ElectroWeak Baryogenesis above the Weak Scale

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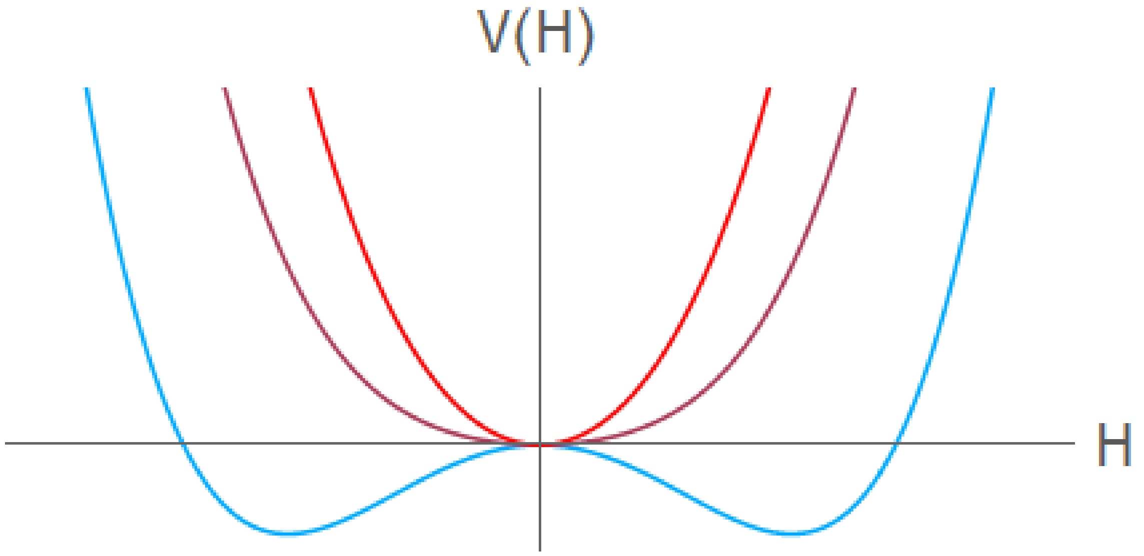
EPFL

+ Meade, Ramani (2018)
+ Baldes, Servant (2018)

Higgs potential: two scenarios

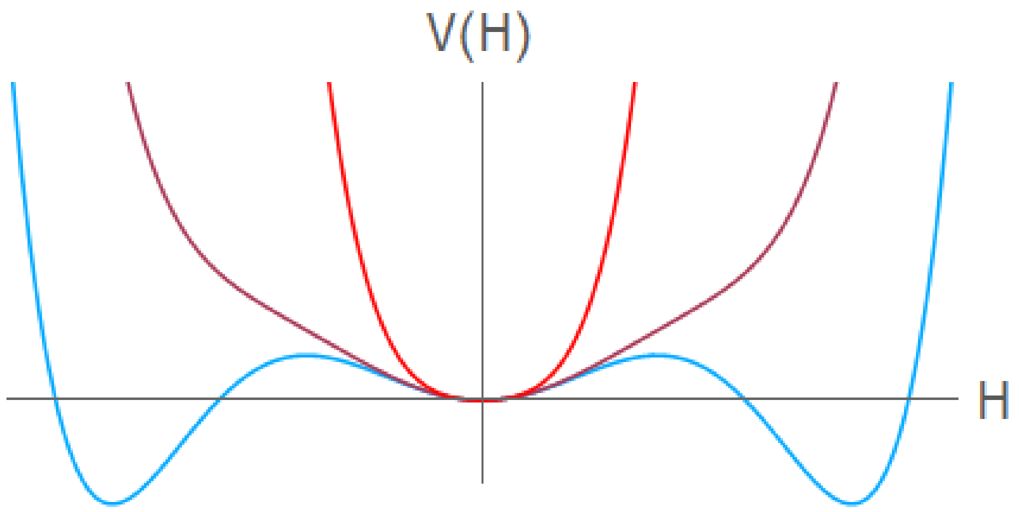
$$V(H) = m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + ??$$

Continuous transition



Ex: Standard Model

Discontinuous transition



Ex: Heavy scalar or 2-step phase transition

ElectroWeak Baryogenesis

Baryogenesis in the SM?

Kuzmin, Rubakov, Shaposhnikov (1985)
Cohen, Kaplan, Nelson (1993)

Exit from thermal equilibrium	$\Longrightarrow$	Higgs phase transition
Baryon number violation	$\Longrightarrow$	Sphalerons
CP violation	$\Longrightarrow$	CKM phase

ElectroWeak Baryogenesis

Baryogenesis in the SM?

