Cold Electroweak Baryogenesis with Two Higgs Doublets

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Cold Electroweak Baryogenesis

- “Hot” EWBG, out-of-equilibrium from bubble nucleation at first order phase transition.
- Leptogenesis, out-of-equilibrium from decay of heavy leptons.
- “Cold” EWBG, out-of-equilibrium from spinodal electroweak transtion from low temperature initial state, triggered by auxiliary field.

$$V(\phi) = \mu_{\rm eff}^2(t)\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \qquad \mu_{\rm eff}^2(t) = g^2\sigma^2(t) - \mu^2$$

- Instability → large IR occupation numbers → classical IR dynamics.
- Late times: Higgs potential energy → thermalized plasma at T < Tc.
- Never equilibrium high-temperature sphalerons! But anomaly, yes.
- Source of CP-violation?

Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov: 1999
Krauss, Trodden: 1999
Copeland, Lyth, Rajantie, Trodden: 2001
AT, Smit: 2003

If SM CP-violation

See poster:

Tomas Brauner, Olli Taanila, AT, Aleksi Vuorinen:

"Temperature dependence of CP violation in the Standard Model"

Based on

Phys. Rev. Lett. 108 (2012) 041601

Strong constraints on effective temperature...

Salcedo: 1997, ..., 2009, 2011
Smit: 2004
Hernandez, Konstandin, Schmidt: 2008
+AT: 2010

If Not SM CP-violation

- Two Higgs Doublets + SU(2):

$$S = \int d^3x\, dt \left[\frac{1}{4g^2} \mathrm{Tr} F^{\mu\nu} \tilde{F}^{\mu\nu} + (D_\mu \phi_1)^\dagger D^\mu \phi_1 + (D_\mu \phi_2)^\dagger D^\mu \phi_2 + V(\phi_1, \phi_2) \right]$$

- CP-violation in scalar potential.

$$\begin{aligned} V(\phi_1, \phi_2) = & -\mu_{11}^2 \phi_1^\dagger \phi_1 - \mu_{22}^2 \phi_2^\dagger \phi_2 - \mu_{12}^2 \phi_1^\dagger \phi_2 - \mu_{12}^{2,*} \phi_2^\dagger \phi_1 \\ & + \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) \\ & + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{\lambda_5}{2} (\phi_1^\dagger \phi_2)^2 + \frac{\lambda_5^*}{2} (\phi_2^\dagger \phi_1)^2 \end{aligned}$$

- Also CKM, but ignore.

Dynamical fermions

See next talk:

Paul Saffin, AT

"Dynamical simulations of electroweak baryogenesis with fermions"

Based on

JHEP 1202 (2012) 102

Aarts, Smit: 1998
Borsanyi, Hindmarsh: 2009
Berges, Gelfand, Pruschke: 2011
Saffin, AT: 2011

Constraint from computer-size...

Bosonic simulations and discrete symmetries

- Otherwise, bosonic simulations: Baryon asymmetry assumed to follow through anomaly equation:

