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ALP-Assisted Electroweak Phase Transition and Baryogenesis

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Based on: 2309.00587, Collaborator: Prof. Keisuke Harigaya

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- Challenges of electroweak baryogenesis and phase transition (EWPT)
  - Baryogenesis problem and principles of solution
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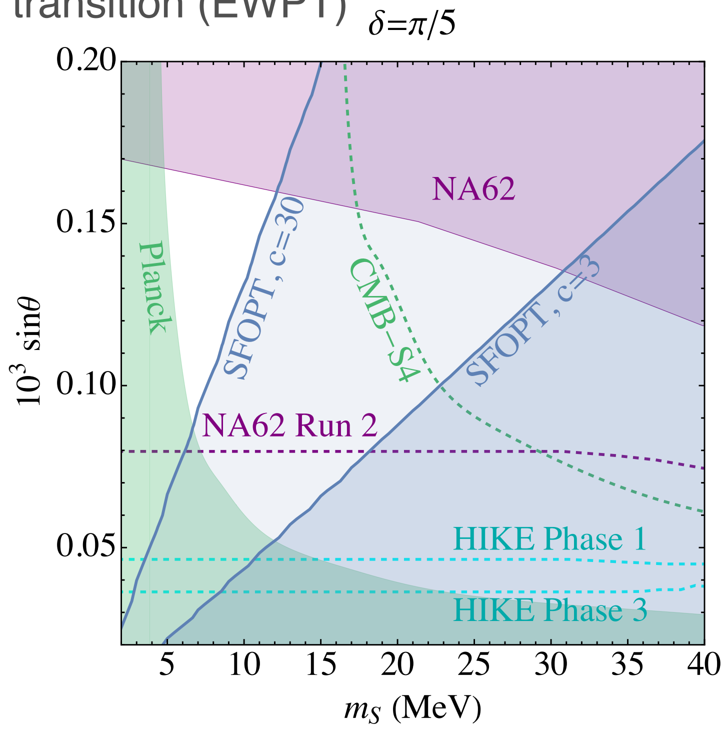
  - Challenges
- Axion-like particle (ALP) couples with Higgs
- Experimental Probes
  - ΔN_{eff} constraint
  - Rare meson decay
  - Collider searches



Part of the final results. White spaces are allowed.

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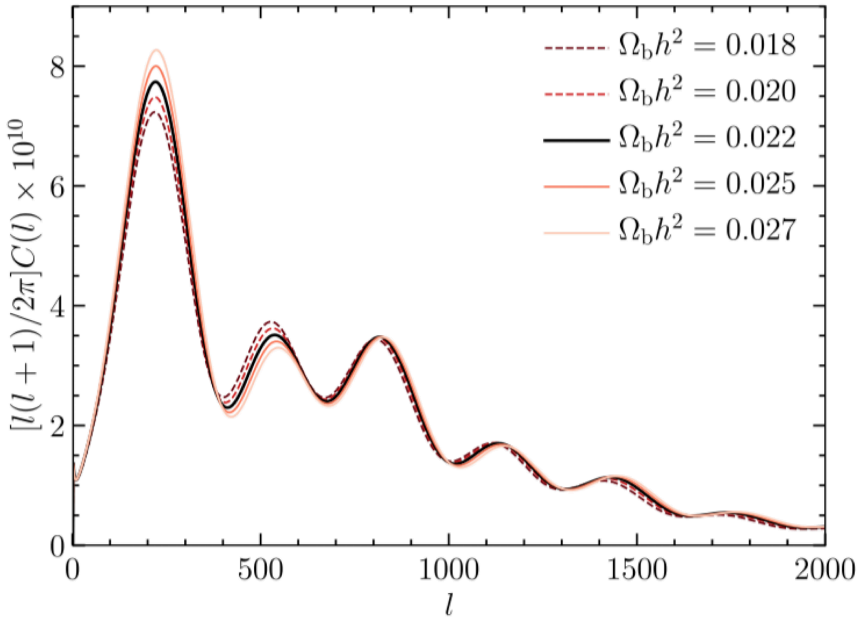
Matter-Antimatter Asymmetry: Baryogenesis Problem

- matter > anti-matter
- Define $n_B = n_{\mathrm{baryon}} - n_{\mathrm{anti-baryon}}$
- $\frac{n_B}{s} \simeq 9 \times 10^{-11}$
- What's the origin?



Planck 2018b

Sakharov Condition

- Baryon number violation

  SM: sphaleron process. Violates $B + L$ but keeps $B - L$.

- C and CP violation

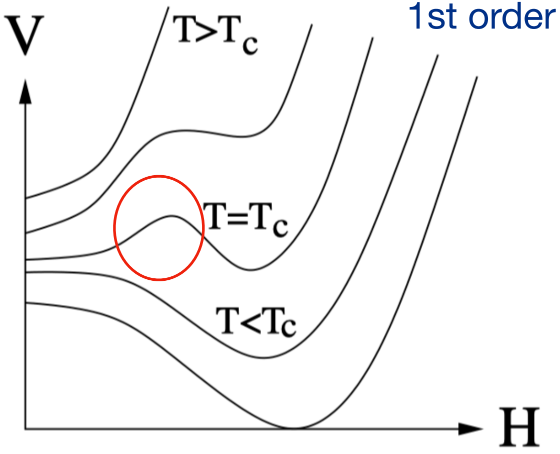
  SM: CKM (too small), or UV scale new physics, model dependent.
  (Not the main focus today.)

