Center for Theoretical Physics
SEOUL NATIONAL UNIVERSITY

Lepton as the source of EW baryogenesis

Theory and experimental signals

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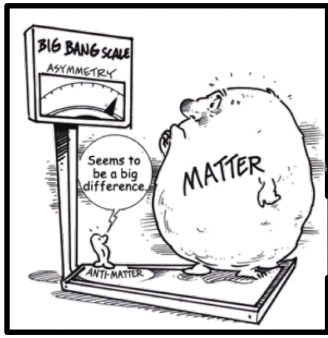
JHEP 02 (2021) 090 [arXiv: 2011.04821]

• Matter-antimatter asymmetry

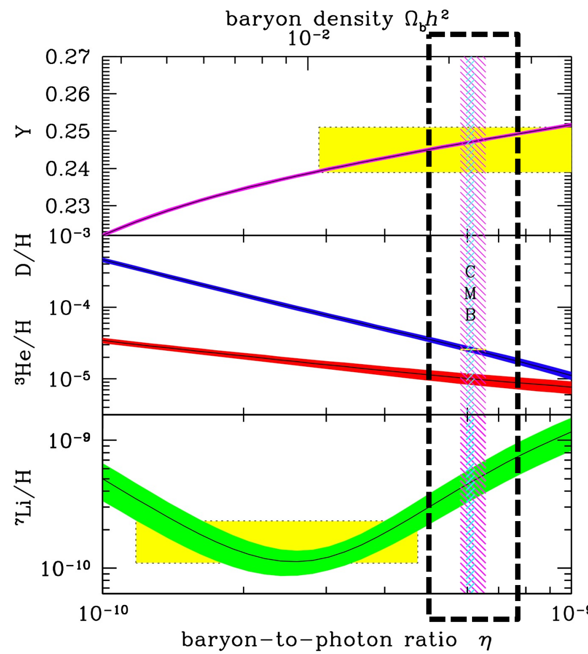
<u>There is almost no primordial antimatter in the Universe.</u>



Characterized by **baryon asymmetry**

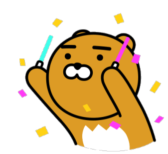
$$\eta_B = \frac{n_B - n_{\bar{B}}}{s} \approx 10^{-10}$$

← CMB BBN



Three important facts:

1. Right after after reheating $\eta_B \approx 0$.
2. An $\eta_B \approx 10^{-10}$ is generated before Big-Bang Nucleosynthesis.
3. The Standard Model cannot explain the asymmetry.



- How to generate the baryon asymmetry?

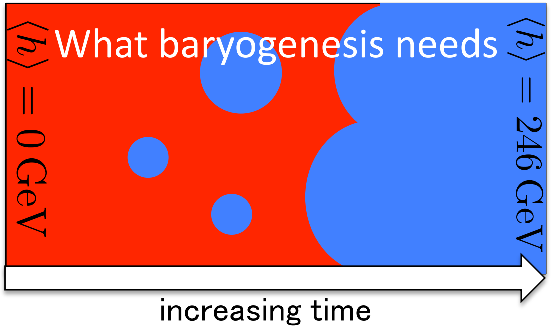
Three conditions to generate the asymmetry:[Sakharov,1967]

(1) Baryon number violation; (2) C/CP violation; (3) Departure from equilibrium.

New physics could satisfy the Sakharov conditions and generate the baryon asymmetry (known as **baryogenesis**).
Baryogenesis can happen at any scale between reheating and BBN.

