Lepton sourced baryon asymmetry in 4th generation model

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Analyticity and SM flavor structure

- Physical observables, being analytical, respect dispersion relations
- Dispersion relation connects various dynamics at different scales; heavy meson lifetimes link EW and strong interactions; Higgs decays into b quark pairs link Yukawa coupling and strong interactions,…
- Numerous observables imply numerous links --- nontrivial constraints
- SM parameters may not be completely free
- SM flavor structure governed by analyticity
- Echo ``S-matrix bootstrap conjecture" (Geoffrey Chew, 1960s)
- A well-defined infinite set of self-consistency conditions determines uniquely aspects of particles in nature

Why 4G model?

- Dispersion relations for heavy quark lifetimes, neutral meson mixing muonium mixing,.., fix fermion masses (ms=0.1, mc=1.3, mb=4 GeV…)
- Predict normal ordering of neutrino masses
- Distinct mixing patterns of quarks and leptons attributed to different mass hierarchies in the two sectors

$$sin\theta_{12} \sim \boxed{\frac{m_2^2}{m_3^2} \approx 3.1 \times 10^{-2} \gg \frac{m_s^2}{m_b^2} \approx 9.0 \times 10^{-4}}$$

- Speculate that only three gauge couplings are fundamental
- 4th generation model is the most economic extension of SM
- Predict masses t' quark b' quark, charged lepton L neutrino ν_4

  200 TeV 2.7 TeV, 270 GeV, 170 GeV

Our SM4 scenario

Li, 2309.15602
Li, 2407.07813

e.g., strong sector, details unimportant
Composite Higgs model, Kaplan, Georgi (1984)

compositeness scale

4G fermions have same Yukawa coupling g_Y
UV 2-loop RG fixed point in SM4 Hung, Xiong 2009

unbroken SU(2)XU(1) SM4

$g_Y^c \approx 8.0 > g_Y^f \approx 7$ 4G cannot form condensates

4G quark g_Y increase, 4G lepton g_Y decrease

$O(10)$ TeV restoration scale

$g_Q^c \approx 9.1$ 4G heavy quark condensates formed

broken SU(2)XU(1) SM4

4G quark form bound-state scalars (as mass > 1.23 TeV)
weak couplings with SM particles, bypass Higgs data

electroweak scale

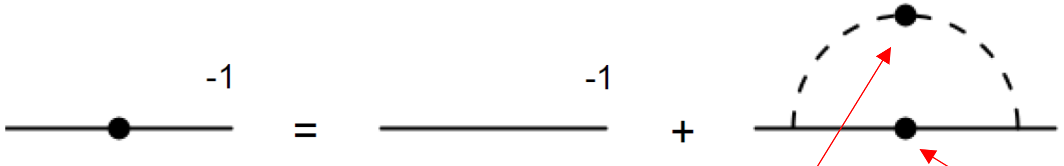
heavy scalars coupled to Higgs modify
T-dependent effective potential, 1st-order EWPT

4G lepton-sourced baryon asymmetry explains baryon-over-entropy ratio $\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$

EW symmetry breaking

Dynamical mass generation

- Dyson-Schwinger equation



bare mass = 0

$$-i[\not p - m(p^2)] = -i(\not p - m_0) - 2(-ig_Y)^2 \int \frac{d^4q}{(2\pi)^4} \frac{i}{(p-q)^2 - \mu^2(q^2)} \frac{i[\not q + m(q)]}{q^2 - m^2(q^2)}$$

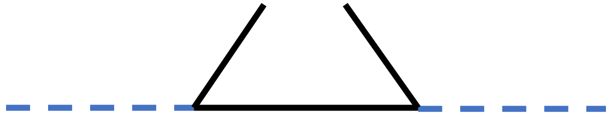
$t' \to t'\phi^0$ or $t' \to b'\phi^+$

large enough Yukawa coupling ➡ dynamically generated masses

- Rainbow approximation and leading-order vertices have been applied
- Scalar mass arises from fermion condensates
- In view of effective theory
  dynamical symmetry breaking

