Lepton-mediated EW baryogenesis, gravitational waves, and the 4τ final state at the collider

Ke-Pan Xie (谢柯盼)

Seoul National University, Korea

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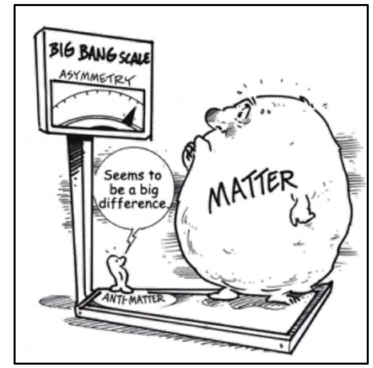
Paper will be released next week. 2011.xxxxx

Explaining the baryon asymmetry

- Matter-antimatter asymmetry

Abundance: (baryonic) matter >> antimatter



$$\frac{n_B}{s} \approx 10^{-10}, \quad n_{\bar{B}} \approx 0$$

Sakharov conditions [Sakharov,1967]:

① Baryon number violation; ② C/CP violation;

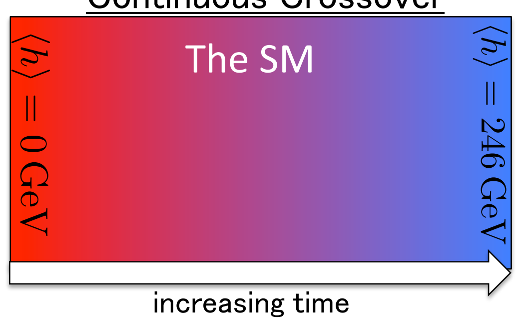
③ Departure from equilibrium.

The Standard Model: satisfies ① by EW sphaleron, however:

② CPV too tiny.

③ Fails in EWPT

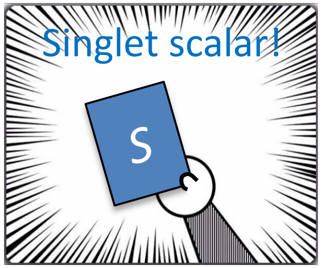
Continuous Crossover



First Order Phase Transition

Needs *new physics*!!

Realizing EW baryogenesis with Higgs+singlet



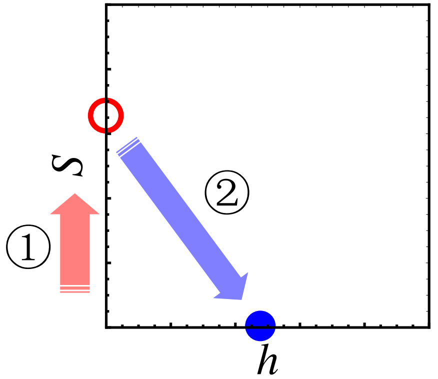
- Satisfying the Sakharov conditions

The thermal potential

$$V_T = \frac{\mu_H^2 + c_H T^2}{2} h^2 + \frac{\mu_S^2 + c_S T^2}{2} S^2 + \frac{\lambda_H}{4} h^4 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{HS}}{2} h^2 S^2$$

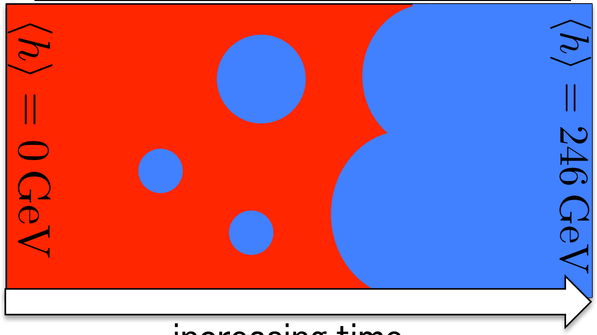
$$\boxed{c_H = \frac{3g^2 + g'^2}{16} + \frac{y_t^2}{4} + \frac{\lambda_H}{2} + \frac{\lambda_{HS}}{12}, \quad c_S = \frac{\lambda_S}{4} + \frac{\lambda_{HS}}{3}}$$

