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Upper limit on particle mass in New Physics model & Strong 1st order Electro-weak phase transition : 2HDM as an example

希格斯物理研讨会

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Based on arXiv: JHEP 04 (2021) 219, Wei Su, Anthony G. Williams, MZ

Outline

1. What is the mass of a New particle: SM Higgs V.S. New Physics
2. Strong 1st order PT constraints New Physics: 2HDM as example
3. Conclusion & outlook

The mass of Higgs

We don't know where the New Physics is.

But, we already knew where the SM Higgs is, before LHC.

The mass of SM Higgs is limited by perturbative unitarity.

A brief introduction for perturbative unitarity (1604.05746)

consider 2 -> 2 process: $(2\pi)^4\delta^{(4)}(P_i - P_f)\mathcal{T}_{fi}(\sqrt{s}, \cos\theta) = \langle f|T|i\rangle$ $S = 1 + iT$

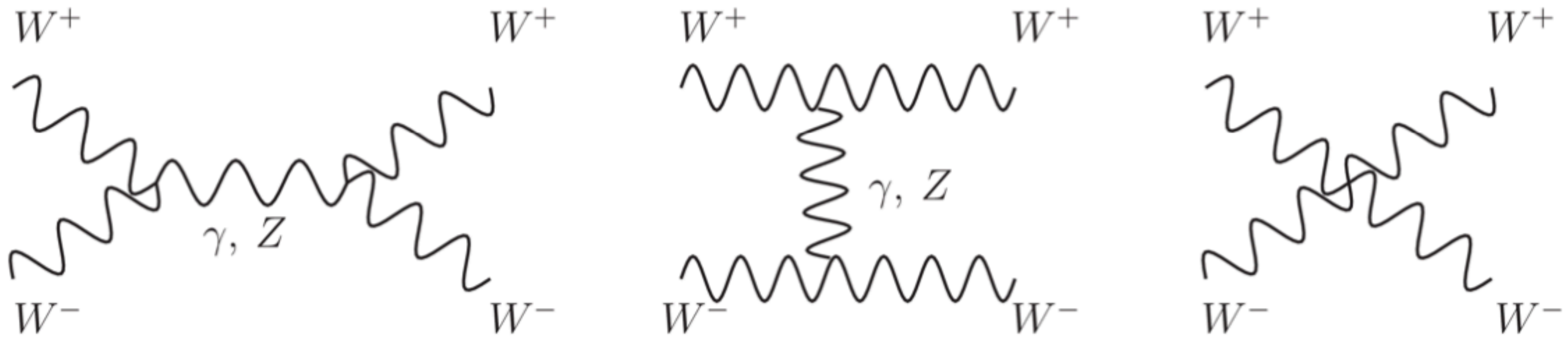
integrate scattering angle: $a^J_{fi} = \frac{\beta_f^{1/4}(s, m_{f1}^2, m_{f2}^2)\beta_i^{1/4}(s, m_{i1}^2, m_{i2}^2)}{32\pi s}\int_{-1}^{1} d(\cos\theta)\, d^J_{\mu_i\mu_f}(\theta)\, \mathcal{T}_{fi}(\sqrt{s}, \cos\theta)$

Then the unitarity of S gives limits: $S^\dagger S = 1 \Rightarrow\ -i(T - T^\dagger) = T^\dagger T \Rightarrow\ \frac{1}{2i}\left(a^J_{fi} - a^{J*}_{if}\right) \geq \sum_h a^{J*}_{hf} a^J_{hi}$

The mass of Higgs

Apply the perturbative unitarity bounds to EW theory: (taken from Giuseppe Degrassi)

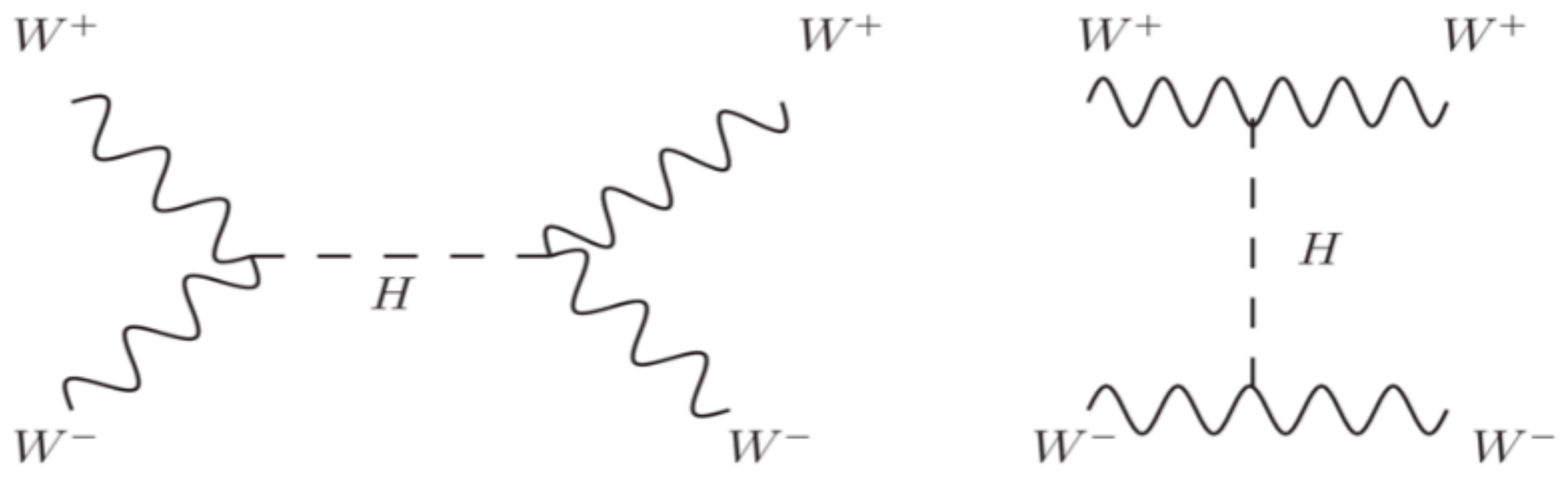
Longitudinal W boson scattering



A B C

$$A + B = i\frac{g^2}{m_W^4}\left\{-\frac{t^2+s^2}{4} - s\,t + \frac{5}{4}m_W^2(s+t)\right\}$$

$$A + B + C = i\frac{g^2}{m_W^2}\frac{s+t}{4}$$



D E

$$A + \cdots + E = -i\sqrt{2}\,G_\mu m_H^2\left(\frac{t}{t-m_H^2} + \frac{s}{s-m_H^2}\right)$$

Tree-level perturbative unitarity $\longrightarrow$ $m_h^2 < \frac{4\pi\sqrt{2}}{G_\mu} \sim (1\text{TeV})^2$

The mass of Higgs

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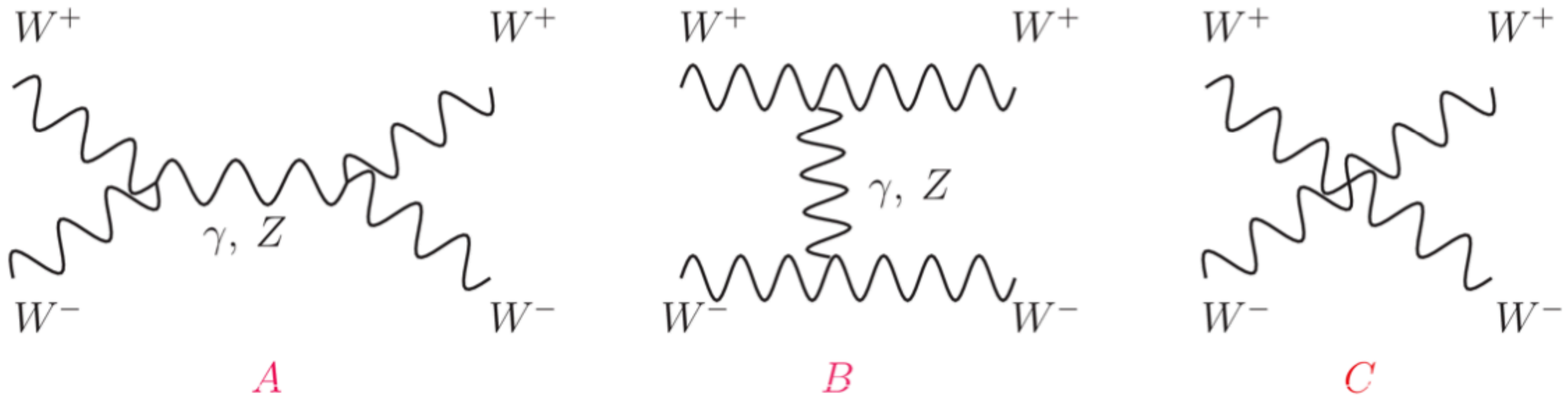
Longitudinal W boson scattering



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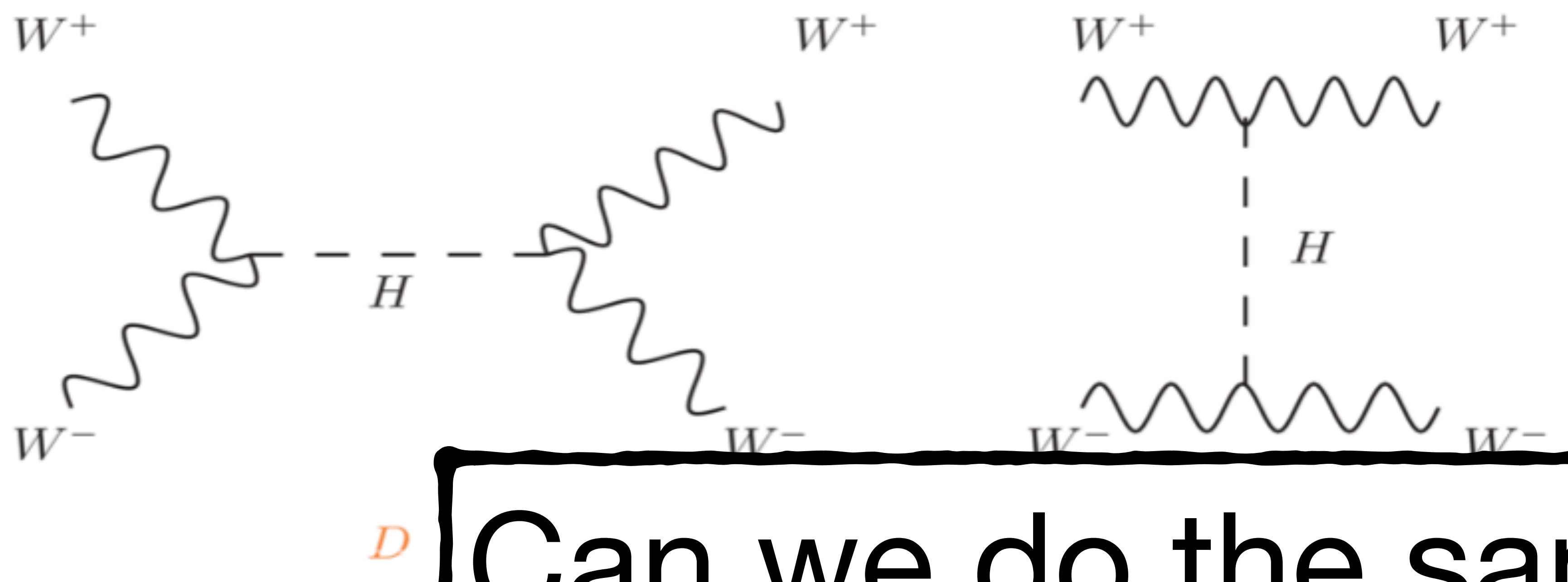


$$A + \cdots + E = -i\sqrt{2}\,G_\mu m_H^2\left(\frac{t}{t-m_H^2} + \frac{s}{s-m_H^2}\right)$$

Can we do the same to New Physics?

What is the “upper-bound” for New Physics?

Tree-level pertu

G_μ

The mass of new particles in New Physics Model

For the search of New Physics, we also want to know the mass range of new particles. But it highly dependent on the problem you want to solve.

Problems to be solved:

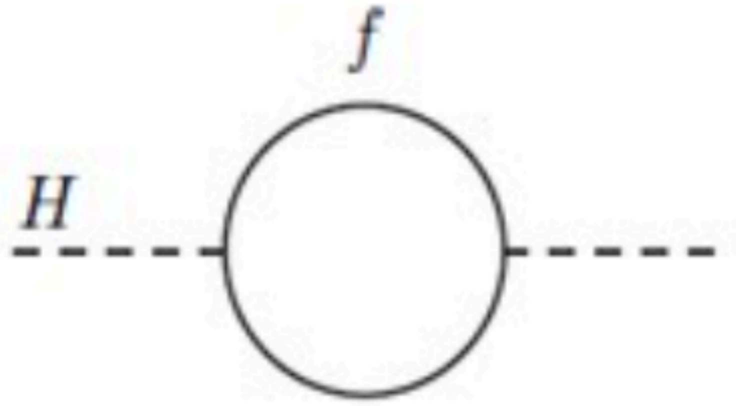
1. Naturalness problem
2. Dark matter
3. Neutrino mass
4. Matter-antimatter asymmetry (BAU)
5. ….

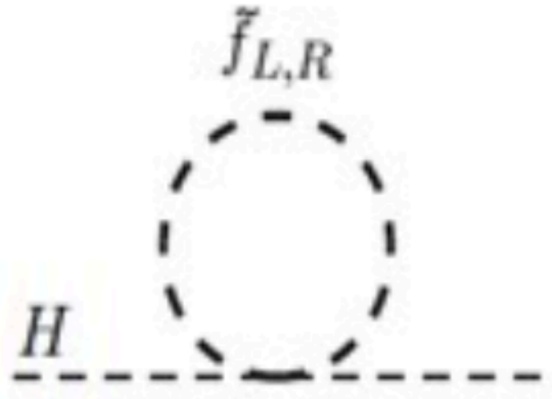
Can we find mass upper limits for new particles in NP models that try to solve above problems?