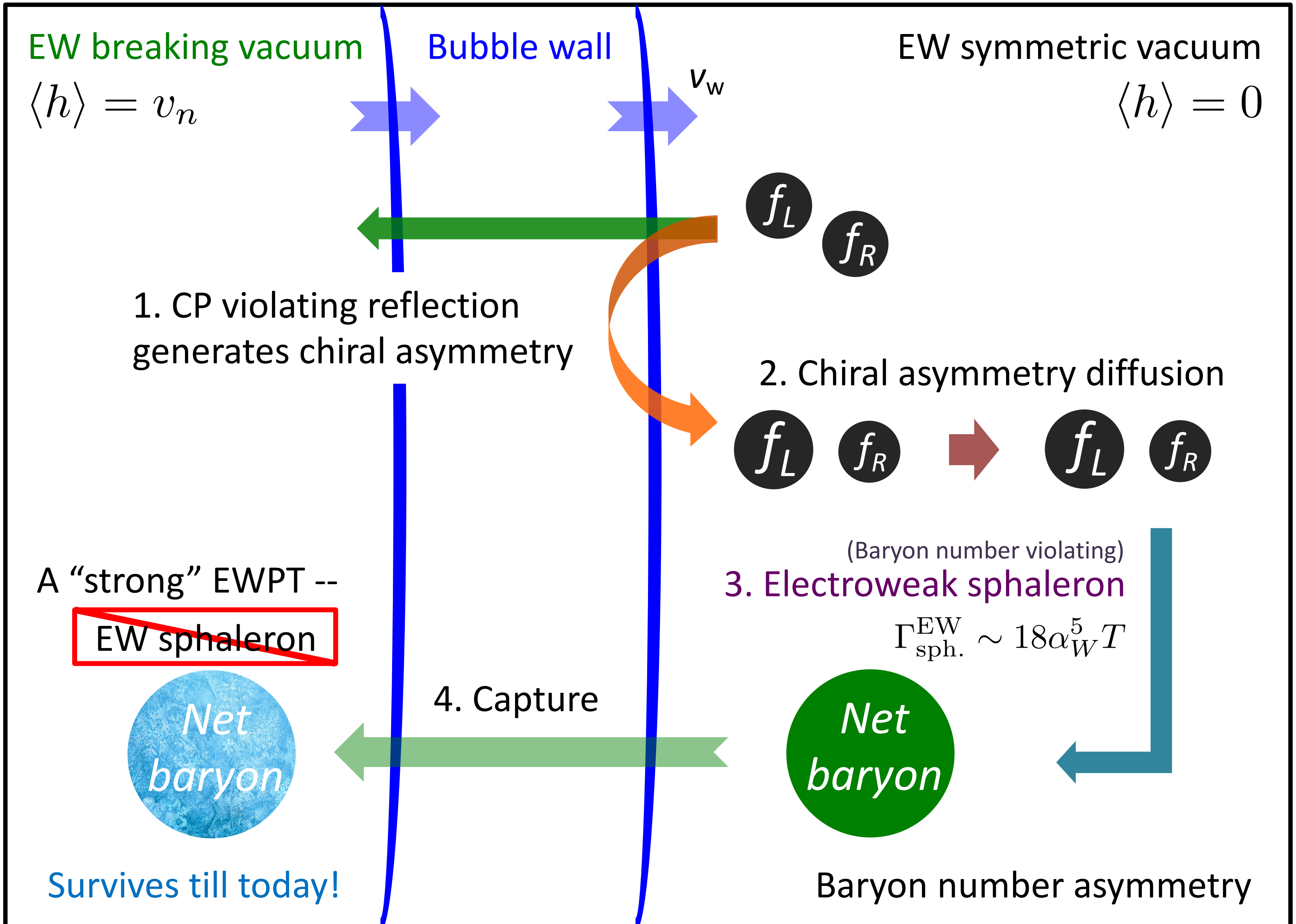
This talk: baryogenesis at EW scale; which needs a strong 1st-order EW phase transition --