Hung, Xiong 2011

$\langle \bar{f} f \rangle < 0$



➡ $\frac{\mu^2}{2}\phi^2$

critical coupling $g_Q^c \approx 9.1$

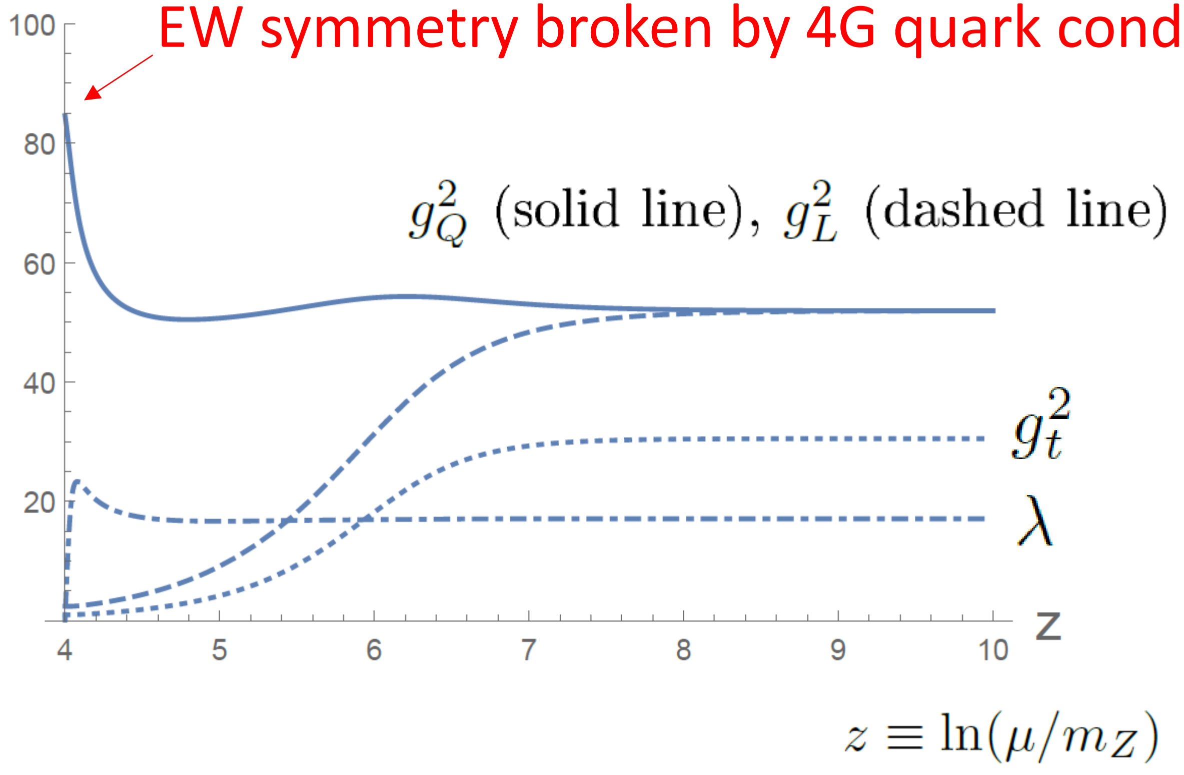
2-loop RG evolution in SM4

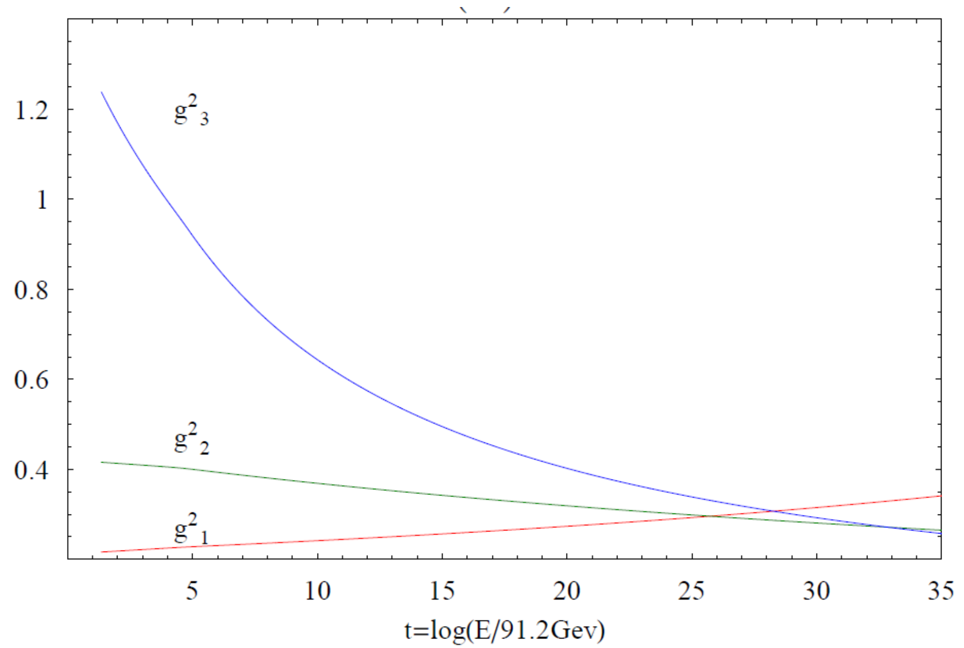
Hung, Xiong 2009

- UV fixed point exists

common Yukawa coupling $g_Y^f \approx 7$ as switching off small gauge interactions