The mass of new particles in New Physics Model

Solution of naturalness problem: SUSY, Composite Higgs, …

SUSY as an example





$$\mathcal{L} = -\lambda_{\tilde{f}} |H|^2 |\tilde{f}_{L,R}|^2$$

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + ...$$

$$\Delta m_H^2 = \frac{2\lambda_{\tilde{f}}}{16\pi^2}\Lambda^2 + ...$$

$$\delta m_h^2 \sim \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\log\frac{m_{\tilde{t}}^2}{m_t^2}$$

The mass of new particles in New Physics Model

Solution of naturalness problem: SUSY, Composite Higgs, …

SUSY as an example

$$\delta m_h^2 \sim \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\log\frac{m_{\tilde{t}}^2}{m_t^2}$$

Thus roughly speaking, light stop means the theory is natural.
However, heavy stop mass, e.g. 10 TeV will not cause problem like unitarity.

So in principle, stop mass can be much heavier than the reach of collider, we can not verify or falsify the SUSY solution of naturalness problem.

The mass of new particles in New Physics Model

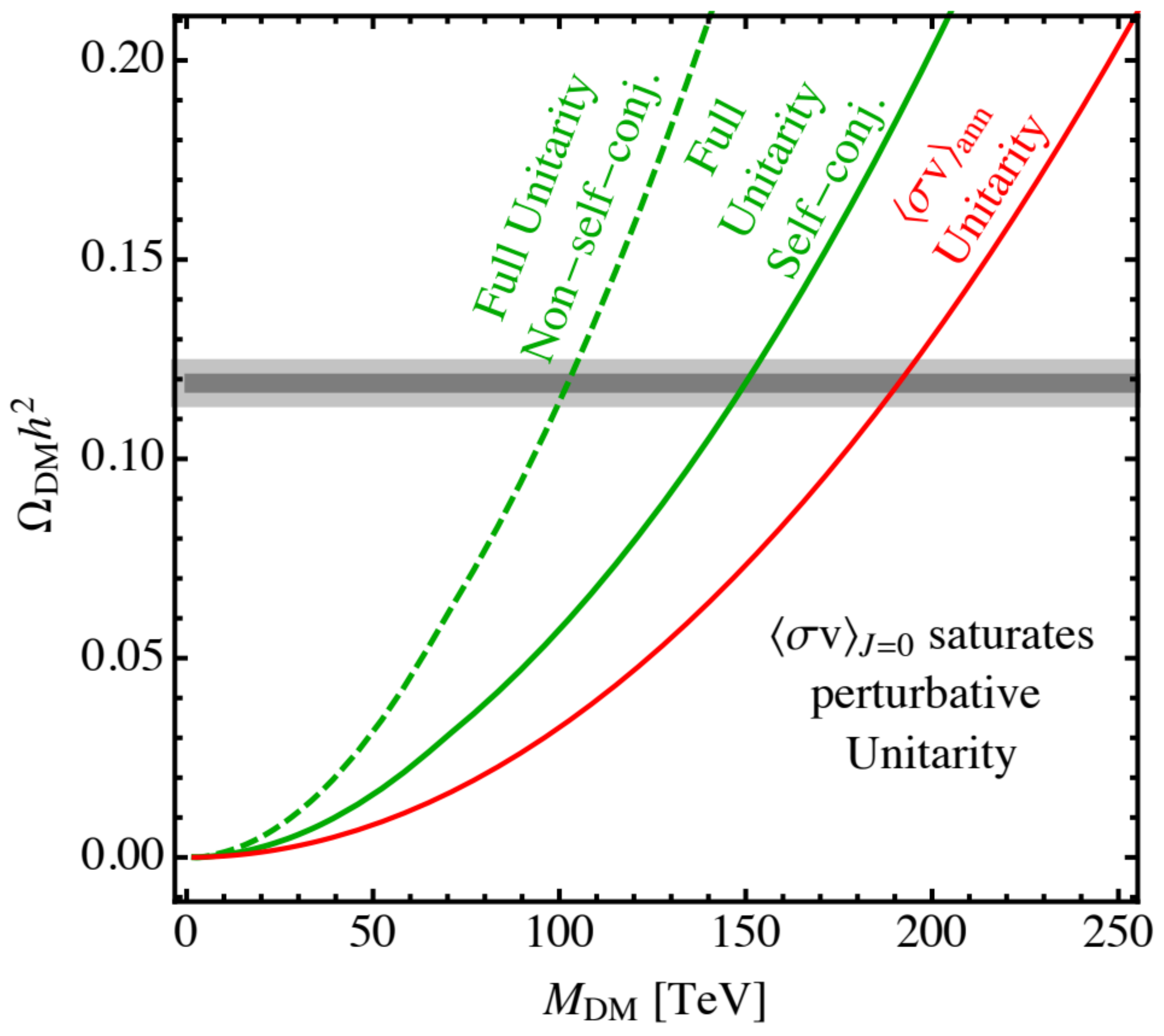
Candidates for Dark Matter: WIMP, SIMP, FIMP, …

WIMP as an example.

$$\Omega_{\rm DM} h^2 (\approx 0.12) \propto \frac{M_{\rm DM}}{\langle \sigma v \rangle}$$

(Sommerfeld effect & bound states included)

(1904.11503)



Too heavy for current or future collider search.
Low number density make direct/in-direct search difficult.

The mass of new particles in New Physics Model

Neutrino mass problem: Right handed neutrino and Seesaw Mechanism

$$\mathcal{L}_m = -\frac{1}{2}\left(\nu_L^c\ ,\nu_R\right)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

if $M_R \gg m_D$

$$m_\nu \approx \frac{m_D^2}{M_R}\ ,\ m_N \approx M_R$$

$$m_N \in (1\text{GeV}\ ,\ 10^{15}\text{GeV})$$

(1303.6912)

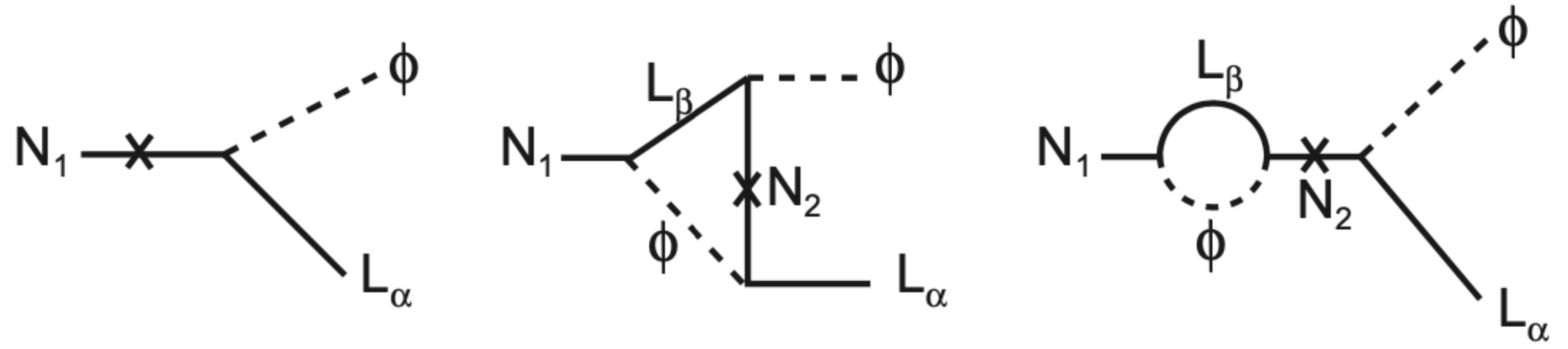
Almost no mass limits.

The mass of new particles in New Physics Model

Solutions for BAU: Leptogenesis, Electroweak baryogenesis, …

Leptogenesis

$$\mathcal{L} = h^*_\beta(\bar{L}_\beta \phi^{c*})E_\beta - \lambda^*_{\alpha k}(\bar{L}_\alpha \phi^*)N_k - \frac{1}{2}\bar{N}_j M_j N^c_j + \text{h.c.},$$



$$\epsilon \equiv \frac{\Gamma(N_1 \to \phi L) - \Gamma(N_1 \to \phi^\dagger \bar{L})}{\Gamma(N_1 \to \phi L) + \Gamma(N_1 \to \phi^\dagger \bar{L})} \sim \frac{3M_1}{16\pi v^2 (\lambda^\dagger \lambda)_{11}} \mathcal{I}m \left[\sum_{\alpha,\beta} \lambda^*_{\alpha 1} \lambda^*_{\beta 1} m^\nu_{\beta\alpha} \right]$$

L → B

Sphaleron

To prevent thermal wash out, RHN need to be quite heavy

$$M_1 \gtrsim 10^{11}\ \text{GeV}$$

The mass of new particles in New Physics Model

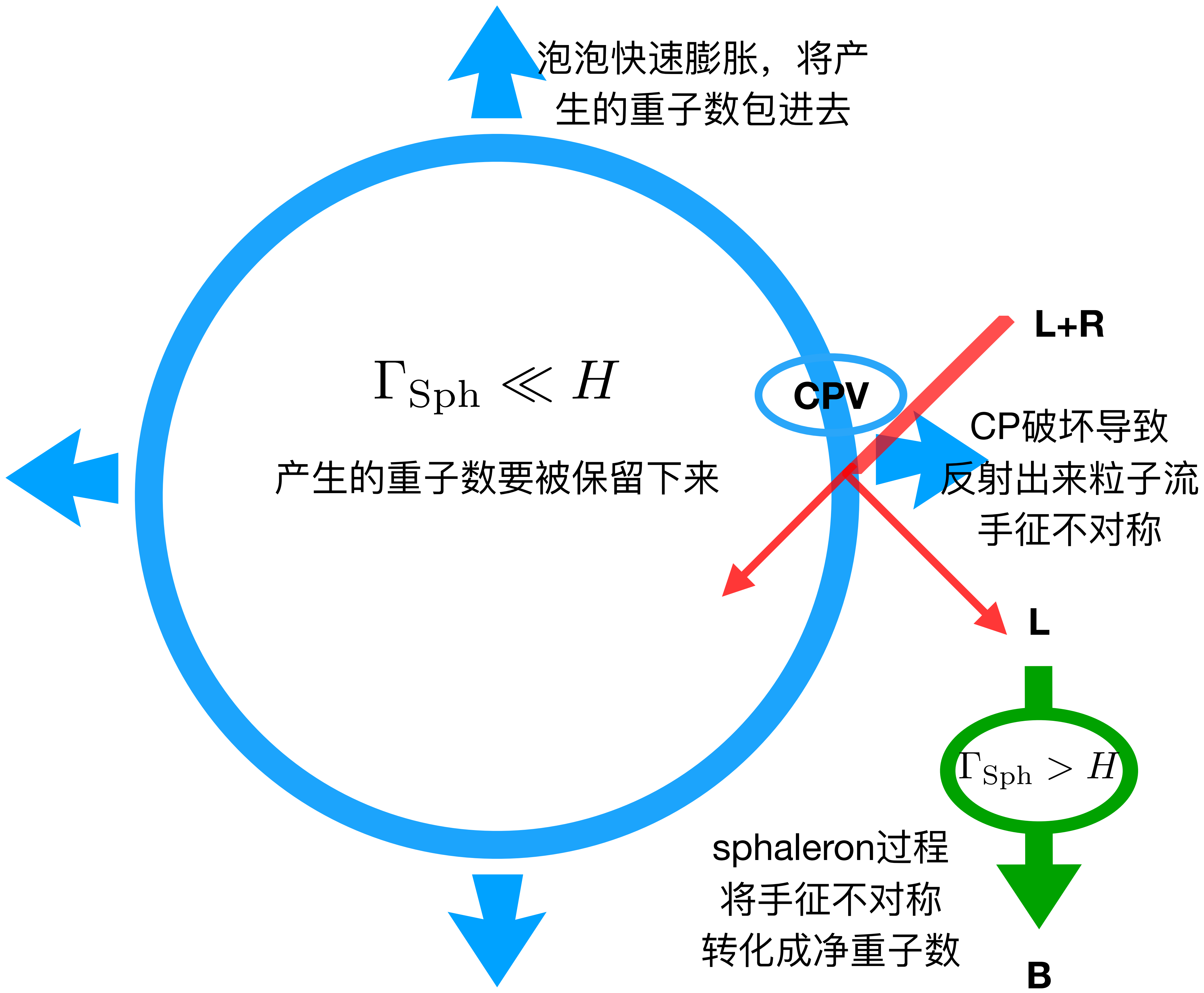
Conclusion by now:

Most New Physics model have a mass upper limit, which is much beyond the reach of current/future collider experiments.

The only promising one seem to be: Electroweak baryogenesis.

