What's up with Cold Electroweak Baryogenesis

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Symmetries of the Standard Model

- In the SM, C and P are broken through the fermion-gauge coupling.

$$D_\mu \psi = (\partial_\mu - i A_\mu P_L)\,\psi.$$

- Fermion-Higgs coupling breaks CP through the CKM matrix (V).

$$-\mathcal{L} = \bar{\psi}_L V_L^\dagger(u,d) M_{\text{Yukawa}}(u,d) \phi V_R(u,d) \psi, \qquad V = V_L(u) V_L^\dagger(d).$$

$$J = \sin\theta_1 \sin\theta_2 \sin\theta_3 \sin\delta.$$

- A quantum anomaly connects baryon number of fermions on a gauge field background to the Chern-Simons number (Ncs) of that background.

$$B(t) - B(0) = 3[N_{cs}(t) - N_{cs}(0)] = \frac{3}{64\pi^2} \int_0^t dt \int d^3x\, \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma}.$$

Electroweak Symmetry Breaking

- The electroweak sector has a high and a low temperature phase.

$$T_c \simeq 70\,\mathrm{GeV}.$$

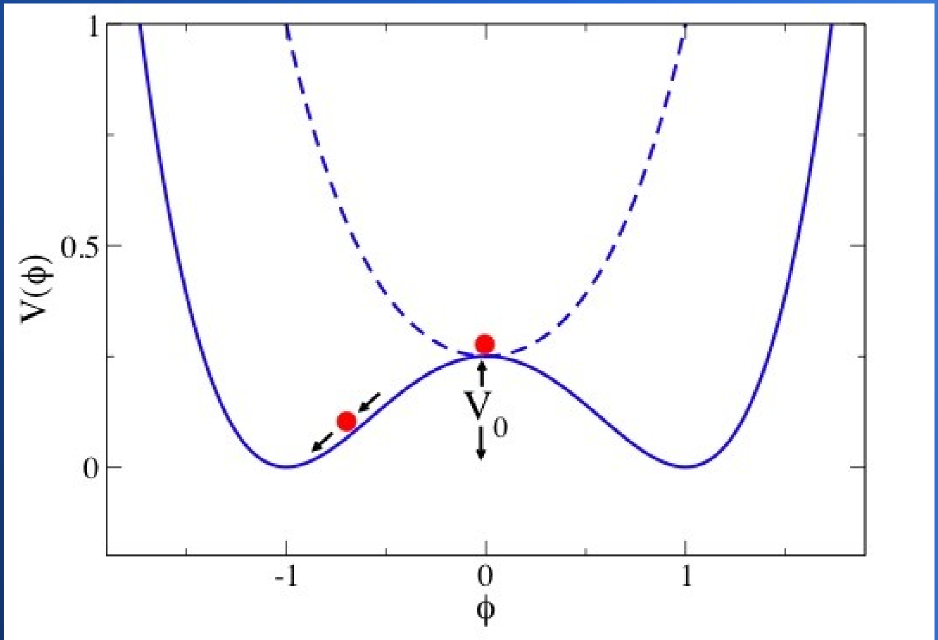
- "Symmetry breaking" is associated with a Higgs v.e.v.

$$\frac{v}{\sqrt{2}} = \langle\phi\rangle : \quad T > T_c, \quad v = 0. \qquad T = 0, \quad v = 246\,\mathrm{GeV}.$$

- Equilibrium Ncs diffusion rate ("sphaleron rate") controlled by Higgs v.e.v.

$$\Gamma_{\mathrm{sph}} = \frac{d}{dt}\left(\langle N_{cs}^2(t)\rangle - \langle N_{cs}(t)\rangle^2\right) \propto T^4 \exp\left(-B\frac{v(T)}{T}\right).$$

- Potentially out-of-equilibrium.



Things we all know about EWBG

- SM EWPT is not first order. No bubble walls.
- Expansion rate H too small to make temperature quench out-of-equilibrium.
- Baryon number generation mediated by sphalerons.
- Equilibrium Ncs diffusion restores and maintains baryon-antibaryon symmetry.
- SM CP too small to account for sufficient baryon asymmetry anyway.

$$\delta_{\mathrm{cp}} \propto J \times \frac{\Pi_{i,j=uct,i,j=dsb}\left(m_i^2 - m_j^2\right)}{T^{12}}$$

- Shaposhnikov (1988)

But!

- Inflation is mediated by an extra scalar d.o.f ("inflaton").
- Inflaton must couple to SM for successful reheating.
- Trigger quench by inflaton-Higgs coupling.
- Reheating temperature must be below Tc
- In fast quench, sphalerons do not apply. Asymmetry from CP biased Ncs/gauge evolution.
- Biased "diffusion"?
- EWBG during electroweak reheating. T=0 to 50 GeV.
- SM CP-violation is not too small at T=0.

