Cosmological first-order phase transition and Higgs phenomenology at colliders

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based on work with Huai-Ke Guo,Yongcheng Wu,Ruiyu Zhou,Ning Chen, Tong Li, PRD101, 035011 (2020),PRD 101, 091903(R) (2020),Phys.Rev.D 101 (2020) 7, 075047,JHEP 01 (2019) 216

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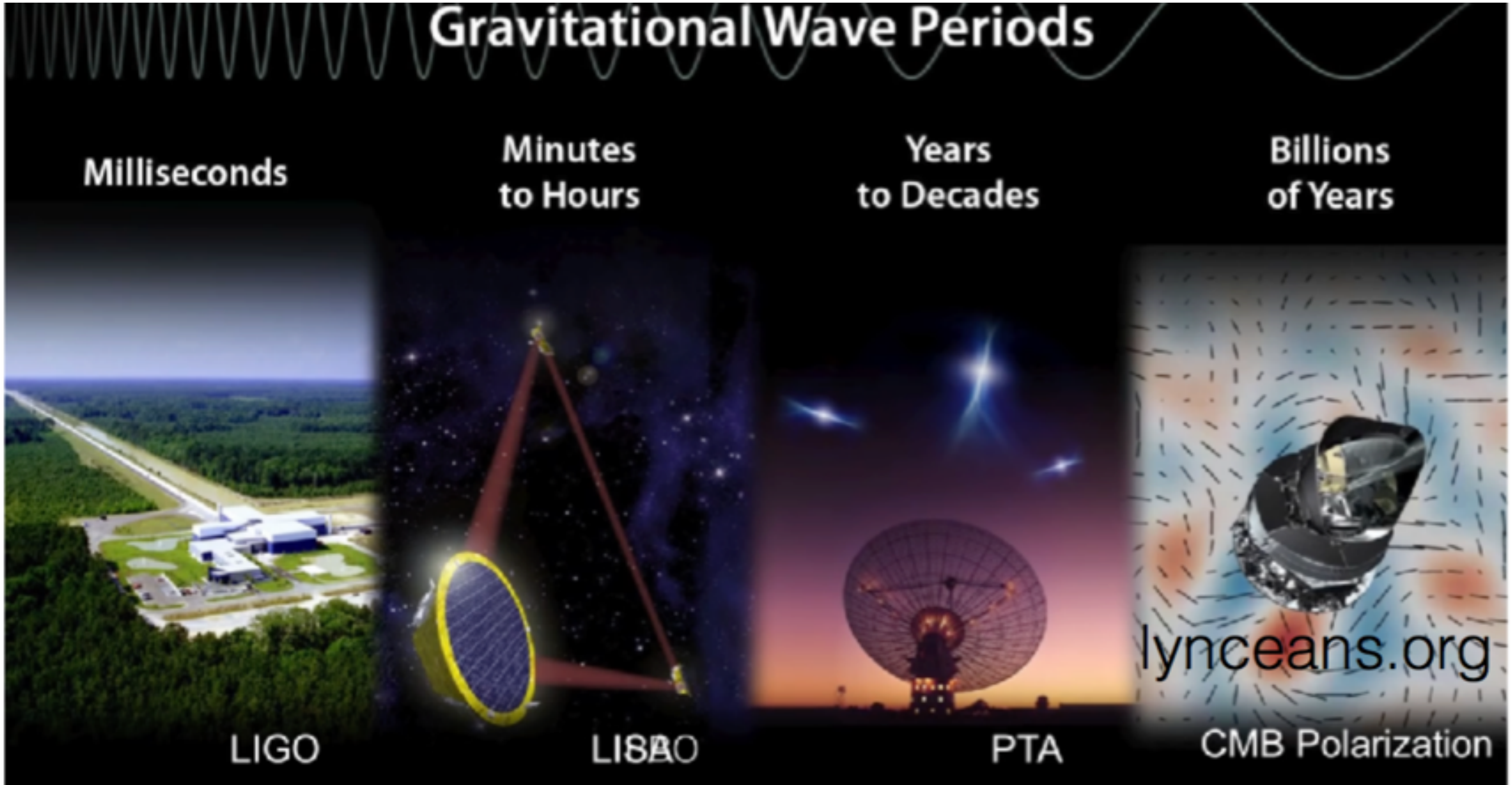
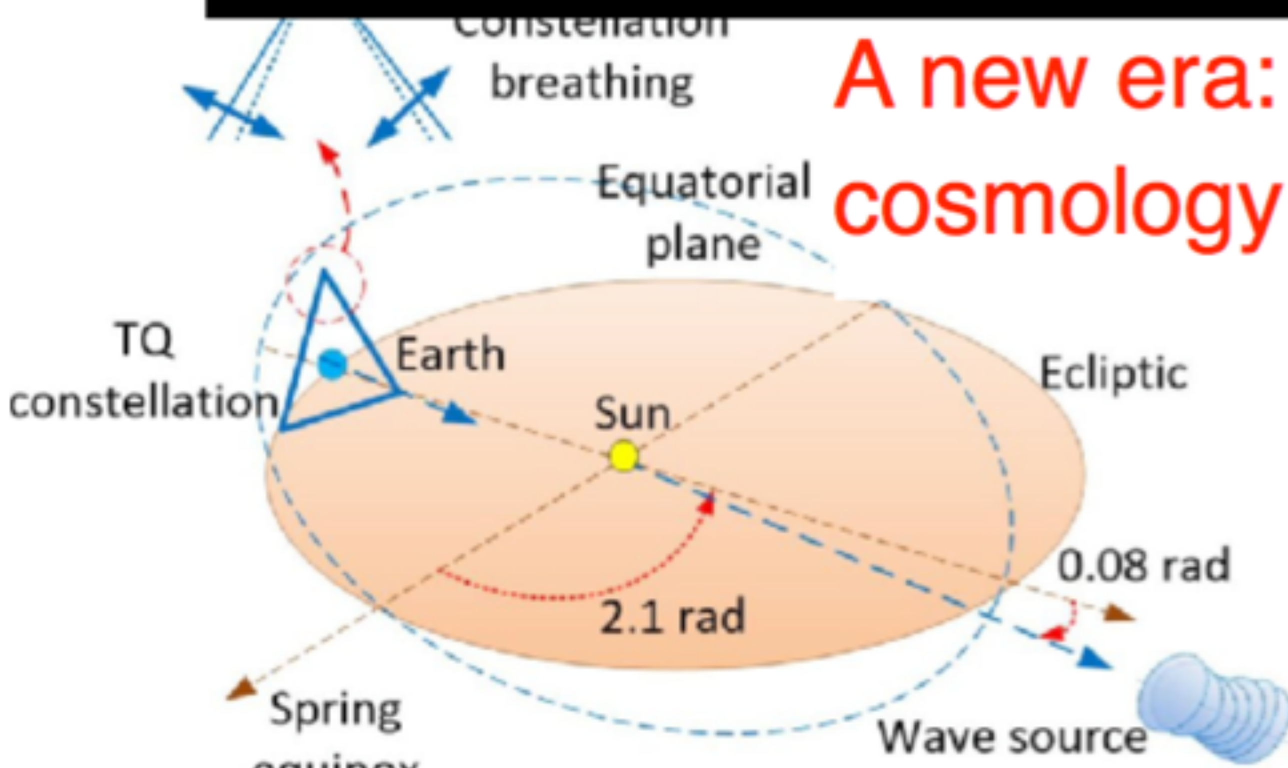