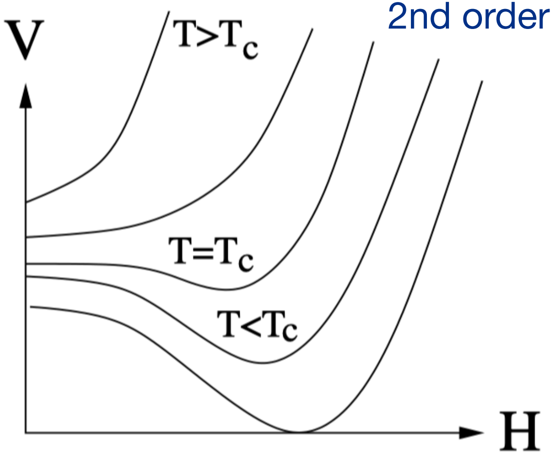
- Out of thermal equilibrium

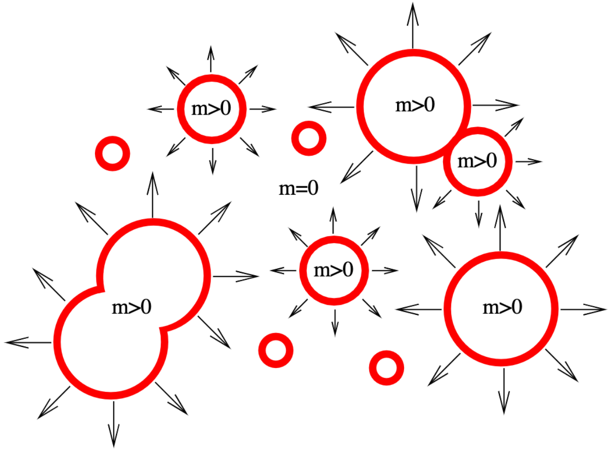
  SM: a strong 1st-order electroweak phase transition (need BSM!)

[Sakharov, 1967]

EWPT: 1st order vs 2nd order





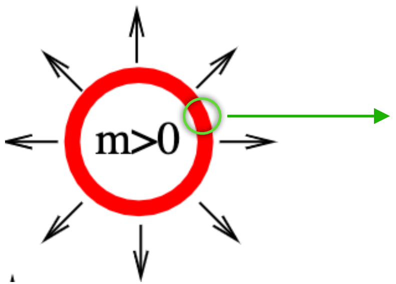


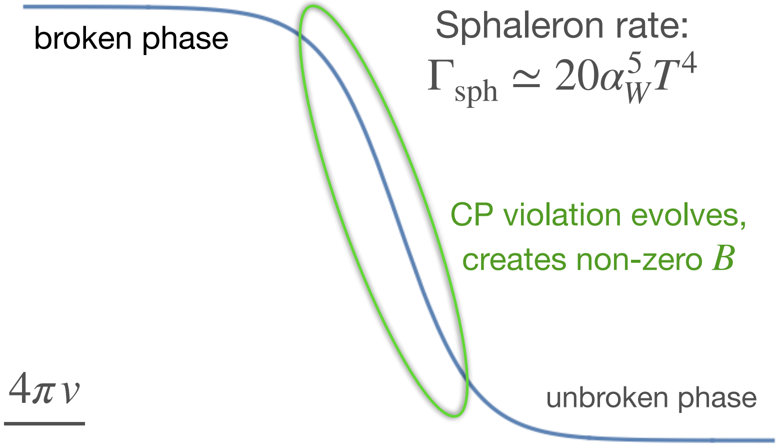
1st order: clear, well-defined barrier
2nd order: smooth crossover.

1st-order PT processes via ***bubble nucleation***

Figure from:
[J Cline: hep-ph/0609145]

Electroweak baryogenesis from 1st-order EWPT





Sphaleron rate:
$\Gamma_{\rm sph} \simeq 20\alpha_W^5 T^4$

Wall profile

Sphaleron rate in the bubble:

$$\Gamma_{\rm sph} \sim \exp(-E_{\rm sph}/T),\ E_{\rm sph} \propto \frac{4\pi v}{g}$$

suppressed by v

Need to be turned off inside the bubble!

Require $\frac{v_n}{T_n} \geq 1$, T_n: bubble nucleation

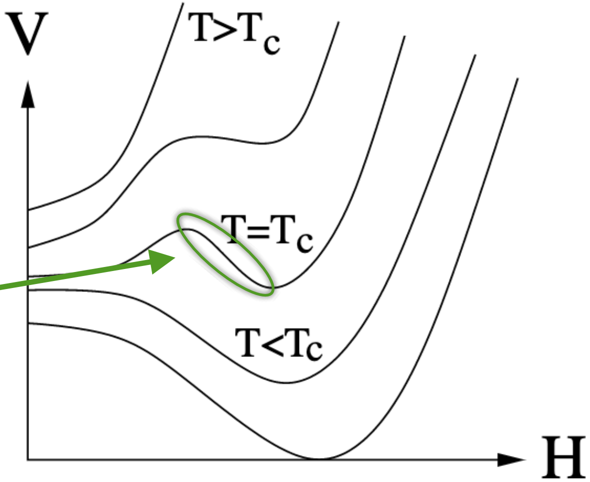
Typically (not supercooling):

$$\frac{v(T_c)}{T_c} \simeq \frac{v(T_n)}{T_n}$$

[F. R. Klinkhamer and N. S. Manton, Phys. Rev. D 30, 2212]
[V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B 155, 36 (1985)]
[M. E. Shaposhnikov, JETP Lett. 44, 465 (1986),Nucl. Phys. B 287, 757 (1987)]
[A. G. Cohen, D. B. Kaplan and A. E. Nelson,hep-ph/9302210]
[D’Onofrio et al: 1404.3565]

