Electroweak Baryogenesis and its phenomenology

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Current Situation

Higgs Discovery 2012

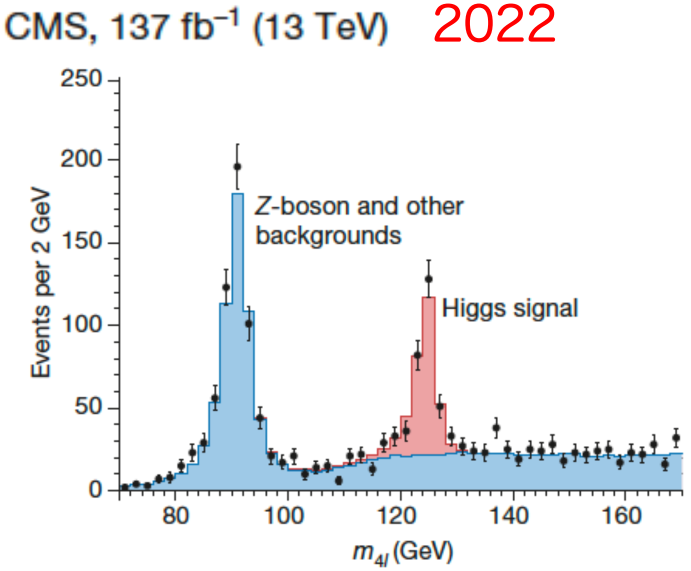
Mass 125 GeV

Spin・Parity

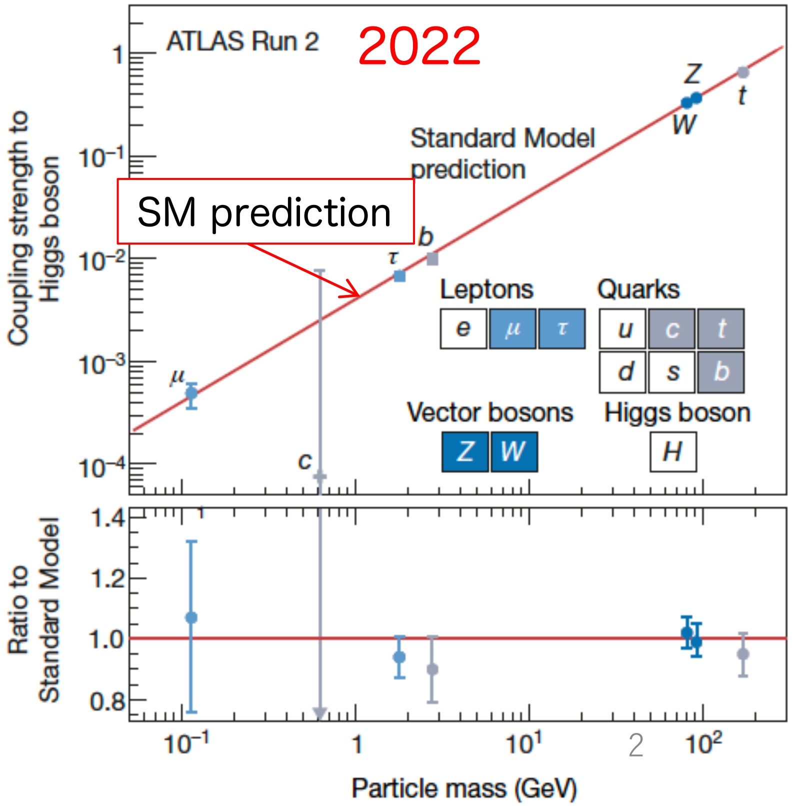
Good agreement with SM prediction

No BSM particle has found up to now

SM is successful



2022



2022

SM prediction

Standard Model:

Lagrangian

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
& +\overline{Q}_L i\gamma^\mu D_\mu Q_L + \overline{L}_L i\gamma^\mu D_\mu L_L \\
& +\bar{u}_R i\gamma^\mu D_\mu u_R + \bar{d}_R i\gamma^\mu D_\mu d_R + \bar{e}_R i\gamma^\mu D_\mu e_R \\
& -\left\{\boxed{Y_u} Q_L \tilde{\Phi} u_R + \boxed{Y_d} Q_L \Phi d_R + \boxed{Y_e} Q_L \Phi e_R + (\mathrm{h.c.})\right\} \\
& +|D_\mu \Phi|^2 - \boxed{V(\Phi)}
\end{aligned}
$$

Yukawa couplings

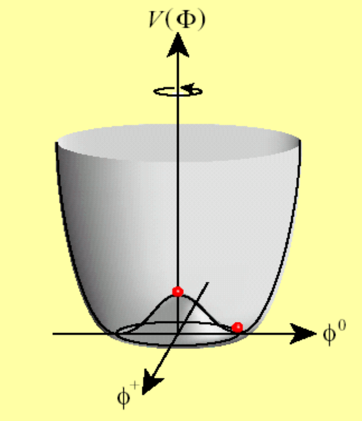
Higgs
Potential

Gauge interactions

Beautiful being
determined by
the gauge principle

EWSB for mass

Yukawa interactions
Kinetic term of Higgs
Higgs potential



No principle, by hand（Dirty）

Perhaps a beautiful principle behind?

Higgs is a probe of new physics!

Motivation to BSM

SM is a good description of the nature around the EW scale, however ….

Problems
- Gravity
- Unification
- Flavor
- No principle in the Higgs sector
  - Hierarchy
  - Strong CP
- Beyond SM phenomena
  - Neutrino oscillation
  - Dark matter
  - Baryon asymmetry
  - …

SM must be replaced by a new more fundamental theory

Higgs sector is a window

The SM Higgs sector: No principle.
The Higgs sector is not well tested yet.

<u>What we have known</u>

Mass 125GeV, SM like couplings with O(10)% accuracy

<u>What we do not know</u>

Nature of the Higgs field, Multiplet Structure, Origin of Yukawa coupling
Higgs potential, Dynamics of EW Symmetry Breaking,
Aspect of EW Phase Transition

Various possibilities for extended Higgs sectors

Understanding the Higgs sector is a promising direct path to New Physics.

Example: 2HDM with softly broken Z2

$$V_{\mathrm{THDM}} = +m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - \underline{m_3^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)}$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2$$
$$+\lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + (\mathrm{h.c.})\right]$$

$$\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + i a_i) \end{bmatrix} \qquad (i = 1, 2)$$

Φ_1 and $\Phi_2 \Rightarrow \underline{h, \quad H,} \quad A^0, H^\pm \oplus$ Goldstone bosons

↑ ↑ ↑charged

CPeven CPodd

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix} \qquad \begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

$$\begin{bmatrix} w_1^\pm \\ w_2^\pm \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} w^\pm \\ H^\pm \end{bmatrix}$$

masses

$$m_h^2 = v^2 \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2}\sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\mathrm{soft}}^2}\right),$$
$$m_H^2 = M_{\mathrm{soft}}^2 + v^2 (\lambda_1 + \lambda_2 - 2\lambda) \sin^2\beta \cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\mathrm{soft}}^2}\right),$$
$$m_{H^\pm}^2 = M_{\mathrm{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2} v^2,$$
$$m_A^2 = M_{\mathrm{soft}}^2 - \lambda_5 v^2.$$

M_{soft}: soft breaking scale

$$\frac{v_2}{v_1} \equiv \tan\beta$$

$M_{\mathrm{soft}} \left(= \frac{m_3}{\sqrt{\cos\beta \sin\beta}}\right)$:

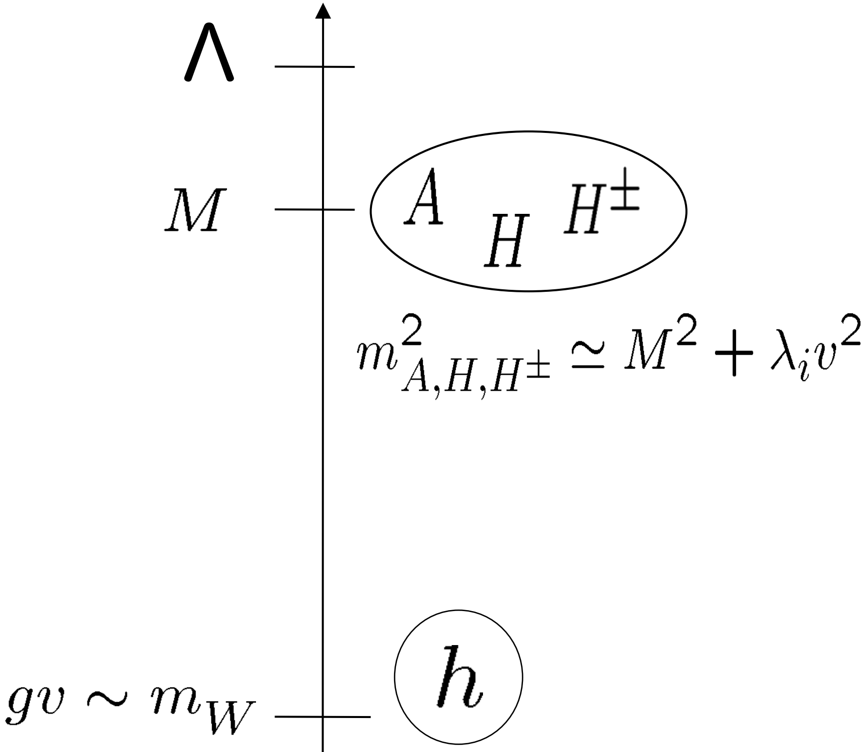
soft-breaking scale

of the discrete symm.

How SM-like is realized?

Λ : Cutoff

M : Mass scale irrelevant to VEV

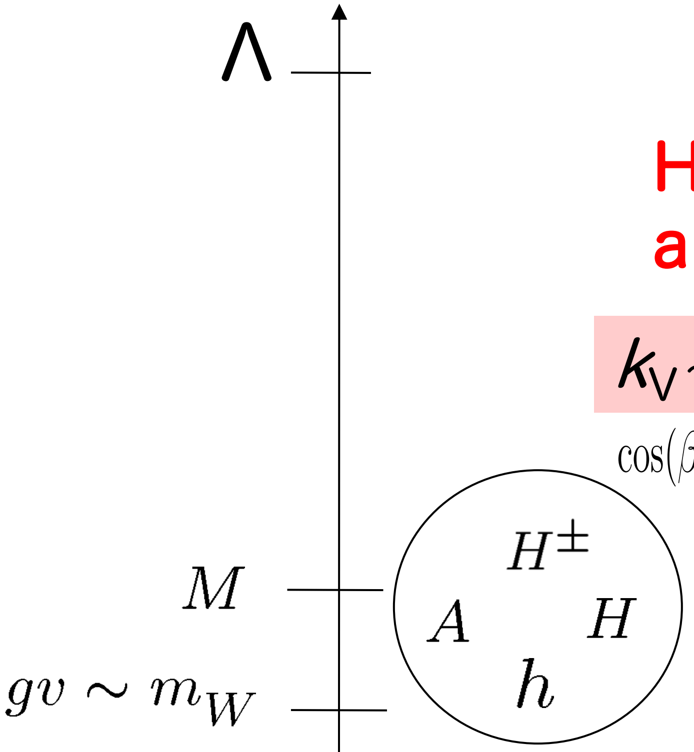


$$m^2_{A,H,H^\pm} \simeq M^2 + \lambda_i v^2$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM

Decoupling



Higgs alignment

$\kappa_V \sim 1$

$\cos(\beta - \alpha) \sim 0$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{nonSM}} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

Effective Theory is an extended Higgs sector

Alignment without decoupling

In this talk

- We discuss an example in which extension of the Higgs sector can solve the problem of BAU.
- EW Baryogenesis
- Viable scenarios for EW Baryogenesis in the aligned 2HDM, and their phenomenology

EW baryogenesis

Baryon Asymmetry of Universe (BAU)

Abundance of Baryon number

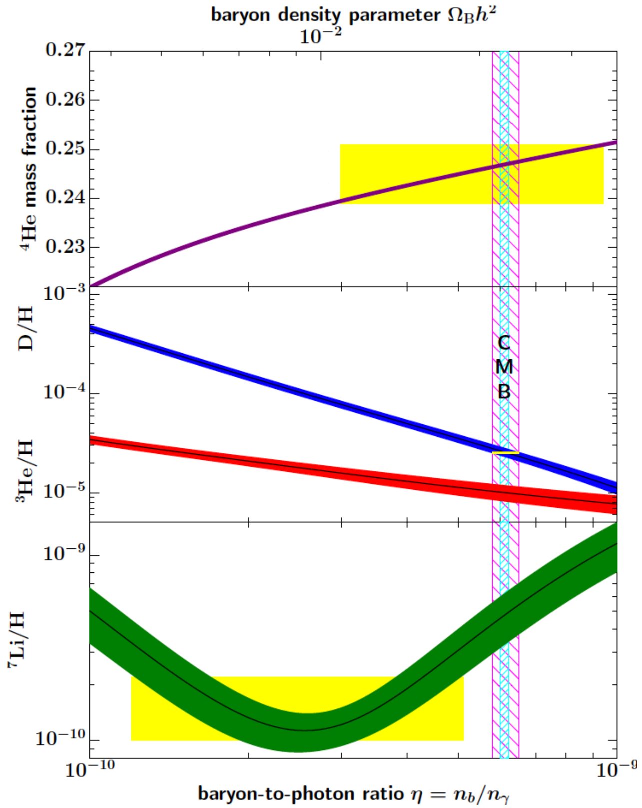
$$\boxed{\eta_B \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}}$$

- BBN

$$\eta^{\mathrm{BBN}} = (5.8 - 6.5) \times 10^{-10}$$

- CMB

$$\eta^{\mathrm{CMB}} = (6.105 \pm 0.055) \times 10^{-10} \qquad 95\%\mathrm{CL}$$



Particle Data Group 2020

SM cannot explain BAU

Necessity for a reasonable explanation of BAU by new physics

EW Baryogenesis

Sakharov Conditions

Kuzmin, Ruvakov, Shaposhnikov (1985)

1） B non-conservation ➡ Sphaleron transition at high T

2） C and CP violation ➡ C violation (SM is a chiral theory)
CP in extended Higgs sectors

3） Departure from thermal equilibrium ➡ EWPT is strongly 1st OPT

SM cannot satisfy them

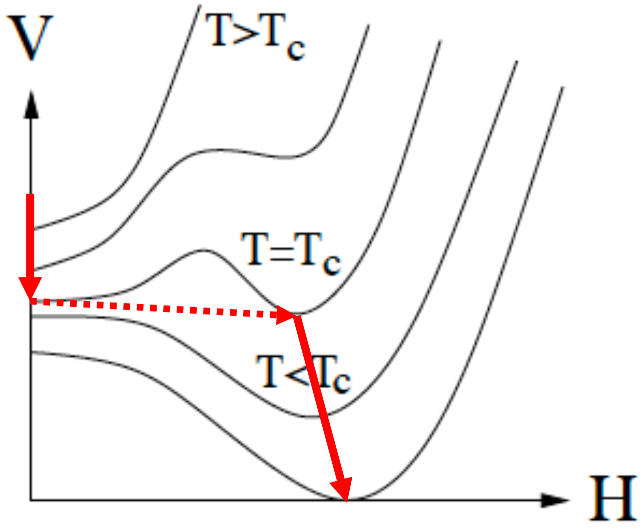
CPV in SM Kobayashi-Maskawa phase not enough

1st OPT not realized in SM Michela D'Onofrio, Kari Rummukainen (2016)