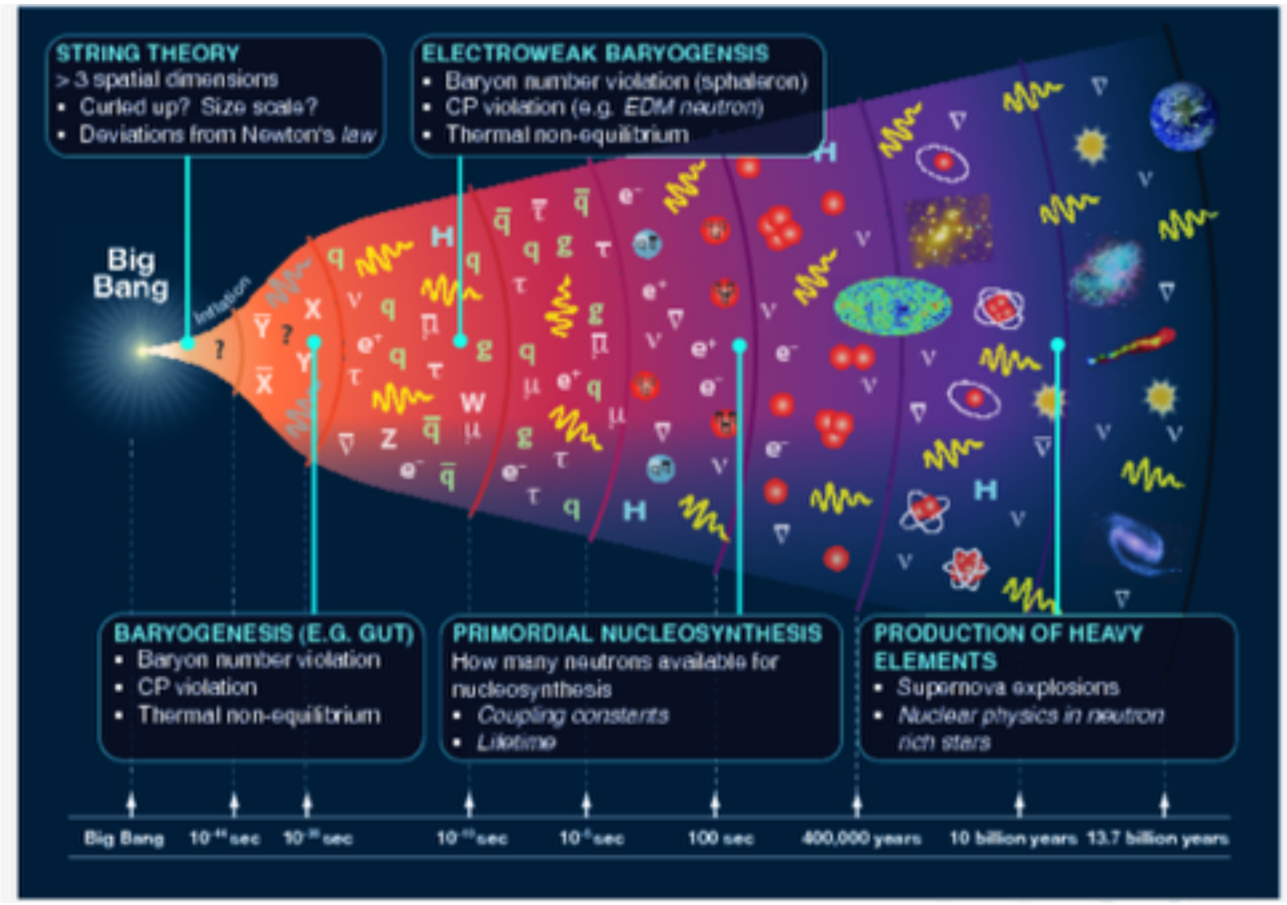


A new era: GWs as a new tool for probing cosmology and high energy physics

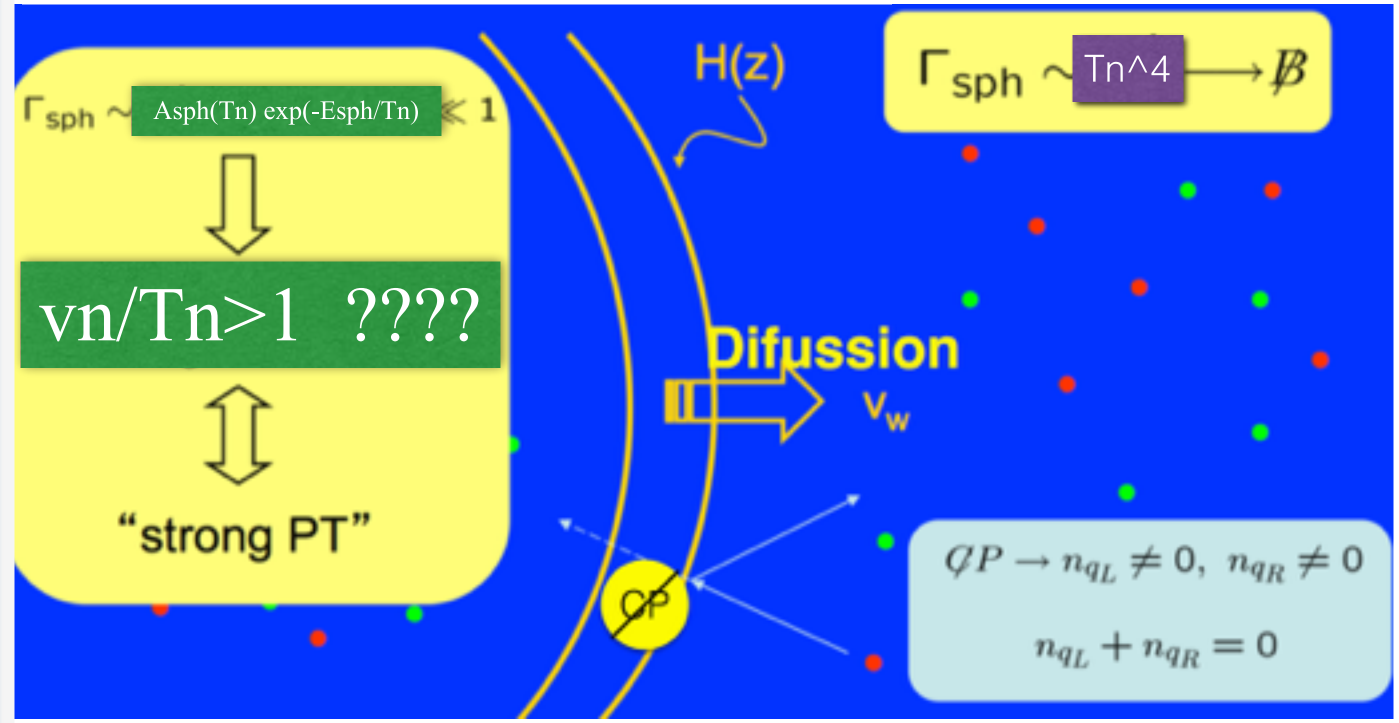
Current: LIGO,PTA,…

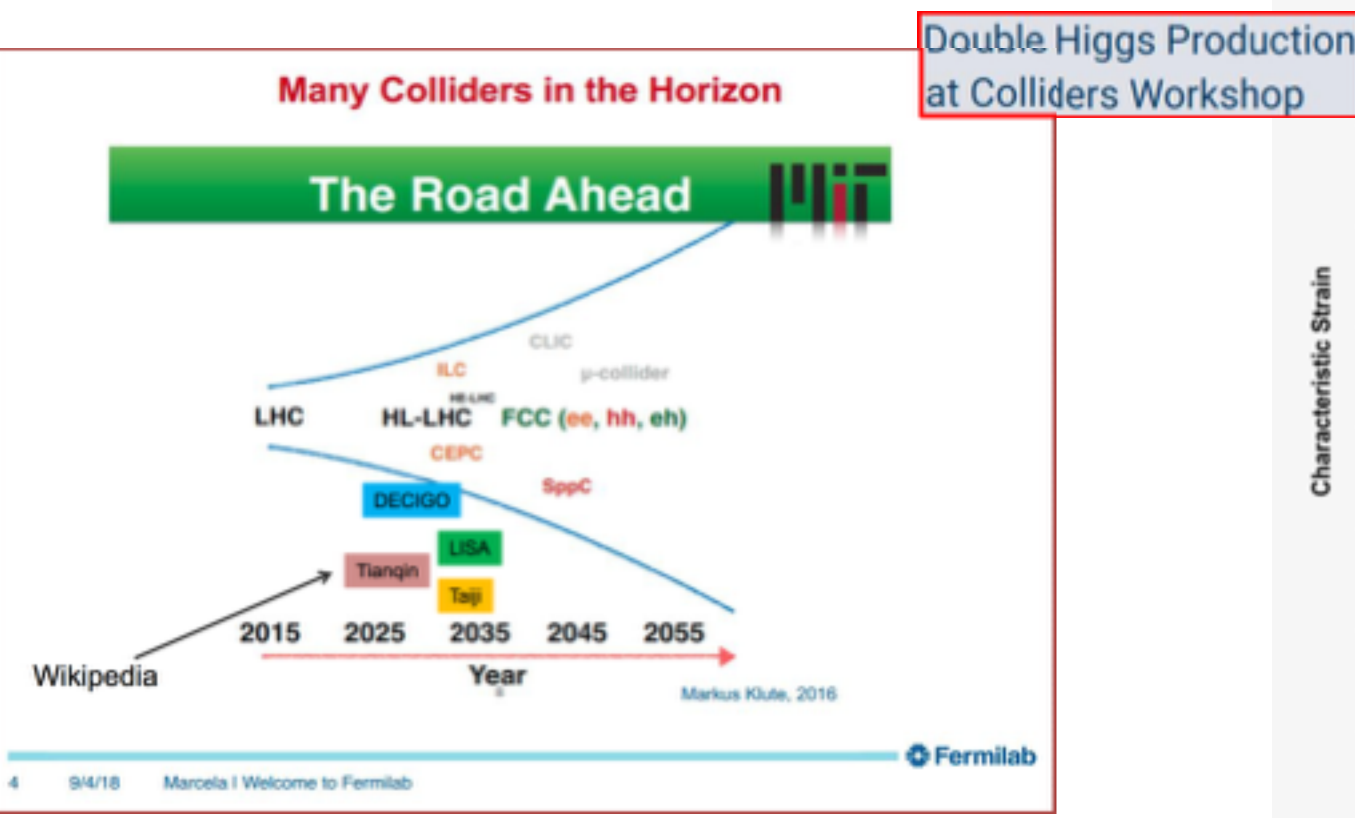
Future GW experiments: LISA, Taiji, TianQin, BBO, DECIGO, ET, CE,...

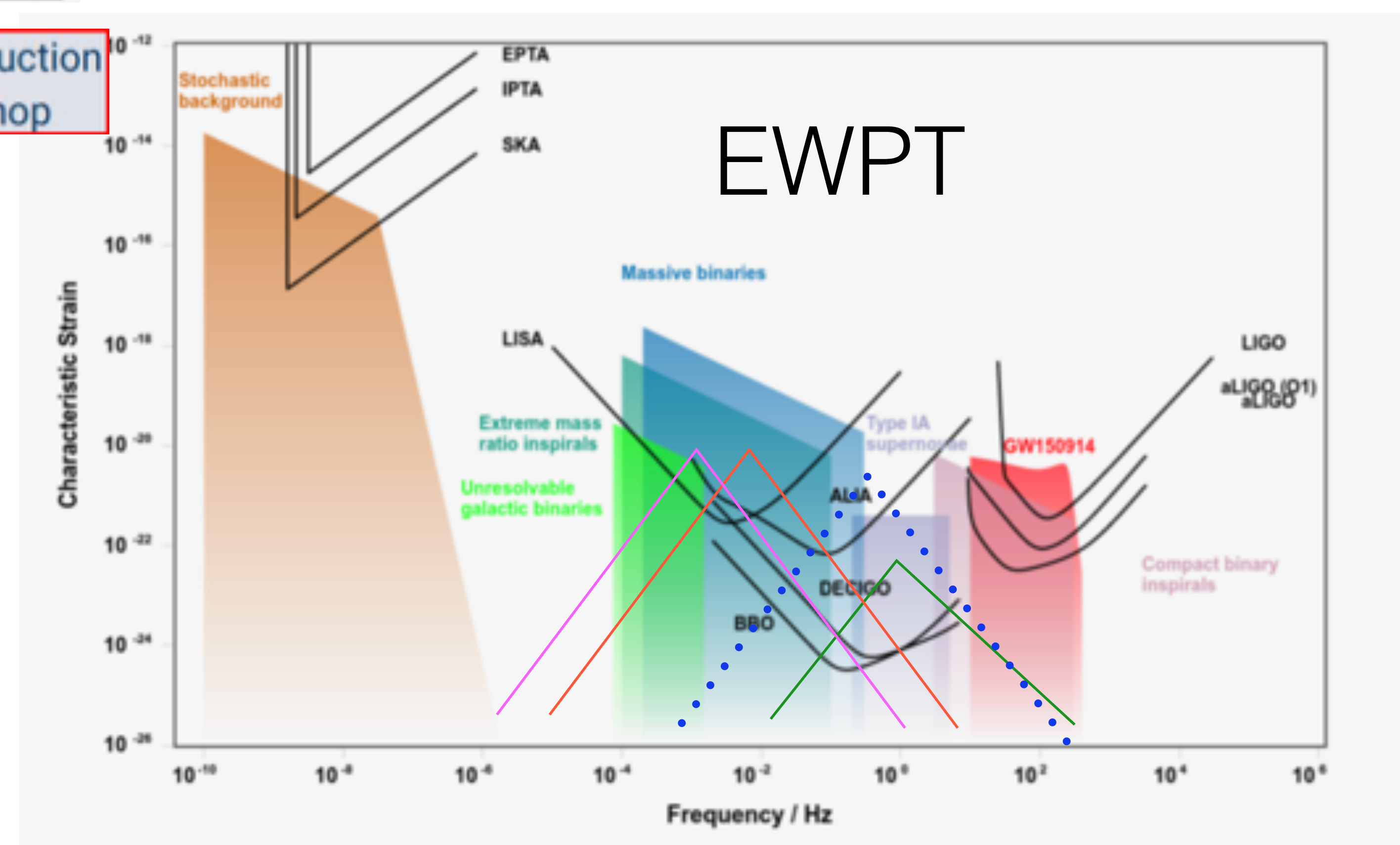
Why SFOEWPT



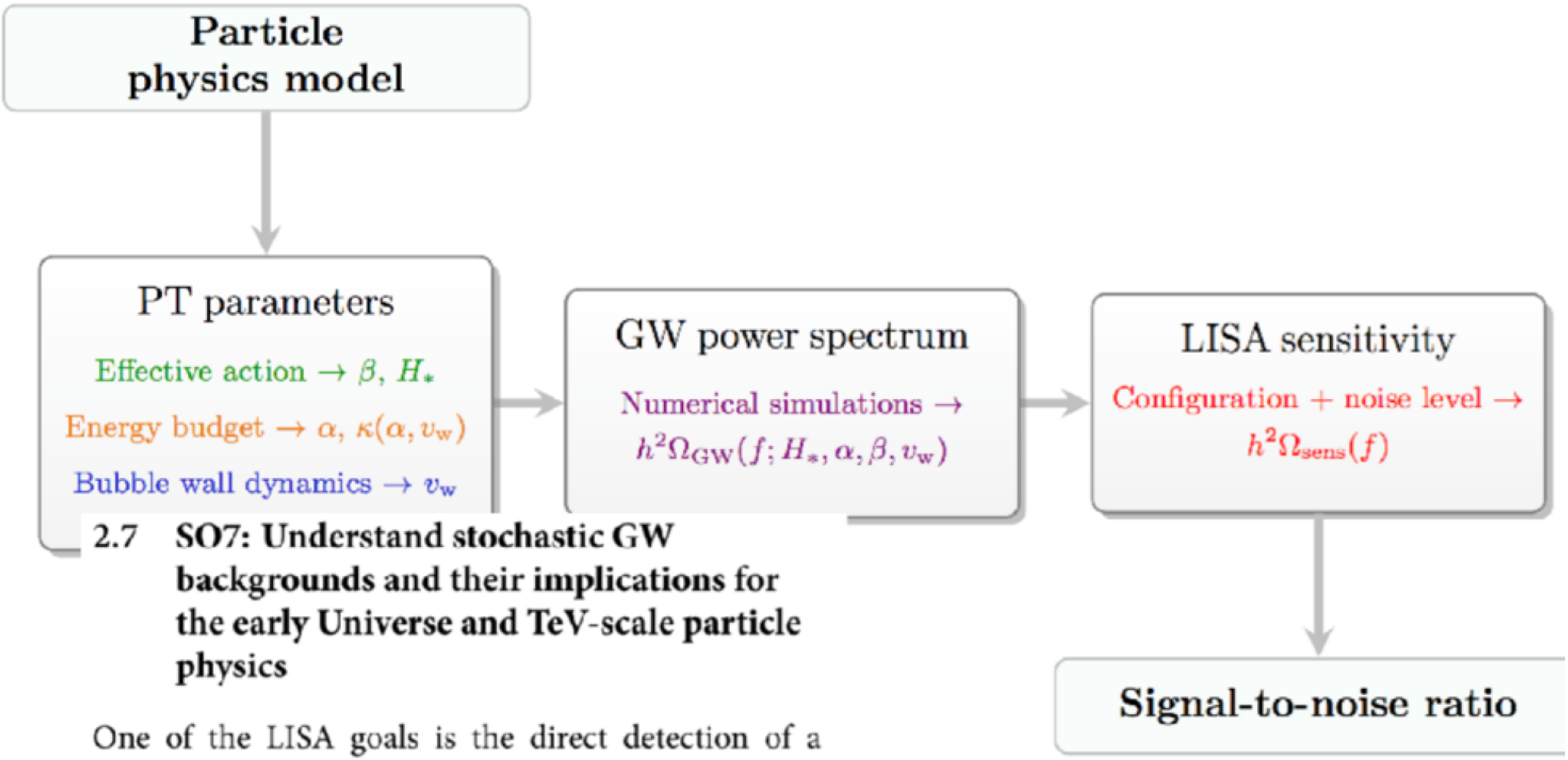
$$\frac{n_b}{s} \approx (0.7 - 0.9) \times 10^{-10} \neq 0$$







C J Moore et al. Class. Quantum Grav. 32 (2015) 015014.



2.7 SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics

One of the LISA goals is the direct detection of a stochastic GW background of cosmological origin (like for example the one produced by a first-order phase transition around the TeV scale) and stochastic foregrounds. Probing a stochastic GW background of cosmological origin provides information on new physics in the early Universe. The shape of the signal gives an indication of its origin, while an upper limit allows to constrain models of the early Universe and particle physics beyond the standard model.