Phase Transition Strength

- Finite-T: thermal correction to the effective potential V.
- Boson contribution: $\frac{T^4}{2\pi^2} n_B (\frac{\pi^2}{12}(\frac{m}{T})^2 - \frac{\pi}{6}(\frac{m}{T})^3 + \ldots)$, n_B: degree of freedom
- Fermion contribution: $\frac{T^4}{2\pi^2} n_F (\frac{\pi^2}{24}(\frac{m}{T})^2 + \ldots)$, n_F: degree of freedom.
- Total: $V = DT^2h^2 - \frac{1}{2}\mu^2h^2 - ETh^3 + \frac{1}{4}\lambda h^4$, cubic from bosons
- $\frac{v(T_c)}{T_c} = \frac{2E}{\lambda}$. **SM: 0.2! (Lattice confirmed.)**



[K. Jansen, hep-lat/9509018], [K. Kajantie et al, hep-lat/9510020]
[K. Rummukainen, hep-lat/9608079], [K. Kajantie et al, hep-ph/9605288.]
[M. Gurtler et al, hep-lat/9704013], [F. Csikor et al, hep-ph/9809291]
[M. Laine and K. Rummukainen, hep-ph/9804255, hep-lat/9804019]
[K. Rummukainen et al, hep-lat/9805013], [Z.Fodor, hep-lat/9909162]

Only for intuition. Needs full form to compute!

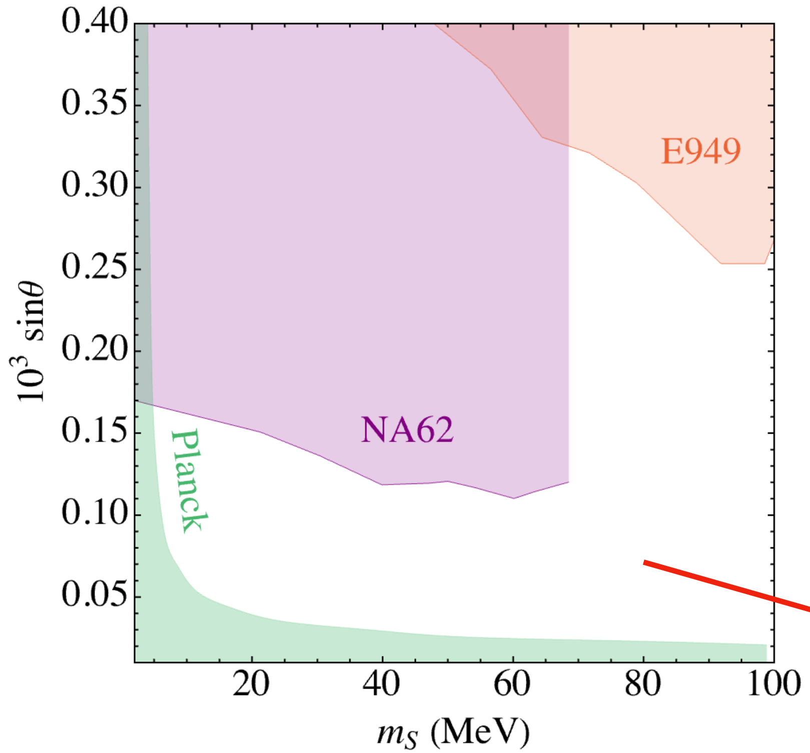
A simple solution: extra singlet scalar

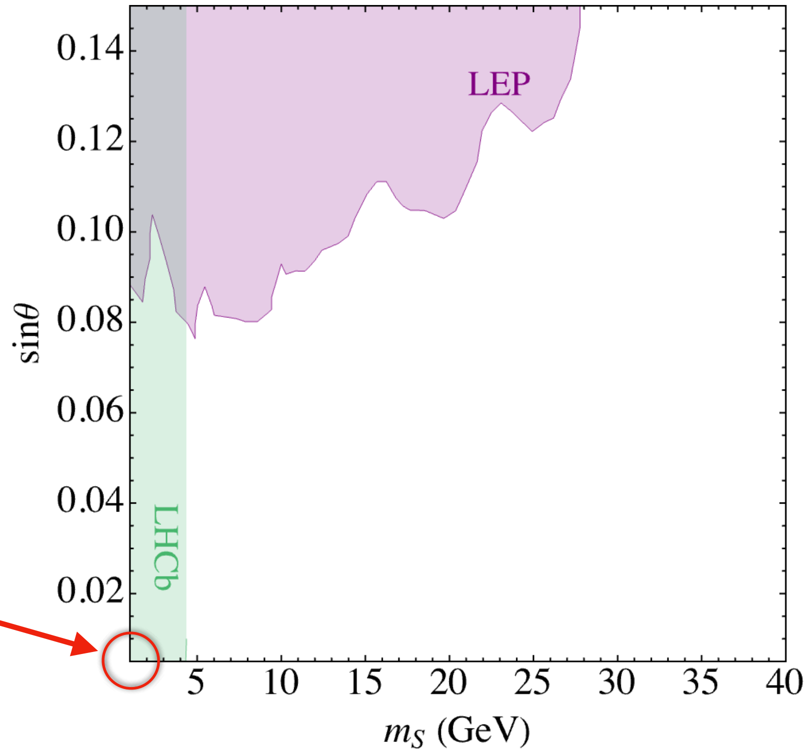
$$\frac{v(T_c)}{T_c} = \frac{2E}{\lambda}$$

- Introduce $S:(1,1,0)$ singlet
- General: $\mathscr{L} = \mathrm{SM} + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4$ + other interactions
- Only interact with Higgs: $SSHH$, S^4, S^3, SHH…., depending on the symmetry
- Probe: mixing with Higgs, $\sin\theta$.

What are the current constraints/status?

