Cold Electroweak Baryogenesis: scanning parameter space

Anders Tranberg[a]
In collaboration with
Jan Smit[b],
a.)University of Sussex
b.)University of Amsterdam

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The baryon asymmetry of the Universe

The Universe contains unequal amounts of matter and anti-matter. Some process (Baryogenesis) in the early Universe produced the asymmetry. From WMAP [Spergel et al.:2003]:

$$\eta = \frac{n_B}{n_\gamma} = 6.5 \times 10^{-10}.$$

n_B, n_γ are number densities of baryons, photons.

One such mechanism is Electroweak Baryogenesis, baryogenesis at the electroweak scale [Kuzmin, Rubakov, Shaposhnikov:1985].

Cold electroweak baryogenesis

An asymmetry can only be generated in the presence of baryon number violating, CP violating processes out of thermal equilibrium. In the Standard Model (SM), this may all be present around the electroweak phase transition/symmetry breaking. Consider a hybrid inflation-type model, ending at the electroweak scale [Copeland et al.:2001, German et al.:2001, v.Tent et al.(AT):2004], with potential

$$V(\sigma, \phi) = V(\sigma) + (\mu^2 - g^2\sigma^2)\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2.$$

Symmetry breaking is triggered when

$$\mu_{\text{eff}}^2(t) = \mu^2 - g^2\sigma^2(t) < 0.$$

Symmetry breaking at zero temperature. Baryogenesis during (p)reheating.

”Reduced standard model...”

We study the $SU(2)$-Higgs model numerically on the lattice including a CP-violating term. No fermions, no QCD. In the continuum [Ambjørn et al.:1989]:

$$S=-\int d^4x\left[\frac{1}{2g^2}\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu}+(D_\mu\phi)^\dagger D^\mu\phi+\mu_{\mathrm{eff}}^2\phi^\dagger\phi+\lambda(\phi^\dagger\phi)^2+V_0+\Delta\mathcal{L}_{CP}\right].$$

How large an asymmetry is created given the amount of CP violation?

Baryon number non-conservation

- Baryon number is not conserved in the SM.
- A quantum anomaly relates changes in the baryon and lepton numbers B, L of fermions coupled axially to a background ($SU(2)$) gauge field to changes in the Chern-Simons number $N_{\rm cs}$ of that gauge field ['t Hooft:1976]:

$$\begin{aligned}
\langle B(t) - B(0) \rangle &= \langle L(t) - L(0) \rangle \\
&= 3\langle [N_{\rm cs}(t) - N_{\rm cs}(0)] \rangle \\
&= \frac{3}{16\pi^2} \int_0^t dt \int d^3x \langle {\rm Tr} \left[F_{\mu\nu} \tilde{F}^{\mu\nu} \right] \rangle .
\end{aligned}$$

- The vacua of the SU(2)-Higgs model have integer Chern-Simons number. In the vacua, Higgs winding number $N_{\rm w}$ is integer and $N_{\rm w} = N_{\rm cs}$.

CP-violation

CP-violation is present in the SM through the CKM matrix. In neutrino sector? Generic in SUSY.

Integrating out fermions/other fields: CP-violation is recovered in a series of terms, combinations of Higgs and Gauge fields. The lowest order term is

$$\Delta\mathcal{L}_{CP} = \kappa\phi^\dagger\phi \mathrm{Tr}\, F_{\mu\nu}\tilde{F}^{\mu\nu}, \;\; \kappa = \frac{3\delta_{\mathrm{cp}}}{16\pi^2 M^2}.$$

From the SM CKM-matrix,

- $\delta_{\mathrm{cp}} \propto J\,\Pi_{ij}(m_i^2 - m_j^2)$: $\times T^{-12},\; T\neq 0$; $\times v^{-12},\; T=0$; $< 10^{-20}$, [Shaposhnikov:1987],
- $\delta_{\mathrm{cp}} = 0$, $T=0$; Next order $\propto J$? [Salcedo:2001,Smit:2004].

($J = \sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)$). We consider general δ_{cp}.