1702.00786

$$\mathrm{SNR} = \sqrt{\mathcal{T}\int_{f_{\min}}^{f_{\max}} \mathrm{d}f \left[\frac{h^2\Omega_{\mathrm{GW}}(f)}{h^2\Omega_{\mathrm{Sens}}(f)}\right]^2}$$

JCAP03(2020)024

GW parameters and FOPT

Bounce solution

$$S_3(T) = \int 4\pi r^2 dr \left[\frac{1}{2} (\frac{d\phi_b}{dr})^2 + V(\phi_b, T) \right]$$

$$\lim_{r\to\infty} \phi_b = 0 \,, \qquad \frac{d\phi_b}{dr}|_{r=0} = 0$$

Bubble nucleation:

$$\Gamma \approx A(T) e^{-S_3/T} \sim 1$$

Latent heat:

$$\alpha = \frac{1}{\rho_R} \left[-(V_{\rm EW} - V_f) + T \left(\frac{dV_{\rm EW}}{dT} - \frac{dV_f}{dT} \right) \right] \Big|_{T=T_*}$$

phase transition inverse duration:

$$\frac{\beta}{H_n} = T \frac{d(S_3(T)/T)}{dT} |_{T=T_n}$$

GW from FOPT

$$\Omega_{\rm GW}(f)h^2 \approx \Omega_{\rm sw}(f)h^2 + \Omega_{\rm turb}(f)h^2$$

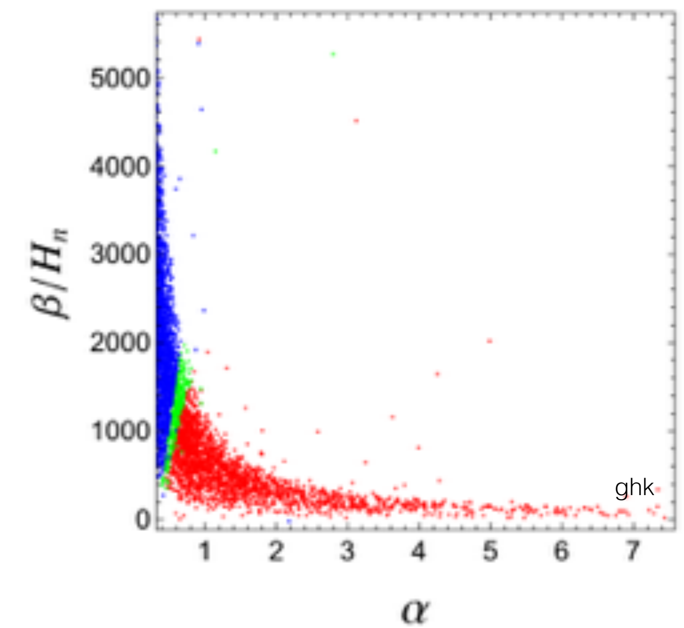
Sound Wave: $$\Omega h^2_{\rm sw}(f) = 2.65\times 10^{-6}(H_*\tau_{sw})\left(\frac{\beta}{H}\right)^{-1} v_b \left(\frac{\kappa_\nu \alpha}{1+\alpha}\right)^2 \left(\frac{g_*}{100}\right)^{-\frac{1}{3}} \left(\frac{f}{f_{\rm sw}}\right)^3 \left(\frac{7}{4+3\,(f/f_{\rm sw})^2}\right)^{7/2}$$

phase transition duration: $$\tau_{sw} = min\left[\frac{1}{H_*}, \frac{R_*}{\bar{U}_f}\right],\ H_* R_* = v_b (8\pi)^{1/3}(\beta/H)^{-1}$$

Root-mean-square four-velocity of the plasma

$$\bar{U}_f^2 \approx \frac{3}{4}\frac{\kappa_\nu \alpha}{1+\alpha}$$

$$f_{\rm sw} = 1.9\times 10^{-5}\frac{\beta}{H}\frac{1}{v_b}\frac{T_*}{100}\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\ {\rm Hz}$$



MHD turbulence: $$\Omega h^2_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{\beta}{H}\right)^{-1}\left(\frac{\epsilon\kappa_\nu \alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{g_*}{100}\right)^{-\frac{1}{3}} v_b \frac{(f/f_{\rm turb})^3\,(1+f/f_{\rm turb})^{-\frac{11}{3}}}{[1+8\pi f a_0/(a_* H_*)]}$$

$$f_{\rm turb} = 2.7\times 10^{-5}\frac{\beta}{H}\frac{1}{v_b}\frac{T_*}{100}\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\ {\rm Hz}$$

GW sources

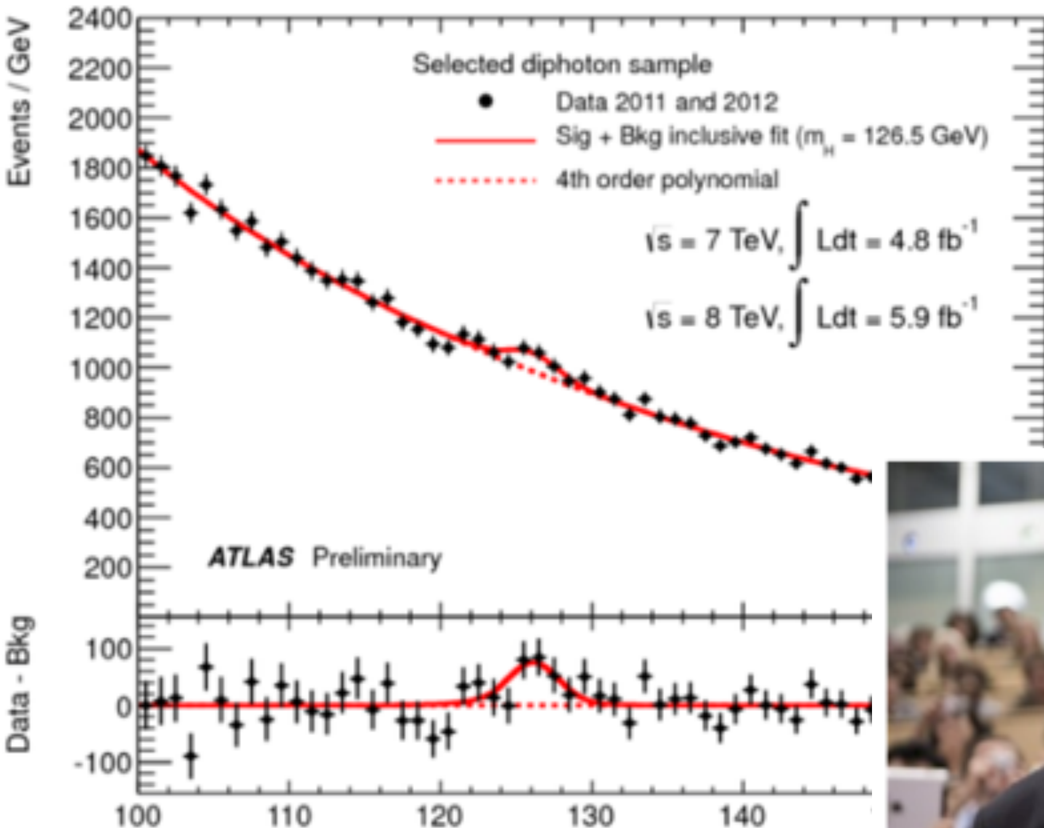
$$\Omega_{GW}(f) = \begin{cases} \Omega_{GW*}\left(\frac{f}{f_*}\right)^{n_{GW1}} & \text{for } f < f_*, \\ \Omega_{GW*}\left(\frac{f}{f_*}\right)^{n_{GW2}} & \text{for } f > f_*, \end{cases}$$