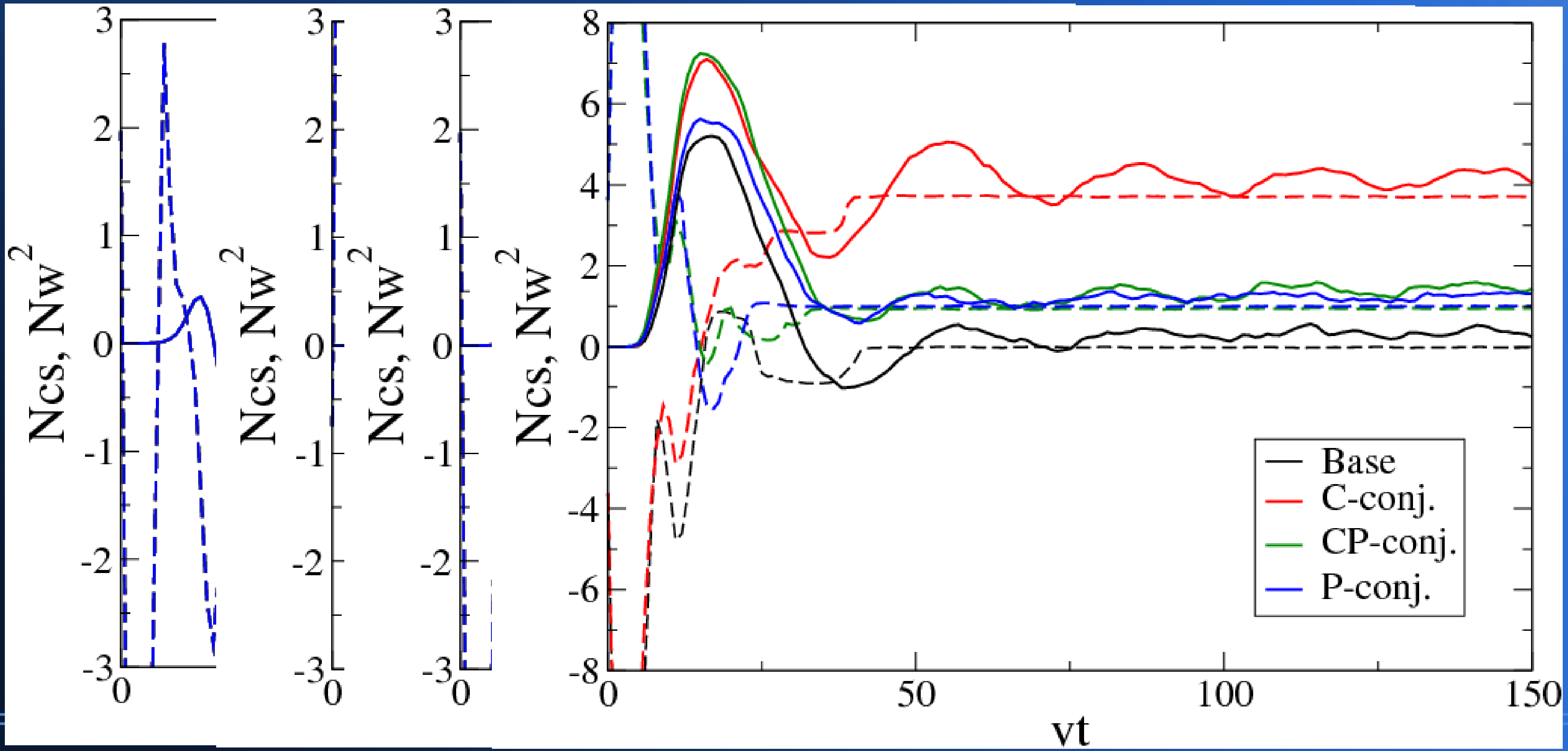
$$B(t) - B(0) = n_g \left[N_{\rm cs}(t) - N_{\rm cs}(0) \right]$$

  - Ncs is P odd and C even; CP odd.
  - Higgs potential is C odd, P even; CP odd → No asymmetry.
  - In combination with C-odd, P-odd; CP-even interactions → Asymmetry.
- Fermion-gauge interactions → integrate out fermions. Simplest term:

$$+S_{C/P} = + \int d^3x \, dt \, \frac{\delta_{C/P}}{16\pi^2 m_w^2} i(\phi_1^\dagger \phi_2 - \phi_2^\dagger \phi_1) {\rm Tr} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Conjugate configurations

- Use sets of 4 C, P, CP conjugate initial configurations. Initial ensemble explicitly C, P and CP symmetric.