Experimental bound

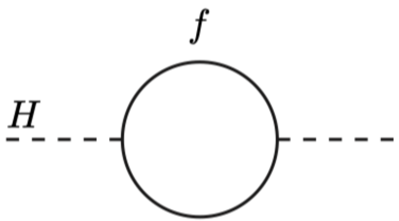




Stringent experimental bound on extra singlet scalar!

Extra hierarchy problem

The SM electroweak hierarchy problem

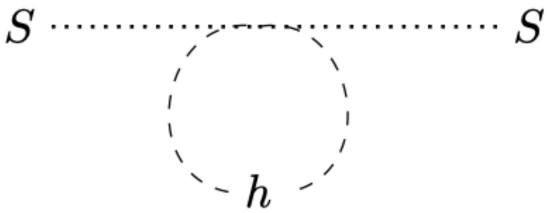


$$\delta m_H^2 = -\frac{y_f^2}{8\pi^2}\Lambda_{\rm UV}^2$$

Quadratic sensitive to $\Lambda_{\rm UV}$:
Huge quantum corrections!

The extra hierarchy problem from extra singlet

Typical models have $\frac{1}{4}\lambda_{hS}S^2h^2$



$$\delta m_S^2 = \frac{\lambda_{hs}}{16\pi^2}\Lambda_{\rm UV}^2$$

Typical singlet scalar model introduced
extra hierarchy problem!

Some traditional solutions: SUSY, compositeness….

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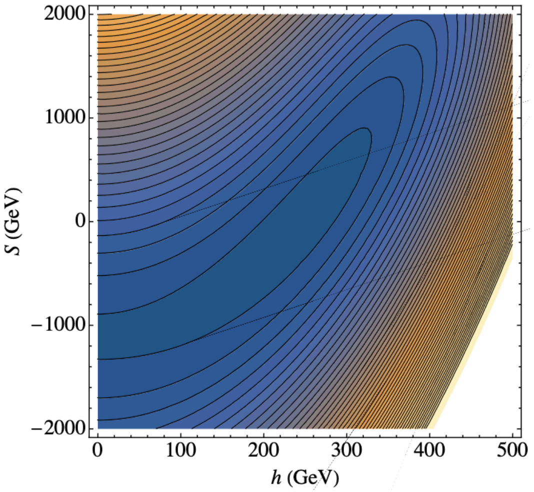
Axion-like Particles (ALP) Couples with Higgs

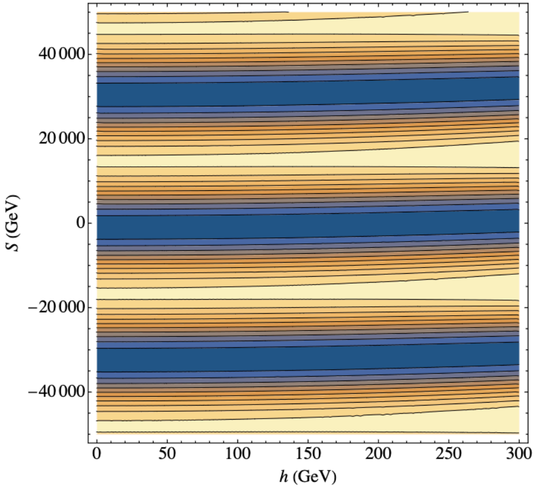
$$A = \frac{1}{2\sqrt{2}v}(m_h^2 - m_S^2)\sin(2\theta)\csc(\delta),$$
$$\lambda = \frac{1}{8v^2}\left(m_h^2 + m_S^2 + (m_h^2 - m_S^2)\cos(2\theta)\right),$$
$$\mu_H^2 = \frac{1}{4}\left(m_h^2 + m_S^2 + (m_h^2 - m_S^2)\cos(2\theta)\right),$$
$$\mu_S^2 = \frac{1}{2}\left(m_h^2 + m_S^2 - (m_h^2 - m_S^2)\cos(2\theta)\right).$$

ALP S: angular mode of P $\quad P = (f + \Phi)^2 \exp(iS/f)$

pNGB. Weakly interacting. Naturally light.

$$V(H,S) = -(\mu_H^2 - Af\cos\delta)|H|^2 + \lambda|H|^4 + \mu_S^2 f^2\left(1 - \cos\left(\frac{S}{f}\right)\right) - Af\left(|H|^2 - v^2\right)\cos\left(\frac{S}{f} - \delta\right),$$





EW scale vev: $\langle h \rangle = v, \langle S \rangle = 0$

Periodic in S.

[K. Harigaya and IRW, 2309.00587]

Generate Barrier at Tree Level

A barrier is generated at the tree level along the path $\partial V/\partial S = 0$

$$S = \frac{Af(h^2 - 2v^2)\sin\delta}{2f\mu_S^2 + A(h^2 - 2v^2)\cos\delta}$$

$$\simeq \frac{Afv^2\sin\delta}{Av^2\cos\delta - f\mu_S^2} + \frac{Af^2\mu_S^2\sin\delta}{2(Av^2\cos\delta - f\mu_S^2)^2}h^2 + \frac{A^2f^2\mu_S^2\sin\delta\cos\delta}{4(Av^2\cos\delta - f\mu_S^2)^3}h^4 + O(h^6).$$

Higgs Quartic term becomes: $\frac{1}{4}(\lambda - \frac{A^2f^3\mu_S^4\sin^2\delta}{2(\mu_S^2 f - Av^2\cos\delta)^3})h^4.$

Quartic becomes negative for viable parameter region where SFOPT is achieved!

Bounded from below condition protected by a positive $O(h^6)$ term!

Extra contribution to the barrier at the tree level.