Exit from thermal equilibrium	$\Longrightarrow$	Higgs phase transition	✗
Baryon number violation	$\Longrightarrow$	Sphalerons	✓
CP violation	$\Longrightarrow$	CKM phase	✗

Kuzmin, Rubakov, Shaposhnikov (1985)
Cohen, Kaplan, Nelson (1993)

But…

First order transition only if $m_h \lesssim 50\ \mathrm{GeV}$

Measured CP violation is not enough to explain the asymmetry

Adding New Physics

- ▶ New physics at the weak scale to trigger a first order phase transition
- ▶ New physics at the weak scale to provide enough CP violation

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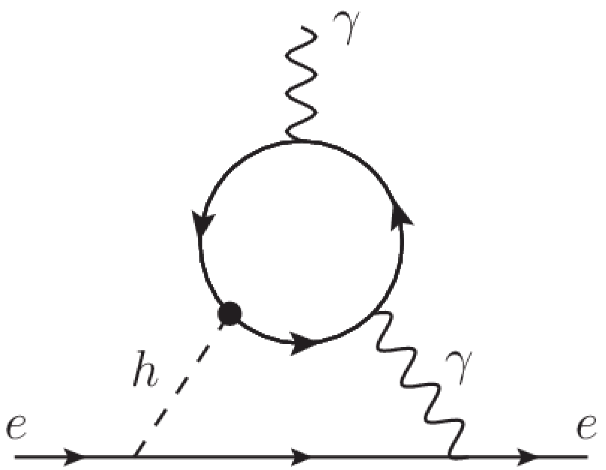
▶ New physics at the weak scale to provide enough CP violation

Heavily constrained by colliders, flavor physics, EDMs…



$$\frac{|d_e|}{e} \sim 10^{-29}\ \text{cm} \sin\phi_{CP} \left(\frac{4\ \text{TeV}}{\Lambda}\right)^2 < 1.1 \times 10^{-29}\ \text{cm}$$

$$\Longrightarrow \Lambda \gtrsim \mathcal{O}(10\ \text{TeV})$$

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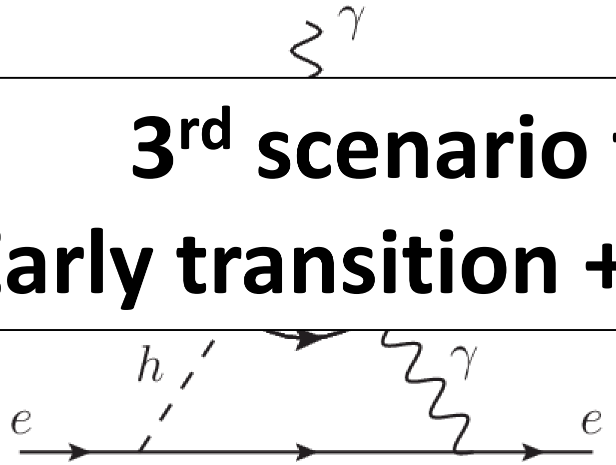

3rd scenario for the Higgs potential:
Early transition + symmetry non-restoration

$\times\, 10^{-29}$ cm

$$\Longrightarrow \Lambda \gtrsim \mathcal{O}(10 \text{ TeV})$$

EWBG at T ≥ 100 TeV

T

100 TeV — **New heavy physics** (free from bounds) provides a **1st order PT** and **CP** violation
→ **BARYOGENESIS**

100 GeV

0

EWBG at T ≥ 100 TeV

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→ **BARYOGENESIS**

New light physics keeps the EW symmetry **broken** while avoiding **B** washout

$$\Gamma_{sph} \sim T e^{-\frac{g h(T)}{T}} \lesssim H \Longrightarrow$$ The mechanism works if $g\dfrac{h(T)}{T} \gtrsim 1$

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100 GeV

The Standard Model keeps the EW symmetry **broken** at lower temperatures.

0

The light sector: O(N) model

$$V(H,S) = m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4}(S^2)^2 + \lambda_{HS} S^2 H^\dagger H$$

$S \in O(N)$

$\lambda_{HS} < 0$ if $\lambda_{HS}^2 < \lambda_H \lambda_S$

Weinberg (1974)

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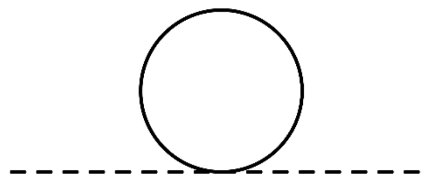
$$m_H^2(T) \sim \left[\underbrace{\frac{1}{2}\lambda_H + \frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}y_t^2}_{\text{Standard Model loops}} + \underbrace{\frac{N}{12}\lambda_{HS}}_{\text{Scalar loop}}\right] T^2$$



Standard Model loops

Scalar loop

If $|\lambda_{HS}|N$ is big enough, the Higgs mass can be **negative** for any temperature

Can we realize this in a perturbative model?