Extension of the Higgs sector is required

Higgs Physics ⇄ Testable

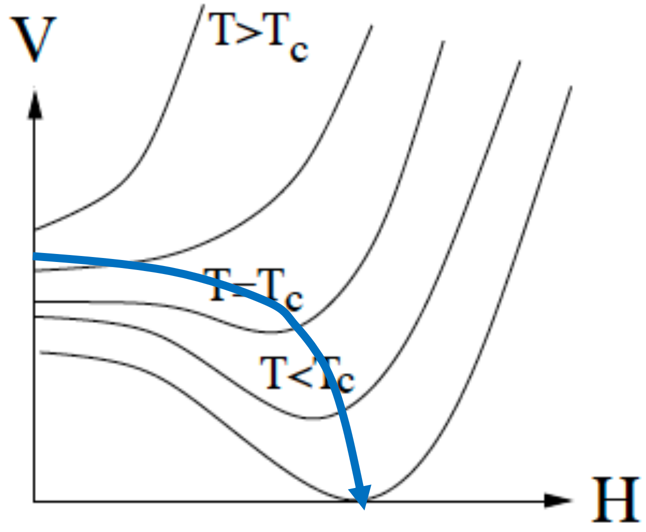
Phase Transition



1st OPT

VEV is discrete

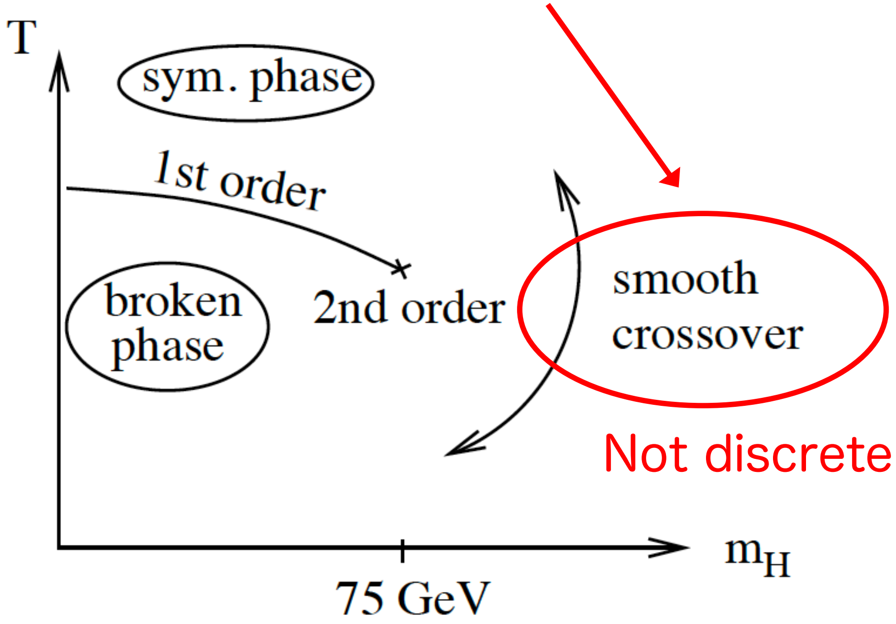
Bubble created



2nd OPT

VEV is continuous

SM



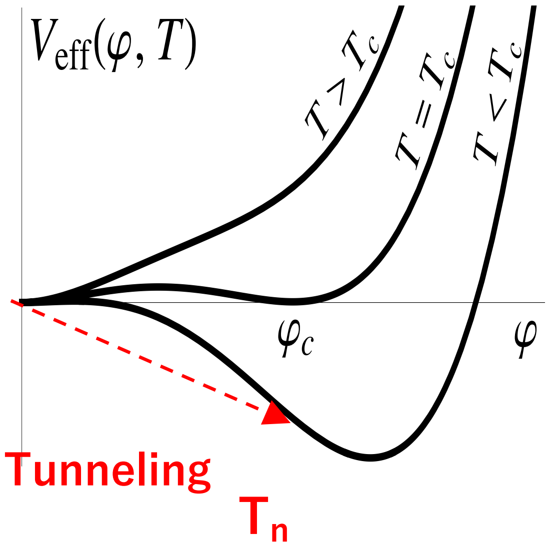
Not discrete

Figure by J. Cline

BSM necessary
to realize 1st OPT

EW Baryogenesis

- 1st OPT ⇒ bubbles of the broken phase



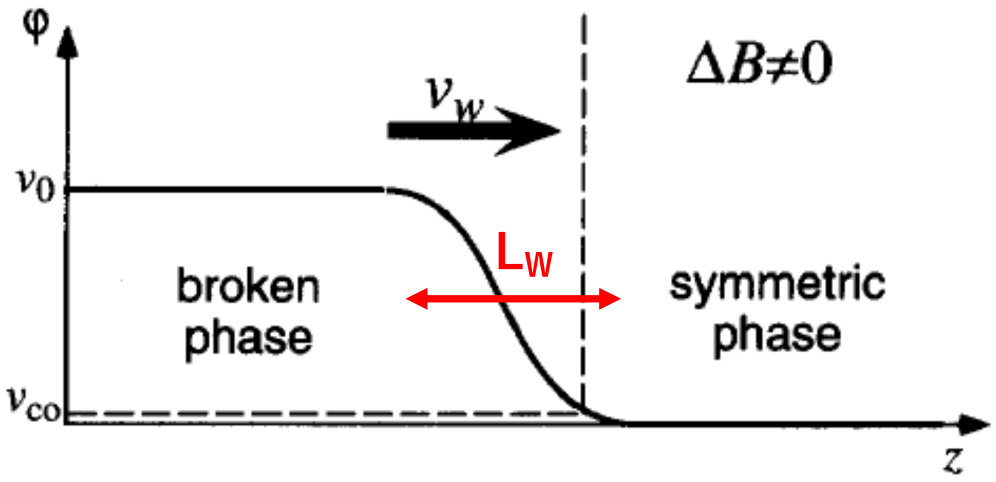
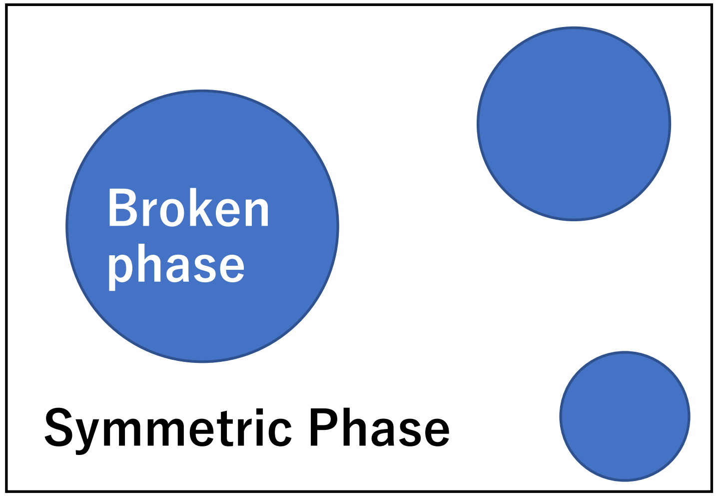
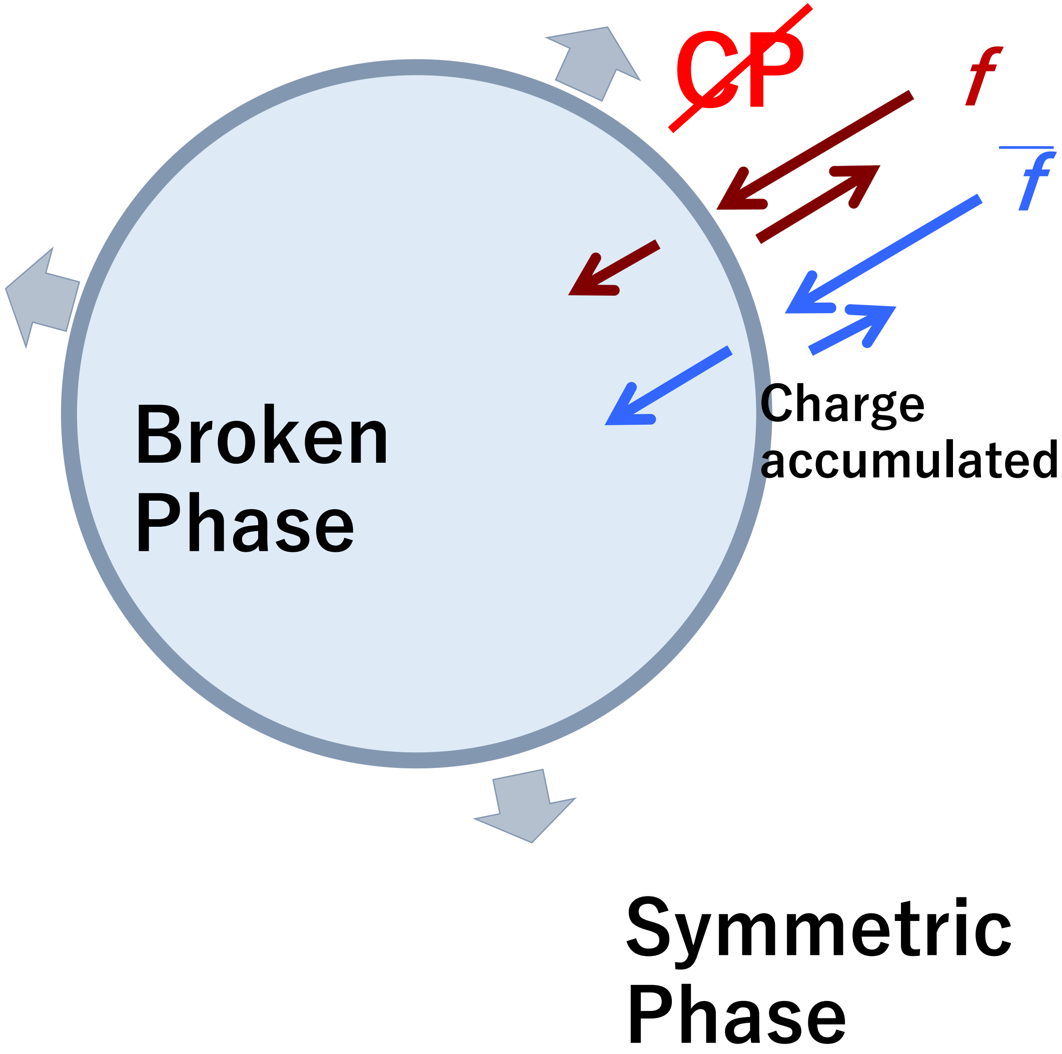


Figure by Funakubo 1996



EW Baryogenesis

- 1^{st} OPT ⟹ bubbles of the broken phase
- CPV ⟹ charge flow around the wall



$\cancel{CP}$

f

$\bar{f}$

Charge accumulated

Broken Phase

Symmetric Phase

Dirac equation solved by WKB method

Cline, Joyce, Kainulainen 2000

Boltzmann equation

$$(\partial_t + \boldsymbol{v}_g \cdot \partial_{\boldsymbol{x}} + \boldsymbol{F} \cdot \partial_{\boldsymbol{p}}) f_i = C[f_i, f_j, \ldots]$$

Different sign between particle and anti-particle

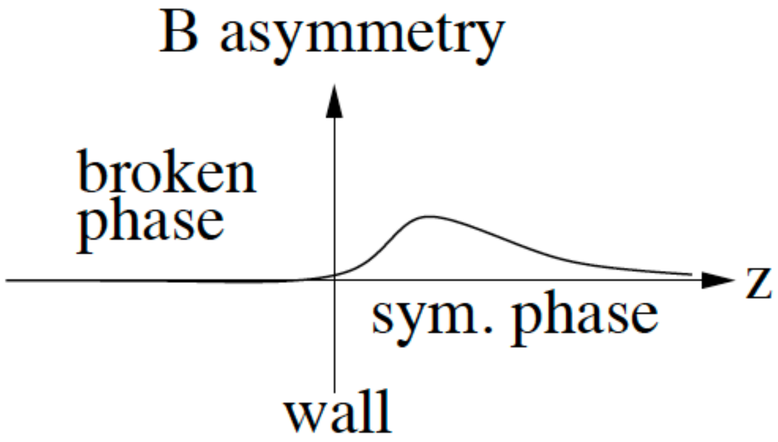
$$f_i = \frac{1}{e^{\beta[\gamma_w(E_i + v_w p_z) - \mu_i]} \pm 1} + \delta f_i$$

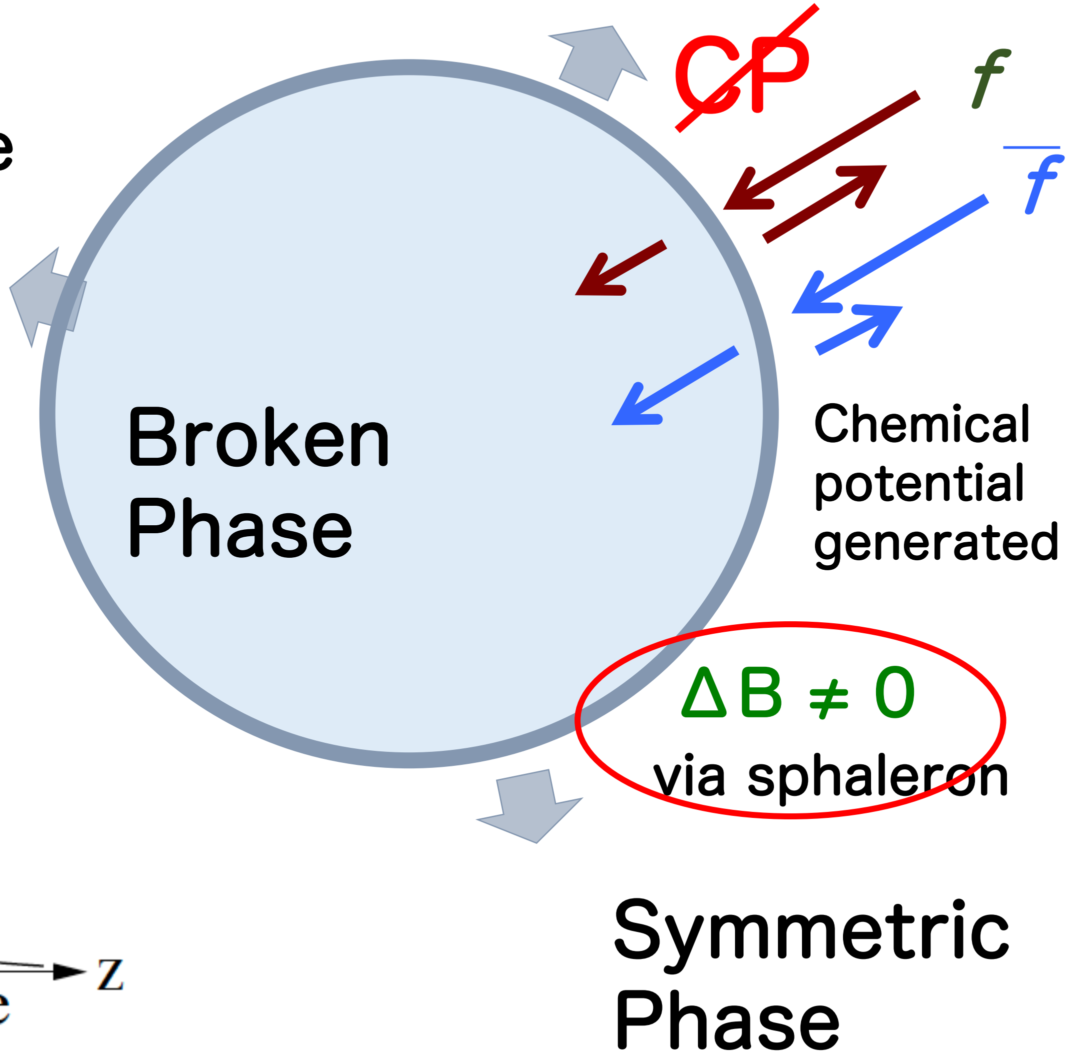
EW Baryogenesis

- 1st OPT ⇒ bubbles of the broken phase
- CPV ⇒ charge flow around the wall
- By accumulated charge in symmetric phase, baryon number is generated via sphaleron

