Exploring dynamical CP violation induced baryogenesis by GWs and colliders

기초과학연구원
Institute for Basic Science

Zhuoni Qian(IBS-CTPU)
2018-08-14 at Panshan

1804.06813 Phys. Rev. D 98, 015014
(On behalf of Fa Peng Huang, ZQ, Mengchao Zhang)

There is more baryon than anti-baryon in our visible universe:

$$\frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10}$$

3 conditions (Sakharov Criteria) are required if one wants to explain baryon asymmetry:

1 baryon number violation
2 C and CP symmetry violation
3 departure from thermal equilibrium

Does the SM work?

1 baryon number violation
sphaleron ✓

2 C and CP symmetry violation
CKM, too small ⊗

3 departure from thermal equilibrium
crossover phase transition (125GeV Higgs) ⊗

Another obstacle is stringent constraints from electric dipole moment (EDM) measurement, CP violation term have to be small :

Dynamical CPV: Large CPV in the early universe, suppressed now.

To realize with a simple example:
A dim-5 operator with additional scalar S:

$$y_t \eta \frac{S}{\Lambda} \bar{Q}_L \tilde{\Phi} t_R + h.c.$$

$$\text{with } y_t = \sqrt{2} m_t / v \text{ and } \eta = a + ib$$

The same scalar S also realizes a strong first order phase transition (SFOPT) with the scalar potential:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{\Phi} t_R + \mathrm{H.c} + \frac{1}{2} \partial_\mu \mathrm{S} \partial^\mu \mathrm{S} + \frac{1}{2} \mu^2 \mathrm{S}^2 - \frac{1}{4} \lambda \mathrm{S}^4 - \frac{1}{2} \kappa \mathrm{S}^2 (\Phi^\dagger \Phi)$$

Now things are much better:

1 baryon number symmetry violation

sphaleron ✓ sphaleron ✓

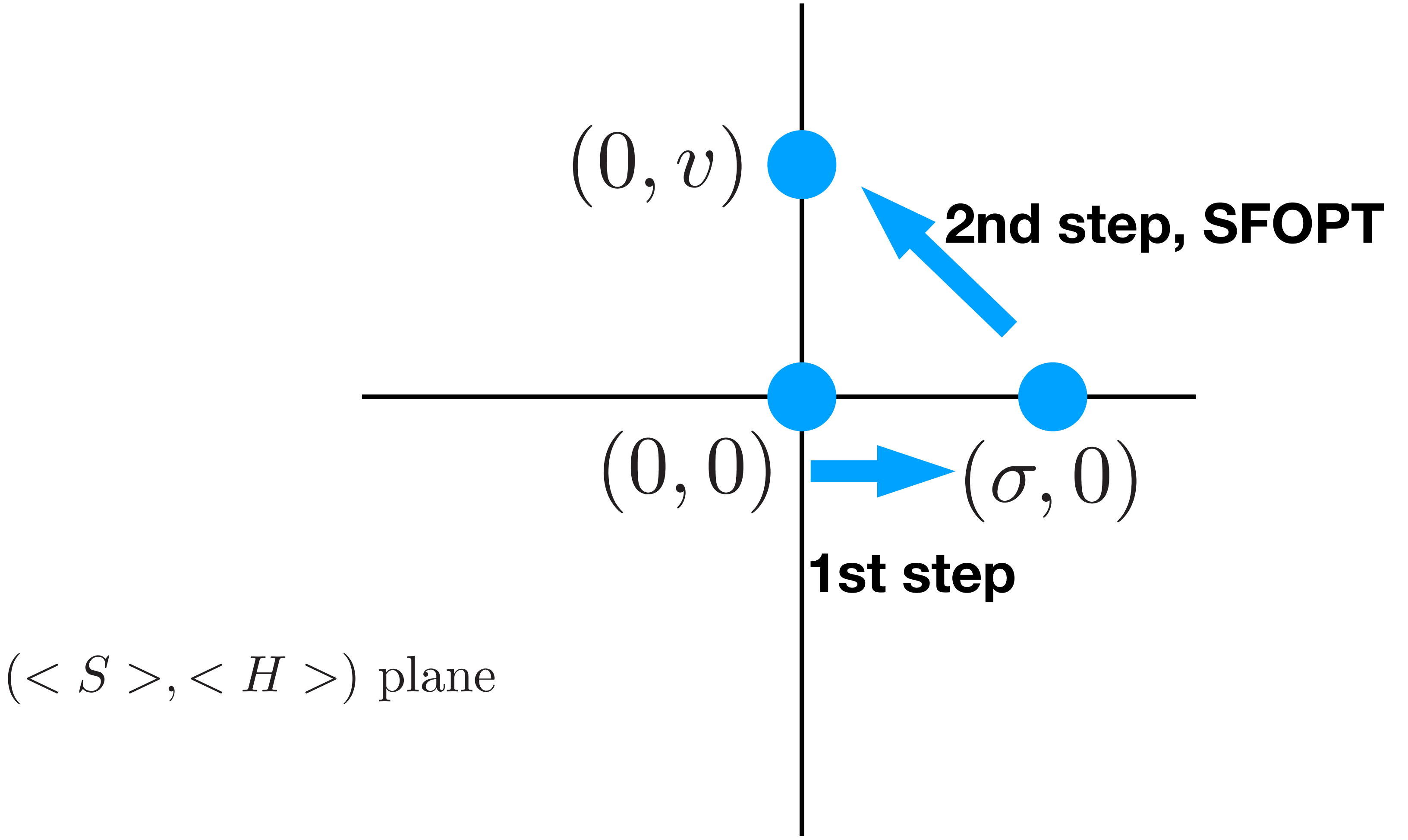
2 C and CP violation

CKM, too small ⊗ $y_t \eta \frac{S}{\Lambda} \bar{Q}_L \tilde{\Phi} t_R$ ✓

3 departure from thermal equilibrium

crossover phase transition(125GeV Higgs) ⊗ H+S ✓

Now we have two scalar fields, so the PT is 2-step:



$$\text{Sizable CPV at SFOPT} : \; y_t \eta \frac{\sigma}{\Lambda} \bar{Q}_L \tilde{\Phi} t_R$$

$$\text{Current time } \Lambda \text{ suppressed operator} : \; y_t \eta \frac{S}{\Lambda} \bar{Q}_L \tilde{\Phi} t_R$$

