Electroweak Baryogenesis and its (Future) Collider Probes

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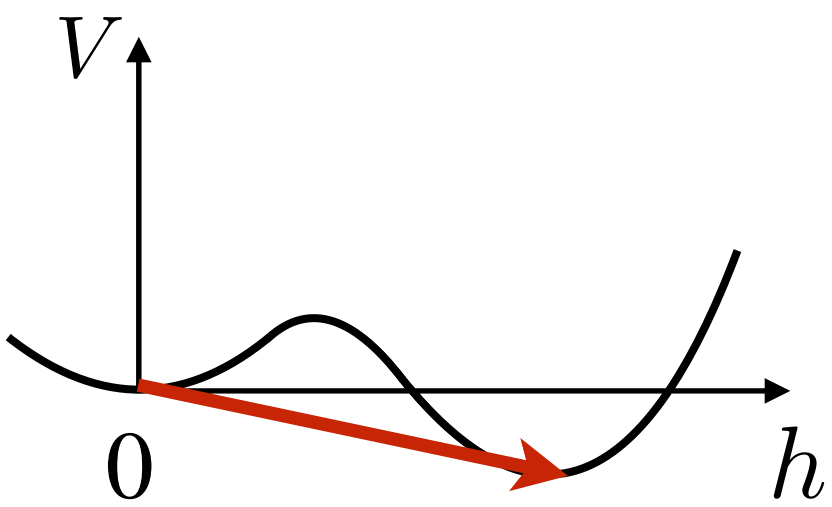
TUM

PASCOS 2024

Intro:
EWBG

Electroweak Baryogenesis

First order EW phase transition proceeds through bubble nucleation:



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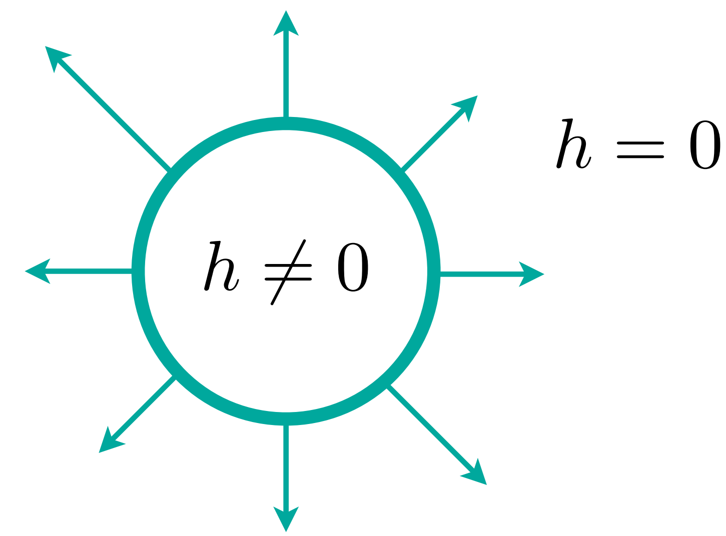

Shaposhnikov '87

Cohen,Kaplan,Nelson '91

Electroweak Baryogenesis

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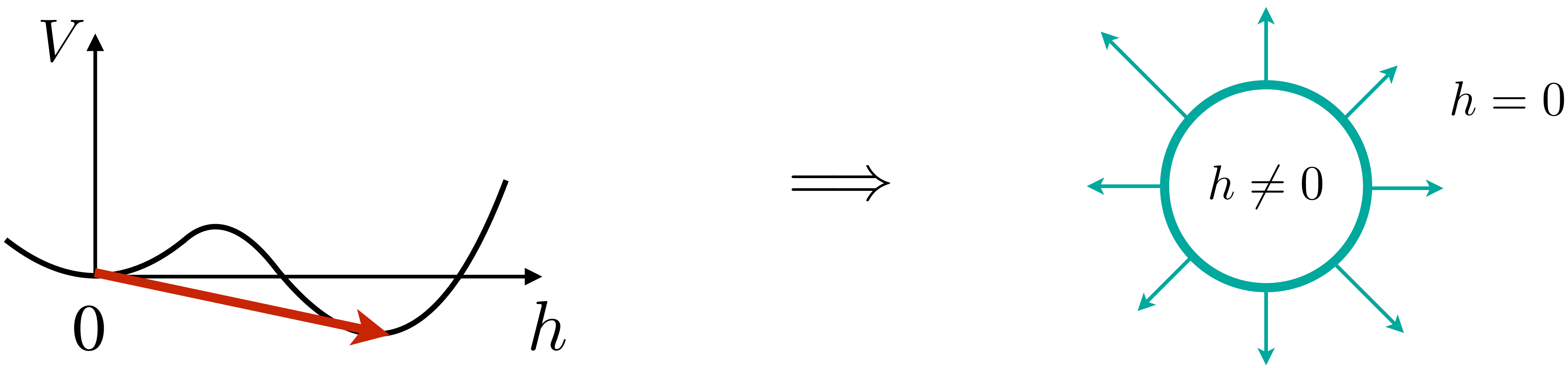
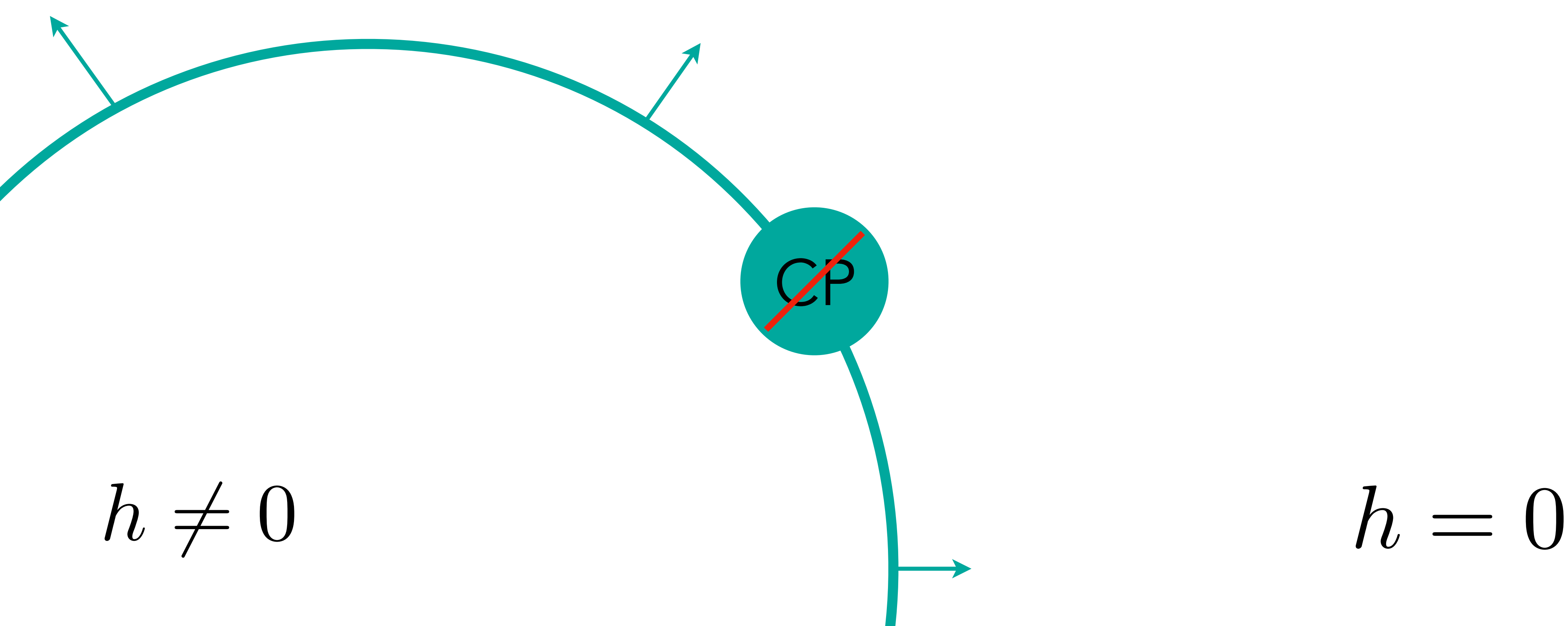


Baryon asymmetry is created close to bubble walls:



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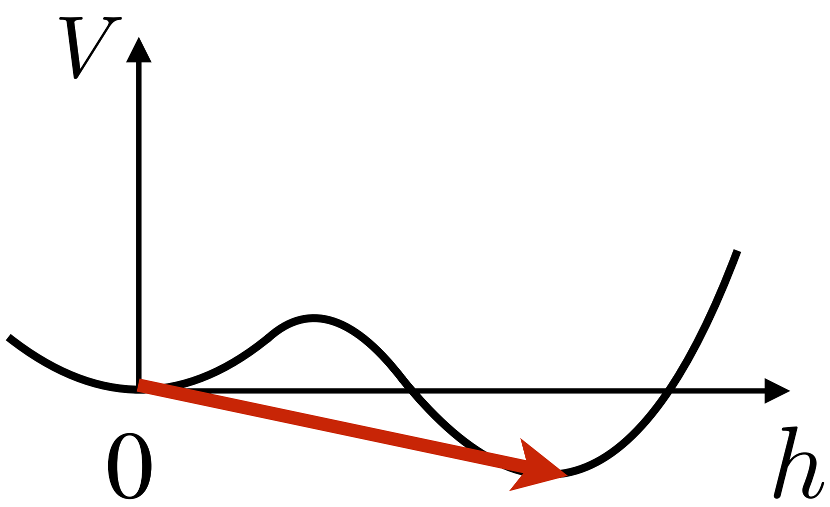

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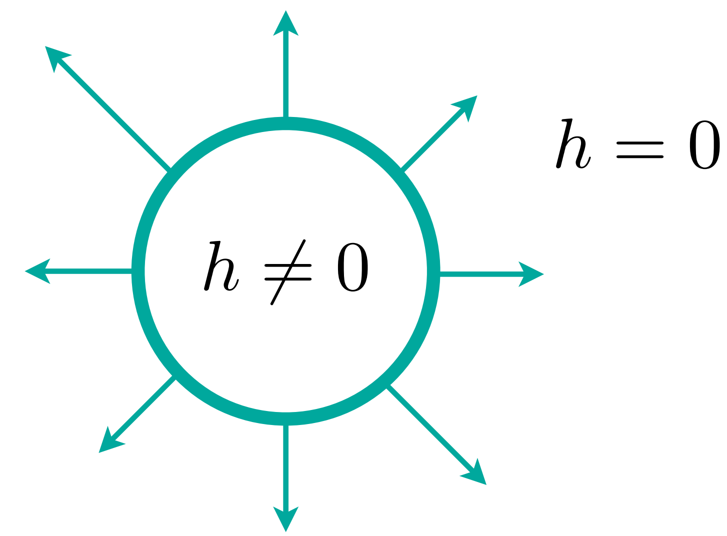

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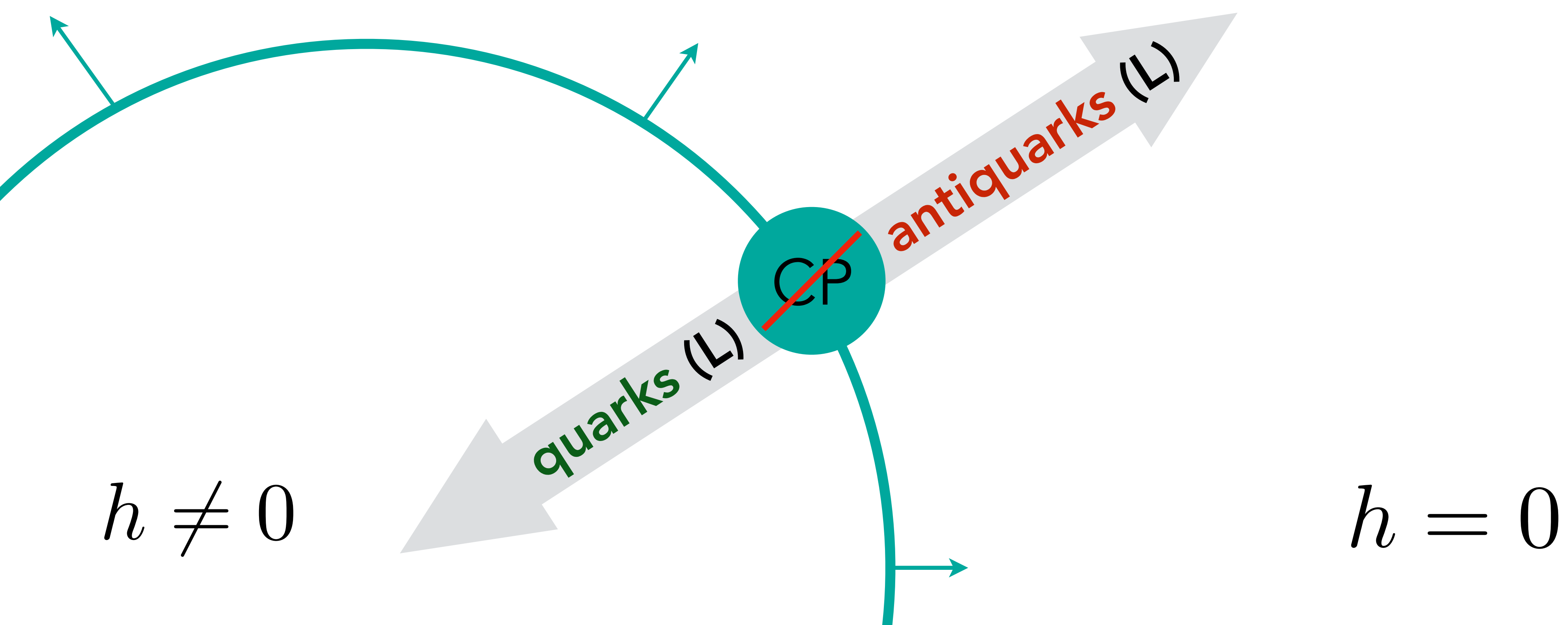

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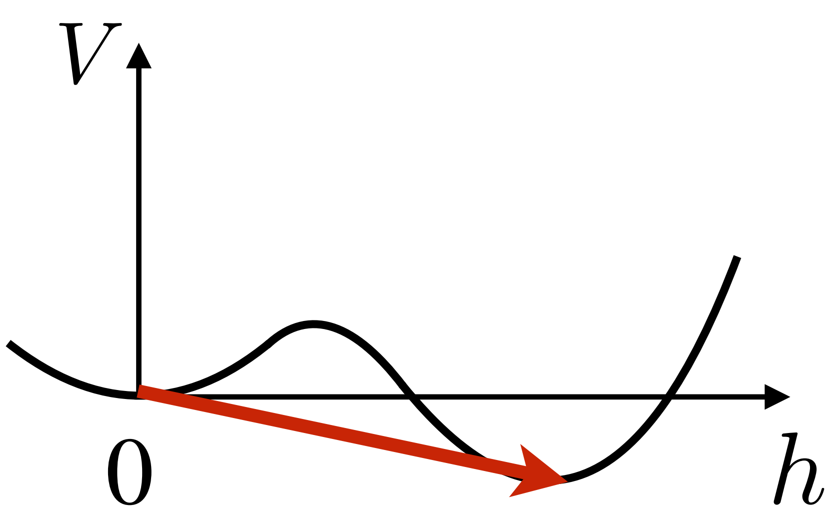

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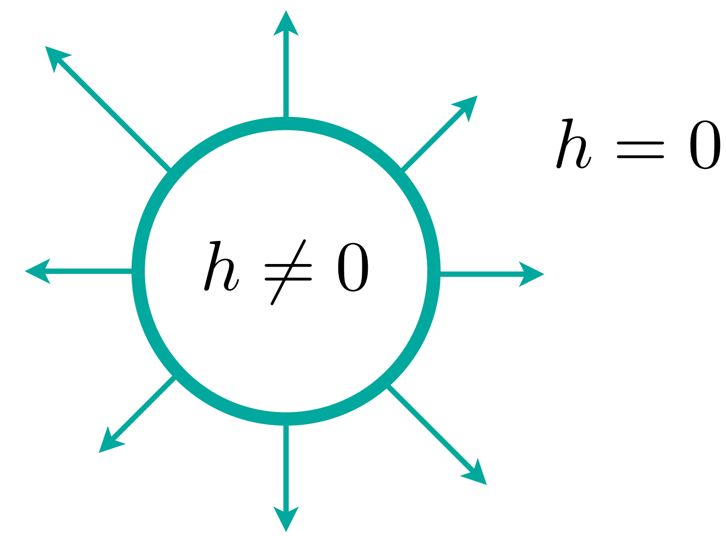

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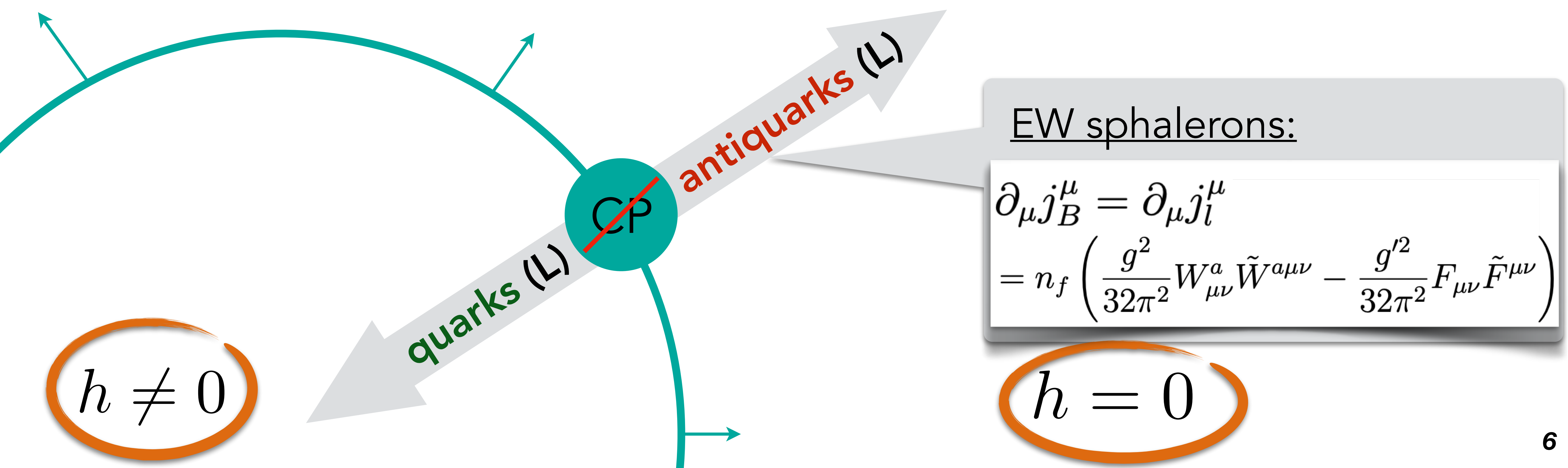