EW symmetry broken by 4G quark condensates





EW phase transition

Effective Higgs potential

Kikukawa, Kohda, Yasuda 2009

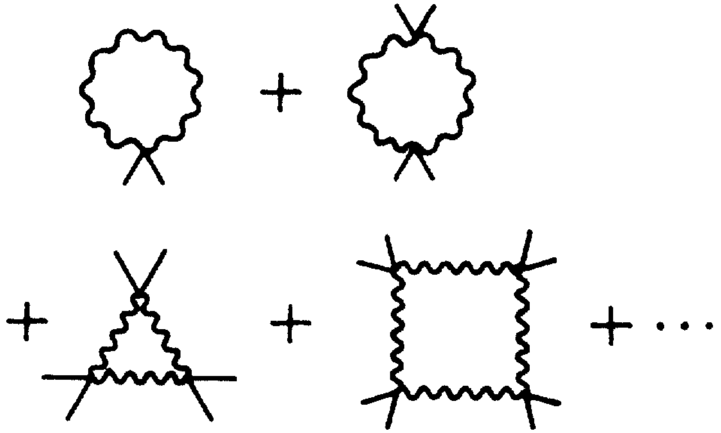
- Following standard formalism, consider

$$V_{\text{eff}}(\phi, T, \mu_R) = V_0(\phi) + V_1(\phi, \mu_R) + V_T(\phi, T)$$

- Tree-level potential, result of RG evolution from restoration scale

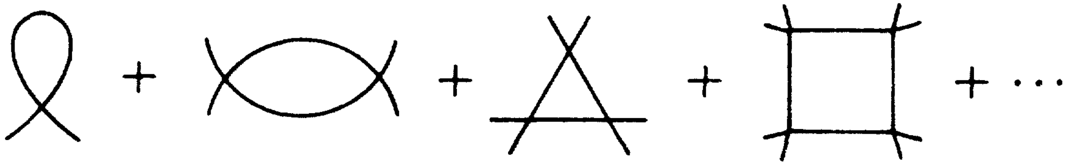
$$V_0(\phi) = \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 \qquad \mu^2 = -m_H^2/2 \text{ and } \lambda = -\mu^2/v^2$$

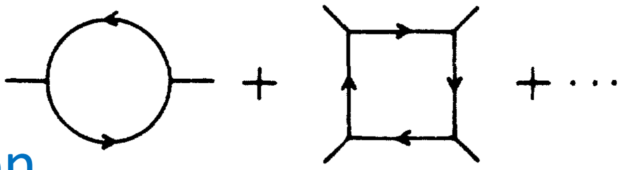
- 1-loop Coleman-Weinberg potential $V_1(\phi, \mu_R)$
- All particles coupled to Higgs contribute



gauge boson

scalar contribution





fermion

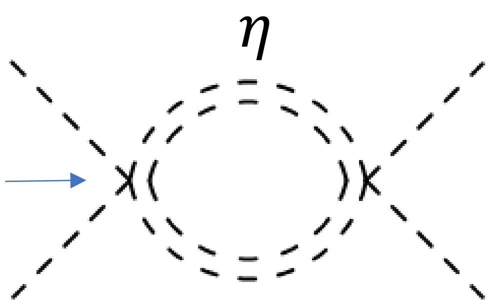
Heavy scalar-Higgs coupling

Hung, Xiong 2011

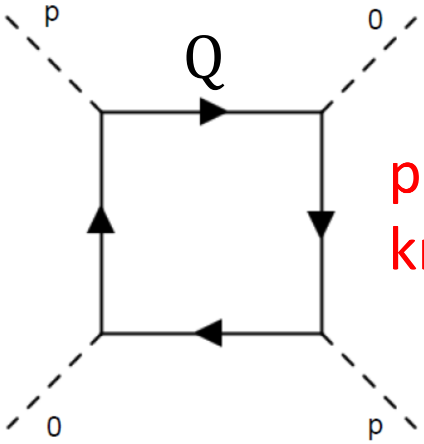
- Heavy fermions with mass above $1.23\ \mathrm{TeV}$ form bound states
- t’ and b’ quarks form bound states, but 4G leptons do not
- Estimate heavy scalar-Higgs coupling using effective theory