Higgs potential

- 10 parameters. Fix:
- Minimum: $v_1^2 + v_2^2 = (246\text{GeV})^2, \qquad v_1/v_2 = \tan\beta = 2$
- Masses:

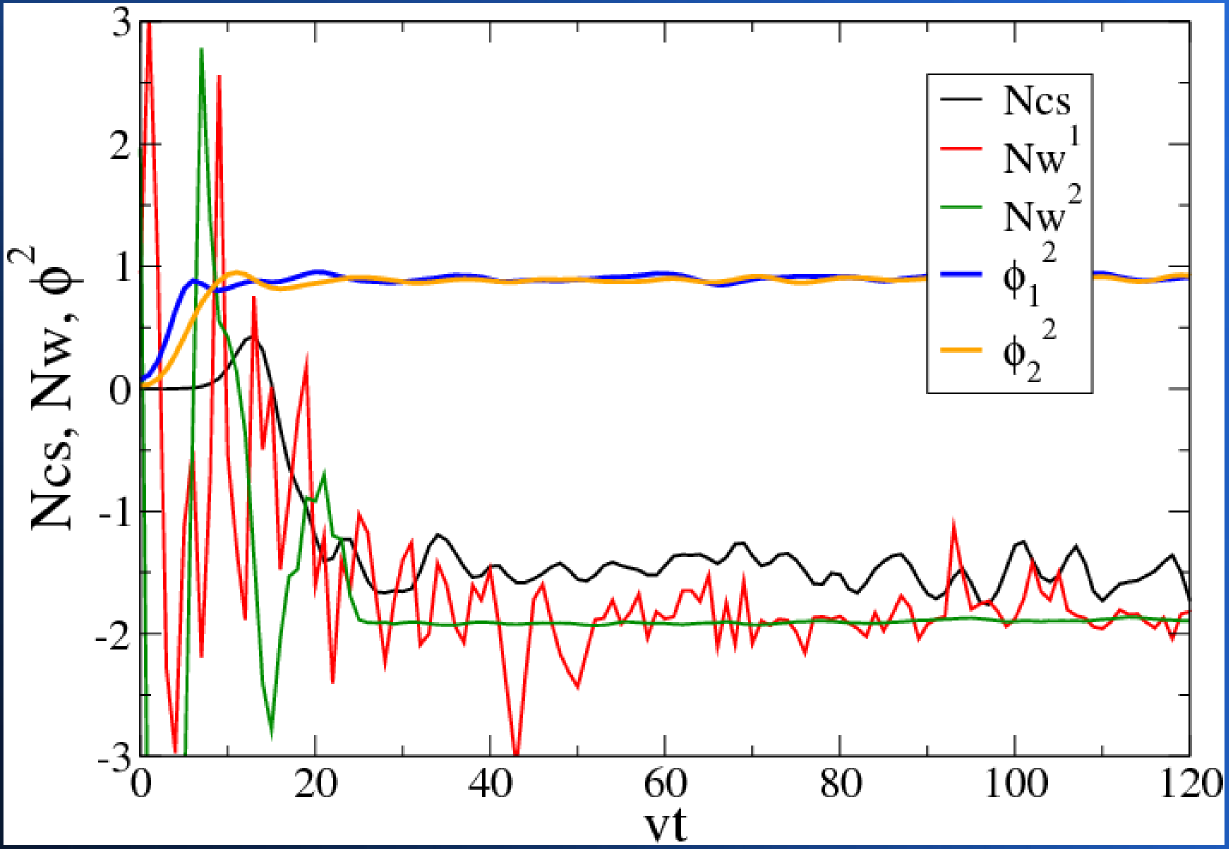
$$m_1 = 125\text{GeV}, \quad m_2 = 300\text{GeV}, \quad m_3 = 350\text{GeV}, \quad m_\pm = 400\text{GeV}$$

- Leaves:

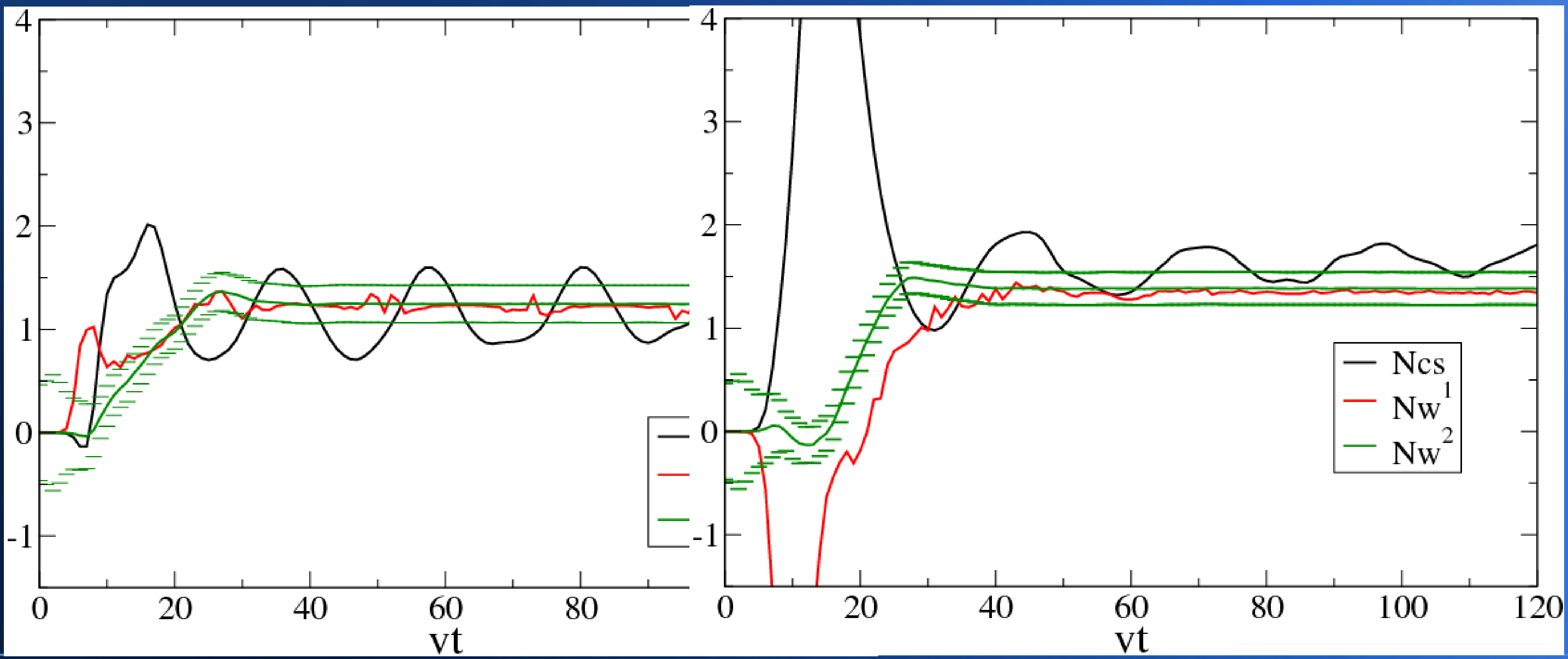
$$\mu_{12}^2, \quad \lambda_5$$

  - Real vevs → $\text{Im}(\lambda_5) v_1 v_2 = \text{Im}(\mu_{12}^2)$
  - Complex vevs → $\text{Im}(\lambda_5) = 0, \quad v_2 = |v_2| e^{i\theta}$