Tachyonic preheating

$$V(\phi) = \mu^2_{\rm eff}(t)\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2.$$

Higgs symmetry breaking is triggered when $\mu^2_{\rm eff}(t) = 0$. We go to the limit of an instantaneous quench, so that at early times ($\lambda = 0$):

$$V(\phi) \simeq \mu^2_{\rm eff}(t)\phi^\dagger\phi,$$

$$\mu^2_{\rm eff}(t) = \mu^2,\ t < 0 \quad ; \quad \mu^2_{\rm eff}(t) = -\mu^2,\ t > 0.$$

$$\ddot{\phi}_{\mathbf{k}} = -(k^2 - \mu^2)\phi_{\mathbf{k}}.$$

Modes with $|\mathbf{k}| < \mu$ grow exponentially:

$$\phi_{\mathbf{k}} \propto a_{\mathbf{k}} e^{i\sqrt{k^2-\mu^2}t} + a^\dagger_{\mathbf{k}} e^{-i\sqrt{k^2-\mu^2}t} \rightarrow a^\dagger_{\mathbf{k}} e^{\sqrt{\mu^2-k^2}t}.$$

Squeezing. Classical behaviour for $|\omega^-_k|t \gg 1$.

Parameters and observables

We study the ensemble averaged quantities

$$\langle B(t) - B(0)\rangle = 3\langle[N_{\rm cs}(t) - N_{\rm cs}(0)]\rangle$$

$$\langle[N_{\rm cs}(t) - N_{\rm cs}(0)]\rangle \quad \text{in vacuum} \simeq \quad \langle[N_{\rm w}(t) - N_{\rm w}(0)],$$

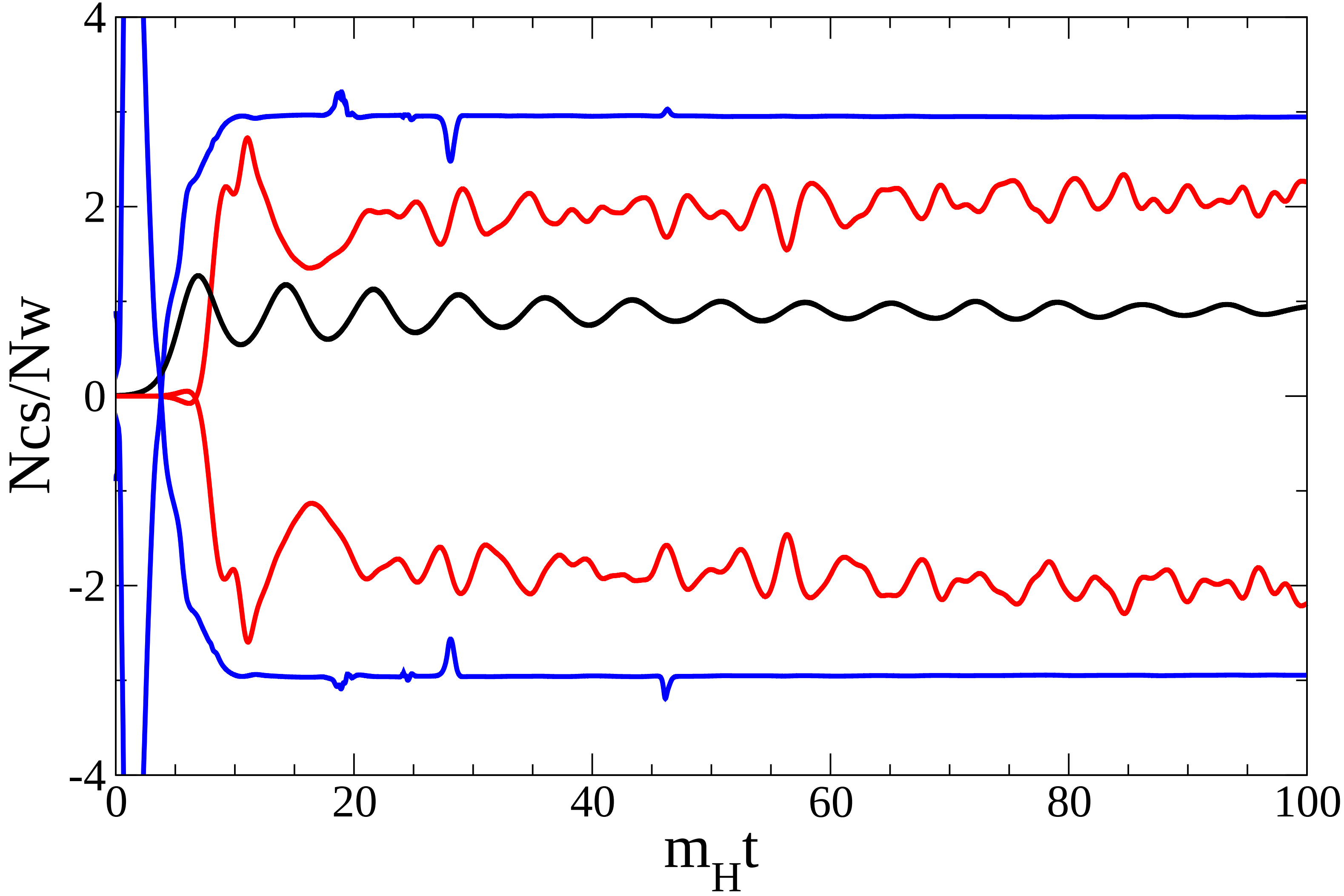
$$\frac{\langle\phi^\dagger\phi\rangle}{v^2} \simeq 0 \quad \rightarrow \quad \frac{\langle\phi^\dagger\phi\rangle}{v^2} \simeq 1$$