(P)reheating

- Reheating: Perturbative decay of inflaton to SM particles. Albrecht, Steinhardt,Turner, Wilczek (1982), Dolgov, Linde (1982)
- Resonant Preheating: Non-perturbative SM particle creation. Kofman, Linde, Starobinski (1994), Shtanov, Trashen, Brandenberger (1994)
- Tachyonic Preheating: Fast symmetry breaking, “rolling off the hill”. Felder, Kofman, Linde, Garcia-Bellido, Greene, Tkachev (2001)

Electroweak Baryogenesis from Preheating

- Resonant:
- Large Higgs occupation numbers
- Large gauge fields.
- CP-biased out-of-equilibrium Ncs diffusion.
- Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov (1999).

- Tachyonic:
- Kibble mechanism leads to (symmetric) distribution of textures.
- Textures unwind asymmetrically under CP-violation.
- Turok, Zadrohny (1990), Copeland, Lyth, Rajantie, Shaposhnikov (2001).

A little bit of this, a little bit of that

- Treh<Tc leaves no room for additional inflaton kinetic energy

$$\frac{\pi^2}{30} g^* T^4 = 15.5 \lambda v^4 (m_H/m_W)^{-2}, \qquad m_H/m_W = 1.5 - 2.5.$$

- Tachyonic energy transfer much faster than resonant.
- Not resonant preheating.
- Mechanism at work is not Kibble.

- Tachyonic:
- Large occupation numbers in Higgs
- Large gauge fields
- CP-biased out-of-equilibrium Ncs diffusion

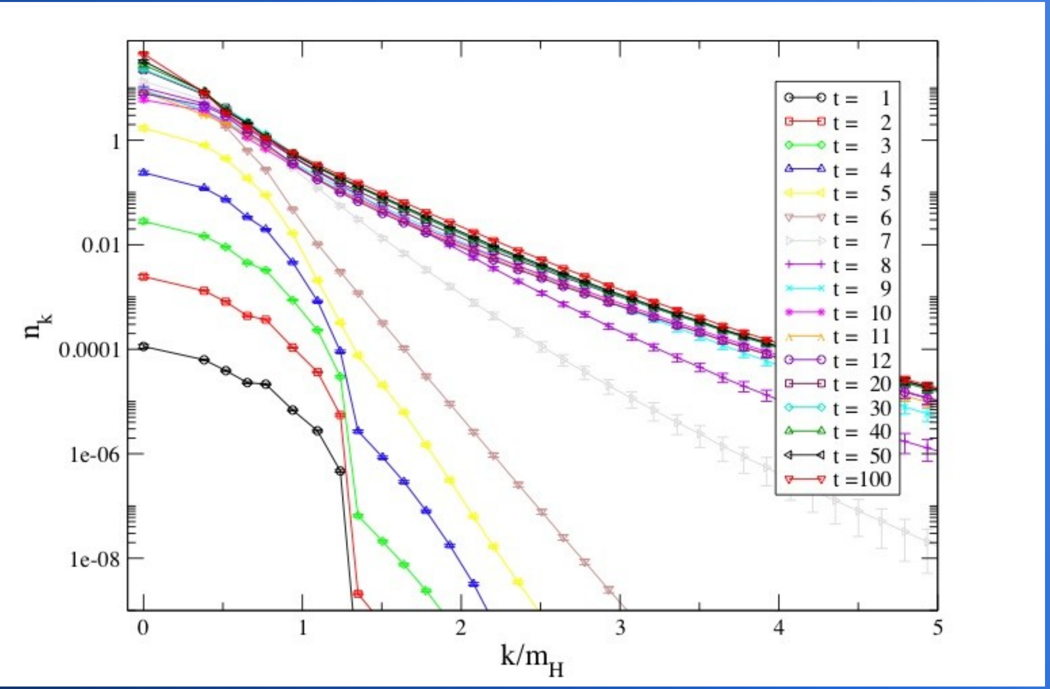
- Garcia-Bellido, Garcia Perez, Gonzalez-Arroyo (2001-3), AT, Smit (2002-3-4-6).

Tachyonic Preheating and Classicality

- Momentum modes with imaginary mass grow exponentially.

$$V(\phi) \simeq -\mu^2\phi^\dagger\phi, \quad \phi_k \propto e^{\sqrt{\mu^2-k^2}t}, \quad |k| < \mu.$$

- Large occupation number leads to classical effective dynamics.
- Energy transfered from Higgs to gauge fields.