[K. Harigaya and IRW, 2309.00587]

Thermal phase transition

High-T limit, large f limit.

At high-T: $\langle h \rangle = 0$, restored symmetry!

At low-T: $\langle h \rangle = v(T)$

$$V_{\rm highT} = -\frac{1}{2}(\mu_H^2 - Af\cos\delta)h^2 + D_{\rm SM}T^2h^2 - E_{\rm SM}Th^3 + \frac{1}{4}\lambda h^4$$
$$-\frac{1}{2}Af\cos\left(\frac{S}{f}-\delta\right)\left(h^2 - 2v^2 + \frac{1}{3}T^2\right)$$
$$-f^2\mu_S^2\cos\left(\frac{S}{f}\right).$$

High-f limit and high-T expansion: $\langle S \rangle = \frac{A}{2\mu_S^2}(h^2 - v^2)$

$$f_c \equiv \frac{A}{\mu_S^2}v^2\sin\delta,$$

1-step PT: $(0, \langle S \rangle(0,T)) \to (v(T), \langle S \rangle(v(T),T))$

Again. For a quick look, not for careful computation!

Parametrize: $f \equiv cf_c$

[K. Harigaya and IRW, 2309.00587]

Full Effective Potential Computation

$$V_{\text{eff}} = V_0 + V_{\text{CW}} + V_{\text{FT}}$$

$$V_{\text{CW}} = \frac{1}{64\pi^2}\left(\sum_B n_B\left(\log\left(\frac{m_B^2(h,S)}{Q^2}\right) - c_B\right) - \sum_F n_F\left(\log\left(\frac{m_F^2(h,S)}{Q^2}\right) - c_F\right)\right)$$

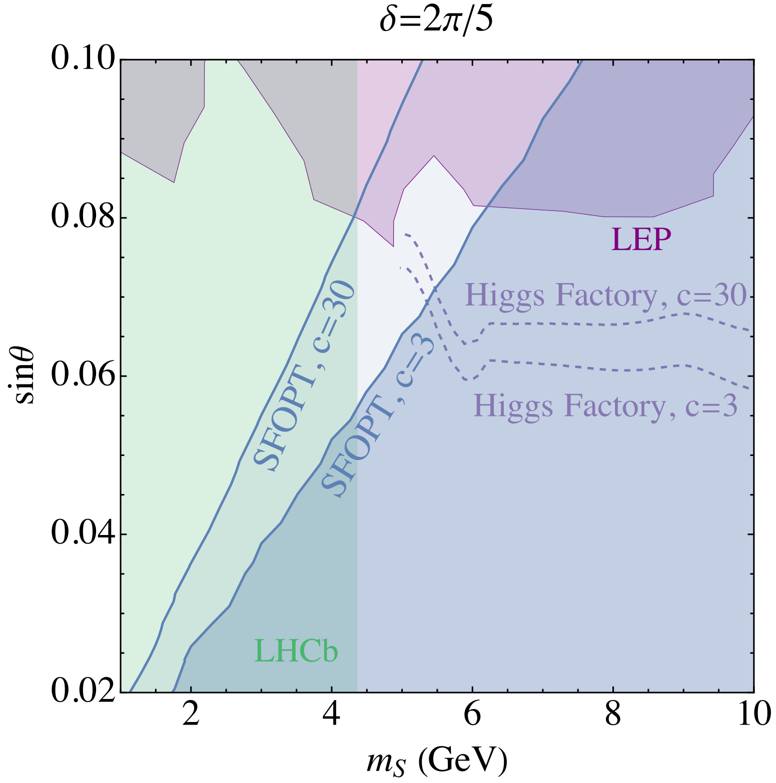
$$V_{\text{FT}} = \frac{T^4}{2\pi^2}\left(\sum_B n_B J_B\left(\frac{m_B^2(h,S)}{T^2}\right) + \sum_F n_F J_F\left(\frac{m_F^2(h,S)}{T^2}\right)\right),$$

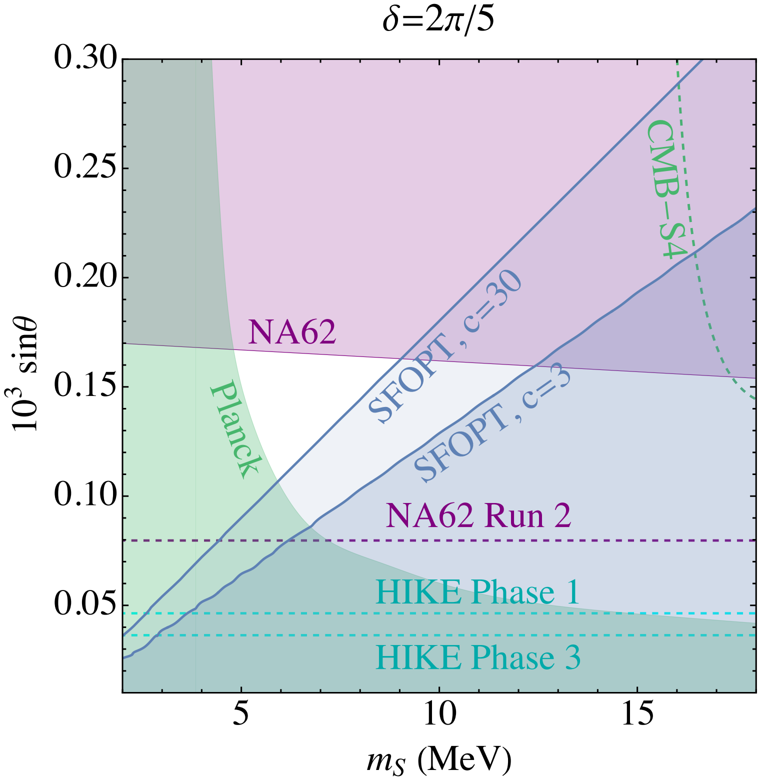
$$J_{B,F}(x^2) = \pm\int_0^\infty dy\; y^2 \log\left(1 \mp \exp\left(-\sqrt{y^2+x^2}\right)\right).$$