Chemical potential

$$\boxed{\dot{n}_B \simeq -\frac{\mu_B \Gamma_{\rm sph}}{T}}$$

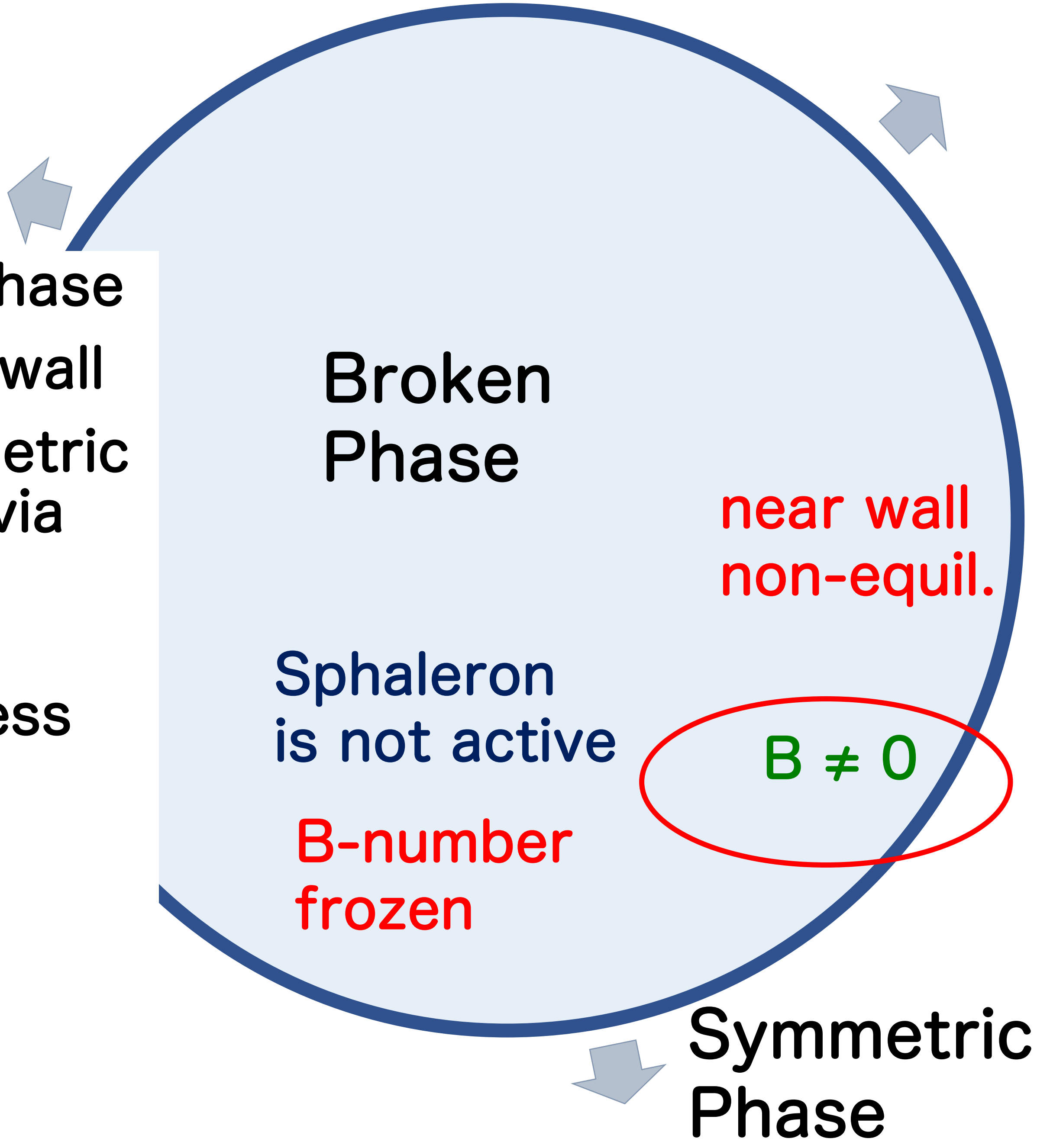




EW Baryogenesis

- 1st OPT ⇒ bubbles of the broken phase
- CPV ⇒ charge flow around the wall
- By accumulated charge in the symmetric phase baryon number is generated via sphaleron
- In broken phase, produced baryon number is frozen, if sphaleron process decouples

BAU $\boxed{\eta \sim 10^{-10}}$



Broken Phase

near wall non-equil.

Sphaleron is not active

$B \neq 0$

B-number frozen

Symmetric Phase

Strongly first order phase transition

Shpaleron transition should quickly decouple
in the broken phase to avoid wash out

Sphaleron Rate in Broken Phase

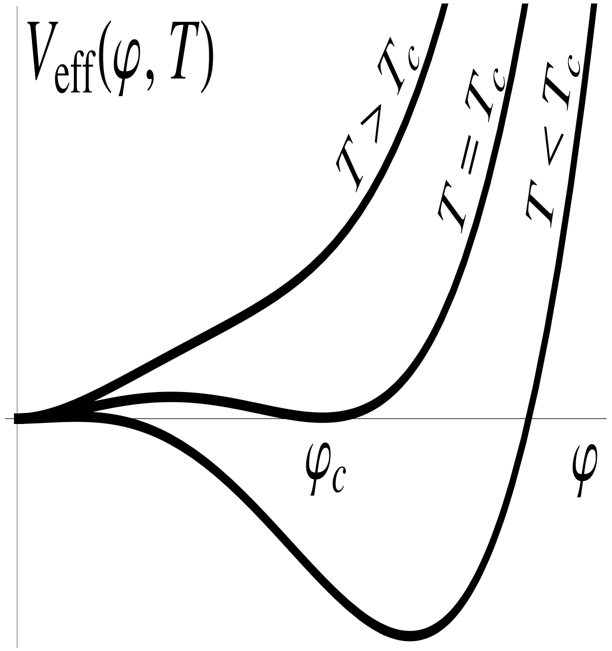
$$\Gamma_{sph} < H$$

Rate of expansion (Hubble at Tc)

$$\frac{\varphi_c}{T_c} \gtrsim 1$$

Condition of
Strongly first OPT

$\Gamma_{sph} \sim e^{-E_{sph}/T_c}$
$\sim e^{-\alpha' \phi_c/T_c}$



Kuzmin, et al.

Physics of Higgs potential

Extended Higgs can satisfy the condition

Effective Potential
at finite T (HTE)

$$\boxed{V_{\rm eff}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 \underline{- ET\varphi^3} + \frac{\lambda_T}{4}\varphi^4 + \cdots}$$

SM

The condition
cannot be satisfied

$$\frac{\varphi_c}{T_c} = \frac{2E}{\lambda_T} \simeq \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1$$

Extended Higgs: Strong 1st OPT possible due to quantum effect

$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \underline{\sum_\Phi m_\Phi^3\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\left(1 + \frac{3M^2}{2m_\Phi^2}\right)}\right\} > 1$$

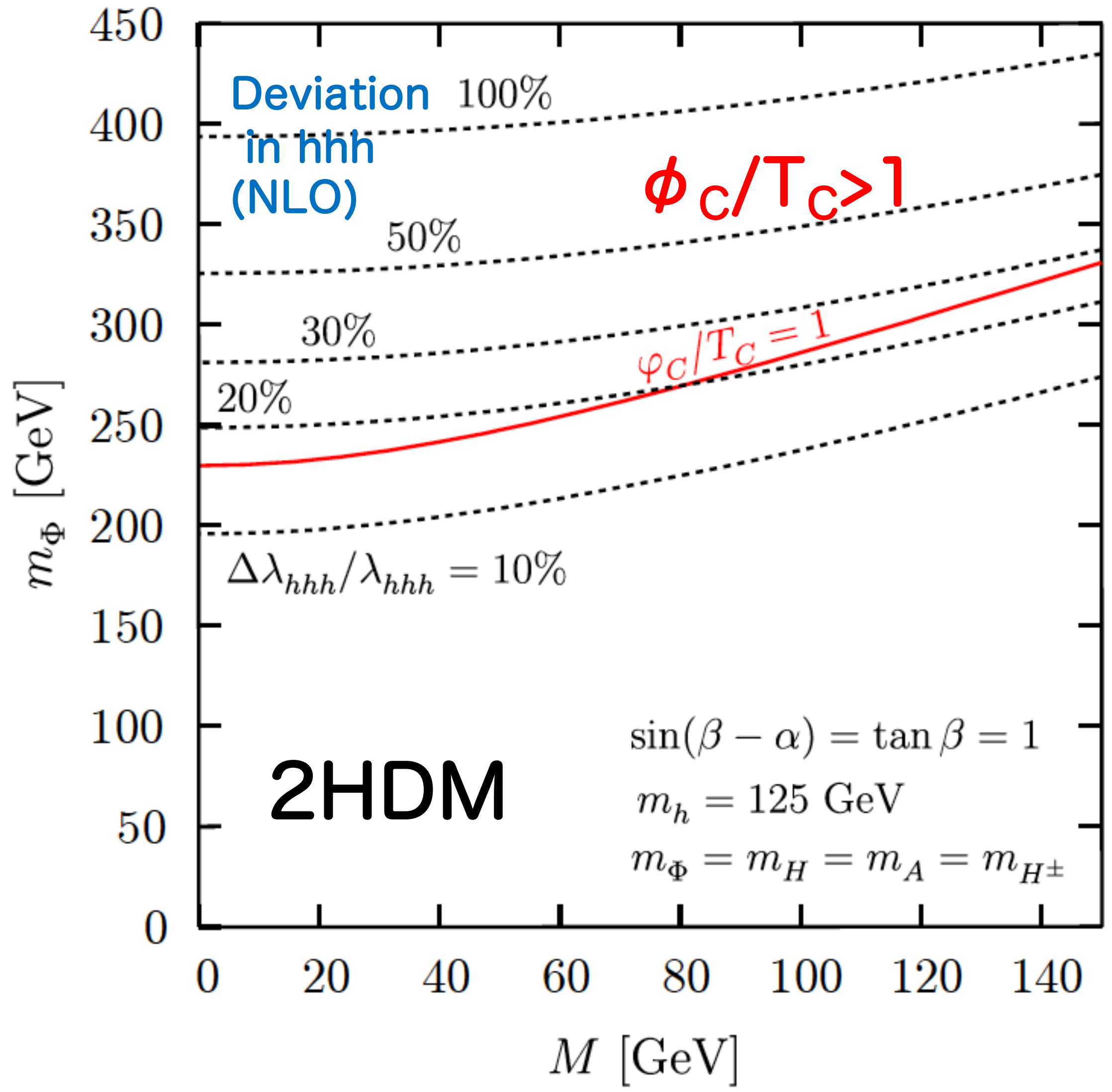
Quantum effects of Φ
(= H, A, H$^+$, …)

Prediction: Deviation in the hhh coupling

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v^2}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \underline{\sum_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3}\right\} > \lambda_{hhh}^{SM}$$

C. Grojean, G. Servant, J. Wells, 2005

SK, Y. Okada, E. Senaha, 2005



SK, Y. Okada, E. Senaha, 2005

2 loop correction to λ_{hhh} in 2HDM

J. Braathen, SK, 2020

A Model for EW baryogenesis

Many possibilities

- Variation of extended Higgs sector
  - Singlets
  - Doublets
  - Others

- How to introduce CPV (complex phases)
  - Yukawa coupling
  - Higgs potential

- How to realize 1st OPT
  - 1 step, 2 step, …

Model building without contradicting the data

LEP, Tevatron, LHC

EDMs

Flavor Experiments

Simple model for EW Baryogenesis:

2HDM

Fromme, Huber and Seniuchi, JHEP 11 (2006);
Cline, Kainulainen and Trott, JHEP 11 (2011); Dorsch et al. JCAP 05 (2017);
Chiang, Fuyuto, Senaha (2016); Fuyuto, Hou, Senaha (2018), ⋯ ⋯

Higgs alignment SM like h No-mixing $\sin(\beta-\alpha)=1$

Additional bosons $H_2, H_3, H^{\pm}$ Rich phenomenology

Sakharov condition

- CPV in Higgs-coupling (and Yukawa coupling)
- Strongly 1st OPT due to quantum effect

Viable model for EW Baryogenesis
Testable at current and future experiments

SK, M. Kubota, K. Yagyu (2020)

K. Enomoto, SK, Y. Mura (2021)

Aligned 2HDM (A2HDM)

General 2HDM

$$V = -\mu_1{}^2(\Phi_1{}^\dagger\Phi_1) - \mu_2{}^2(\Phi_2{}^\dagger\Phi_2) - \left(\mu_3{}^2(\Phi_1{}^\dagger\Phi_2) + h.c.\right)$$
$$+\frac{1}{2}\lambda_1(\Phi_1{}^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2{}^\dagger\Phi_2)^2 + \lambda_3(\Phi_1{}^\dagger\Phi_1)(\Phi_2{}^\dagger\Phi_2) + \lambda_4(\Phi_2{}^\dagger\Phi_1)(\Phi_1{}^\dagger\Phi_2)$$
$$+\left\{\left(\frac{1}{2}\lambda_5\Phi_1{}^\dagger\Phi_2 + \lambda_6\Phi_1{}^\dagger\Phi_1 + \lambda_7\Phi_2{}^\dagger\Phi_2\right)\Phi_1{}^\dagger\Phi_2 + h.c.\right\}, \quad (\mu_3, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C})$$

Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

$$m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$$

To satisfy LHC data、avoid mixing between *h* and heavy Higgs bosons: $\lambda_6 \sim 0$

Mass matrix of neutral scalar bosons

$$\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 & \mathrm{Re}[\lambda_6] & -\mathrm{Im}[\lambda_6] \\ \mathrm{Re}[\lambda_6] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + \mathrm{Re}[\lambda_5]) & \cancel{-\frac{1}{2}\mathrm{Im}[\lambda_5]} \\ -\mathrm{Im}[\lambda_6] & \cancel{-\frac{1}{2}\mathrm{Im}[\lambda_5]} & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - \mathrm{Re}[\lambda_5]) \end{pmatrix} = \begin{pmatrix} m_h^2 & 0 & 0 \\ 0 & m_{H_2}^2 & 0 \\ 0 & 0 & m_{H_3}^2 \end{pmatrix}$$

rephasing

Higgs alignment

$\arg[\lambda_7] \equiv \theta_7$

Avoiding FCNC: Yukawa alignment is imposed by hand $y_f^2 = \zeta_f y_f^1 \quad (f = u, d, e)$

$$\mathcal{L}_y = -\overline{Q}_L \frac{\sqrt{2}M_u}{v}\left(\tilde{\Phi}_1 + \zeta_u^*\tilde{\Phi}_2\right)u_R - \overline{Q}_L \frac{\sqrt{2}M_d}{v}\left(\Phi_1 + \zeta_d\Phi_2\right)d_R - \overline{L}_L \frac{\sqrt{2}M_e}{v}\left(\Phi_1 + \zeta_e\Phi_2\right)e_R + h.c.$$

Yukawa alignment

Pich and Tuzon (2009)

Higgs potential $\arg[\lambda_7] \equiv \theta_7$

Yukawa couplings $\arg[\zeta_u] \equiv \theta_u$, $\arg[\zeta_d] \equiv \theta_d$, $\arg[\zeta_e] \equiv \theta_e$

Constraint from eEDM

$$\boxed{H_{\rm EDM} = -d_f \frac{\vec{S}}{|\vec{S}|}\cdot \vec{E}}$$

T violation if ≠0 ⇄ CPV (CPT theorem)

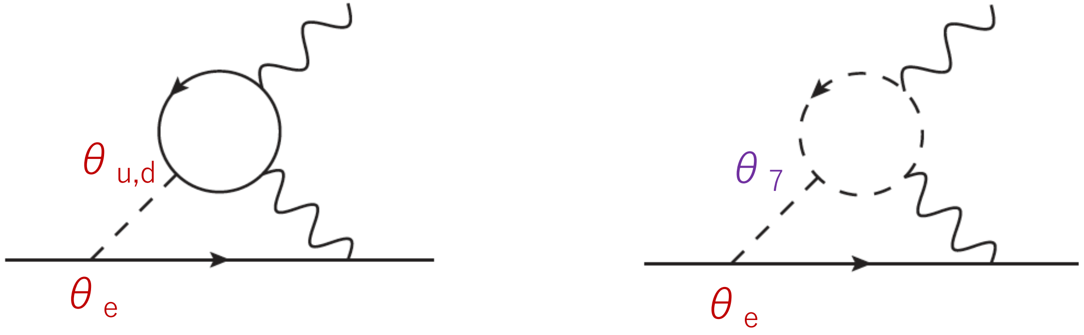
$$\mathcal{L}_{\rm EDM} = -\frac{d_f}{2}\bar{f}\sigma^{\mu\nu}(i\gamma^5)fF_{\mu\nu}$$

$$\boxed{|d_e| < 1.1\times 10^{-29} e\ \mathrm{cm}}$$

ACME(2018)

Barr-Zee type diagrams

$d_e \simeq$



Aligned 2HDM

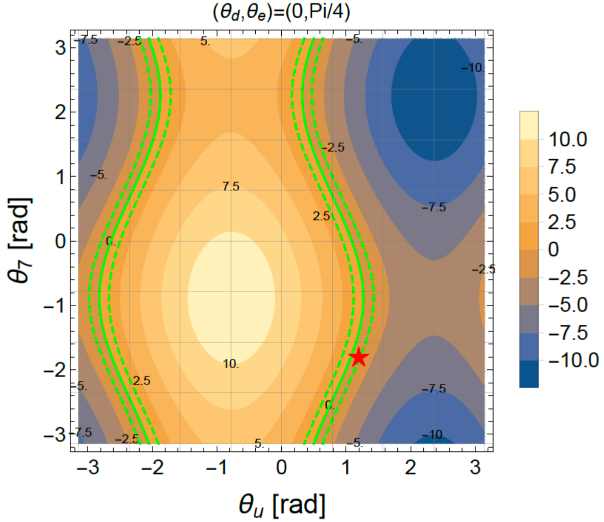
Higgs potential $\arg[\lambda_7] \equiv \theta_7$

Yukawa couplings $\arg[\zeta_u] \equiv \theta_u,\ \arg[\zeta_d] \equiv \theta_d,\ \arg[\zeta_e] \equiv \theta_e$

eEDM data can be satisfied by destructive interference of diagrams.