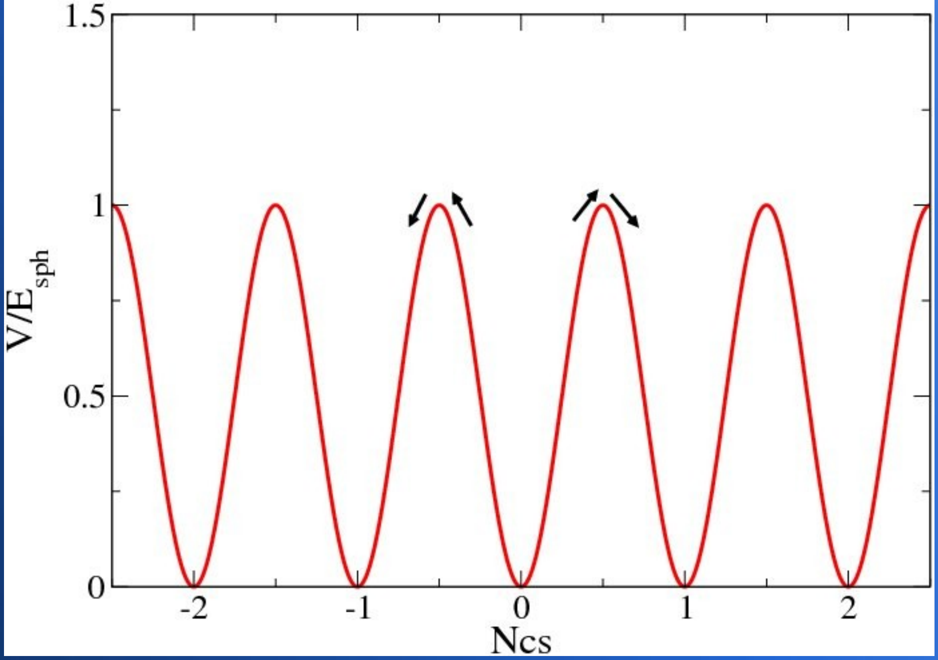


From Skullerud, Smit, AT (2003)

- Also Garcia-Bellido, Garcia Perez Gonzale-.Arroyo, Diaz-Gil (2003-)

Equilibrium diffusion and Sphalerons

- Gauge-Higgs vacua have Nw=Ncs, integer.
- Most likely transitions via lowest energy configuration, sphaleron.
- Rate suppressed by sphaleron energy.
- Equilibrium rate in symmetric and broken phase is known.
- Ambjørn, Krasnitz, Shaposhnikov, Porter, Askgaard, Moore, Bödeker, Rummukainen, Philipsen, Smit, Tang (1988-2001)



- Ncs=+/-1/2 for a Sphaleron
- What does Nw do? Dressed winding number change?

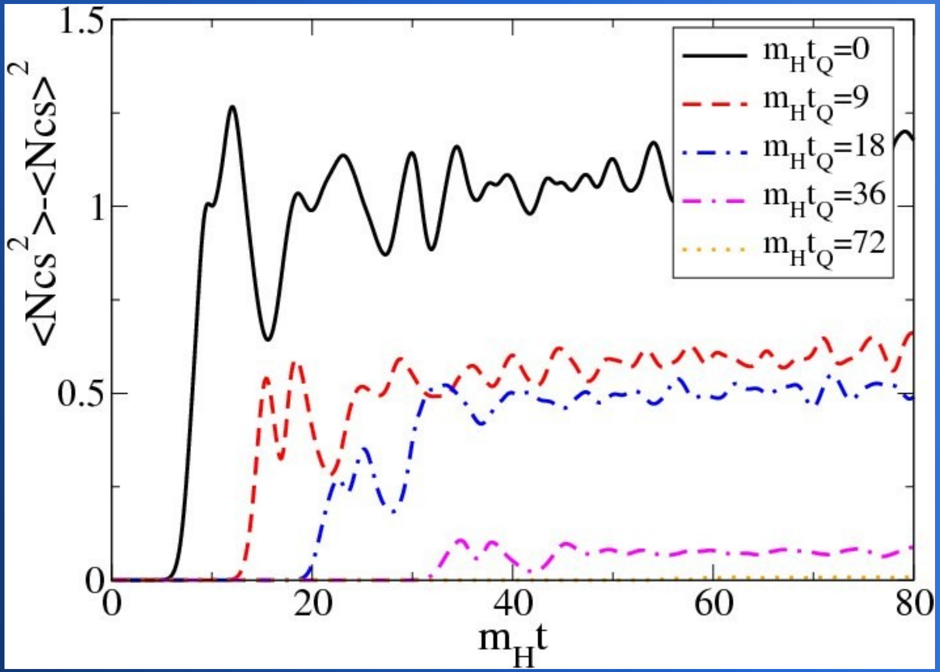
CP-biased out-of-equilibrium Ncs diffusion

- Gauge fields grow during the transition. Also the Ncs mode grows.
- Define a "diffusion rate"

$$\Gamma_{\text{diff.}}(t) = \frac{d}{dt}\left(\langle N_{cs}^2(t)\rangle - \langle N_{cs}(t)\rangle^2\right).$$