HH scatter into HH

λ'=3.8



nonperturbative unknown
at low energy



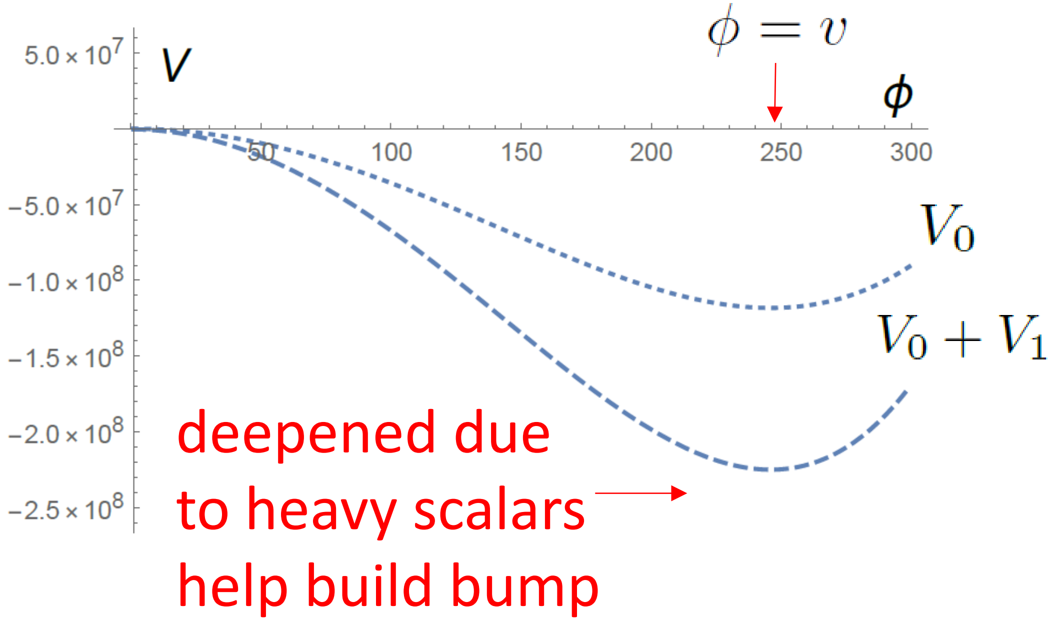
perturbative
known

match the two theories at large $p^2 \approx s$, solve for scale-dependent effective coupling, run it to $p^2 \approx v^2$

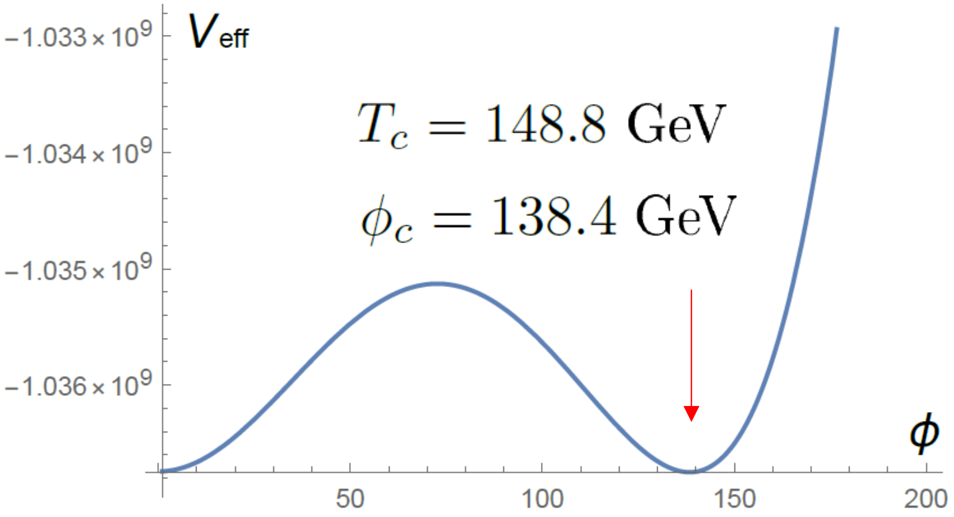
compute one-loop corrections to $V_1(\phi, \mu_R)$

Effective potential

- 4G quarks play crucial role for making 1st-order EWPT through their bound states (fermions only cannot do the job)



$\phi_c/T_c \approx 0.9$



meets criterion $\phi_c/T_c \gtrsim 1$ roughly, Implying strong 1st-order EWPT

EW baryogenesis

Sakharov's conditions

- To explain baryon asymmetry in the Universe (BAU)