Weinberg (1974)

Scaling

The model is perturbative if

$$\epsilon_H \equiv \frac{\lambda_H}{16\pi^2} \ll 1 \qquad \epsilon_S \equiv \frac{\lambda_S N}{16\pi^2} \ll 1 \qquad \epsilon_{HS} \equiv \frac{\lambda_{HS}\sqrt{N}}{16\pi^2} \ll 1$$

$|\lambda_{HS}|N \propto \sqrt{N}\epsilon_{HS}$ can be big!

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$|\lambda_{HS}|N \propto \sqrt{N}\epsilon_{HS}$ can be big!

Naively $\dfrac{h(T)}{T} \sim \dfrac{|\lambda_{HS}|N}{\sqrt{\lambda_H}}$

$|\lambda_{HS}|N \gtrsim 4.5$ Symmetry non-restoration

$|\lambda_{HS}|N \gtrsim 8$ Sphaleron suppression

Finite Temperature Effects

$|\lambda_{HS}|N \gtrsim 8$ ——— $\lambda_{HS}^2 < \lambda_H \lambda_S$ (for all T)

$$\boxed{N \gtrsim 800 \left(\frac{0.01}{\epsilon_S(100 \text{ TeV})} \right)}$$

λ_H running and y_t value makes N really big

Finite Temperature Effects

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λ_H running and y_t value makes N really big

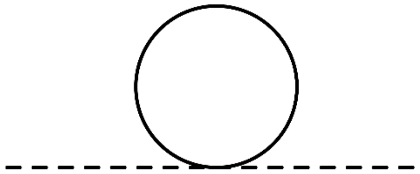
But we should take into account

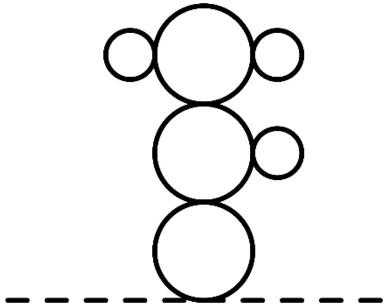
Large Higgs vev → top, W, Z, Higgs effects are suppressed

Sizable $\sqrt{\epsilon_S}$ corrections due to different expansion parameters in the 3D finite temperature theory

Exploit Large-N to systematically resum these effects!

$$\mathcal{L} = D_\mu H^\dagger D^\mu H - \left(m_H^2 + \frac{\lambda_{HS}}{\lambda_S}\sigma\right) H^\dagger H - \lambda_H \left(1 - \frac{\lambda_{HS}^2}{\lambda_H \lambda_S}\right)(H^\dagger H)^2 + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}(m_S^2 + \sigma)S^2 + \frac{1}{4\lambda_S}\sigma^2$$





$$\begin{aligned} V_{\text{eff}}(h,\sigma_c) &= \frac{1}{2}\left(m_H^2 + \frac{\lambda_{HS}}{\lambda_S}\sigma_c\right)h^2 + \frac{\lambda_H}{4}\left(1 - \frac{\lambda_{HS}^2}{\lambda_H\lambda_S}\right)h^4 \\ &- \frac{1}{4\lambda_S}\sigma_c^2 + \boxed{N V_0(m_S^2 + \sigma_c)} \\ &+ V_0\left(m_H^2 + \frac{\lambda_{HS}}{\lambda_S}\sigma_c + \lambda_H\left(3 - \frac{\lambda_{HS}^2}{\lambda_H\lambda_S}\right)h^2\right) \\ &+ 3V_0\left(m_H^2 + \frac{\lambda_{HS}}{\lambda_S}\sigma_c + \lambda_H\left(1 - \frac{\lambda_{HS}^2}{\lambda_H\lambda_S}\right)h^2\right) \\ &+ 6V_1\left(\frac{g^2}{4}h^2\right) + 3V_1\left(\frac{g^2 + g'^2}{4}h^2\right) + 12V_{1/2}\left(\frac{y_t^2}{2}h^2\right) \end{aligned}$$