The phase transition pattern: two-step



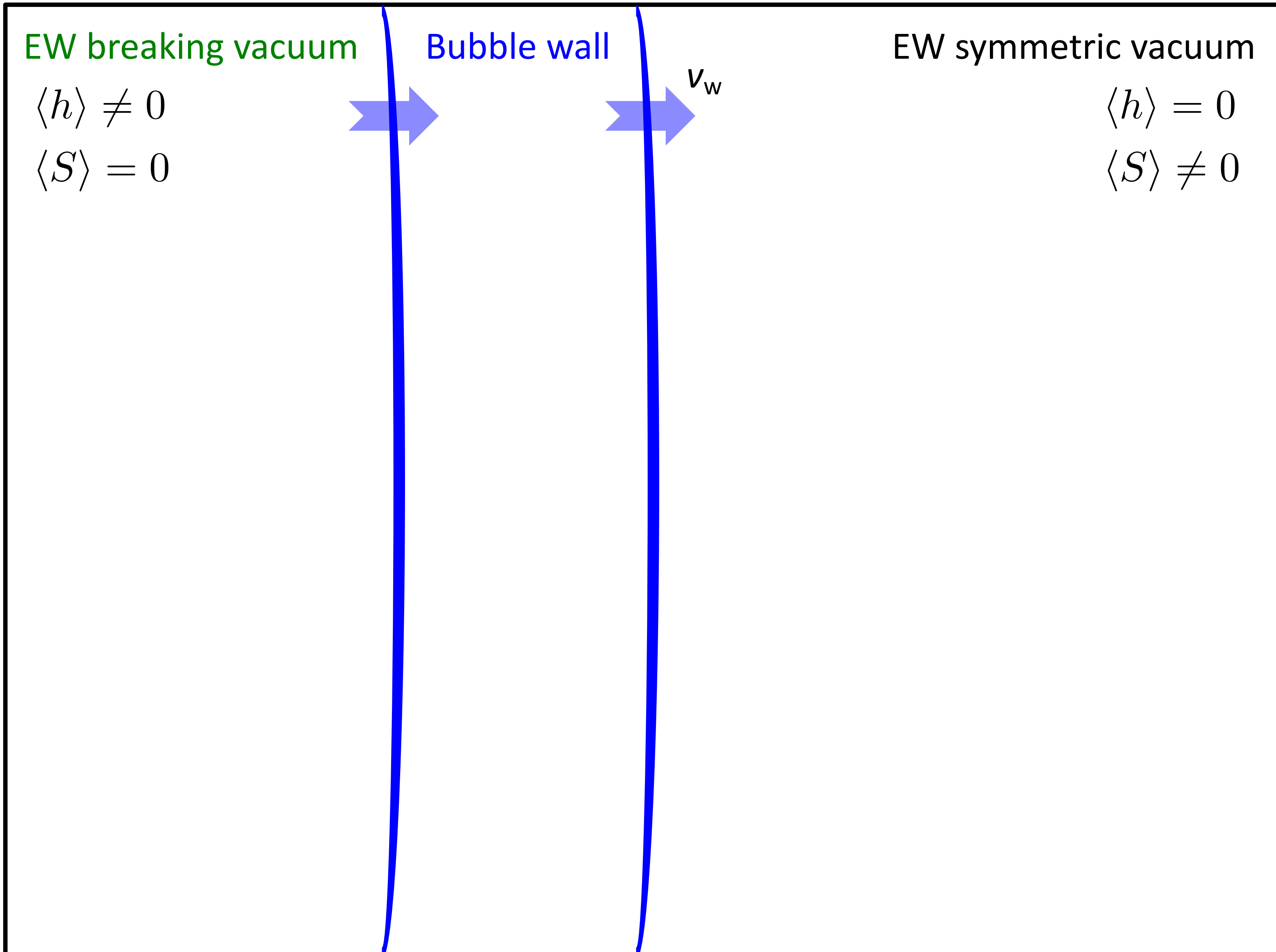
① 2nd-order PT
② 1st-order EWPT

First Order Phase Transition

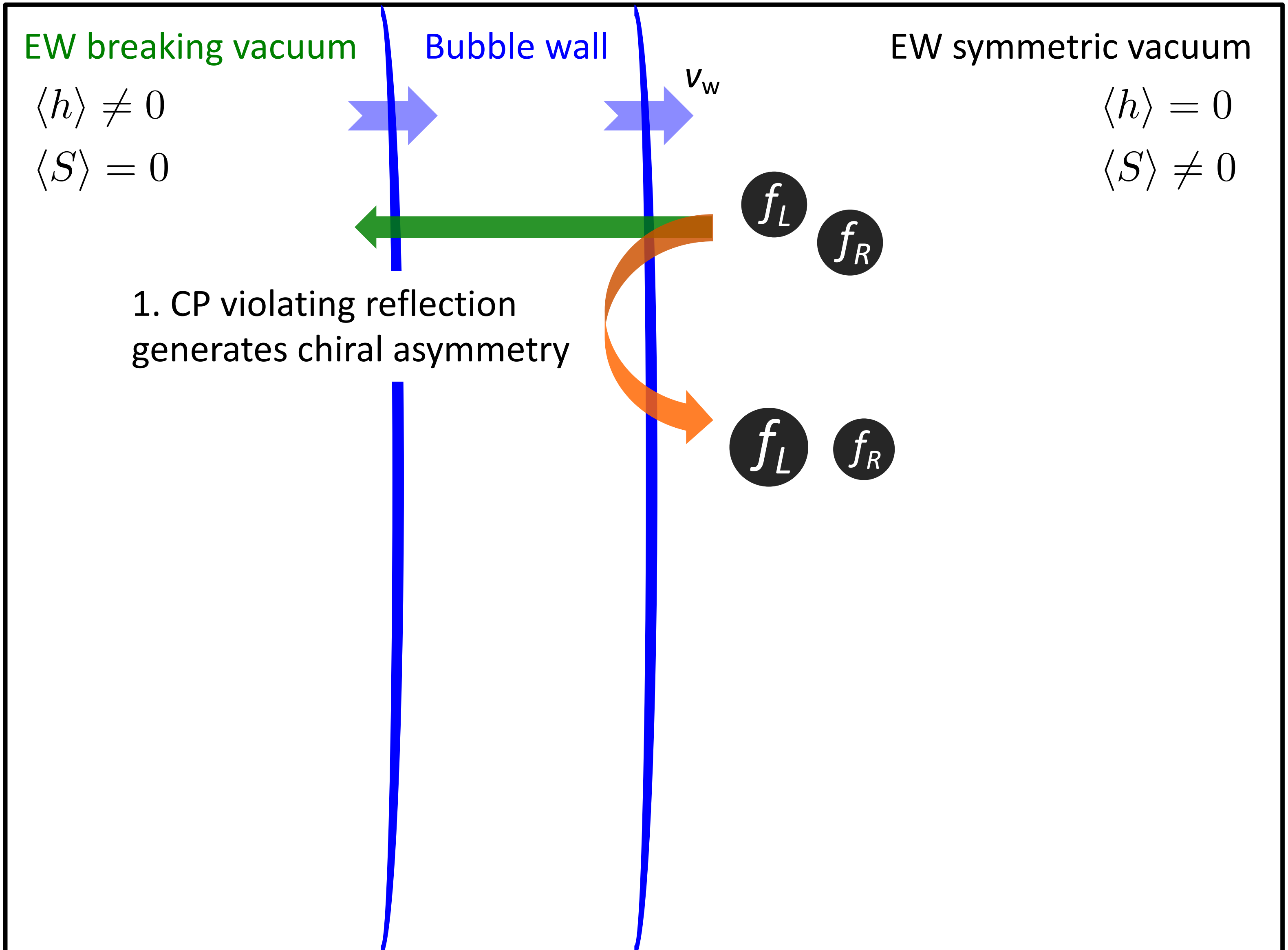