Three free parameters ($m_W = 80\text{GeV}$, $g^2 = 4/9$):

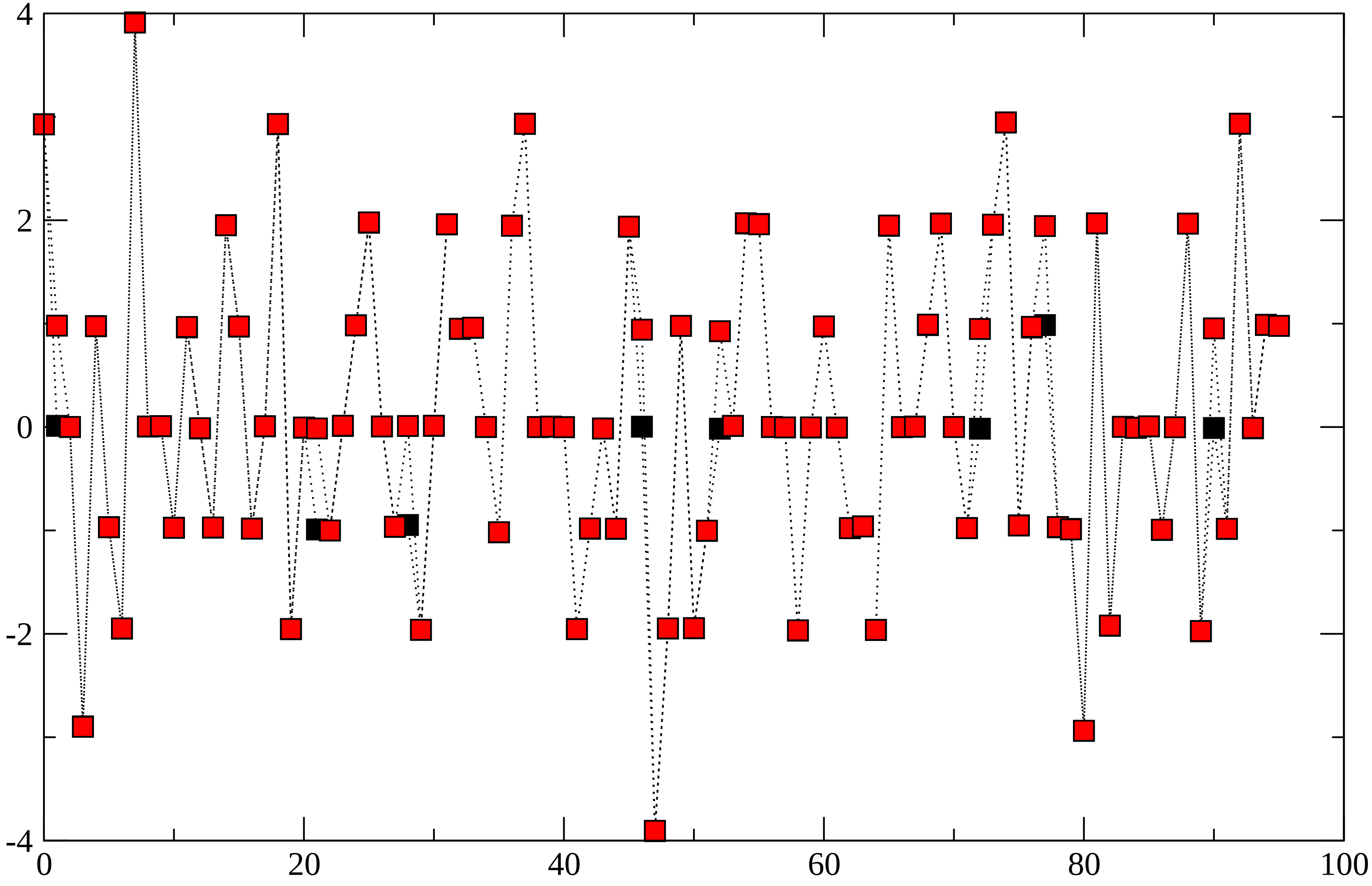
$$\left(\frac{m_H}{m_W}\right)^2 = \frac{8\lambda}{g^2} = 2, \ldots, 4,$$