- Linear response to an effective chemical potential

$$\frac{dn_B}{dt} = \Gamma_{\text{diff.}}(t)\frac{\mu_{\text{eff}}}{T_{\text{eff}}}.$$



- From AT, Smit, Hindmarsh (2006)

Asymmetric texture unwinding

- A texture in a scalar theory is unlocalised and has integer Nw.
- With gauge fields, the analogue is to have integer Ncs not equal to Nw.
- Gauge equivalent to A=Ncs=0, Nw=integer.
- In symmetry breaking transition, Nw can be created via Kibble mechanism. At first: Localised Skyrmions.
- Given a CP-symmetric set of Skyrmions <Nw>=0.
- Go to vacuum Nw=Ncs by either moving Ncs or Nw.
- Depends on size of Skyrmion.
- CP-violation shifts critical size dependent on sign of Nw: Net asymmetry.
- Turok, Zadrohny (1990), Copeland, Lyth, Rajantie, Trodden (2001), v.d.Meulen, Sexty, Smit, AT (2005)

The SM and some Approximations

- No SU(3) or U(1).
- Integrate out fermions (TrLog D). Leading order in (covariant) gradient expansion.

$$\int_0^t dt \int d^3x \, \frac{3\delta_{\rm cp}}{64\pi^2} \frac{\phi^\dagger \phi}{m_W^2} \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma}.$$

- Replace inflaton-Higgs coupling

$$(\mu^2 - \lambda_{\sigma\phi}\sigma^2)\phi^\dagger\phi$$

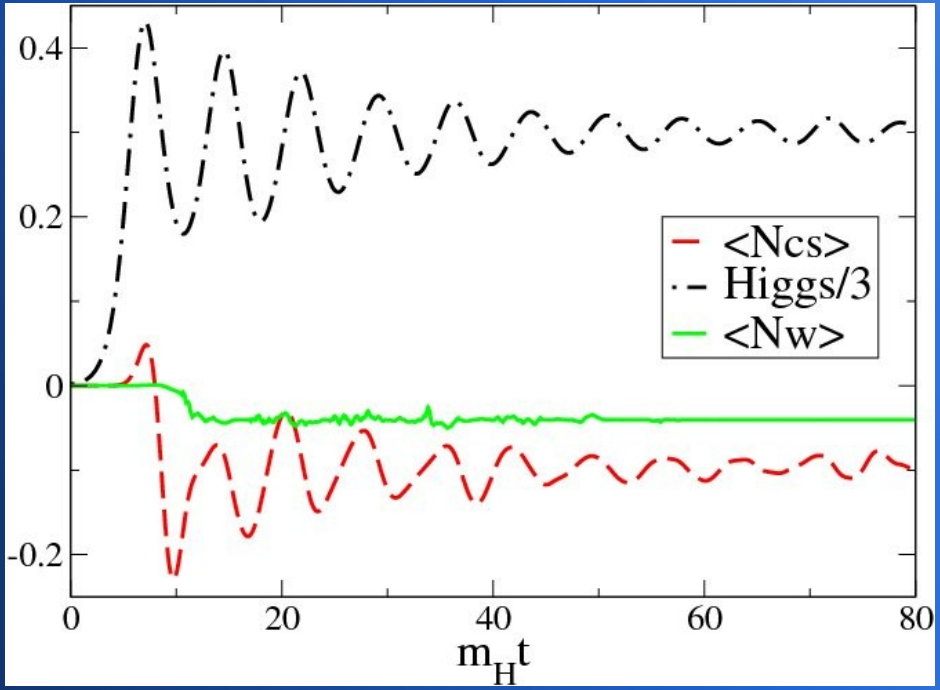
- by time-dependent mass

$$\mu^2 \left(1 - \frac{2t}{t_Q}\right) \phi^\dagger \phi$$

- 114 < mH/GeV < 200.