Resummation: all boson masses replaced by thermal mass: $m^2 \to m^2 + \Pi$, $\Pi \sim g^2T^2$

[K. Harigaya and IRW, 2309.00587]

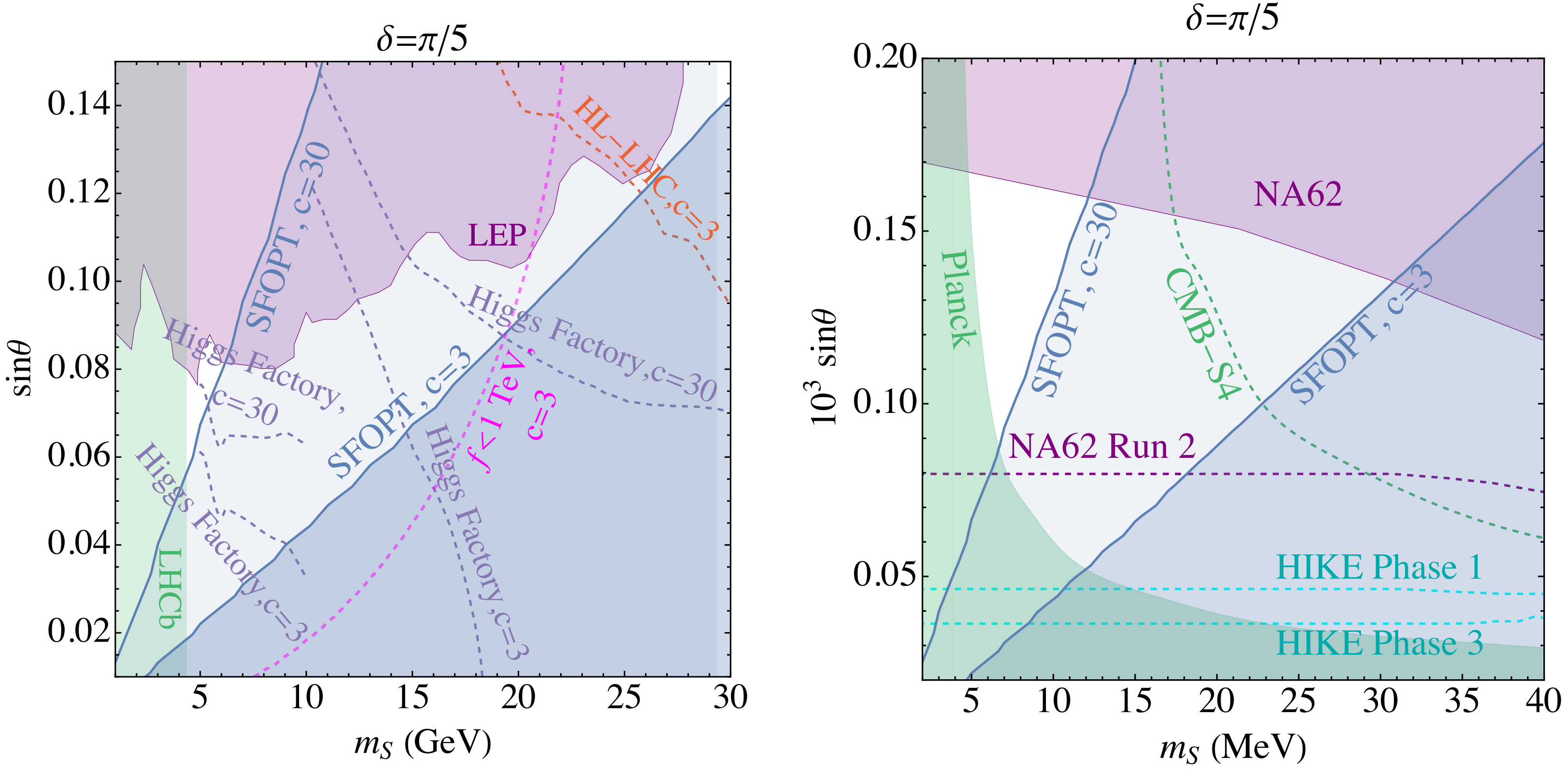
Results





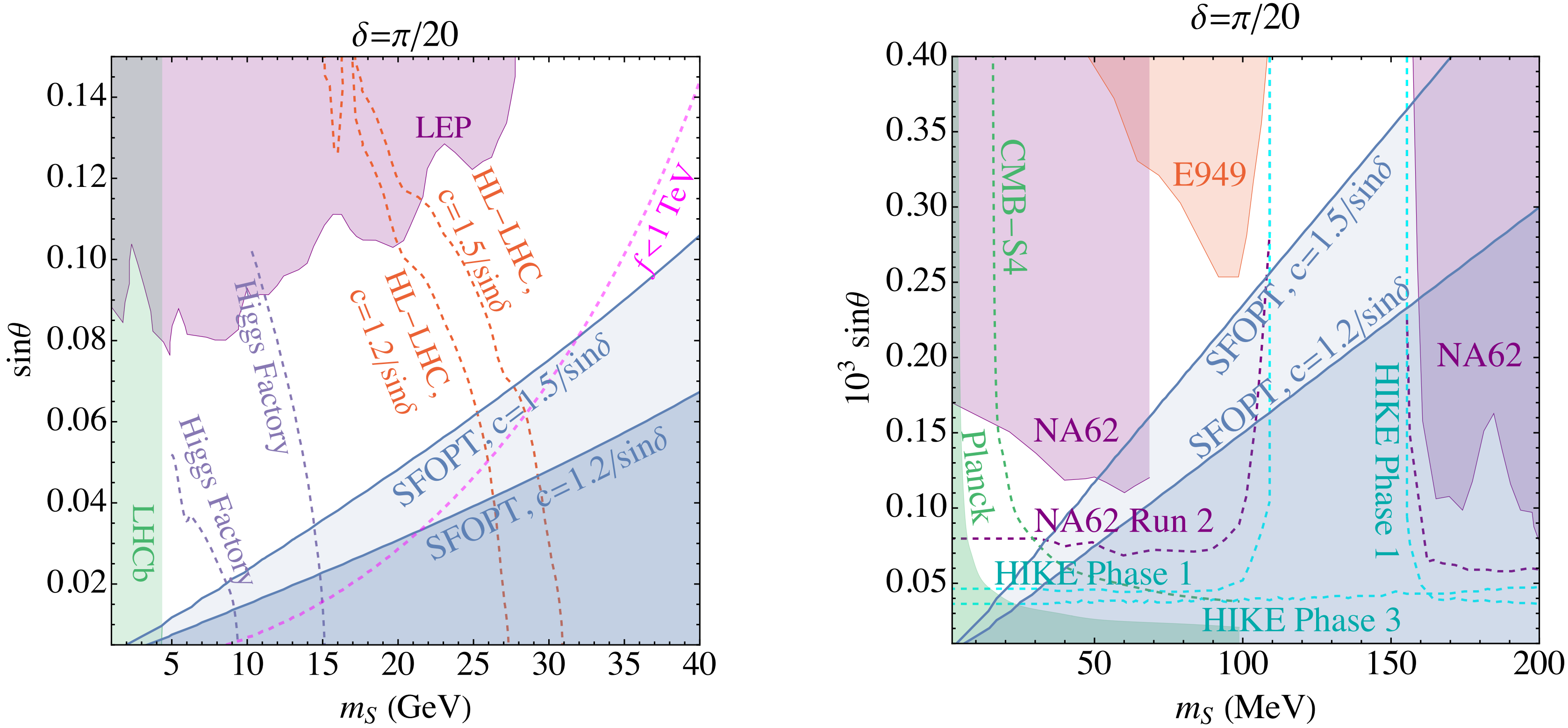
[K. Harigaya and IRW, 2309.00587]

Results



[K. Harigaya and IRW, 2309.00587]

Results



[K. Harigaya and IRW, 2309.00587]

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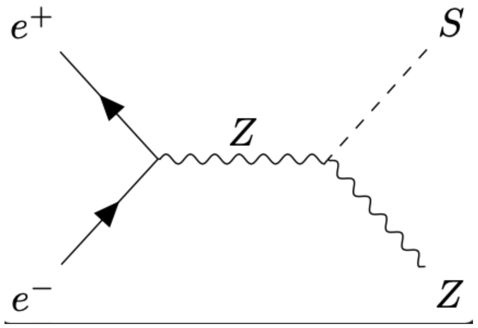
Collider Signals

S can mix with h, mixing angle $\sin\theta$.

Generating vertex:

$hZZ \to \sin\theta\ SZZ$

$h^3 \to \sin\theta\ hhS, \sin^2\theta\ hSS$



General probe:

- scalar production: $\mathrm{SM} \to S + \mathrm{SM}$
- Higgs exotic decay: $h \to SS$

Collider search can probe the extra singlet scalar at GeV scale

[K. Harigaya and IRW, 2309.00587]

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Rare Meson Decay and $\Delta N_{\rm eff}$

- Extra decay channel for B meson:
- $B^0 \to K^0 S, B^+ \to K^+ S$, searched by LHCb at $200~\mathrm{MeV} < m_S < 4~\mathrm{GeV}$

- Extra decay channel for Kaon:
- $K^+ \to \pi^+ S, K^0 \to \pi^0 S$, searched by NA62, KLEVER…. for MeV scale.

- MeV scale m_S: large energy density when neutrino decouples.
- S decays into γ: negative $\Delta N_{\rm eff}$

Review: [PBC Group, 1901.09966], [E. Goudzovski et al, 2201.07805]
[LHCb Collaboration, 1508.04094, 1612.07818, 1703.08501]
[NA62 Collaboration, 2010.07644, 2103.15389]
[KLEVER Project Collaboration, 1901.03099]
[M. Ibe et al, 2112.11096], [Planck Collaboration, 1807.06209]
[CMB-S4 Collaboration, 1610.02743],[K. Harigaya and IRW, 2309.00587]

Local EWBG

$$\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{3g^2}{32\pi^2} W\tilde{W}$$

A general effective CP-violating operator: $\mathscr{L} = \frac{\alpha_2}{8\pi}\frac{S}{M}W\tilde{W}, \frac{\partial_\mu S}{M}q^\dagger\bar{\sigma}^\mu q$, or $\frac{\partial_\mu S}{M}\ell^\dagger\bar{\sigma}^\mu\ell, M$: UV scale.

CP-violation comes from $W\tilde{W}$ or $f^\dagger\bar{\sigma}f$! This operator itself is CP-violating.

Rewrite: $\mathscr{L}_{CP} \propto \frac{1}{M}(\partial_0 S)n_B$ in thick-wall regime!