First Order Phase Transition



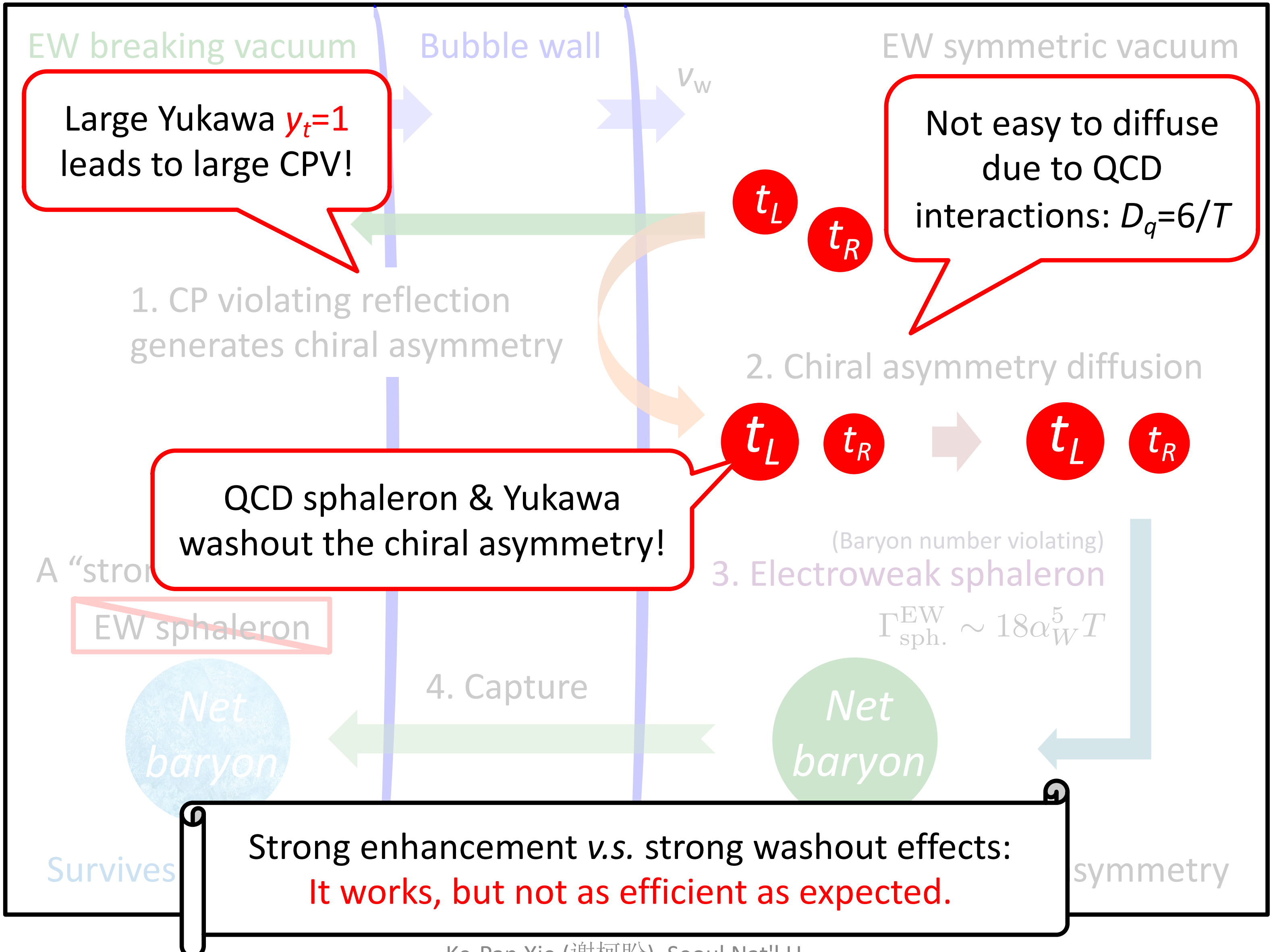
Continuous Crossover

• EW baryogenesis: 4 steps



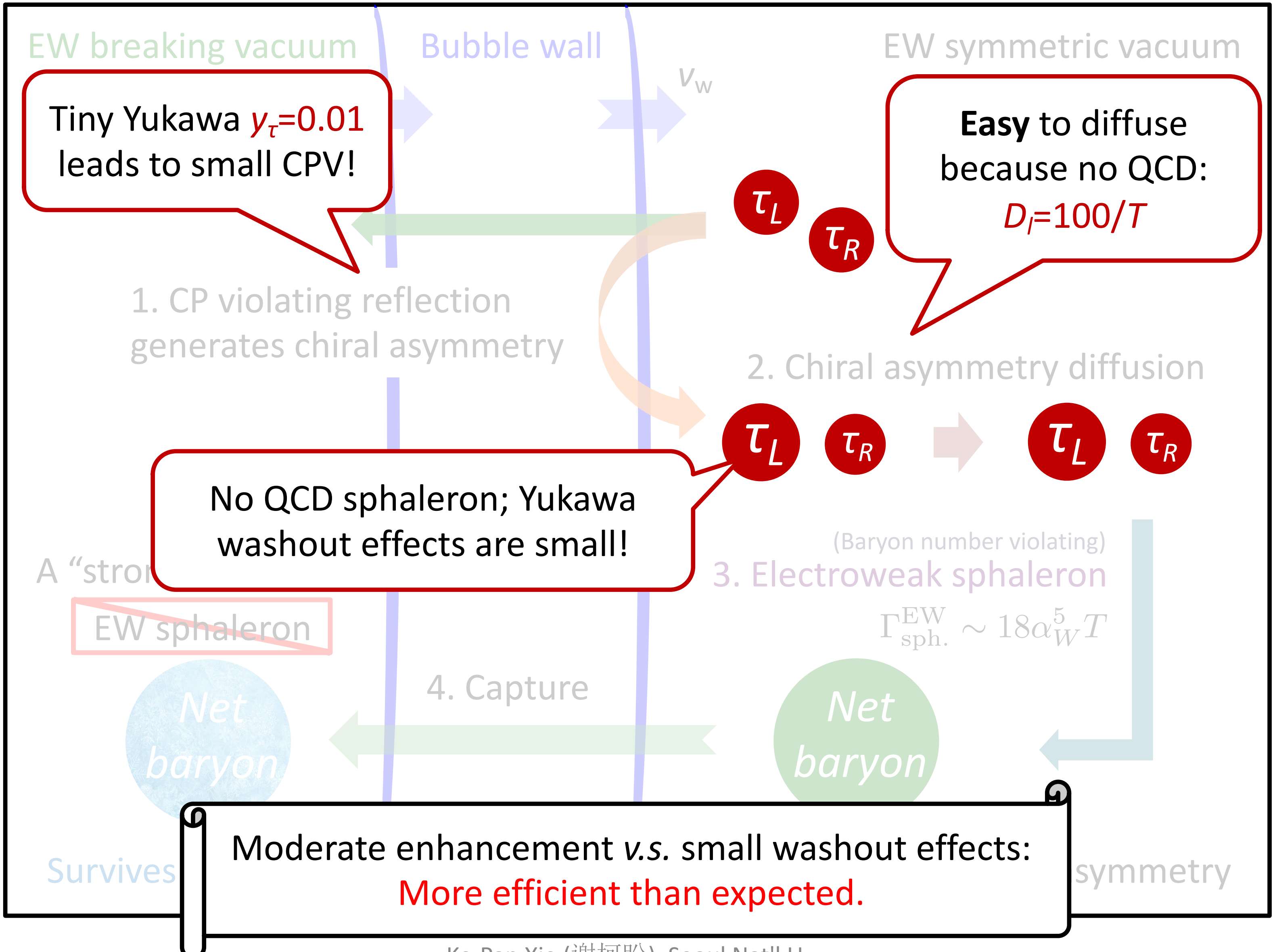
- The most popular scenario: top quark transport

[M. Joyce *et al*, PRL1995]



- Alternative scenario: the τ lepton transport

[Jordy de Vries *et al*, JHEP2018]



This talk!