Constraints from EDM are much weaker:

Approximate analysis: high-temperature expansion

$$V_{\rm eff}(H,\sigma,T) = V_{\rm tree}(H,\sigma) + \Delta V_1^{T\neq 0}(H,\sigma,T) + V_1^{T=0}(H,\sigma)$$

$$V_{\rm tree}(H,\sigma) = -\frac{1}{2}\mu_{SM}^2 H^2 - \frac{1}{2}\mu^2\sigma^2 + \frac{1}{4}\lambda_{SM}H^4 + \frac{1}{4}\lambda\sigma^4 + \frac{1}{4}\kappa H^2\sigma^2$$

$$V(H,\sigma;T) = (D_H T^2 - \frac{\mu_{SM}^2}{2})H^2 + (D_\sigma T^2 - \frac{\mu^2}{2})\sigma^2 + \frac{1}{4}(\lambda_{SM}H^4 + \kappa H^2\sigma^2 + \lambda\sigma^4)$$

with

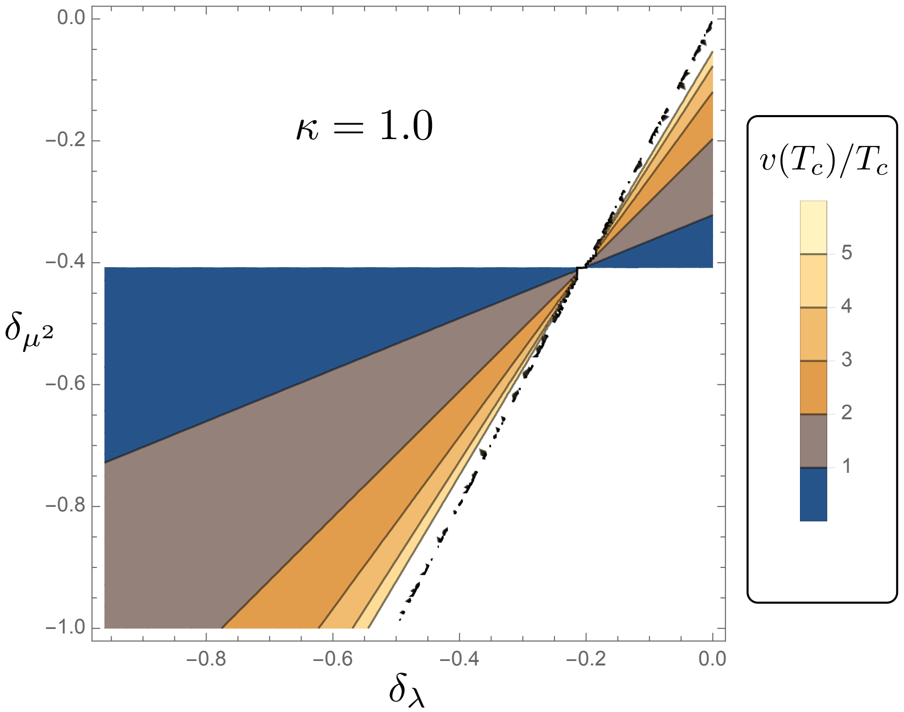
$$D_H = \frac{1}{32}(8\lambda_{SM} + g'^2 + 3g^2 + 4y_t^2 + 2\kappa/3), \quad D_\sigma = \frac{1}{24}(2\kappa + 3\lambda)\ ,$$

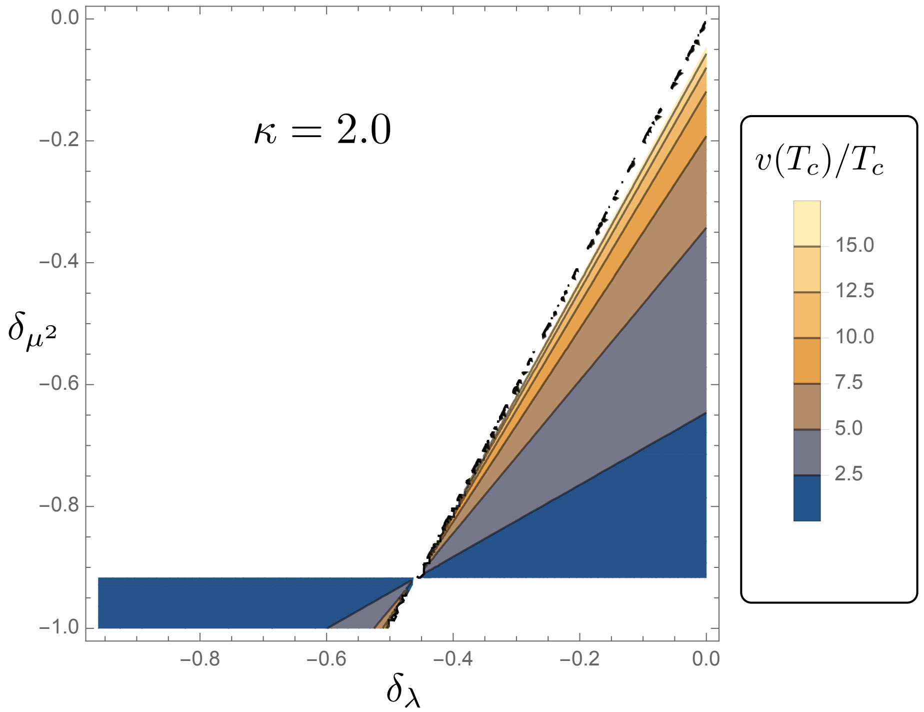
---

define $\lambda = (\frac{\kappa}{2\lambda_{SM}})^2\lambda_{SM}(1+\delta_\lambda), \quad \mu^2 = \mu_{SM}^2\frac{\kappa}{2\lambda_{SM}}(1+\delta_{\mu^2})$

then $\frac{v(T_c)}{T_c} \approx \frac{2v}{m_H}\sqrt{\frac{D_H - D_\sigma}{\delta_\lambda - 2\delta_{\mu^2}}}$

wash out parameter





Exact analysis: alpha and beta

finite temperature effective 1-loop potential is:

$$V_{\text{eff}}(H,\sigma,T) = \sum_i \frac{n_i}{64\pi^2} m_i^4(H,\sigma,T)\left(\ln\frac{m_i^2(H,\sigma,T)}{Q^2} - c_i\right) + \Delta V_T(H,\sigma,T)$$

$$\Delta V_T(H,\sigma,T) = \frac{T^4}{2\pi^2}\left\{\sum_{i=Bosons} n_i J_{\text{B}}(a_i^2) + \sum_{i=Fermions} n_i J_{\text{F}}(a_i^2)\right\}$$

$$J_{\text{B,F}}(a_i^2) = \int_0^\infty dx x^2 \ln\left[1 \mp \exp\left(-\sqrt{x^2+a_i^2}\right)\right], \quad a_i^2 = m_i^2(H,\sigma,T)/T^2$$