The mass of new particles in New Physics Model

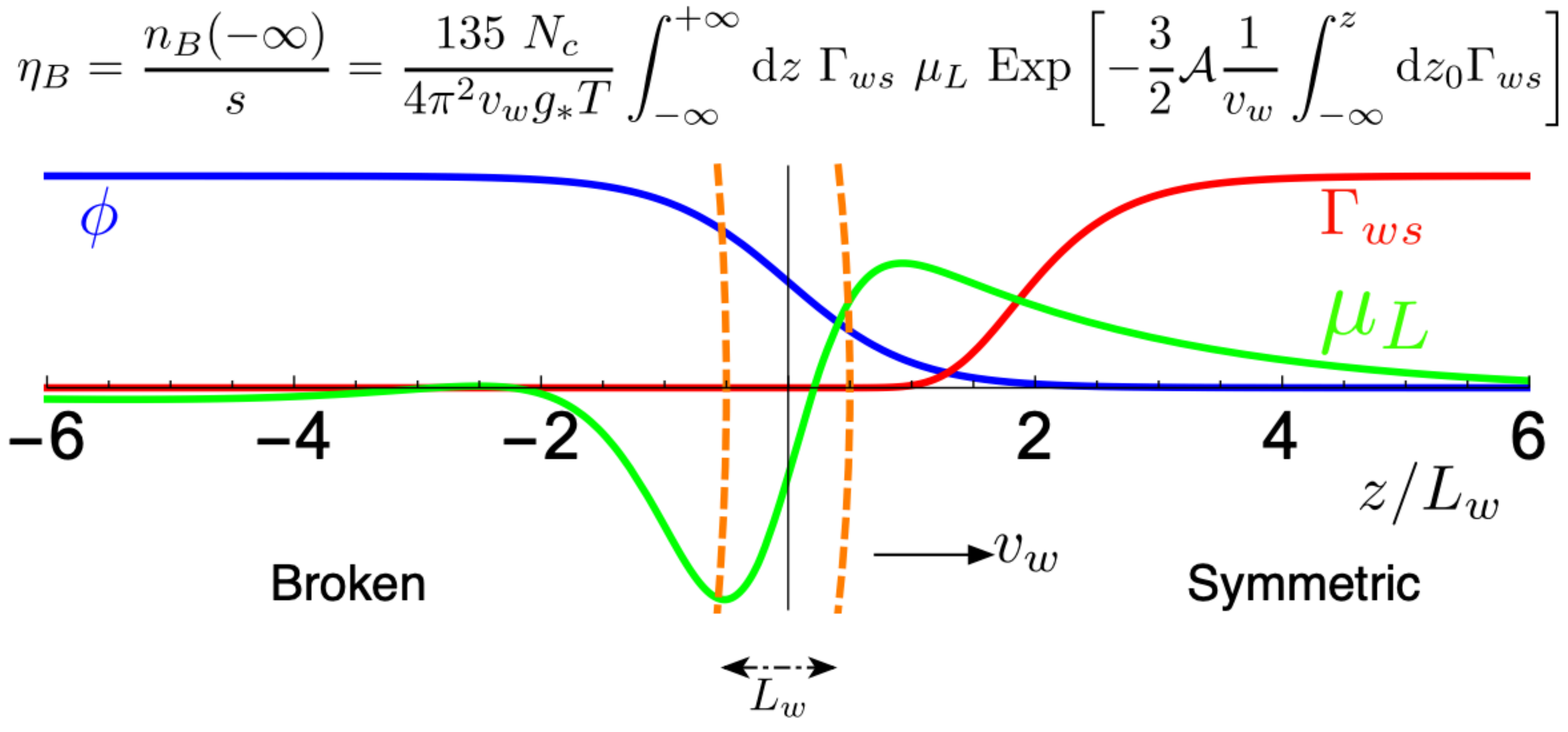
Electroweak baryogenesis



$$\frac{dn_B}{dt} + 3Hn_B = \frac{3}{2}\frac{\Gamma_{sph}(\mathrm{sym})}{T}\left(\mu_L(\mathrm{sym}) - \frac{15}{2}\frac{n_B}{T^2}\right)$$

chemical potential
Induced by diffusion

(borrowed from Chang Sub Shin)



(1706.08534)

The mass of new particles in New Physics Model

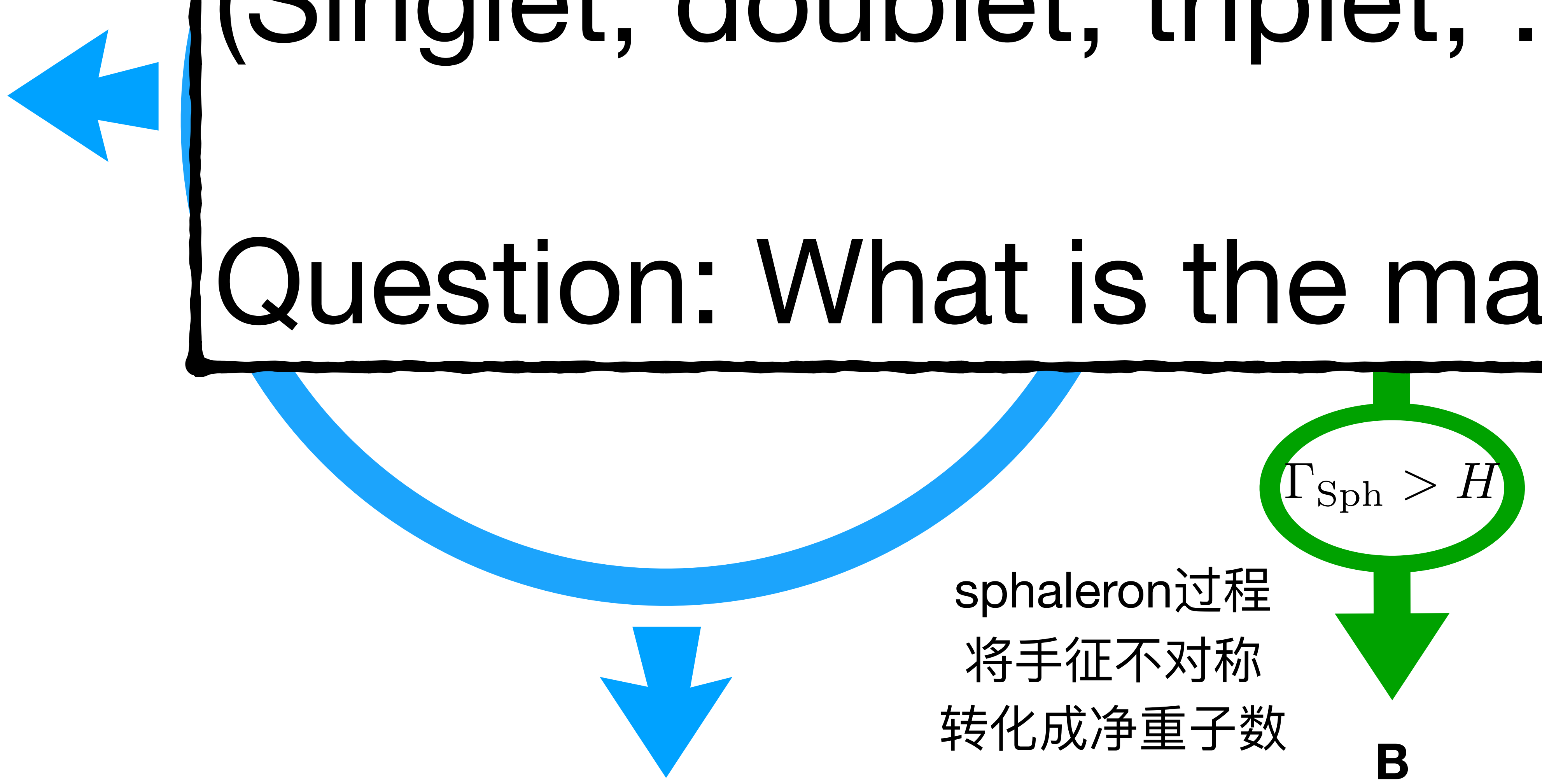
Electr

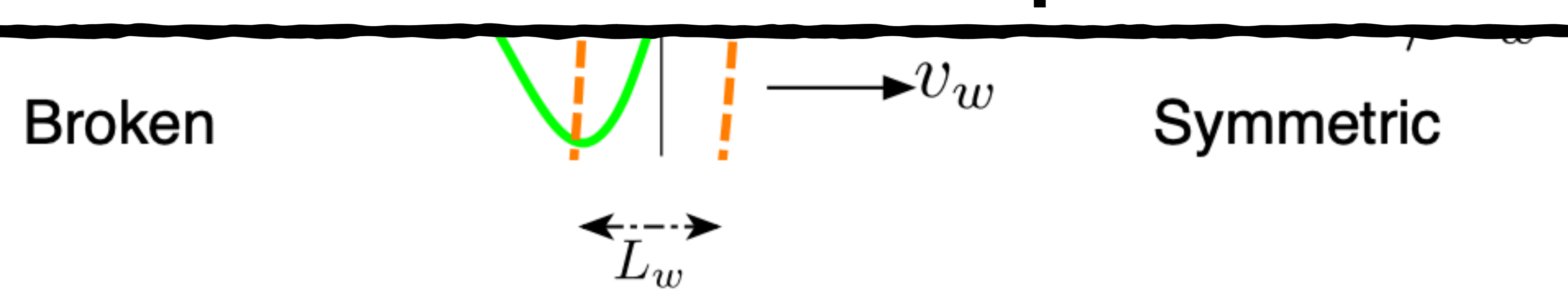
The SM EW phase transition is “crossover”.

For nucleation process we need 1st order PT.

Thus SM should be extended by some new particles.
(Singlet, doublet, triplet, …)

Question: What is the mass up-limits for these new particles?





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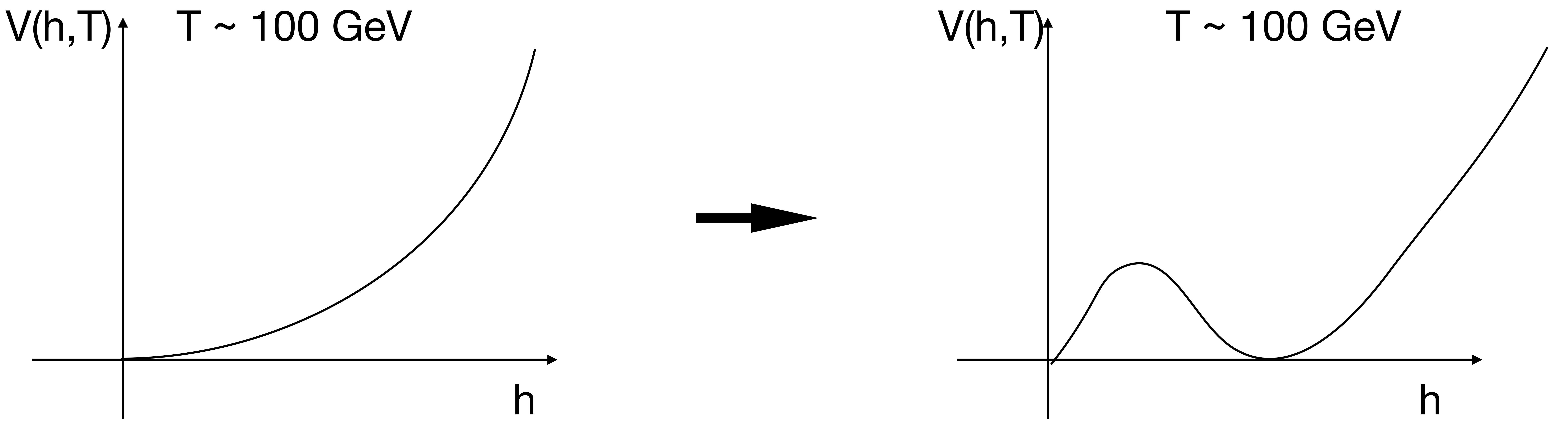
Strong 1st order PT constraints New Physics

We need to modify the shape of Higgs thermal potential when T ~ 100 GeV:

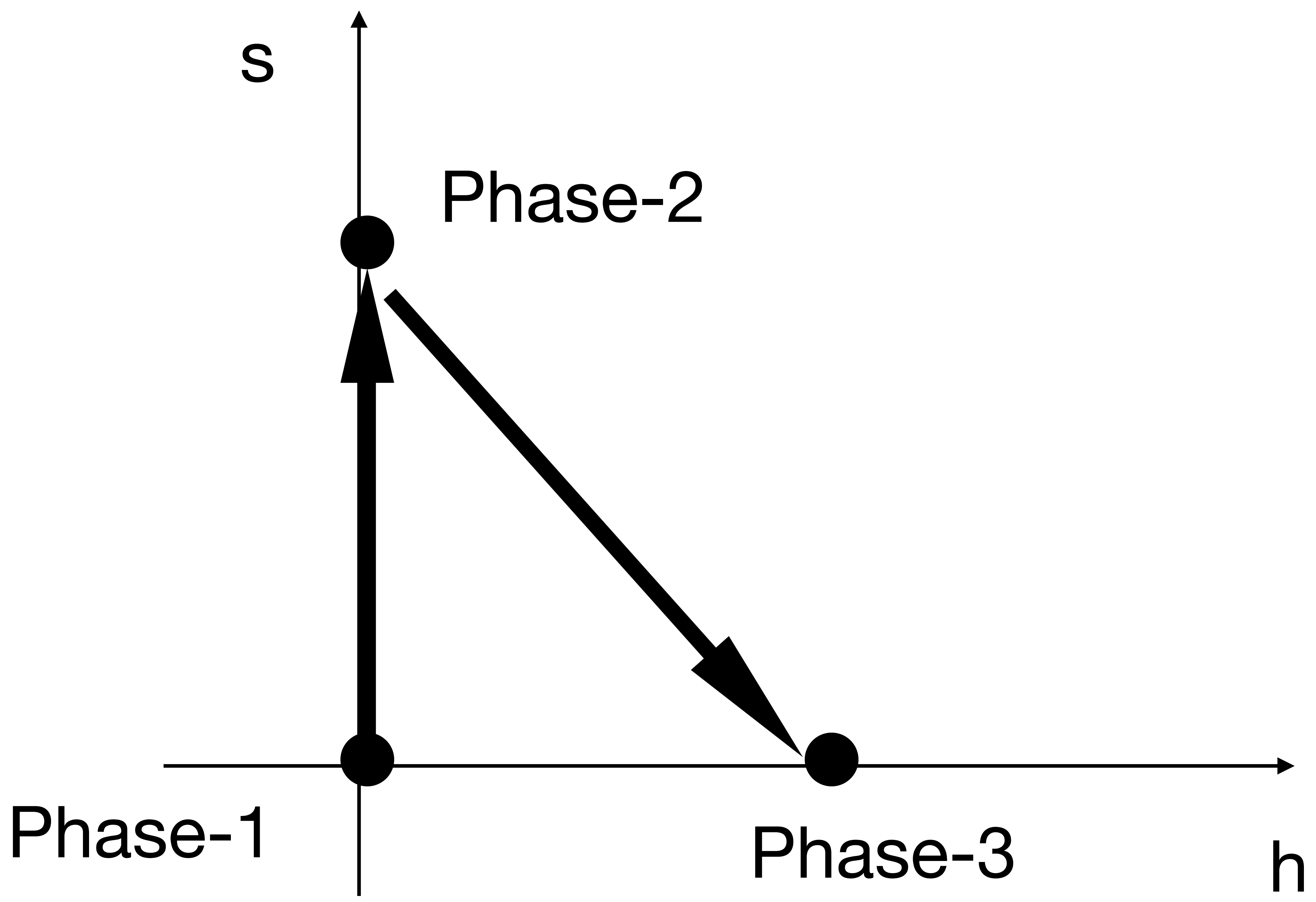


If the New particles are all very heavy, then Higgs thermal potential at T ~ 100 GeV will be SM like, and there is only “crossover”.