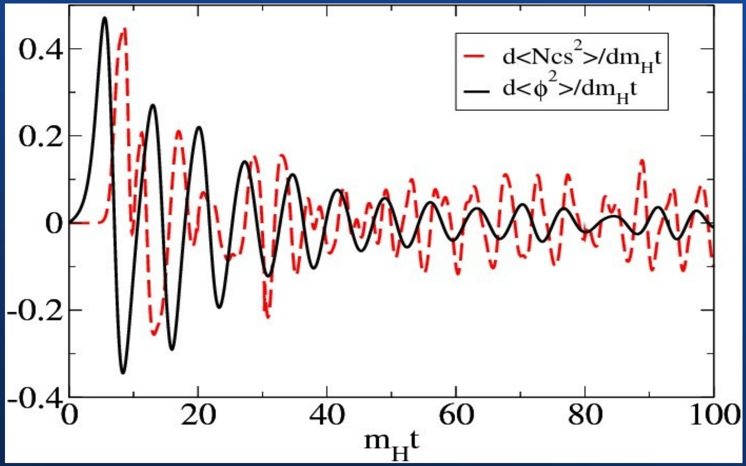
Numerical simulations

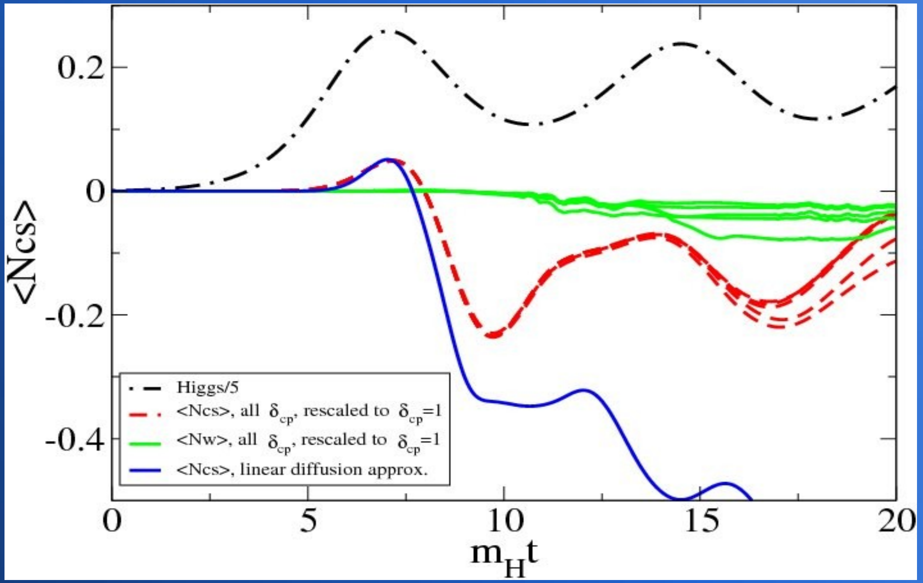
- Solve classical equations of motion numerically. Average over intial conditions.
- 1) Damped oscillation of Higgs field
- 2) Ncs moves first.
- 3) Then Nw moves to accommodate Ncs asymmetry.
- 4) Nw moves at Higgs oscillation minimum.



- From Tranberg, Smit (2006)

It is asymmetric “diffusion”





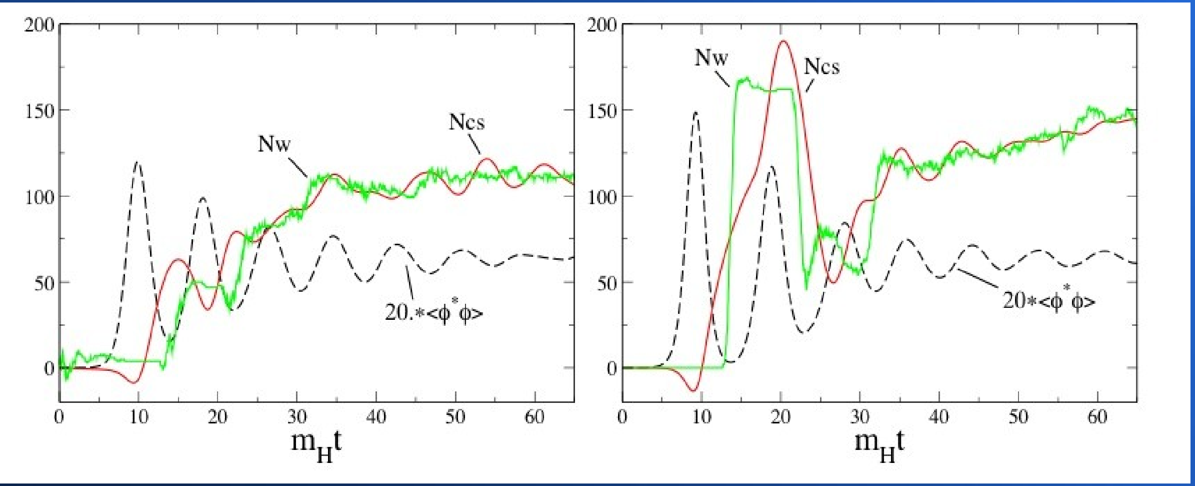
- Integrating up the effective chemical potential with the “diffusion” rate
- Teff from energy in infrared modes.

$$\Gamma_{\text{diff.}}(t) = \frac{d}{dt}\left(\langle N_{cs}^2(t)\rangle - \langle N_{cs}(t)\rangle^2\right).$$

$$\mu_{\text{eff}} = \frac{\delta_{\text{cp}}}{m_W^2}\frac{d\langle\phi^\dagger\phi\rangle}{dt}$$

$$\frac{dn_B}{dt} = \Gamma_{\text{diff.}}(t)\frac{\mu_{\text{eff}}}{T_{\text{eff}}}.$$

