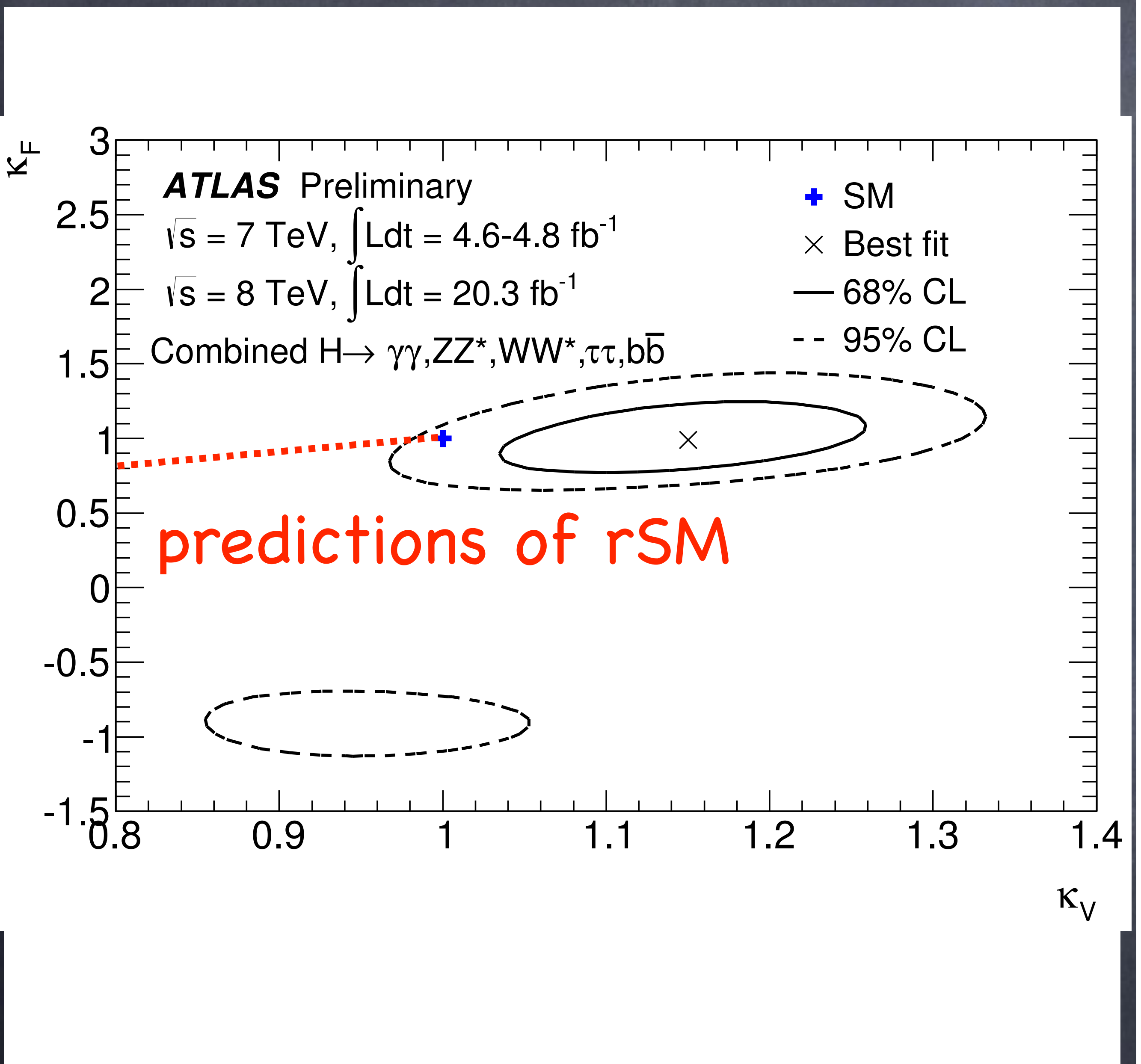
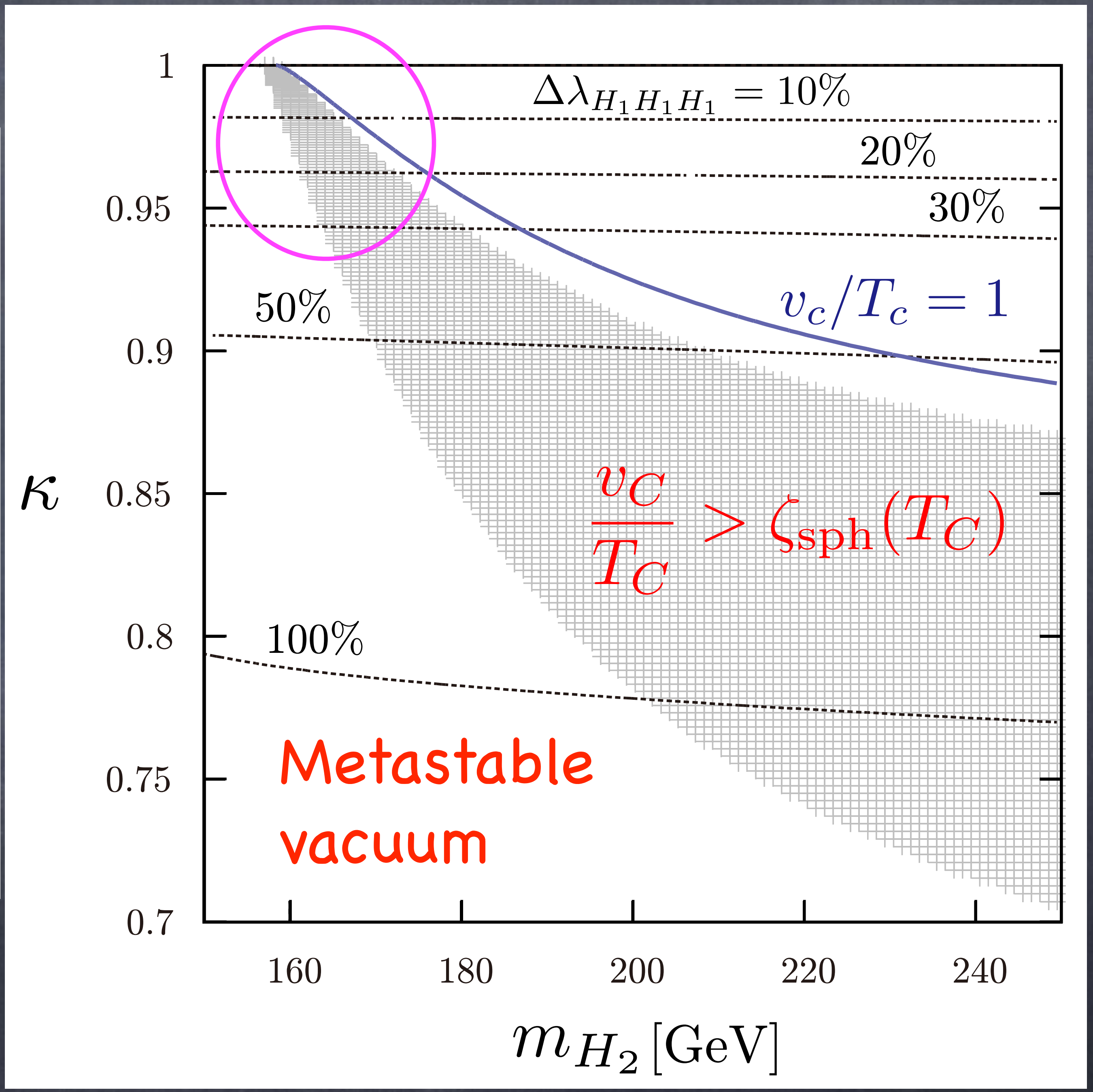




– HVV, Hff, hhh couplings can deviate from their SM values.