$$k = 16\pi^2\kappa m_W^2 = 3\,\delta_{\rm cp} = 0, \ldots, 3,$$

$$\mu^2(t) = \mu^2\left(1 - \frac{2t}{t_{\rm quench}}\right), \qquad m_H\, t_{\rm quench} = 0, \ldots, 72.$$



4
2
0
-2
-4
Ncs/Nw
0
20
40
60
80
100
m_Ht



4
2
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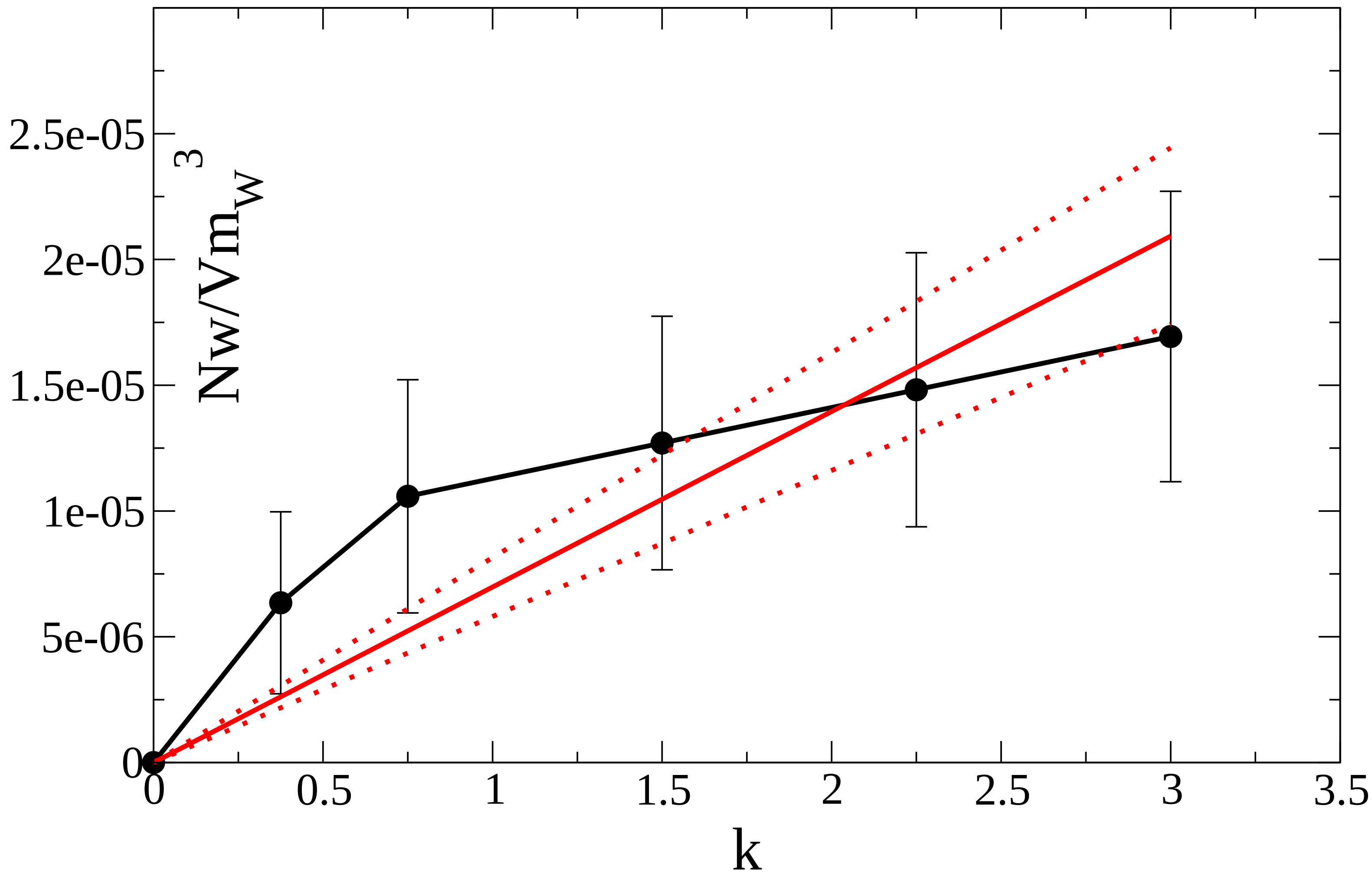