- τ-mediated EW baryogenesis with Higgs+singlet

Approximately the thermal potential [assume a Z2 for simplicity]

Thermal corrections

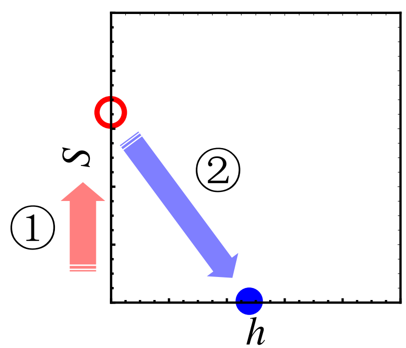
$$V_T = \frac{\mu_H^2 + c_H T^2}{2} h^2 + \frac{\mu_S^2 + c_S T^2}{2} S^2 + \frac{\lambda_H}{4} h^4 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{HS}}{2} h^2 S^2$$

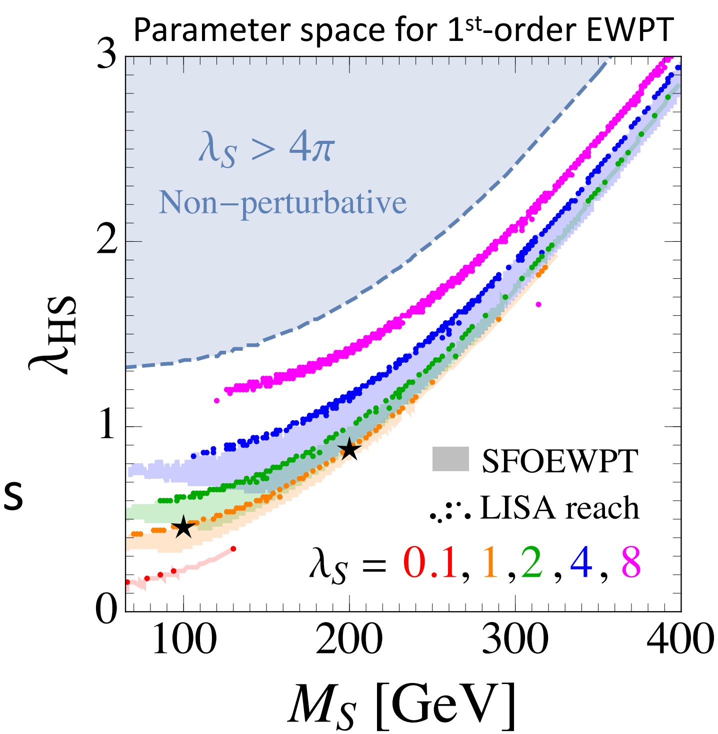
5 parameters, 2 fixed by M_h = 125 GeV and v = 246 GeV.

Barrier for EWPT

EW phase transition pattern

Two steps:
① 2nd-order PT
② 1st-order EWPT





Phase transition gravitational waves

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

• τ-mediated EW baryogenesis with Higgs+singlet

The leptophilic dim-5 operator

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

From dim-5 operator

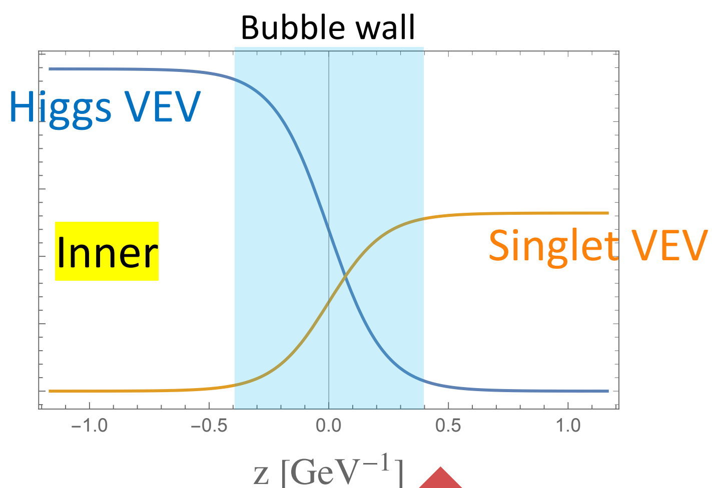
$$\bar{m}_\tau(z) = \frac{y_\tau}{\sqrt{2}} \hat{h}(z) + \frac{e^{i\phi_\tau}}{\sqrt{2}\Lambda_\tau} \hat{h}(z) \hat{S}(z)$$