$$d_f = d_f(\text{fermion}) + d_f(\text{Higgs}) + d_f(\text{gauge})$$

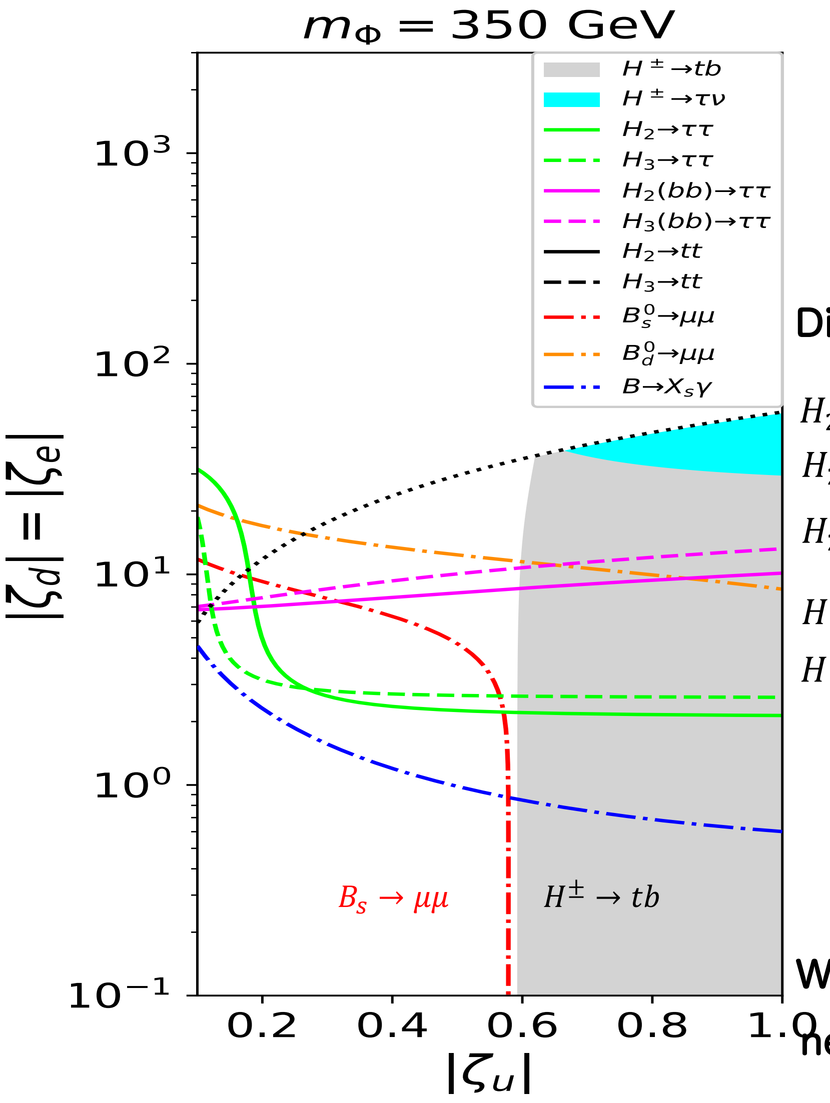
Other data： LEP (S, T, U), flavor experiments、LHC, …



S.K., M. Kubota, K. Yagyu (2022)

Constraints on the model

K. Enomoto, SK, Y. Mura, arXiv: 2207.00060



$m_\Phi \equiv m_{H_2} = m_{H_3} = m_{H^\pm}$

Direct search exp.

$H_{2,3} \to \tau\tau$	Aad *et al.* [ATLAS] Phys. Rev. Lett. 125 (2020)
$H_{2,3}(bb) \to \tau\tau$	Aaboud *et al.* [ATLAS] Eur. Phys. J. C 78 (2018); Sirunyan *et al.* [CMS] JHEP 04 (2020)
$H_{2,3} \to tt$	
$H^\pm \to tb$	Aad *et al.* [ATLAS] JHEP 06 (2021)
$H^\pm \to \tau\nu$	Sirunyan *et al.* [CMS] JHEP 07 (2019)

Flavor exp.

$B_d \to \mu\mu$
$B_s \to \mu\mu$
$B \to X_s\gamma$

Amhis *et al.* [HFLAV] Eur. Phys. J. C 81 (2021); Haller *et al.* Eur. Phys. J. C 78 (2018); Aaboud *et al.* [ATLAS] JHEP 04 (2019); Sirunyan *et al.* [CMS] JHEP 04 (2020); Aaij. *et al.* [LHCb] Phys. Rev. D 105 (2022)

ζ_u is important for BAU and we found $|\zeta_u| \lesssim 0.6$

We also considered,

neutron EDM, STU parameters, perturbative unitarity, vacuum stability

Evaluation of BAU

L_w : wall width

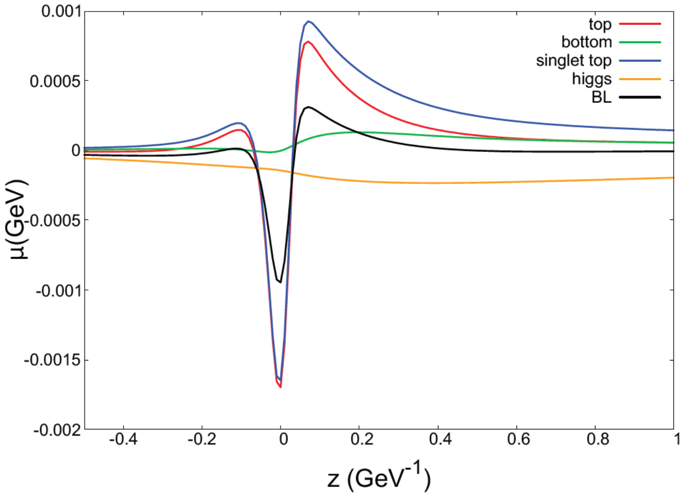
T_n : nucleation temp

$$M = 30\ \text{GeV},\quad \lambda_2 = 0.1,\quad |\lambda_7| = 0.8,\quad \theta_7 = -0.9,$$

$$|\zeta_u| = |\zeta_d| = |\zeta_e| = 0.18,\quad \theta_u = \theta_d = -2.7,\quad \delta_e = -0.04$$

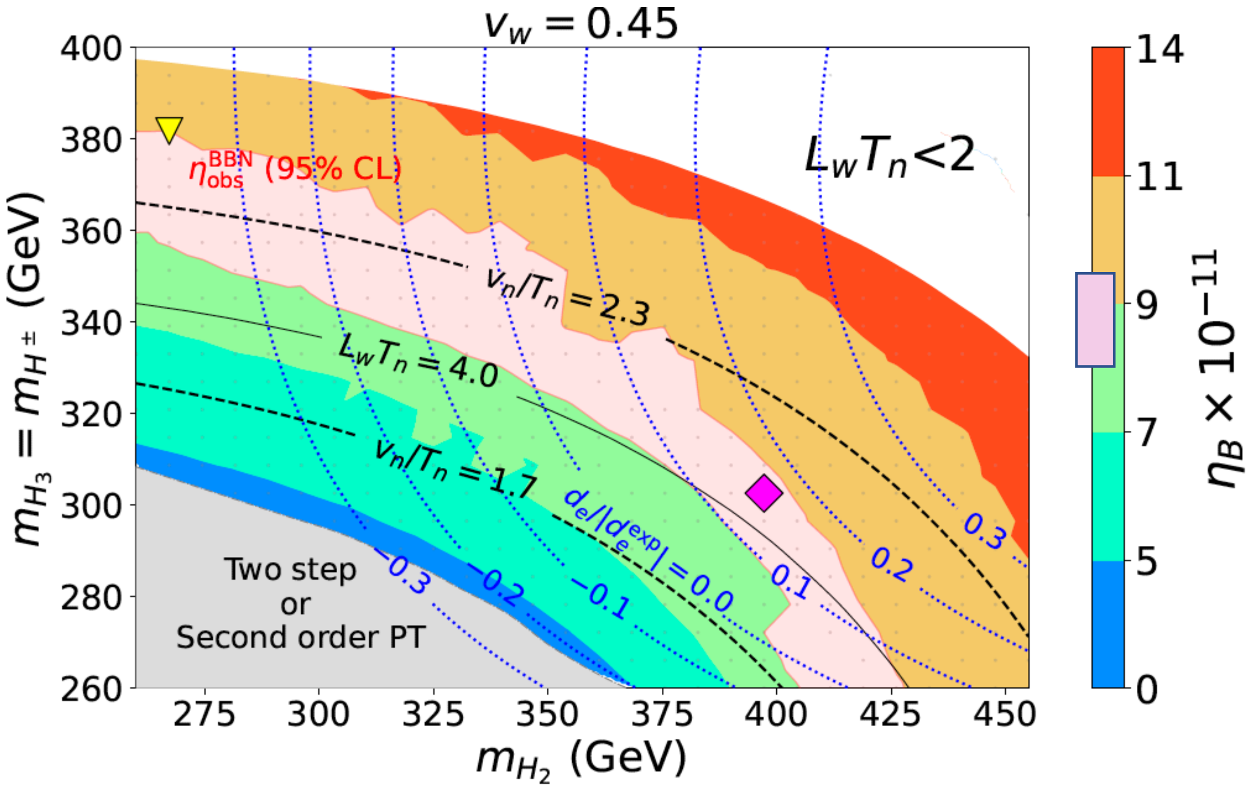
Aligned 2HDM

Chemical potential



Top transport scenario

K. Enomoto, SK, Y. Mura, arXiv: 2207.00060



In symmetric phase, B is produced by sphaleron

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 v_w g_* T}\int_0^\infty dz\ \mu_{B_L} f_{\rm sph} e^{-45\Gamma_{\rm sph} z/(4v_w)}$$

BAU data reproduced（pink region)

Frozen at the Broken phase

$$\eta_{obs}^{\rm BBN} \equiv \frac{n_B}{s} = 8.2\text{–}9.2 \times 10^{-11}$$

$$s = 0.74 n_\gamma$$

Cline, Kainulainen, ⋯

Test of model for EW baryogenesis

Test of the model for EW Baryogenesis

1st OPT (Relatively universal)

Triple Higgs boson coupling (hhh)

Gravitational Waves

PBHs may also be used

K. Hashino, SK, T. Takahashi, 2021

HL-LHC, ILC etc (E> 500 GeV), …
LISA, DECIGO, BBO, …
Subaru HSC, Ogle, PRIME, Roman, …

CPV (Strongly depends on models)

Various EDM (e, n, …)

Flavor experiments

High Energy Colliders

ACME, …
LHCb, Belle, …
HL-LHC, ILC, FCC, CEPC, CLIC, …

Extended Higgs itself

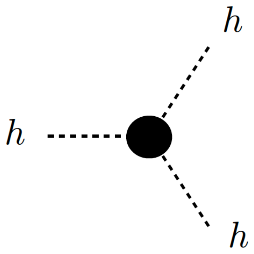
Direct searches of H2, H3, H±

Precision measurements of h (=H1) physics

LHC, ILC ,…
ILC, CEPC, FCCee, …

Test of strongly 1st OPT

(1)Future Colliders



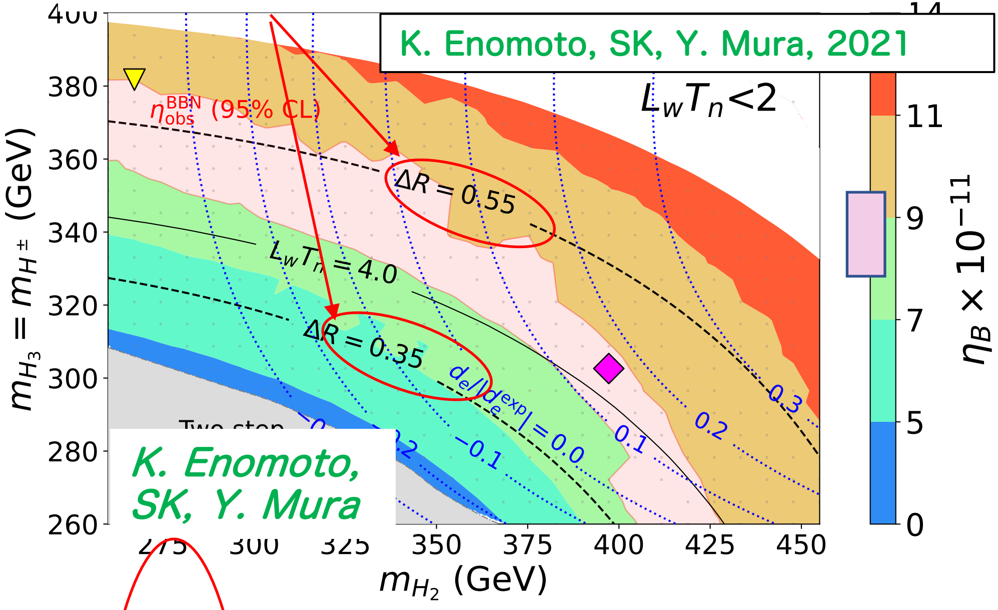
Stronlgly 1st OPT

→ A large deviation in the hhh coupling

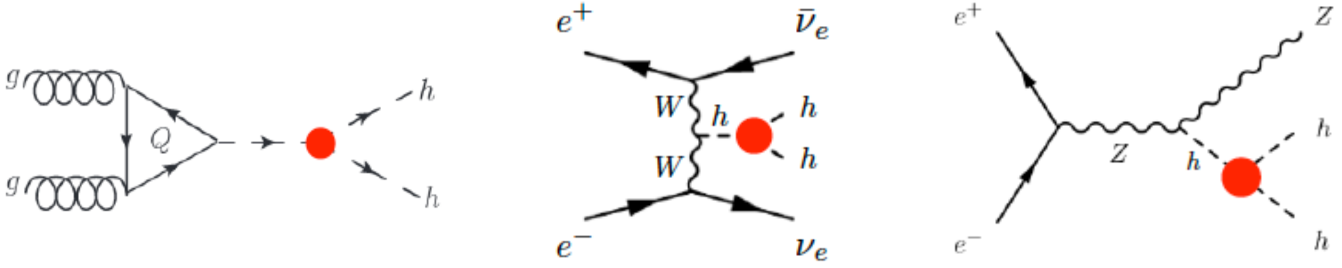
SK, Y. Okada, E. Senaha, 2005

Deviation in the hhh coupling (%)

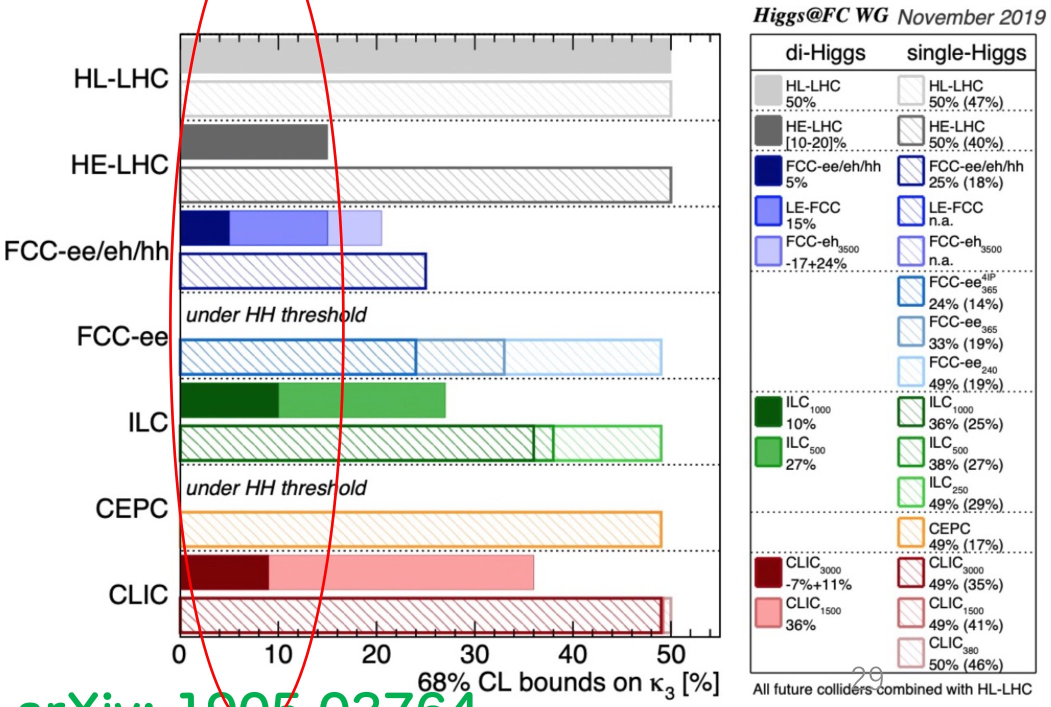
K. Enomoto, SK, Y. Mura, 2021



The hhh coupling can be measured at HL-LHC, or future e+e- colliders



EW Baryogenesis can be directly tested by the hhh measurement



arXiv: 1905.03764

Test of 1st OPT（2）GWs

GW detection (2016)

GW Astronomy: GW from BH binary, stars, etc.