CP violation: comes from the *S*-relevant interactions

- EW baryogenesis during EWPT



- EW baryogenesis: 4 steps



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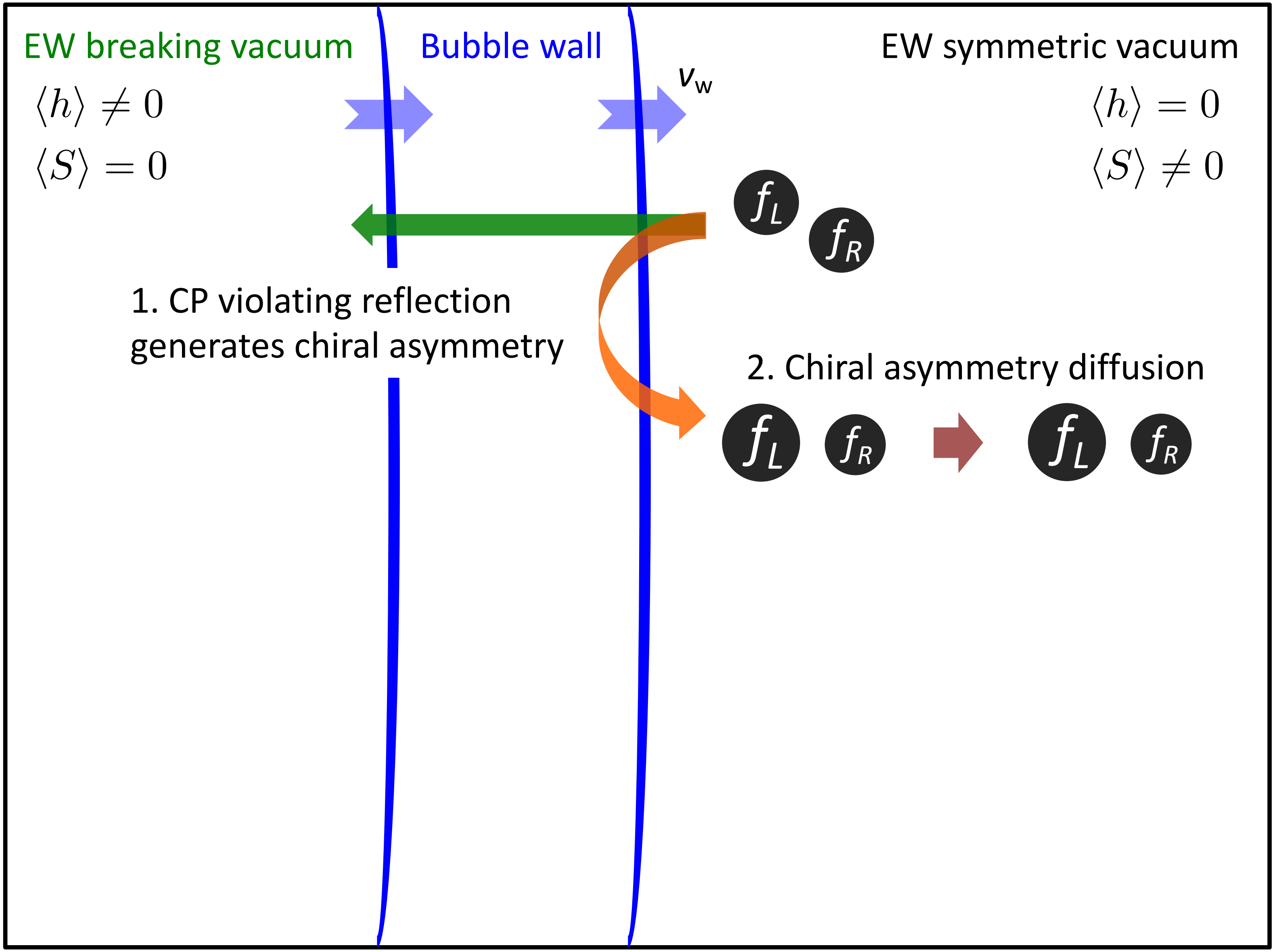