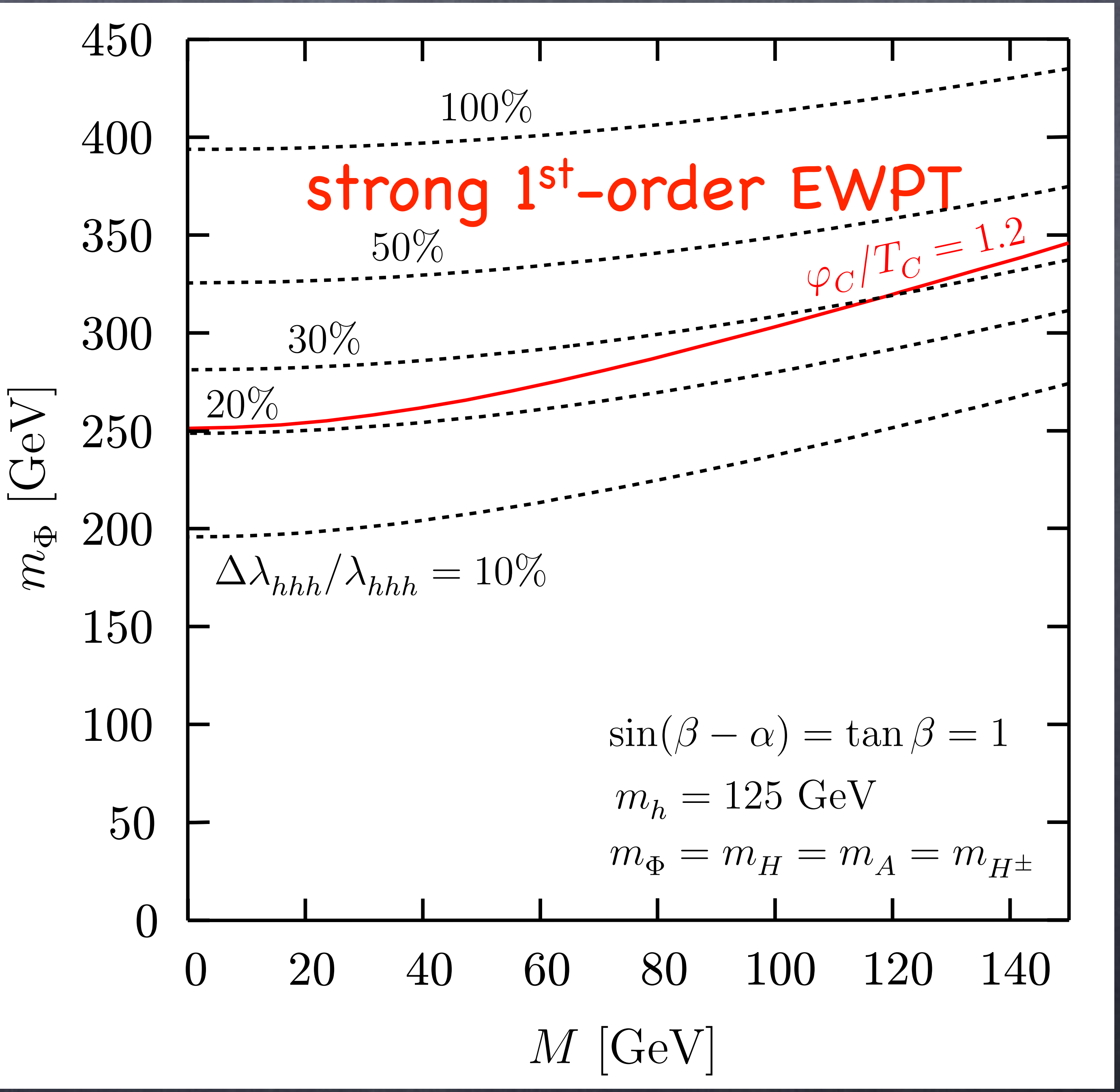
2 Higgs doublet model

[Kanemura, Okada, E.S., PLB606,(2005)361]

- Extra Higgs doublet is added

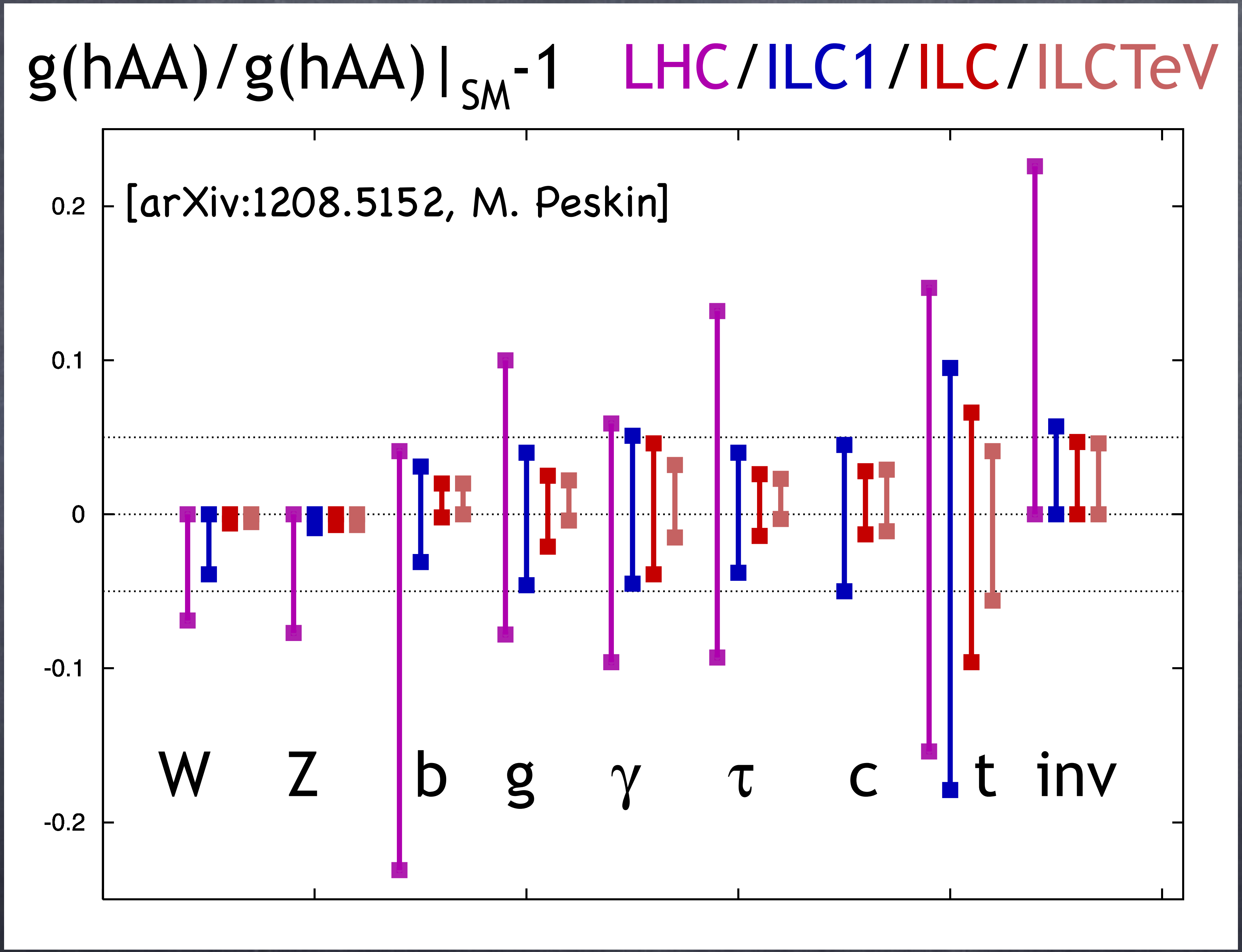
- Strong 1^{st}-order EWPT is driven by the heavy Higgs boson loops.

- λ_{hhh} can significantly deviate even when hVV/hff couplings are SM-like.



- More than **+20%** deviation if $v_C/T_C > 1.2$.

Higgs coupling measurements@LHC/ILC



$\Delta\lambda_{hhh}/\lambda_{hhh} = 13\%$ @ILCTeV [ILC white paper, 1310.0763]

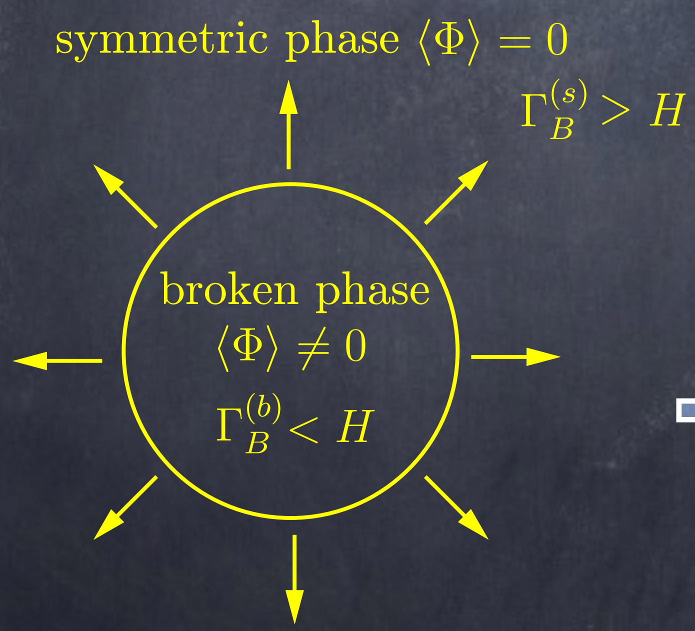
LHC/ILC can probe EWBG-favored region.

Summary

❐ MSSM EWBG was excluded by the Higgs signal strengths and light stop searches.

❐ EWBG in other models (NMSSM, 2HDM etc) are still viable.

❐ In most cases, strong 1st-order EWPT leads to the significant deviations of the Higgs boson couplings from the SM values.



1st-order EWPT

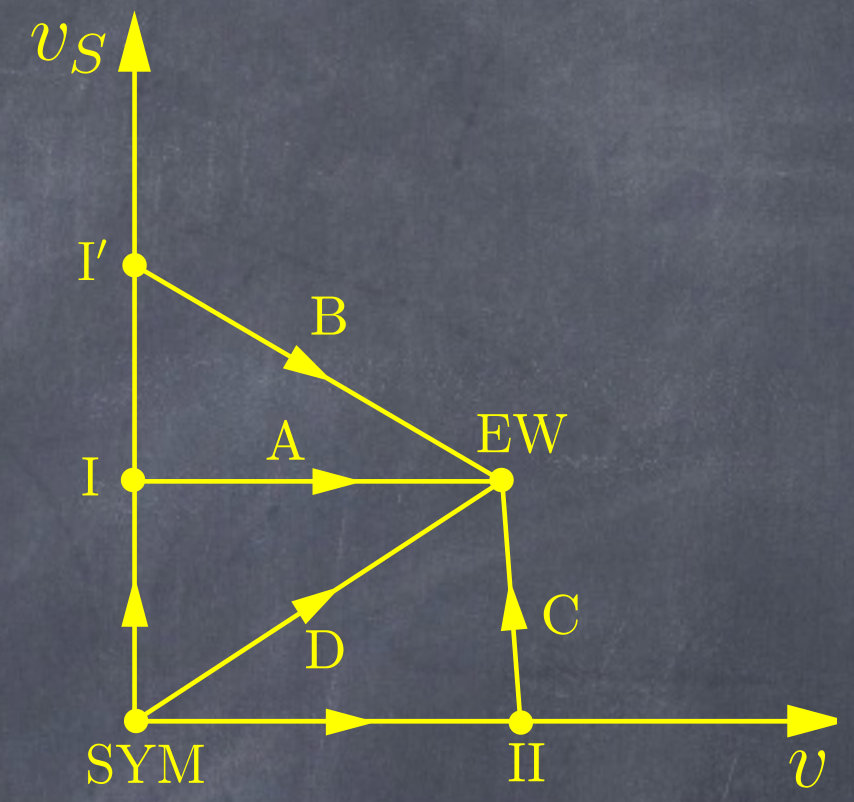
Deviations of the Higgs boson couplings:

HVV, Hff, hγγ, hhh

❐ Higgs coupling measurements are the crucial tests of EWBG.