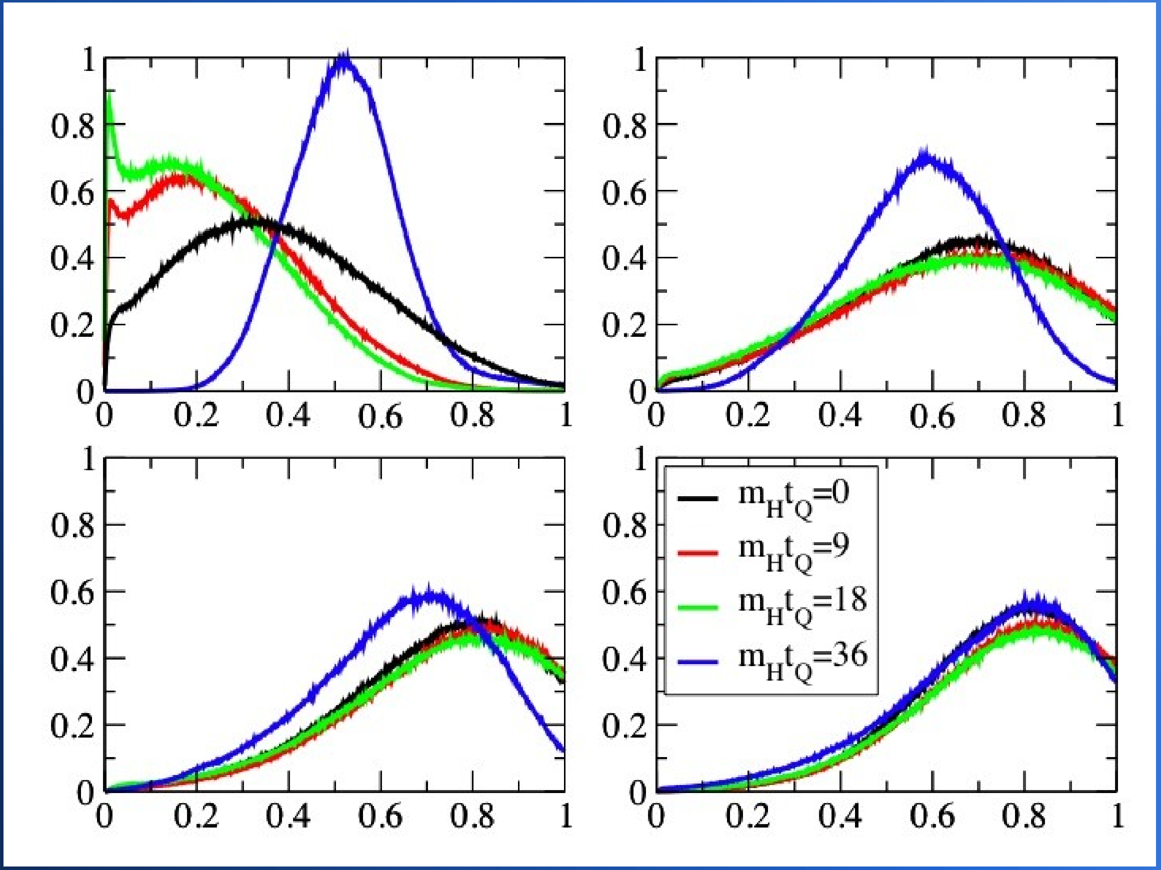
It ain't Kibble



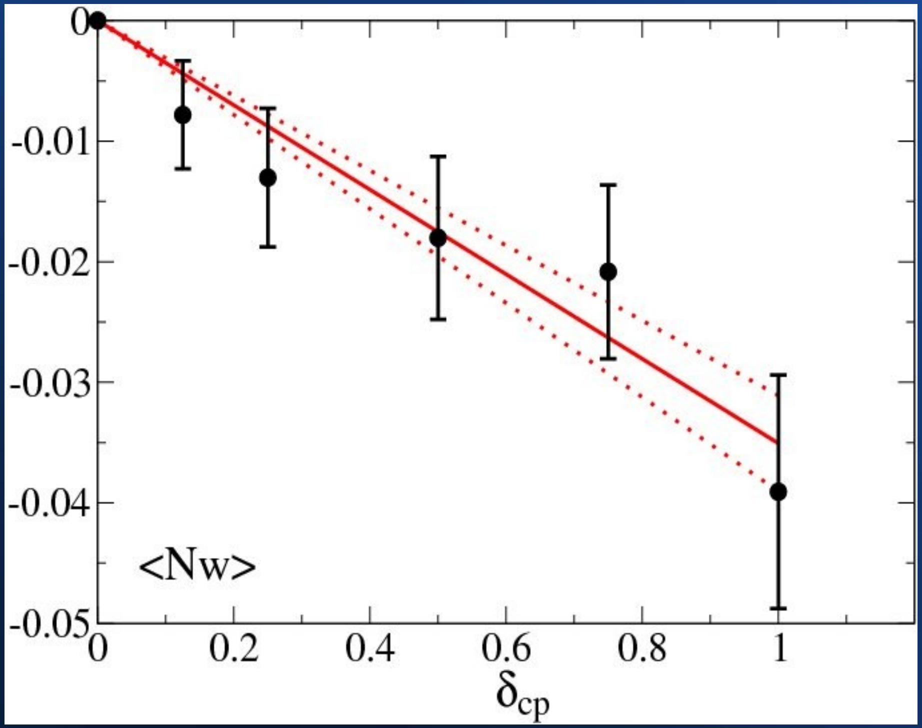
- Test is 1+1D. Random initial phases vs. Zero initial phases.
- Ncs is driven by force. Not random creation of Higgs winding.
- There will also be a population of defects from Kibble mechanism. The effect on the net asymmetry is sub-leading.