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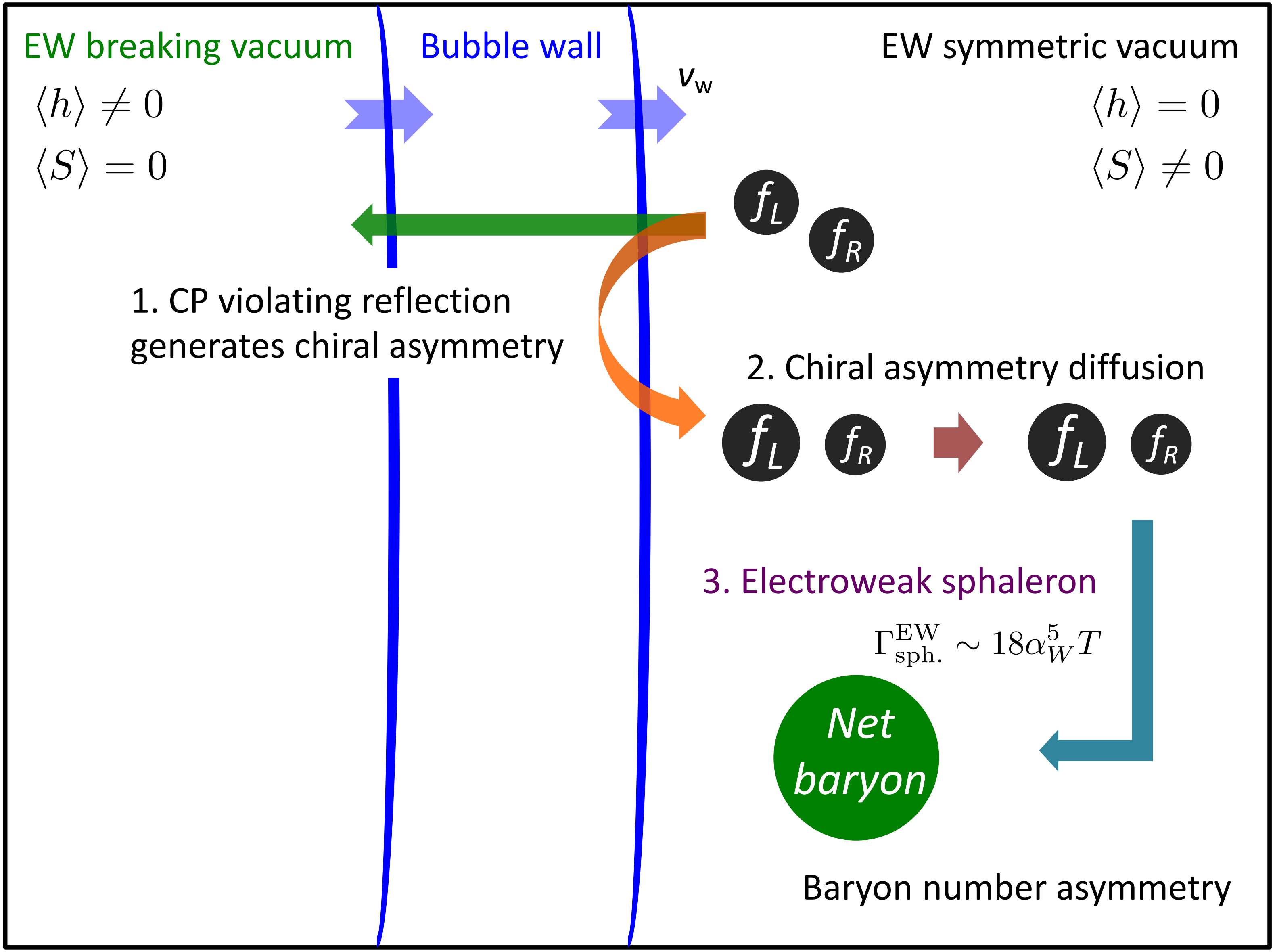

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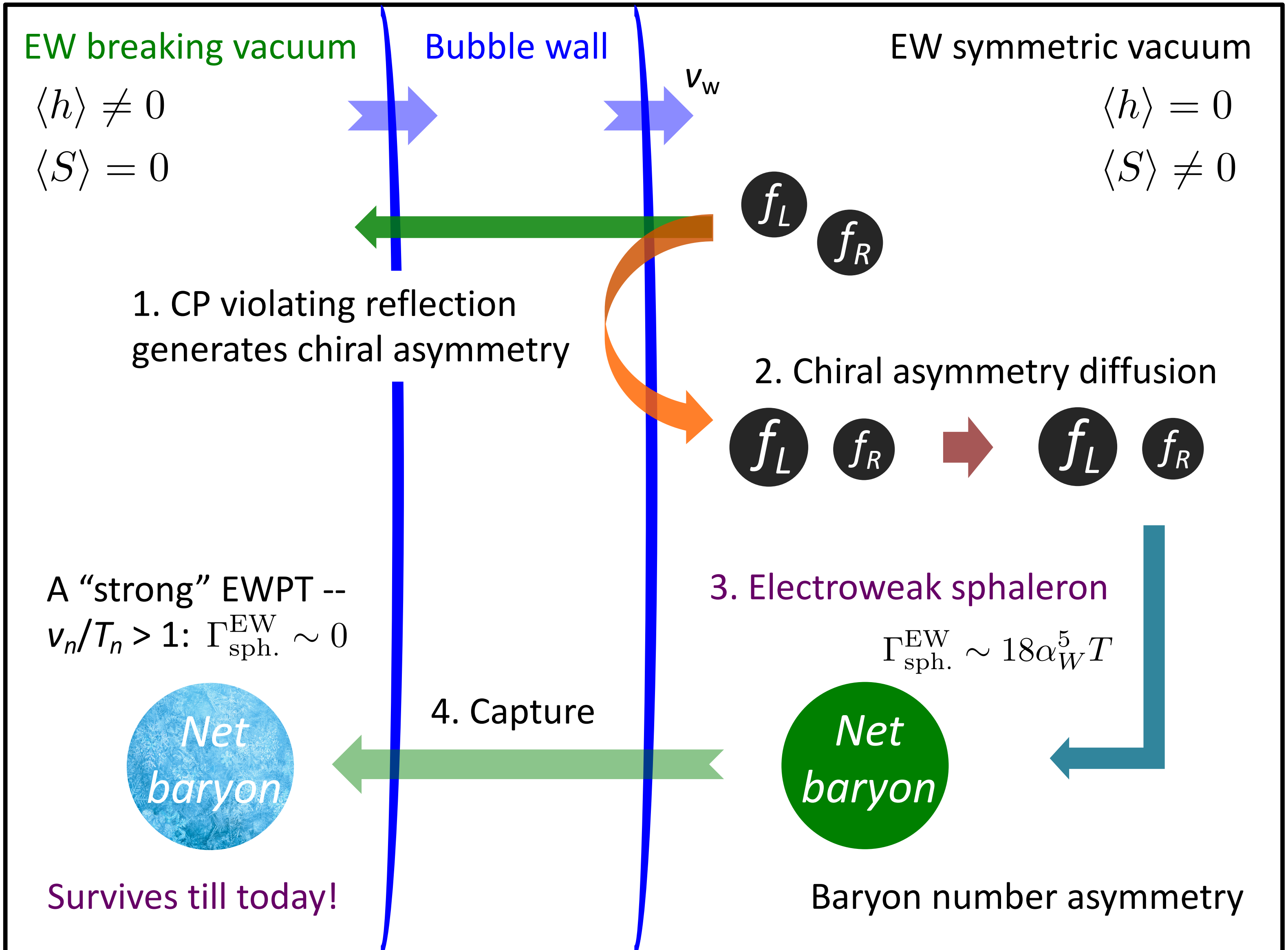