Backup

NMSSM EWPT in a nutshell



❒ Diverse patterns of the phase transitions.

[K.Funakubo, S. Tao, F. Toyoda., PTP114,369 (2005)]

A: SYM $\rightarrow$ I $\Rightarrow$ EW   B: SYM $\rightarrow$ I′ $\Rightarrow$ EW

C: SYM $\Rightarrow$ II $\rightarrow$ EW   D: SYM $\Rightarrow$ EW

Type B

❒ v_S changes a lot during the PT.

v_S (I′) >> v_S (EW) ≃ v (246 GeV)

$\kappa \lesssim 0.1$ (∵ v_S (I′) is scaled by $1/\kappa$)

$\lambda \gtrsim 0.75$ (∵ chargino > 104 GeV) $\tan\beta = 5,\ v_S = 200$ GeV

-> "resonance condition ($\lambda = 2\kappa$) cannot be realized."

❒ light stop.$(<m_t)$ is not required.

(cf. such a light stop is needed in the MSSM.)

Singlino-driven EWBG in the NMSSM

[K. Cheung, TJ. Hou, JS. Lee, E.S., PLB710 (2012) 188]

- ❒ Strong 1st-order EWPT is driven by the doublet-singlet mixing effects.
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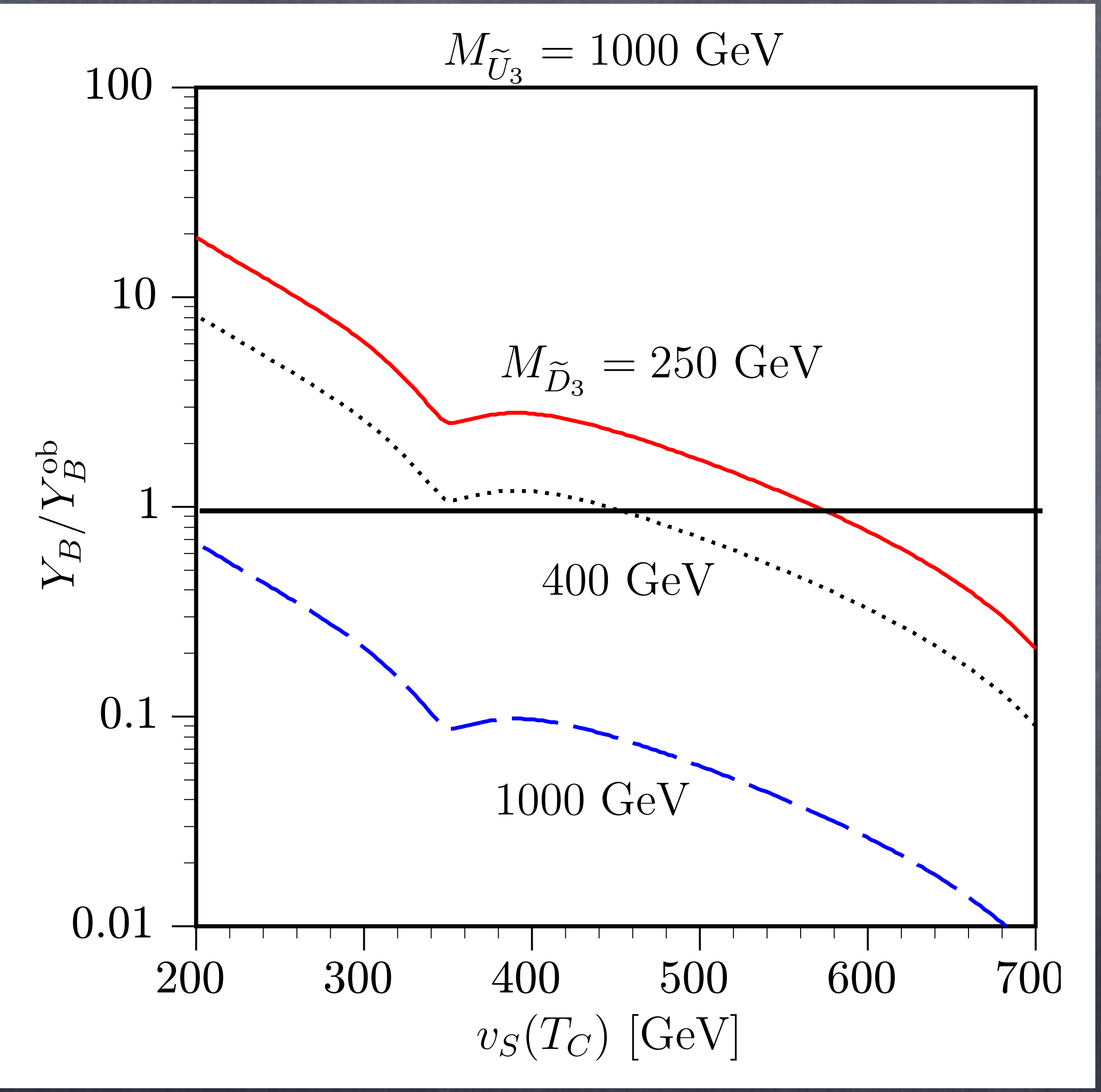

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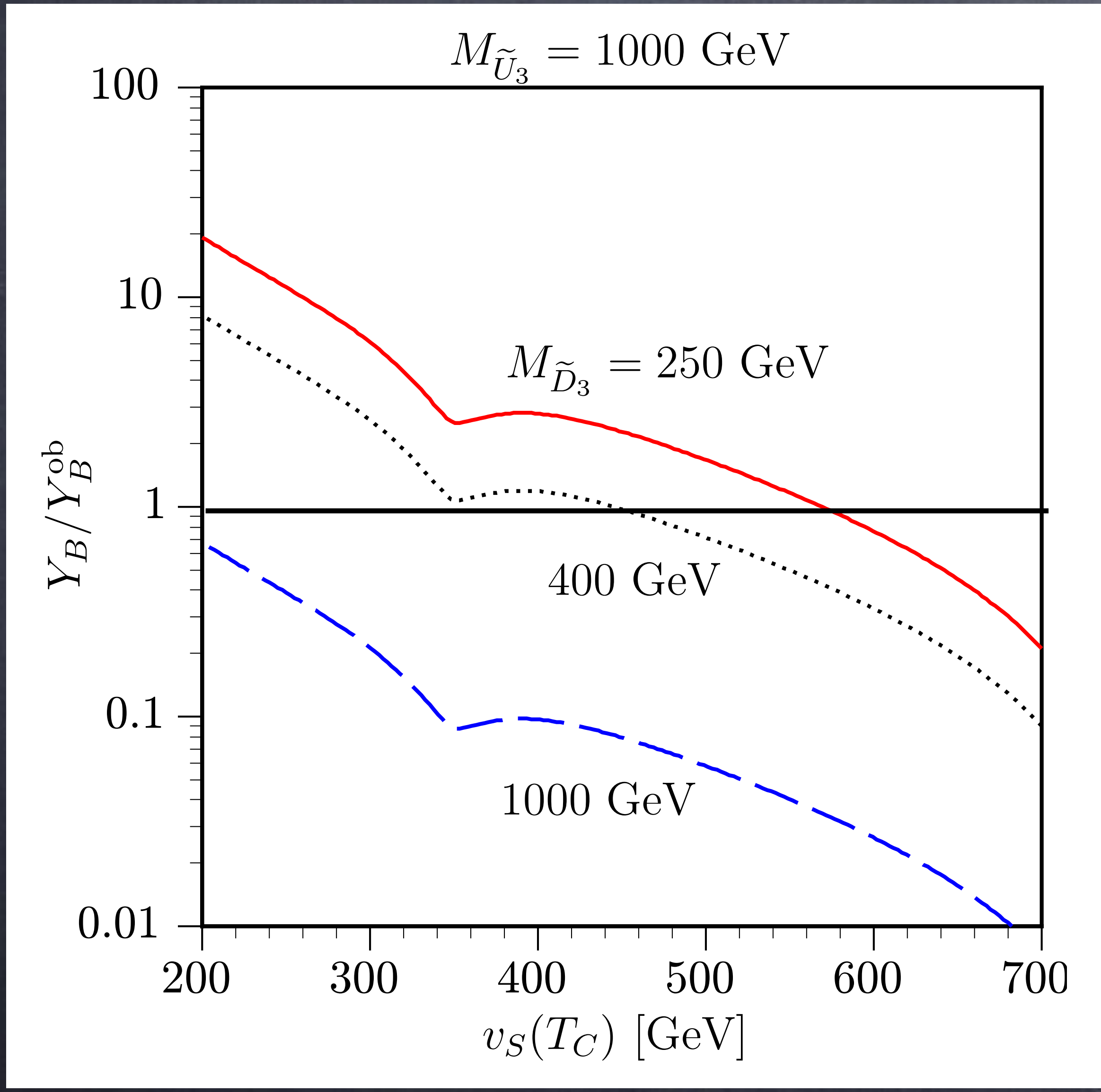