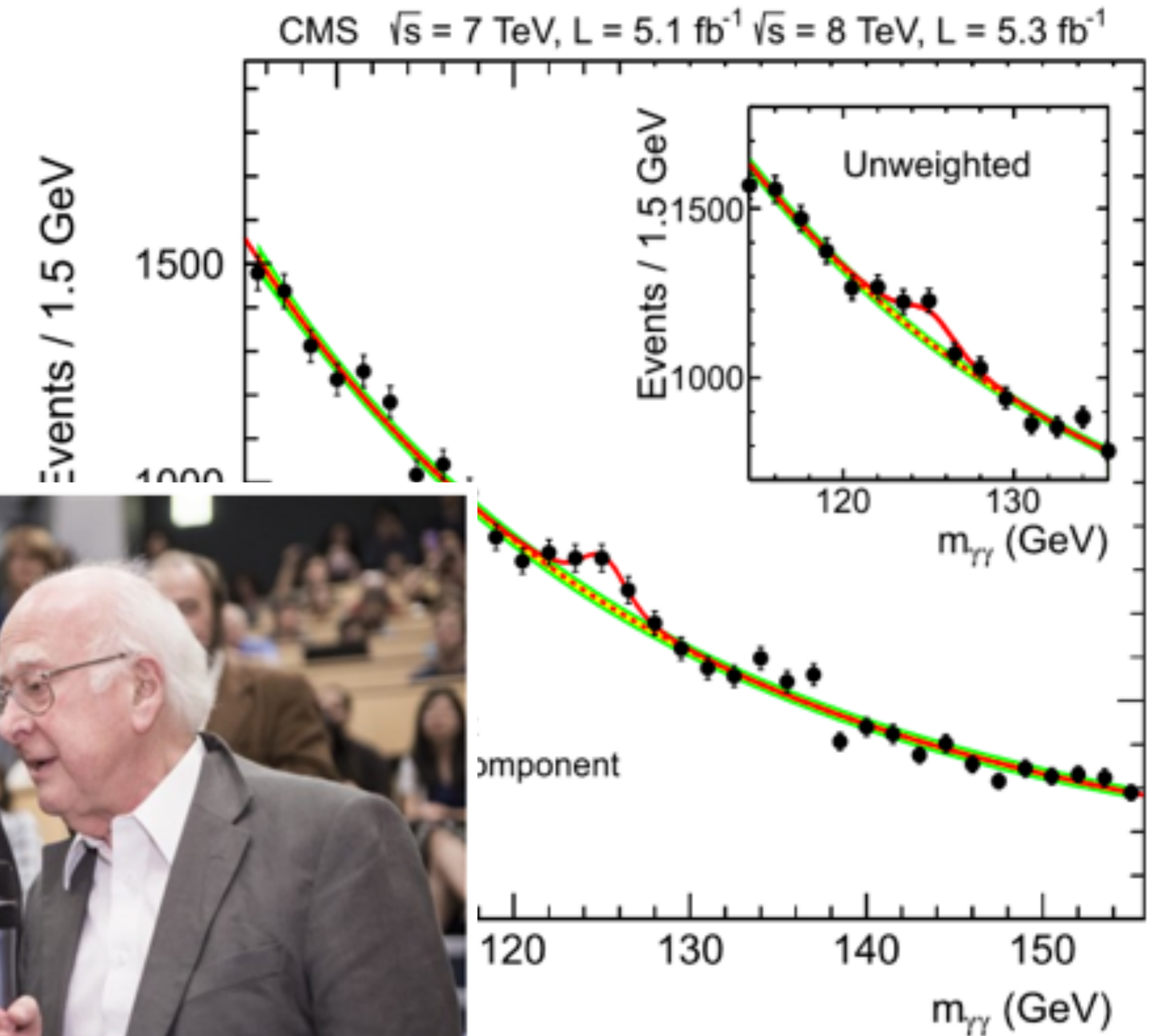
1807.00786

Table 1. Cosmological GW sources

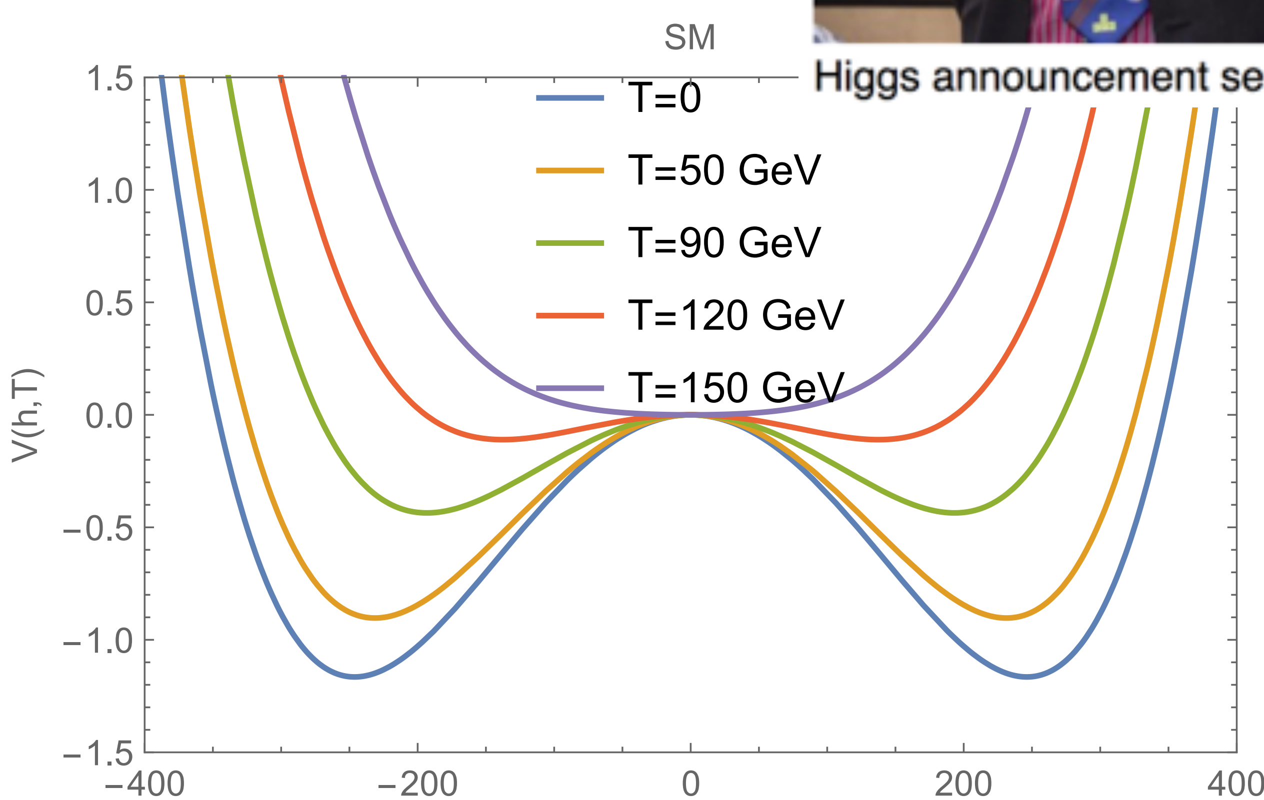
source	n_{GW1}	n_{GW2}	f_* [Hz]	Ω_{GW}
Phase transition (bubble collision)	2.8	-2	$\sim 10^{-5}\left(\frac{f_{PT}}{\beta}\right)\left(\frac{\beta}{H_{PT}}\right)\left(\frac{T_{PT}}{100\text{ GeV}}\right)$	$\sim 10^{-5}\left(\frac{H_{PT}}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2\left(\frac{0.11v_w^3}{0.42+v_w^2}\right)$
Phase transition (turbulence)	3	$-5/3$	$\sim 3\times 10^{-5}\left(\frac{1}{v_w}\right)\left(\frac{\beta}{H_{PT}}\right)\left(\frac{T_{PT}}{100\text{ GeV}}\right)$	$\sim 3\times 10^{-4}\left(\frac{H_{PT}}{\beta}\right)\left(\frac{\kappa_{turb}\alpha}{1+\alpha}\right)^{3/2} v_w$
Phase transition (sound waves)	3	-4	$\sim 2\times 10^{-5}\left(\frac{1}{v_w}\right)\left(\frac{\beta}{H_{PT}}\right)\left(\frac{T_{PT}}{100\text{ GeV}}\right)$	$\sim 3\times 10^{-6}\left(\frac{H_{PT}}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2 v_w$
Preheating ($\lambda\phi^4$)	3	cutoff	$\sim 10^7$	$\sim 10^{-11}\left(\frac{g^2/\lambda}{100}\right)^{-0.5}$
Preheating (hybrid)	2	cutoff	$\sim \frac{g}{\sqrt{\lambda}}\lambda^{1/4}10^{10.25}$	$\sim 10^{-5}\left(\frac{\lambda}{g^2}\right)^{1.16}\left(\frac{v}{M_{pl}}\right)^2$
Cosmic strings (loops 1)	$[1,2]$	$[-1,-0.1]$	$\sim 3\times 10^{-8}\left(\frac{G\mu}{10^{-11}}\right)^{-1}$	$\sim 10^{-9}\left(\frac{G\mu}{10^{-12}}\right)\left(\frac{\alpha_{loop}}{10^{-1}}\right)^{-1/2}$ (for $\alpha_{loop} \gg \Gamma G\mu$)
Cosmic strings (loops 2)	$[-1,-0.1]$	0	$\sim 3\times 10^{-8}\left(\frac{G\mu}{10^{-11}}\right)^{-1}$	$\sim 10^{-9.5}\left(\frac{G\mu}{10^{-12}}\right)\left(\frac{\alpha_{loop}}{10^{-1}}\right)^{-1/2}$ (for $\alpha_{loop} \gg \Gamma G\mu$)
Cosmic strings (infinite strings)	$[0,0.2]$	$[0,0.2]$	—	$\sim 10^{-[11,13]}\left(\frac{G\mu}{10^{-8}}\right)$
Domain walls	3	-1	$\sim 10^{-9}\left(\frac{T_{ann}}{10^{-2}\text{GeV}}\right)$	$\sim 10^{-17}\left(\frac{\sigma}{1\text{TeV}^3}\right)^2\left(\frac{T_{ann}}{10^{-2}\text{GeV}}\right)^{-4}$
Self-ordering scalar fields	0	0	—	$\sim \frac{511}{N}\Omega_{rad}\left(\frac{v}{M_{pl}}\right)^4$
Self-ordering scalar + reheating	0	-2	$\sim 0.4\left(\frac{T_R}{10^7\text{ GeV}}\right)$	$\sim \frac{511}{N}\Omega_{rad}\left(\frac{v}{M_{pl}}\right)^4$
Magnetic fields	3	α_B+1	$\sim 10^{-6}\left(\frac{T_*}{10^2\text{GeV}}\right)$	$\sim 10^{-16}\left(\frac{B}{10^{-10}\text{G}}\right)$
Inflation+reheating	~ 0	-2	$\sim 0.3\left(\frac{T_R}{10^7\text{ GeV}}\right)$	$\sim 2\times 10^{-17}\left(\frac{r}{0.01}\right)$
Inflation+kination	~ 0	1	$\sim 0.3\left(\frac{T_R}{10^7\text{ GeV}}\right)$	$\sim 2\times 10^{-17}\left(\frac{r}{0.01}\right)$
Particle prod. during inf.	-2ϵ	$-4\epsilon(4\pi\xi-6)(\epsilon-\eta)$	—	$\sim 2\times 10^{-17}\left(\frac{r}{0.01}\right)$
2nd-order (inflation)	1	drop-off	$\sim 7\times 10^5\left(\frac{T_{reh}}{10^9\text{ GeV}}\right)^{1/3}\left(\frac{M_{inf}}{10^{16}\text{ GeV}}\right)^{2/3}$	$\sim 10^{-12}\left(\frac{T_{reh}}{10^9\text{ GeV}}\right)^{-4/3}\left(\frac{M_{inf}}{10^{16}\text{ GeV}}\right)^{4/3}$
2nd-order (PBHs)	2	drop-off	$\sim 4\times 10^{-2}\left(\frac{M_{PBH}}{10^{20}\text{ g}}\right)^{-1/2}$	$\sim 7\times 10^{-9}\left(\frac{\mathcal{A}^2}{10^{-3}}\right)^2$
Pre-Big-Bang	3	$3-2\mu$	—	$\sim 1.4\times 10^{-6}\left(\frac{H_s}{0.15M_{pl}}\right)^4$