- Which fermion do we need?

Naively: large Yukawa => large CPV => large baryon asymmetry?

The most studied scenario: top quark transport [M. Joyce *et al*, 1994]

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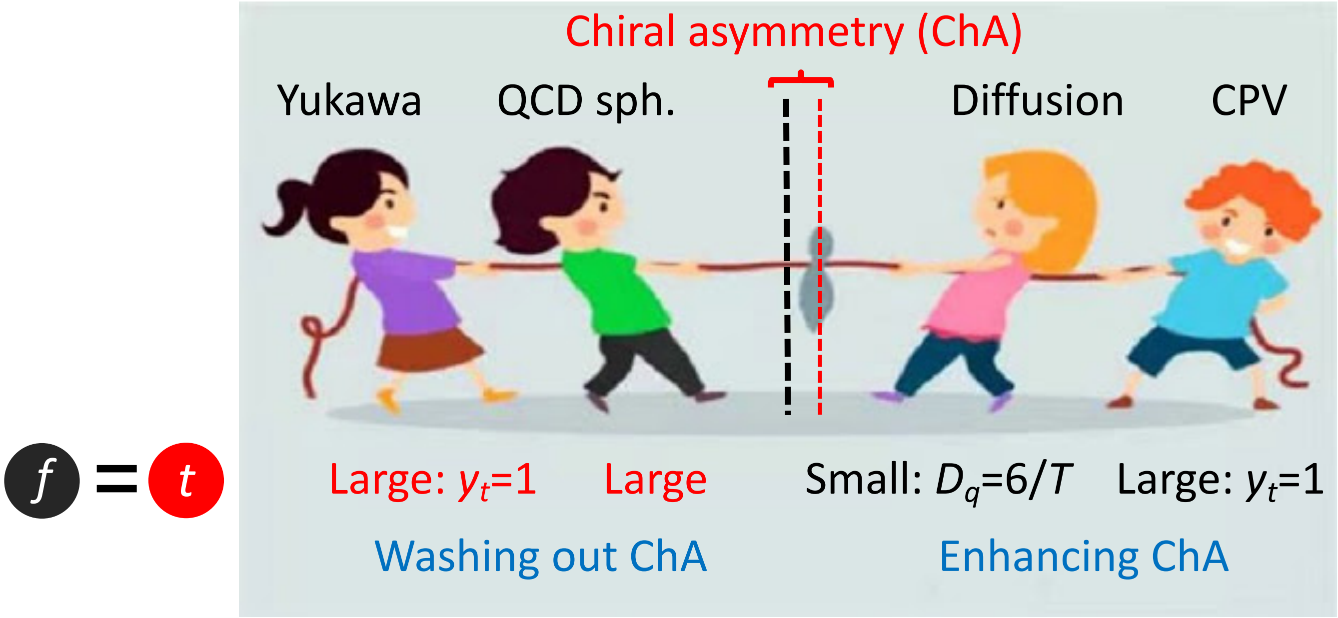
For the top quark, inside the plasma:



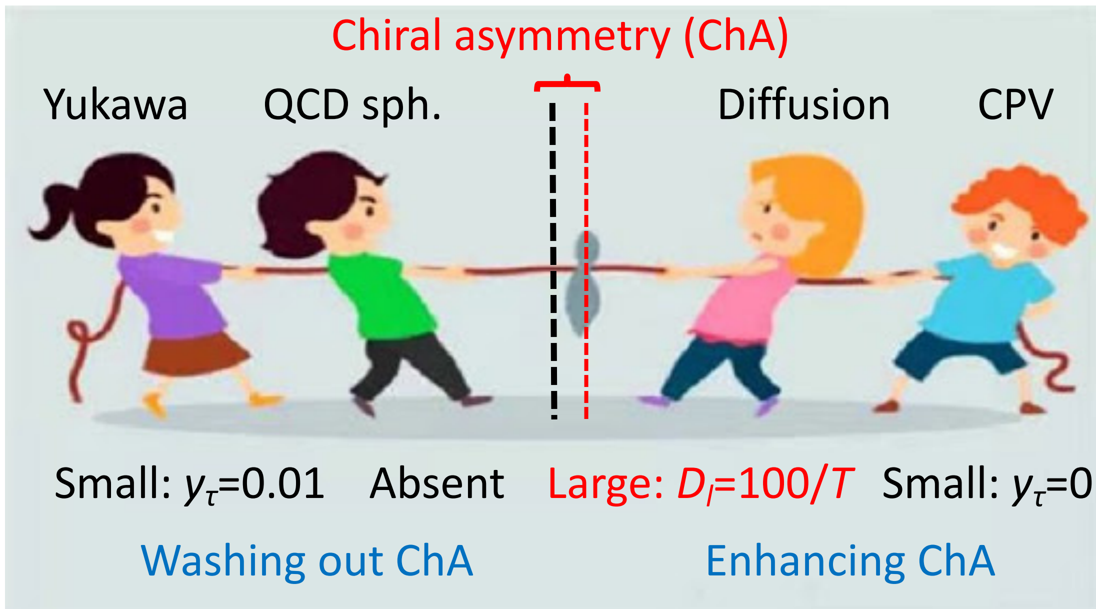
Strong enhancement v.s. strong washout effects: not as efficient as expected.