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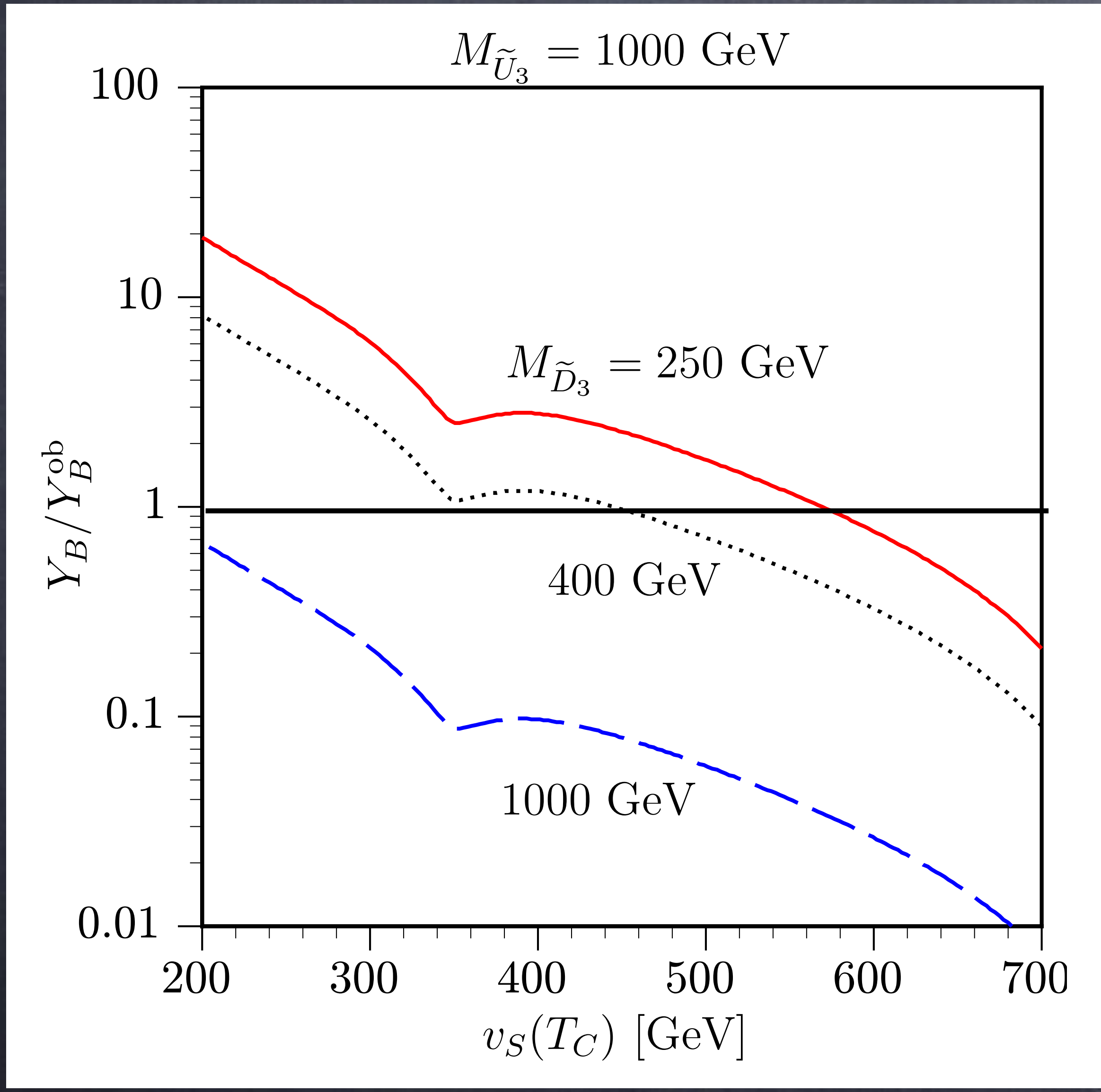

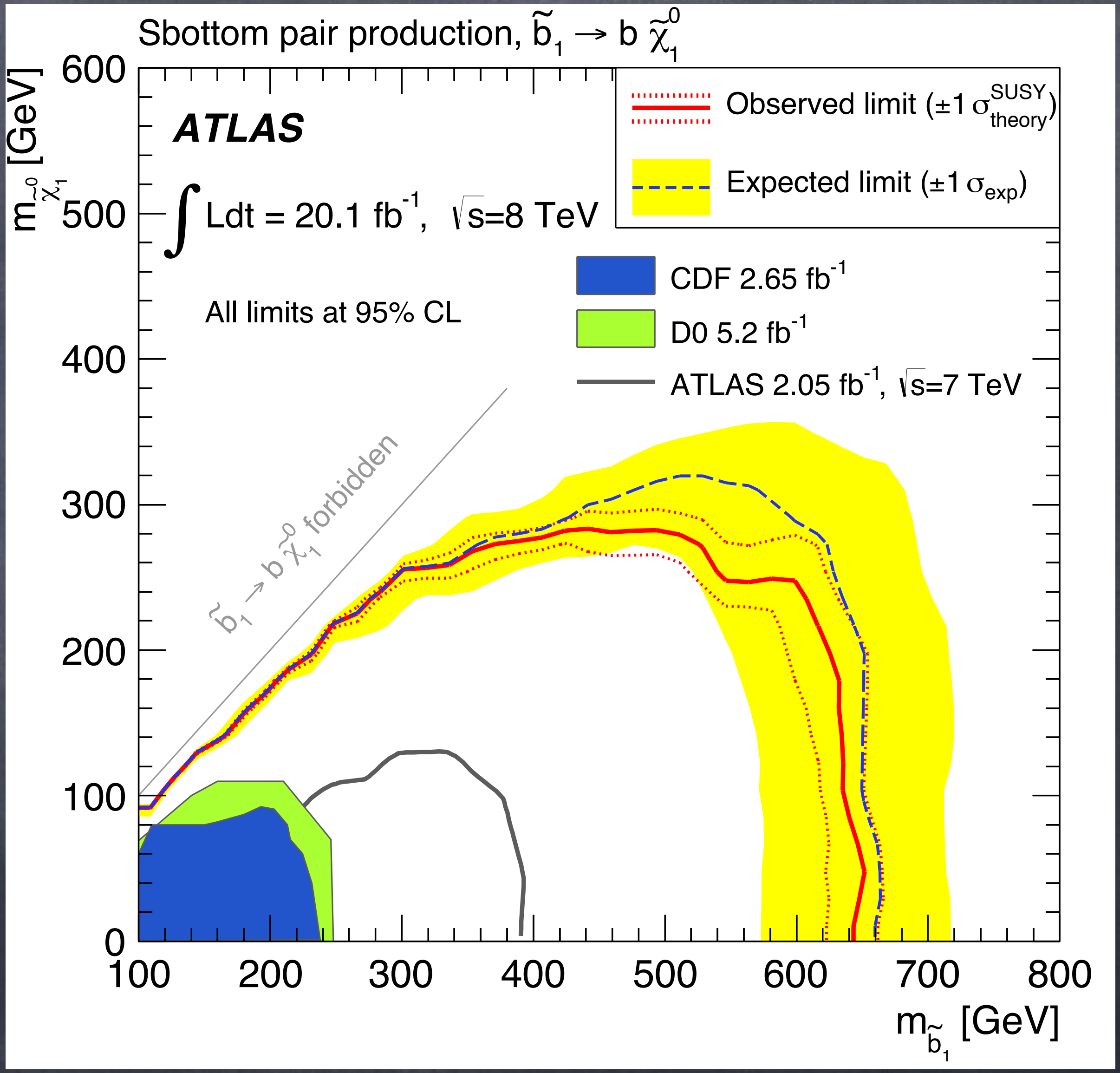

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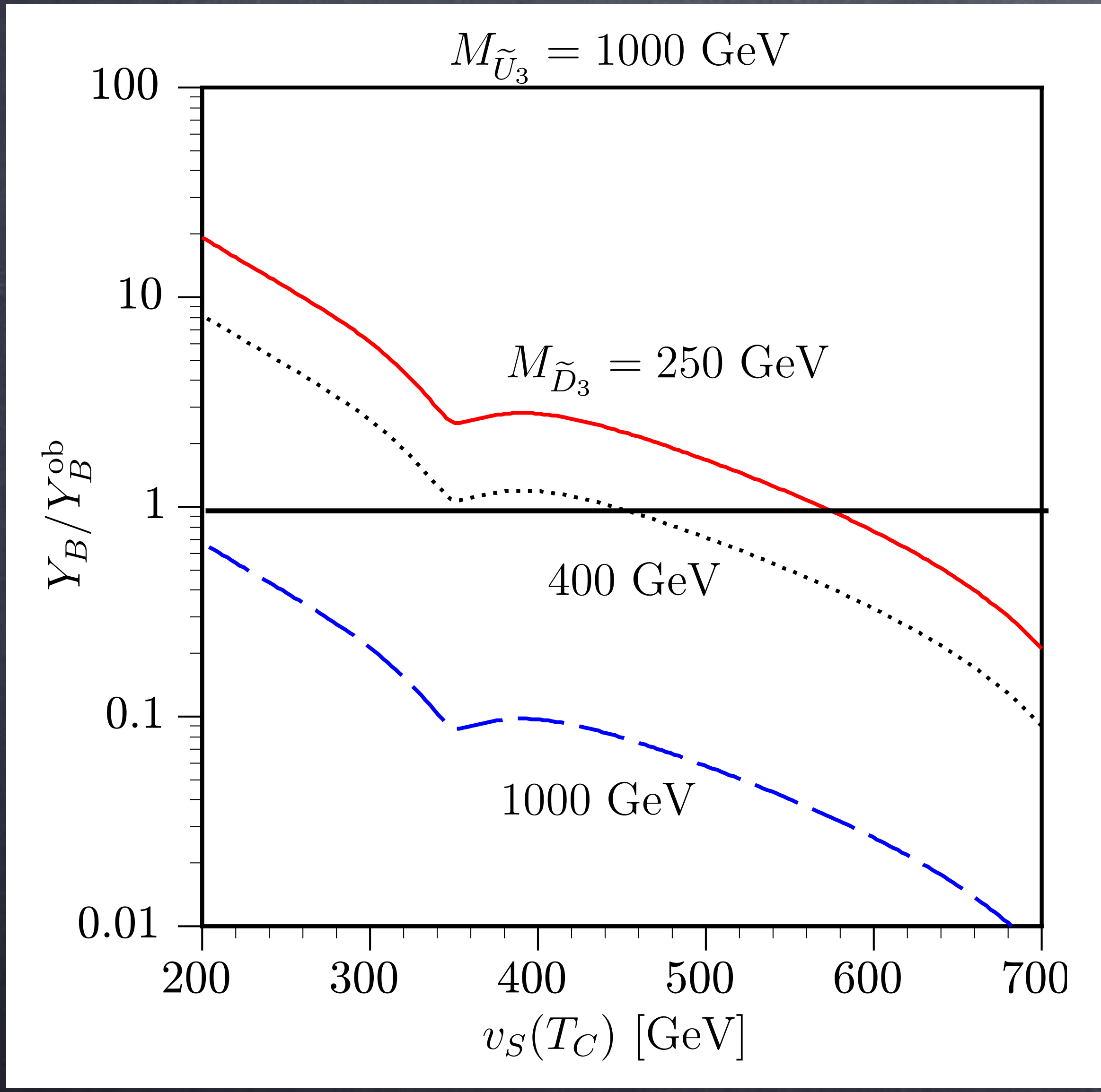