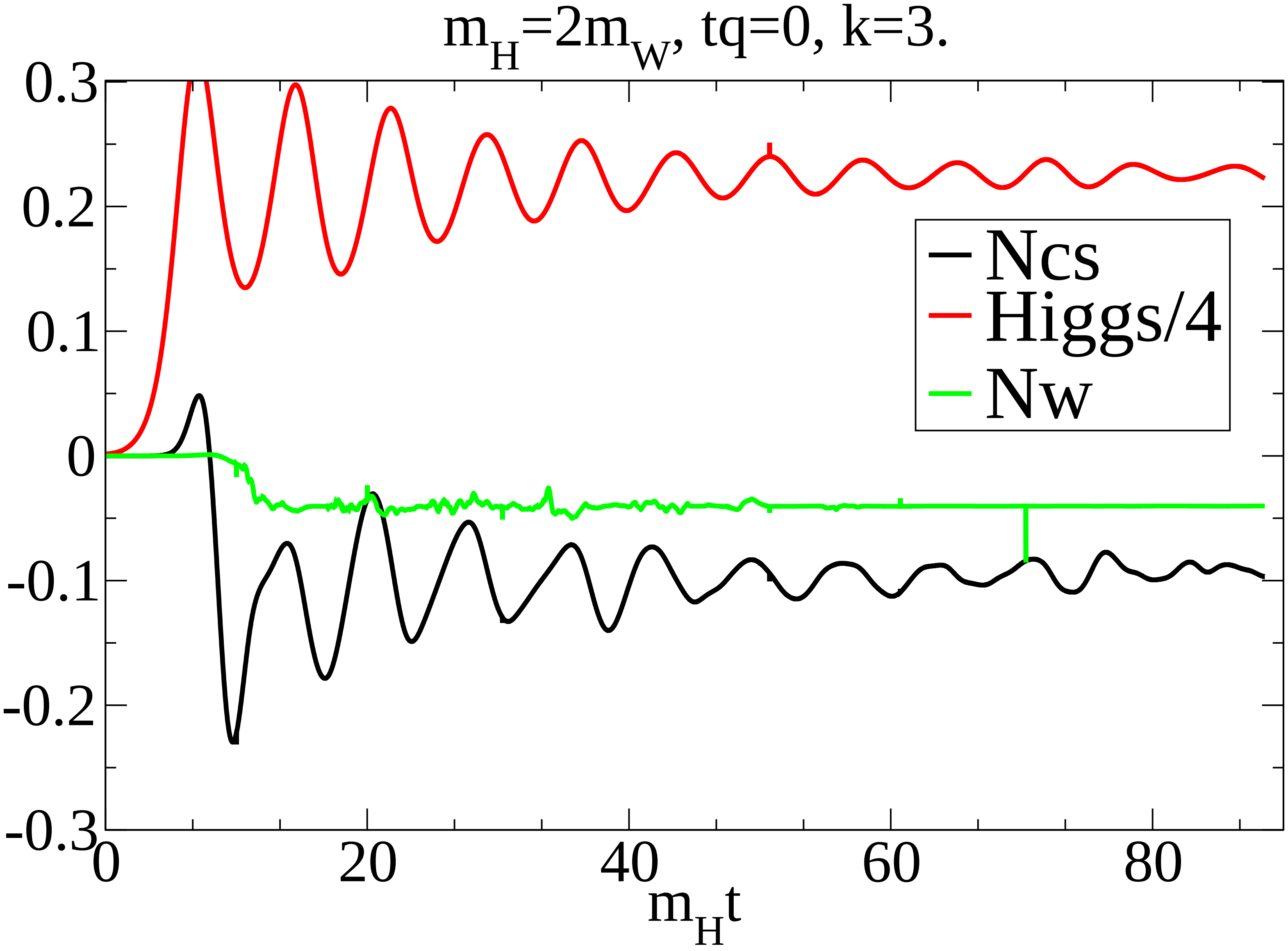
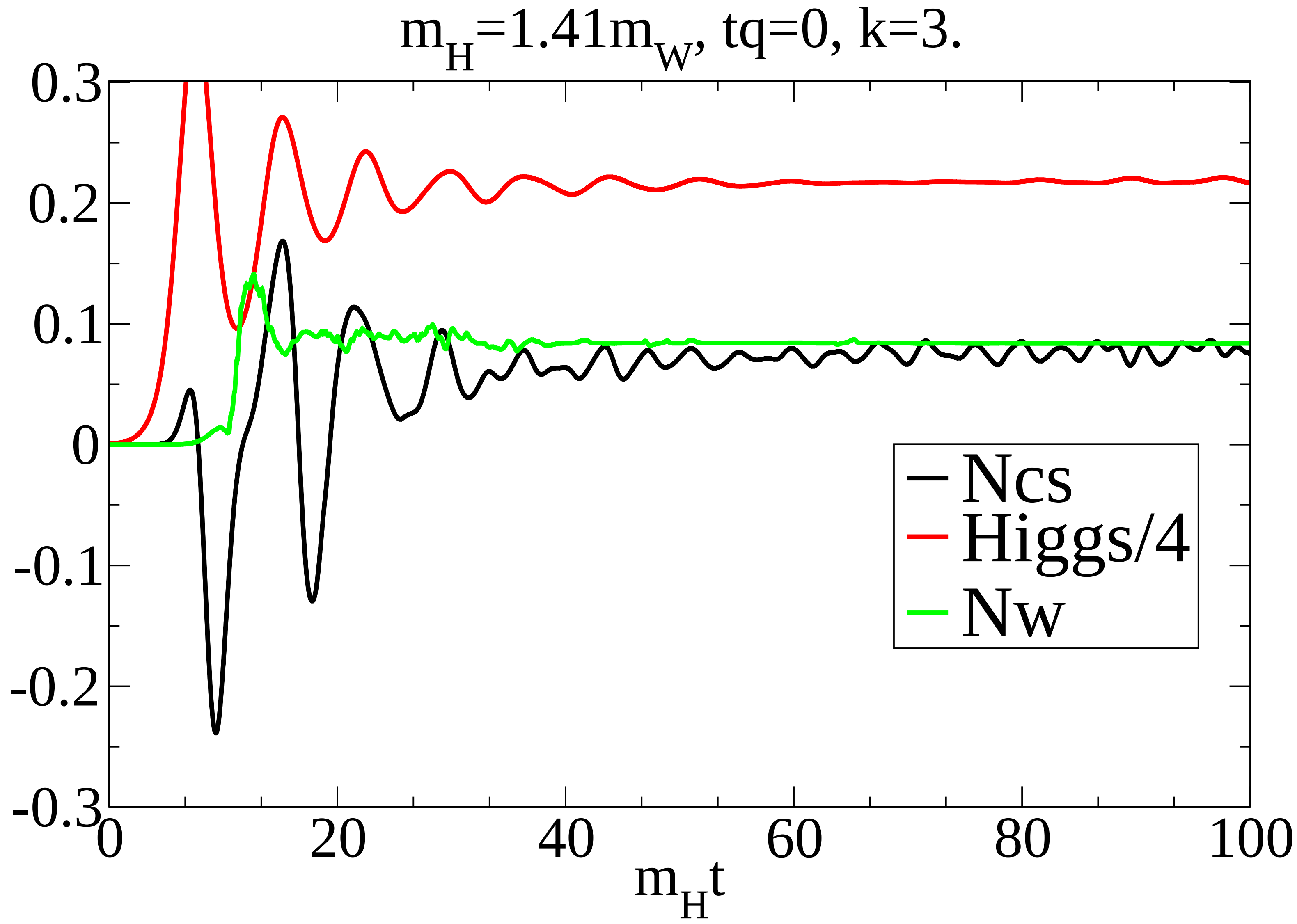
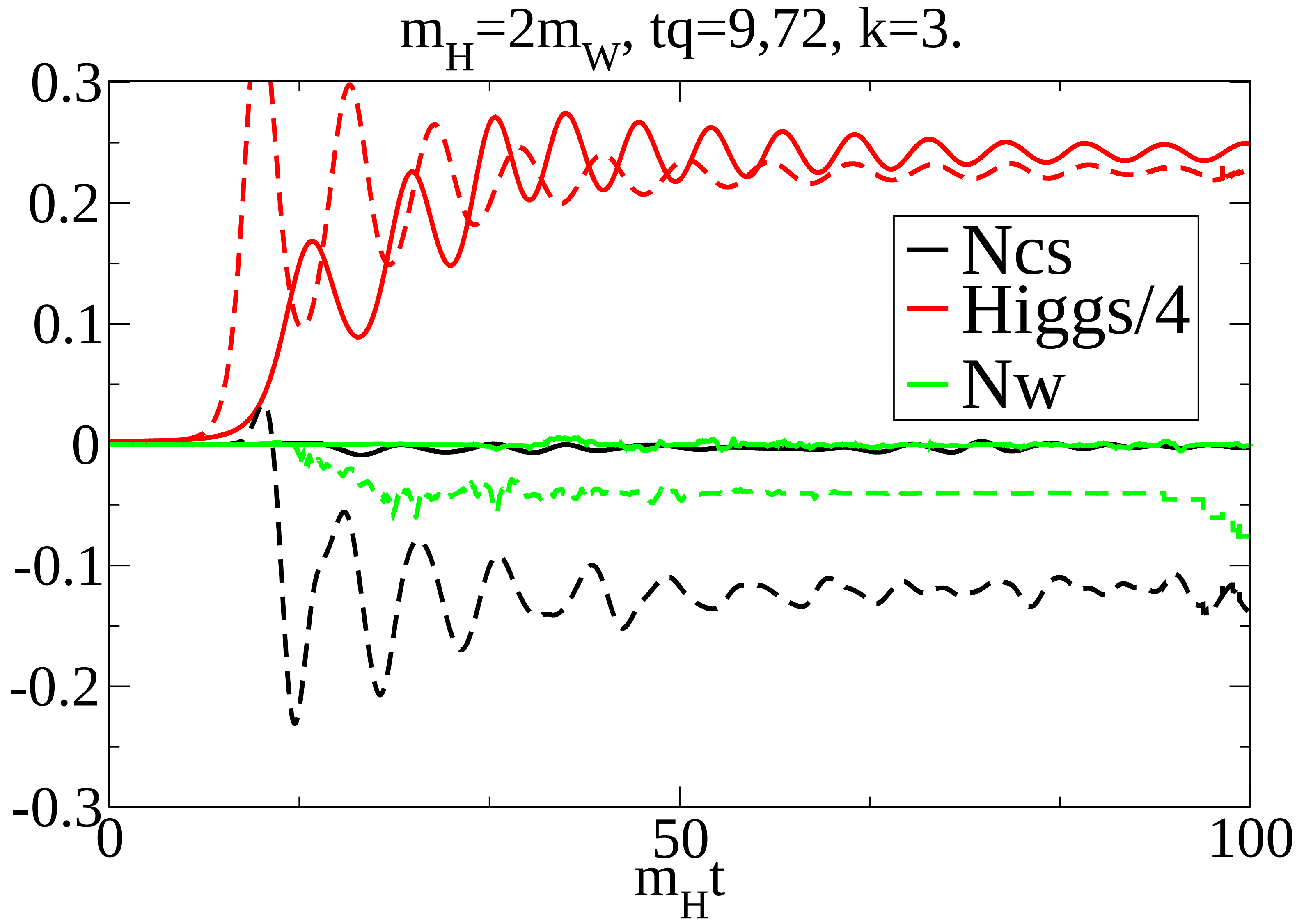