CPV Source

Diffusion in wall frame:

Net density of τ_L

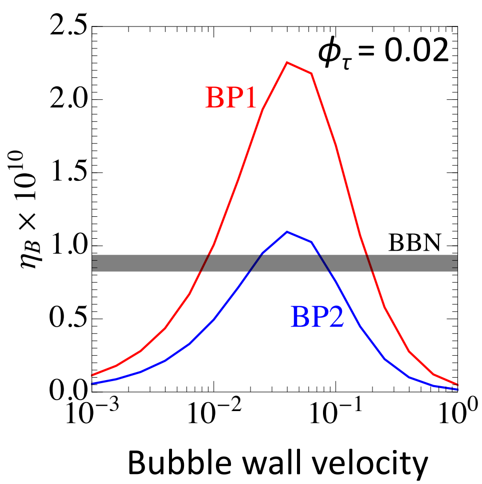
$$-D_\ell \ell'' + v_w \ell' + (\Gamma_M + \Gamma_Y) \left(\frac{1}{k_\ell} + \frac{1}{k_\tau} \right) \ell = -\frac{v_w}{\pi^2} \mathrm{Im} \left[\bar{m}_\tau' m_\tau^* \right] J_\tau$$



Chiral asymmetry of τ_L is generated in front of the wall

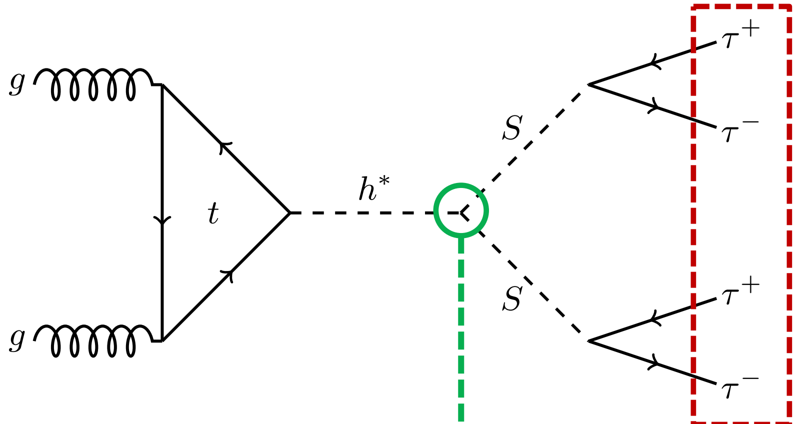
EW sphaleron converts chiral asymmetry into **baryon asymmetry**