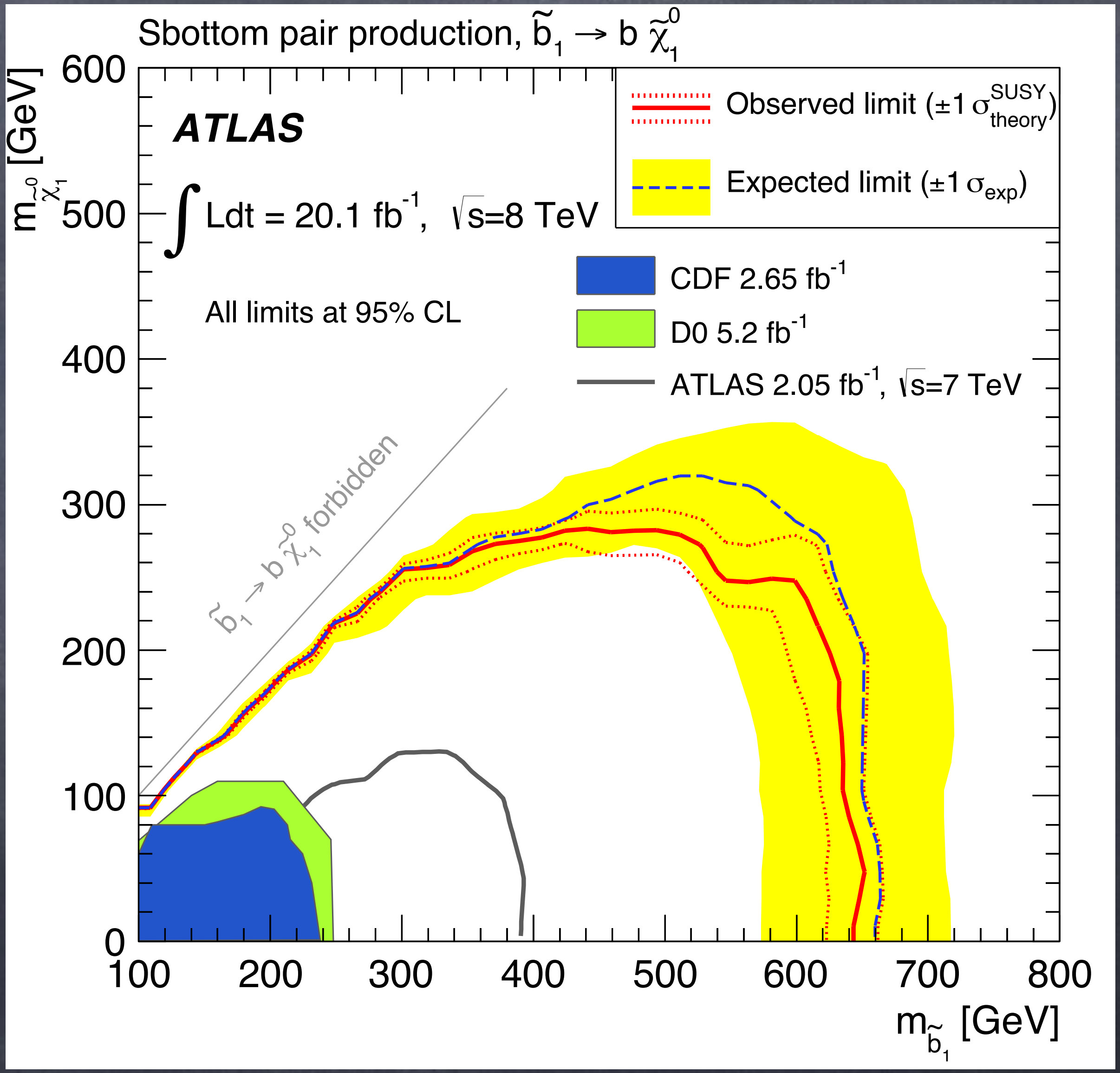

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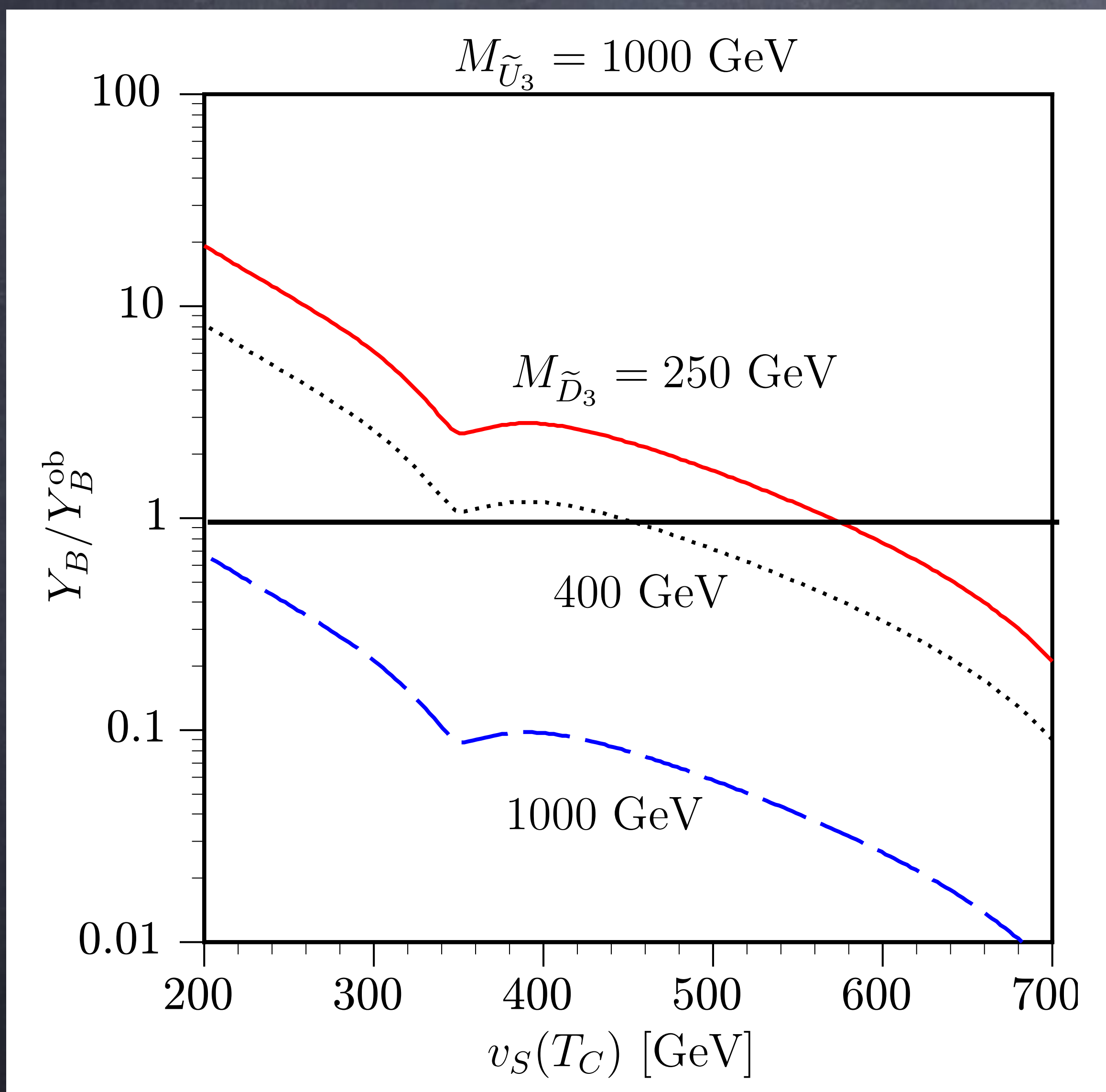