Single configuration

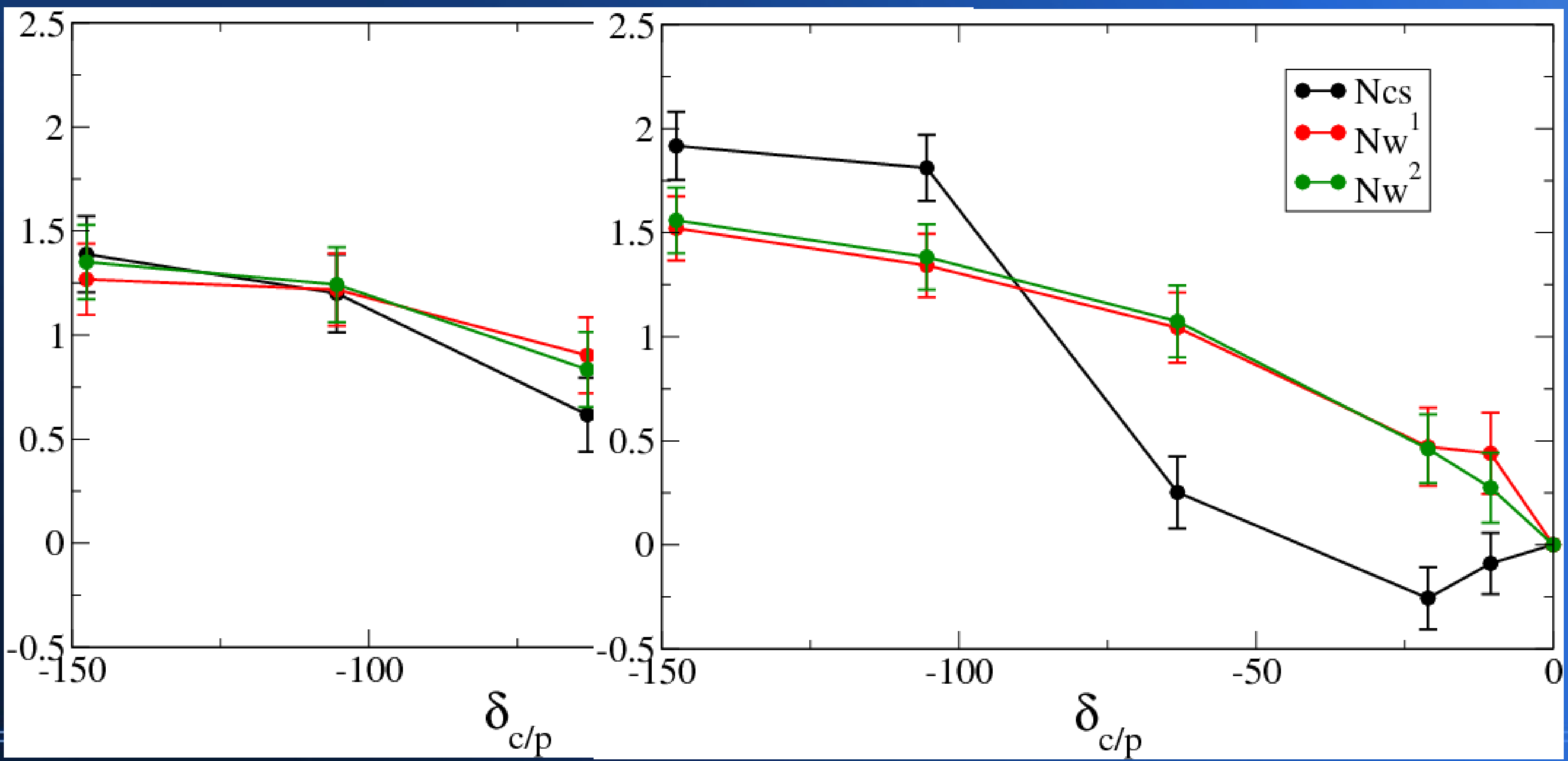


Averages

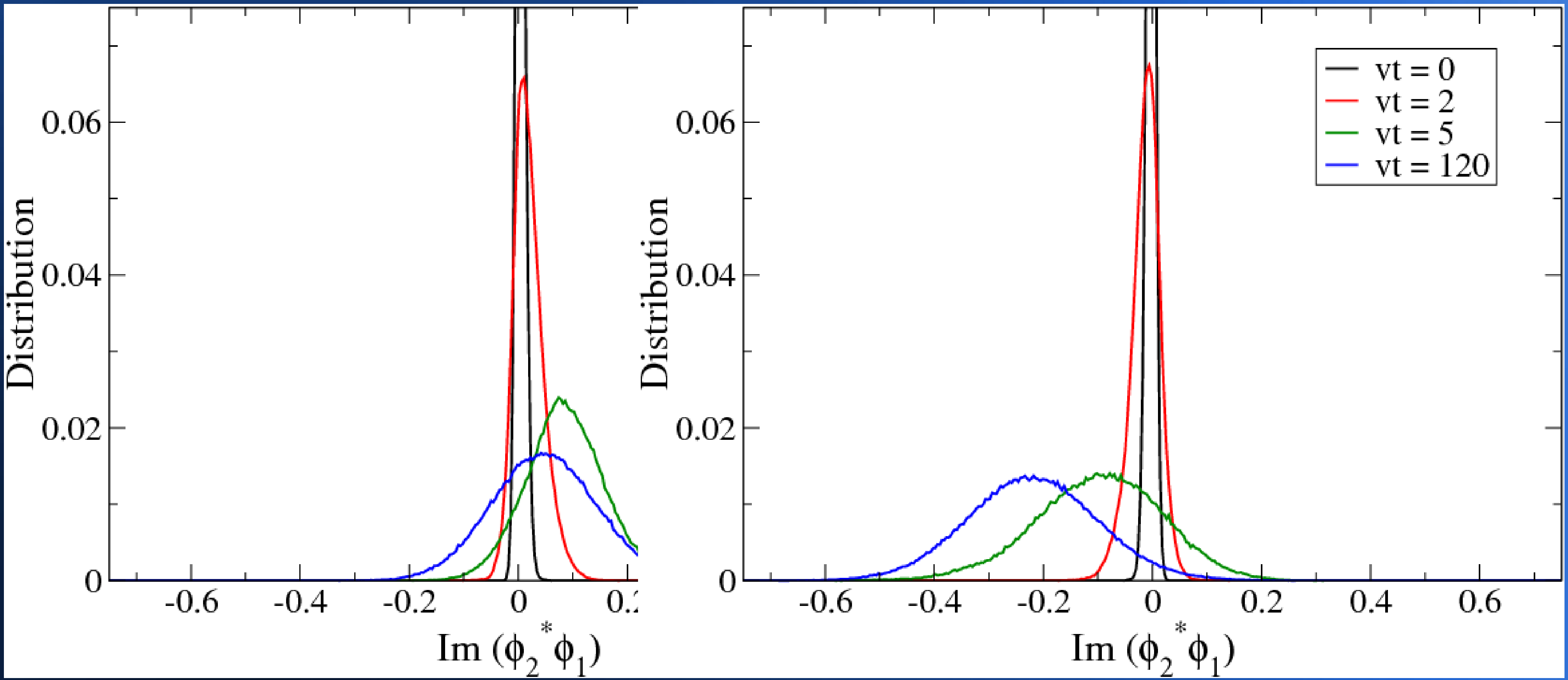


Dependence on $\delta_{C/P}$

- Average over ensemble for different values of $\delta_{C/P}$. Nw the preferred observables.



Complex Phase



Final asymmetry

- Final asymmetry:

$$\frac{n_B}{n_\gamma} = \frac{3\overline{N_{\rm cs}}/L^3}{(2\pi^2/45g^*T^3)/7.04}, \qquad \frac{\pi^2}{30}g^*T^4 = V(0,0) - V(v_1,v_2)$$

- Real vev: $$\frac{n_B}{n_\gamma} = -\delta_{\rm C/P} \times (1.6 \pm 1.2) \times 10^{-6}$$

- Complex vev: $$\frac{n_B}{n_\gamma} = -\delta_{\rm C/P} \times (2.8 \pm 1.2) \times 10^{-6}$$

- To get observed baryon asymmetry $\rightarrow \delta_{\rm C/P} \simeq 10^{-4}$

Conclusion

- If there are two Higgses, the electroweak transition may be first order. → (H)EWBG.
- If not, a tachyonic transition may arise from coupling to other fields. → (C)EWBG.
  - C(P) violation from scalar potential.
  - C- & P-odd, CP-even in gauge-fermion interaction → baryon asymmetry.
  - In bosonized model, need both since Ncs is P-odd, but C-even.
- Similar to SM! CKM is C(P) violating. Integrating out fermions gives only C(P) breaking effective operators at LO (see poster by Tomas Brauner). Bosonized SM needs also the whole C- & P-odd, CP-even sector! Or fermions see next talk.
- Direct classical bosonic simulation show that combination gives asymmetry. In present implementation/parameters requires

$$\rightarrow \delta_{\mathrm{C/P}} \simeq 10^{-4}$$

- Also here, we need to compute C- & P-odd, CP-even sector (roughly = SM).
- Varying potential → w. Bin Wu, in progress.