- Ground Based experiments: LIGO, Virgo, KAGRA, …

GW Physics:

- GW from Early Universe（Long wavelength by red shift)
- Space based experiments: LISA (10^{-3} Hz), DECIGO (10^{-1} Hz), …

approved planned

GW from bubble collision at 1st order EWPT?

LISA (Laser Interferometer Space Antena)

- Laser intereferometer

  Measure spacetime distortion
- Space-based
- Arm length 2.5 Million km
- Approved (starting in 2030s)

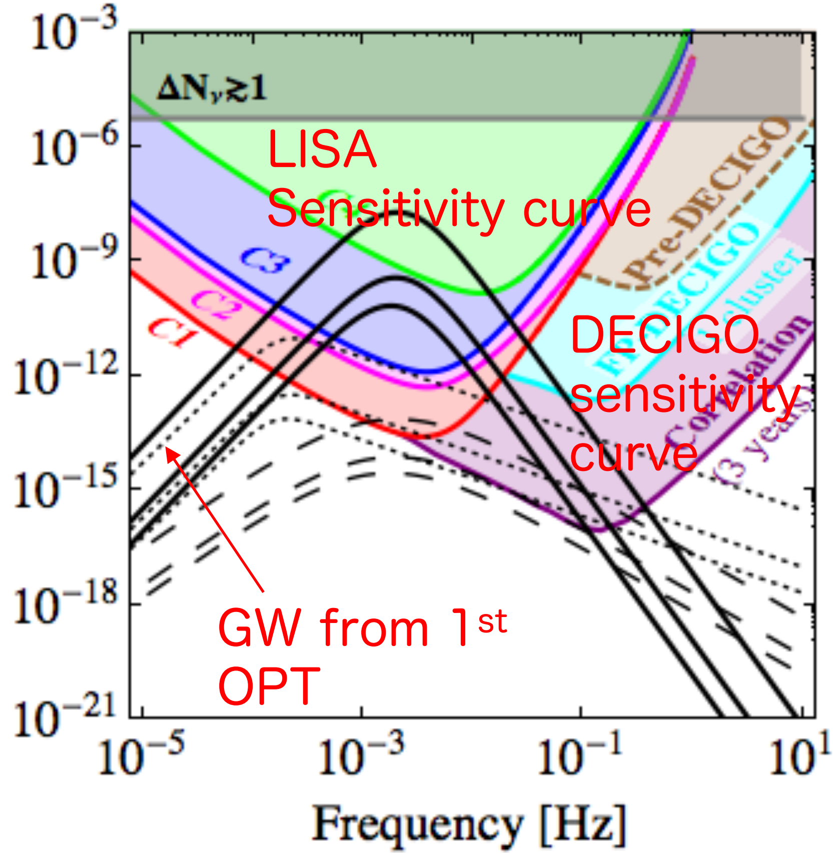
- Explore low frequency GW caused at early Universe

  Expected to detect GWs from 1st OPT

Grojean and Servant (2007)

M. Kakizaki, S.K., T. Matsui (2015)

N-singlet model

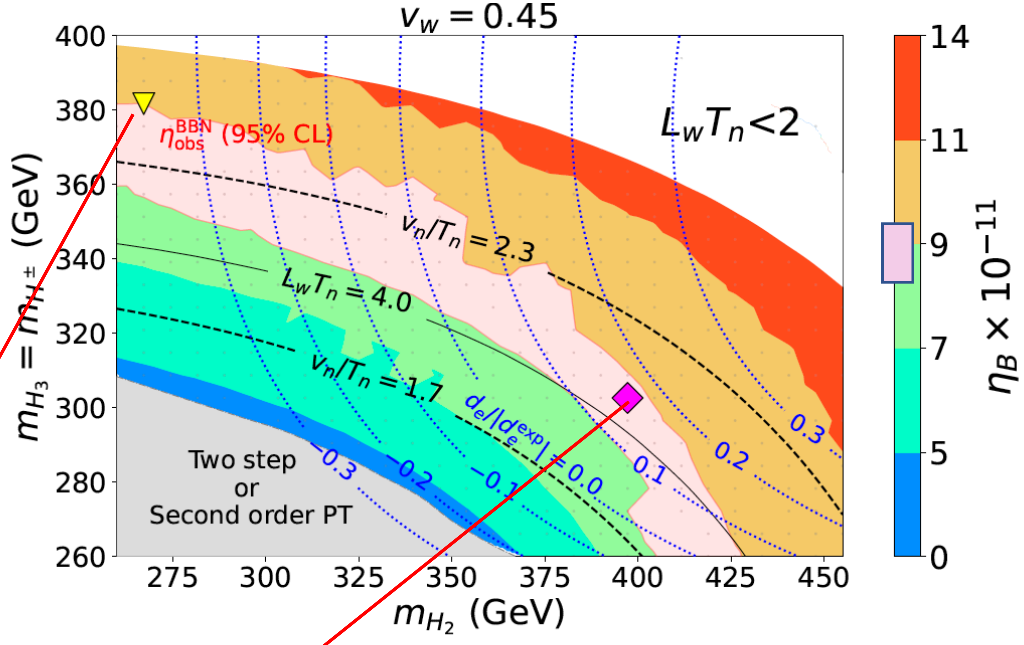


LISA, DECIGO

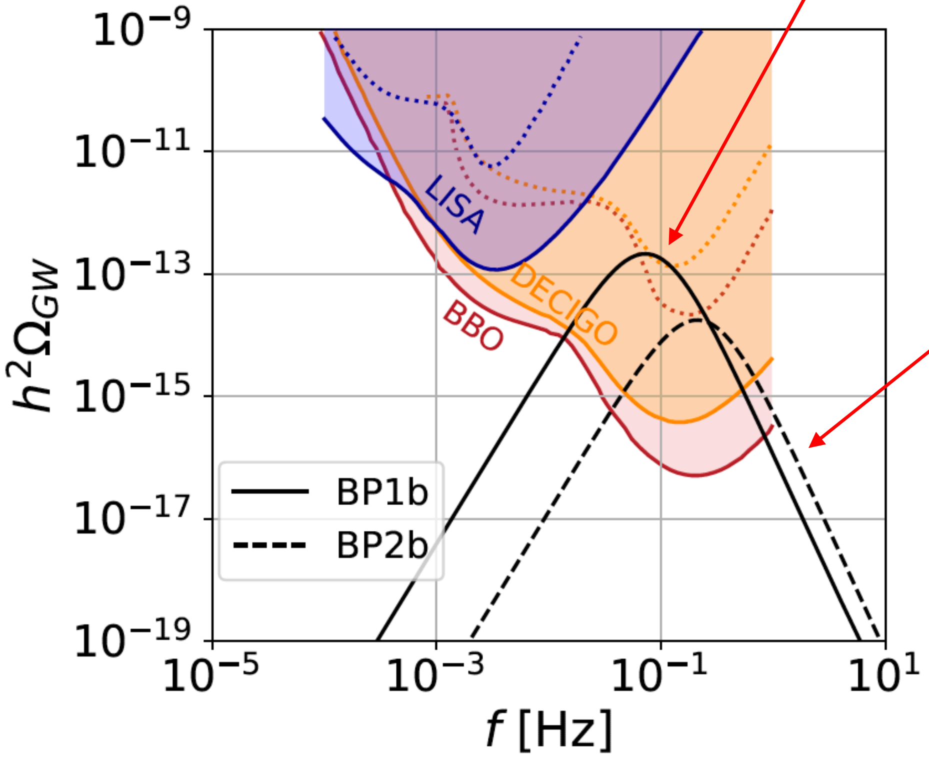
K. Enomoto, SK, Y. Mura, arXiv: 2207.00060

Case of aligned 2HDM

GW spectrum for the benchmark points to reproduce BAU, which satisfy current constraints from collider, flavor and EDM data



BP1 and BP2 may be tested by future GW experiments



Dotted curves: Sensitivity Curve
M. Breitbach et al., arXiv: 1811.11175

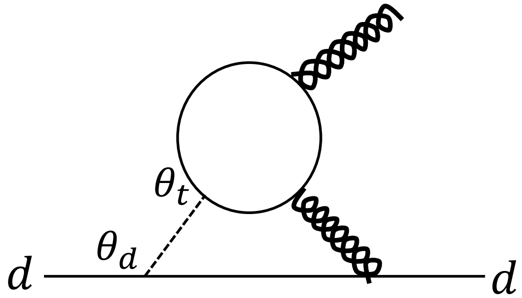
Solid curves: $h^2\Omega_{\rm PISC}$ [SNR criterion]
J. Cline et al., arXiv: 2102.12490

K. Enomoto, SK, Y. Mura, arXiv: 2207.00060

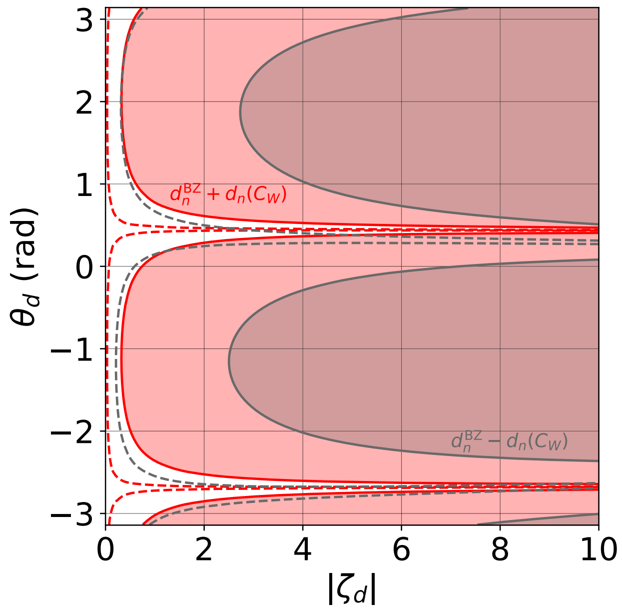
Test of CPV

EDM experiments

eEDM $|d_e| < 1.1 \times 10^{-29} e$cm
nEDM $|d_n| < 1.8 \times 10^{-26} e$cm



cEDM



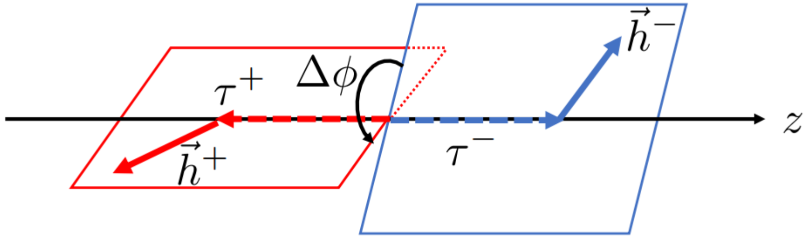
Future 1,2 order improvements can test our scenario of aligned 2HDM

Various flavor experiments

CPV from various meson experiments B (Belle II), etc

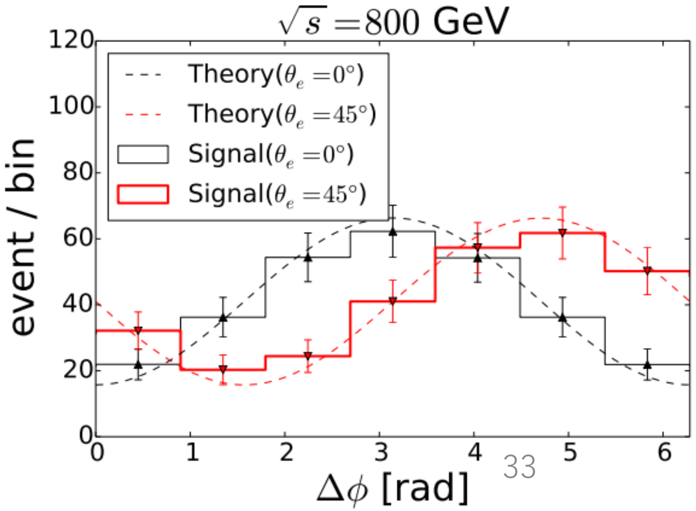
Future collider experiments (Heavy Higgs decays)

Azimuthal angle dependence in $H_{2,3} \to \tau^+\tau^- \to X^+\overline{\nu}X^-\nu$



ILC800GeV
L=3 ab⁻¹

Decay of
$H_{2,3} \to \tau\ \tau$



SK, M. Kubota, K. Yagyu (2020)

The CPV in this scenario can be tested

Test of CP violation

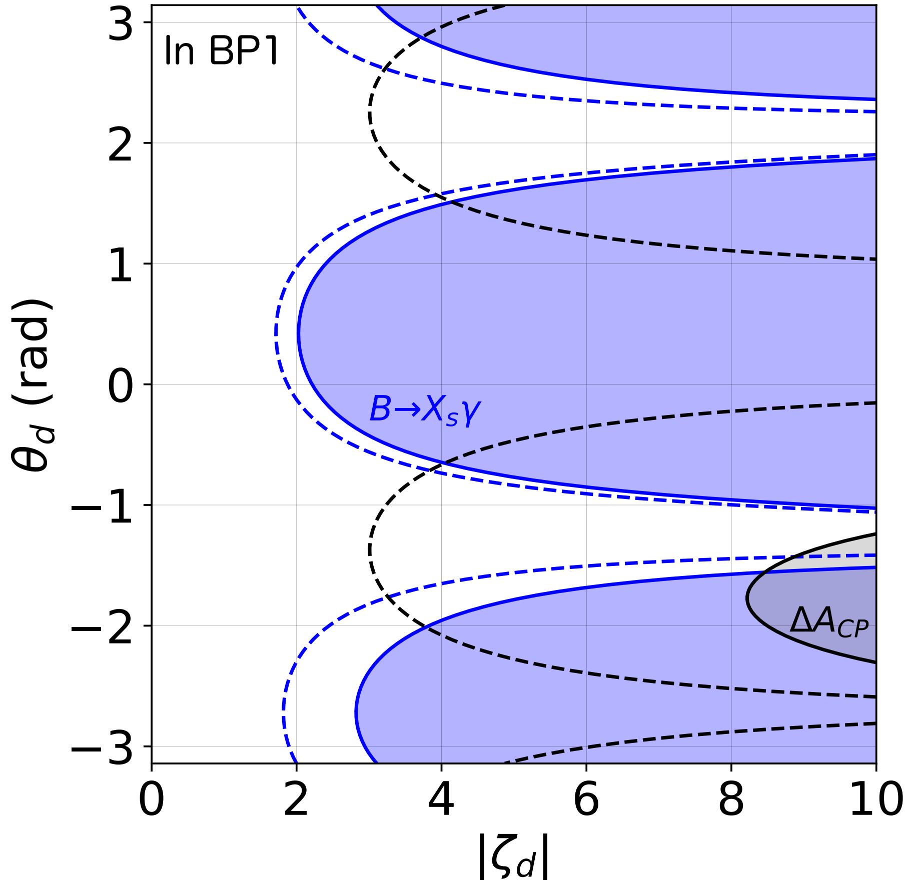
CPV in the future flavor experiments

Benzke *et al.* Phys. Rev. Lett. 106 (2011);
Watanuki *et al.* [Belle] Phys. Rev. D 99 (2019); and more

$$\Delta A_{CP} = A_{CP}(B^+ \to X_s^+ \gamma) - A_{CP}(B^0 \to X_s^0 \gamma)$$

$$A_{CP}(X \to Y) \equiv \frac{\Gamma(\bar{X} \to \bar{Y}) - \Gamma(X \to Y)}{\Gamma(\bar{X} \to \bar{Y}) + \Gamma(X \to Y)}$$

Solid : current excluded
Dashed : future excluded (Belle Ⅱ)



ζ_d can be constrained from the future flavor exp.