- # Which fermion do we need?

<u>Naively:</u> small Yukawa => small CPV => small baryon asymmetry?

The τ lepton transport [Jordy de Vries *et al*, 2018]
For the τ lepton, inside the plasma:

$f = \tau$



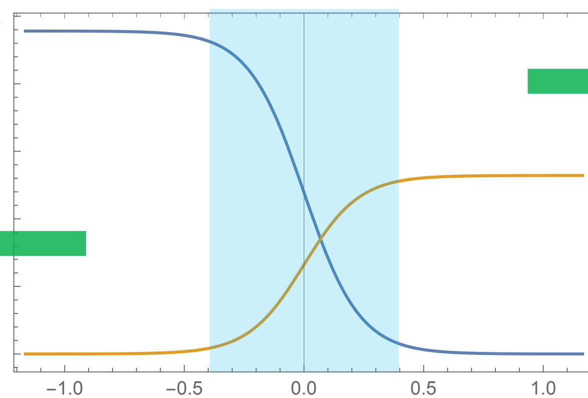
Moderate enhancement v.s. small washout effects: more efficient than expected!

New!

τ-mediated EW baryogenesis with Higgs+singlet

- Satisfying the Sakharov conditions

During the 1st-order EWPT: wall frame, planar approximation



Dim-5 operator with CP violation phase ϕ_τ: effective mass

$$\boxed{\mathcal{L}_5 \supset \frac{e^{i\phi_\tau}}{\Lambda_\tau} S\bar{\ell}_L H \tau_R + \text{h.c.}} \quad \Longrightarrow \quad \bar{m}_\tau(z) = \frac{y_\tau}{\sqrt{2}}\hat{h}(z) + \boxed{\frac{e^{i\phi_\tau}}{\sqrt{2}\Lambda_\tau}\hat{h}(z)\hat{S}(z)}$$

• τ-mediated EW baryogenesis

① Boltzmann equation: generating a chiral asymmetry (ChA)

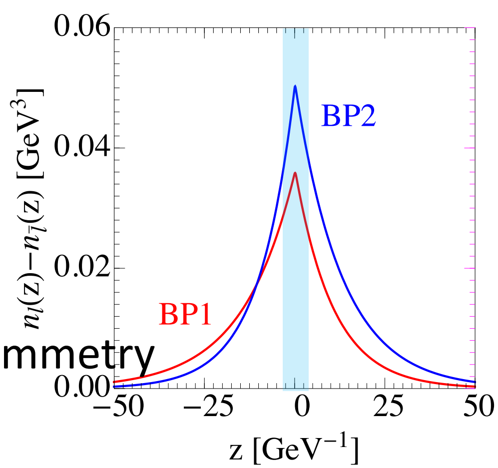
Diffusion constant | Wall velocity | CP violating source

$$-D_\ell \ell'' + v_w \ell' + (\Gamma_M + \Gamma_Y)\left(\frac{1}{k_\ell} + \frac{1}{k_\tau}\right)\ell = -\frac{v_w}{\pi^2}\mathrm{Im}\left[\bar{m}'_\tau m^*_\tau\right] J_\tau$$

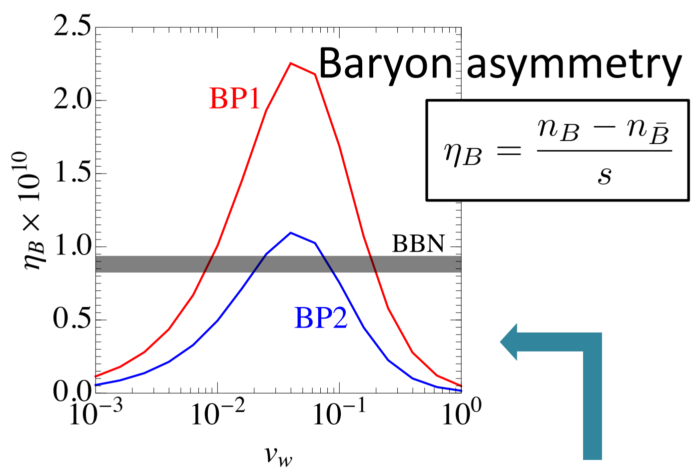
Net density of τ_L

Helicity flipping & Yukawa rates

m_τ : the (space-dependent) mass



Chiral asymmetry



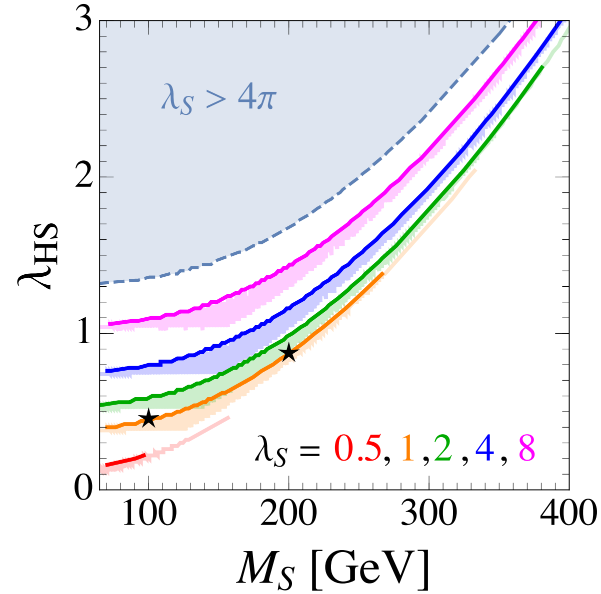
② EW sphaleron: converting the ChA to baryon asymmetry

- # Phase transition and gravitational waves

5 parameters, 2 fixed by M_h = 125 GeV and v = 246 GeV.