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} \sim 10^{-10}$$

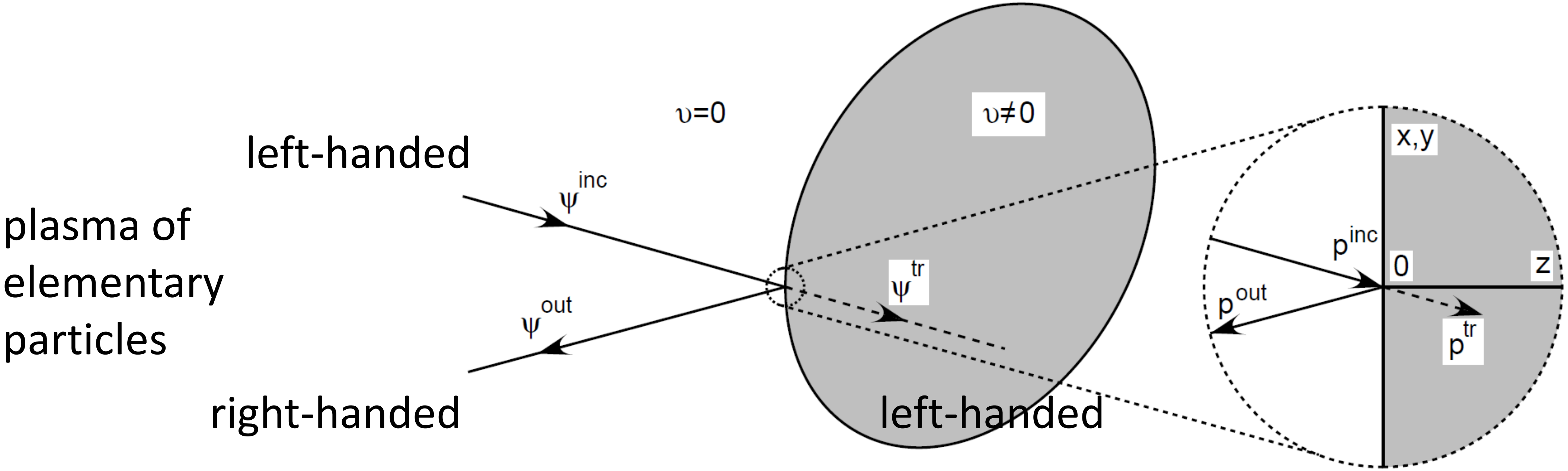
entropy

require three conditions

- B violation
- Departure from thermal equilibrium
- C, CP violations
- Whether they are sufficient depends on their strength; need quantitative analysis
- SM contains all three sources, but 2nd and 3rd not strong enough

Particle scattering off bubble wall

- Bubbles formed and expand in 1st order EWPT
- Particles collide with bubble walls; some reflect and some transmit
- Left-handed and right-handed, quarks and antiquarks may have different reflection rates due to CPV



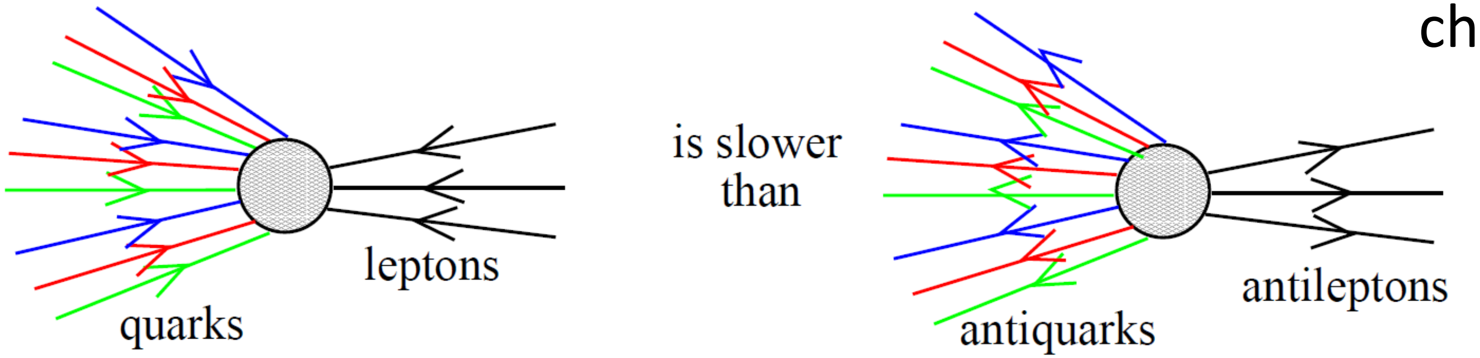
Weak sphaleron (due to axial anomaly)

- Recall CPT invariance; fewer d quarks compensated by fewer anti-s
- Need weak sphalerons (B violating interaction)
- Change of B number occurs only to left-handed fermions
- Due to