To precisely describe dynamics of the PT need to calculate two parameters,

α describes the strength of PT

$\tilde{\beta}$ describes the inverse of PT duration

They are calculated in nucleation time T_N:

$$\Gamma/\mathcal{H}^4|_{T=T_N} \simeq 1 \quad \Longrightarrow \quad \frac{S_3(T_N)}{T_N} = 4\ln(T_N/100\mathrm{GeV}) + 137$$

3-d Euclideam action is:

$$S_3 = \int d^3 r \left\{ \frac{1}{2}\left(\frac{dH}{dr}\right)^2 + \frac{1}{2}\left(\frac{d\sigma}{dr}\right)^2 + V_{\mathrm{eff}}(H,\sigma,T) \right\}$$

scalars profiles are obtained by solving differential equation (the minimization of free energy):

$$\frac{d^2\varphi_b}{dr^2} + \frac{2}{r}\frac{d\varphi_b}{dr} = \frac{\partial V_{\mathrm{eff}}}{\partial \varphi_b} \qquad \lim_{r\to\infty} \varphi_b = 0, \quad \left.\frac{d\varphi_b}{dr}\right|_{r=0} = 0.$$

then:

$$\tilde{\beta} = T_N \frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Bigg|_{T=T_N}. \qquad \alpha = \frac{\varepsilon(T_N)}{\rho_{\mathrm{rad}}(T_N)},$$

with $\varepsilon(T) = -V_{\mathrm{eff}}(\varphi_B(T),T) + T\dfrac{\partial V_{\mathrm{eff}}(\varphi_B(T),T)}{\partial T}$ **and** $\rho_{\mathrm{rad}}(T) = (\pi^2/30) g_*(T) T^4$

some benchmark points

κ	δ_λ	δ_{μ^2}	T_N[GeV]
0.88	-0.21	-0.61	128.4
0.88	-0.21	-0.51	171.8
0.88	-0.21	-0.41	115.3
1.00	-0.21	-0.41	116.0
2.00	-0.21	-0.41	121.1
2.00	-0.21	-0.22	106.6
2.00	-0.21	-0.30	113.6
4.00	-0.21	-0.21	115.9

Benchmark set	κ	m_S [GeV]	T_N [GeV]	α	$\tilde{\beta}$
I	2.00	115	106.6	0.035	107
II	2.00	135	113.6	0.04	120

$$\Delta\sigma/\Lambda \sim 0.1 - 0.3$$

we calculate GWs signals for benchmark points

BAU estimation:

$$m_t(z) = \tfrac{y_t}{\sqrt{2}} H(z) \left(1 + (1+i)\tfrac{S(z)}{\Lambda}\right) \equiv |m_t(z)| e^{i\Theta(z)}$$

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 \tilde{v}_b g_* T} \int dz\, \mu_{B_L} f_{\rm sph}\, e^{-45\,\Gamma_{\rm sph}|z|/(4\tilde{v}_b)}$$

induce observed BAU

Collider and EDM analysis

current tree-level Lagrangian :

$$\mathcal{L}_{Stt} = -\left(\frac{m_t}{\Lambda} + \frac{m_t H}{\Lambda v}\right) S\left(a\bar{t}t + ib\bar{t}\gamma_5 t\right)$$

Effective operators can be obtained by integrating out the massive top-loop.
We use CDE(covariant derivative expansion) for relevant terms: Sgg, Sγγ.

$$\begin{aligned}\mathcal{L}'_{SVV} &= \frac{a\alpha_S}{12\pi\Lambda} S G^a_{\mu\nu} G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda} S G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \\ &+ \frac{2a\alpha_{EW}}{9\pi\Lambda} S F_{\mu\nu} F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda} S F_{\mu\nu}\tilde{F}^{\mu\nu}\end{aligned}$$