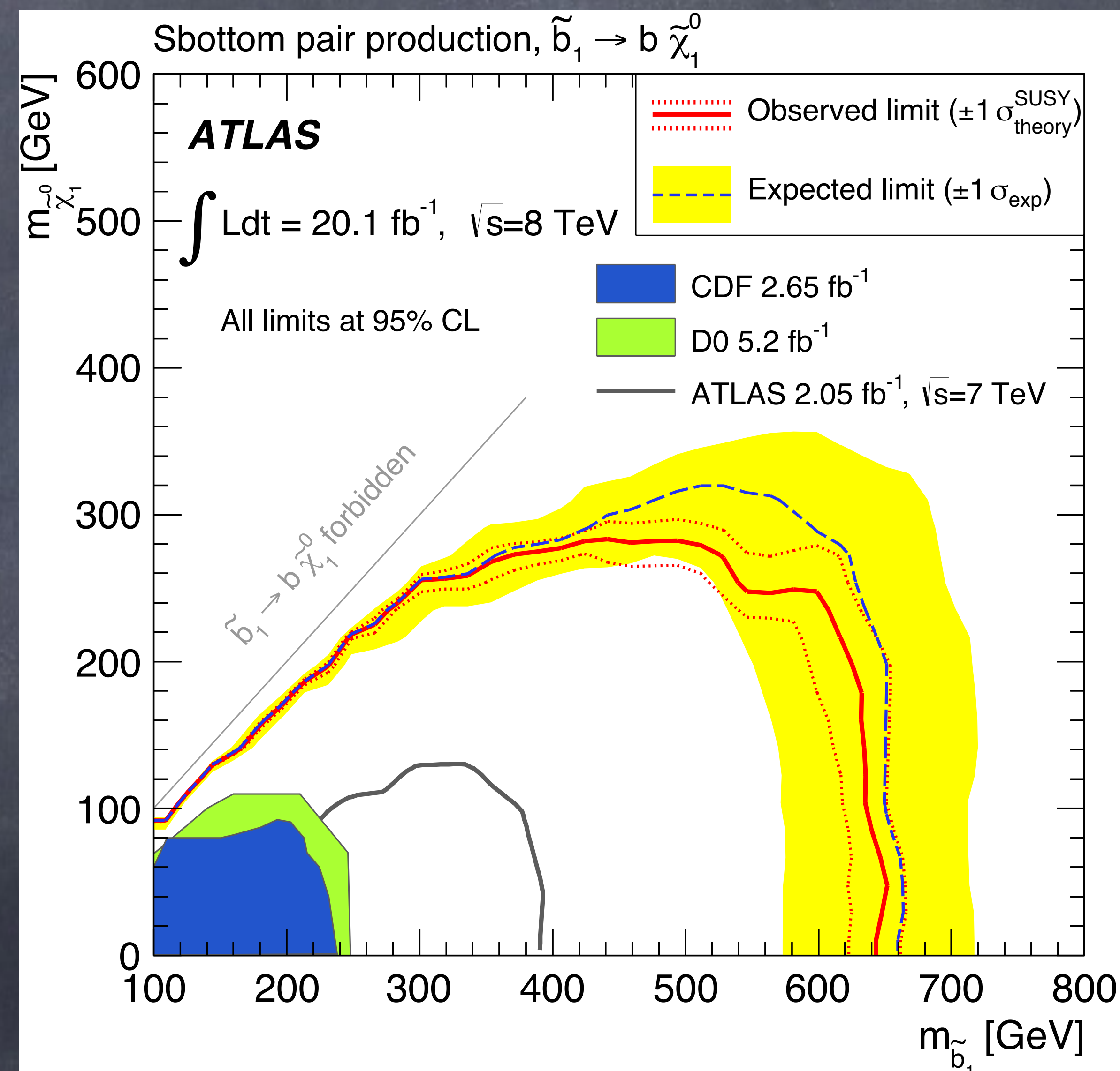

- ❒ This specific scenario is disfavored by sbottom searches.
- ❒ However, successful scenario still remain, e.g. bino-driven scenario.

Z′-ino-driven EWBG in the UMSSM

[E.S., PRD88, 055014 (2013)]

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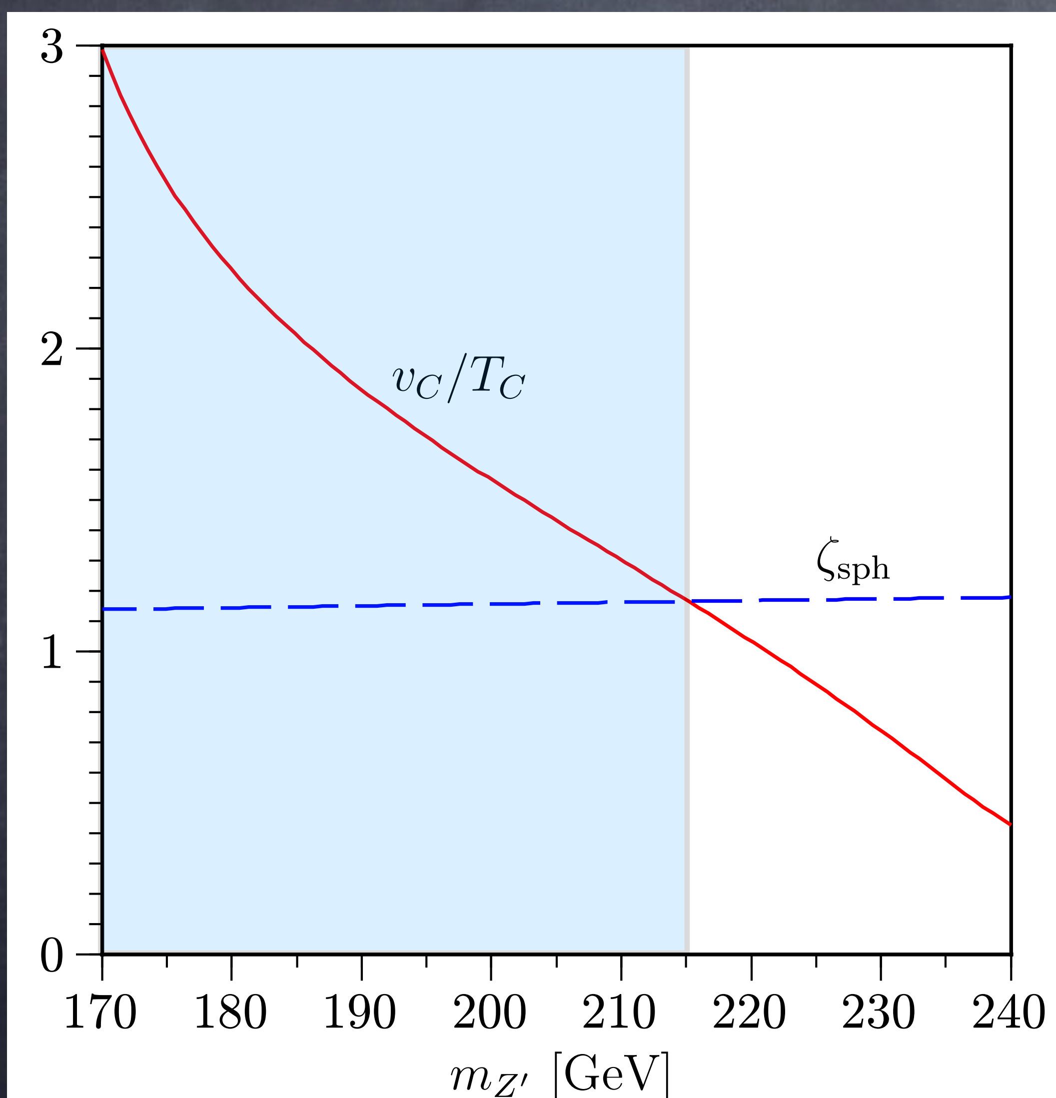