$$n(d_L) < n(\overline{d_R})$$

$$n(L) + n(R) = n(\bar{L}) + n(\bar{R})$$

chiral asymmetry

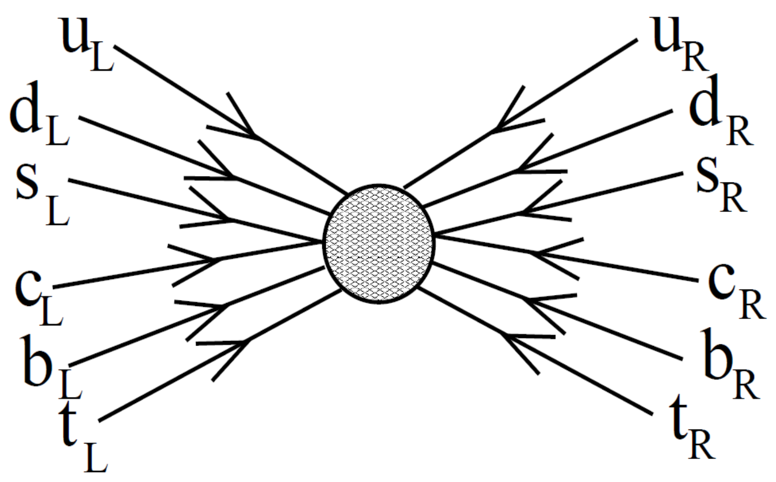


B-L conserved

- Left-handed quark asymmetry washed out, matter asymmetry created
- Lepton asymmetry also contributes due to B-L conservation

Strong sphalerons (also due to axial anomaly)

- Chiral asymmetry (more R than L) created in front of bubbles
- Strong sphalerons with higher rates are faster than weak sphalerons
- Strong sphalerons, interacting with both chirality, wash out chiral asymmetry of quarks (not leptons)
- No quark chiral asymmetry to be converted into matter asymmetry
- Turn out that quark-sourced BAU is tiny (inefficient source)
- Lepton source plays more crucial role
- 4G lepton source explains BAU

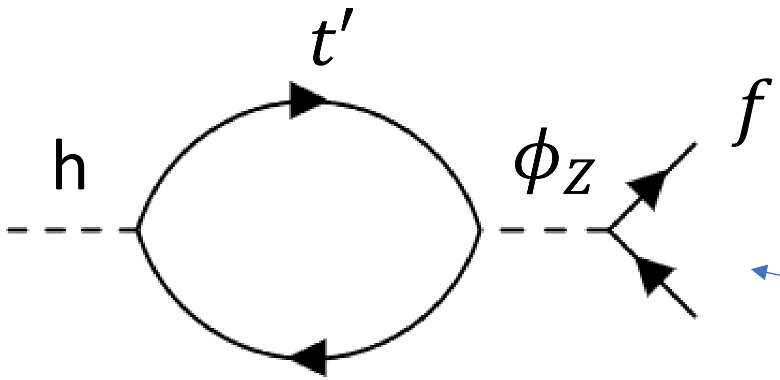


Baryon asymmetry

Effective operators with CPV source

- Construct dim-6 operators from 4G heavy quarks, no free parameters
- One-loop diagram in R_ξ gauge, no CP-odd phase

pass electron EDM bound



$$\mathcal{L}_6 = -i\left[\bar{Q}_L \tilde{Y}_U \tilde{H}\, u_R + \bar{Q}_L \tilde{Y}_D H\, d_R + \bar{L}_L \tilde{Y}_L H\, e_R\right](H^\dagger H) + \text{h.c.}$$

after breaking EW symmetry and integrating out heavy quarks

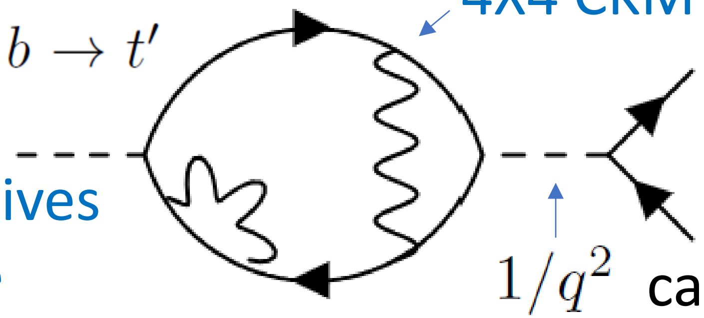
- Three-loop diagram, add charged scalars, CP-odd phase shows up

$$t' \to b' \to t \to b \to t'$$

4X4 CKM matrix element

$$\mathrm{Im}(V^*_{t'b'} V_{tb'} V^*_{tb} V_{t'b})$$

Jarlskog invariant



this arrangement gives leading CPV source

pseudoscalar penguin

$1/q^2$ cancelled, 4-fermion operator

Transport equations

- Implemented into coupled transport equations for particle number densities (left-handed quarks, right-handed leptons, Higgs, ….),