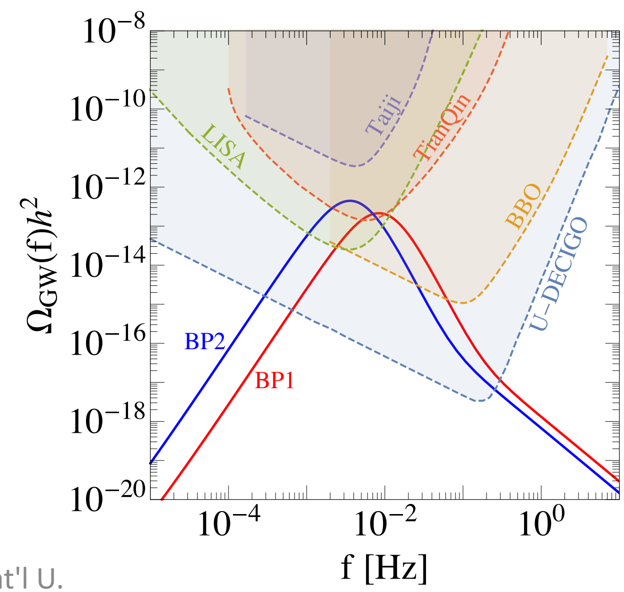
$$V_0 = \frac{\mu_H^2}{2}h^2 + \frac{\mu_S^2}{2}S^2 + \frac{\lambda_H}{4}h^4 + \frac{\lambda_S}{4}S^4 + \frac{\lambda_{HS}}{2}h^2S^2$$

Deriving the strong 1st-order EWPT by calculating the vacuum decay rate.



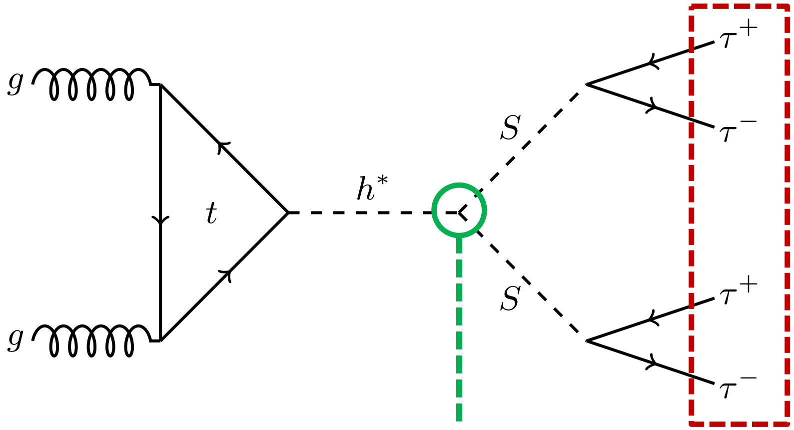
1st-order EWPT generates stochastic gravitational waves:

- ✓ Collision of the bubbles
- ✓ Sound waves in plasma
- ✓ Turbulence in plasma



- Collider phenomenology: the 4τ final state

Pair production of the singlet at a *pp* collider



Required by CP violation

$$\mathcal{L}_5 \supset \frac{e^{i\phi_\tau}}{\Lambda_\tau} S\bar{\ell}_L H \tau_R + \text{h.c.}$$

Required by a 1st-order EWPT

$$V_0 = \frac{\mu_H^2}{2}h^2 + \frac{\mu_S^2}{2}S^2 + \frac{\lambda_H}{4}h^4 + \frac{\lambda_S}{4}S^4 + \frac{\lambda_{HS}}{2}h^2S^2$$

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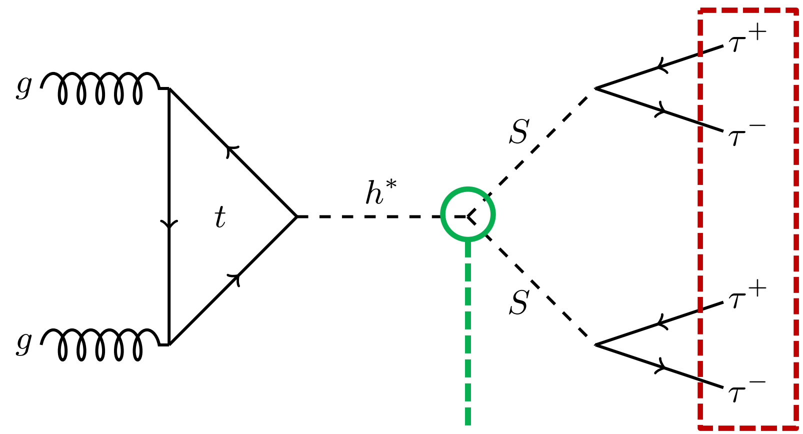

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The decay of τ: leptonic (35%) and hadronic (65%)
Consequently, the 4τ final state yields