loop induced S-gg and S-jj couplings

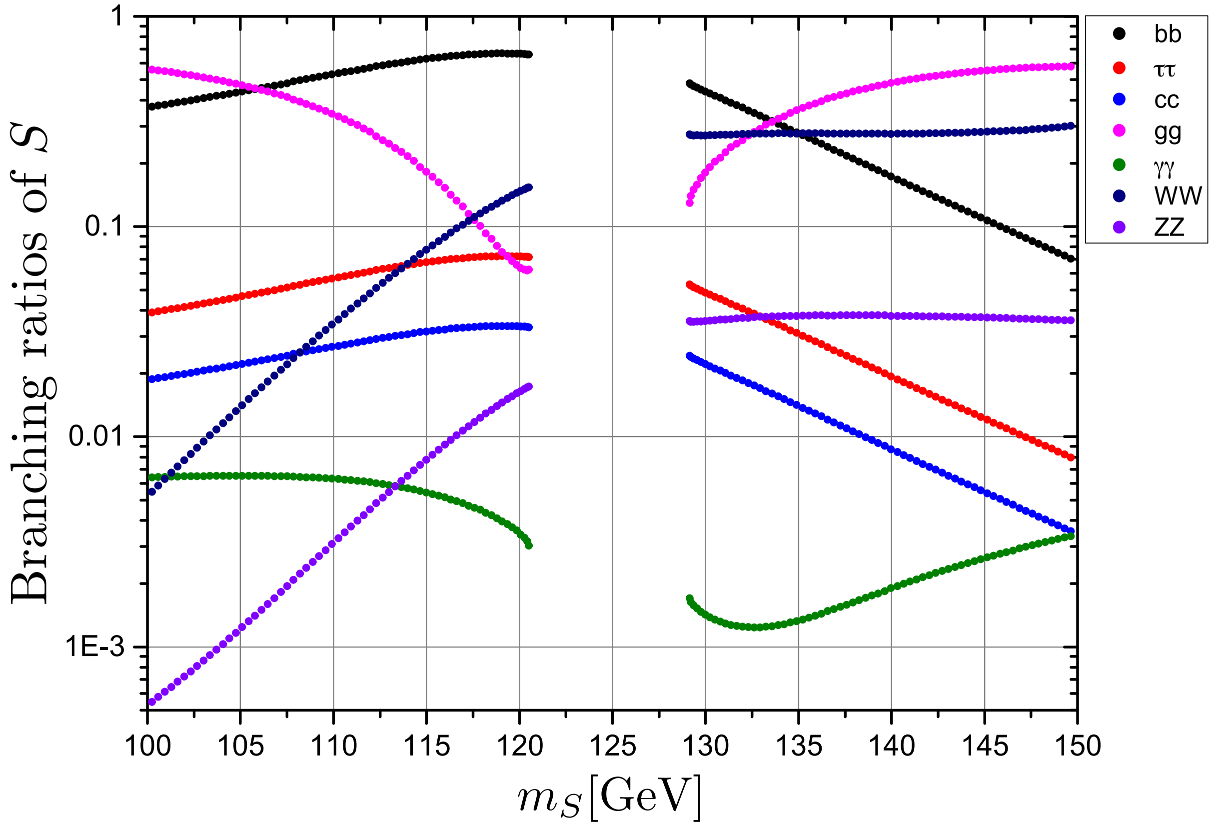
$$\mathcal{L}_{mass} = -\frac{1}{2}\begin{pmatrix} S & H \end{pmatrix}\begin{pmatrix} m^2_{S,\text{tree}} + \Delta m^2_S & \Delta m^2_{HS} \\ \Delta m^2_{HS} & m^2_{H,\text{tree}} + \Delta m^2_H \end{pmatrix}\begin{pmatrix} S \\ H \end{pmatrix}$$

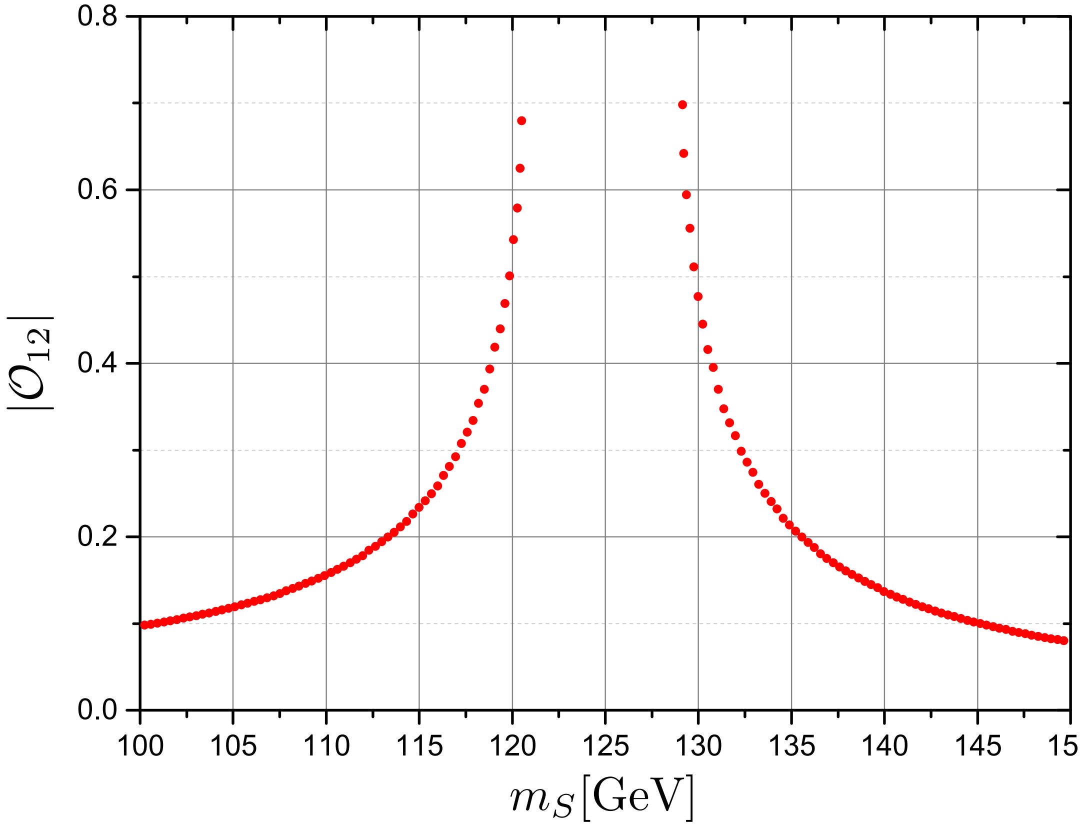
mixing between S and H

$$\Delta m^2_H = \frac{3m_t^4}{4\pi^2 v^2}\,, \quad \Delta m^2_{HS} = a\frac{3m_t^4}{2\pi^2\Lambda v}\,, \quad \Delta m^2_S = (a^2 - b^2)\frac{3m_t^4}{4\pi^2\Lambda^2} \quad \tan\theta = \frac{2\Delta m^2_{HS}}{\sqrt{4(\Delta m^2_{HS})^2 + (m^2_H - m^2_S)^2}}$$

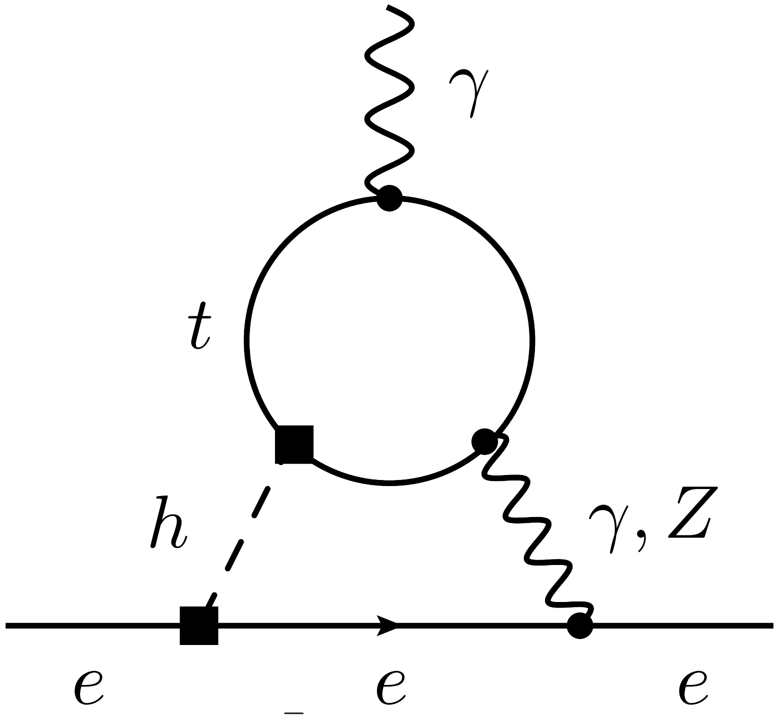
they affect Higgs data, light resonance search, and EDM