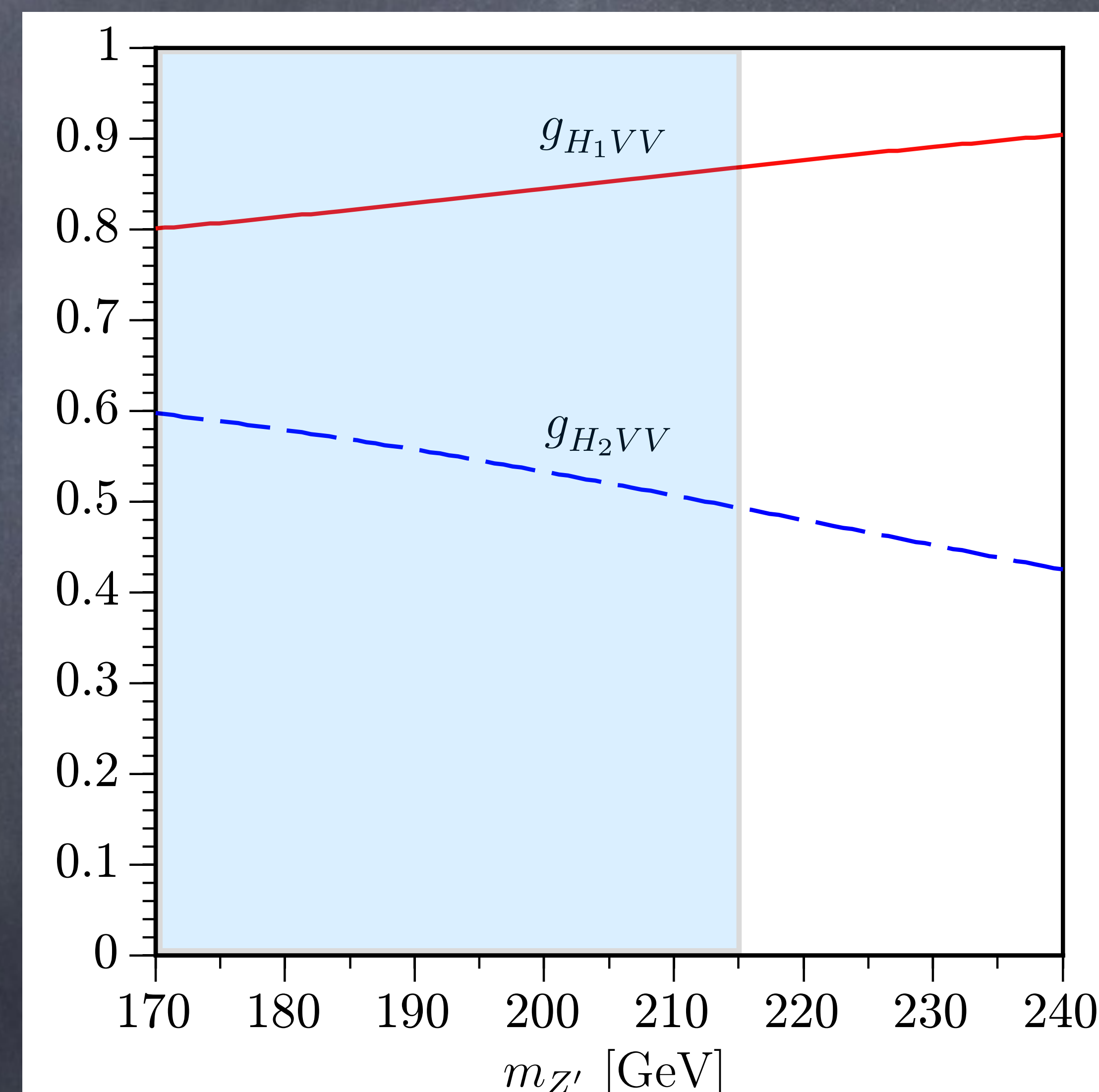

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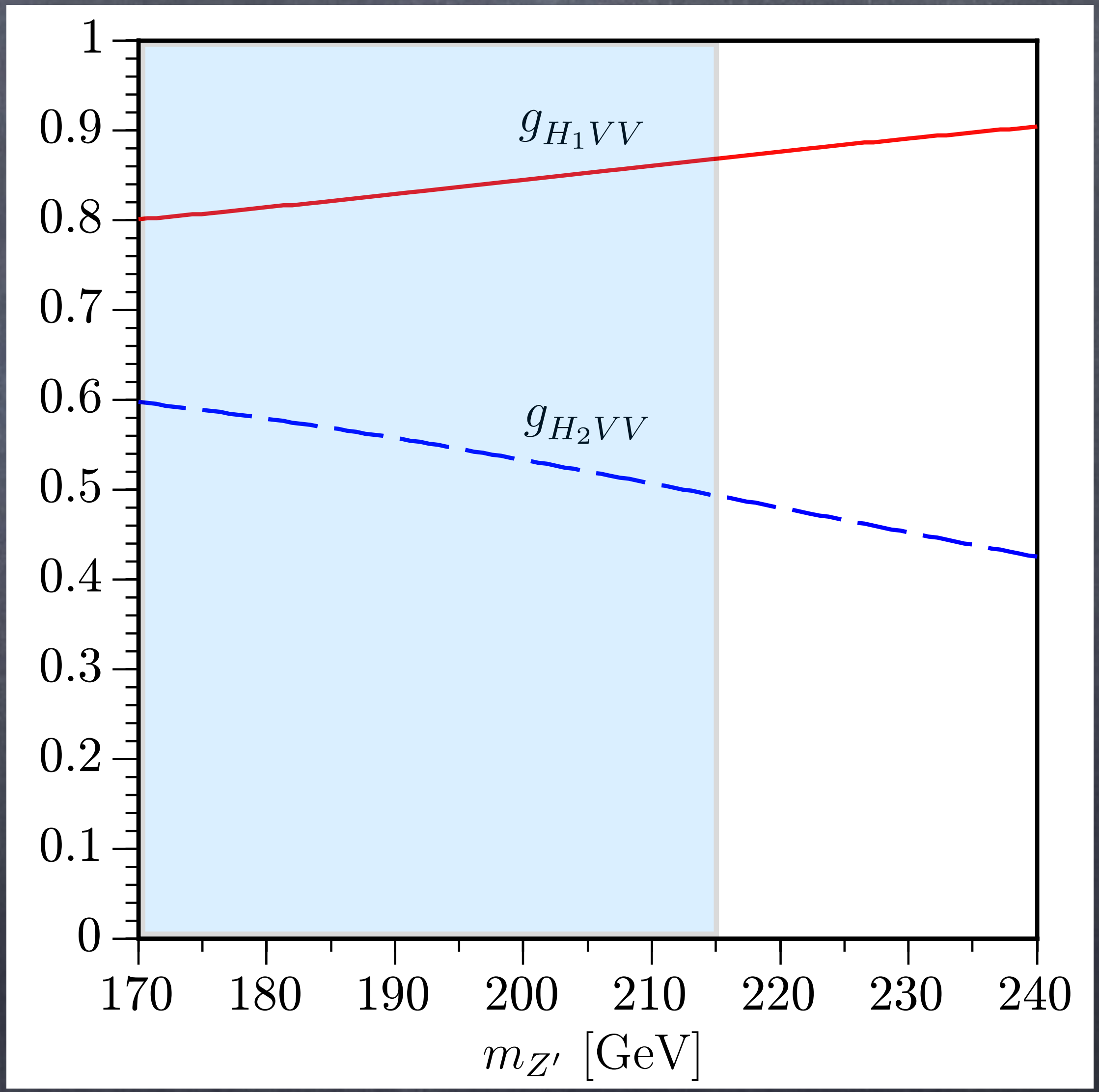

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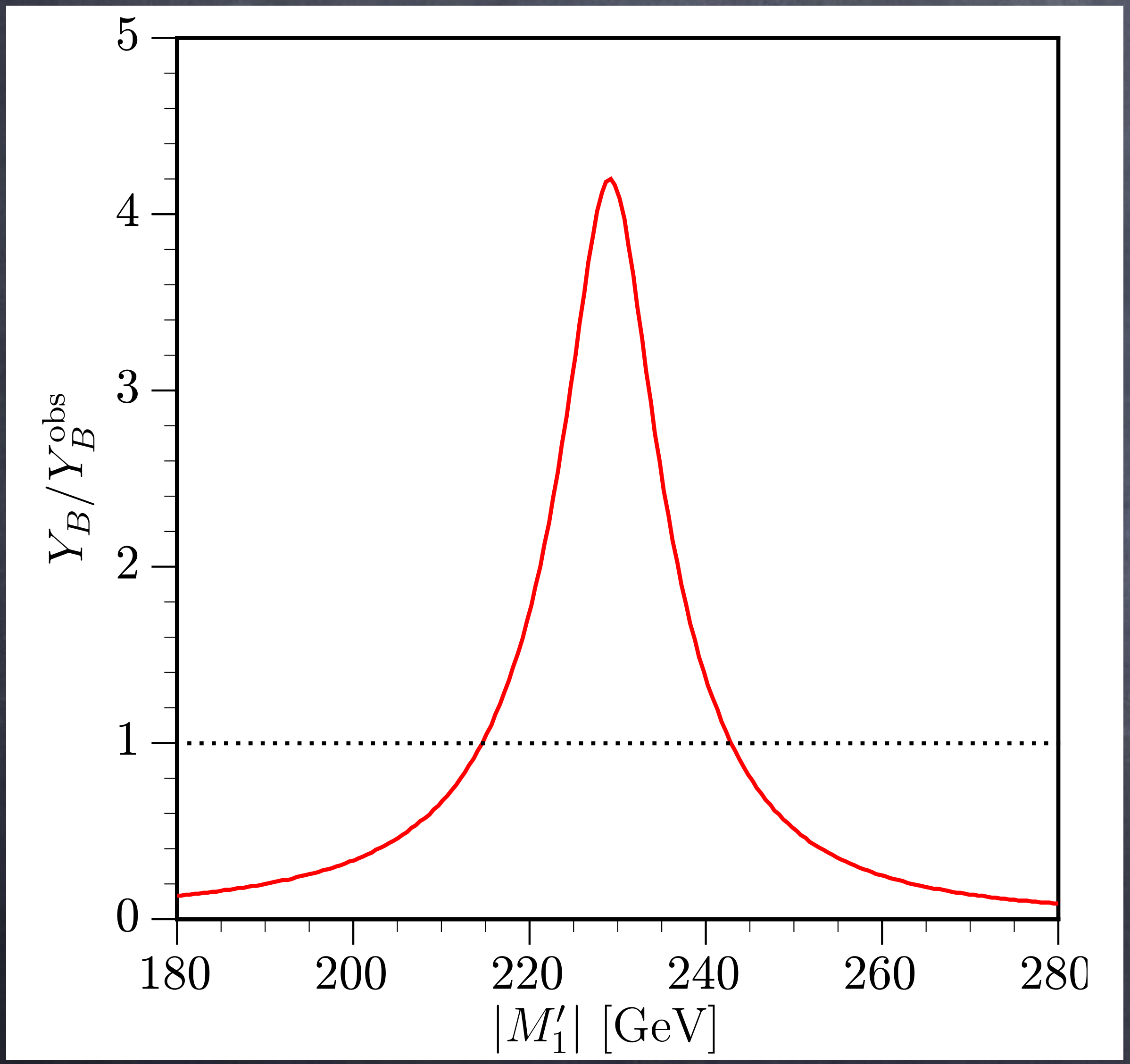