$$\Gamma_{\rm sph.}^{\rm EW} \sim 18 \alpha_W^5 T$$



• Collider phenomenology

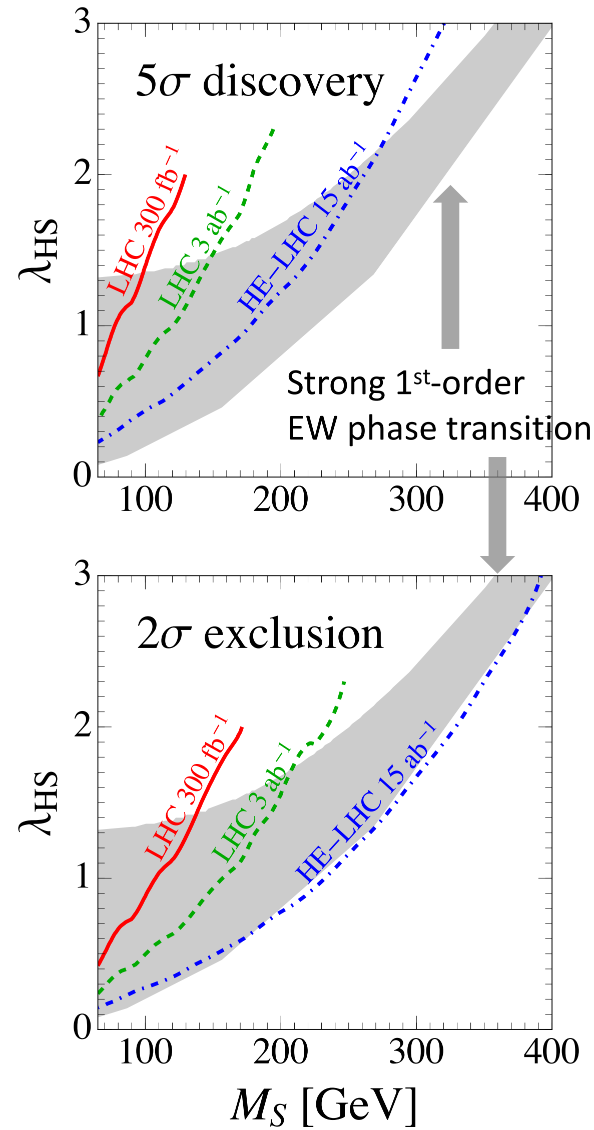
At a *pp* collider --



Required by a 1st-order EWPT

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

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



Signal: 1 lepton + 3 τ-jet;

Backgrounds: *V* + jets and *V* + τs, ttbar.

The 4τ final state is a good probe!

• 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.

This model has experimental signals:

- ❑ The gravitational waves from EWPT is detectable at future detectors such as LISA;
- ❑ The 4τ final state can be efficiently probed at the LHC or future colliders.

Thank you!

Osaka
Photographed on Feb 17, 2019

Backup

Details of BP1 and BP2

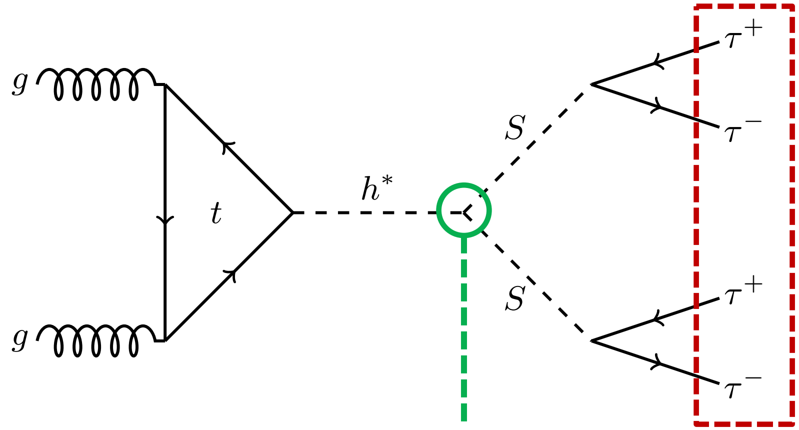
$$\text{BP1}: \quad M_S = 100\ \text{GeV}, \quad \lambda_{HS} = 0.46; \quad T_n = 64.44\ \text{GeV}, \quad v_n = 239.06\ \text{GeV}, \quad w_n = 132.13\ \text{GeV};$$
$$\text{BP2}: \quad M_S = 200\ \text{GeV}, \quad \lambda_{HS} = 0.88; \quad T_n = 94.32\ \text{GeV}, \quad v_n = 220.55\ \text{GeV}, \quad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

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	$\tau^+\tau^-\tau^+\tau^-$
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
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