From minimizing free energy, n_B gets a minimum $n_B^0 \propto \frac{1}{M}(\partial_0 S)\langle S\rangle \simeq \frac{A}{2\mu_S^2}h^2$

Thus $\dot{n}_B \propto \frac{\Gamma_{\text{sph}}}{T^3}(n_B - n_B^0) \simeq \frac{\Gamma_{\text{sph}}}{T^3}n_B^0 = \frac{\Gamma_{\text{sph}}}{T^3}\dot{S}$ Large field-value shift!

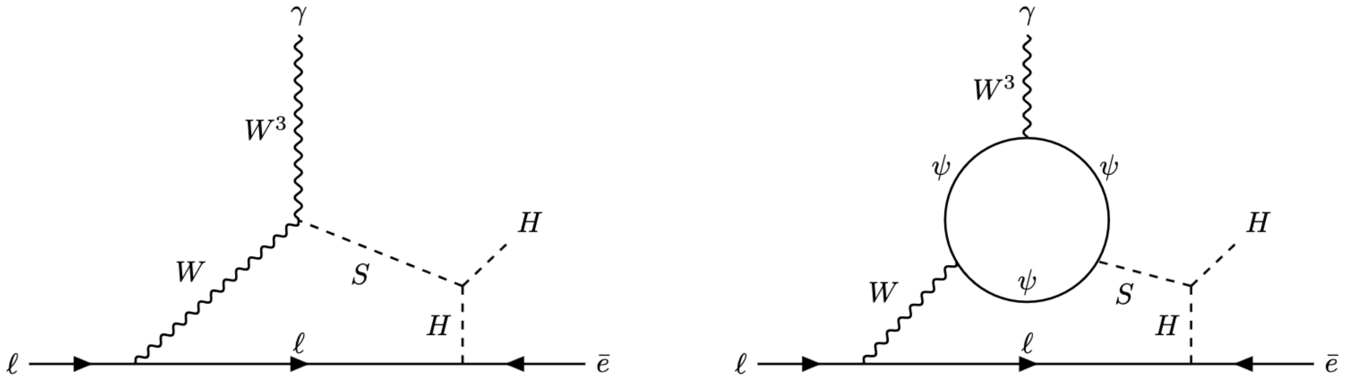
For old literature using $\mathscr{L}_{CP} \propto \frac{\sin(\delta)}{M^2}h^2W\tilde{W}$:

[A. Cohen and B. Kaplan, Phys.Lett.B 199 (1987) 251-258, Nucl.Phys.B 308 (1988) 913-928]
[M. Dine et al, Phys.Lett.B 257 (1991) 351-356]
[M. Dine, hep-ph/9206220]
[K. Harigaya and IRW, 2309.00587]

$$\frac{n_B}{s} \simeq \frac{3\Gamma_{\text{ws}}T^2\Delta S}{Ms},$$

BAU properly produced for $M \gtrsim f$

The electric dipole moment



$$iF_{\mu\nu}\ell\sigma^{\mu\nu}\bar{e}H \times \frac{ey_e}{(16\pi^2)^2}\frac{A\sin\delta}{Mv^2}.$$

when M consistent with n_B:

EDM around $10^{-32} - 10^{-30}$ for GeV scale m_S, can be probed by future experiments.

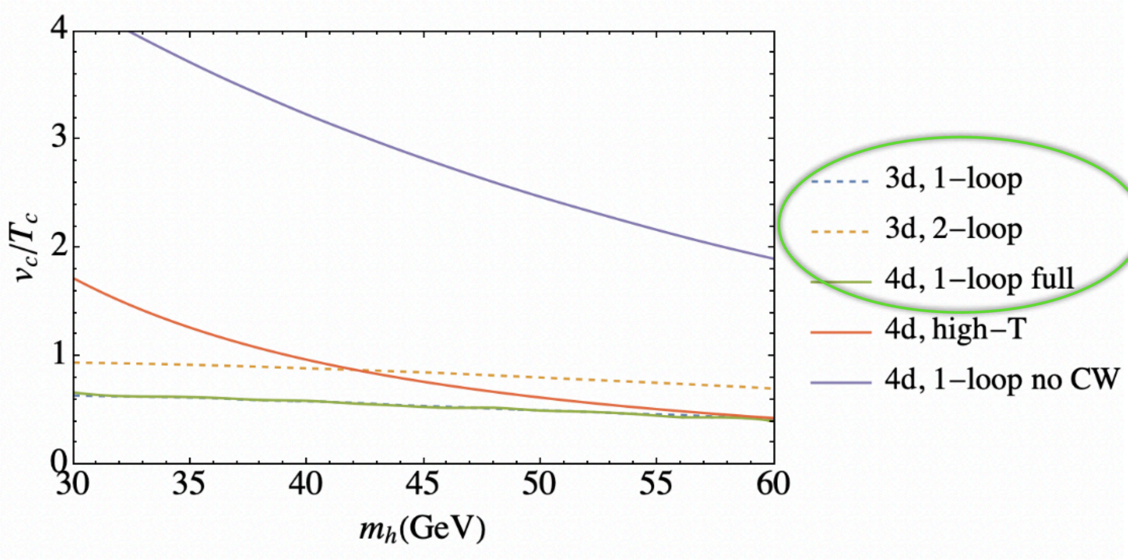
[K. Harigaya and IRW, 2309.00587]

Conclusion

- Baryon number asymmetry remains unsolved. SM EWBG fails due to lack of a SFOPT at the EW scale.
- We propose an ALP to enhance the EWPT strength.
- Successful baryogenesis can be achieved via the local baryogenesis mechanism.
- Various experiments can be applied to probe the parameter space.

Backups

SM EWPT strength with lighter Higgs



Most trustable.

Main suppression:

top Yukawa correction

[P. Arnold, O. Espinosa, hep-ph/9212235]
[K. Harigaya and IRW, 2309.00587]