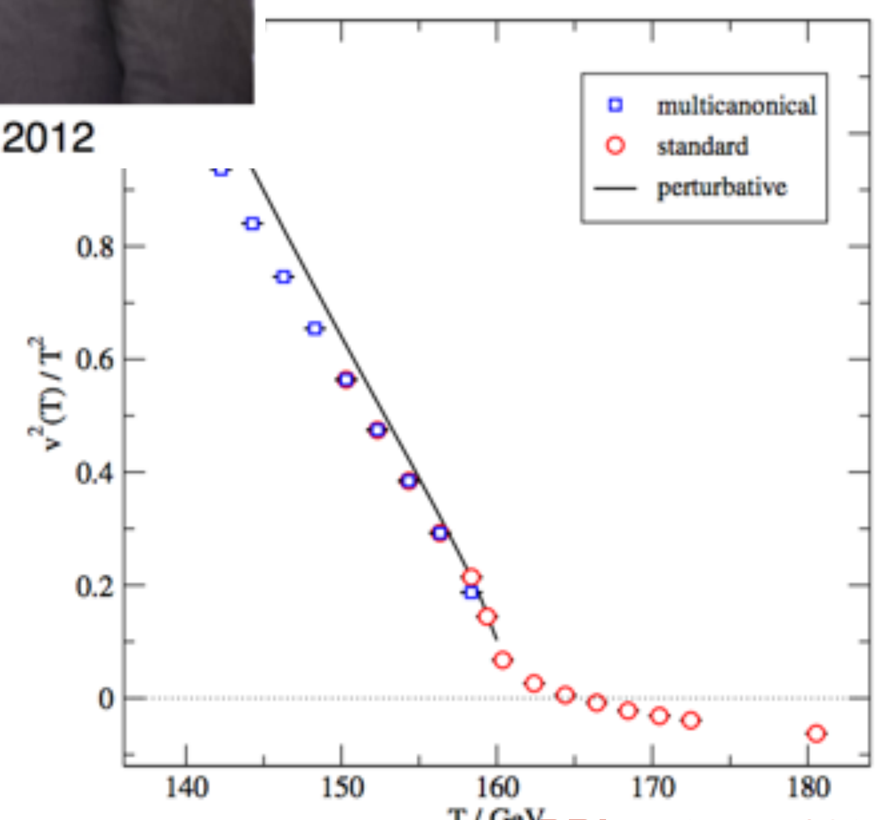
Implication of 125 GeV Higgs





Higgs announcement seminar on 4 July 2012

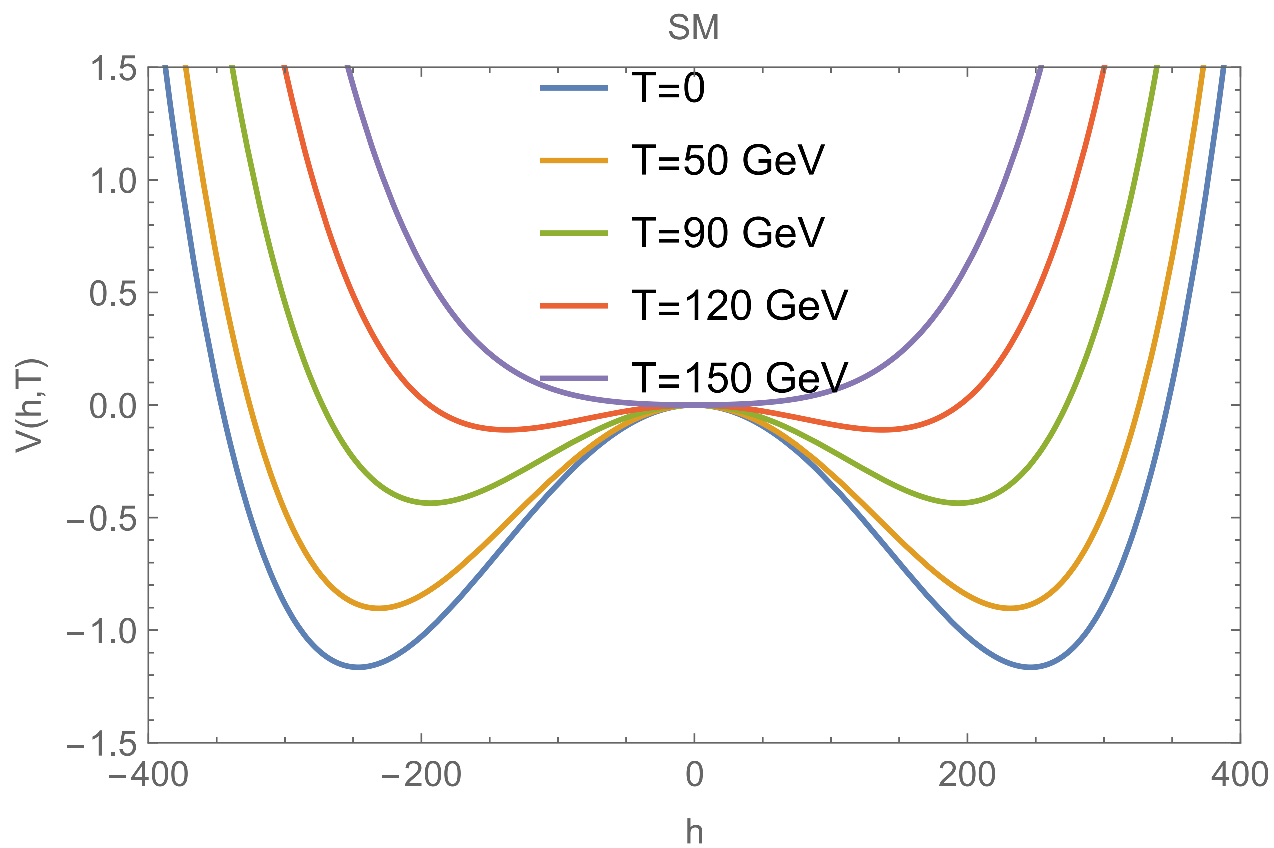


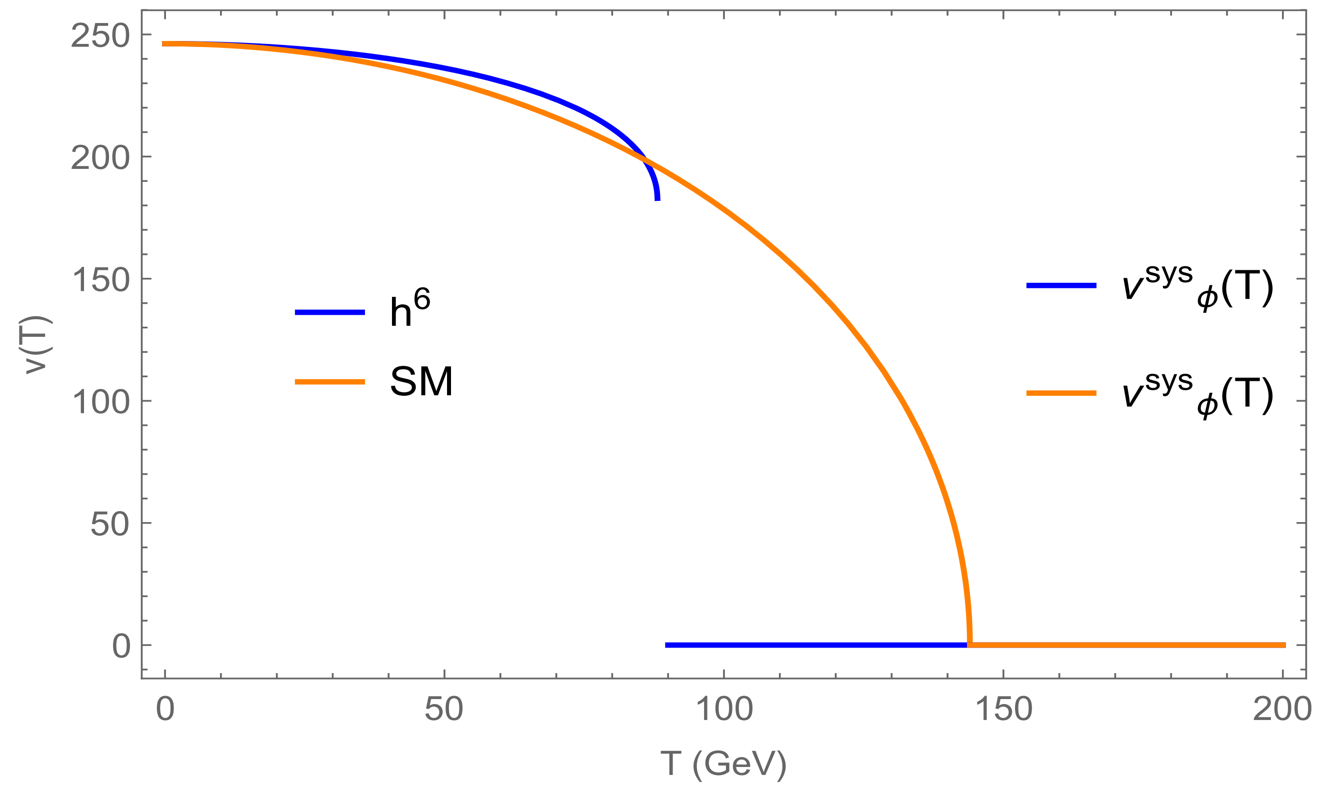


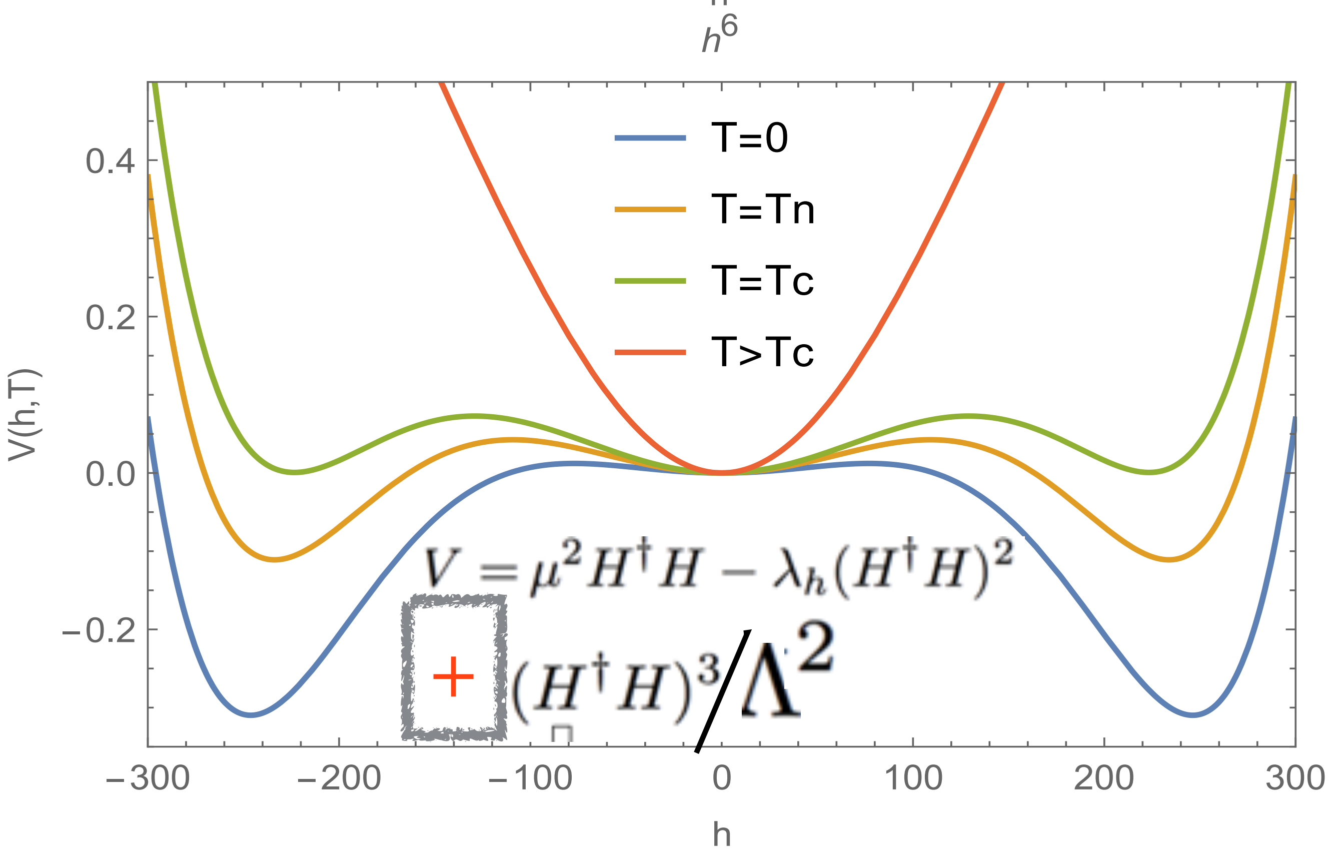
PRL 113, 141602 (2014)

Higgs Potential Shape??? EFT or ???

First or second order



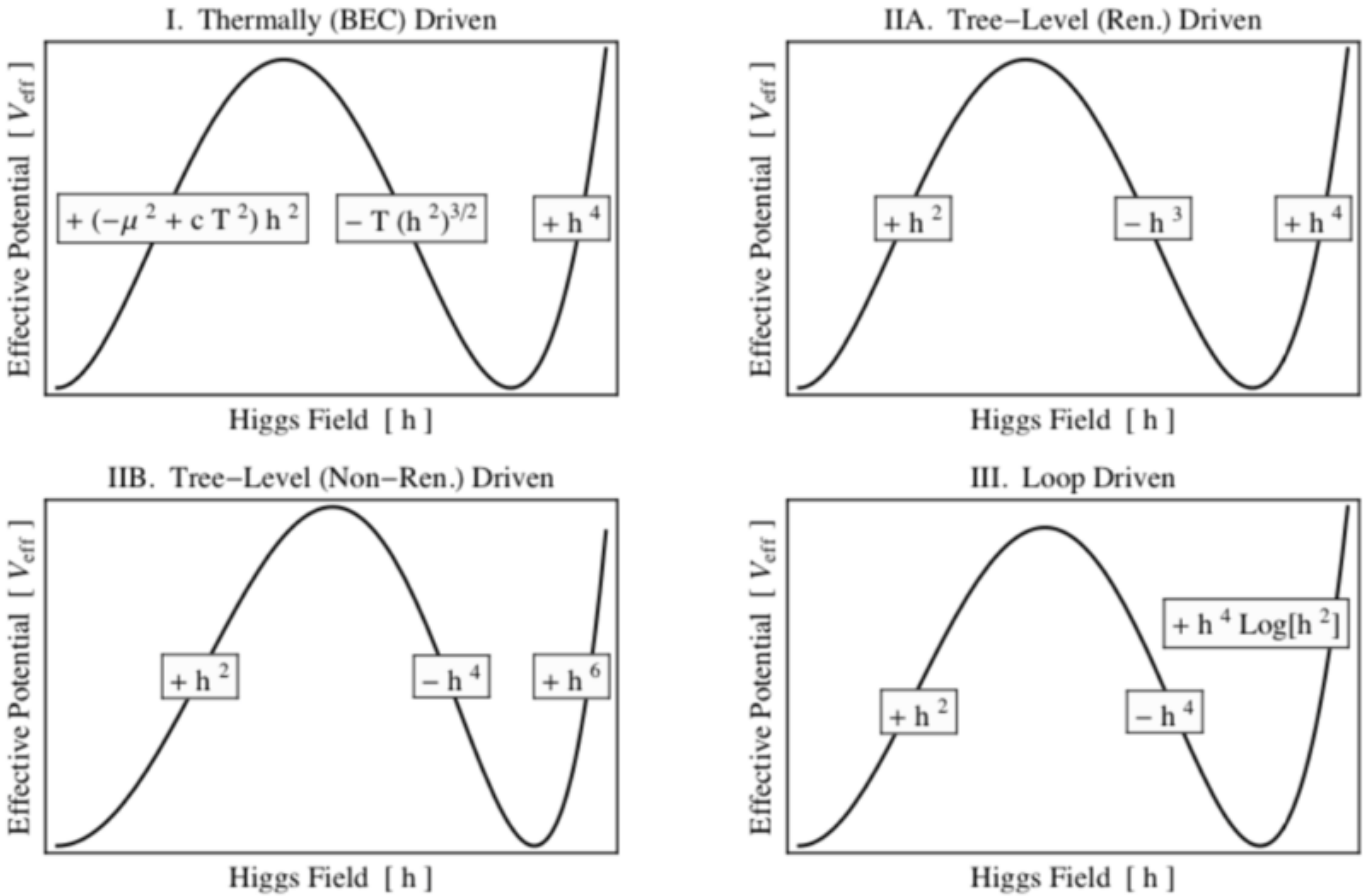




Grojean, Servant, Wells 05, P. Huang, Jokelar, Li, Wagner (2015)
F.P. Huang, Gu, Yin, Yu, Zhang (2015) F.P. Huang, Wan, Wang, Cai, Zhang (2016) Cao, F.P. Huang, Xie, & Zhang (2017)

LHC say the quantum fluctuation (quadratic oscillation) around h=v with mh=126 GeV, not sensitive to the specifically potential shape

Model classes for SFOEWPT

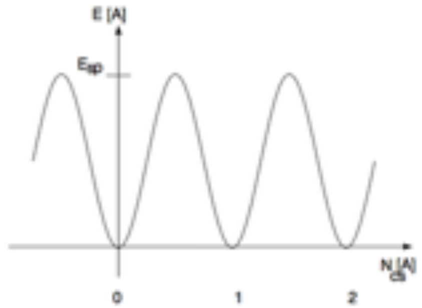


Daniel J H. Chung, Andrew J. Long, and Lian-Tao Wang PRD87, 023509 (2013)

BSM for EWPT

SM+Scalar Singlet	Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel- Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, Bian, Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17,Cheng, Bian 17, Bian, Tang 18,Chen, Li, Wu, Bian,19…
SM+Scalar Doublet	Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Bian, Liu 18,…
SM + Scalar Triplet	Profumo, Ramsey-Musolf 12, Chiang 14, Zhou, Cheng, Deng, Bian, Wu 18,Zhou, Bian, Guo,Wu 19,…
NMSSM	Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15, Bi, Bian, Huang, Shu, Yin 15, Bian, Guo, Shu 17,…
Composite Higgs	Espinosa, Gripaios, Konstandin, Riva 11, Bruggisser, Von Harling, Matsedonskyi, Servant 18, Bian,Wu,Xie 19, De Curtis, Delle Rose, Panico 19, Bian,Wu,Xie 20,…
EFT	Grojean, Servant, Wells 05, Bodeker, Froome, Huber, Seniuch 05, Huang, Joglekar, Li, Wagner 15,Cai,Sasaki ,Wang17,Zhou, Bian, Guo 19, …