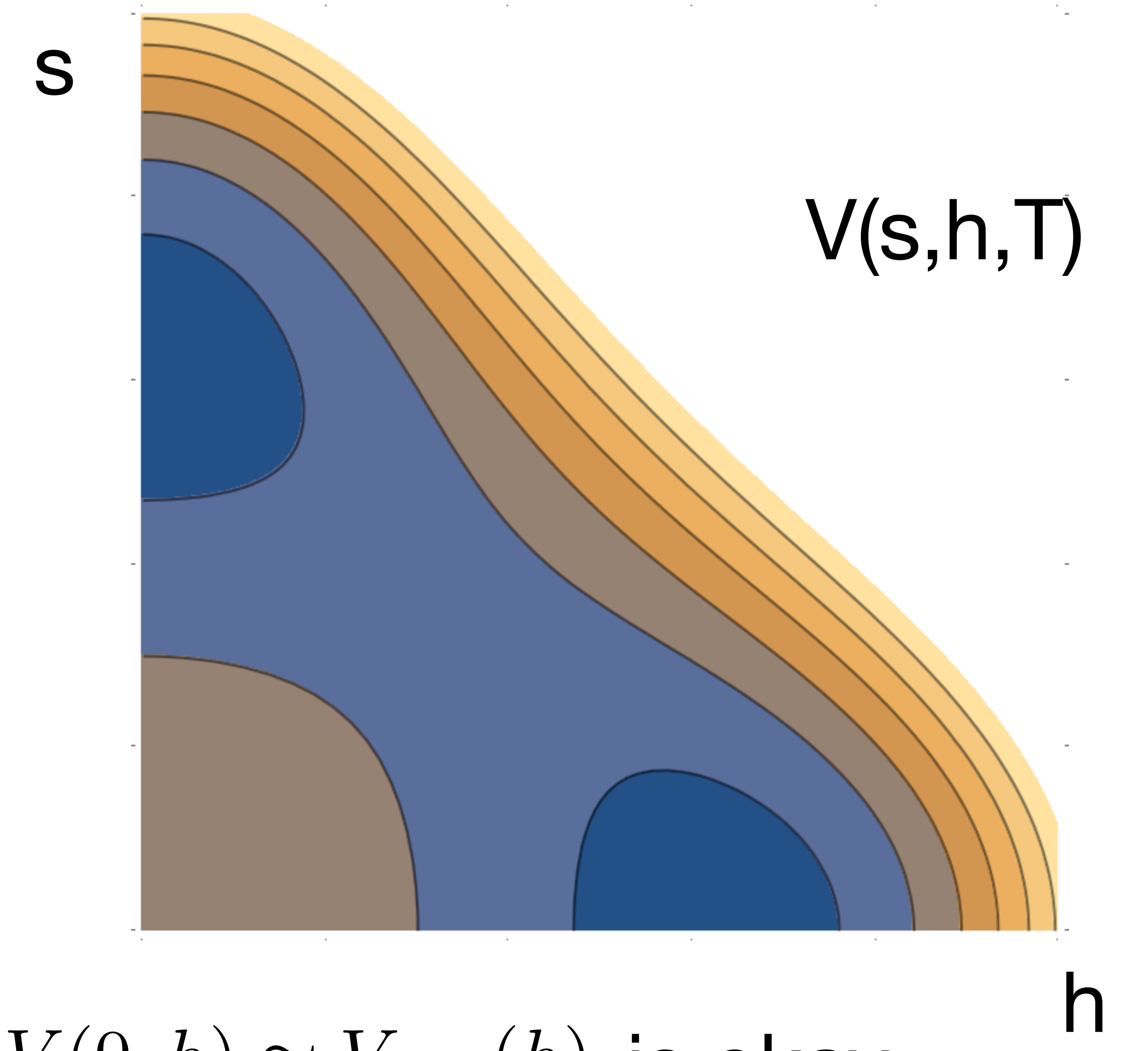
So, at least some new particles need to be light enough. (Mass up-limits)

Strong 1st order PT constraints New Physics

But above argument can not be used on singlet extension. Because of 2-step phase transition



Energy barrier is between “s” and “h”, not between two minimum of “h”.



$V(0,h) \approx V_{SM}(h)$ is okay.

So we choose doublet extension (2HDM) as our benchmark model.

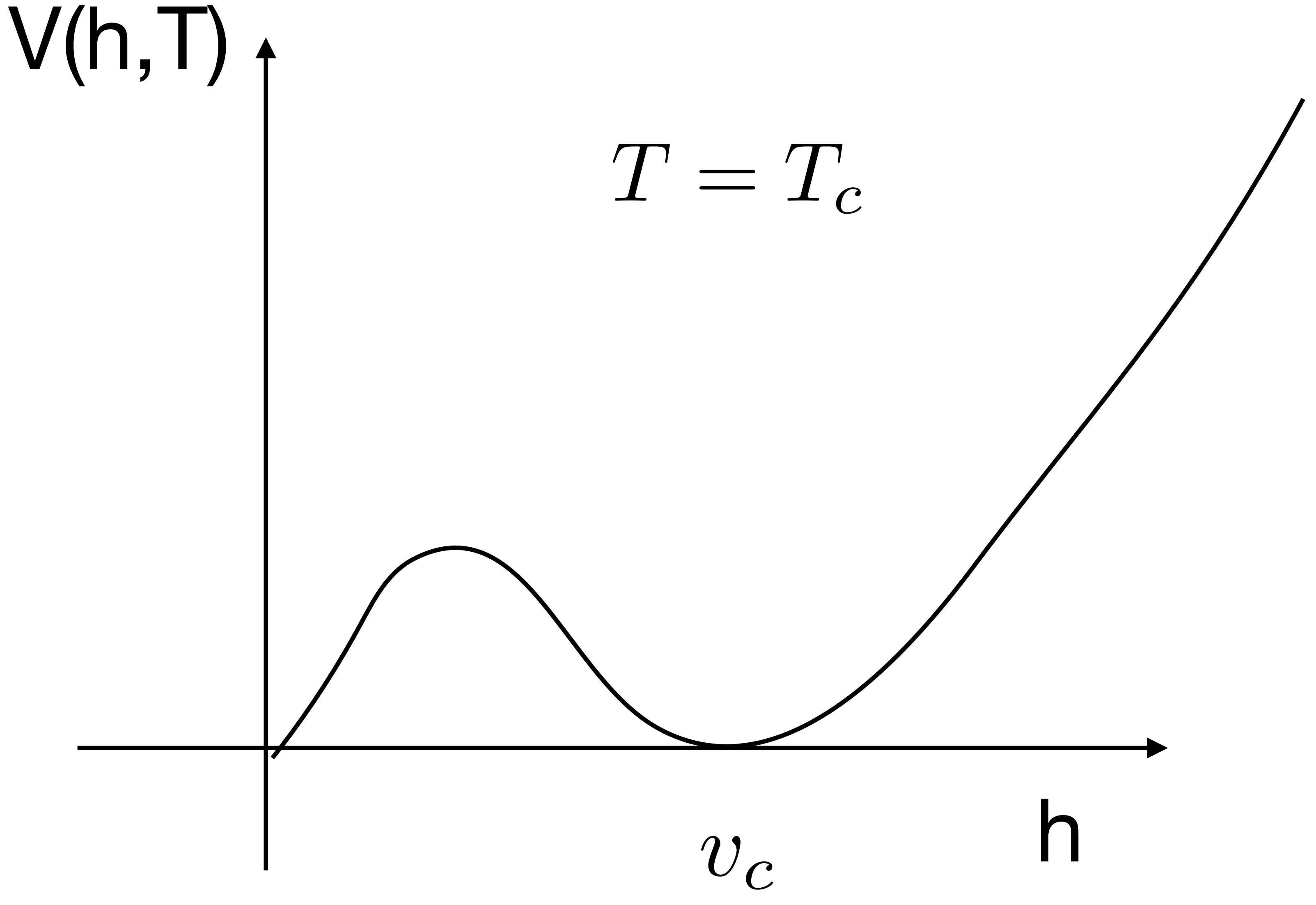
Strong 1st order PT constraints New Physics

"Strong" means the baryon generated around bubble wall will not be "washed out" inside bubble:

(1101.4665)

$$\frac{dn_B}{dt} = -\frac{13n_f}{2}\frac{\Gamma_{\rm sph}}{T^3}n_B$$

$$\frac{n_B\left(\Delta t_{\rm EW}\right)}{n_B(0)} = \exp\left[-\frac{13n_f}{2}\int_0^{\Delta t_{\rm EW}} dt \frac{\Gamma_{\rm sph}(T(t))}{T^3(t)}\right]$$



$$\Gamma_{\rm sph} \sim \left(\frac{E_{\rm Sph}}{T}\right)^3 \left(\frac{m_w(T)}{T}\right)^4 T^4 e^{\frac{-E_{\rm Sph}}{T}}$$

$\longrightarrow$ $\frac{v_c}{T_c} \gtrsim 1$ (wash-out parameter)

Thermal effective potential

To study phase transition, you need to know Free-energy as a function of order parameter.
In our case, free-energy (density) is the thermal effective potential, order parameter is Higgs field value.

$$V(\phi_1,\phi_2,T) = V^0(\phi_1,\phi_2) + V^{\mathrm{CW}}(\phi_1,\phi_2) + V^{\mathrm{CT}}(\phi_1,\phi_2) + V^{\mathrm{T}}(\phi_1,\phi_2,T)$$

Tree-level potential

$$V^0(\phi_1,\phi_2) = \frac{1}{2}m_{11}^2\phi_1^2 + \frac{1}{2}m_{22}^2\phi_2^2 - m_{12}^2\phi_1\phi_2 + \frac{1}{8}\lambda_1\phi_1^4 + \frac{1}{8}\lambda_2\phi_2^4 + \frac{1}{4}\lambda_{345}\phi_1^2\phi_2^2.$$

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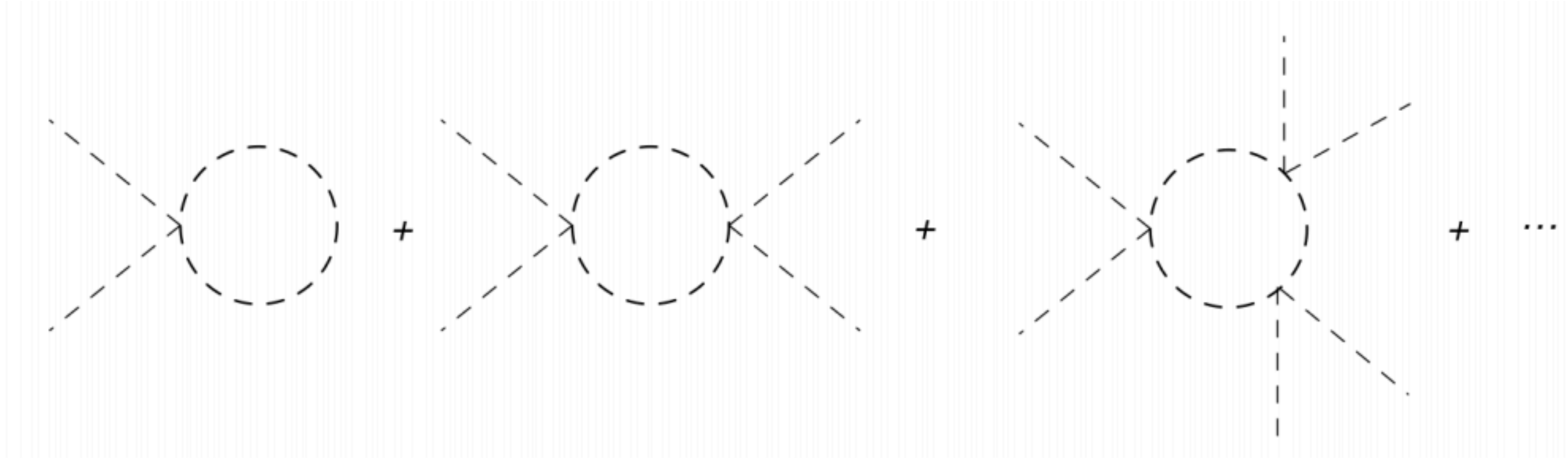
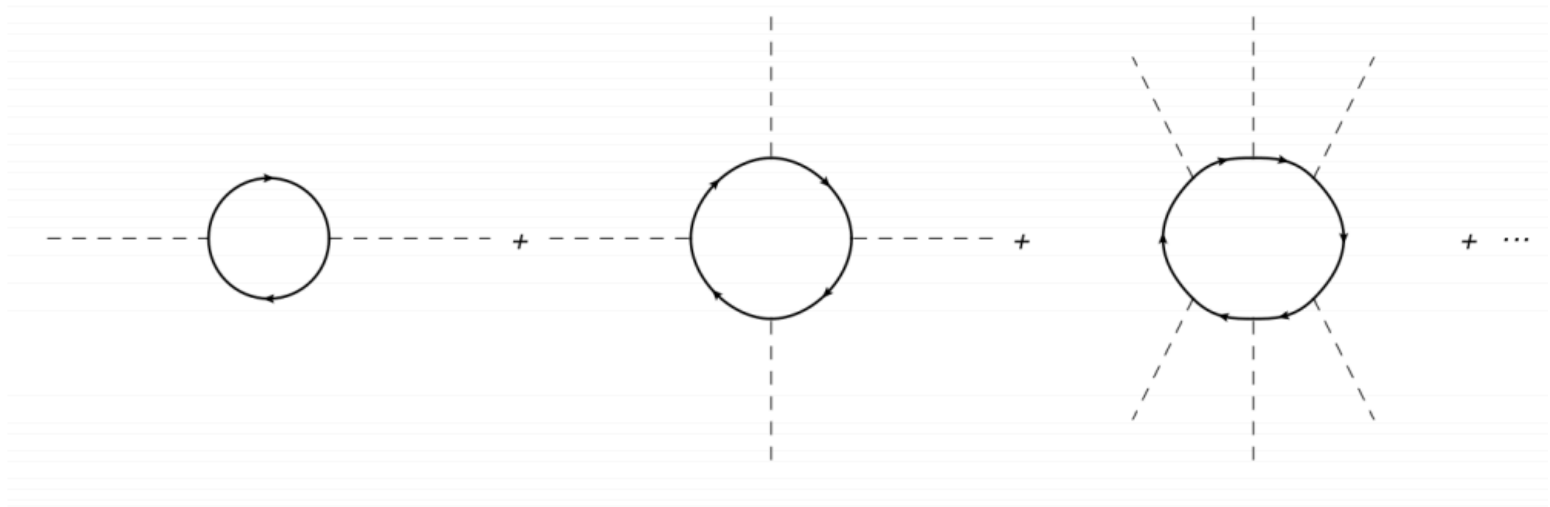
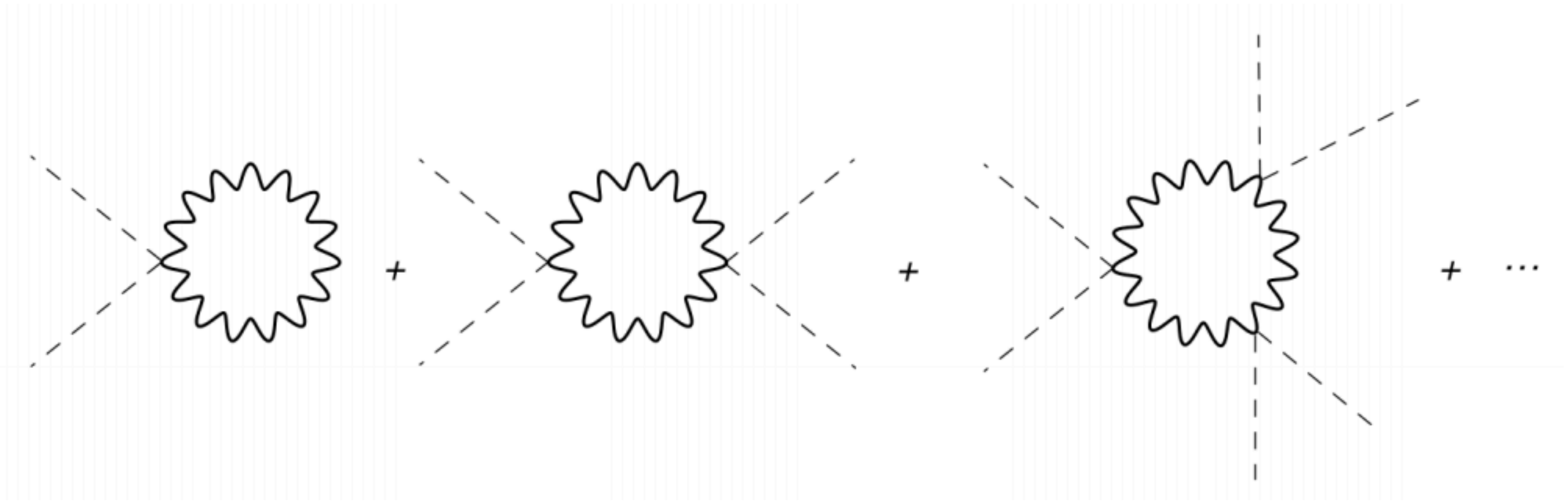
Coleman-Weinberg potential