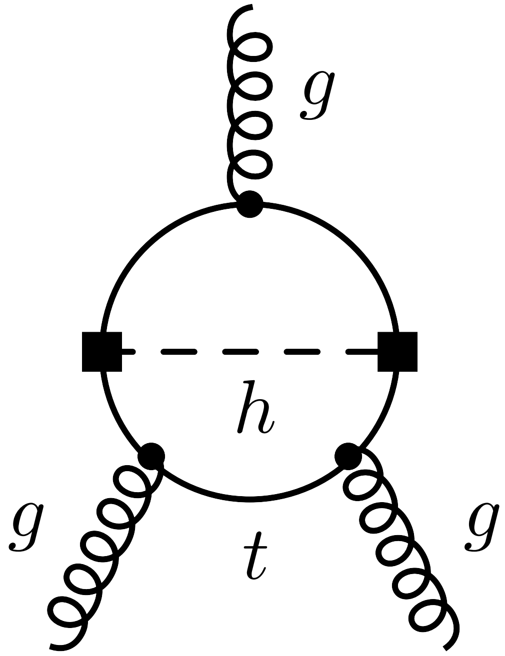
property of S, there is a huge mixing with H, even the HS mass term is small





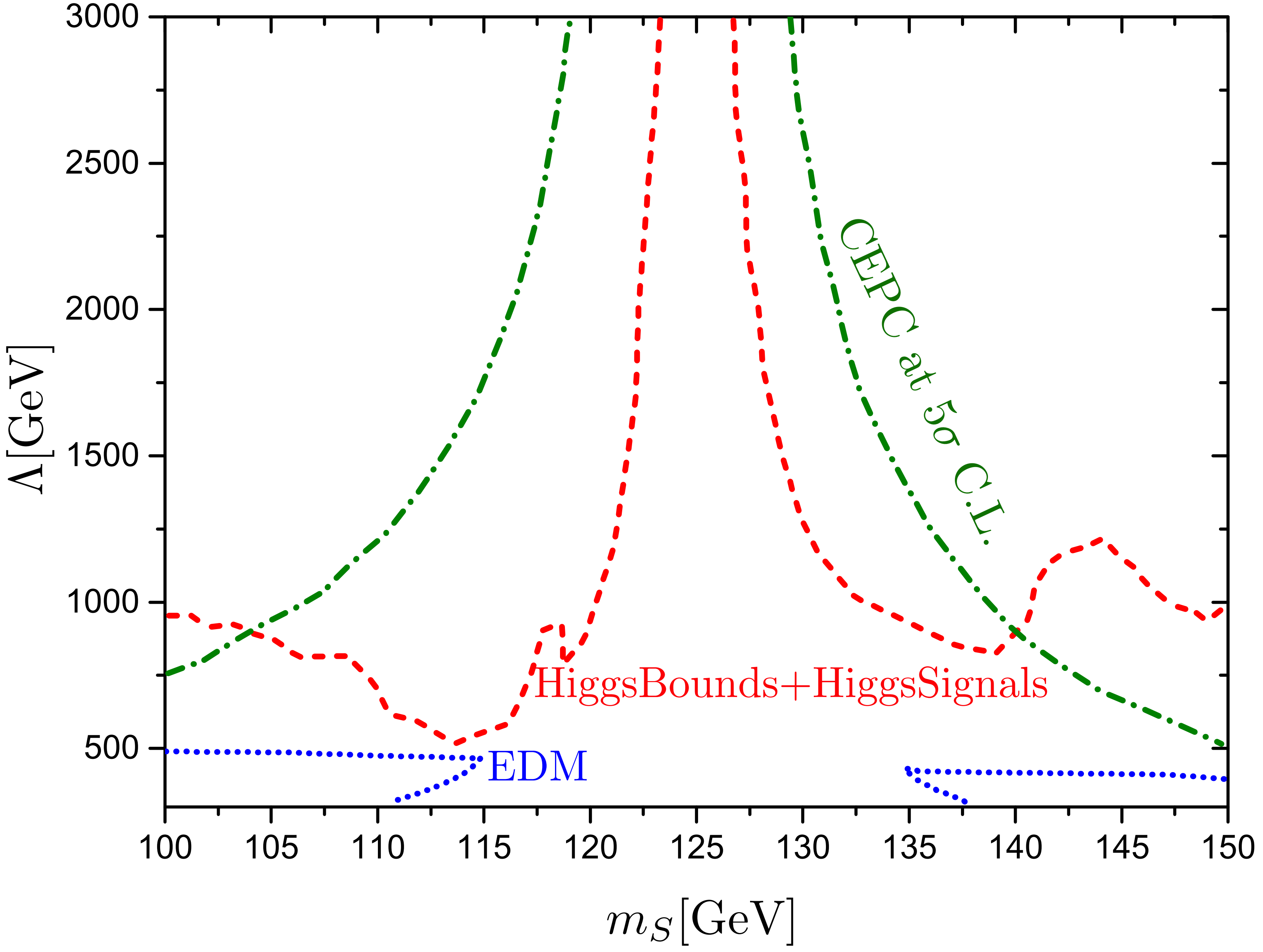
contribution to EDM (neutron EDM)





$|d_e| < 8.7 \times 10^{-29}$ cm · e **(ACME 2014)**

Current limit:



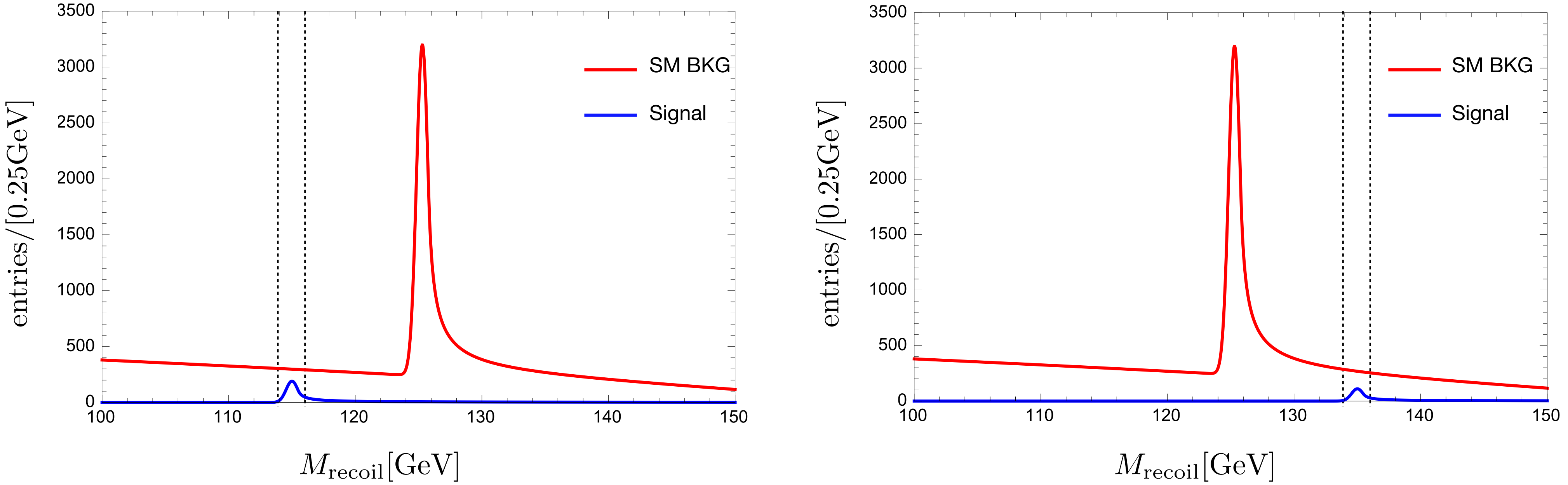
limit from EDM is much weaker than Higgs data

future search

LHC future running: di-photon, 4-leptons, pp-> SH

electron collider(CEPC for example), simple and clear:

direct search at CEPC: recoiled muon pair mass distribution:

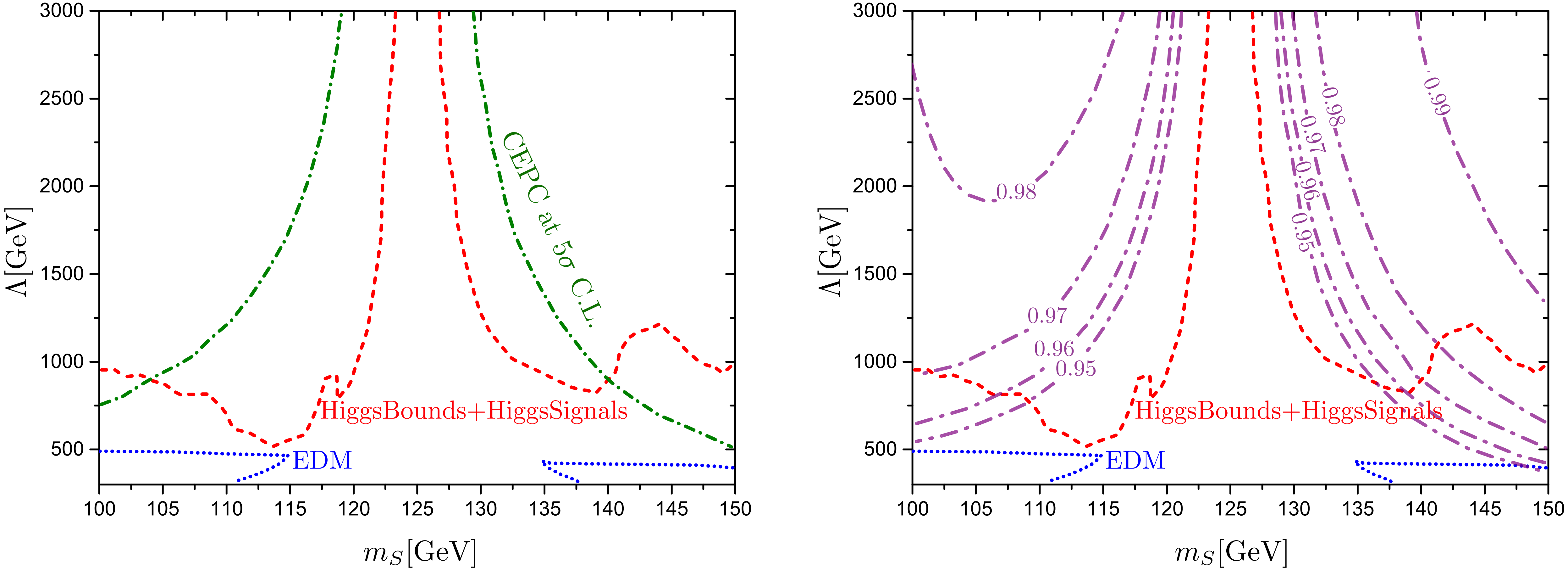


indirect search: ZH Xsection deviation, from mixing and field strength renormalization:

$$\mathcal{Z} = 1 + \frac{\kappa^2 v^2}{32\pi^2 m_H^2}\left(1 - \frac{4m_S^2}{m_H^2}\frac{1}{\sqrt{\frac{4m_S^2}{m_H^2}-1}}\arctan\frac{1}{\sqrt{\frac{4m_S^2}{m_H^2}-1}}\right)$$