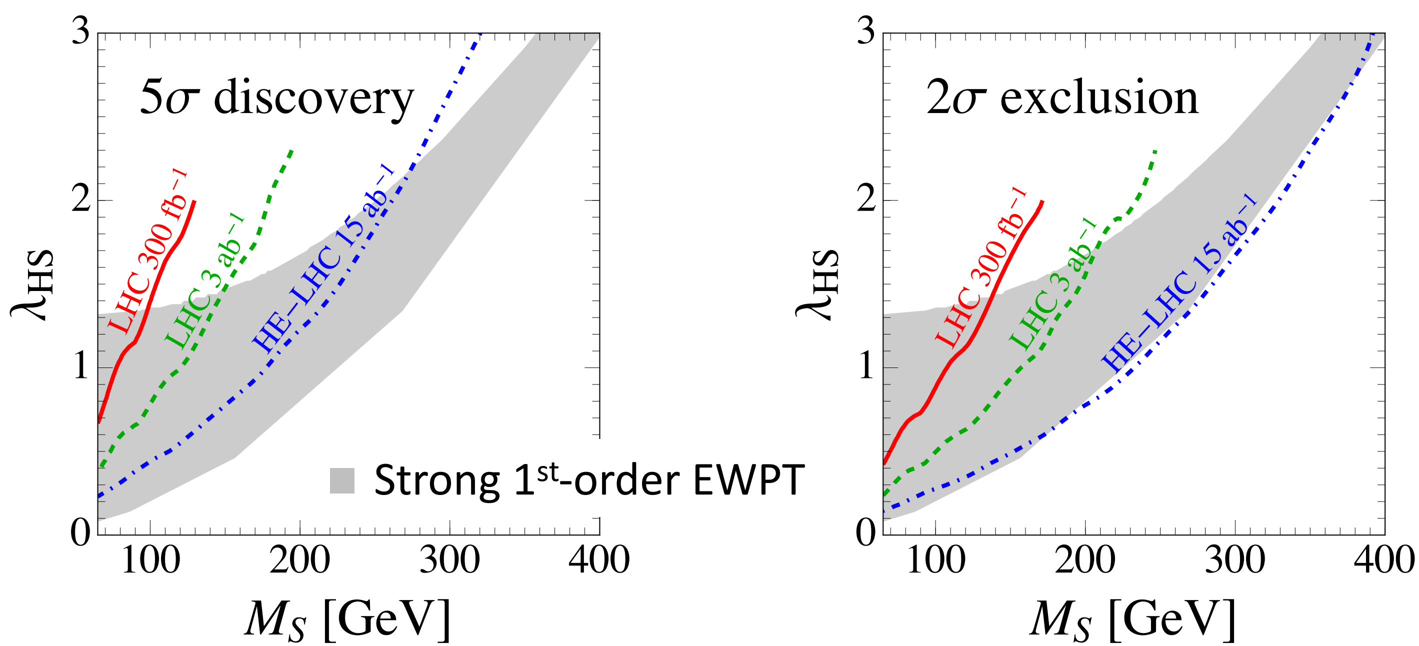
$$4\tau_j\ (17.9\%),\quad \underline{1\ell 3\tau_j\ (38.4\%)},\quad \underline{2\ell 2\tau_j\ (31.1\%)},\quad 3\ell 1\tau_j\ (11.1\%),\quad 4\ell\ (1.5\%)$$

New! Searched within SUSY [ATLAS 1804.03602]

• Collider phenomenology: the 4τ final state

Search for the <u>1 lepton + 3 τ-jet</u> channel.
Cut I: 1 lepton + 3 jets; Cut II: 3 τ-jets; Cut III: *b*-veto.

Unit: fb		Signal BP1	Signal BP2	$W^\pm + \text{jets}$	$Z + \text{jets}$	$t\bar{t}$	$W^\pm\tau^+\tau^- j$	$\tau^+\tau^- + \text{jets}$	$\tau^+\tau^-\tau^+\tau^-$
14 TeV LHC	Before	12.3	1.19	1.45×10^6	6.18×10^5	1.21×10^5	129	1.49×10^5	7.15
	Cut I	1.76	0.352	2.43×10^5	5.91×10^4	6.73×10^4	34.5	6.35×10^3	0.511
	Cut II	0.0733	0.0269	0.832	3.28	3.41	0.152	0.841	0.0378
	Cut III	0.0661	0.0245	0.681	2.64	0.243	0.134	0.762	0.0356



Conclusion

We propose an EW baryogenesis model:

- ❑ The 1st-order EWPT is induced by SM extended with a singlet
- ❑ The chiral asymmetry is meditated by τ lepton transport.

The gravitational waves from EWPT is detectable at future space-based interferometers such as LISA.

The 4τ final state can be efficiently probed at current or future colliders.

Thank you!

Backup

Details of BP1 and BP2

$$\text{BP1}: \quad M_S = 100 \text{ GeV}, \quad \lambda_{HS} = 0.46; \quad T_n = 64.44 \text{ GeV}, \quad v_n = 239.06 \text{ GeV}, \quad w_n = 132.13 \text{ GeV};$$
$$\text{BP2}: \quad M_S = 200 \text{ GeV}, \quad \lambda_{HS} = 0.88; \quad T_n = 94.32 \text{ GeV}, \quad v_n = 220.55 \text{ GeV}, \quad w_n = 108.97 \text{ GeV}$$

Details of cut flow

Unit: fb		Signal BP1	Signal BP2	$W^\pm$ + jets	Z + jets	$t\bar{t}$	$W^\pm\tau^+\tau^-j$	$\tau^+\tau^-$ + jets	$\tau^+\tau^-\tau^+\tau^-$
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27 TeV HE-LHC	Before	42.7	5.30	4.10×10^6	1.59×10^6	1.06×10^6	321	3.34×10^5	13.4
	Cut I	6.74	1.64	6.66×10^5	1.69×10^5	5.55×10^5	95.8	1.72×10^4	1.19
	Cut II	0.267	0.115	2.54	13.9	45.7	0.369	2.23	0.0724
	Cut III	0.245	0.103	2.05	10.9	9.14	0.315	1.87	0.0635