- From Smit, Tranberg (2002)

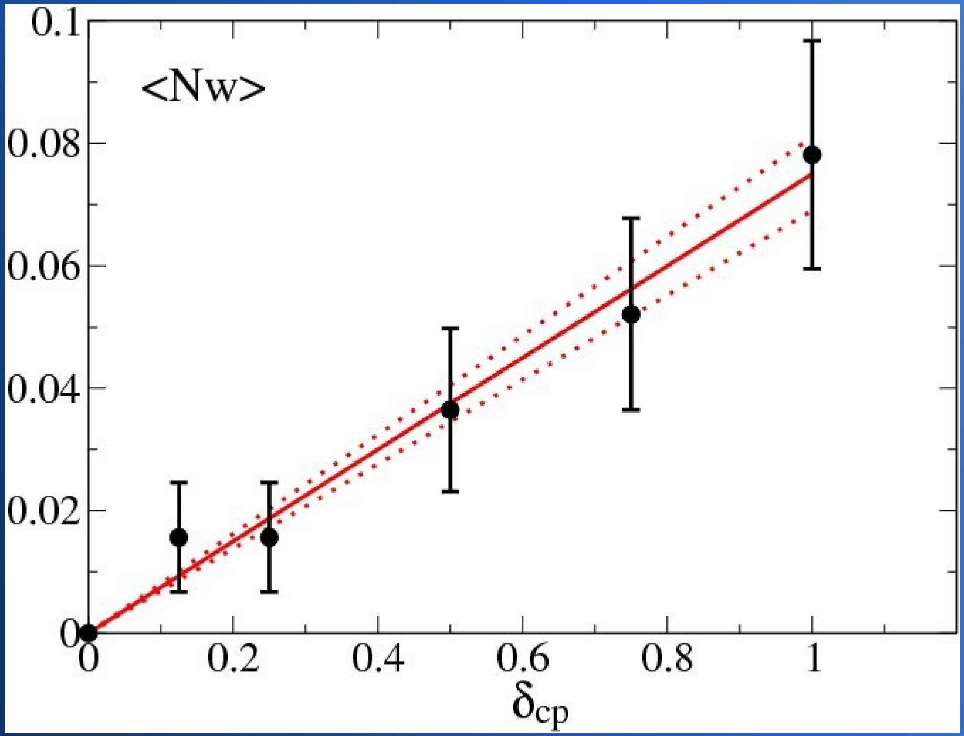
The importance of zeros

- Nw can only change in the presence of a Higgs field zero.
- These occur at the minima of the Higgs oscillation.
- Nw=1/2 around a zero
- v.d. Meulen, Sexty, Smit, AT (2005)