$$V^{\mathrm{CW}}(\phi_1, \phi_2) = \frac{1}{64\pi^2} \sum_i n_i m_i^4(\phi_1, \phi_2) \left[\ln \frac{m_i^2(\phi_1, \phi_2)}{\mu^2} - c_i \right]$$







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Counter term

$$\begin{aligned} V^{\rm CT}(\Phi_1,\Phi_2) =& \delta m_{11}^2 \Phi_1^\dagger\Phi_1 + \delta m_{22}^2 \Phi_2^\dagger\Phi_2 - \delta m_{12}^2\left(\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{\delta\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\delta\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\ &+\delta\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \delta\lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\delta\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] + \delta t_1\phi_1 + \delta t_2\phi_2. \end{aligned}$$

Fixed by “on-shell” condition

$$\begin{aligned} \partial_{\psi_i}\left(V^{\rm CT}(\Phi_1,\Phi_2) + V^{\rm CW}(\Phi_1,\Phi_2)\right) &= 0 \\ \partial_{\psi_i}\partial_{\psi_j}\left(V^{\rm CT}(\Phi_1,\Phi_2) + V^{\rm CW}(\Phi_1,\Phi_2)\right) &= 0, \end{aligned}$$

Thermal effective potential

To study phase transition, you need to know Free-energy as a function of order parameter.
In our case, free-energy (density) is the thermal effective potential, order parameter is Higgs field value.

$$V(\phi_1, \phi_2, T) = V^0(\phi_1, \phi_2) + V^{\rm CW}(\phi_1, \phi_2) + V^{\rm CT}(\phi_1, \phi_2) + V^{\rm T}(\phi_1, \phi_2, T)$$

Thermal correction:

$$\begin{aligned} V^T(\phi_1, \phi_2, T) = & \frac{T^4}{2\pi^2} \sum_i n_i J_B\left(\frac{m_i^2(\phi_1, \phi_2)}{T^2}\right) + \frac{T^4}{2\pi^2} \sum_j n_j J_F\left(\frac{m_j^2(\phi_1, \phi_2)}{T^2}\right) \\ & - \frac{T^4}{12\pi} \sum_k n_k \left[\left(\frac{\tilde{m}_k^2(\phi_1, \phi_2, T)}{T^2}\right)^{3/2} - \left(\frac{m_k^2(\phi_1, \phi_2)}{T^2}\right)^{3/2}\right]. \end{aligned}$$

Thermal effective potential

Theoretical uncertainty in wash-out parameter calculation is quite small:

Comparing with Lattice result: (1904.01329) . Uncertainty is around 10%.

	Method	T_c/GeV	L/T_c^4	ϕ_c/T_c	L/GeV^4
BM1	1-loop Parwani resum.	134.0 ± 8.75	0.396 ± 0.002	1.01 ± 0.06	1.27×10^8
	1-loop A-E resum.	142.4 ± 6.88	0.33 ± 0.02	1.00 ± 0.07	1.37×10^8
	2-loop V_{eff} in 3d	111.6 ± 2.30	0.57 ± 0.10	0.98 ± 0.09	0.89×10^8
	3d lattice	116.40 ± 0.005	0.60 ± 0.02	1.08 ± 0.02	1.11×10^8
BM2	1-loop Parwani resum.	142.6 ± 18.0	0.29 ± 0.04	0.91 ± 0.06	1.19×10^8
	1-loop A-E resum.	162.5 ± 21.0	0.20 ± 0.03	0.88 ± 0.05	1.36×10^8
	2-loop V_{eff} in 3d	104.9 ± 2.30	0.61 ± 0.10	0.97 ± 0.06	0.74×10^8
	3d lattice	112.5 ± 0.01	0.81 ± 0.05	1.09 ± 0.03	1.29×10^8

Thermal effective potential

With the expression of thermal effective potential, we can search for the critical temperature & Higgs vev

Numerical method can be performed by public package:
1.CosmoTransitions
2.BSMPT
3.PhaseTracer

Analytical method to understand EWPT:
1.High temperature expansion
2.Higgs Vacuum Uplifting

Now let's focus on 2HDM

2HDM

$$V^0(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right]. \quad (2.1)$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + ia_1) \end{pmatrix} \quad , \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ia_2) \end{pmatrix}$$

$$\mathcal{M}_{\text{even}}^2 = \begin{pmatrix} m_{12}^2\tan\beta + \lambda_1 v_1^2 & -m_{12}^2 + v_1 v_2\lambda_{345} \\ -m_{12}^2 + v_1 v_2 \lambda_{345} & m_{12}^2/\tan\beta + \lambda_2 v_2^2 \end{pmatrix}$$

$$\mathcal{M}_{\text{odd}}^2 = (m_{12}^2 - v_1 v_2 \lambda_5)\begin{pmatrix} \tan\beta & -1 \\ -1 & 1/\tan\beta \end{pmatrix},$$

$$\mathcal{M}_{\text{charged}}^2 = \left(m_{12}^2 - \frac{1}{2}v_1 v_2\left(\lambda_4+\lambda_5\right)\right)\begin{pmatrix} \tan\beta & -1 \\ -1 & 1/\tan\beta \end{pmatrix}$$

Mass square for non-SM Higgs can be expressed as:

$$m_\alpha^2(\phi_h) = M^2 + \lambda_\alpha \phi_h^2 \qquad M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

2HDM

Limits on parameter space:

- **Vacuum stability**

$$\lambda_1 > 0\ ,\ \ \lambda_2 > 0\ ,\ \ \lambda_3 > -\sqrt{\lambda_1\lambda_2}\ ,\ \ \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$$

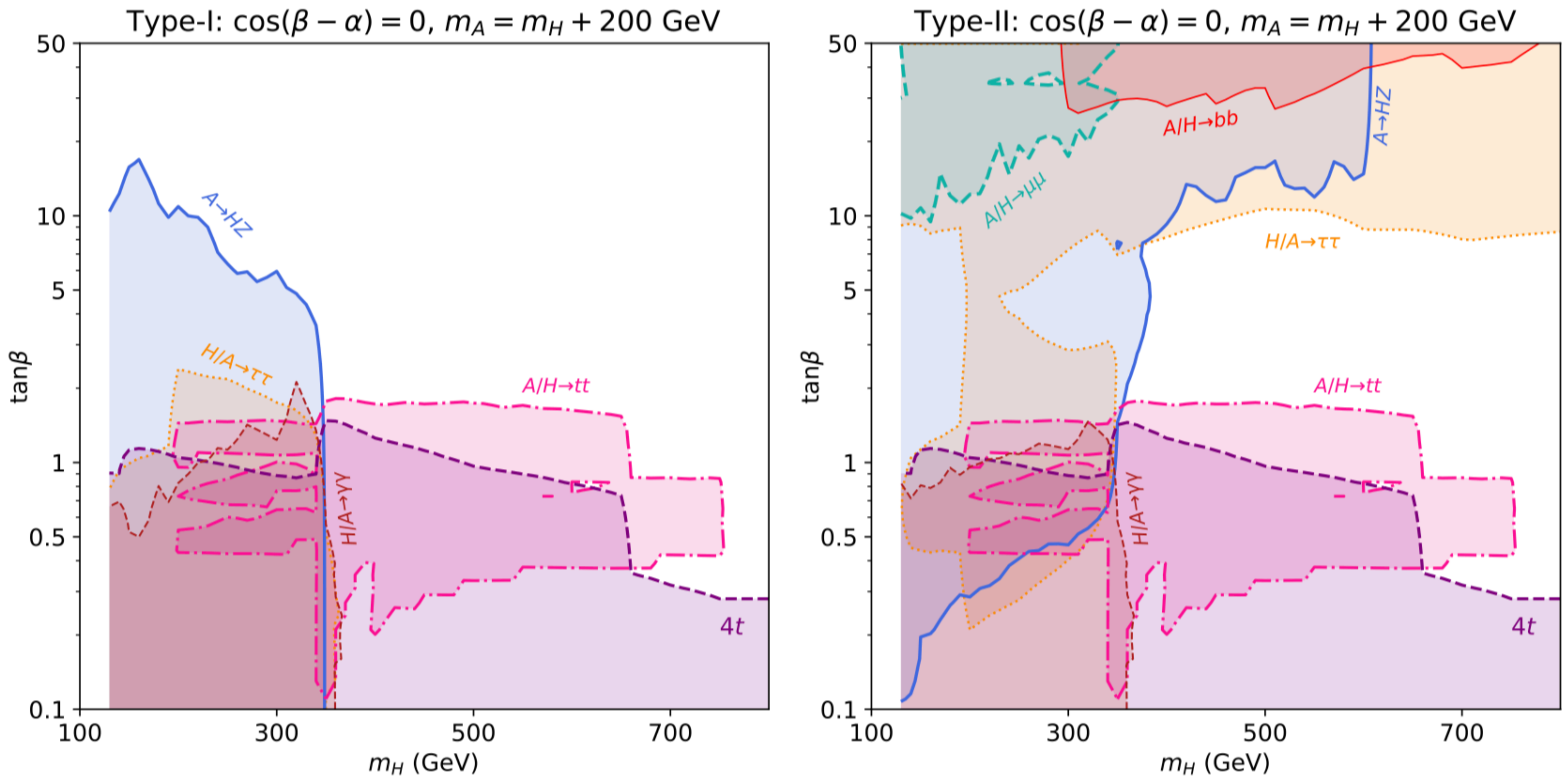
- **Perturbativity and unitarity**

$$\left|3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2}\right| < 16\pi\ ,$$
$$\left|(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right| < 16\pi\ ,$$
$$\left|(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2}\right| < 16\pi\ ,$$
$$|\lambda_3 + 2\lambda_4 \pm 3\lambda_5| < 8\pi\ ,\ \ |\lambda_3 \pm \lambda_4| < 8\pi\ ,\ \ |\lambda_3 \pm \lambda_5| < 8\pi$$

2HDM

Limits on parameter space:

Direct searches at LHC Run-II



Indirect searches with Higgs and Z pole precision measurements

Flavour constraints $B \to X_s \gamma$ $B_s \to \mu^+ \mu^-$

High temperature expansion

Before we present the scan result, let's do some analytical analysis.
When temperature is high enough:

$$\frac{T^4}{2\pi^2}J_B(\frac{m^2(\phi_h)}{T^2}) \approx -\frac{\pi^2 T^4}{90} + \frac{1}{24}T^2 m^2(\phi_h) - \frac{1}{12\pi}T(m^2(\phi_h))^{3/2} + \cdots$$
$$\frac{T^4}{2\pi^2}J_F(\frac{m^2(\phi_h)}{T^2}) \approx +\frac{7}{8}\frac{\pi^2 T^4}{90} - \frac{1}{48}T^2 m^2(\phi_h) + \cdots$$

$$\longrightarrow \quad V(\phi_h, T) \approx (DT^2 - \mu^2)\phi_h^2 - ET\phi_h^3 + \frac{\tilde{\lambda}}{4}\phi_h^4 \quad \longrightarrow \quad \xi_c \equiv \frac{v_c}{T_c} \approx \frac{2E}{\tilde{\lambda}}$$

$$\mu^2 = \frac{1}{4}m_h^2 \ , \ \tilde{\lambda} = \frac{m_h^2}{2v^2}$$

$$D = \frac{1}{24}\left[6\frac{m_W^2}{v^2} + 3\frac{m_Z^2}{v^2} + \frac{m_h^2}{v^2} + 6\frac{m_t^2}{v^2} + \frac{m_H^2 - M^2}{v^2} + \frac{m_A^2 - M^2}{v^2} + 2\frac{m_{H^\pm}^2 - M^2}{v^2}\right]$$

$$E = \frac{1}{12\pi}\left[6\frac{m_W^3}{v^3} + 3\frac{m_Z^3}{v^3} + \frac{m_h^3}{v^3}\right] + E_{(H/A/H^\pm)}$$

High temperature expansion

E-term determine the strength of PT. It comes from the m^3 term in J_B:

$$\frac{T^4}{2\pi^2}J_B(\frac{m^2(\phi_h)}{T^2}) \approx -\frac{\pi^2 T^4}{90} + \frac{1}{24}T^2 m^2(\phi_h) - \frac{1}{12\pi}T(m^2(\phi_h))^{3/2} + \cdots$$

$$\frac{T^4}{2\pi^2}J_F(\frac{m^2(\phi_h)}{T^2}) \approx +\frac{7}{8}\frac{\pi^2 T^4}{90} - \frac{1}{48}T^2 m^2(\phi_h) + \cdots$$

$\longrightarrow$

$$E = \frac{1}{12\pi}\left[6\frac{m_W^3}{v^3} + 3\frac{m_Z^3}{v^3} + \frac{m_h^3}{v^3}\right] + E_{(H/A/H^\pm)}$$

$$m_\alpha^2(\phi_h) = M^2 + \lambda_\alpha \phi_h^2$$

$\longrightarrow$

$$-\frac{1}{12\pi}T(m_\alpha^2(\phi_h))^{3/2} = -\frac{1}{12\pi}T(M^2 + \lambda_\alpha\phi_h^2)^{3/2}$$

$$-\frac{1}{12\pi}T(M^2 + \lambda_\alpha\phi_h^2)^{3/2} \approx \begin{cases} -\frac{T}{12\pi}\lambda_\alpha^{3/2}\phi_h^3, & M^2 \ll \lambda_\alpha\phi_h^2 \\ -\frac{T}{12\pi}M^3\left(1 + \frac{3}{2}\frac{\lambda_\alpha\phi_h^2}{M^2}\right), & M^2 \gg \lambda_\alpha\phi_h^2 \end{cases}$$

$\longrightarrow$

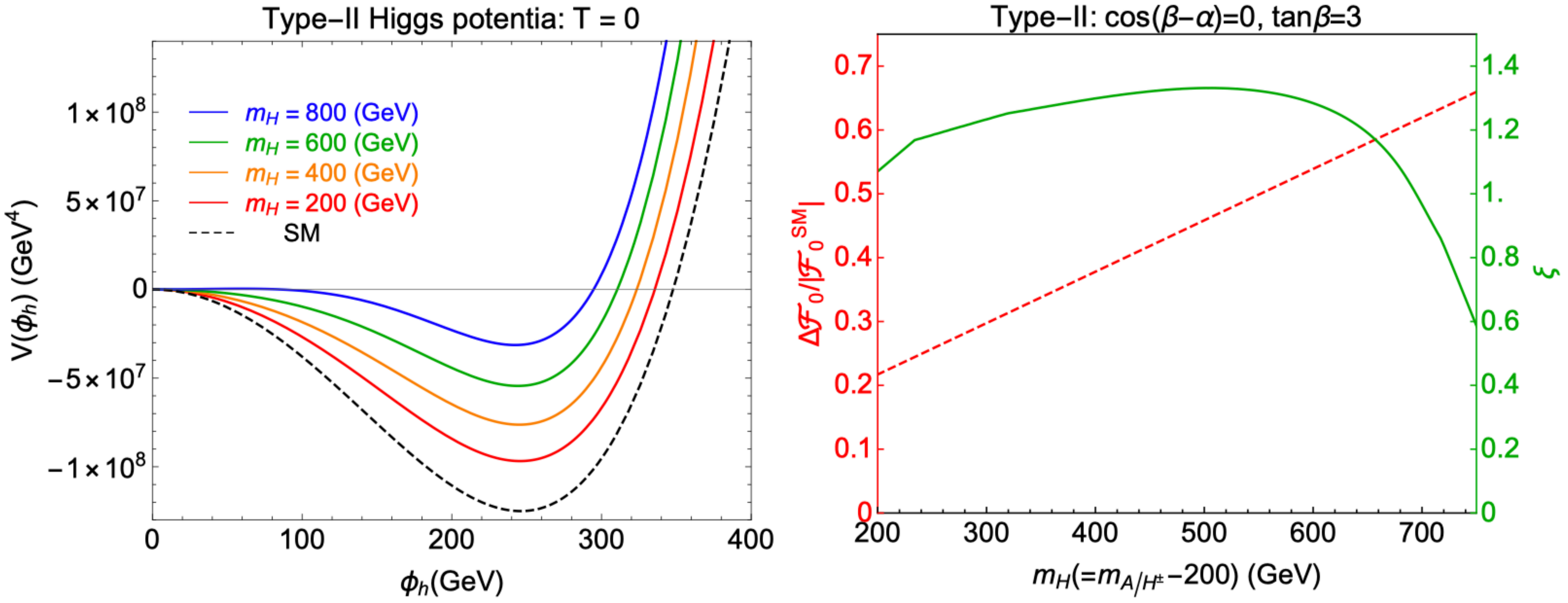
$$E_{(\alpha)} \approx \begin{cases} \frac{1}{12\pi}\lambda_\alpha^{3/2} = \frac{1}{12\pi}\frac{m_\alpha^3}{v^3}, & M^2 \ll \lambda_\alpha\phi_h^2 \\ 0, & M^2 \gg \lambda_\alpha\phi_h^2 \end{cases}$$

Higgs Vacuum Uplifting

Argument in “1705.09186”: a shallow Higgs potential is easier to develop an energy barrier between symmetric phase and broken phase than a deep Higgs potential, when temperature is high.

Consider a simplified scenario:

$$\tan\beta = 3.0\ ,\ \ \cos(\beta-\alpha) = 0,\ m_H \in [200\text{GeV}, 1000\text{GeV}]\ ,$$
$$\sqrt{\lambda v^2} = 0,\ \Delta m = m_{A/H^\pm} - m_H = 200\ \text{GeV}.$$



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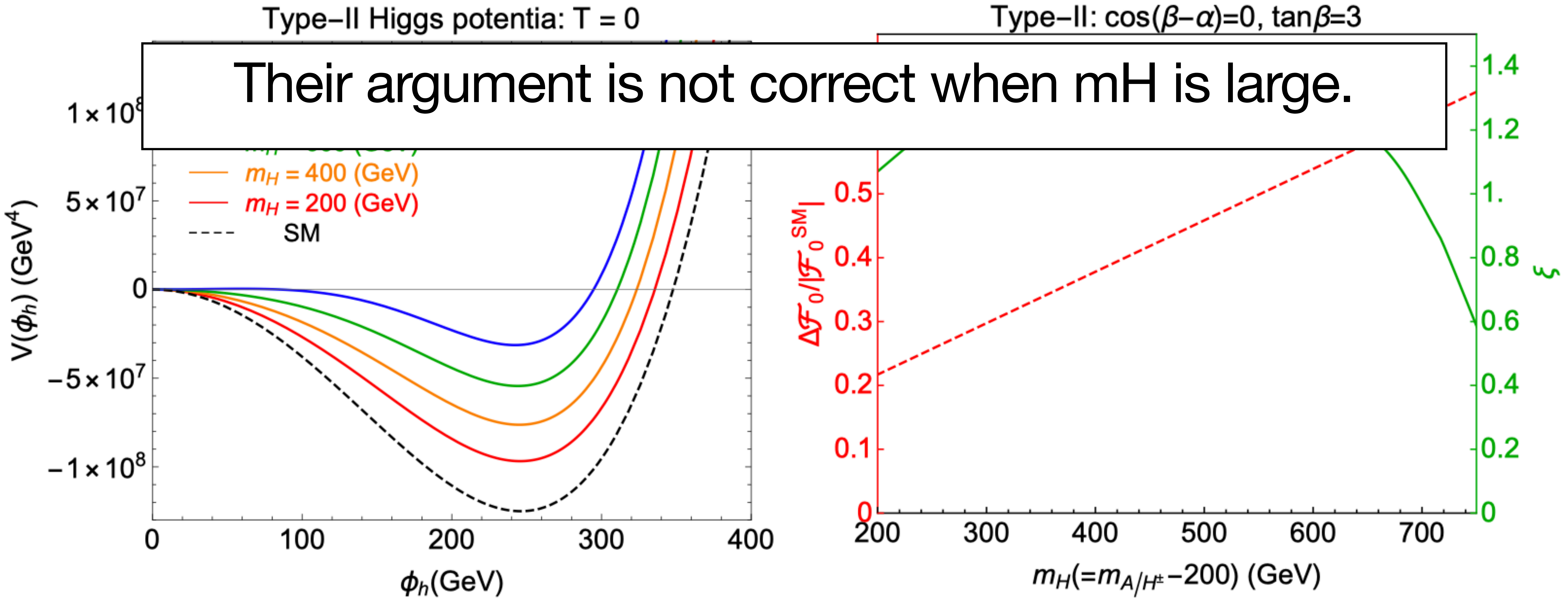
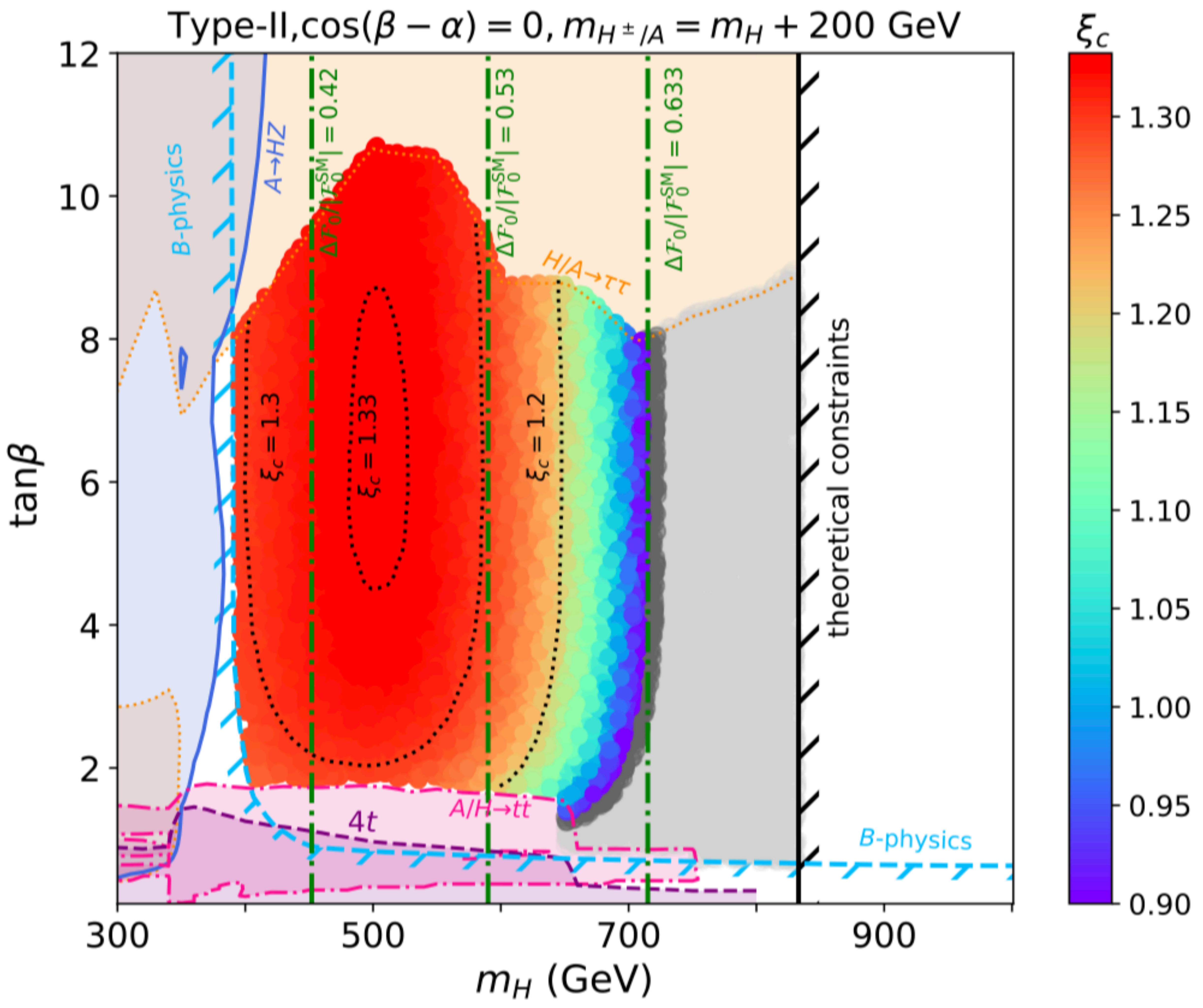


Their argument is not correct when mH is large.