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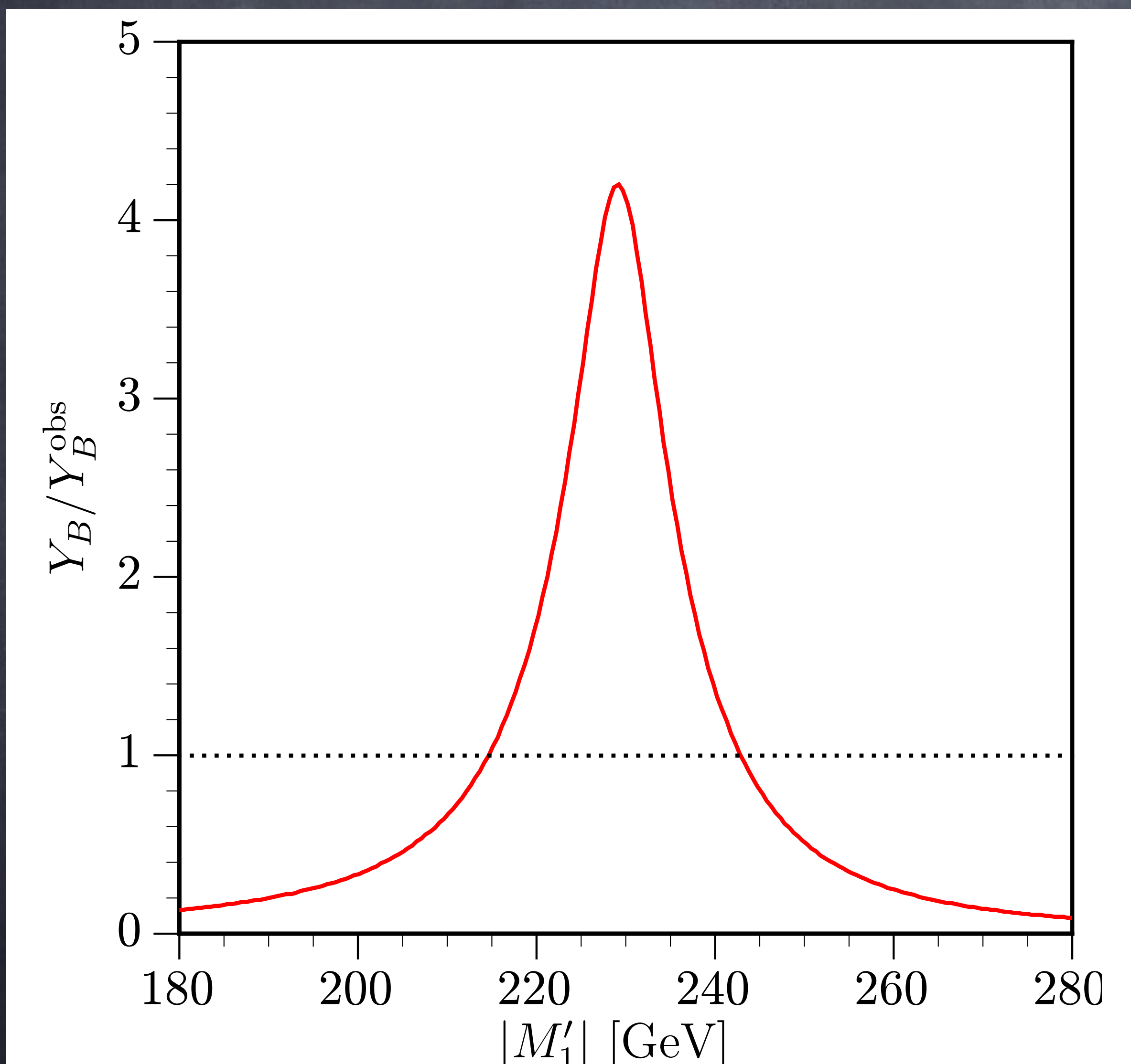

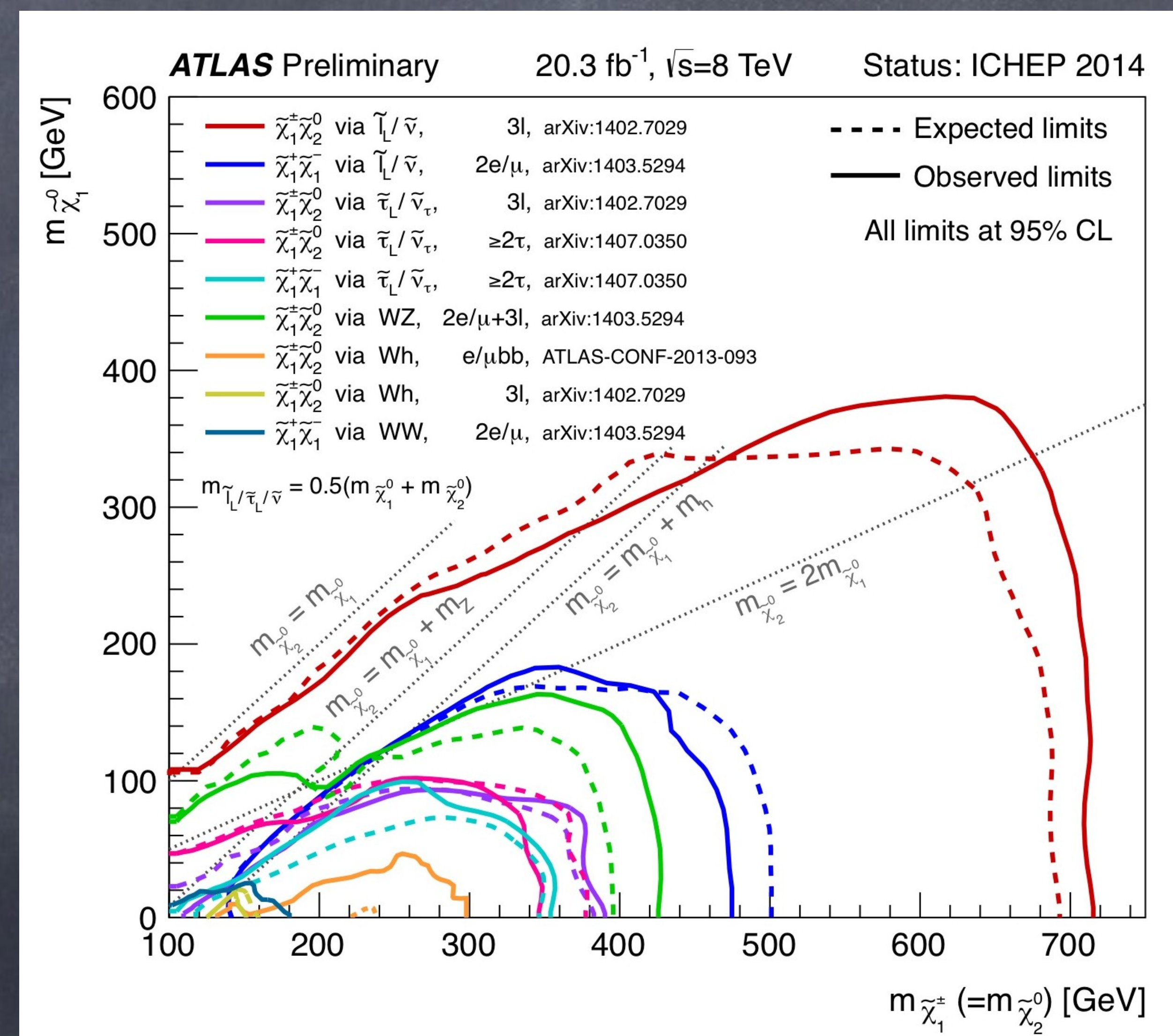

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Experimental constraints on light leptophobic Z′

- 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

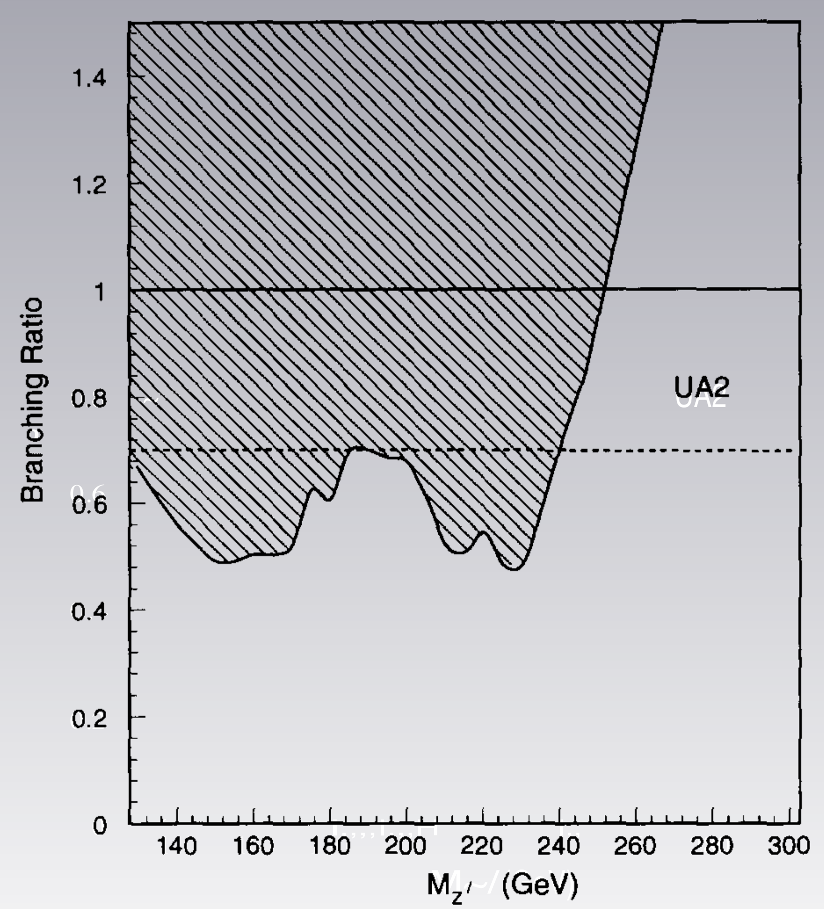

Fig. 5. Excluded region to 90% for $Z' \to \bar{q}q$, (excluded region is hatched). The branching ratio is given as a fraction of standard model branching ratio. The solid line shows a branching ratio of 1 for $Z' \to \bar{q}q$ whilst the dashed line shows a branching ratio of 0.7.

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