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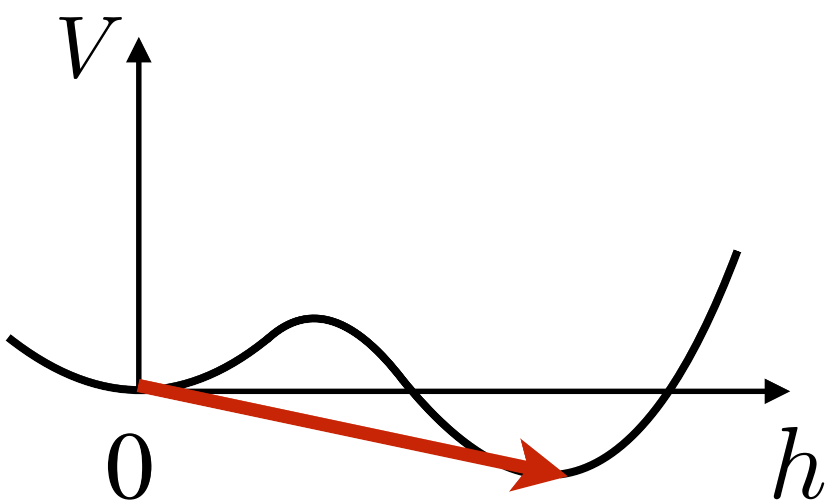

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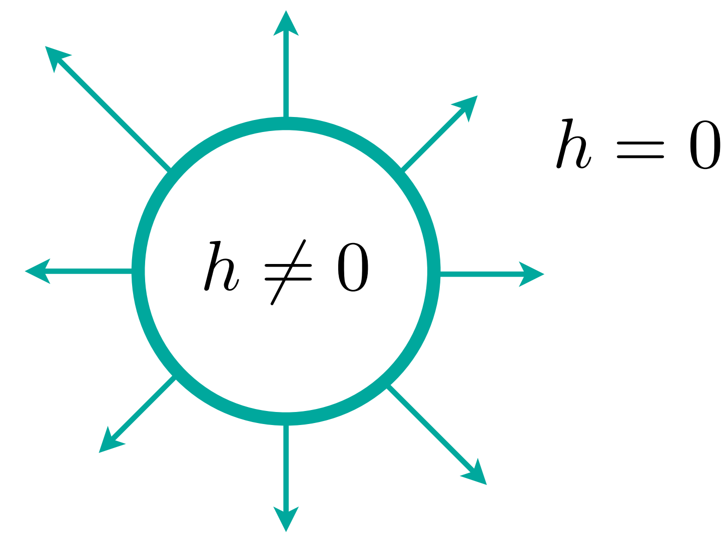

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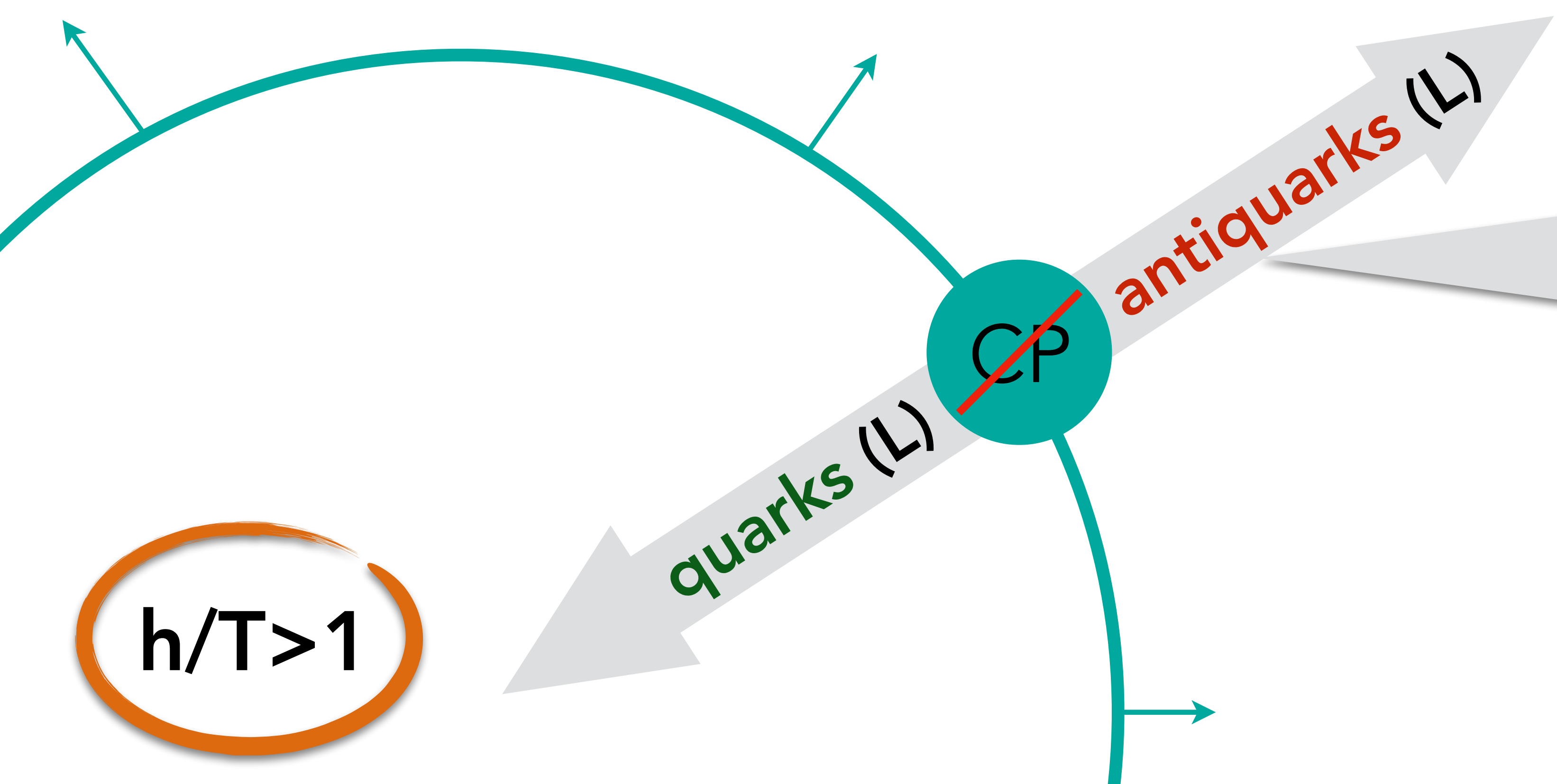

EW sphalerons:

rate $\sim \exp[-h/T]$

convert B into L **at h/T<1**

$h = 0$

Electroweak Baryogenesis

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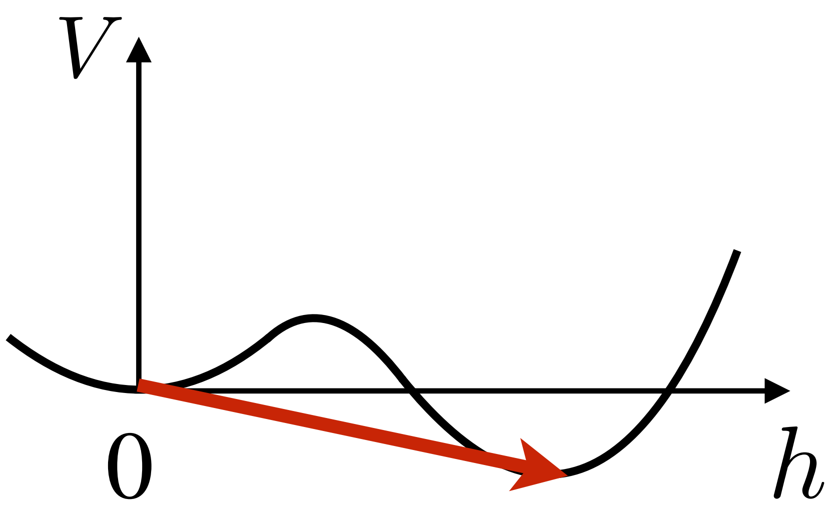

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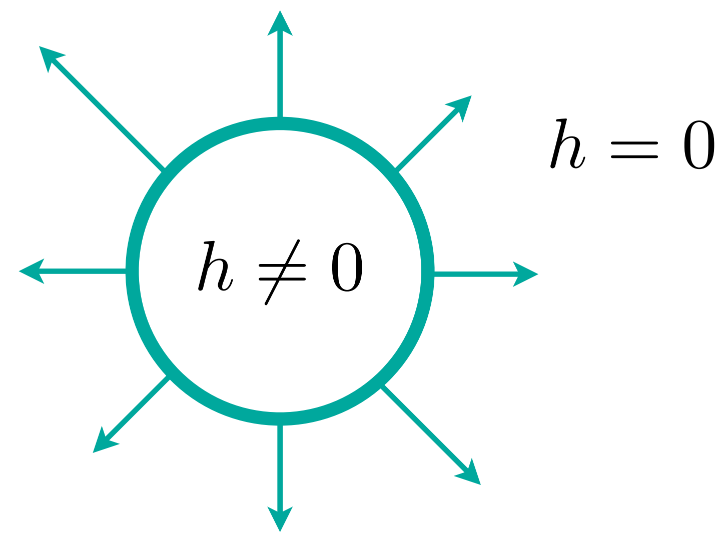

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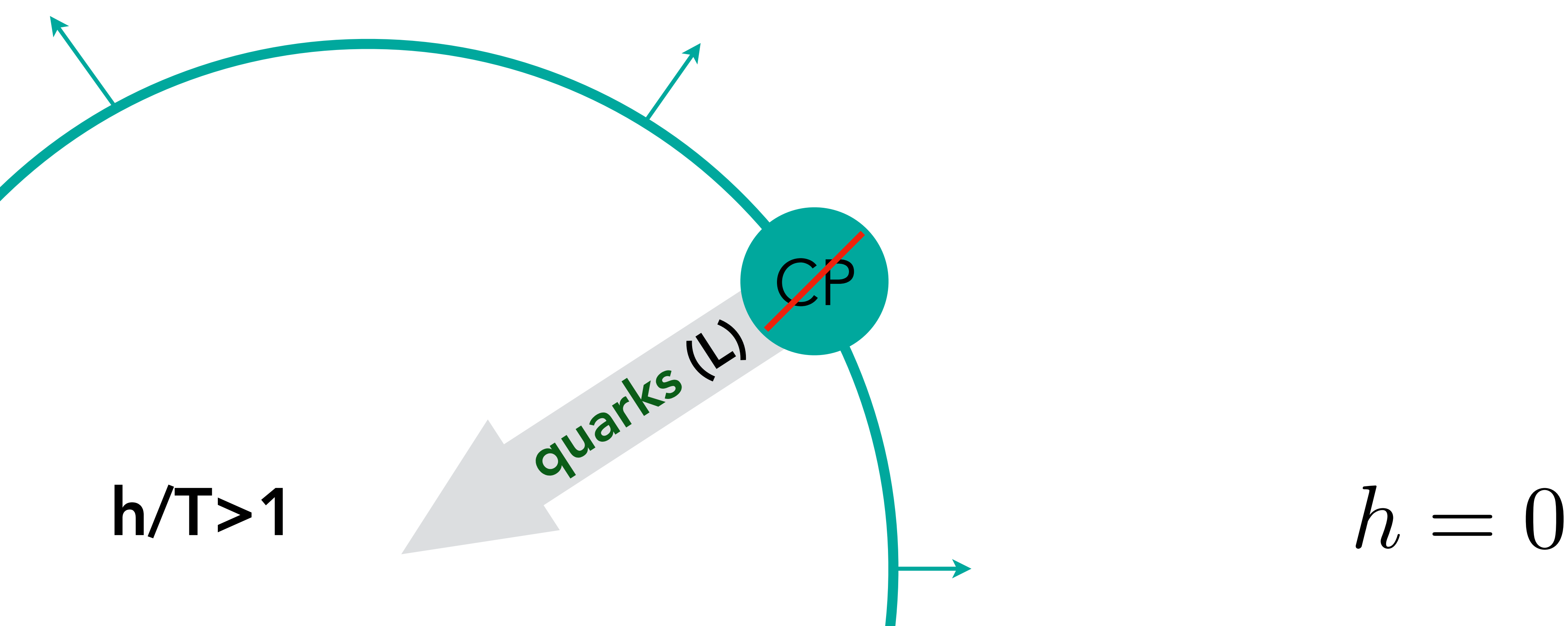

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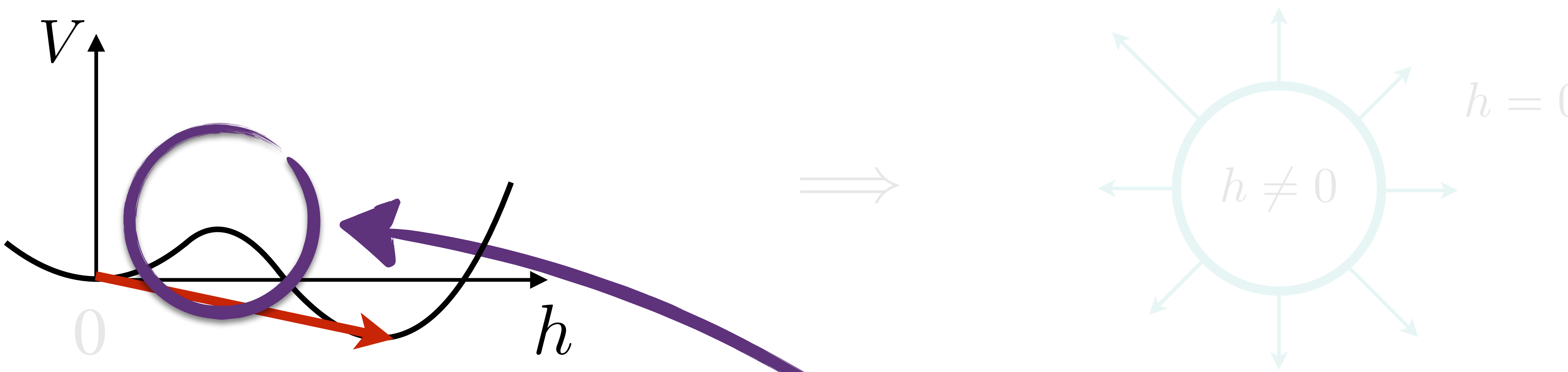

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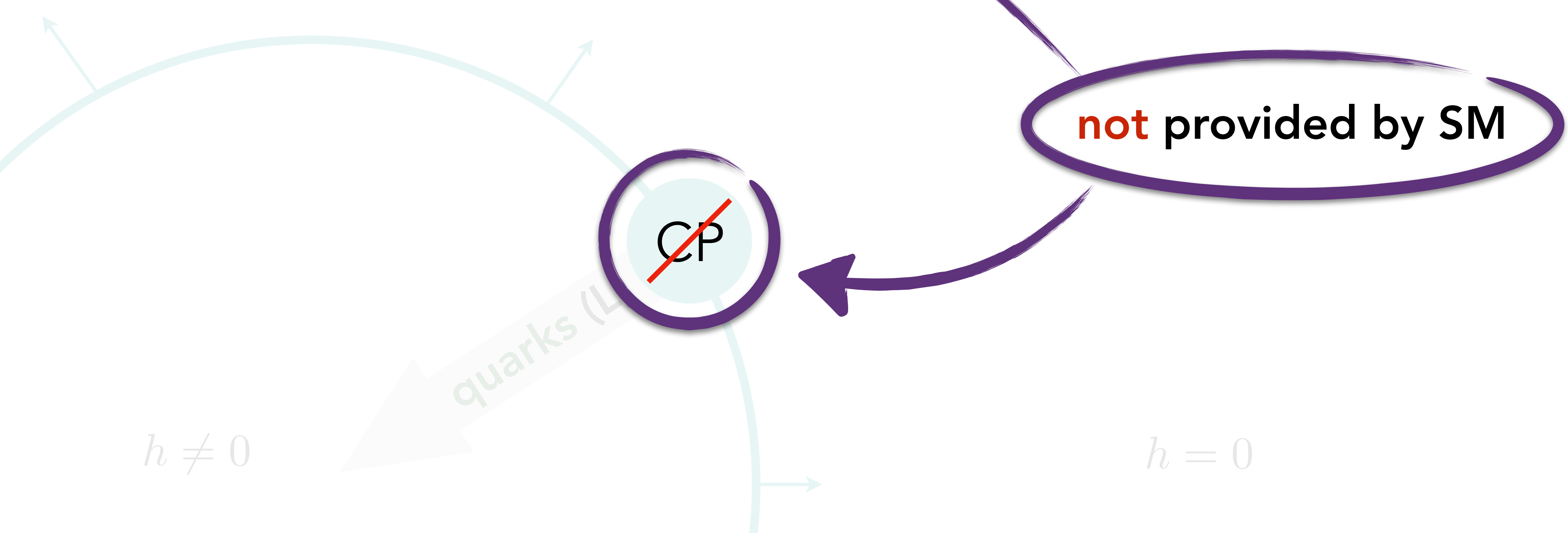
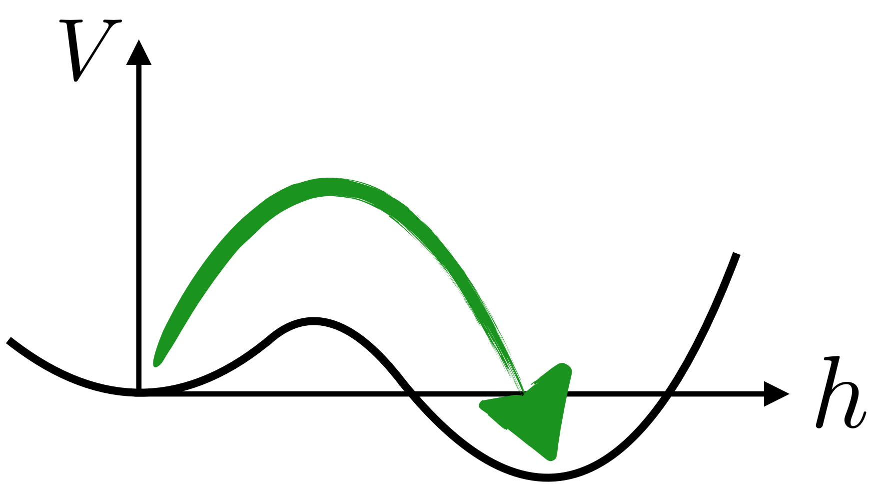