Test of extended Higgs models itself

New physical degree of freedom in extended Higgs models

H_2, H_3, H^+, H^-, …

- Direct searches at HL-LHC

$H_{2,3}^0 \to \tau\tau$, $H^\pm \to tb$, …

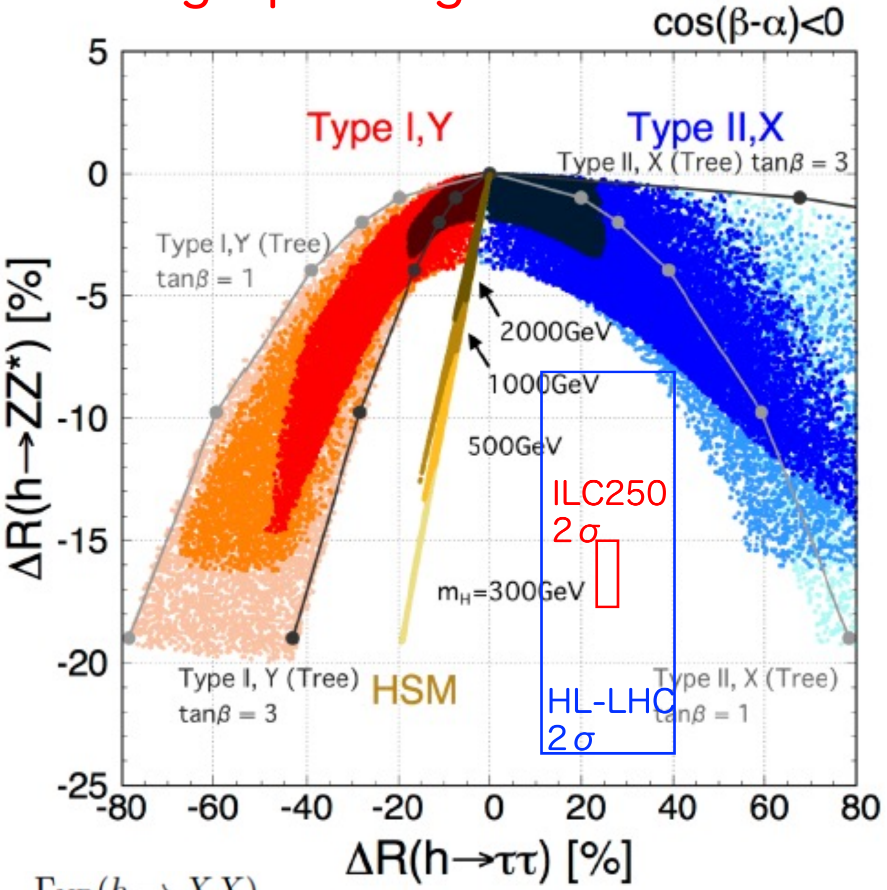
- Flavor experiments

$B \to X_s \gamma$, $B_s \to \mu\mu$, …

- Deviations in h-couplings

SK, Kikuchi, Sakurai, Yagyu, 2018

Fingerprinting models



$$\Delta R(h \to XX) = \frac{\Gamma_{\rm NP}(h \to XX)}{\Gamma_{\rm SM}(h \to XX)} - 1$$

We need ILC

Constraints on H+ from flavor experiments

Observables

$\mathcal{B}(B \to X_s \gamma)$

$\mathcal{B}(B_s \to \mu\mu)$

$\mathcal{B}(B_d \to \mu\mu)$

$\mathcal{B}(B \to \tau\nu)$

$\mathcal{B}(D_s \to \mu\nu)$

$\mathcal{B}(D_s \to \tau\nu)$

Δm_d

Δm_s

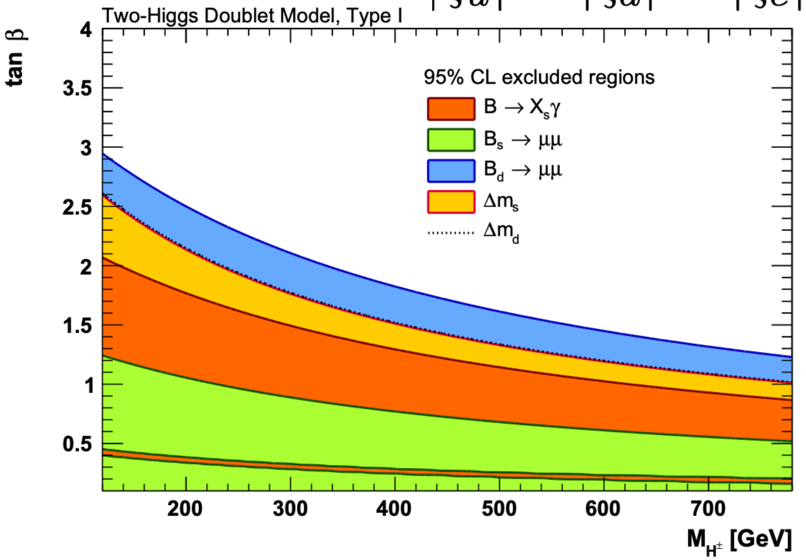
$\mathcal{B}(K \to \mu\nu)/\mathcal{B}(\pi \to \mu\nu)$

Figures from 1803.01853

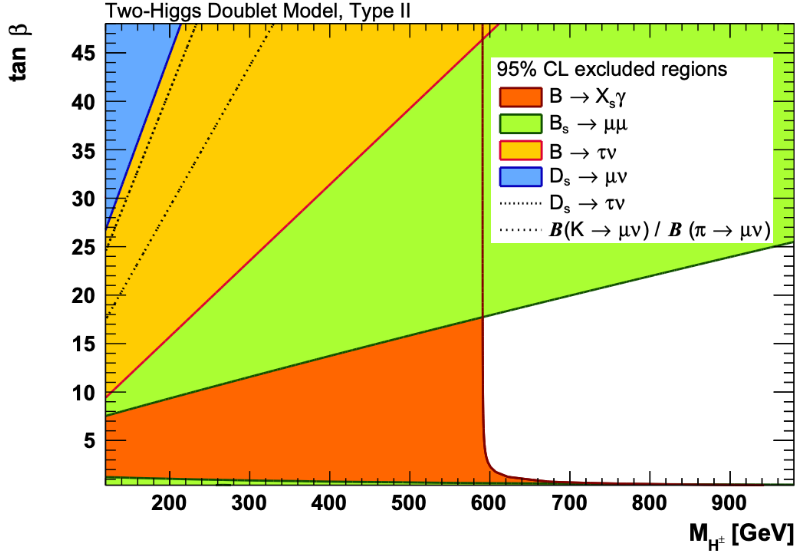
Y-axis: $\tan\beta = 1/|\zeta_u|$

$$\frac{1}{|\zeta_u|} =$$

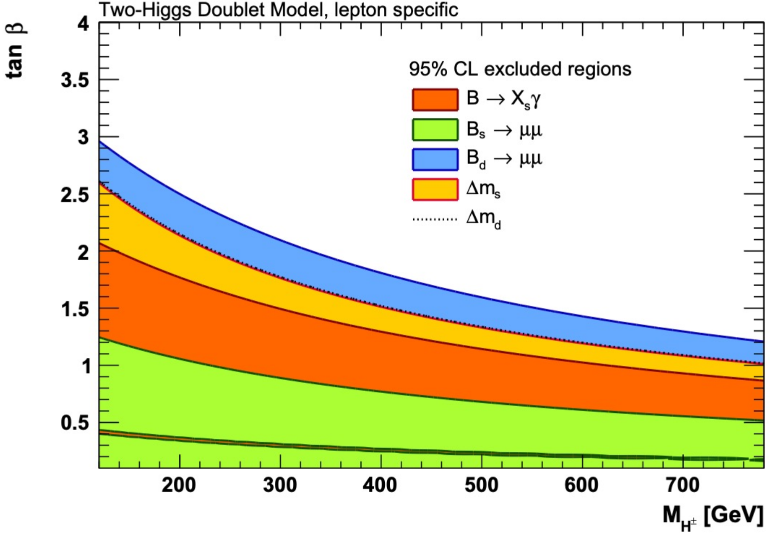
$|\zeta_u| = |\zeta_d| = |\zeta_e|$



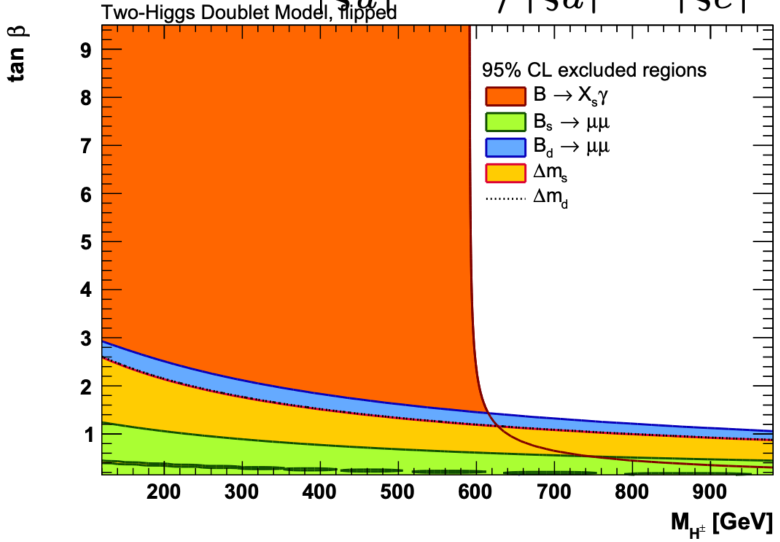
$|\zeta_u| = 1/|\zeta_d| = 1/|\zeta_e|$



$|\zeta_u| = |\zeta_d| = 1/|\zeta_e|$



$|\zeta_u| = 1/|\zeta_d| = |\zeta_e|$



Which matter generates BAU？

$$\rho^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \rho_{cc} & \rho_{ct} \\ 0 & \rho_{tc} & \rho_{tt} \end{pmatrix},$$

- Top transport ρ_{tt} (= $m_u \zeta_u$)
- Top-charm ρ_{tc} : No strong constraint ~O(1) possible
  Absolute value of ρ_{tc} contributes to EWBG via the CPV in the Higgs potential.
  Deviation $K_L \to \pi^0 \nu \nu$ O(1)%
  $K^+ \to \pi^+ \nu \nu$ O(10)%
  Test at KOTO2、NA62? SK, Y. Mura, arXiv: 2303.11252
- Bottom
- Tau
- …

EW Baryogenesis with top-charm mixing

SK, Y. Mura, arXiv: 2303.11252

Up type quark

$$-\mathcal{L}_Y = \overline{u_{i,L}}\frac{y_i\delta_{ij}}{\sqrt{2}}u_{j,R}h - \overline{u_{i,L}}\frac{\rho_{ij}}{\sqrt{2}}u_{j,R}H_2 - \overline{u_{i,L}}\frac{i\rho_{ij}}{\sqrt{2}}u_{j,R}H_3 + \text{h.c.}$$

$$\rho^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \rho_{cc} & \rho_{ct} \\ 0 & \rho_{tc} & \rho_{tt} \end{pmatrix}$$

$$\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})_{\text{EXP}} = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$$

$$\mathcal{B}(K_L \to \pi^0\nu\overline{\nu})_{\text{EXP}} < 3.0 \times 10^{-9}$$

$$\mathcal{R}^+_\nu = \frac{\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})}{\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})_{\text{SM}}}$$

$$\mathcal{R}^0_\nu = \frac{\mathcal{B}(K_L \to \pi^0\nu\overline{\nu})}{\mathcal{B}(K_L \to \pi^0\nu\overline{\nu})_{\text{SM}}}$$

$$\Delta\mathcal{R}^+_\nu \equiv \mathcal{R}^+_\nu - 1$$

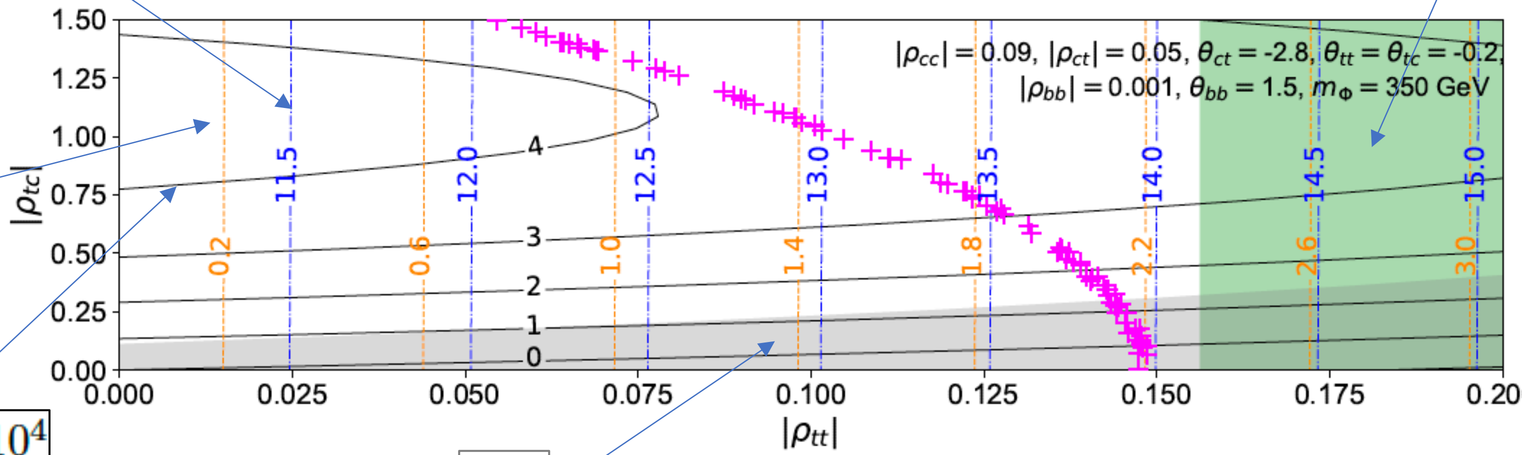
$$\Delta\mathcal{R}^0_\nu \equiv \mathcal{R}^0_\nu - 1$$

$\Delta\mathcal{R}^+_\nu \times 10^2$

BAU

$B_s \to \mu\mu$

$\Delta\mathcal{R}^0_\nu \times 10^2$



$(\epsilon'/\epsilon)_{\text{2HDM}} \times 10^4$

Direct CPV KL→π π

ϵ_K

KK mixing

Strategy of testing scenarios of EWBG

- 1st Step Test EWBG-Like Phenomena
  by CPV, non-standard interactions, Yukawa couplings, …
  ⟹ Narrowing down the scenarios of EWBG

- 2nd Step Evidence of 1st OPT at HL-LHC, ILC, LISA, DECIGO
  Deviation in the hhh coupling, GW spectrum
  Direct search of heavy Higgs bosons, precision tests
  ⟹ Determination of the scenario of EWBG

- Direction of high energy physics.

Summary

- Current data would require some alignment (both Higgs alignment and Yukawa alignment) in 2HDM.

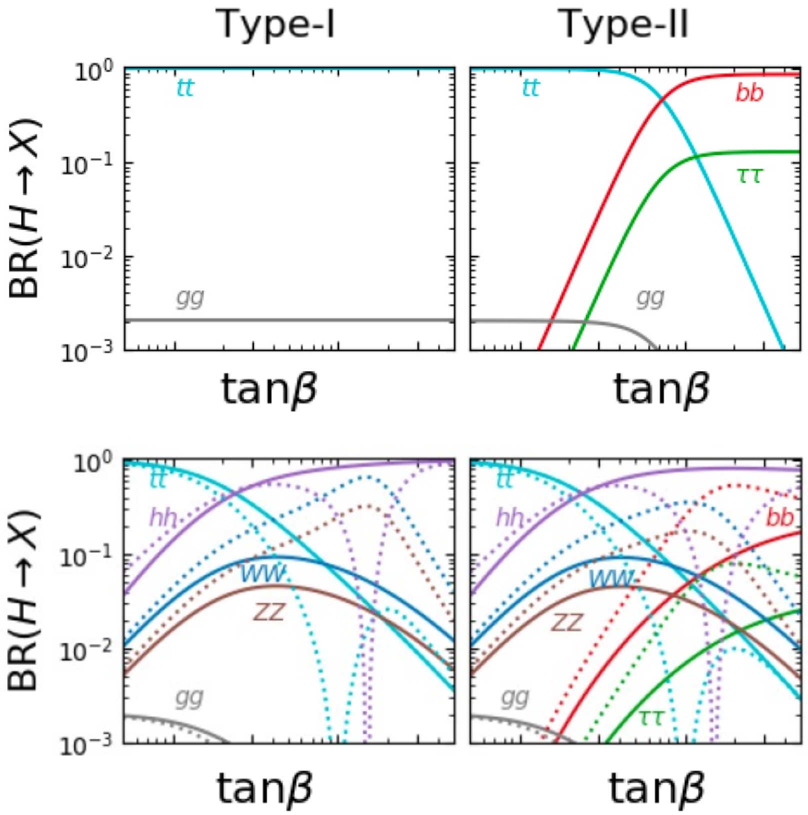
  h (SM like) H_2, H_3, H^+, H^- (CPV in the heavy Higgs sector)
- EW Baryogenesis is discussed in the aligned 2HDM
- Non-decoupling loop effects for 1st OPT, multiple CPV phases
- Benchmark point to explain BAU with satisfying current data.
- Many channels to test the model by current/future experiments