- # 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

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

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

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

New! ($1\ell 3\tau_j$)

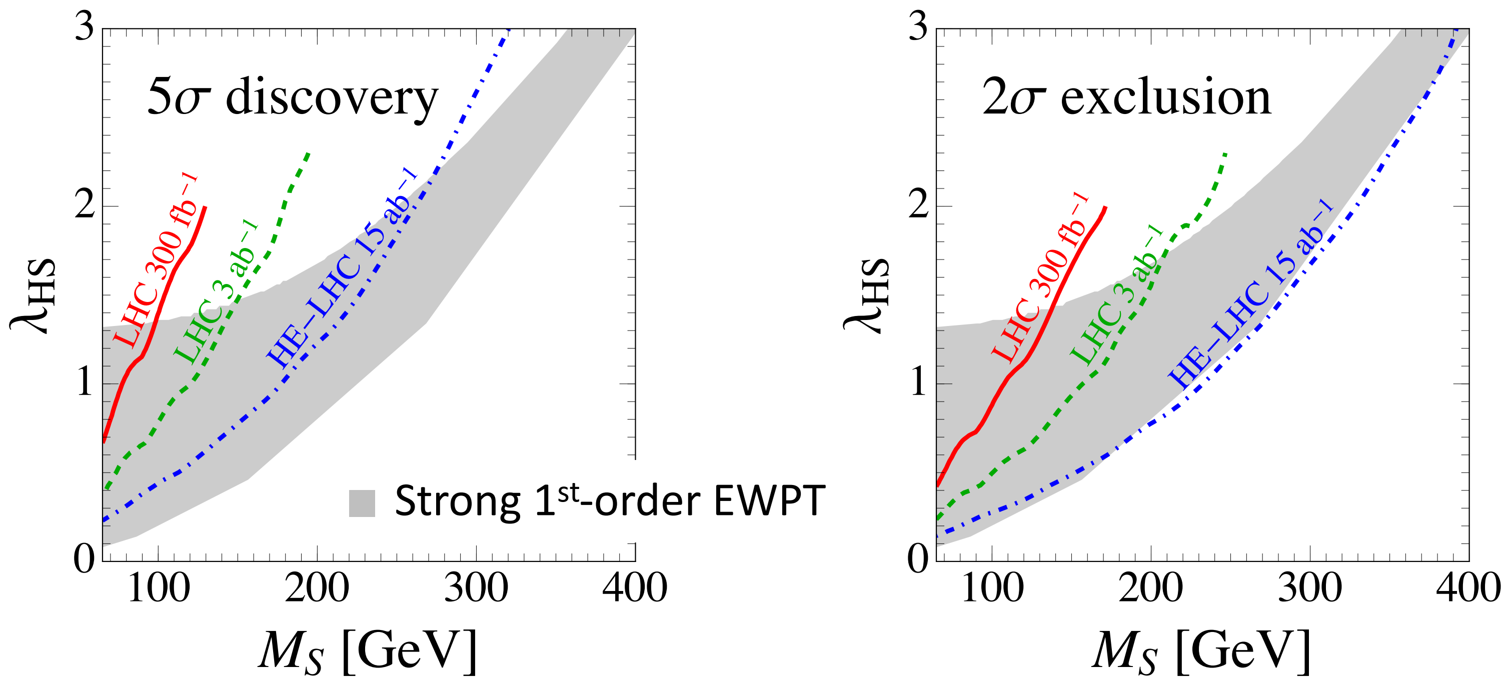
Searched within SUSY [ATLAS 1804.03602] ($2\ell 2\tau_j$)

- # Collider phenomenology: the 4τ final state

Search for the 1 lepton + 3 τ-jet channel.

Cut I: 1 lepton + 3 jets; Cut II: 3 τ-jets; Cut III: *b*-veto.

Main SM backgrounds: V + jets and V + τs, ttbar.



If an excess is obtained, further observables can be constructed to reveal the CP structure.[See 2012.13922]