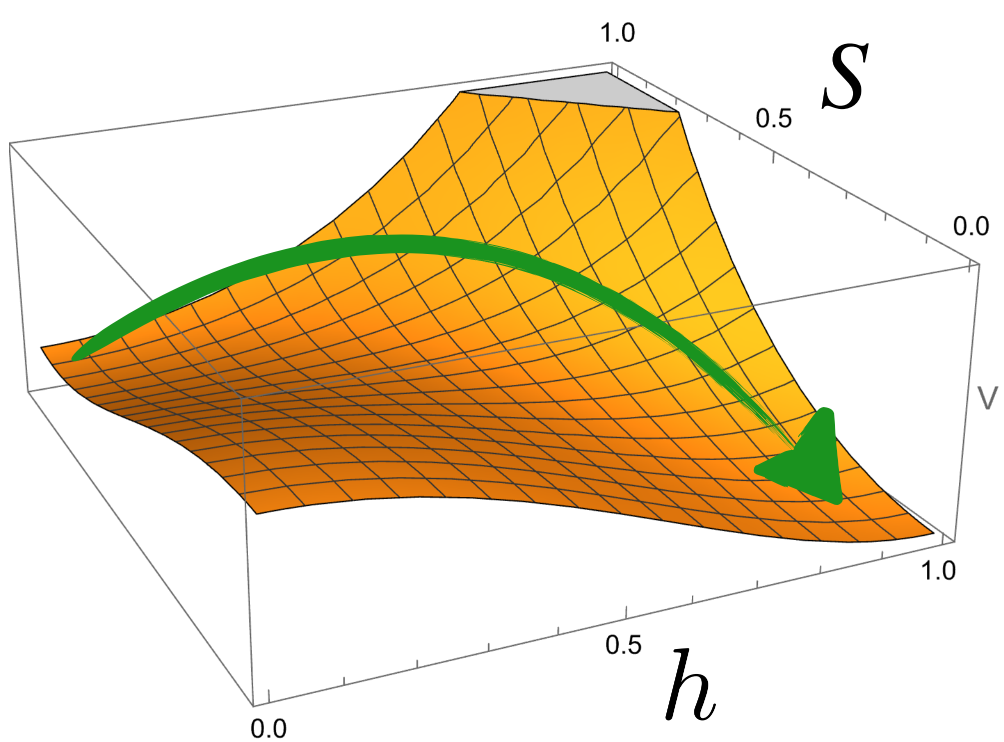
How to get first-order EWPT?

How to get first-order EWPT?

- New particles s.t. thermal/quantum corrections modify SM Higgs potential



- New field directions



SM + Singlet

$$V_{\text{tree}}(h,S) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4$$

- Only an extremely small explicit $S \to -S$ breaking is needed to get B asymmetry and remove domain walls. Espinosa et al, 1110.2876

- Consider the case with $S \to -S$ respected by the EWSB minimum

(For models with spontaneous or sizeable explicit breaking see 2210.16305,1911.10206)

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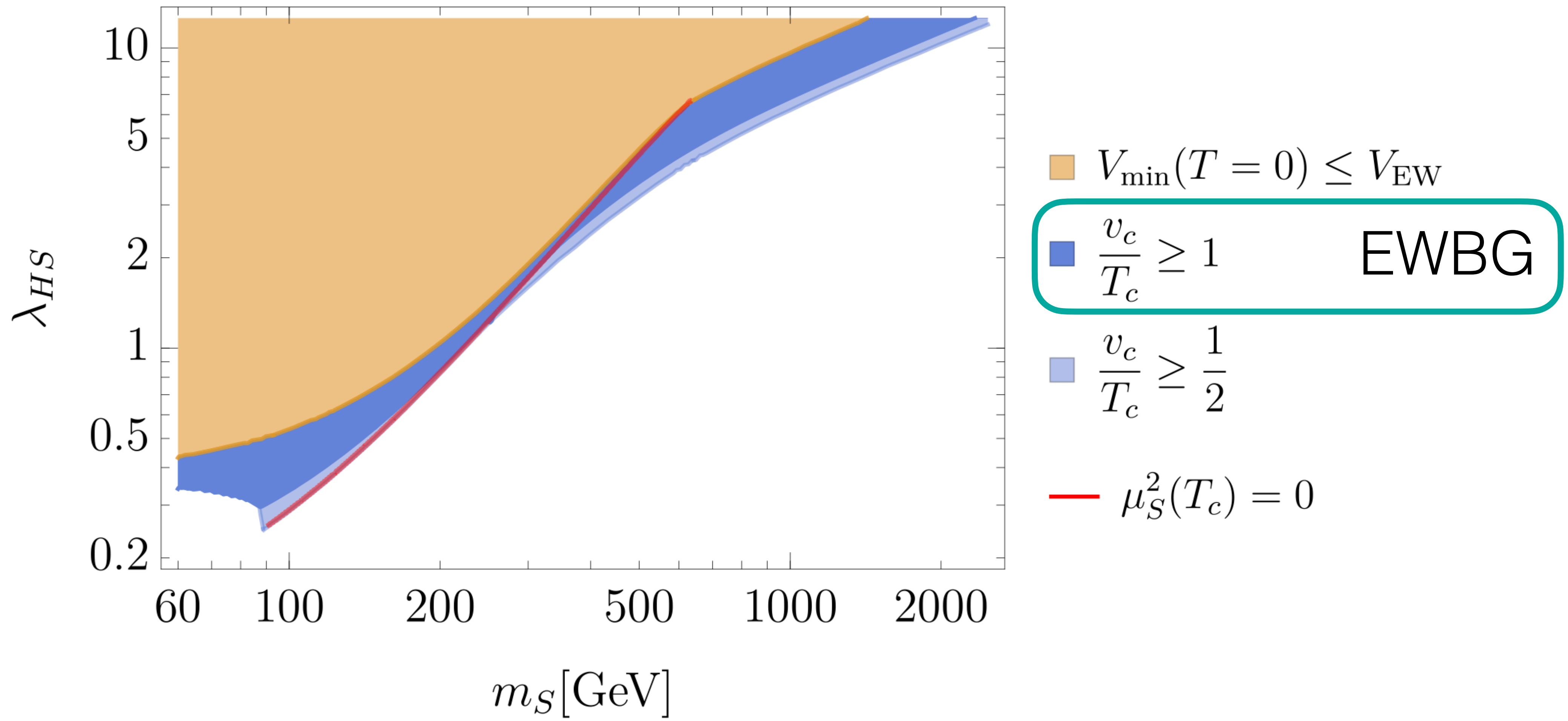

A.Benival et al, 1702.06124

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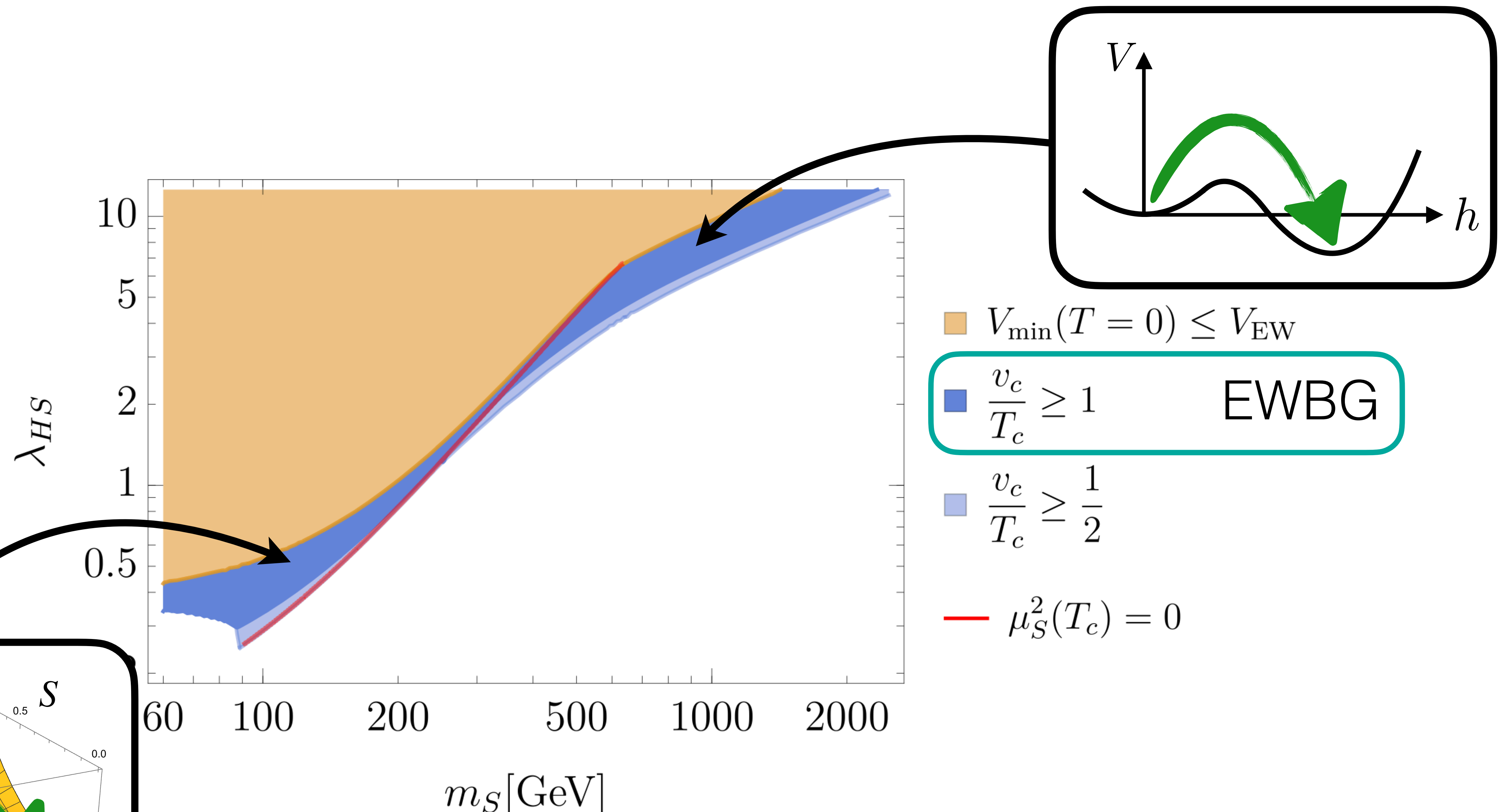

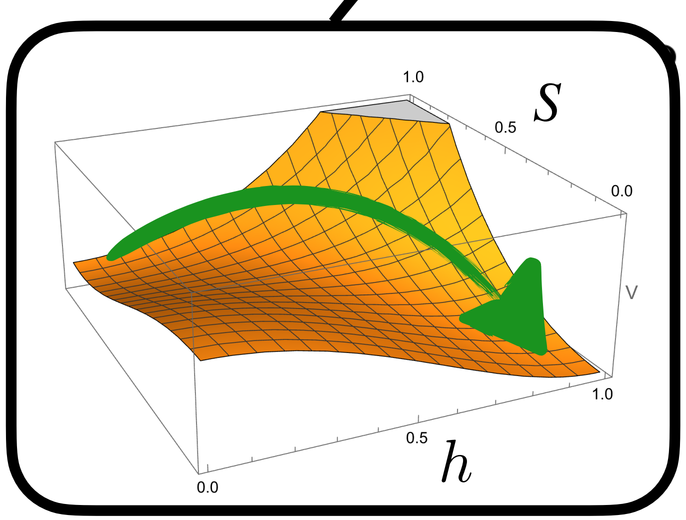

A.Benival et al, 1702.06124

SM + Singlet

Pheno: S-h mixing

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- $S \to -S$ symmetry:

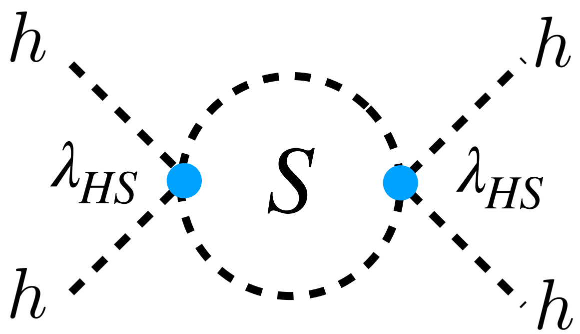
  $\Rightarrow$ no sizeable Higgs-S mixing

  $$\sin\theta \propto \lambda_{HS} \langle h \rangle \langle S \rangle$$

  $\Rightarrow$ loop-induced effects of λ_{HS}

SM + Singlet

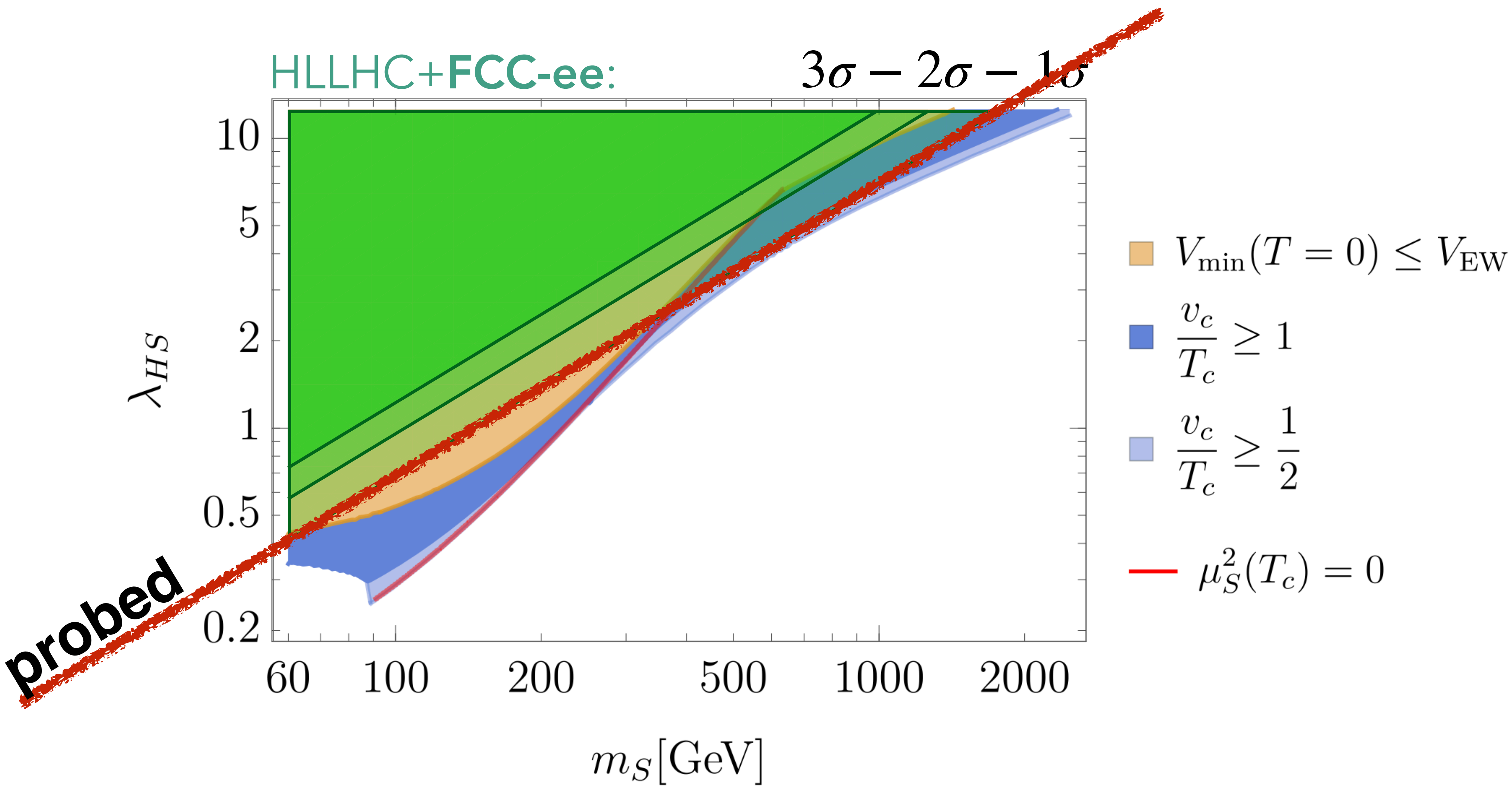
Pheno: c_H



$$\mathcal{O}_H = \frac{1}{2}(\partial_\mu |H|^2)^2$$

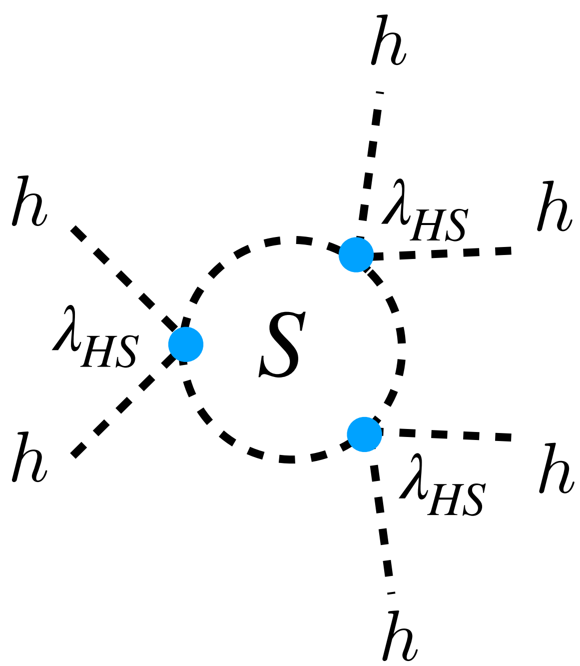
$$\frac{c_H}{\Lambda^2} = \frac{\lambda_{HS}^2}{48\pi^2}\frac{1}{m_S^2}$$