  Hadron & lepton colliders, Flavor experiments, GW, PBH, …

Backup slides

HL-LHC and the Higgs Factory (like ILC250) may exclude cases of $\kappa \neq 1$

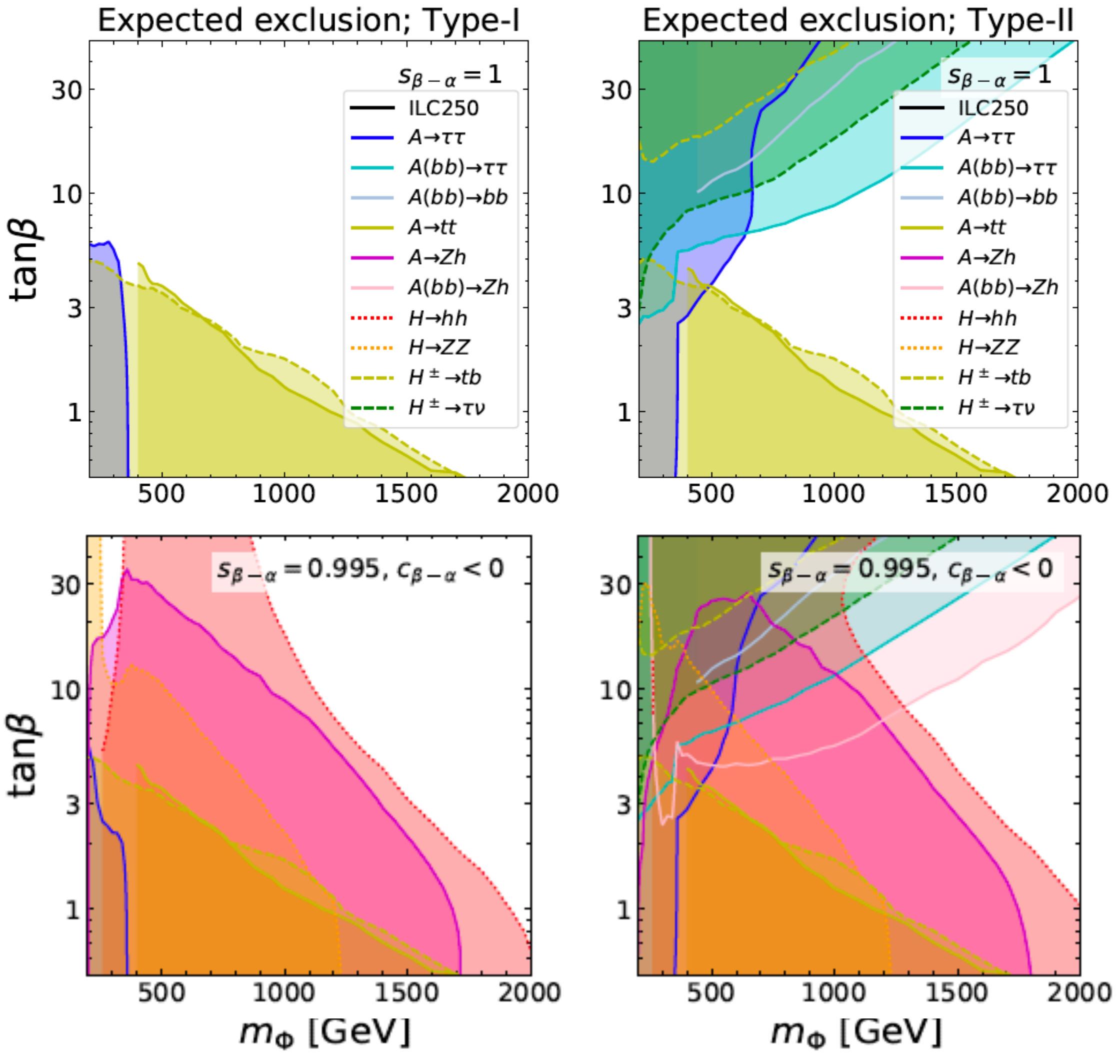
Near and exact are drastically different



Kv =1
Alignment

Kv =0.995
Near alignment

H to H decays
become important



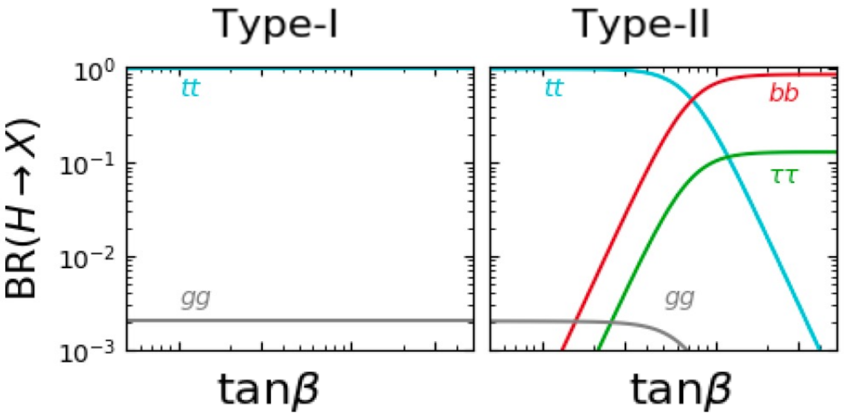
SuSHI-1.7.0
2HDM-C, used
Extrapolate from data

Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu, 2020

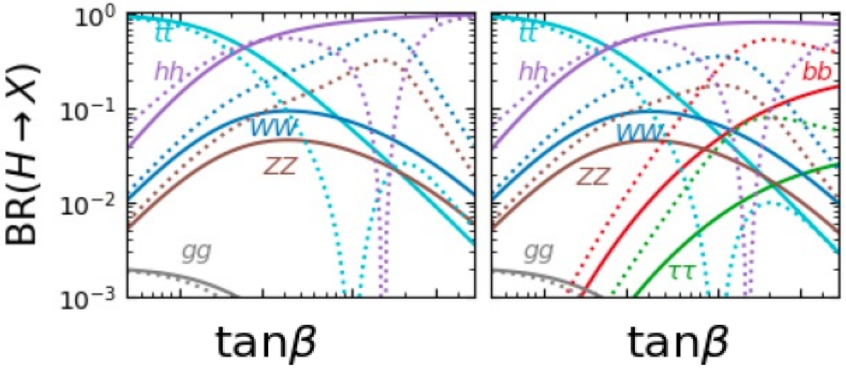
HL-LHC and the Higgs Factory (like ILC250) may exclude cases of $\kappa \neq 1$

Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu, 2020

Near and exact are drastically different

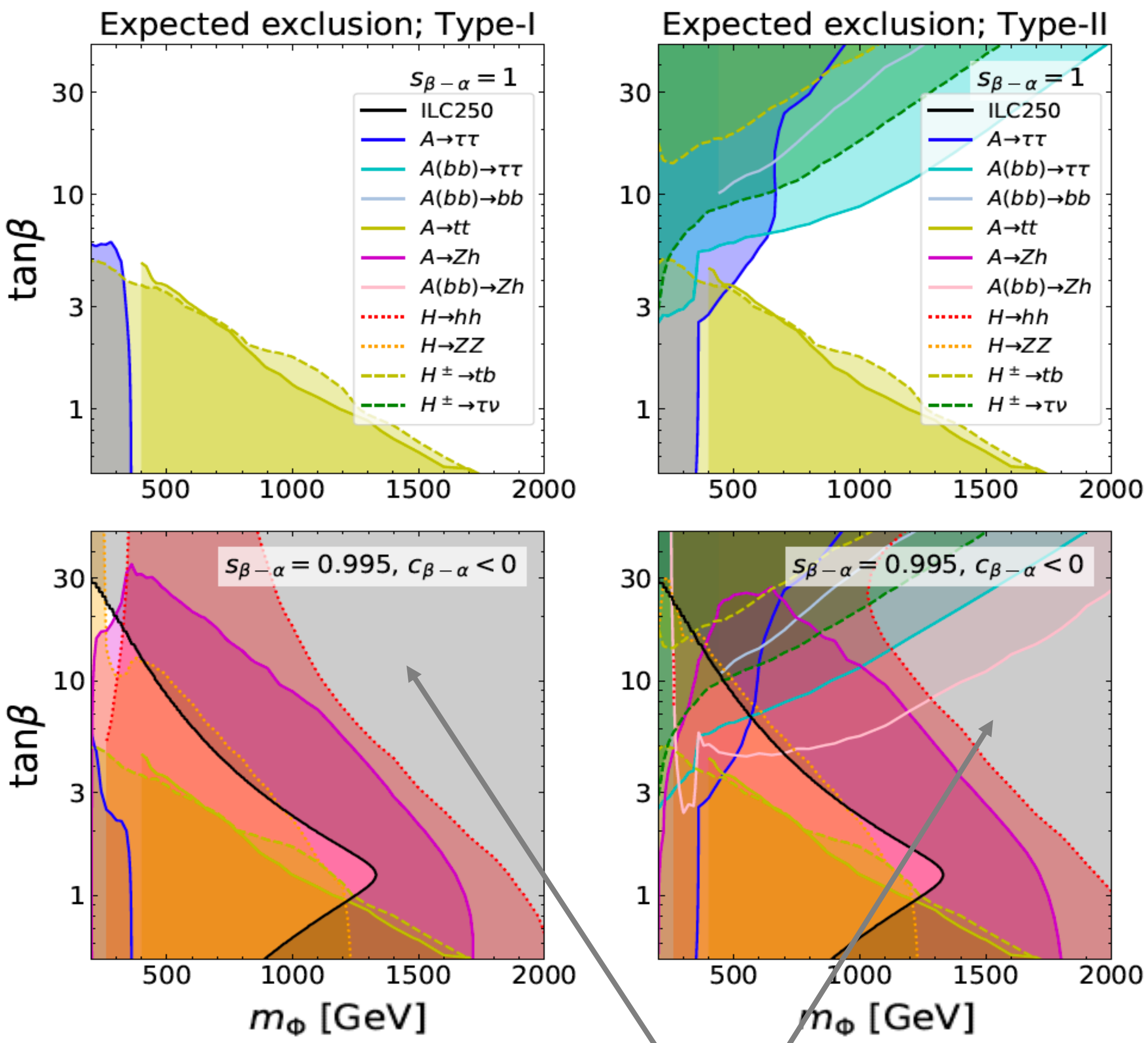


Kv =1
Alignment



Kv =0.995
Near alignment

H to H decays become important



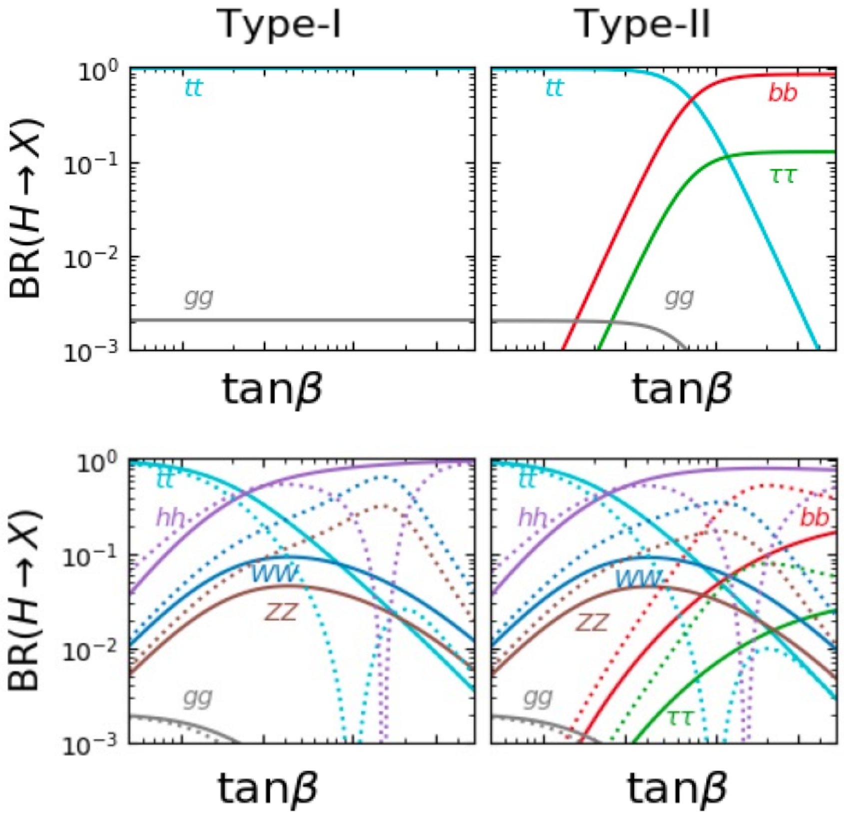
For near alignment cases, all the parameter regions are excluded by 95%CL

By the perturbative unitarity

HL-LHC and the Higgs Factory (like ILC250) may exclude cases of $\kappa \neq 1$

Regions of alignment without decoupling

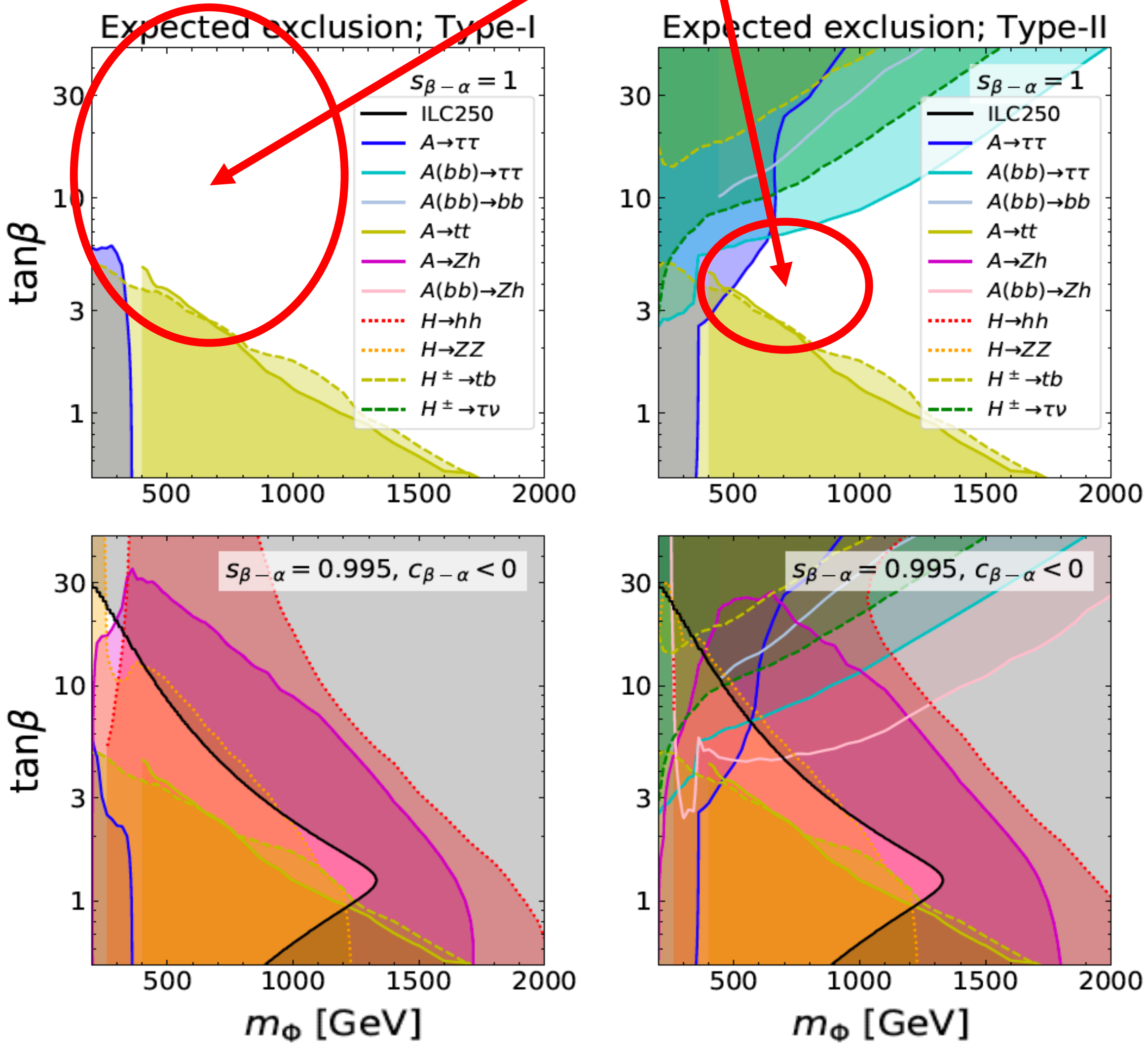
Near and exact are drastically different