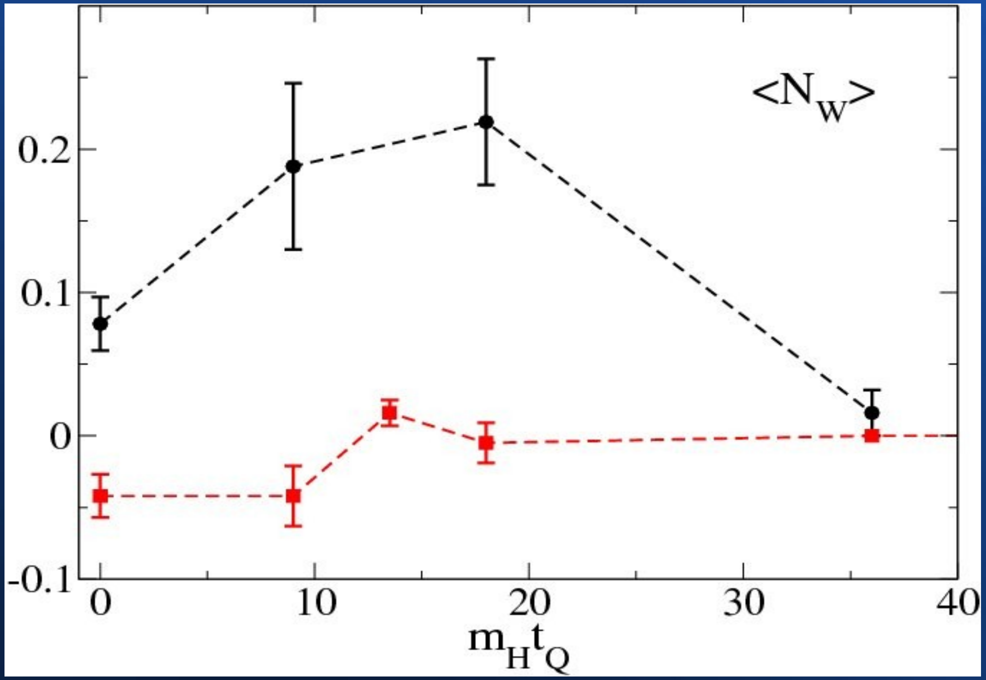


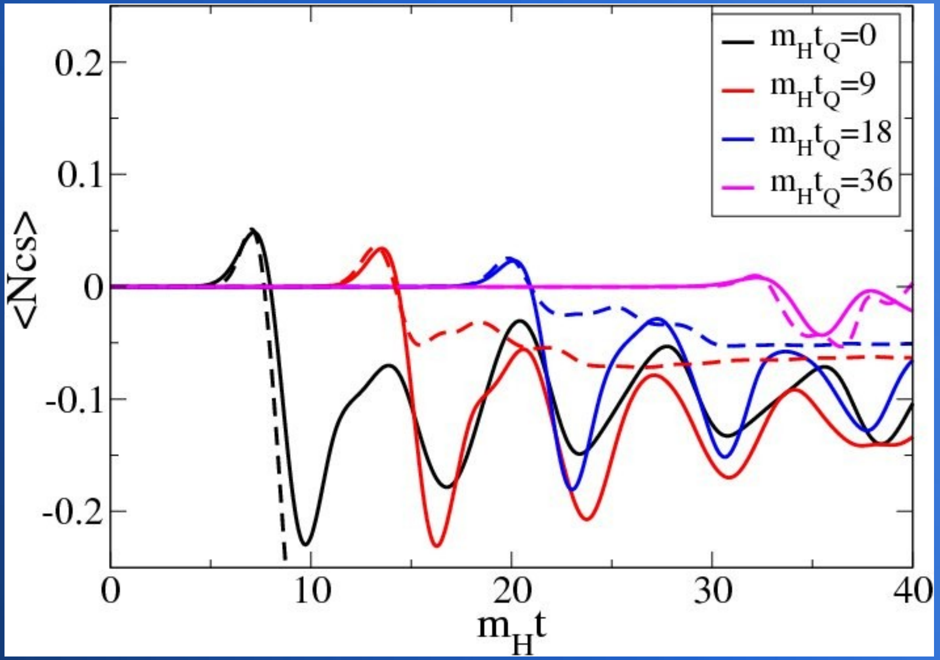
Dependence on CP-violation





Dependence on quench time





The final asymmetry

- Final asymmetry is linear in CP-violation

$$\frac{n_B}{n_\gamma} = (0.20 \pm 0.04) \times 10^{-3} \delta_{\rm cp} \quad \rightarrow \quad \delta_{\rm cp} > 3 \times 10^{-6}.$$

- Quench time < 20/mH.
- Some dependence on Higgs mass.
- Detailed inflaton dynamics?
- Garcia-Bellido, Garcia Perez, Gonzalez-Arroyo, Diaz-Gil (2003-)

CP violation in the SM

- Integrate out fermions, T=0.
- Expand in A and Dϕ
- Salcedo (–2009)
- LO: coefficient zero!
- Smit (2004)
- But: Yukawa couplings cancel out. Only J remains.
- NLO: coefficient non-zero!
- And Yukawa couplings still cancel out . J remains.
- Hernandez, Konstandin, Schmidt (2008)
- Maybe...
- Garcia-Recio, Salcedo (2009)
- White-board!

Outlook and things under way

- The LHC will give us the Higgs mass.
- Simulation with the correct leading CP-violating operator
- AT with Michael G. Schmidt, Andres Hernandez.
- Experimental signatures of the inflaton-Higgs coupling and mixing at the LHC.
- Quench time.
- AT with Michael Ramsey-Musolf

  (this workshop)