BNPC, v/T and EW sphaleron



$$\partial_\mu J_B^\mu = i\frac{N_F}{32\pi^2}\left(-g_2^2 F^{a\mu\nu}\widetilde{F}^a_{\mu\nu} + g_1^2 f^{\mu\nu}\widetilde{f}_{\mu\nu}\right),$$

$$\Delta B = N_F(\Delta N_{CS} - \Delta n_{CS}),$$

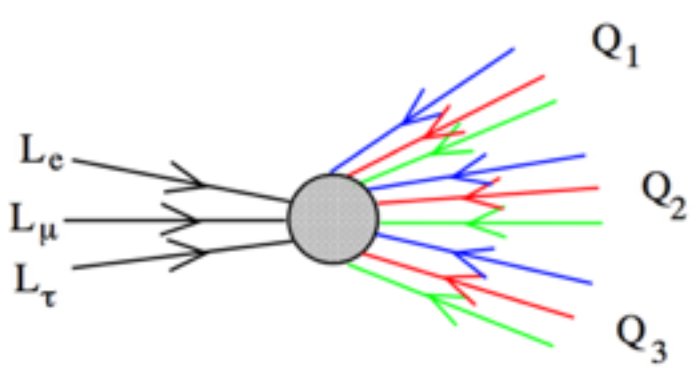
$$N_{CS} = -\frac{g_2^2}{16\pi^2}\int d^3x\, 2\epsilon^{ijk}\,\mathrm{Tr}\left[\partial_i A_j A_k + i\frac{2}{3}g_2 A_i A_j A_k\right],$$

$$n_{CS} = -\frac{g_1^2}{16\pi^2}\int d^3x\,\epsilon^{ijk}\,\partial_i B_j B_k,$$

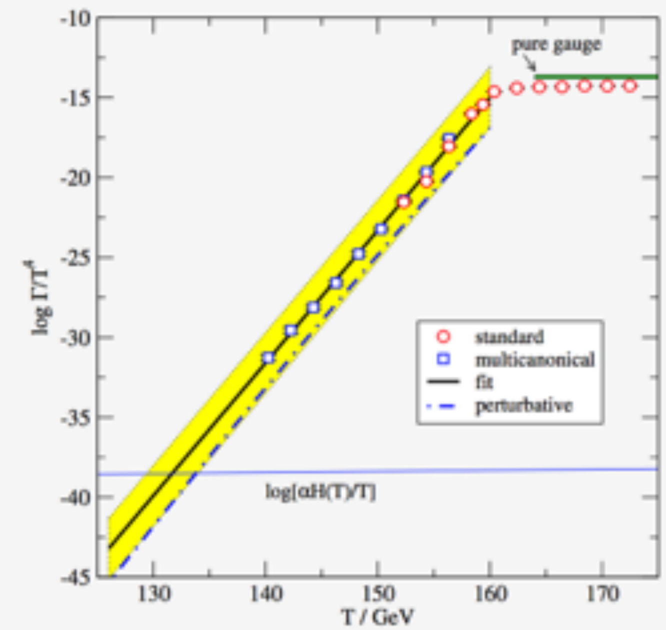
$$A_i \to U A_i U^{-1} + \frac{i}{g_2}(\partial_i U)U^{-1},$$

$$\delta N_{CS} = \frac{1}{24\pi^2}\int d^3x\,\mathrm{Tr}\left[(\partial_i U)U^{-1}(\partial_j U)U^{-1}(\partial_k U)U^{-1}\right]\epsilon^{ijk}.$$

The Standard Model already contains a process that violates B-number. It is known as the electroweak sphaleron ("sphaleros" is Greek for "ready to fall").



Klinkhammer & Manton (1984); Kuzmin, Rubakov, & Shaposhnikov (1985); Harvey & Turner (1990) but also identified earlier by Dashen, Hasslacher, & Neveu (1974) and Boguta (1983)



Lattice result, $T_C = (159.5 \pm 1.5)\mathrm{GeV}$, Phys.Rev.Lett,113, 141602 (2014

$$\Gamma^{\rm sym} \approx 6\times(18\pm3)\alpha_W^5 T^4, \qquad \Gamma^{\rm brok} \sim T^4 \exp\left(-\frac{E_{\rm sph}}{T}\right)$$

Washout avoidance,BNPC

$$\Gamma_{\rm sph} = A_{\rm sph}(T)\exp[-E_{\rm sph}(T)/T] < \mathrm{H(T)}$$

$$PT_{sph} \equiv \frac{E_{\rm sph}(T)}{T} - 7\ln\frac{v(T)}{T} + \ln\frac{T}{100\ \mathrm{GeV}} \qquad PT_{sph} > (35.9 - 42.8)$$

$$E_{\rm sph}(T) \approx E_{\rm sph,0}\frac{v(T)}{v} \qquad \frac{v(T)}{T} > (0.973 - 1.16)\left(\frac{E_{\rm sph,0}}{1.916\times 4\pi v/g}\right)^{-1}$$

Class IIB

Dim. six operator, SMEFT

Higgs potential

$$V(H) = -m^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \frac{(H^\dagger H)^3}{\Lambda^2}$$

Finite temperature potential

$$V_T(h,T) = V(h) + \frac{1}{2}c_{hT}h^2$$

Thermal correction

$$c_{hT} = (4y_t^2+3g^2+g'^2+8\lambda)T^2/16$$

Electroweak minimum being the global one

$$\Lambda \geq v^2/m_h$$

Potential barrier requirement

$$\Lambda < \sqrt{3}v^2/m_h$$

Class IIA (1) no extra EWSB: xSM

For the "xSM" model, the gauge invariant finite temperature effective potential is found to be:

$$V(h,s,T) = -\frac{1}{2}[\mu^2 - \Pi_h(T)]h^2 - \frac{1}{2}[-b_2 - \Pi_s(T)]s^2 + \frac{1}{4}\lambda h^4 + \frac{1}{4}a_1 h^2 s + \frac{1}{4}a_2 h^2 s^2 + \frac{b_3}{3}s^3 + \frac{b_4}{4}s^4, \quad \text{(C1)}$$

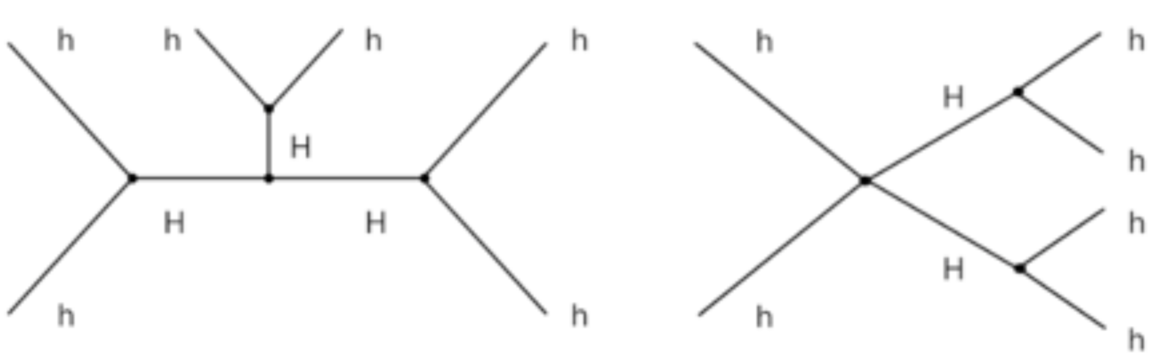
with the thermal masses given by

$$\Pi_h(T) = \left(\frac{2m_W^2 + m_Z^2 + 2m_t^2}{4v^2} + \frac{\lambda}{2} + \frac{a_2}{24}\right)T^2,$$
$$\Pi_s(T) = \left(\frac{a_2}{6} + \frac{b_4}{4}\right)T^2, \quad \text{(C2)}$$

PT strength

$$v^{\rm xSM}/T \equiv \frac{v_h(T)}{T} = \frac{\sqrt{v_h^2(T) + v_s^2(T)}\cos\theta(T)}{T},$$

$$\cos\theta(T) \equiv \frac{v_h(T)}{\sqrt{v_h^2(T) + v_s^2(T)}},$$



For small mixing limit between the extra Higgs and the SM Higgs, one have

$$c_4^{xSM} = -\frac{a_1^2 - 8b_2\lambda}{32b_2} + \frac{\theta^2(a_1^2(6b_2 - \mu^2) - 8a_1b_2b_3 + 8b_2^2(a_2 - 2\lambda))}{32b_2^2} + O(\theta^3)$$

$$c_6^{xSM} = -\frac{a_1^2(a_1b_3 - 3a_2b_2)}{192b_2^3} - \frac{\theta^2 a_1}{256b_2^4}(a_1^3b_2 + 4a_1^2b_3(\mu^2 - 3b_2) + 4a_1b_2(a2(11b_2 - 2\mu^2) - 6b_2(b4 + \lambda) + 4b_3^2) - 32a_2b_2^2b_3) + O(\theta^3)$$

$$c_8^{xSM} = \frac{a_1^4 b_4}{1024b_2^4} + \frac{a_1^3\theta^2}{1024b_2^5}(a_1(a_2b_2 + 4b_4(\mu^2 - 3b_2)) + 16b_2b_3b_4) + O(\theta^3)$$

Class IIA (1) with extra EWSB: **GM model**

The most general scalar potential $V(\Phi, \Delta)$ invariant under $SU(2)_L \times SU(2)_R \times U(1)_Y$ is given by

extra EWSB

$$v_\phi^2 + 8 v_\xi^2 \equiv v^2 \approx (246\text{GeV})^2$$

$$\begin{aligned} V(\Phi,\Delta) =& \frac{1}{2} m_1^2 \mathrm{tr}[\Phi^\dagger \Phi] + \frac{1}{2} m_2^2 \mathrm{tr}[\Delta^\dagger \Delta] + \lambda_1 \left(\mathrm{tr}[\Phi^\dagger \Phi]\right)^2 \\ &+ \lambda_2 \left(\mathrm{tr}[\Delta^\dagger \Delta]\right)^2 + \lambda_3 \mathrm{tr}\left[\left(\Delta^\dagger \Delta\right)^2\right] + \lambda_4 \mathrm{tr}[\Phi^\dagger \Phi] \mathrm{tr}[\Delta^\dagger \Delta] \\ &+ \lambda_5 \mathrm{tr}\left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2}\right] \mathrm{tr}[\Delta^\dagger T^a \Delta T^b] \\ &+ \mu_1 \mathrm{tr}\left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2}\right] (P^\dagger \Delta P)_{ab} + \mu_2 \mathrm{tr}[\Delta^\dagger T^a \Delta T^b] (P^\dagger \Delta P)_{ab} , \end{aligned} \quad (3)$$

Custodial symmetry

$$v_\chi = \sqrt{2} v_\xi$$

$$\Phi \equiv (\varepsilon_2 \phi^*, \phi) = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{pmatrix}, \quad \Delta \equiv (\varepsilon_3 \chi^*, \xi, \chi) = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}, \quad (1)$$

with

$$\varepsilon_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad \varepsilon_3 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \quad (2)$$

where the phase convention for the scalar field components is: $\chi^{--} = \chi^{++*}$, $\chi^- = \chi^{+*}$, $\xi^- = \xi^{+*}$, $\phi^- = \phi^{+*}$. Φ and Δ are transformed under $SU(2)_L \times SU(2)_R$ as $\Phi \to U_{2,L} \Phi U_{2,R}^\dagger$ and $\Delta \to U_{3,L} \Delta U_{3,R}^\dagger$ with $U_{L,R} = exp(i\theta^a_{L,R} T^a)$ and T^a being the $SU(2)$ generators.

where summations over $a, b = 1, 2, 3$ are understood, σ's and T's are the 2×2 (Pauli matrices) and 3×3 matrix representations of the $SU(2)$ generators, respectively

$$T_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, T_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}, T_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \quad (4)$$

The P matrix, which is the similarity transformation relating the generators in the triplet and the adjoint representations, is given by

$$P = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 & i & 0 \\ 0 & 0 & \sqrt{2} \\ 1 & i & 0 \end{pmatrix}. \quad (5)$$

Class IIA (1) with extra EWSB: GM

Finite-T potential

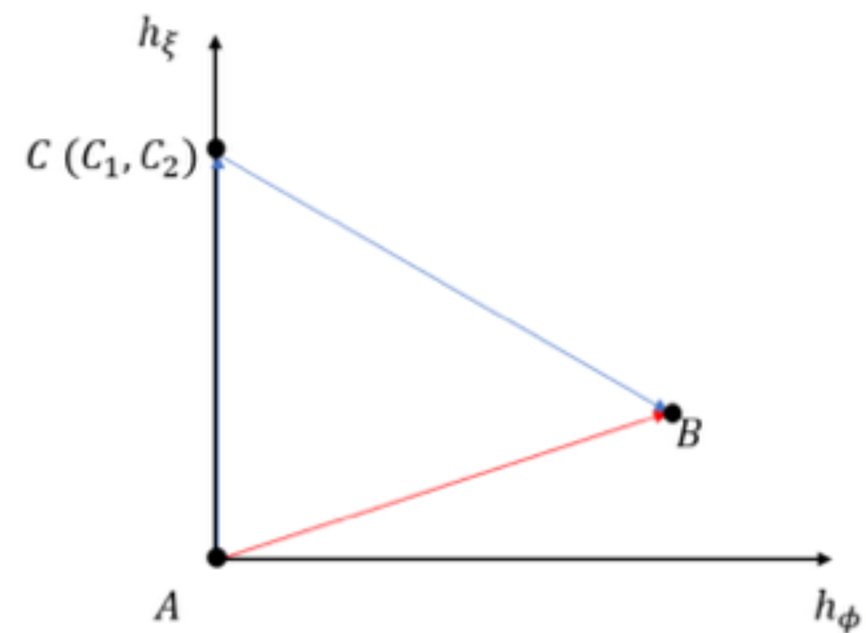
$$V_T = V_0 + \frac{1}{2}c_\phi T^2 h_\phi^2 + \frac{1}{2}c_\xi T^2 h_\xi^2 + \frac{1}{2}c_\chi T^2 h_\chi^2$$