Kv =1
Alignment

Kv =0.995
Near alignment

H to H decays
become important

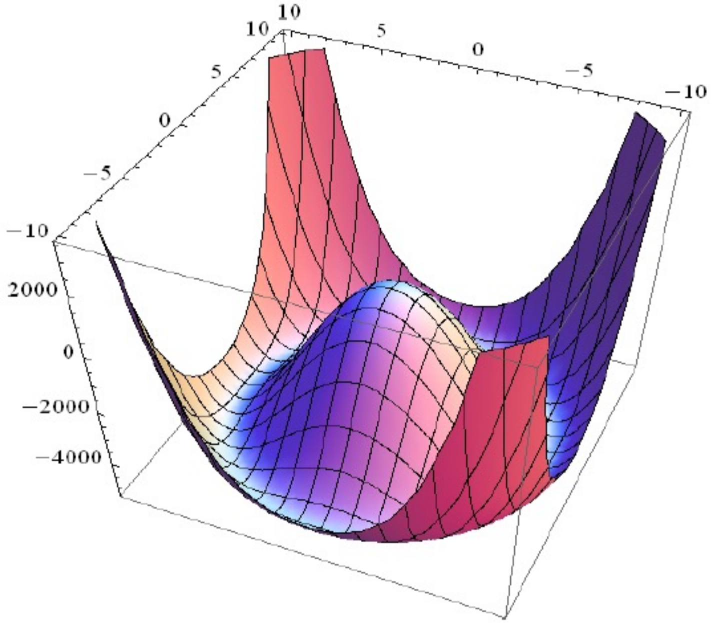


Region of alignment without decoupling can be explored by higher energy e^+e^- collisions, and also by the hhh measurement

M. Aiko, SK, M. Kikuchi, K. Mawatari, K. Sakurai, K. Yagyu, 2020

Higgs Potential

Dynamics of EWSB $SU(2)_I \times U(1)_Y \to U(1)_{\rm em}$



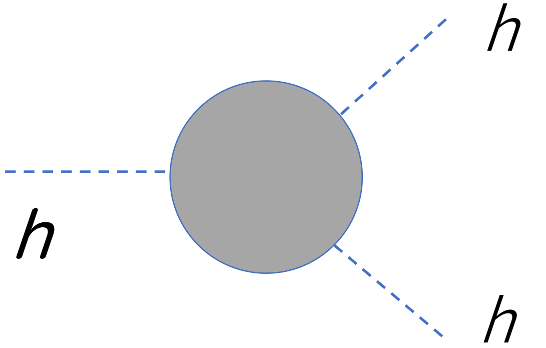
It is very important to know the *hhh* coupling to reconstruct the Higgs potential

$$\boxed{V_{\rm Higgs} = \frac{1}{2}\underline{m_h^2}h^2 + \frac{1}{3!}\underline{\lambda_{hhh}}h^3 + \frac{1}{4!}\lambda_{hhhh}h^4 + \cdots}$$

$$\boxed{\lambda_{hhh}^{\rm SMloop} \sim \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)}$$

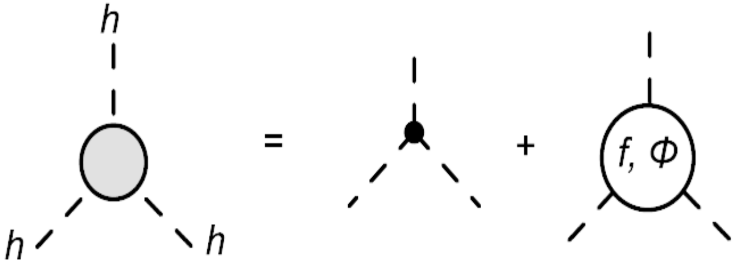
Top loop
effect
in the SM

Non-decoupling effect



hhh in extended Higgs sectors

$$\boxed{\lambda^{\rm 2HDM}_{hhh} \simeq \frac{3m_h^2}{v}\left[1+\underbrace{\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3}_{\text{Extra scalar loop}}-\underbrace{\frac{m_t^4}{\pi^2 v^2 m_h^2}}_{\text{Top loop}}\right]}$$



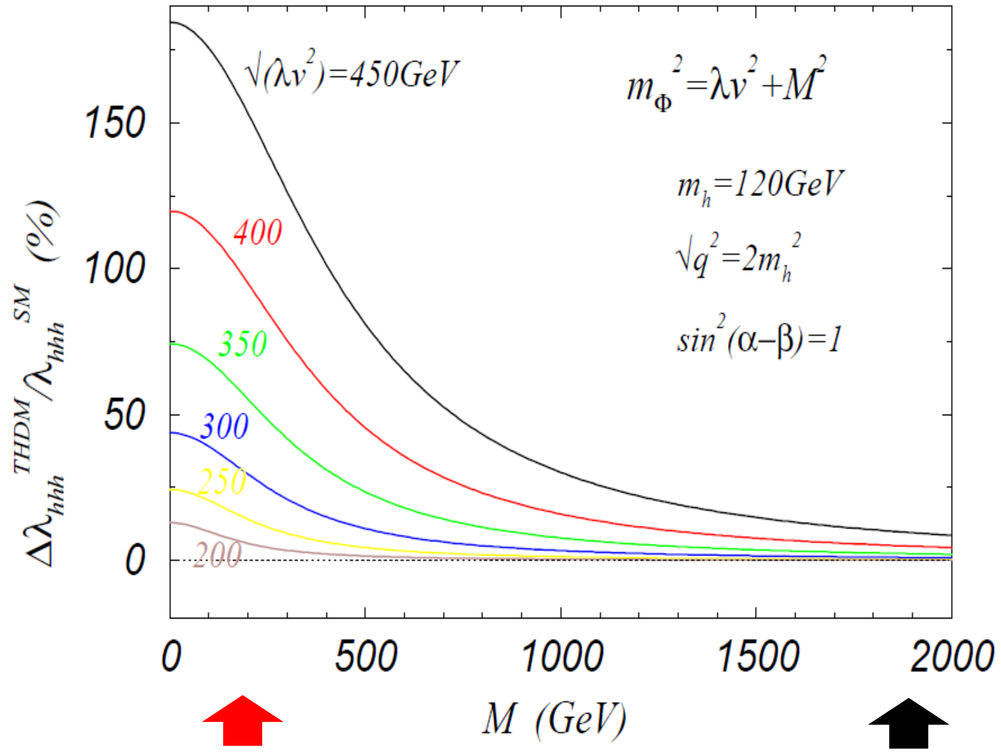
Φ ＝H, A, H±

Mass of extra Higgs bosons

$$m_\Phi^2 = M^2 + \lambda_i v^2$$ (Φ ＝H, A, H±)

- Consider the case: *h* is SM-like
- At 1-loop, powerlike effect m_Φ^4

Deviation can be huge
～ 100% (NLO)
under constraint from unitarity bounds etc



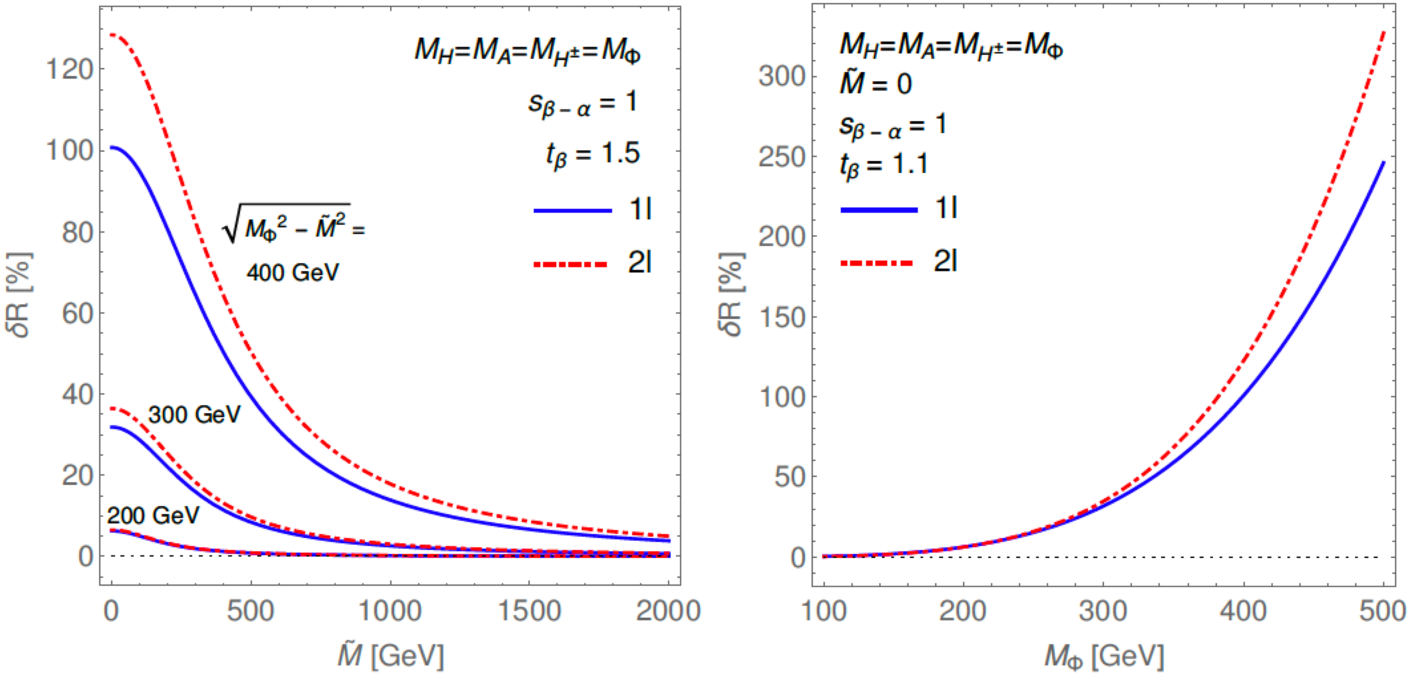
Non-decoupling effect

Decoupling

SK, Kiyoura, Okada, Senaha, Yuan, 2003

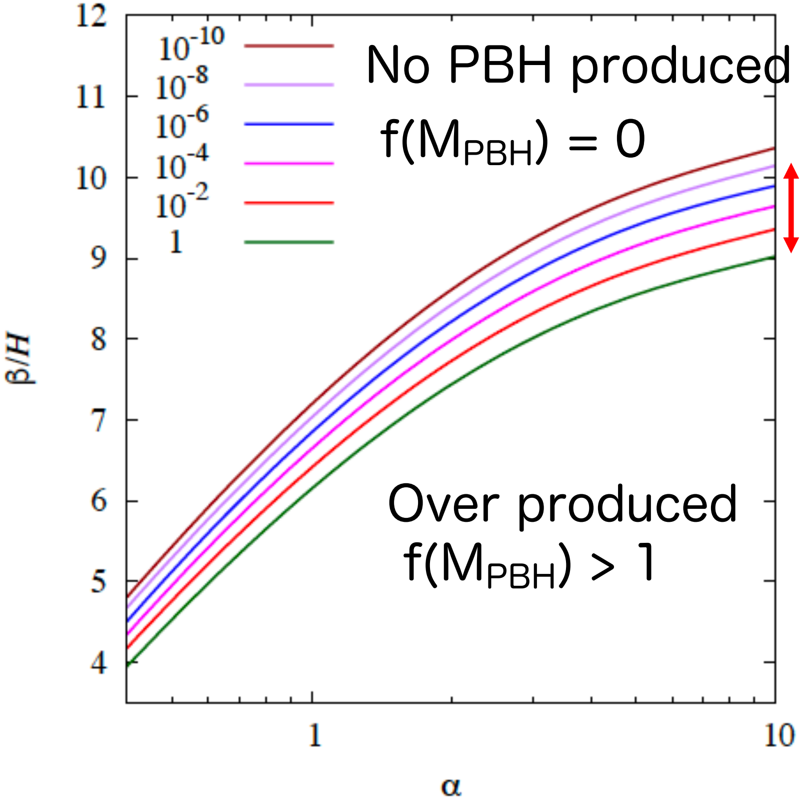
Two loop correction to the hhh coupling

J. Braathen, SK, 2019



$$
\begin{aligned}
\delta^{(2)}\hat{\lambda}_{hhh} = {} & \frac{48 M_\Phi^6}{v_{\text{phys}}^5}\left(1-\frac{\tilde{M}^2}{M_\Phi^2}\right)^4 \left\{4 + 3\cot^2 2\beta\left[3 - \frac{\pi}{\sqrt{3}}\left(\frac{\tilde{M}^2}{M_\Phi^2}+2\right)\right]\right\} \\
& + \frac{576 M_\Phi^6 \cot^2 2\beta}{v_{\text{phys}}^5}\left(1-\frac{\tilde{M}^2}{M_\Phi^2}\right)^4 + \frac{288 M_\Phi^4 M_t^2 \cot^2\beta}{v_{\text{phys}}^5}\left(1-\frac{\tilde{M}^2}{M_\Phi^2}\right)^3 \\
& + \frac{168 M_\Phi^4 M_t^2}{v_{\text{phys}}^5}\left(1-\frac{\tilde{M}^2}{M_\Phi^2}\right)^3 - \frac{48 M_\Phi^6}{v_{\text{phys}}^5}\left(1-\frac{\tilde{M}^2}{M_\Phi^2}\right)^5 + \mathcal{O}\left(\frac{M_\Phi^2 M_t^4}{v_{\text{phys}}^5}\right)
\end{aligned}
$$

Contour of the fraction of the ratio with DM abundance

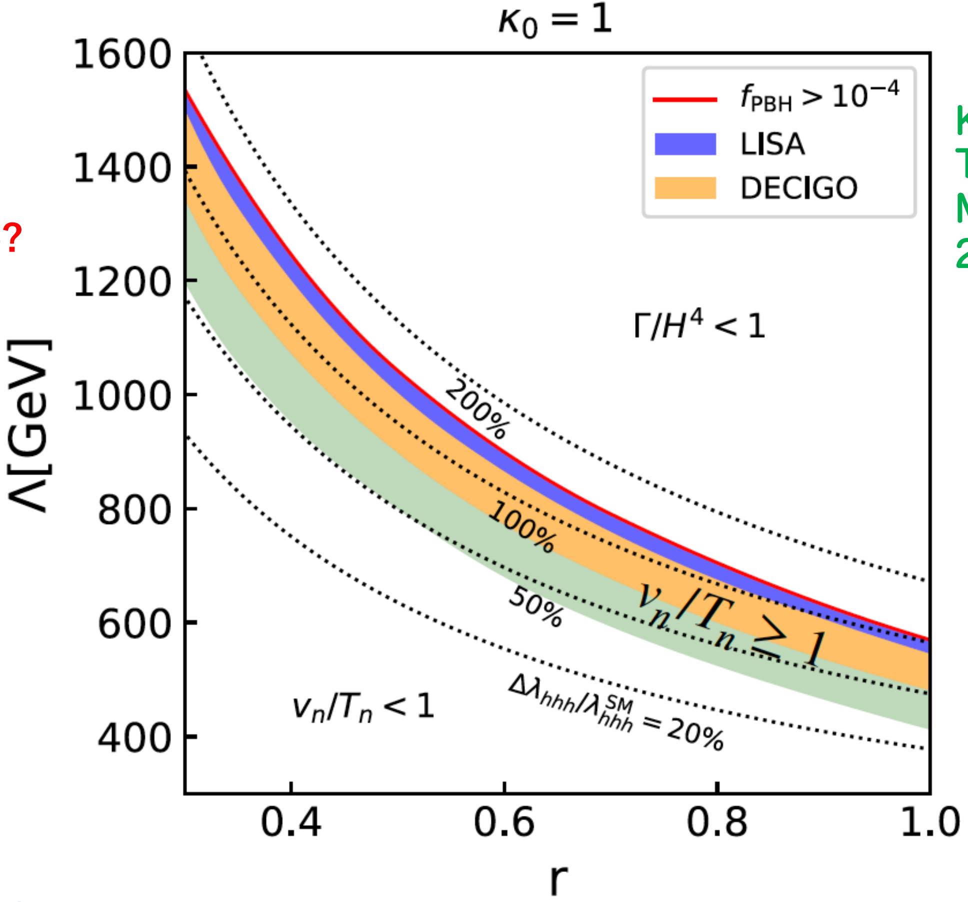


PBH Detectable?

naHEFT

SK, R. Nagai, 2021

κ_0: DOF of NP
Λ : Mass scale of NP
r : Nondecouplingness



K. Hashino, SK, T. Takahashi, M. Tanaka 2023

Red: PBH ($f > 10^{-4}$)

Blue: LISA

Cyan: DECIGO

White: only hhh

Large α and slow PT (β<10) makes fraction large

In addition to the hhh measurement and GW observation, we may use PBH for testing the Higgs physics

PBH observatory@ Subaru HyperSuprimeCam, OGLE, PRIME, Roman Telescope,…