Case1: alignment limit with fixed mass splitting

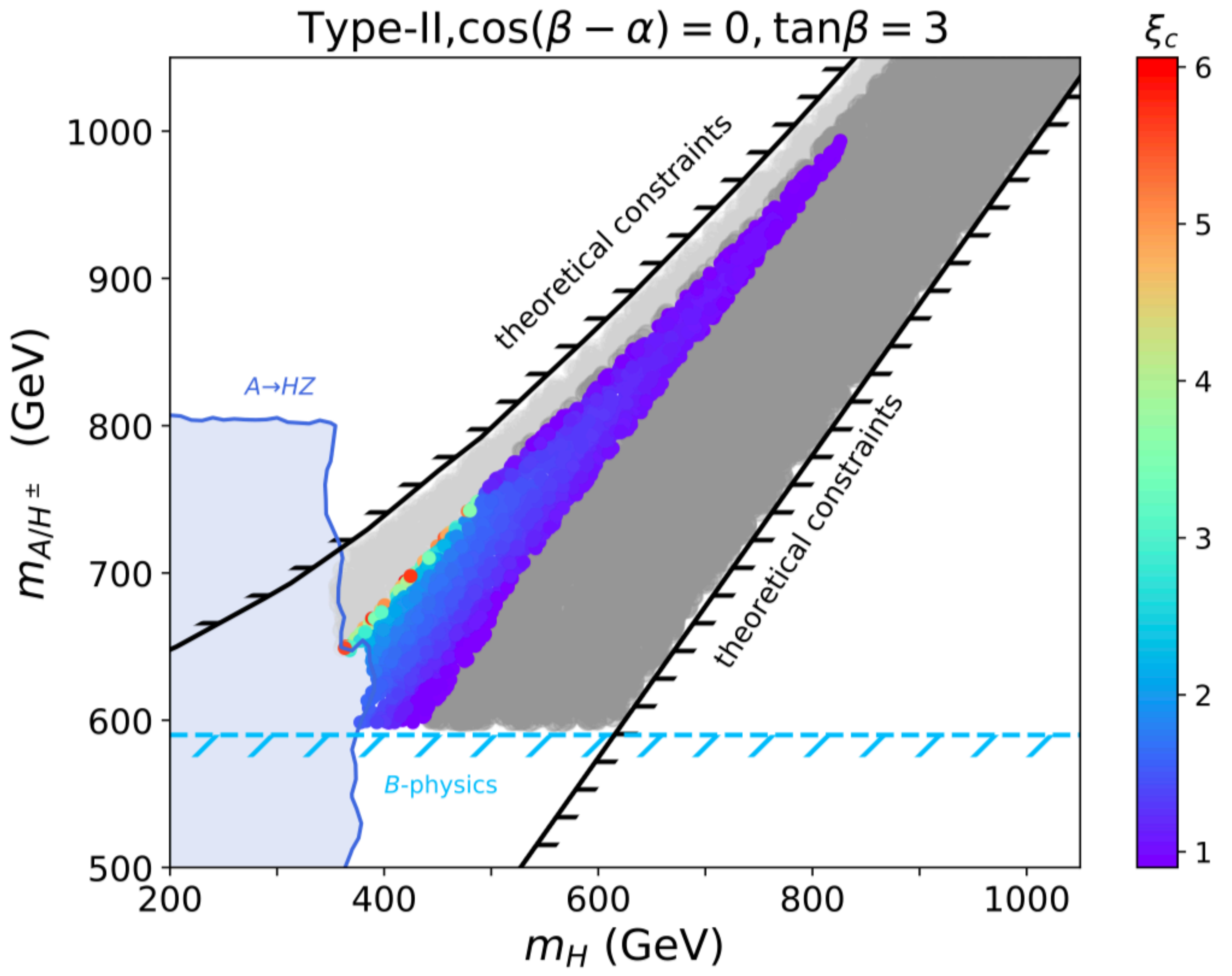
$$\tan\beta \in (0.2, 50),\ m_H \in (200, 1000)\ \text{GeV}\ ,$$

$$\cos(\beta-\alpha)\ = 0, \sqrt{\lambda v^2} = 0,\ \Delta m = m_{A/H^\pm} - m_H = 200\ \text{GeV}.$$



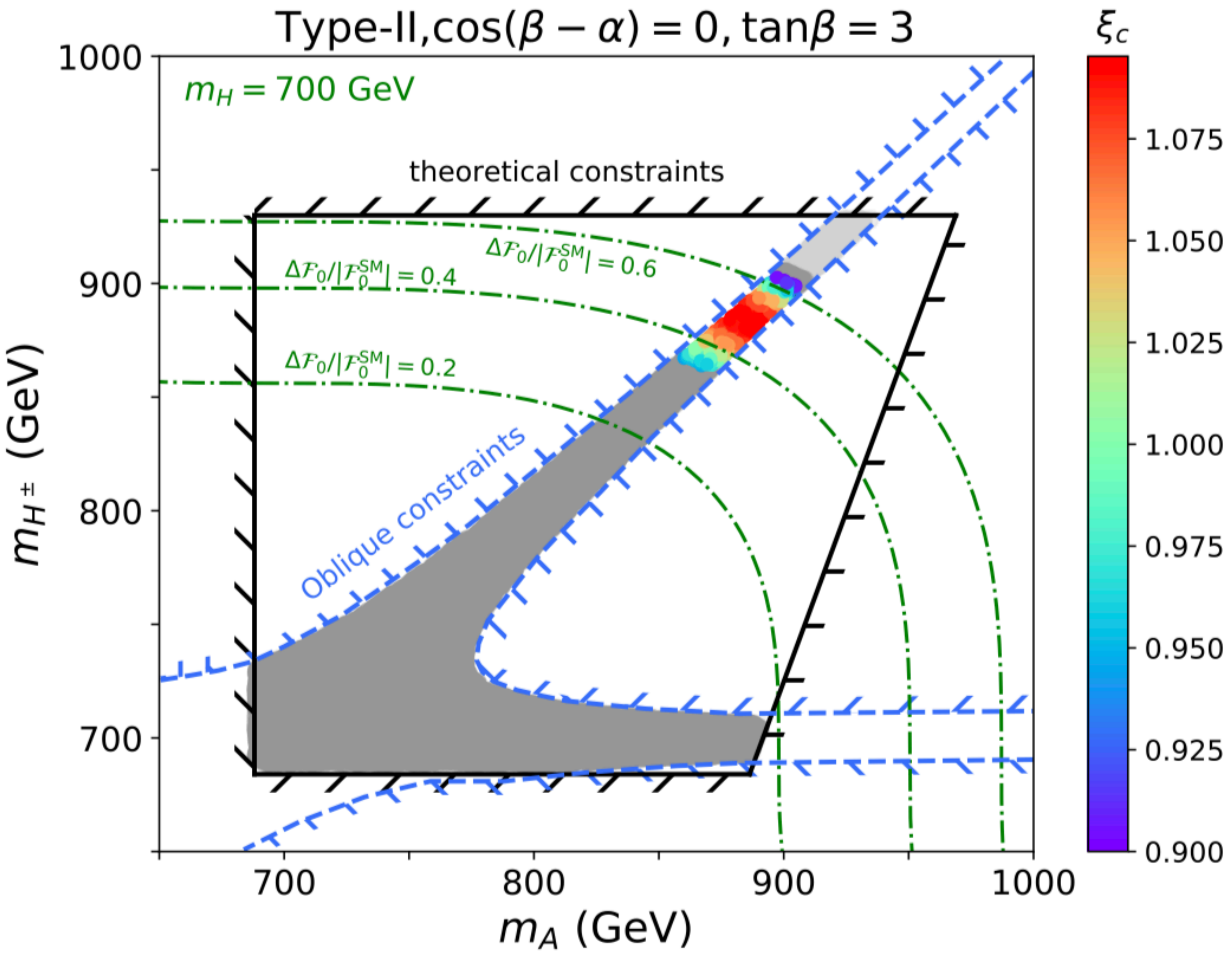
Case2: alignment limit with $m_A = m_{H^\pm}$

$$m_{A/H^\pm} \in (500, 1200)\ \text{GeV},\ m_H \in (200, 1000)\ \text{GeV}\ ,$$
$$\cos(\beta-\alpha) = 0, \sqrt{\lambda v^2} = 0,\ \tan\beta = 3.$$



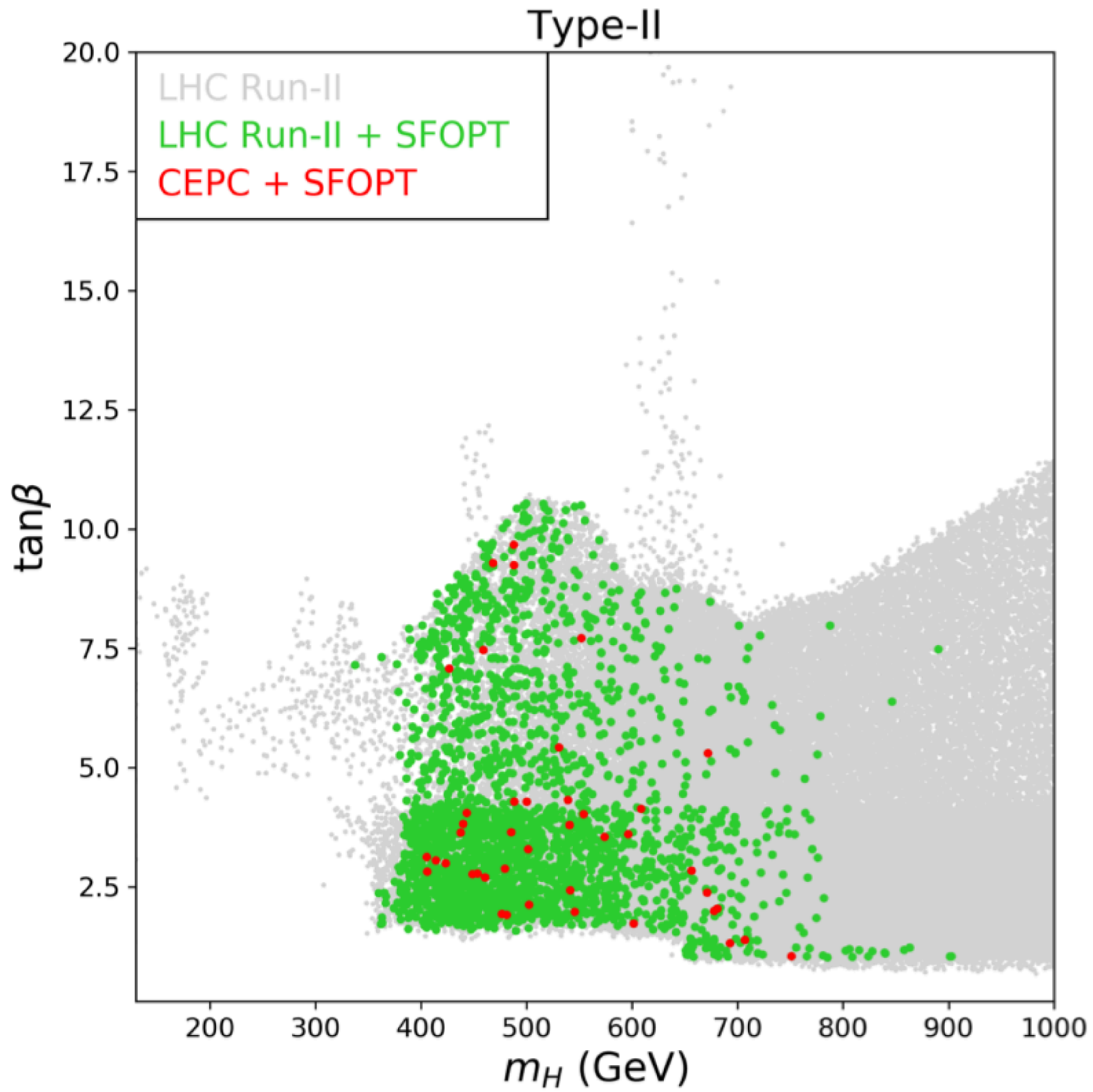
Case3: alignment limit with mH=700 GeV

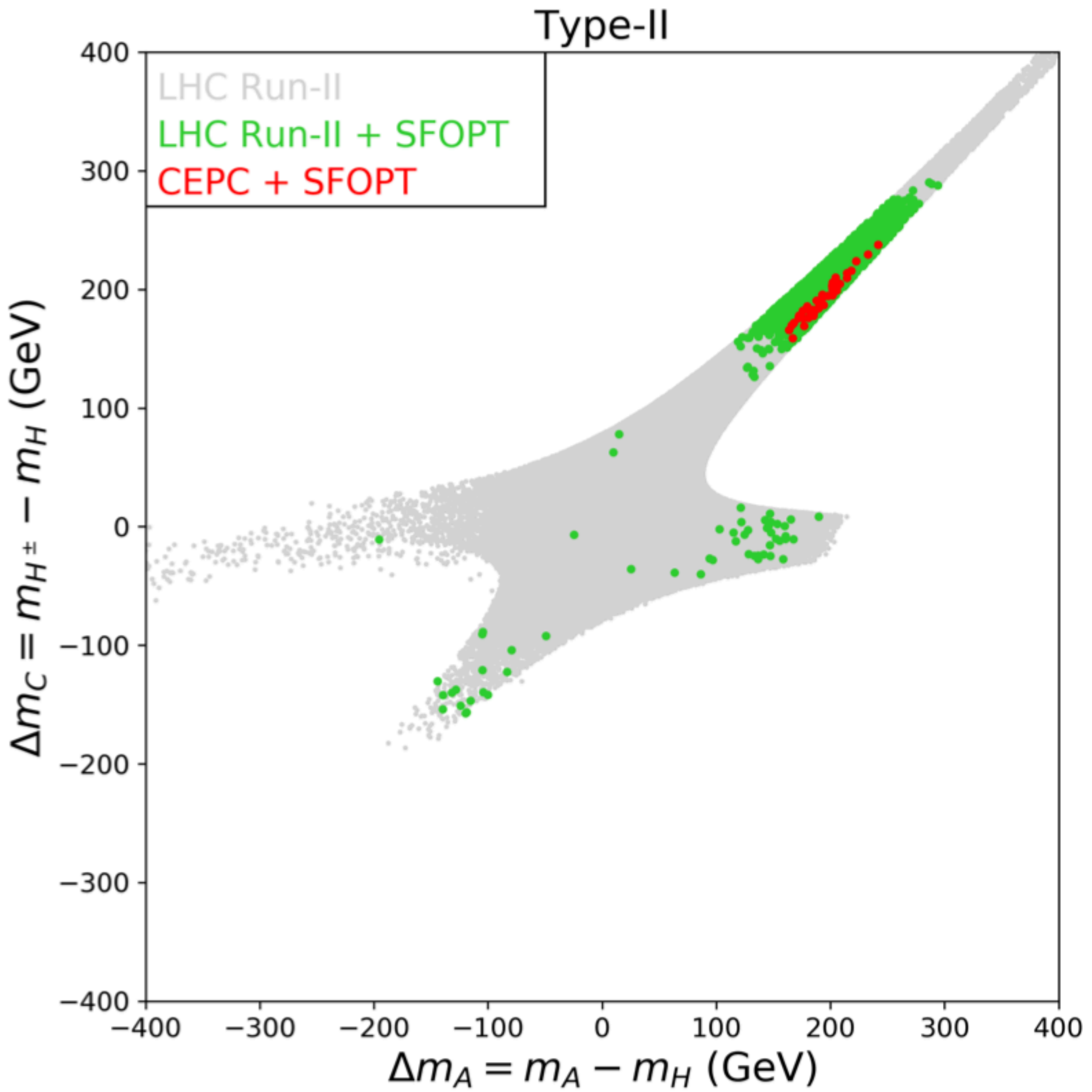
$$m_A \in (500, 1200)\ \text{GeV},\ m_{H^\pm} \in (500, 1200)\ \text{GeV},$$
$$m_H = 700\ \text{GeV},\ \cos(\beta-\alpha) = 0, \sqrt{\lambda v^2} = 0,\ \tan\beta = 3.$$