M.Carena et al, 2104.00638



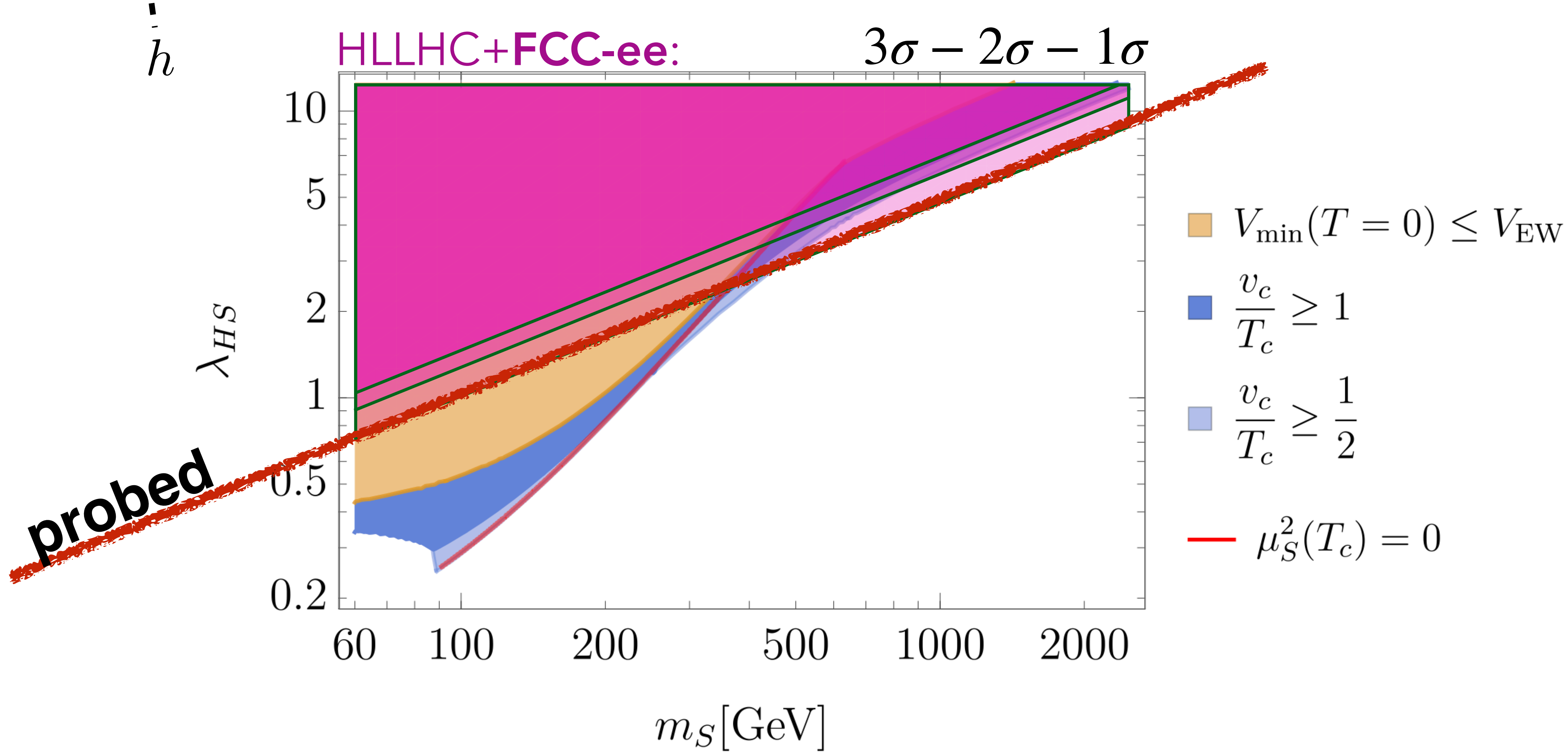
SM + Singlet

Pheno: h^3



$$\lambda_3 = \frac{1}{6}\frac{\partial^3 V(h,S=0,T=0)}{\partial h^3}\bigg|_{h=v_0} \approx \frac{m_h^2}{2v_0} + \frac{\lambda_{HS}^3 v_0^3}{24\pi^2 m_S^2}$$

A.Benival et al, 1702.06124



Intermediate Conclusion

$$V_{\mathrm{tree}}(h,S) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4$$

Most minimal model:

- Will be partly probed at the next (?) collider
- EDMs, tree level Higgs couplings modifications suppressed
- GW signal typically too weak (where $v_{wall} < 1$)

J.Ellis et al, 2210.16305

Intermediate Conclusion

Anything more exciting?

- EWBG models can be arbitrarily more complex and also provide much more signals
  - sizeable Z_2 breaking
  - 2HDM
  - embedding in more "complete" models with their own typical signals
  - …
- I will now consider the opposite limit: models which are already on the border of exclusion, yet motivated by other considerations

Origin of EWBG vs EXP Tensions

$\langle H \rangle$'s Thermal History and EW Baryogenesis

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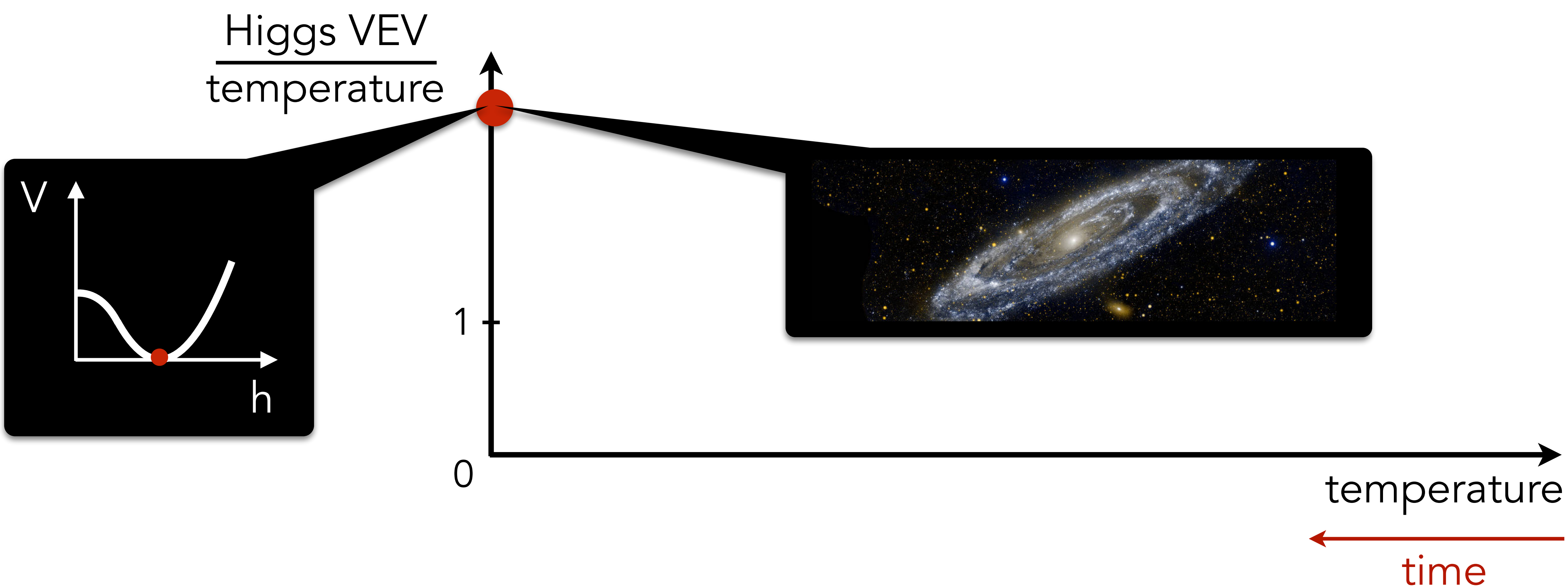
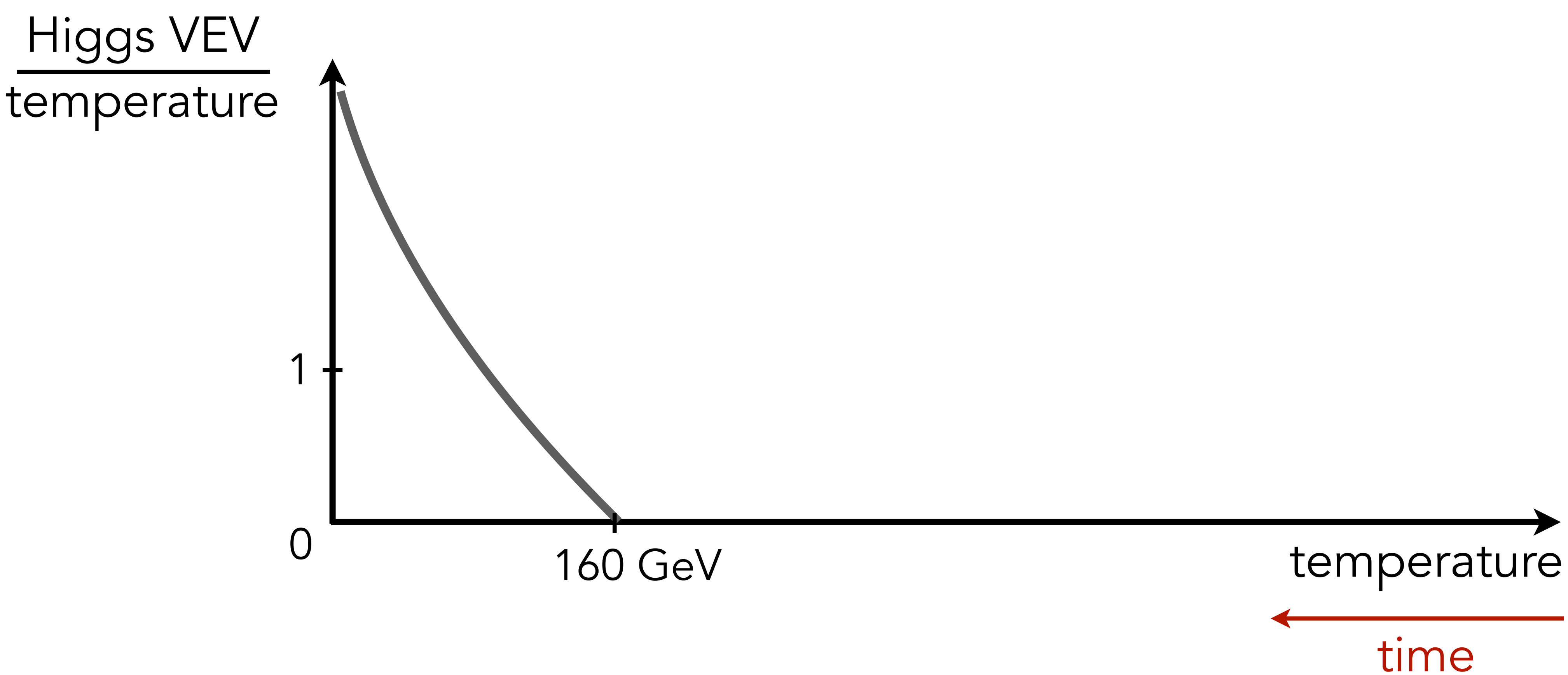


$\langle H \rangle$'s Thermal History and EW Baryogenesis

in Standard Model: high-T symmetry restoration



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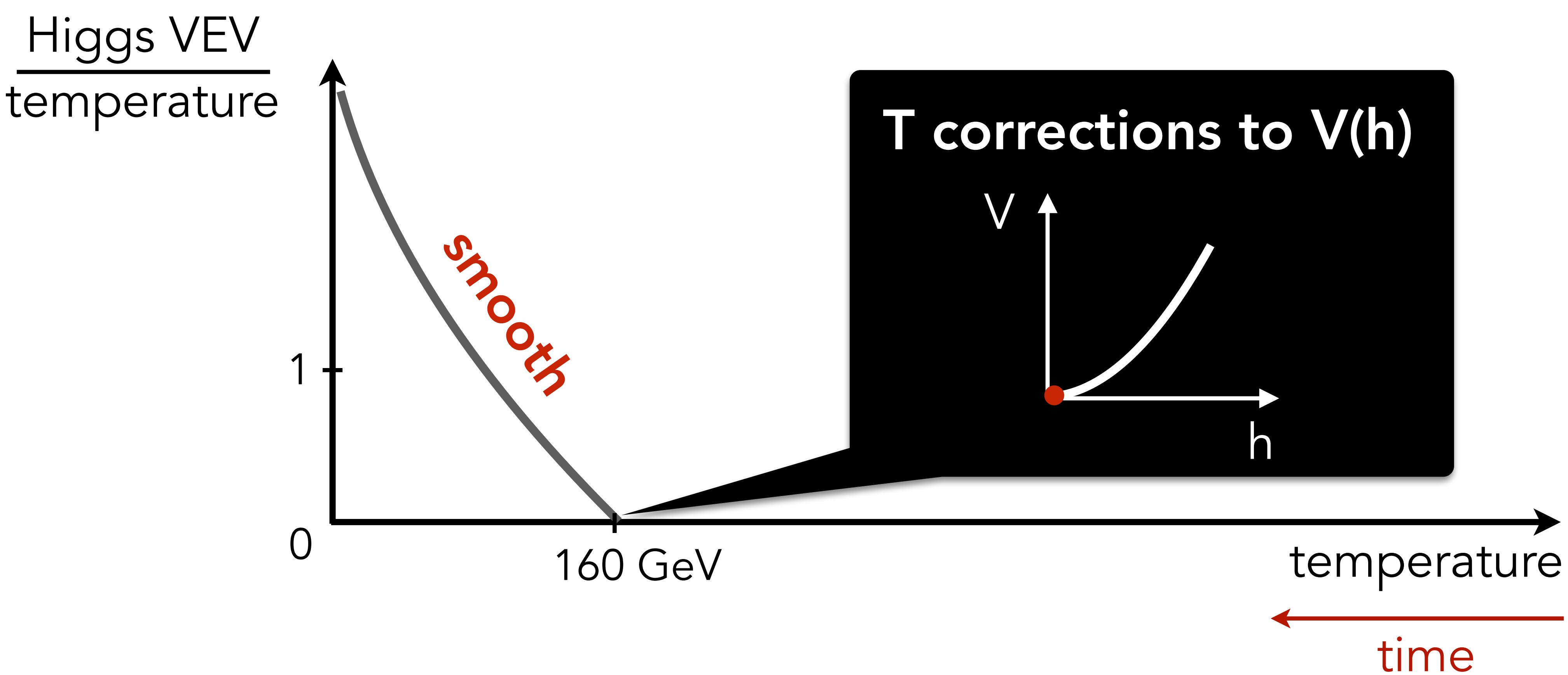
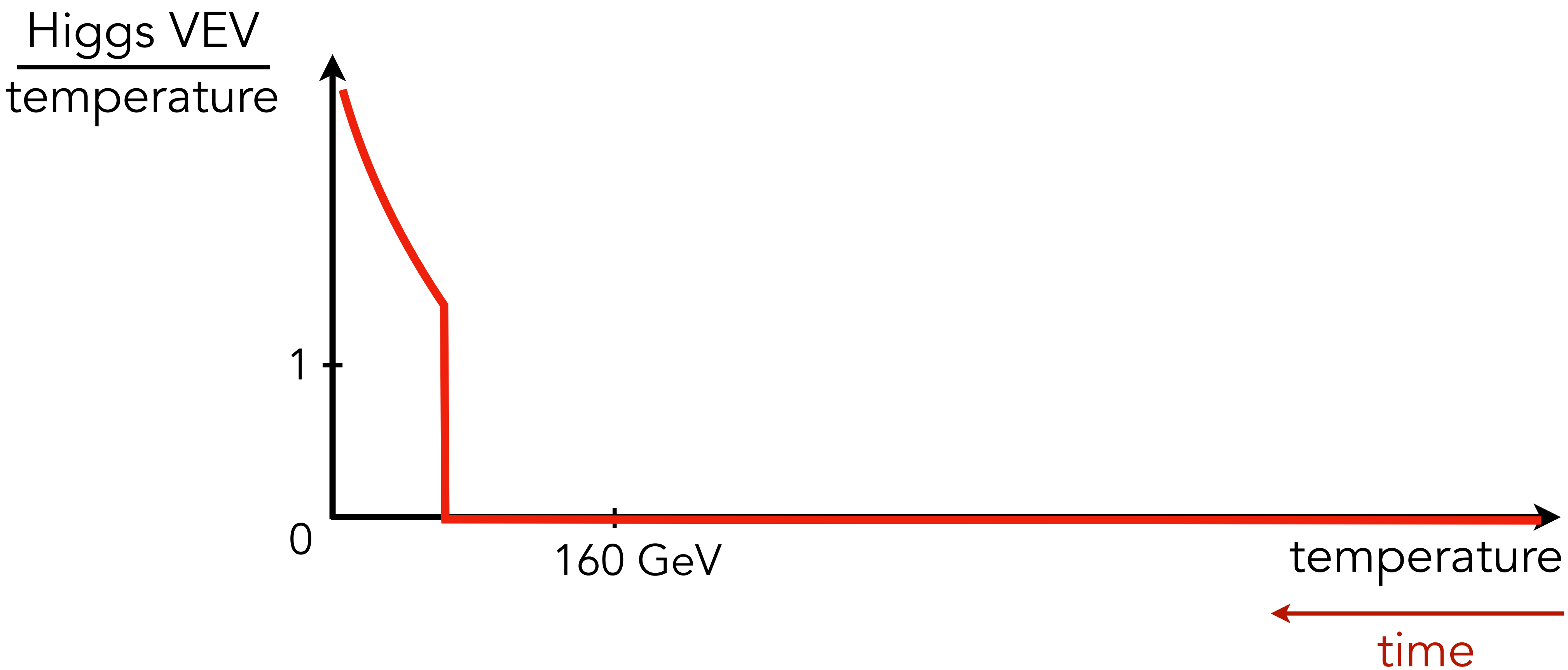


