Electroweak baryogenesis and CP violation from fourth generation

Masaya Kohda (National Taiwan Univ., Taiwan)
in collaboration with Wei-Shu Hou (National Taiwan Univ.) and Yoshio Kikukawa (Univ. of Tokyo)
email: mkohda@hep1.phys.ntu.edu.tw

Introduction

An addition of 4th-generation quarks to standard model introduce new sources of CP violation. Based on electroweak baryogenesis scenario, we demonstrate that the effect of CP violation from the quark flavor mixing is highly enhanced compared to 3 generation case and may be large enough to explain the baryon asymmetry of the universe.

Baryon Asymmetry of the Universe

$$\left.\frac{n_B}{s}\right|_{obs.} \simeq 0.9 \times 10^{-10}$$

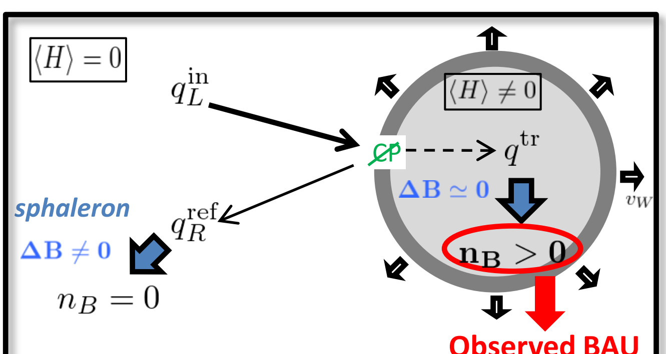
- In principle, Standard Model (SM) can satisfy all three **Sakharov's conditions**:

1. B violation by sphaleron-induced anomalous process
2. CP violation by Kobayashi-Maskawa mechanism
3. Out of eq. by ElectroWeak Phase Transition (EWPhT)

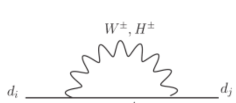
If EWPhT is 1st order, EW baryogenesis can be operative

Electroweak Baryogenesis in SM

- Proposed by Farrar and Shaposhnikov (1993)
- The mechanism assumes EWPhT is 1st order
  - Bubble nucleation of Higgs condensate
  - quarks and anti-quarks are scattered by the bubble wall
  - Due to CP violation, n_B (B-density) is separated by the wall
  - n_B in symmetric phase is eliminated by sphaleron process



- Described as scattering of ***quasi-particle***
  - Thermal excitation of quarks and anti-quarks
  - Obtain "thermal mass" via the self-energy at finite T



- L-R asymmetric phase space structure
- **Flavor change** and **CP violation** during propagation

- However, thermal effect also induces quasi-particle **width**
  - Inclusion of width largely reduce the CP asymmetry [M.B. Gavela et al. (1994)]
  - This effect can be interpreted as **quantum decoherence** [P. Huet and E. Sather (1994)]

Upper limit on BAU:

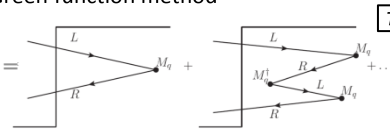
$$\left|\frac{n_B}{s}\right|_{\text{SM}} < 10^{-26}$$

- Too short **coherence length**: $\ell \sim 1/(3 \times \text{Width}) \simeq 1/(120 \text{ GeV}) << 1/m_q \ (q \neq t)$ ⟵ m.f.p. of wall-scat.
- Multiple scat. with wall

BAU in SM with 4th generation

- 4th generation quarks t' & b' do not suffer from QCD-decoherence so much, as they are heavy
  - Suppression for CP asymmetry becomes milder than 3 gen. case
- We estimated BAU by extending Huet-Sather's method
  - Reflection coefficient $R(q_L \to q'_R)$ is obtained by solving effective Dirac eq. for quasi-particle w/ space dep. mass term
  - Based on Green function method

Thin wall limit

$R(q_L \to q'_R) =$ 

- $$\frac{n_B}{s} \simeq -10^{-2}\alpha_W v_W \langle \Delta(\omega)\rangle_T$$
  $$\Delta(\omega) \equiv -\sum_{flavor} \left(|R(q_L \to q'_R)|^2 - |R(\bar{q}_R \to \bar{q}'_L)|^2\right) \sim Tr[M_u M_u^\dagger, M_d M_d^\dagger]^3$$
- Simple formula for BAU is obtained under assumption for unknown CKM elements: $|V_{td}V^*_{t'd}| << |V_{ti}V^*_{t'i}| \ (i = s, b, b')$

$$\frac{n_B}{s} \simeq 0.9 \times 10^{-10} \left(\frac{A_{sb}^{tt'}}{9 \times 10^{-4}}\right) \left(\frac{m_{t'}}{500 \text{ GeV}}\right)^4 \left(\frac{m_{b'}}{500 \text{ GeV}}\right)^4$$

$$A_{sb}^{tt'} \equiv \text{Im}\,(V^*_{ts}V^*_{t'b}V_{tb}V_{t's}) \simeq 2 \times (\text{Area of } b \to s \text{ quadrangle})$$

Seems to be in the right ballpark!

[Remarks]

- Above result is semi-quantitative, as the mass terms of heavy quarks are treated as perturbation
- We just assumed EWPhT is 1st order. A possible way to realize this may be formation of $\langle \bar{q}q\rangle$ by large Yukawa coupling or new interaction strongly acting on 4th generation

Conclusion

We demonstrated that CP violation from 4th-generation quark can be large enough to explain BAU mainly due to large t' and b' masses. The relevant parameters can be probed at LHC. (See also the poster by Wei-Shu Hou).