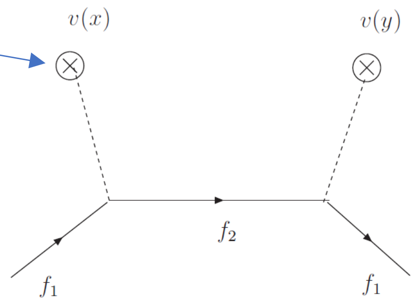
de Vires et al, 1811.11104

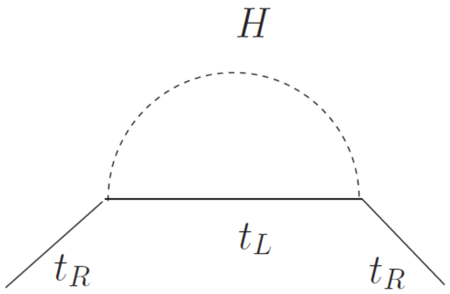
left-handed t+b density | Relaxation rates | Yukawa rates | strong sphalerons | CPV sources

$$\partial_\mu q^\mu = +\Gamma_M^{(t)}\mu_M^{(t)} + \Gamma_M^{(b)}\mu_M^{(b)} + \Gamma_Y^{(t)}\mu_Y^{(t)} + \Gamma_Y^{(b)}\mu_Y^{(b)} - 2\,\Gamma_{\rm ss}\,\mu_{\rm ss} + \Gamma_{\rm QL}\,\mu_{\rm QL} - S_t - S_b$$

space-dep vev

quark-lepton coupling





- Then implement weak sphalerons, solve another transport equation, get $\eta_B = (7.3\text{-}8.3) \times 10^{-11}$

Summary

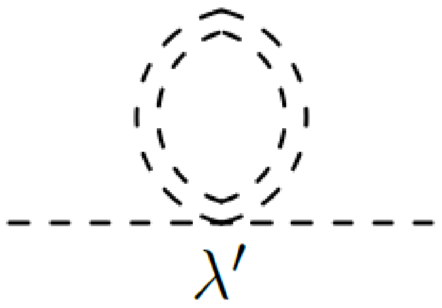
- SM flavor structure governed by analyticity (bootstrap)
- Only three gauge couplings are fundamental, motivating 4G model
- EW symmetry broken dynamically by 4G quark condensates
- Heavy scalars formed by 4G quarks couple to gluons weakly
- Irrelevant dim-5 operators in IR region bypass Higgs data constraints
- Heavy scalars important for 1st-order EW phase transition
- 4G leptons sourced by 4X4 CKM (also fixed by dispersion relations) important for making BAU
- EW baryogenesis can be realized in SM4 (contrary to literatures)
- Likely to detect b’ by end of LHC Run4 (sensitivity ~ 5σ), if 4G exists

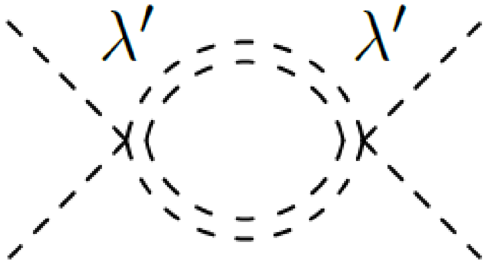
Back-up slides

Heavy scalar contribution

- Estimate heavy scalar-Higgs coupling using effective theory
- Derive effective coupling λ'=3.8

- Compute one-loop corrections to $V_1(\phi, \mu_R)$ in effective theory
- Diagrams similar to those from Higgs





… to all orders

Coleman-Weinberg potential

Coleman, Weinberg 1973

- One-loop Coleman-Weinberg potential

$$V_1(\phi,\mu_R) = \frac{1}{64\pi^2}\sum_{i=h,\eta,t,L,\nu_4} n_i m_i^4(\phi)\left[\ln\frac{m_i^2(\phi)}{\mu_R^2} - \frac{3}{2}\right] + \frac{1}{2}A(\mu_R)\phi^2$$

light- quarks, gauge bosons neglected

degeneracies per particle $n_h = 1,\ n_\eta = 1,\ n_t = -12,\ n_L = -4 \text{ and } n_{\nu_4} = -4$

field-dependent masses $m_h^2(\phi) = \mu^2 + a_h\phi^2,\ m_\eta^2(\phi) = \mu^2 + a_\eta\phi^2,\ m_t^2(\phi) = a_t\phi^2,\ m_L^2(\phi) = a_L\phi^2$

$m_{\nu_4}^2(\phi) = a_{\nu_4}\phi^2$

coefficients $a_h = 3\lambda,\ a_\eta = \lambda',\ a_t = g_t^2/2,\ a_L = g_L^2/2 \text{ and } a_{\nu_4} = g_{\nu_4}^2/2$

- Renormalization condition on quadratic term enforces minimum of

$V_{\text{eff}}(\phi, T, \mu_R)$ to be at $\phi = v$

$$A(\mu_R) = -\frac{1}{16\pi^2}\sum_{i=h,\eta,t,L,\nu_4} n_i a_i m_i^2(v)\left[\ln\frac{m_i^2(v)}{\mu_R^2} - 1\right]$$