$\langle H \rangle$'s Thermal History and EW Baryogenesis

in Electroweak Baryogenesis scenarios



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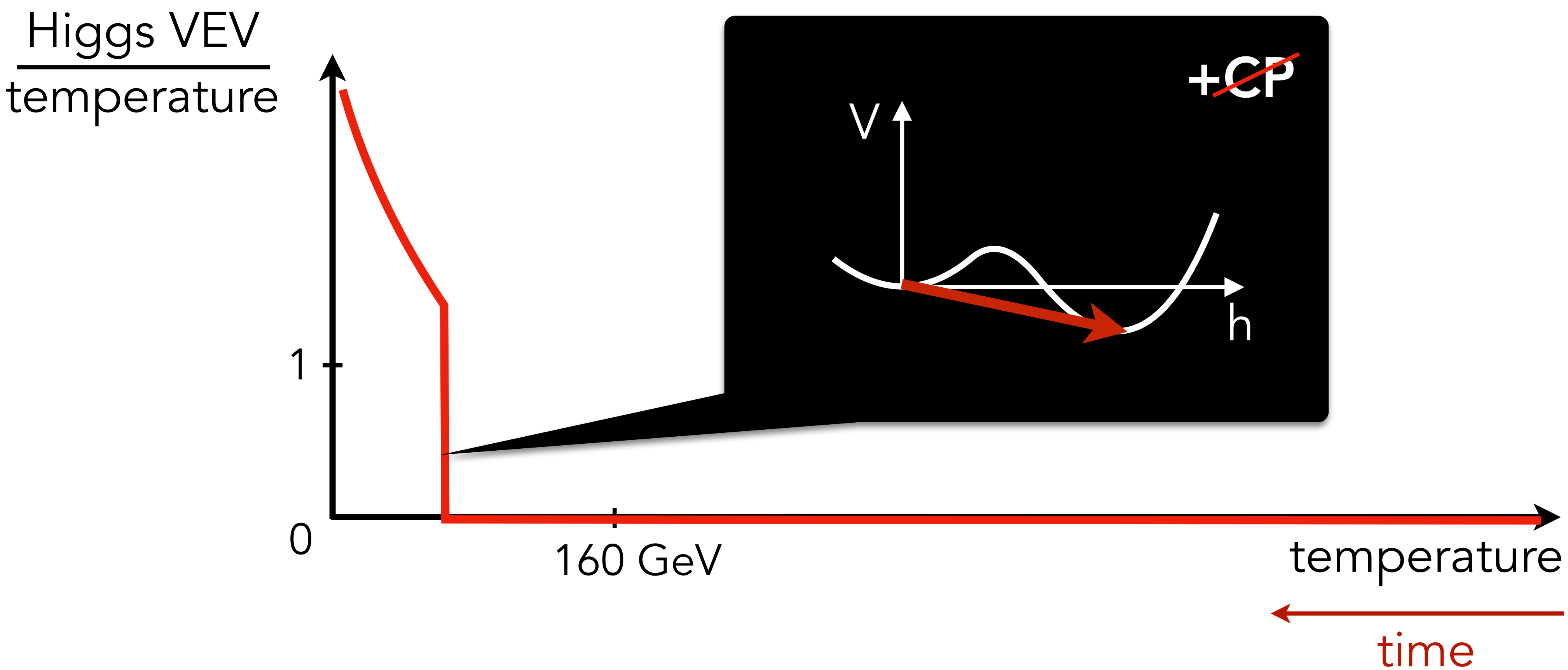

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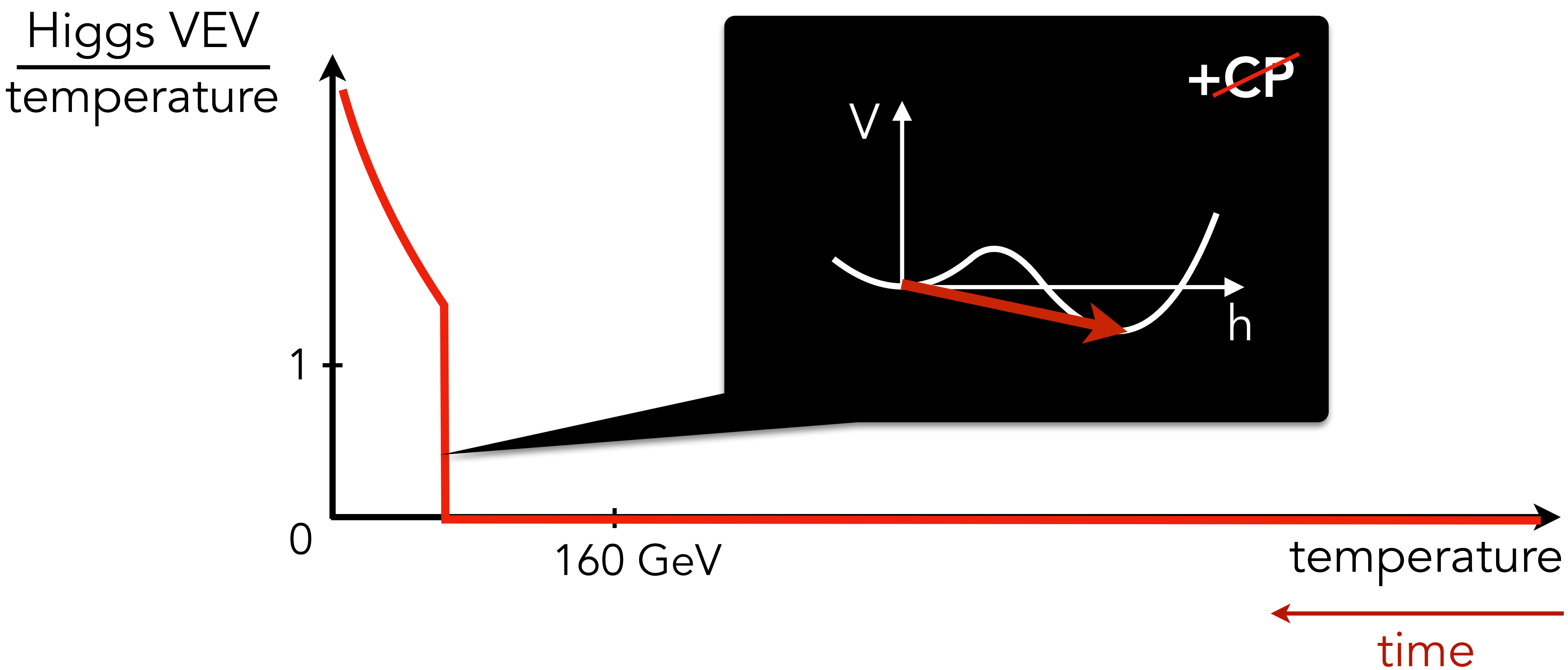
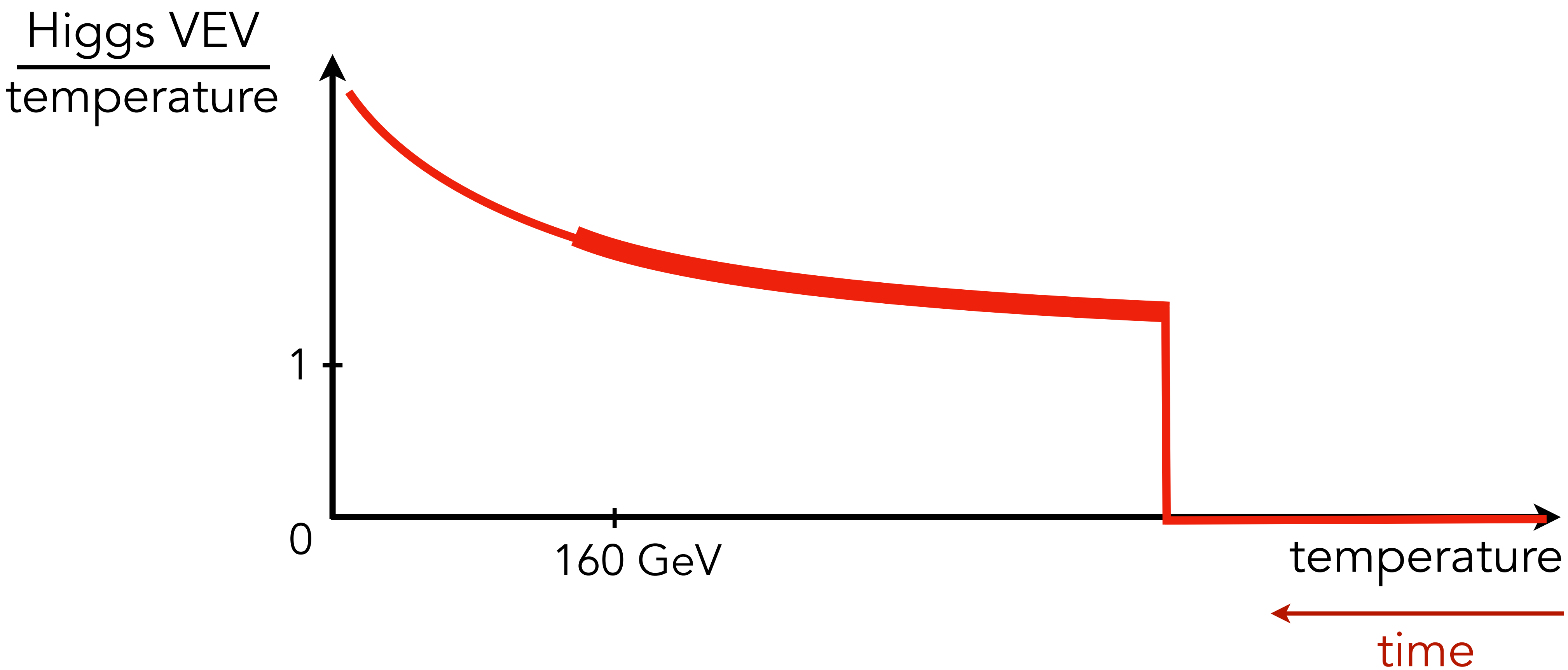


- new physics responsible for CP violation and first-order phase transition is at a few 100 GeV scale
- ~**unique prediction for the energy scale of new physics**
- **EXP TENSIONS**

$\langle H \rangle$'s Thermal History and EW Baryogenesis

EW symmetry Non-Restoration



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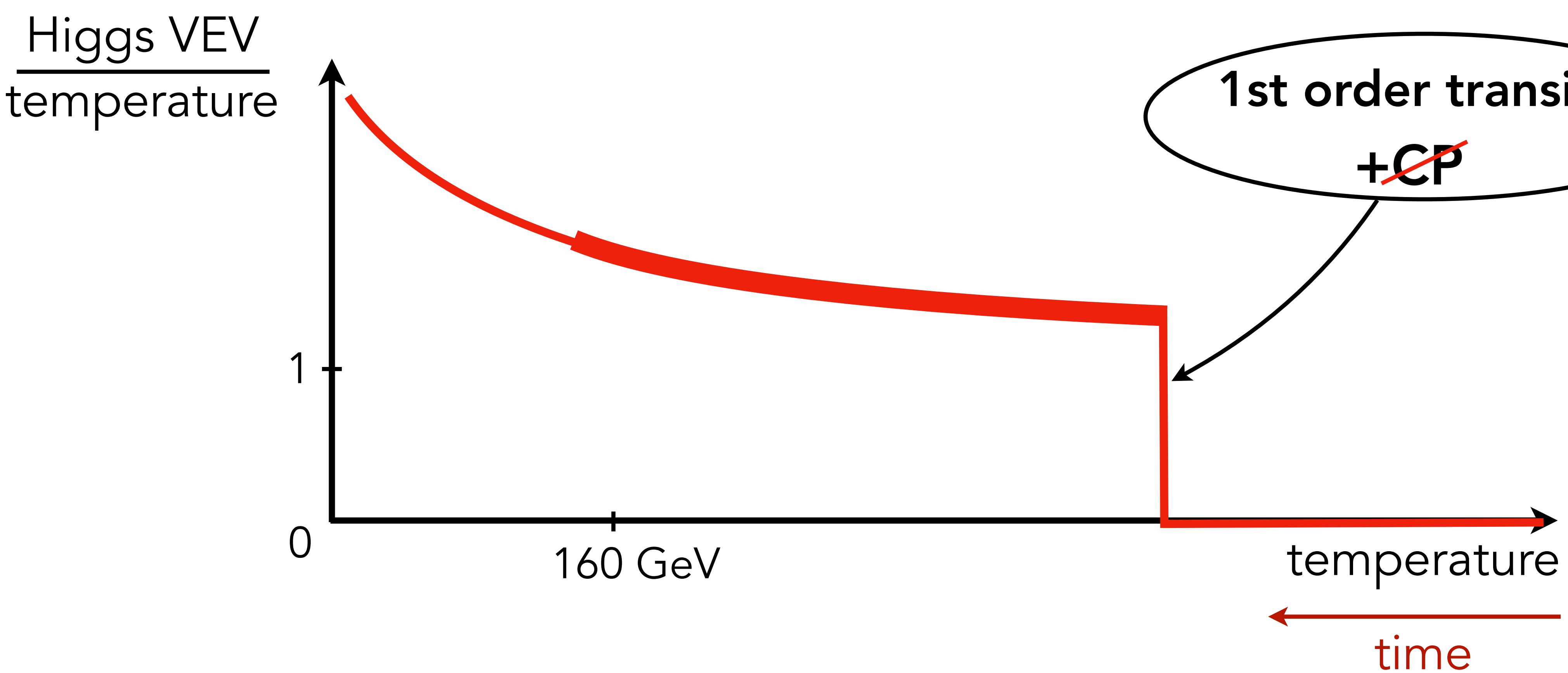


- new physics responsible for CP violation and first-order phase transition is **above** 100 GeV scale

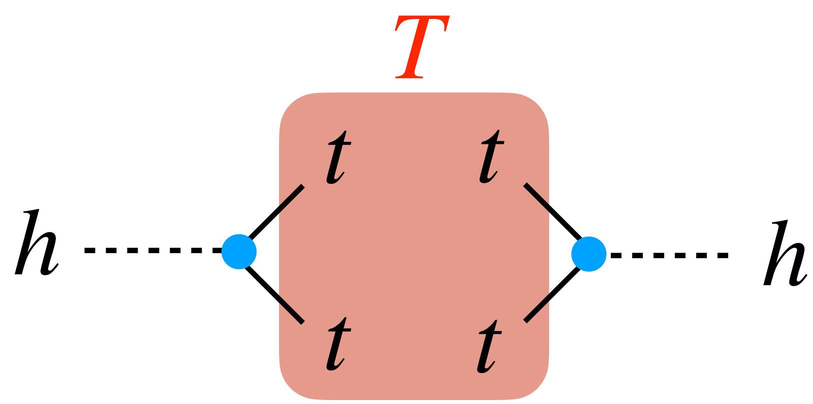
- **new phenomenology**

High-T EWBG

Electroweak Symmetry Non-Restoration at High T

➤ SM states

$$\frac{\lambda_t}{\sqrt{2}}\bar{t}th \quad \Rightarrow$$



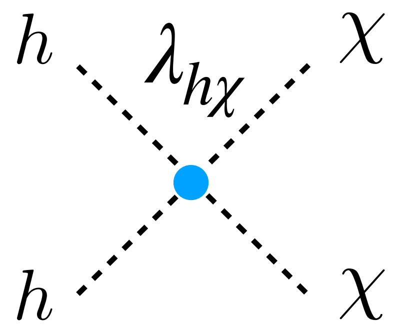
$$\Rightarrow \quad \delta V_h = \frac{1}{8}\lambda_t^2\, T^2\, h^2$$