Tree Level

$$V_0 = \frac{1}{4}(4h_\phi^4\lambda_1 + 2(h_\xi^2 + h_\chi^2)(m_2^2 + 2\lambda_2(h_\xi^2 + h_\chi^2)) + 2\lambda_3(2h_\xi^4 + h_\chi^4)$$
$$+ h_\phi^2(2m_1^2 + 4\lambda_4 h_\xi^2 + h_\xi(2\sqrt{2}\lambda_5 h_\chi + \mu_1) + h_\chi(4\lambda_4 h_\chi + \lambda_5 h_\chi + \sqrt{2}\mu_1)) + 12\mu_2 h_\xi h_\chi^2)$$

Thermal correction

$$c_\phi = \frac{3g^2}{16} + \frac{g'^2}{16} + 2\lambda_1 + \frac{3\lambda_4}{2} + \frac{1}{4}y_t^2 \sec^2\theta_H$$
$$c_\xi = \frac{g^2}{2} + \frac{11\lambda_2}{3} + \frac{7\lambda_3}{3} + \frac{2\lambda_4}{3},$$
$$c_\chi = \frac{g^2}{2} + \frac{g'^2}{4} + \frac{11\lambda_2}{3} + \frac{7\lambda_3}{3} + \frac{2\lambda_4}{3}.$$



PT strength

$$v^{GM}/T \equiv \frac{\sqrt{v_\phi^2(T) + 8v_\xi^2(T)}}{T} = \frac{v_\phi(T)\cos\theta_H(T)^{-1}}{T},$$
$$\cos\theta_H(T) \equiv \frac{v_\phi(T)}{\sqrt{v_\phi^2(T) + 8v_\xi^2(T)}},$$

$h_\chi = \sqrt{2}h_\xi$ as required by the custodial symmetry

Match to SMEFT

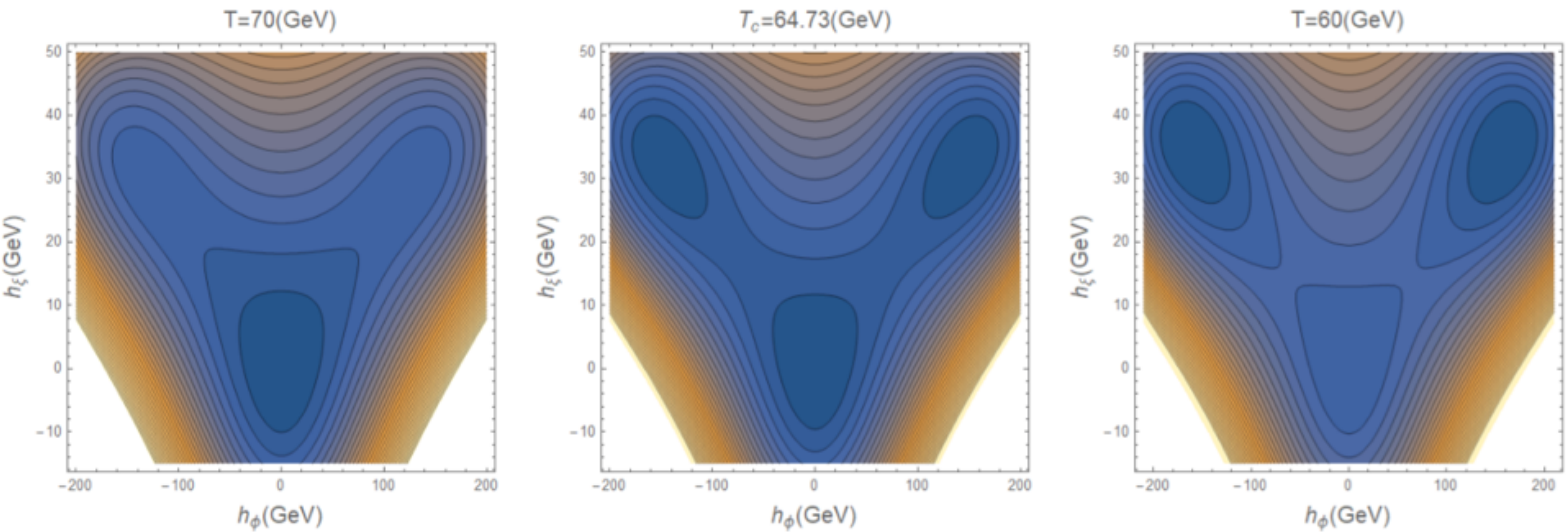
$$c_4^{\mathrm{GM}} = \lambda_1\cos^4\alpha_H + \sin^4\alpha_H\left(\lambda_2 + \frac{\lambda_3}{3}\right) + \lambda_4\sin^2\alpha_H\cos^2\alpha_H + \frac{1}{8}\lambda_5\sin^2 2\alpha_H - \frac{3\cos^2\alpha_H(\cos 2\alpha_H(8\mu_2 - 3\mu_1) + \mu_1 - 8\mu_2)^2}{128(m_1^2\sin^2\alpha_H + m_2^2\cos^2\alpha_H)}$$

$$c_6^{\mathrm{GM}} = \frac{1}{2048(m_1^2\sin^2\alpha_H + m_2^2\cos^2\alpha_H)^3} 3\cos^2\alpha_H(\cos 2\alpha(8\mu_2 - 3\mu_1) + \mu_1 - 8\mu_2)^2$$
$$\times (4(m_1^2\sin^2\alpha_H + m_2^2\cos^2\alpha_H)(\cos 4\alpha_H(-6\lambda_1 - 6\lambda_2 - 2\lambda_3 + 6\lambda_4 + 3\lambda_5)$$
$$+ 6\lambda_1 + 6\lambda_2 + 2\lambda_3 + 2\lambda_4 + \lambda_5) - \cos^2\alpha_H(\cos 2\alpha_H(3\mu_1 - 8\mu_2) - \mu_1 + 8\mu_2)(3\mu_1\sin^2\alpha_H + 8\mu_2\cos^2\alpha_H)),$$

$$c_8^{\mathrm{GM}} = \frac{1}{32768(m_1^2\sin^2\alpha_H + m_2^2\cos^2\alpha_H)^4} 3\cos^4\alpha_H(\cos 2\alpha_H(8\mu_2 - 3\mu_1) + \mu_1 - 8\mu_2)^4$$
$$\times (3(8\lambda_1\sin^4\alpha_H + \sin^2 2\alpha_H(2\lambda_4 + \lambda_5)) + 8\cos^4\alpha_H(3\lambda_2 + \lambda_3)).$$