Temperature-dependent potential

- One-loop T-dependent potential

Dolan, Jackiw 1974

$$V_T(\phi, T) = \frac{T^4}{2\pi^2}\left[\sum_{i=h,\eta} n_i J_B(m_i^2(\phi)/T^2) + \sum_{i=t,L,\nu_4} n_i J_F(m_i^2(\phi)/T^2)\right]$$

- Thermal function

$$J_{B,F}(x) = \int_0^\infty dy y^2 \ln\left[1 \mp \exp\left(-\sqrt{y^2+x}\right)\right]$$

- Derivation similar to one-loop potential, but with temperature-dependent propagator

$$D_\beta(k) = \frac{i}{k^2 - m^2}$$

$$= \frac{-i}{(4\pi^2 n^2/\beta^2) + \vec{k}^2 + m^2}$$

~ 1/T

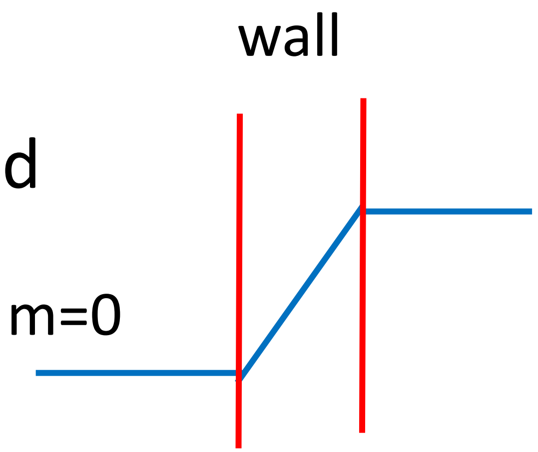
CPV & CPT invariance

- Need CP-odd phase, CP-even phase and interference of different channels
- CPV gives $R(d_L \to s_R) > R(\overline{d_R} \to \overline{s_L})$
- Fewer d quarks, $n(d_L) < n(\overline{d_R})$
- But CPT invariance

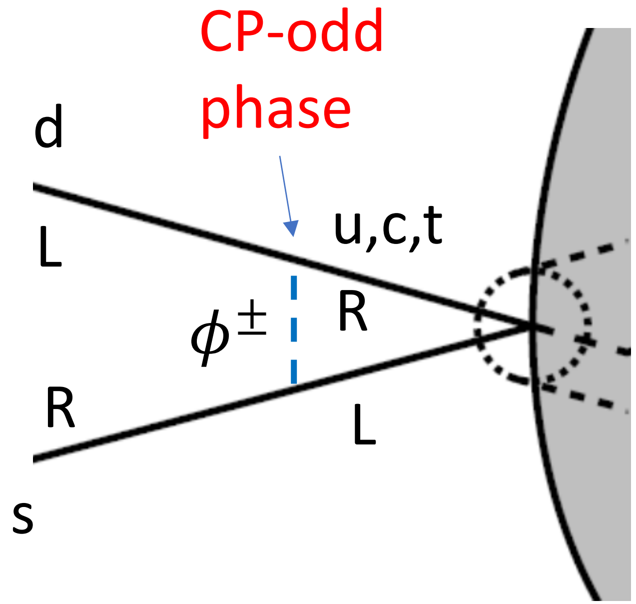
  $R(d_L \to s_R) = R(\overline{s_L} \to \overline{d_R})$

  $R(\overline{d_R} \to \overline{s_L}) = R(s_R \to d_L)$
- fewer anti-s quarks due to

  $R(\overline{s_L} \to \overline{d_R}) > R(s_R \to d_L)$
- Compensation, no baryon asymmetry



on-shell internal particles give CP-even phases
different quarks
different masses
⇒ different CP-even phases



Effective operators with CPV source

- Instead of engaging cumbersome exercise on individual models, model-independent effective theory approach developed
- Dimention-6 operators

de Vires et al, 1811.11104

$$\mathcal{L}_6 = -i\left[\bar{Q}_L \tilde{Y}_U \tilde{H}\, u_R \; + \bar{Q}_L \tilde{Y}_D H\, d_R + \bar{L}_L \tilde{Y}_L H\, e_R\right](H^\dagger H) + \text{h.c.}$$

- After EW symmetry breaking

proportional to Yukawa coupling of fermion f

discretionary sign, chosen to explain the observation

$$-\frac{s_f m_f}{\Lambda_f^2}\,\bar{f}\,i\gamma^5 f\, vh$$

CPV source in collisions with bubbles

unknown new physics scale, bounded by EDM

CP-odd phase

- Strategy: translate SM4 to effective theory, derive Wilson coefficient, implement effective operators into formalism for EW baryogenesis