⇒ positive thermal mass &
restoration at $T \simeq 160\,\mathrm{GeV}$

Electroweak Symmetry Non-Restoration at High T

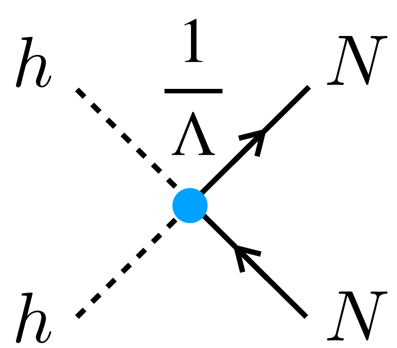
- **new light scalars**

  Weinberg '74 (toy model)
  Meade, Ramani, 1807.07578
  Baldes, Servant, 1807.08770
  Glioti, Rattazzi, Vecchi, 1811.11740



- **new light fermions**

  OM, Servant, 2020.05174



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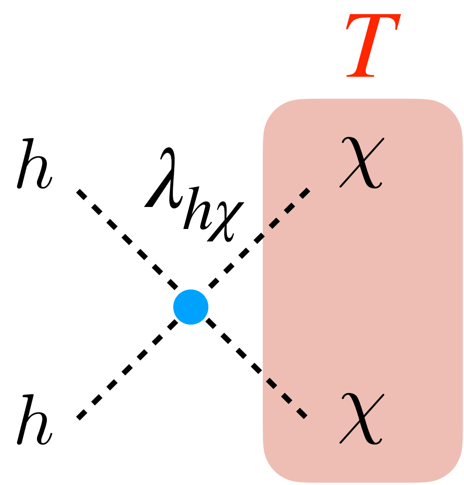

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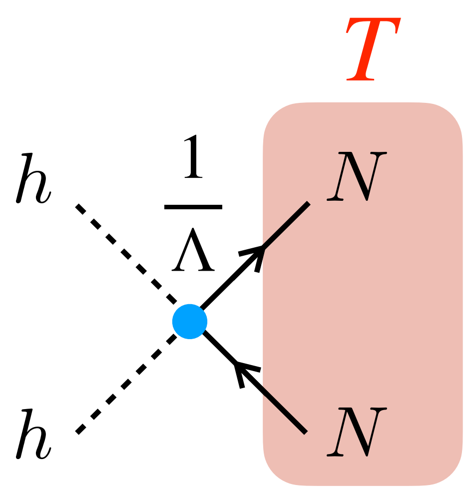

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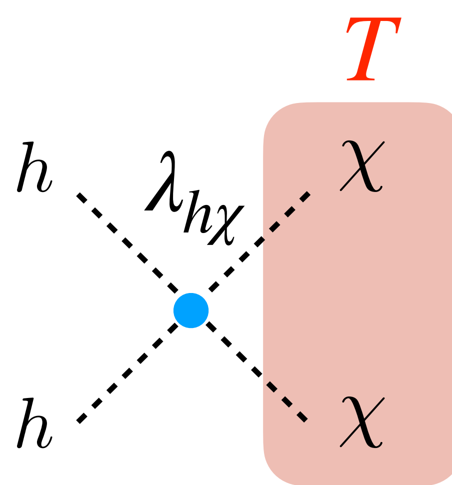

$$\Rightarrow \quad \delta V_h \sim \lambda_{h\chi} T^2 h^2$$

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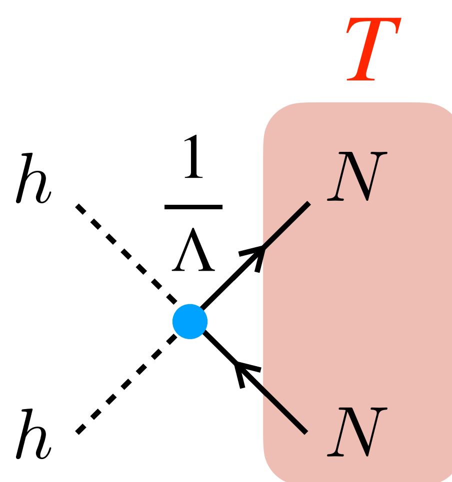

$$\Rightarrow \quad \delta V_h \sim \frac{m_N}{\Lambda} T^2 h^2$$

Electroweak Symmetry Non-Restoration at High T

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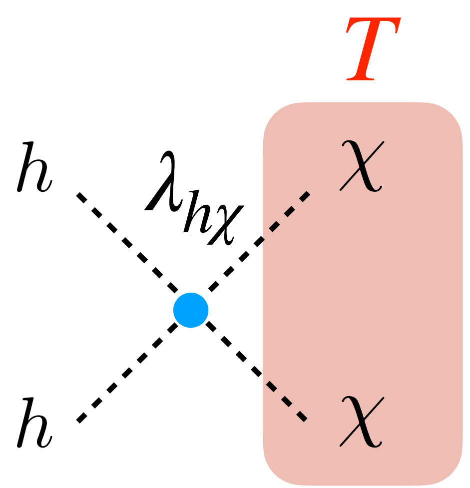

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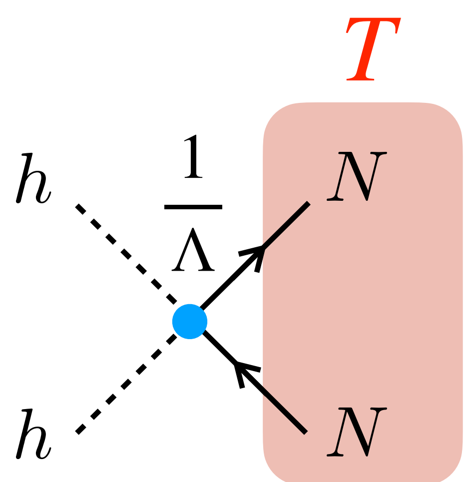


$$\Rightarrow \quad \delta V_h \sim \frac{m_N}{\Lambda} T^2 h^2$$

can be < 0

SNR: # of new d.o.f.

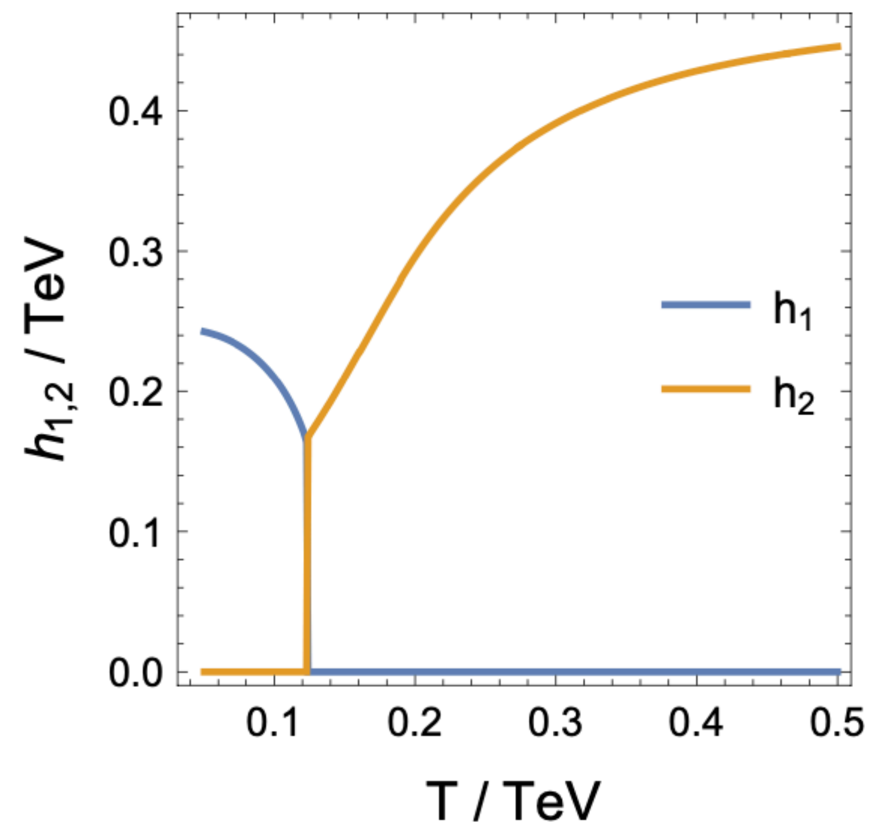
- large multiplets needed for perturbativity:
  - $\mathcal{O}(10)$ Dirac **fermions** for T < 1 TeV $\quad (T_{\rm SNR}^{\rm max} \sim \sqrt{n}\, m_N)$
  - $\mathcal{O}(100)$ **scalars**

- In 2HDM: ~5 less d.o.f. and **DM candidate**

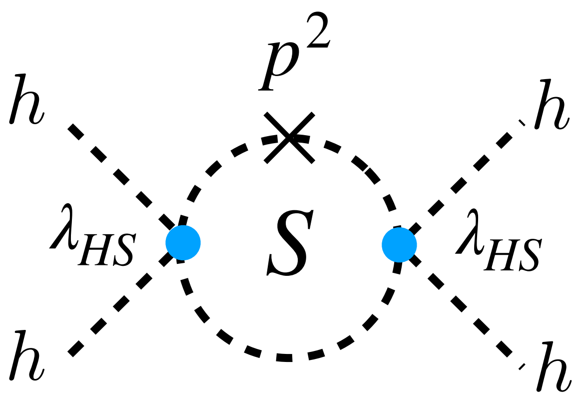
M.Carena,C.Krause,Z.Liu,Y.Wang 2104.00638

OM,J.Unwin,Q.Wang 2107.07560

$$\frac{\lambda_t}{\sqrt{2}}\bar{t}th_2$$



Pheno: c_H



$$\frac{c_H}{\Lambda^2} = n\frac{\lambda_{HS}^2}{48\pi^2}\frac{1}{\mu_\chi^2}$$

Glioti, Rattazzi, Vecchi, 1811.11740
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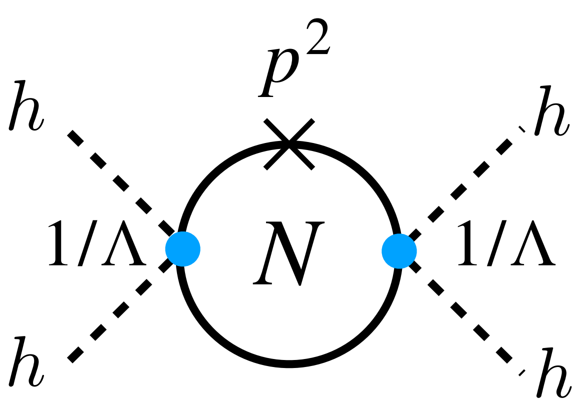
$$\mathcal{O}_H = \frac{1}{2}(\partial_\mu |H|^2)^2$$



$$\frac{c_H}{\Lambda^2} \sim n\frac{4}{16\pi^2}\frac{1}{\Lambda^2}$$

future sensitivities (1σ):

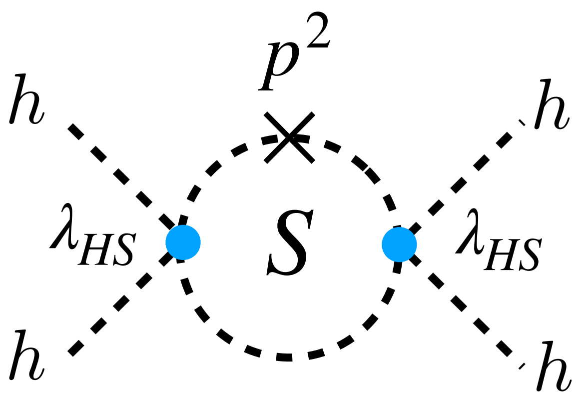
HL-LHC: $\Lambda/\sqrt{|c_H|} < 1.4(1.8)\, TeV$

+**FCC-ee**: $\Lambda/\sqrt{|c_H|} < 3.2(5)\, TeV$

J de Blas, Eur. Phys. J. Plus (2021) 136:897

High-temperature EWPT

Pheno: c_H



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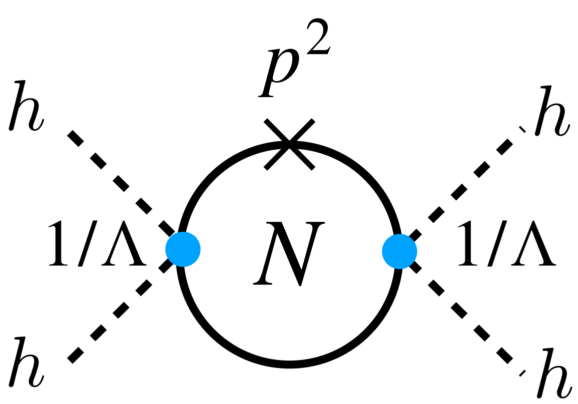


$$\frac{c_H}{\Lambda^2} \sim n\frac{4}{16\pi^2}\frac{1}{\Lambda^2}$$

perturbativity

$$n\frac{\lambda_{HS}^2}{16\pi^2} \ll \lambda_h(\mu)$$

$$n\frac{T^2}{\Lambda^2} \ll 1$$

$$\Lambda/\sqrt{|c_H|} \gtrsim 3\,TeV$$

future sensitivities (1σ):

HL-LHC: $\Lambda/\sqrt{|c_H|} < 1.4(1.8)\,TeV$

+**FCC-ee**: $\Lambda/\sqrt{|c_H|} < 3.2(5)\,TeV$

J de Blas, Eur. Phys. J. Plus (2021) 136:897

High-T EWSB vs Naturalness

SNR & Naturalness

- Can SNR be motivated by, or at least compatible with EW naturalness-motivated physics?

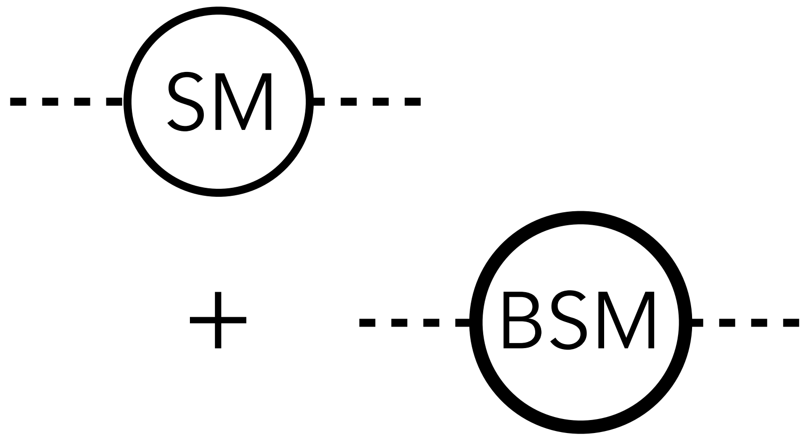
SNR & Naturalness

- no quadratic UV sensitivity of Higgs mass

$\Rightarrow$

add new d.o.f. such that

$$\delta V_{1loop} \propto \Lambda^2\, \mathbf{STr}[M^2] \neq f[h]$$



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- thermal potential (high-T)

$$\delta V_T \supset \frac{1}{24} T^2 \mathbf{Tr}[M_0^2 + |M_{1/2}|^2 + 3M_1^2]$$

SNR & Naturalness

- **different-spin** naturalness (SUSY)

e.g. chiral superfield

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$\times 3$

$$\delta V_T \supset \frac{1}{24} T^2 \mathbf{Tr}[M_0^2 + |M_{1/2}|^2 + 3M_1^2]$$

$$\supset \frac{1}{8} T^2 \mathbf{Tr}|M_{1/2}|^2$$

H.E.Haber '82

M.Mangano '84

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- way around, e.g. additional superfields with non-renormalizable interactions and large-n

Dvali, Tamvakis '96

Bajc, Melfo, Senjanovic '96

OM, Unwin, Wang 2211.09147

SNR & Naturalness

- **same-spin** naturalness (e.g. Goldstone Higgs)

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e.g. top effect $\delta V_h = \frac{1}{8}\lambda_t^2 T^2 h^2$ is cancelled $\Rightarrow$ potential SNR

SNR & Naturalness

- **same-spin** naturalness (e.g. Goldstone Higgs)