Tree

Exact S integration

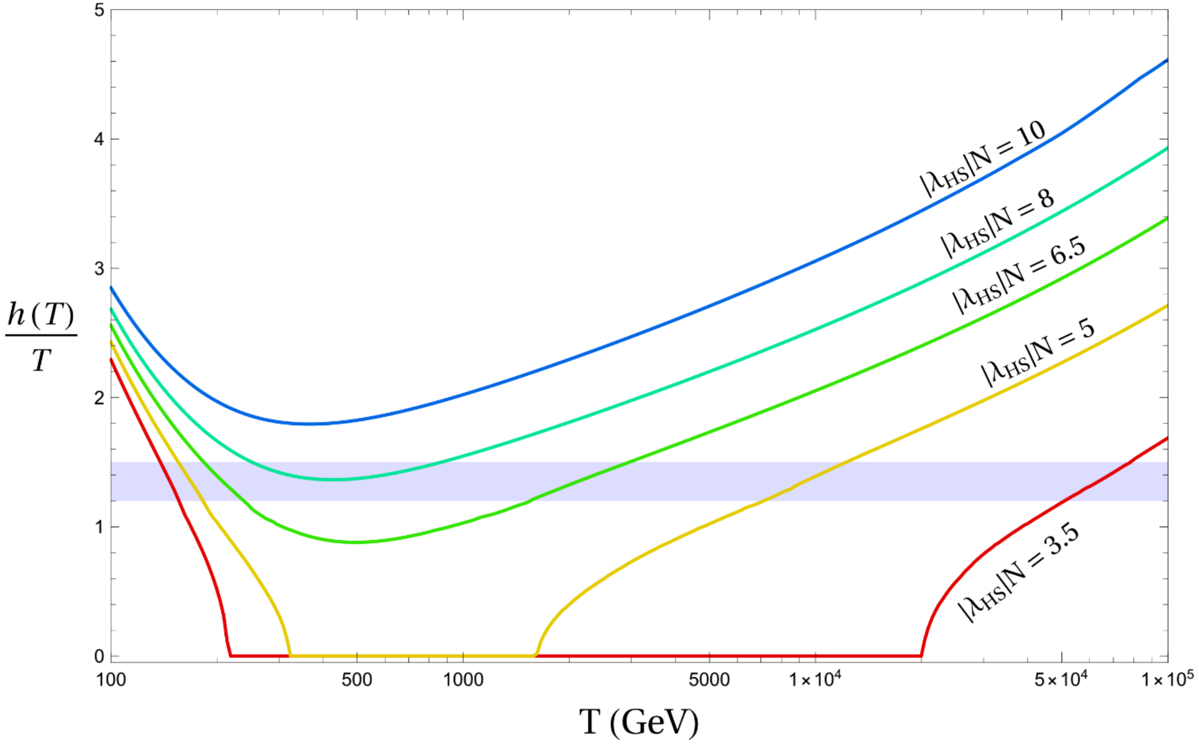
H + NGB loop

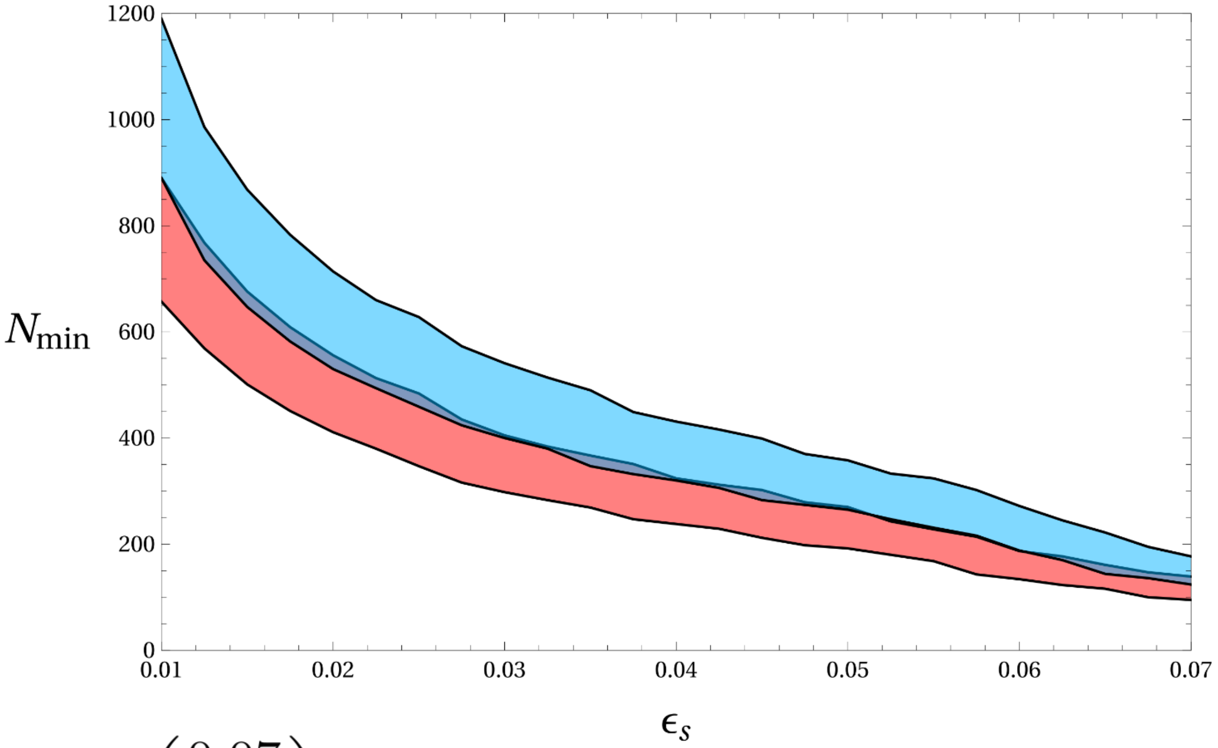
W, Z, t loop

Leading order in 1/N
All orders in $\lambda_S N$ and $\lambda_{HS} N$
1-loop Standard Model

$$V_j(M^2) = (-)^{2j}\frac{1}{64\pi^2}(M^2)^2[\ln(M^2/\mu^2) - c_j] + (-)^{2j}T\int \frac{d\vec{p}}{(2\pi)^3}\ \ln\left[1 - (-)^{2j}\exp\left(-\frac{1}{T}\sqrt{\vec{p}^2 + M^2}\right)\right]$$

Results





$$N \gtrsim \mathcal{O}(50 - 100)\left(\frac{0.07}{\epsilon_S}\right)$$

Collider bounds

$$\frac{m_h}{2} \leq m_s \lesssim 130 - 150 \text{ GeV}$$

h → SS decay

Early thermal decoupling

Collider bounds

$$\frac{m_h}{2} \leq m_s \lesssim 130 - 150 \text{ GeV}$$

h → SS decay

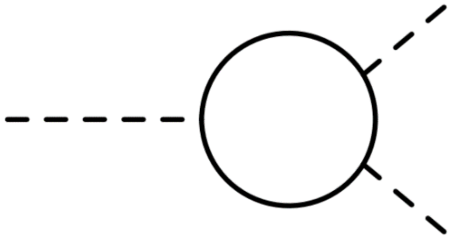
Early thermal decoupling

All collider observables are suppressed by 1/N

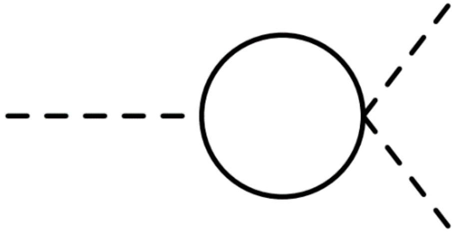
Wave function correction:

$$\delta Z_H \sim \frac{\lambda_{HS}^2 N v^2}{16\pi^2 m_s^2} \sim \frac{1}{N}$$

Trilinear coupling correction:



$$\frac{\delta\lambda_3}{\lambda_3} \sim \frac{1}{N}$$



$$\frac{\delta\lambda_3}{\lambda_3} \sim \frac{100}{N^2}$$

N = O(100) testable at a future colliders.

Curtin, Meade, Yu (2014)

Dark Matter bounds

In the minimal model S is stable → **excluded by dark matter bounds**

$N \lesssim \mathcal{O}(100)$		$N \gtrsim \mathcal{O}(2000)$
To reproduce the right abundance	**VS.**	From direct detection bounds

Three possibilities:

1) **O(N)** + **lighter particles** that can be dark matter
2) **Softly breaking** O(N)
3) **Gauge** O(N) → possibility of meson dark matter

Conclusions

A hidden sector at the weak scale with a large amount of degrees of freedom can heavily change the Higgs mass while having perturbative contributions in all the other physical quantities.

At finite temperature this can lead to symmetry non restoration and sphaleron rate suppression allowing to have ElectroWeak baryogenesis at scales much above the Weak scale as suggested by strong bounds on CP violation.

The minimal scenario is realized with a large number of degrees of freedom, but some extensions and/or a lower cutoff can greatly reduce this number (left for future work…).