2.5e-05
2e-05
1.5e-05
1e-05
5e-06
0
0
0.5
1
1.5
2
2.5
3
3.5
k
Nw/Vm_W^3



m_H=2m_W, tq=0, k=3.
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
20
40
60
80
m_Ht
Ncs
Higgs/4
Nw



m_H=1.41m_W, tq=0, k=3.
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
20
40
60
80
100
$m_H t$
Ncs
Higgs/4
Nw



m_H=2m_W, tq=9,72, k=3.
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
50
100
$m_H t$
Ncs
Higgs/4
Nw

Final asymmetry

$$\langle B(t) - B(0)\rangle = 3\langle N_{\rm cs}(t) - N_{\rm cs}(0)\rangle, \;\; n_B = \frac{\langle B(t) - B(0)\rangle}{V}.$$

$$\frac{n_B}{n_\gamma} = 7.04\,\frac{n_B}{s}, \;\; s = \frac{2\pi^2}{45} g^* T^3, \;\; \frac{\pi^2}{30} g^* T^4 = V_0 = \frac{m_H^4}{16\lambda}.$$

$$\begin{aligned} \frac{n_B}{n_\gamma} &= -(0.23 \pm 0.05) \times 10^{-2} \kappa m_W^2, \;\; (m_H = 2m_W), \\ &= (0.21 \pm 0.05) \times 10^{-2} \kappa m_W^2, \;\; (m_H = \sqrt{2} m_W). \end{aligned}$$

To reproduce the observed asymmetry, we require

$$\kappa = \frac{3\delta_{\rm cp}}{16\pi^2 m_W^2}, \qquad \begin{aligned} \delta_{\rm cp} &\simeq -1.5 \times 10^{-5}, \;\; (m_H = 2m_W), \\ &\simeq 1.6 \times 10^{-5}, \;\; (m_H = \sqrt{2} m_W). \end{aligned}$$

Conclusion and outlook

- Including CP-violation in the gauge-Higgs equations of motion results in a net asymmetry in Chern-Simons number.
- κ-dependence is consistent with linear for small enough κ.
- The dependence on the Higgs to W mass ratio is substantial; the overall sign depends on it(!)
- At finite quench time the asymmetry decreases, and we expect the mass dependence to become less dramatic.

For more on Cold Electroweak Baryogenesis, see [Krauss & Trodden:1999,Garcia-Bellido et al.:1999,2003,2004, Smit et al(AT).: 2002,2003,2004] and Jan Smit's talk.