- Twin Higgs — Chacko et al, hep-ph/0506256

SM states couplings to the Higgs $\propto \sin h/f$

$\updownarrow Z_2$

Twin states couplings to the Higgs $\propto \cos h/f$

SNR & Naturalness

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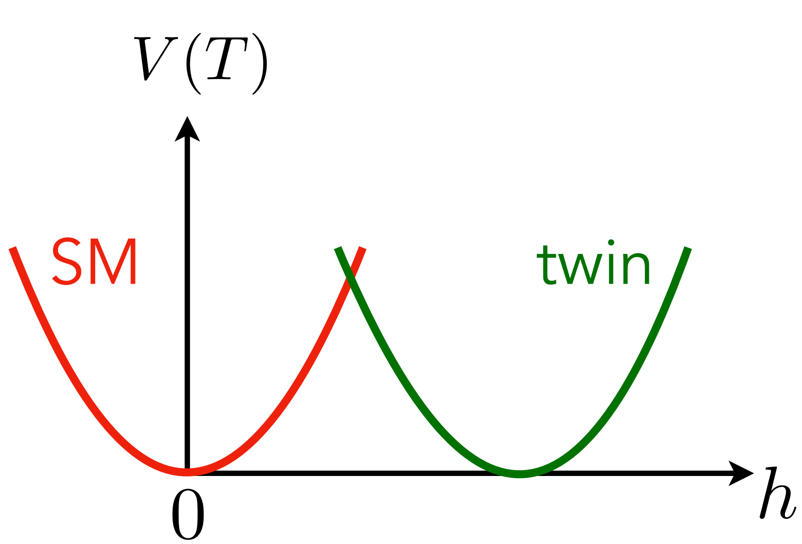
Chacko et al, hep-ph/0506256

also talk by Marcin Badziak

$$V \sim f^2\Lambda^2(\sin^2 h/f + \cos^2 h/f) = f^2\Lambda^2$$

SM contribution

Twin contribution



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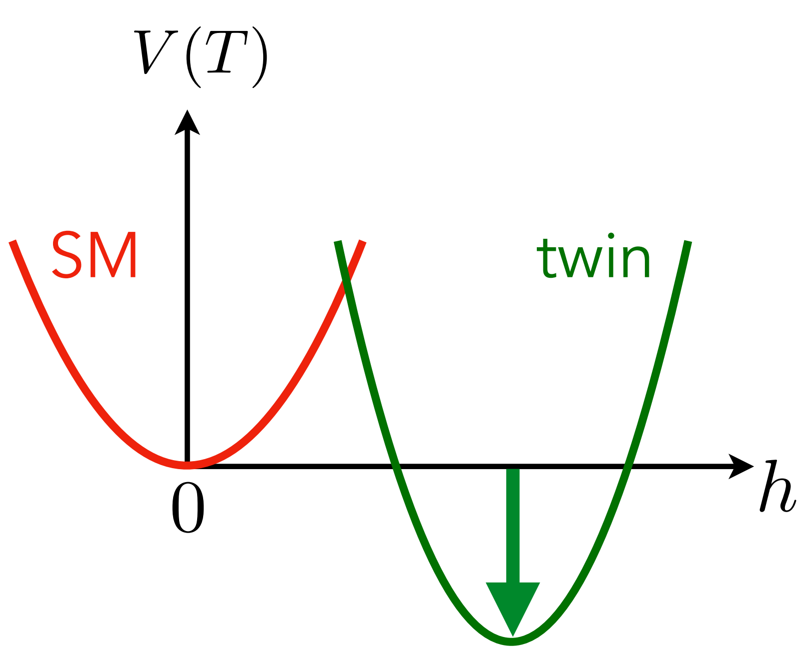


Z_2 breaking by light quark/ lepton Yukawas

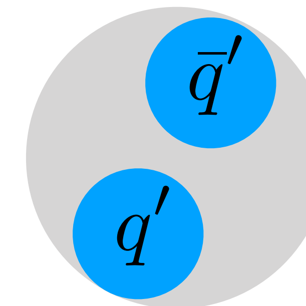
$$\tilde{\lambda}_q \, f \bar{q} q \, \cos h/f$$

OM, 2008.13725

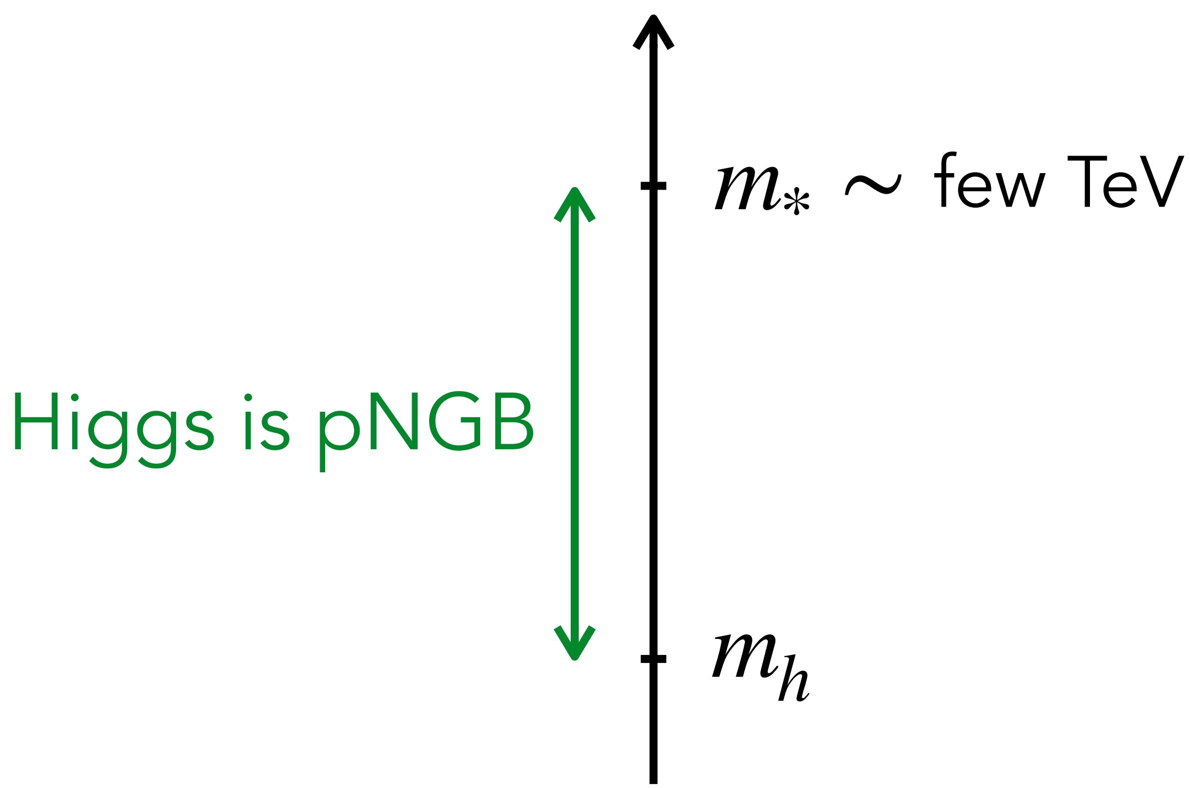
Concrete EWBG model with SNR

Composite Higgs

- Higgs is a bound state of new strong interactions confining at f ~ 1TeV

$h =$ 

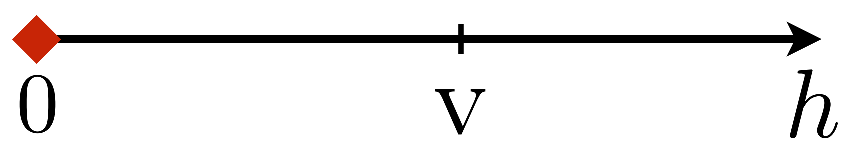
spectrum:



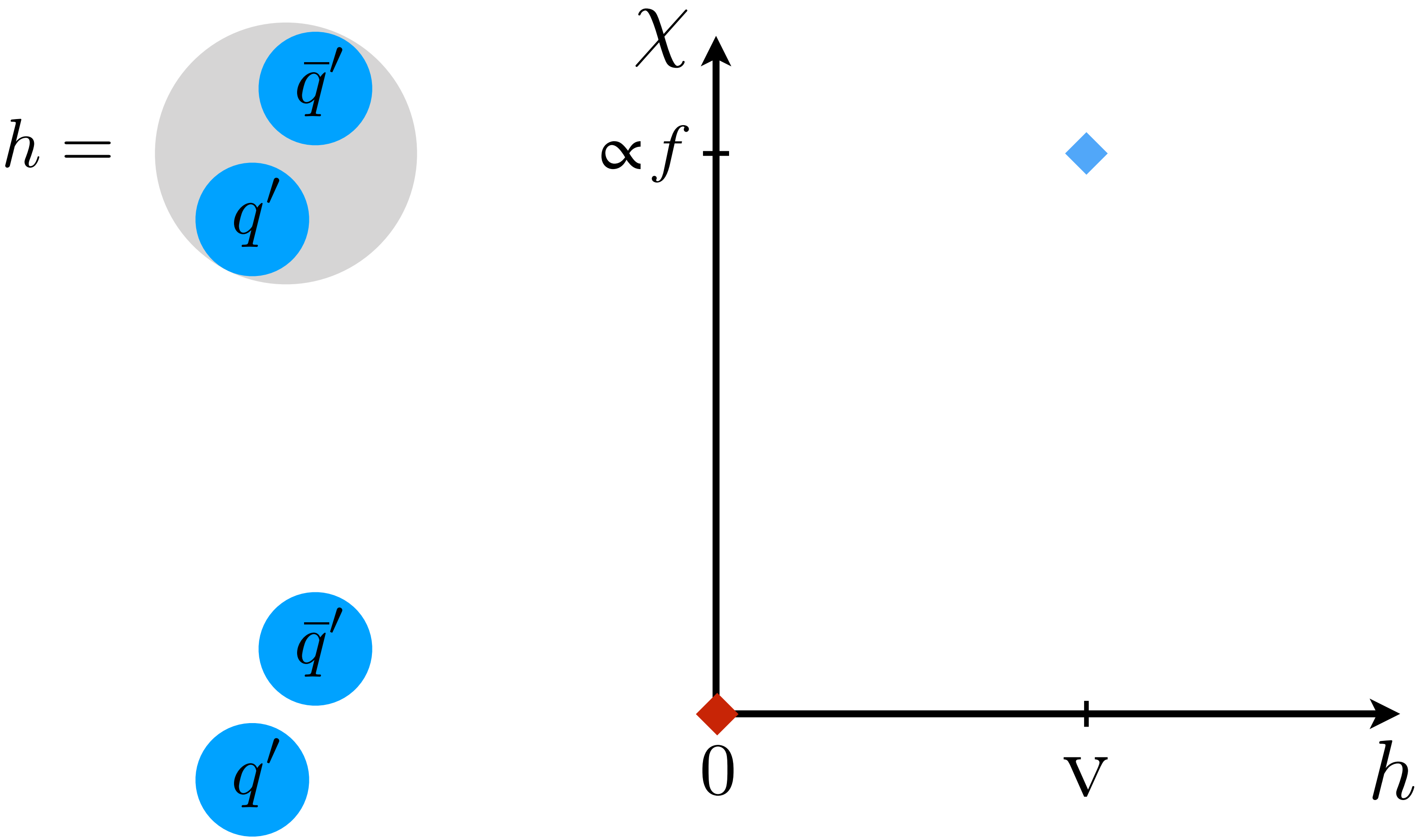
Kaplan,Georgi '84

Agashe,Contino,Pomarol '04

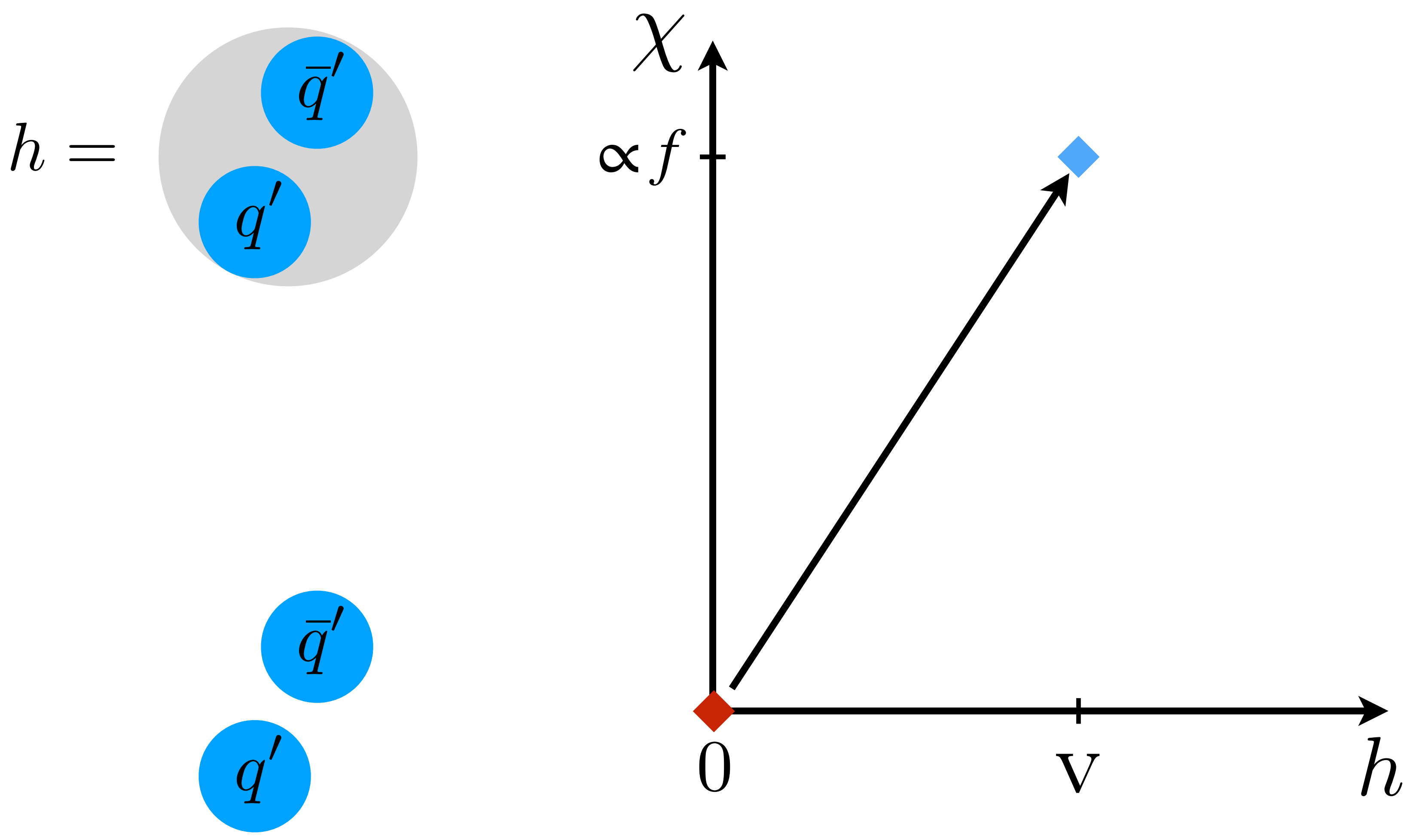
Phase Transitions in CH models



Phase Transitions in CH models



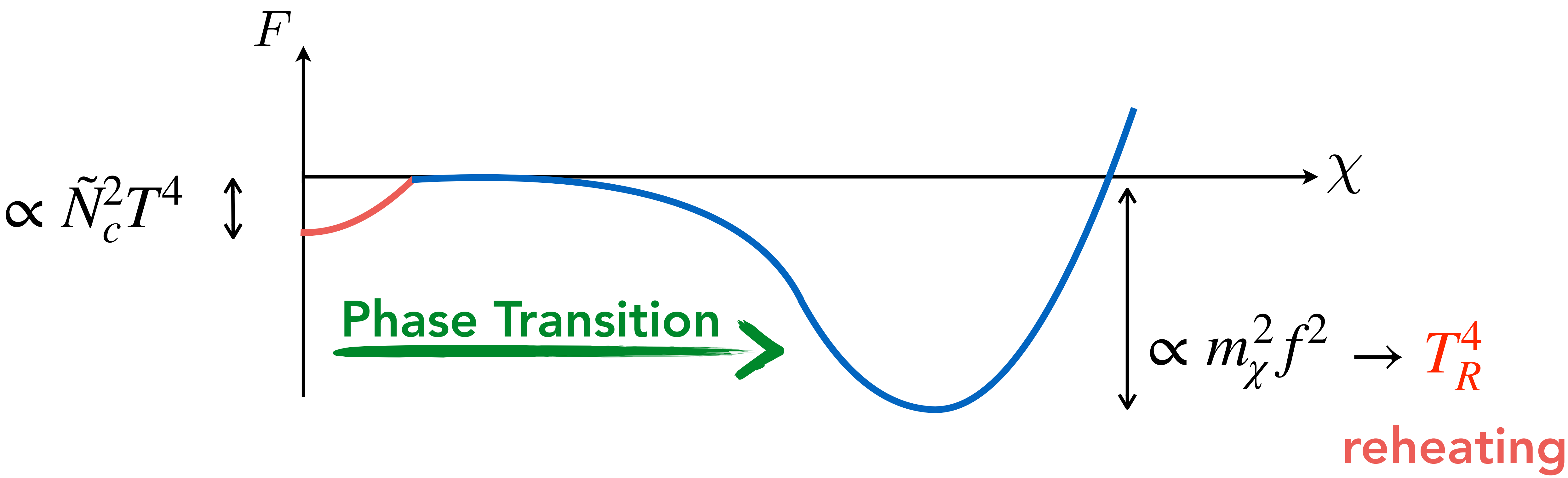
Phase Transitions in CH models



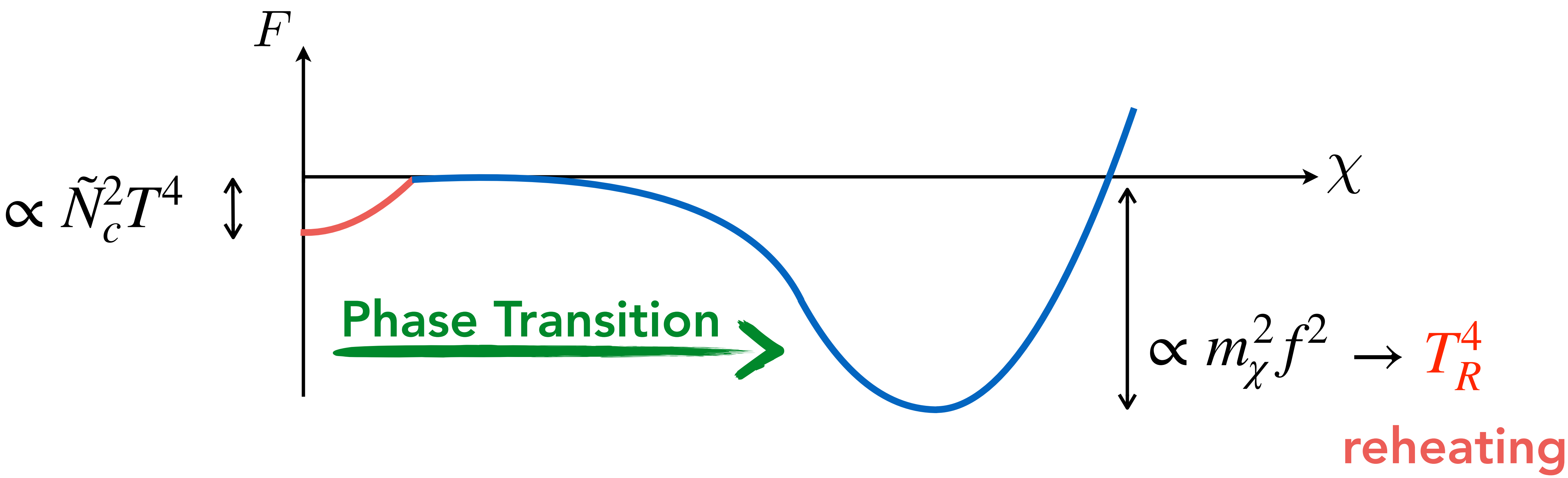
1-step: if T(confinement) < T(EWSB)