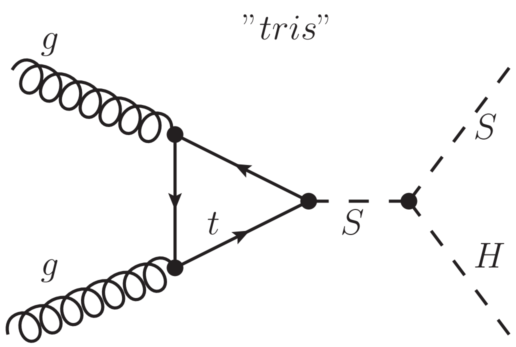
So $\sigma(e^+e^- \to HZ)$ will be rescaled by a factor $|\mathcal{O}_{22}|^2\mathcal{Z}$

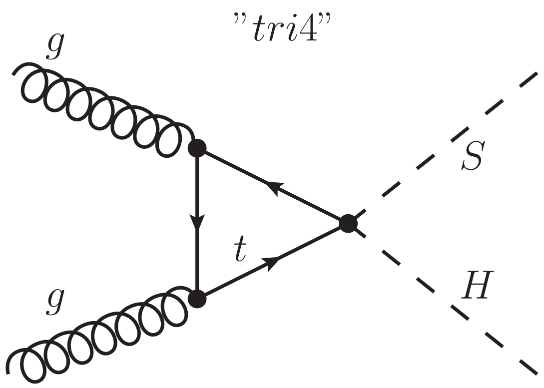
Current Bounds and Future Reach

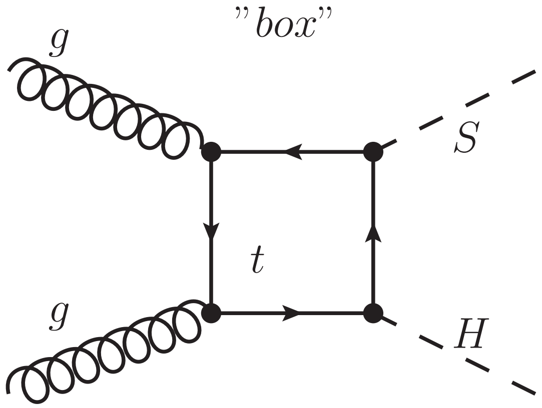


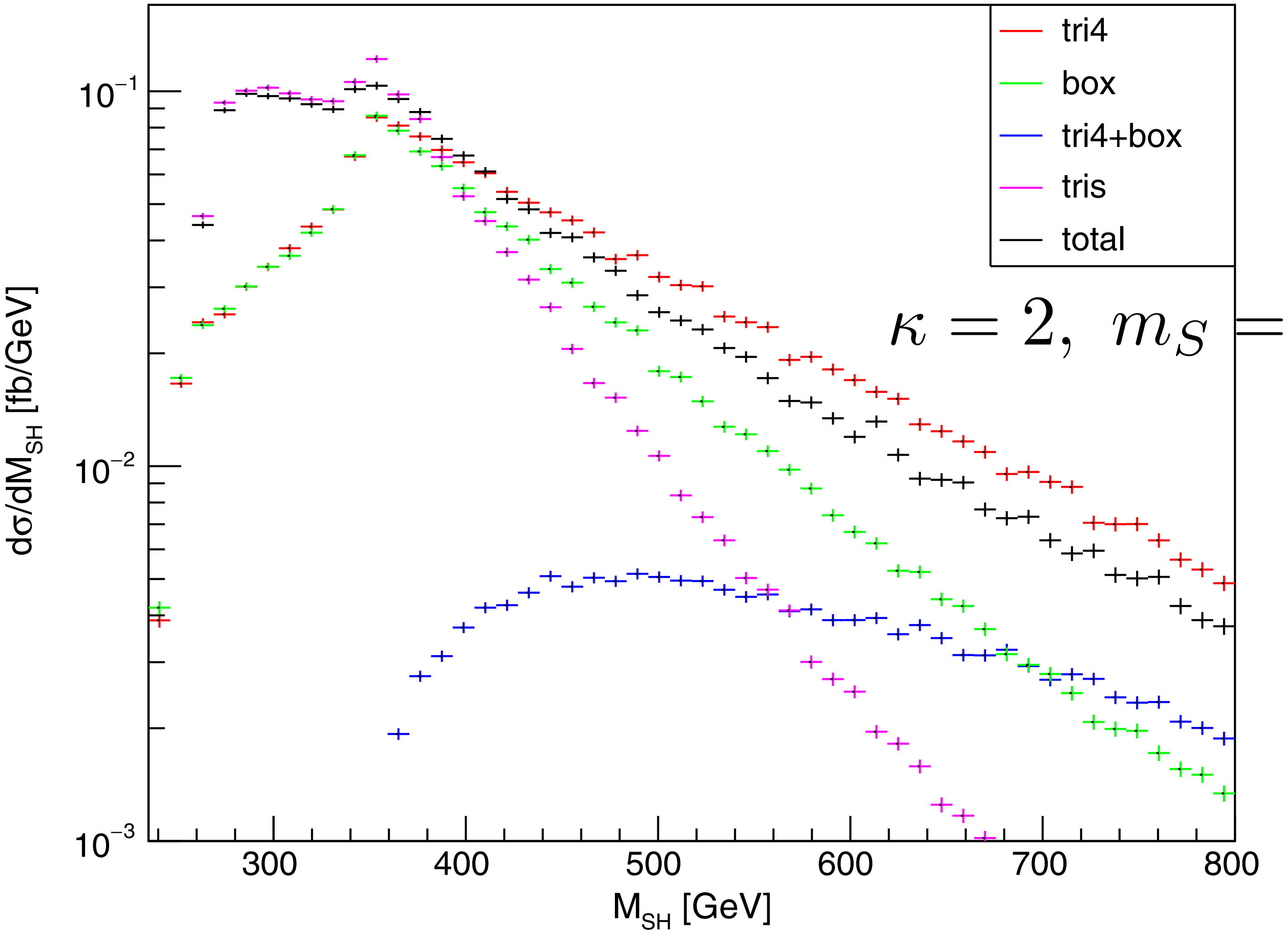
future search

LHC future running: di-photon, 4-leptons, pp-> SH









$$\kappa = 2,\ m_S = 115\ \mathrm{GeV},\ \Lambda = 1\ \mathrm{TeV}\ @14\mathrm{TeV}$$