General results

$$|\alpha| < \frac{\pi}{2}, \tan\beta \in (0.2, 50),\ m_A \in (10, 1500)\ \text{GeV}\ ,\ m_{H^\pm} \in (10, 1500)\ \text{GeV}\ ,$$
$$m_{12}^2 \in (0, 1500^2)\ \text{GeV}^2,\ m_h = 125.1\ \text{GeV}, m_H \in (130, 1500)\ \text{GeV}.$$





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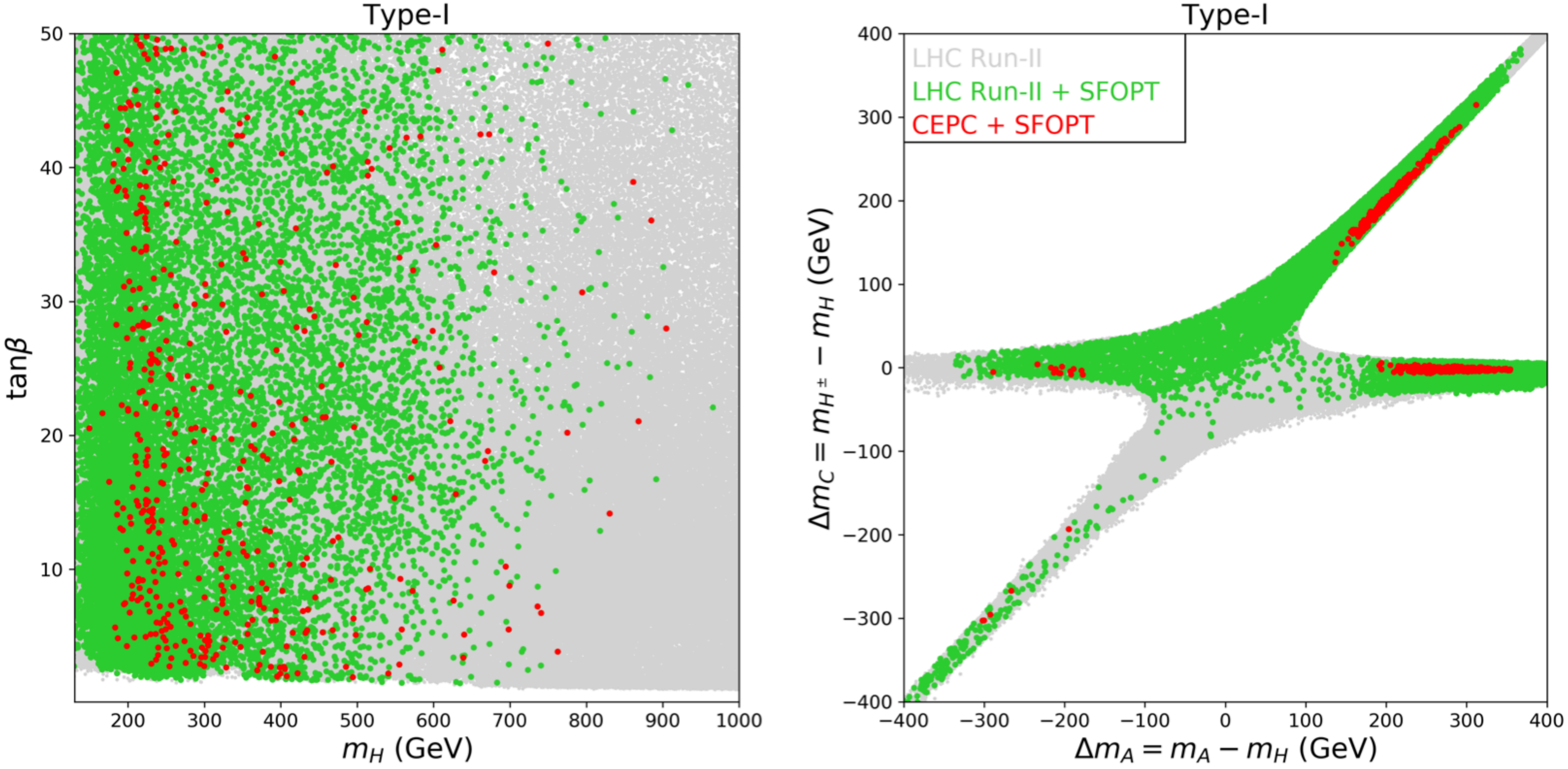
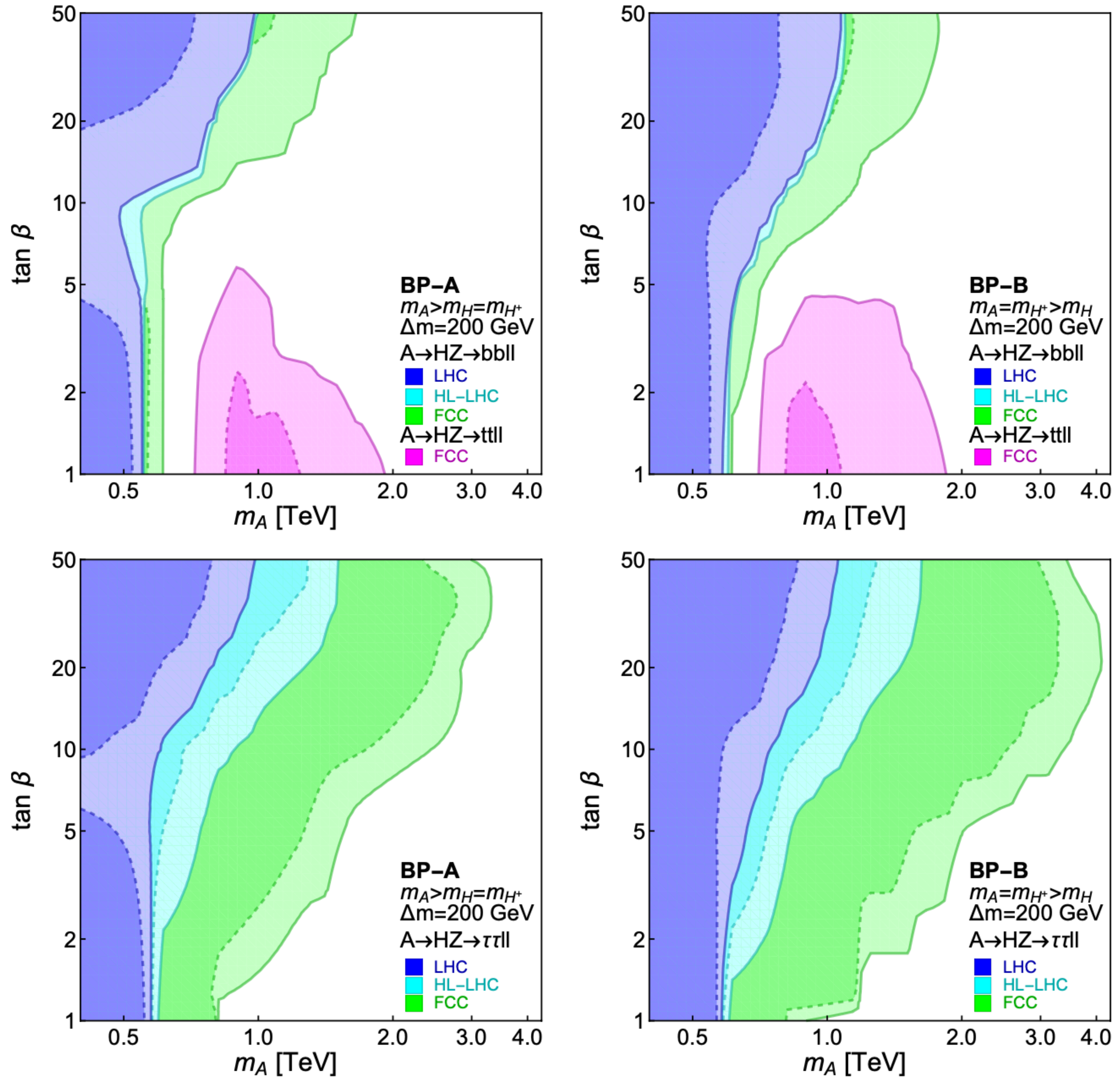


Future search



100 TeV pp collider can fully cover the parameter space of Type-II
“1812.01633”

GWs looks not so important

For 2HDM, collider is much more important than GWs. “2108.05356”

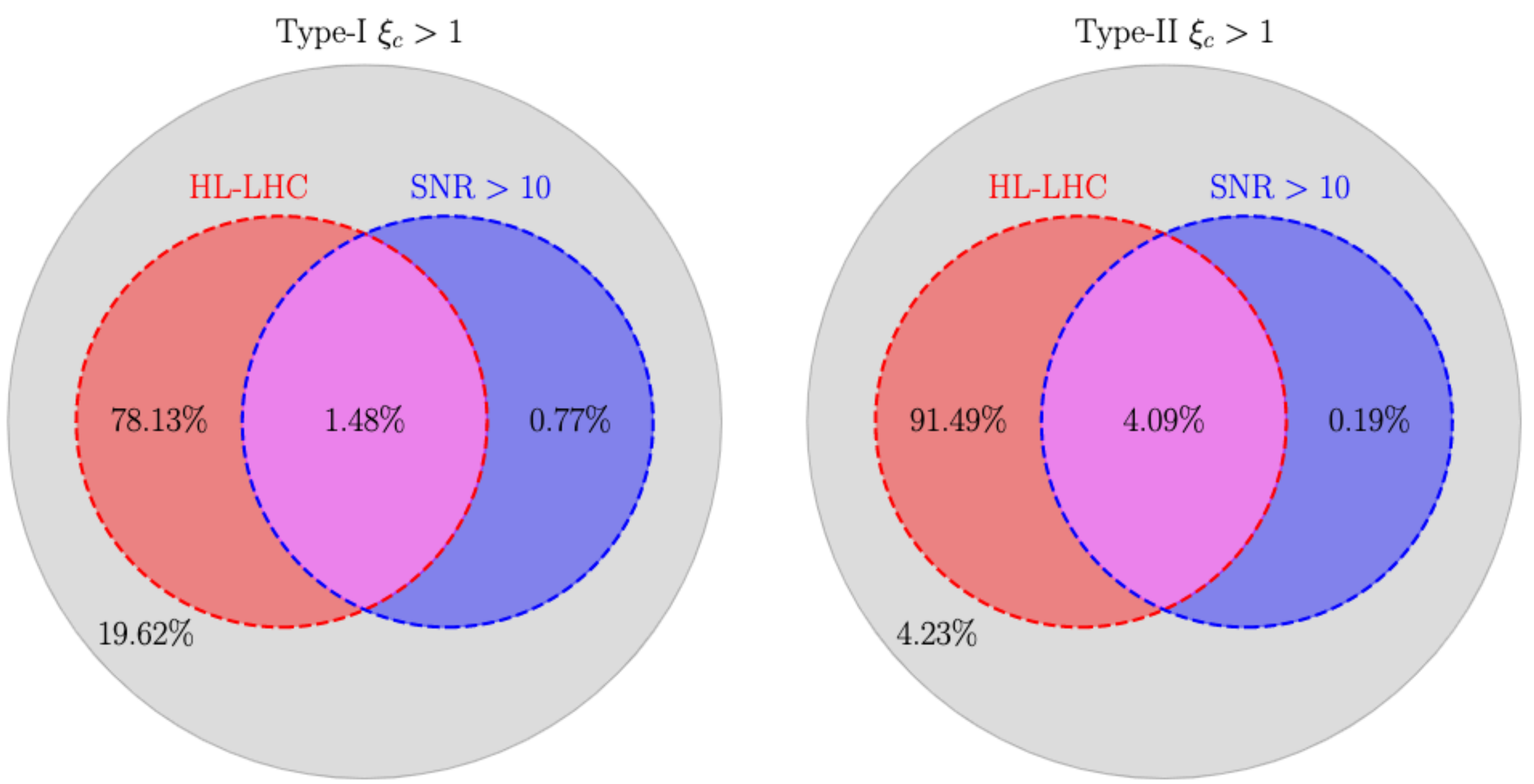


FIG. 13. The summary of the capabilities of the HL-LHC and GW experiments. The number in each region indicates the fraction of parameter points from our scan in that particular region.

Conclusion:

EW Baryogenesis is a promising New Physics search target in the near future.

For 2HDM, SFOPT require non-SM Higgs to be lighter than 1TeV.

So it’s possible for us to fully falsify/verify this model in the near future.

Thank you!