$h \propto \chi$ and EWPT is 1st order if confinement PT is

Confinement Phase Transition



Confinement Phase Transition



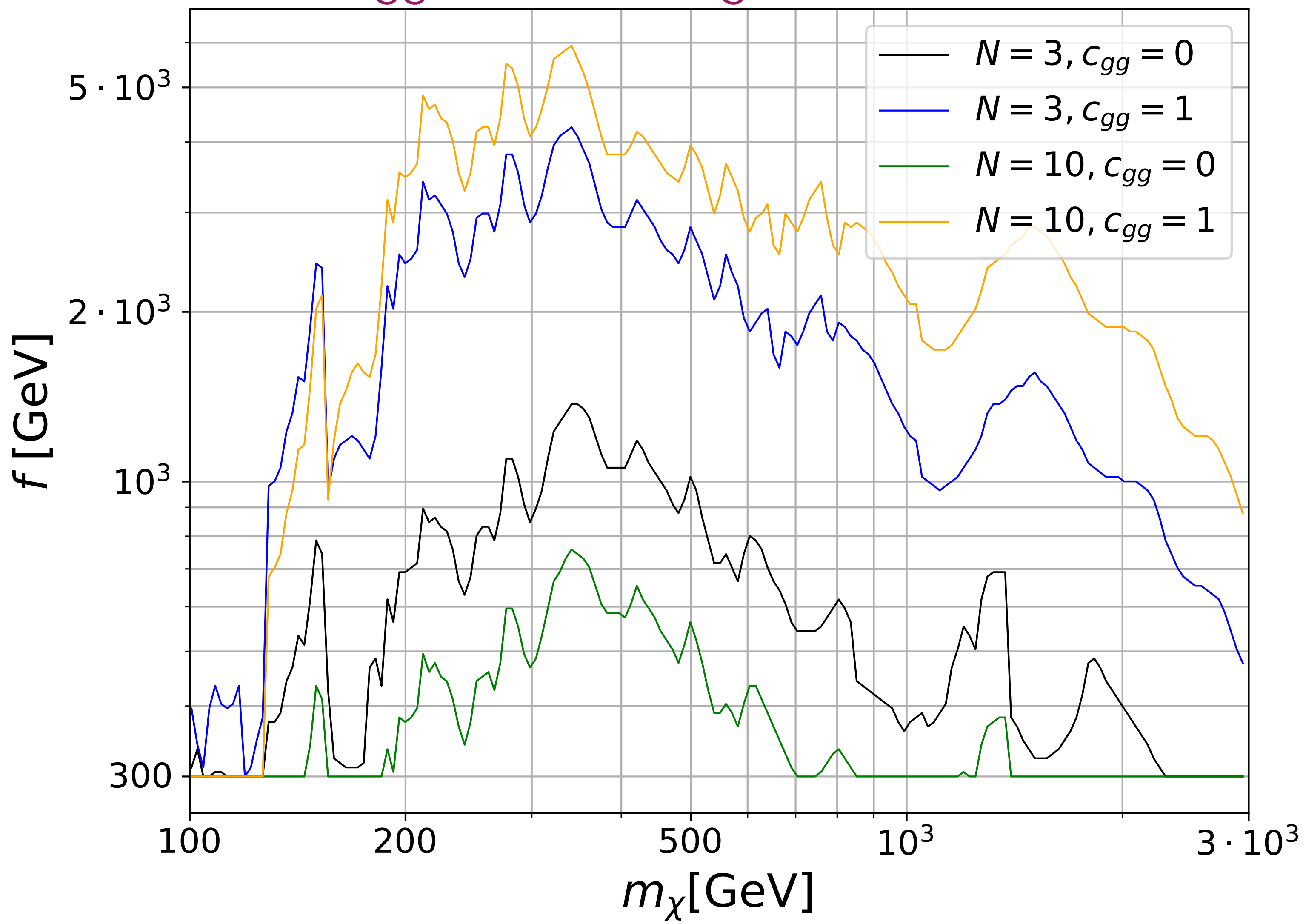
- If $T_R > 130\, GeV$ the EW symmetry is ~restored again (EW sphalerons are on)

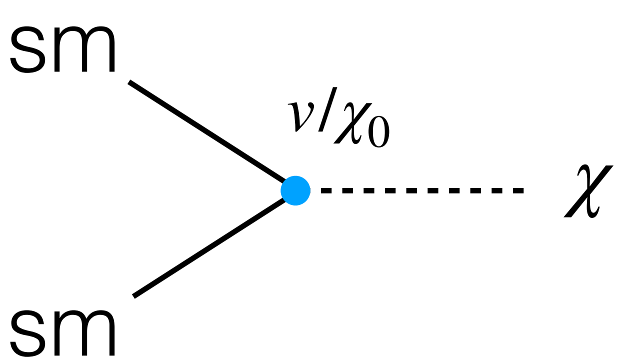
- To keep EWBG results we need

$$T_R \lesssim 130\, GeV \quad \Rightarrow \quad m_\chi \lesssim 500\, GeV \times \frac{800\, GeV}{f} \frac{1}{\tilde{N}_c^{\,1/2}}$$

LHC bounds

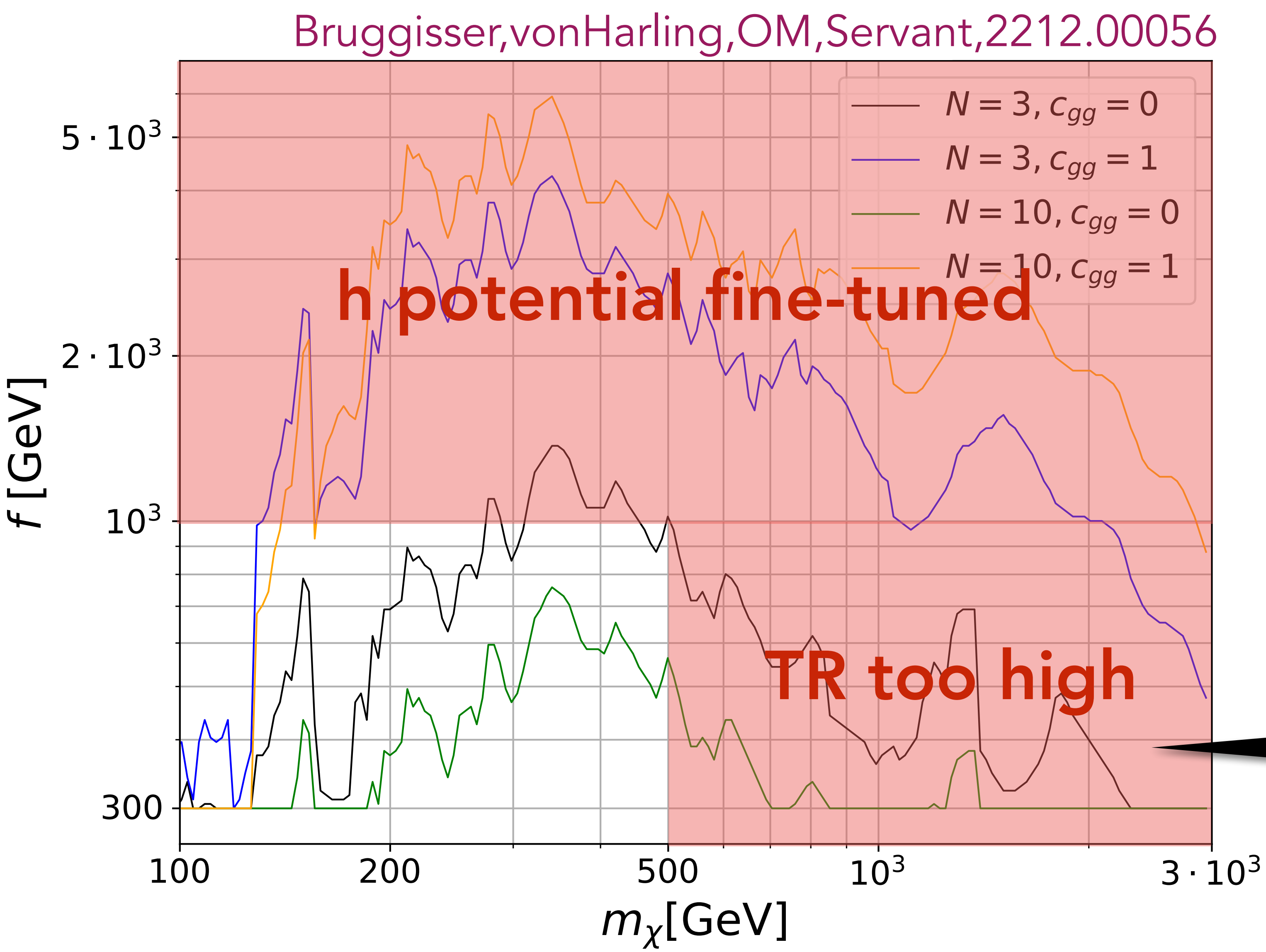
Bruggisser,vonHarling,OM,Servant,2212.00056



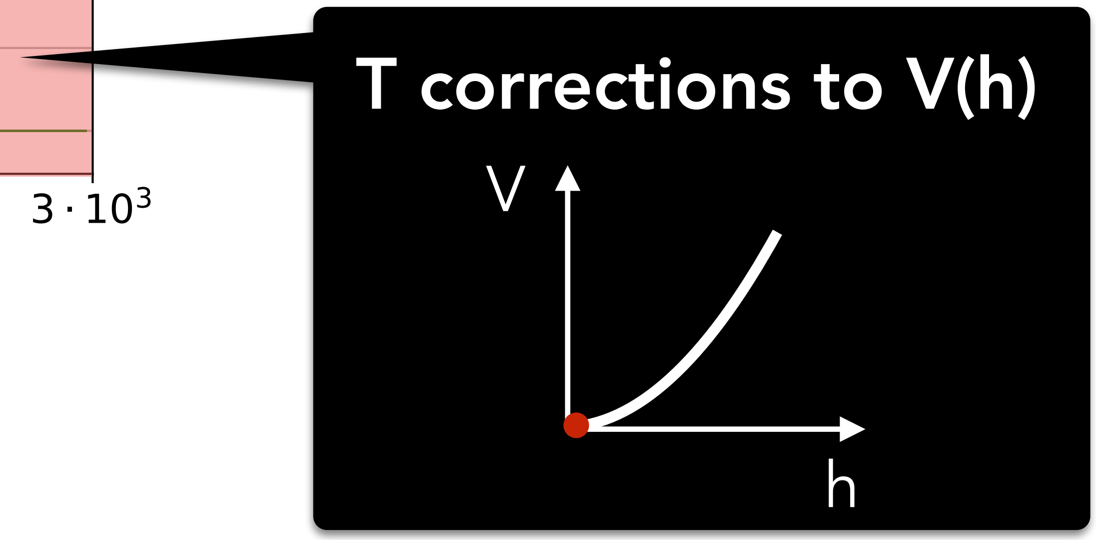


*extra N for $gg\chi$

LHC bounds



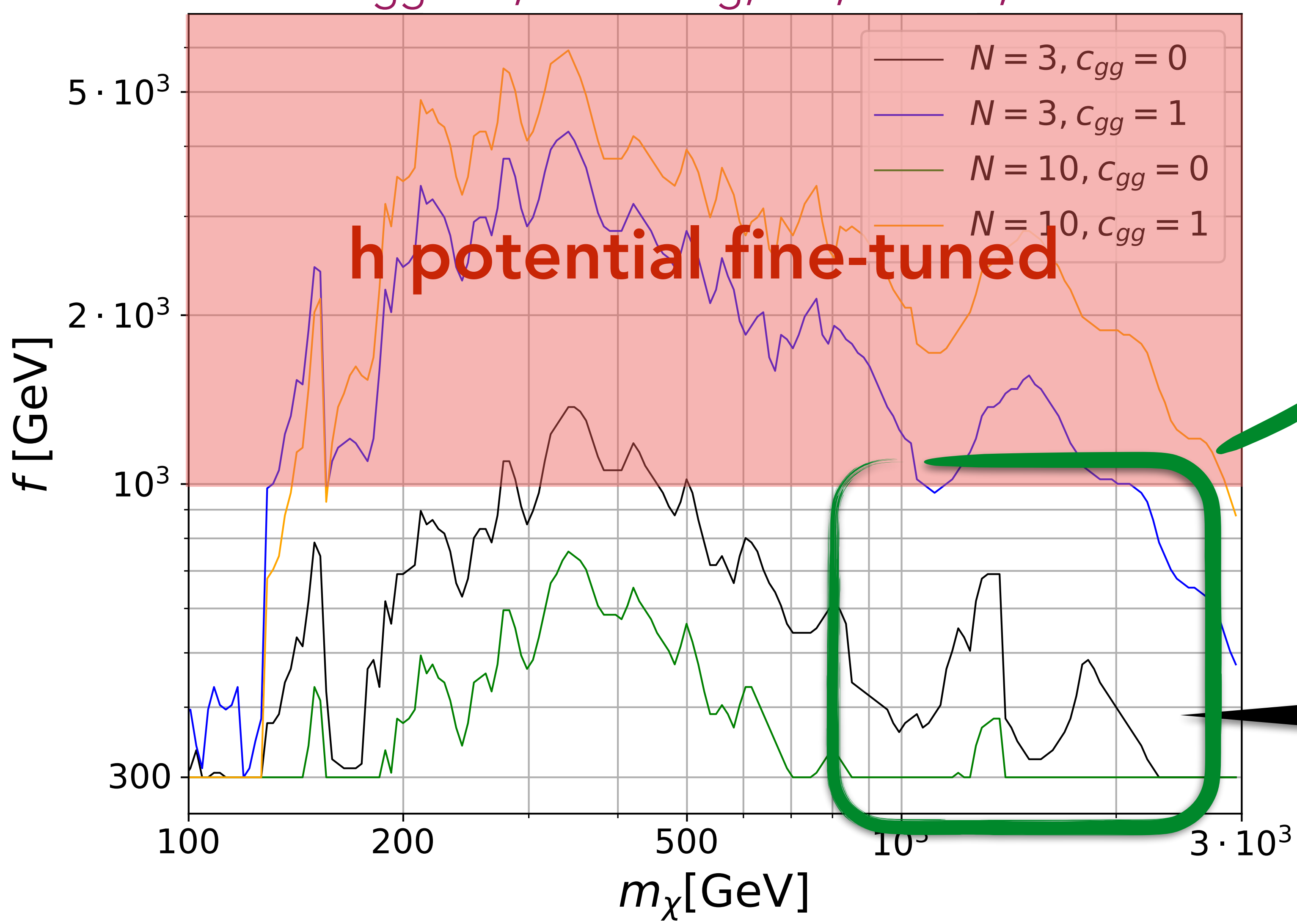
Bruggisser,vonHarling,OM,Servant,2212.00056
$N = 3, c_{gg} = 0$
$N = 3, c_{gg} = 1$
$N = 10, c_{gg} = 0$
$N = 10, c_{gg} = 1$
h potential fine-tuned
TR too high
$5 \cdot 10^3$
$2 \cdot 10^3$
10^3
300
f [GeV]
100
200
500
10^3
$3 \cdot 10^3$
m_χ[GeV]



T corrections to V(h)
V
h

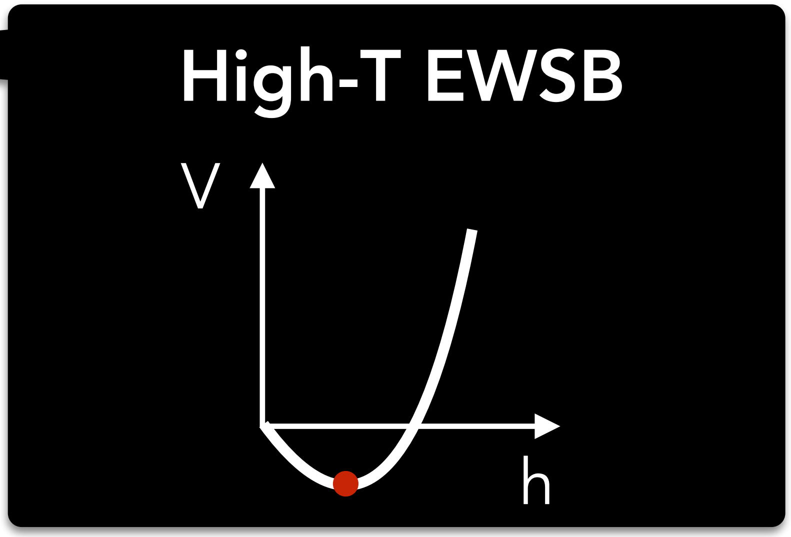
LHC bounds

Bruggisser,vonHarling,OM,Servant,2212.00056



Search for heavy dilaton

Assume twin Higgs structure



Summary

- EWBG necessarily predicts $\lesssim$ TeV scale new physics, providing an important target for future colliders

- Large variety of implementations with various signatures

- Combined explanation with EW naturalness may require to alter the h VEV thermal history, still allowing the near future collider tests

Thank you!