$$\sigma_{\mathrm{LO}} \sim 25\mathrm{fb}$$

$$\sigma_{HH}^{\mathrm{SM}} \sim 40\ \mathrm{fb}$$

GWs calculation

our input parameters are just α $\tilde{\beta}$ and energy efficiency factors λ

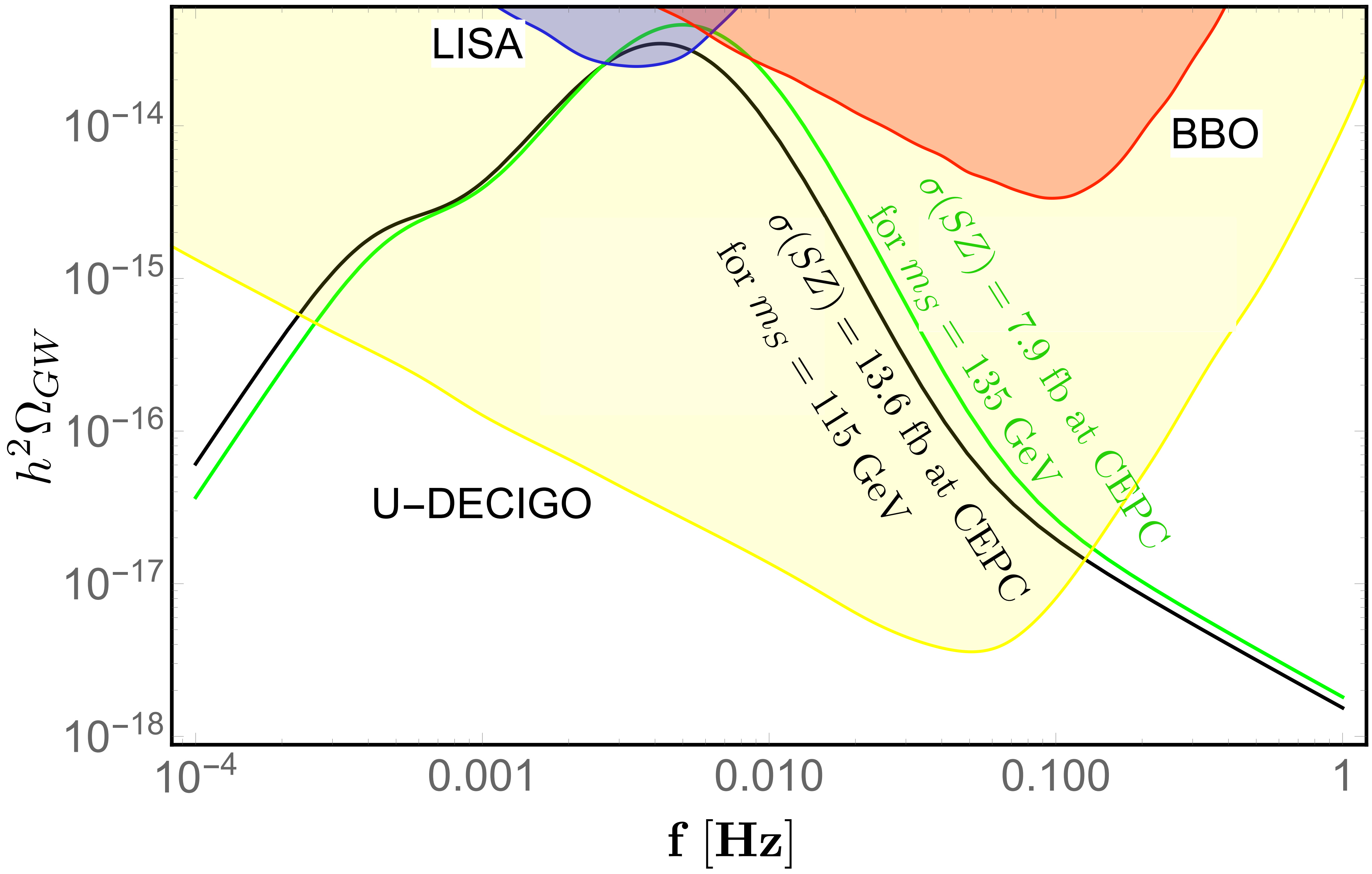
there are 3 kinds of GWs sources: bubble collision, sound wave, turbulence.

$$\Omega_{\rm col}(f)h^2 \simeq 1.67\times10^{-5}\times\left(\frac{0.11v_b^3}{0.42+v_b^2}\right)\tilde{\beta}^{-2}\left(\frac{\lambda_{\rm col}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*(T_N)}\right)^{1/3}\frac{3.8(f/\tilde{f}_{\rm col})^{2.8}}{1+2.8(f/\tilde{f}_{\rm col})^{3.8}},$$

$$\Omega_{\rm sw}(f)h^2 \simeq 2.65\times10^{-6}v_b\tilde{\beta}^{-1}\left(\frac{\lambda_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*(T_N)}\right)^{1/3}\times(f/\tilde{f}_{\rm sw})^3\left(\frac{7}{4+3(f/\tilde{f}_{\rm sw})^2}\right)^{7/2}$$

$$\Omega_{\rm turb}(f)h^2 \simeq 3.35\times10^{-4}v_b\tilde{\beta}^{-1}\left(\frac{\lambda_{\rm turb}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*(T_N)}\right)^{1/3}\times\frac{(f/\tilde{f}_{\rm turb})^3}{(1+f/\tilde{f}_{\rm turb})^{11/3}(1+8\pi f/\mathcal{H}_0)}$$

GWs and Collider signal double check:



Conclusion

We have studied the collider search and GW detection of the EW baryogenesis scenario with a dynamical source of CP violation realized by a two-step phase transition. The VEV of a new scalar field $\langle S\rangle$ evolves with the two-step phase transition, and provides both the SFOPT and sufficient CP violation at early universe. At current time, $\langle S\rangle$ becomes zero at tree level, which makes it easy to evades the severe EDM constraints. Nevertheless, the loop-induced mixing between the scalars S and H can produce abundant collider signals. We have shown possible collider signals at future collider experiments, especially at the lepton colliders. Meanwhile, collider signals and GW surveys could cross check this EW baryogenesis scenario. As a by product, the discussion here suggests potentially interesting collider signals for additional generic light scalar searches near the Higgs mass. The analysis in this work may help to understand the origin of CP violation and EW baryogenesis, furthering the connection between cosmology and particle physics. More systematical study is left to our future study.