SFOEWPT patterns

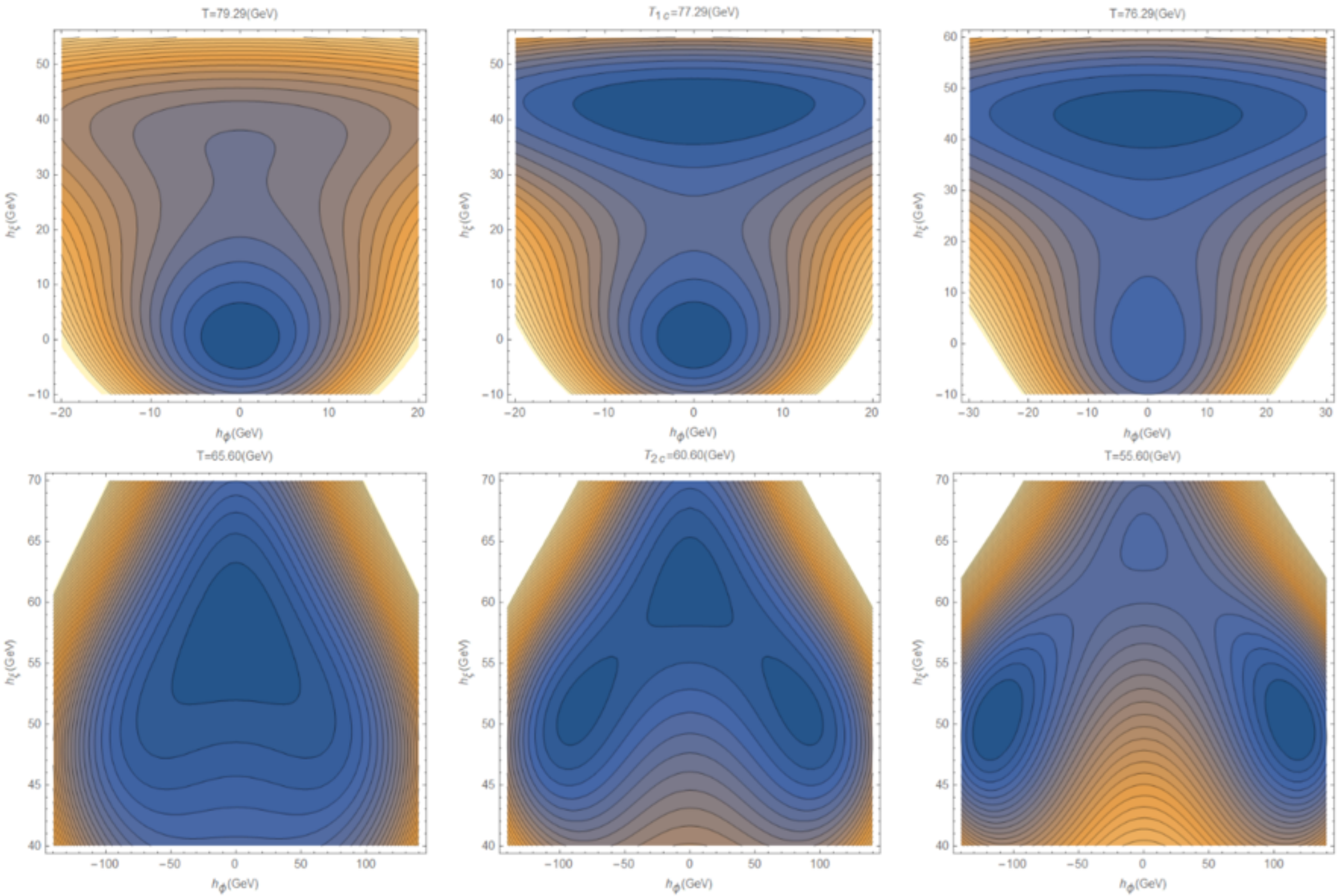
one-step



$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \quad \text{EWSB}$$

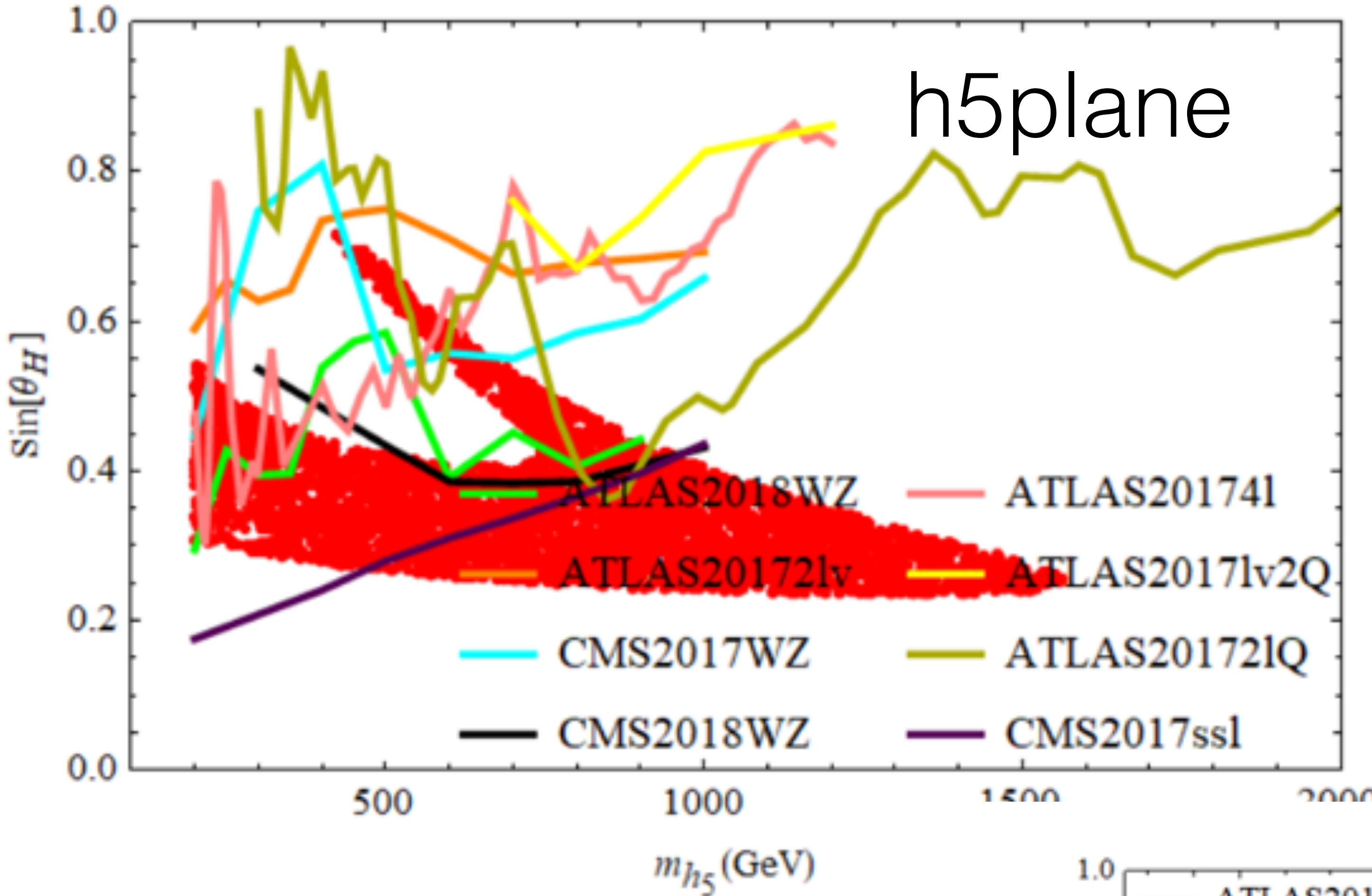
SFOEWPT patterns

multi-step



0->(0,<hxi>) ->(<hphi>,<hxi>)

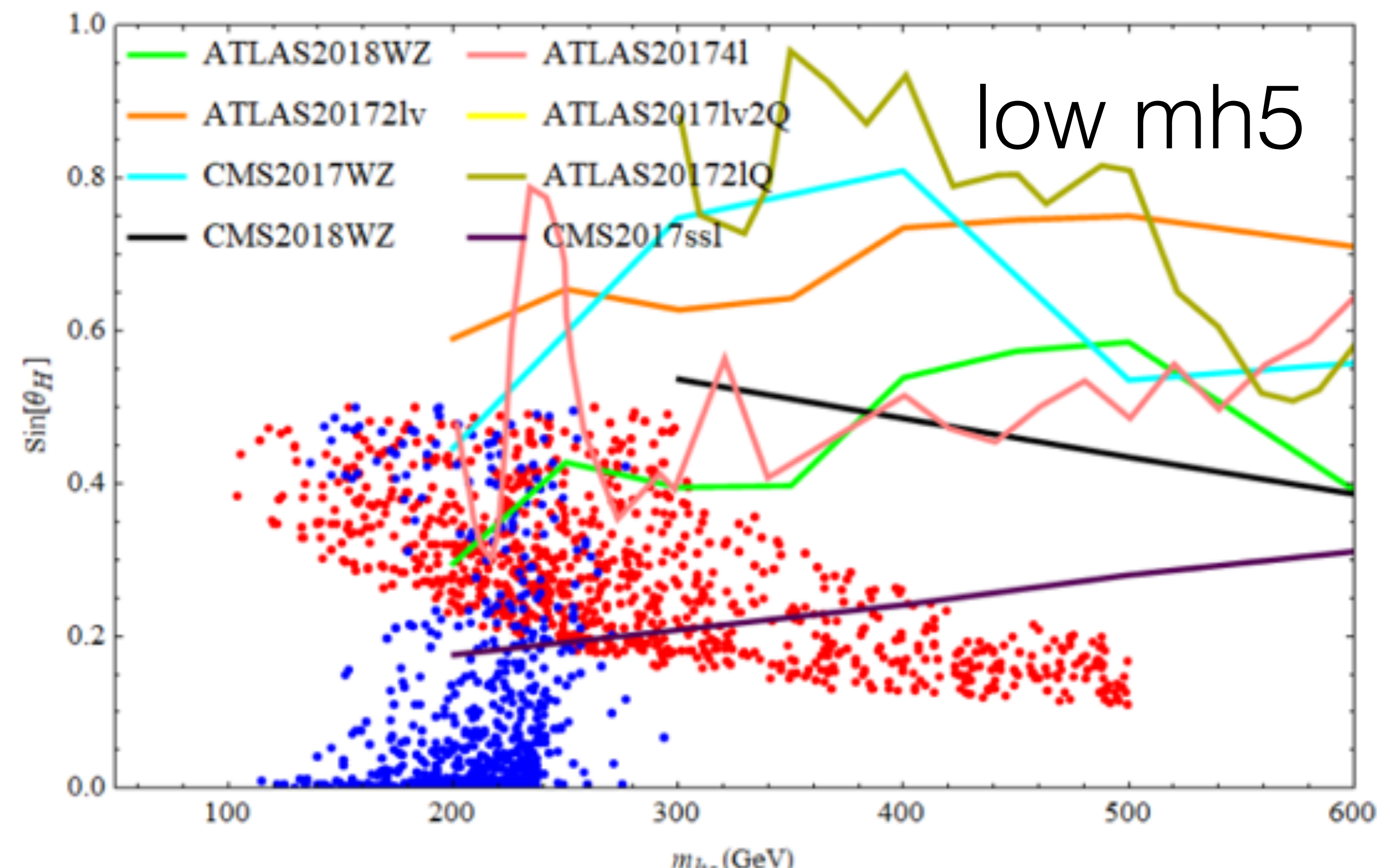
GM model



$$\sin\theta_H = \frac{2\sqrt{2}v_\xi}{v}$$

one step

two step



xSM: without extra EWSB GM: with extra EWSB

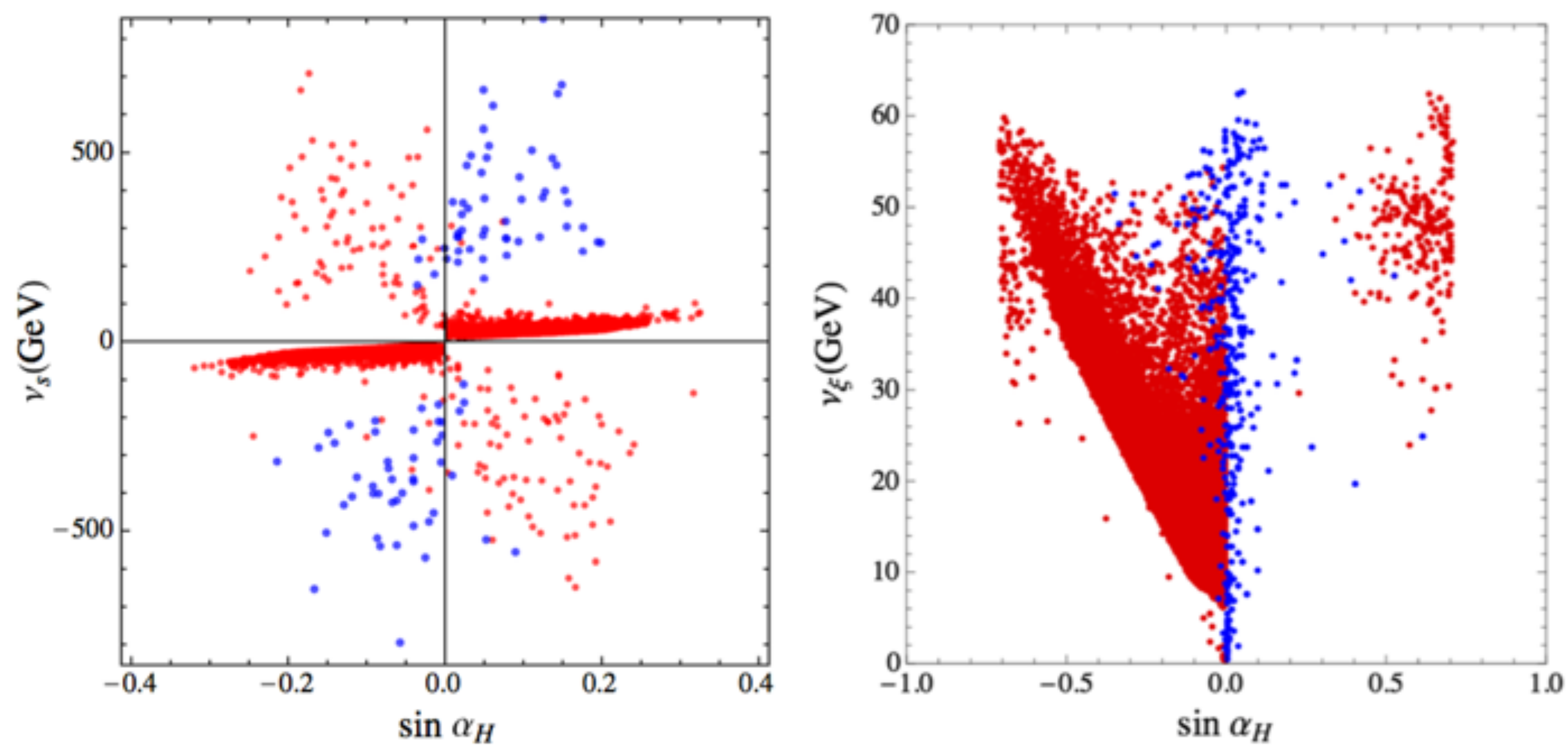


FIG. 4. The $v_C/T_C > 1$ viable points [both one-step (red) and two-step (blue)] in the $\sin\alpha_H - v_{s,\xi}$ plane for the xSM (left) and the GM (right) model.

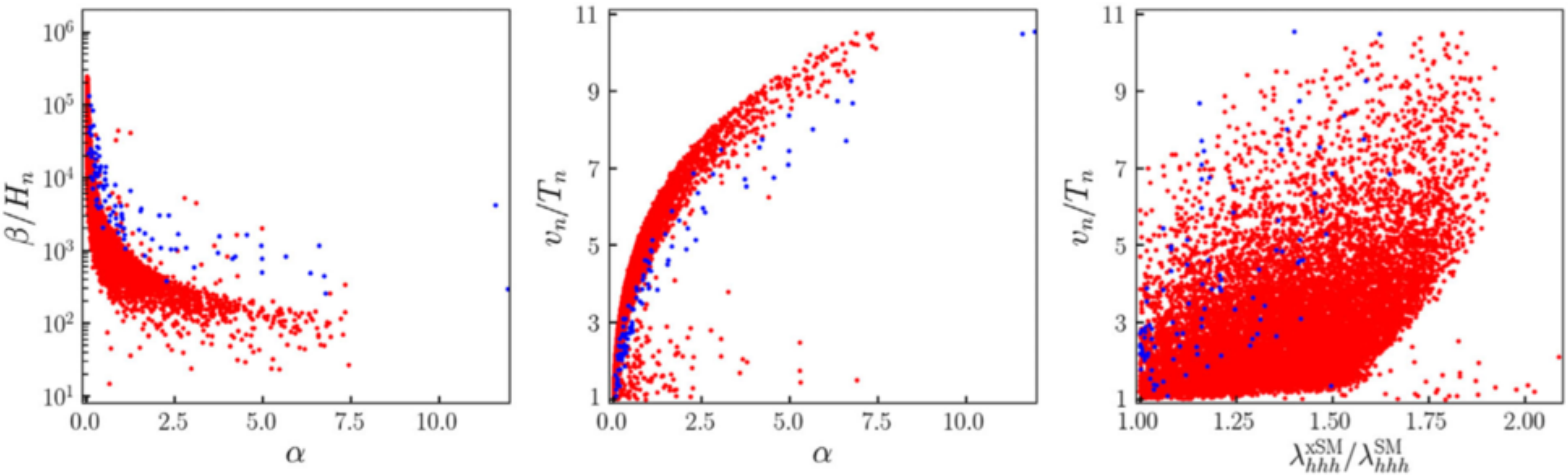
$$g_{hxx} = \cos\alpha g_{hxx}^{SM}$$

$$g_{hf\bar{f}} = \cos\alpha/\cos\theta_H g_{hf\bar{f}}^{SM},\ g_{hVV} = (\cos\alpha\cos\theta_H - \sqrt{\frac{8}{3}}\sin\alpha\sin\theta_H)g_{hf\bar{f}}^{SM},$$

$$g_{Hf\bar{f}} = \sin\alpha/\cos\theta_H g_{hf\bar{f}}^{SM},\ g_{HVV} = (\sin\alpha\cos\theta_H + \sqrt{\frac{8}{3}}\cos\alpha\sin\theta_H)g_{hVV}^{SM}.$$

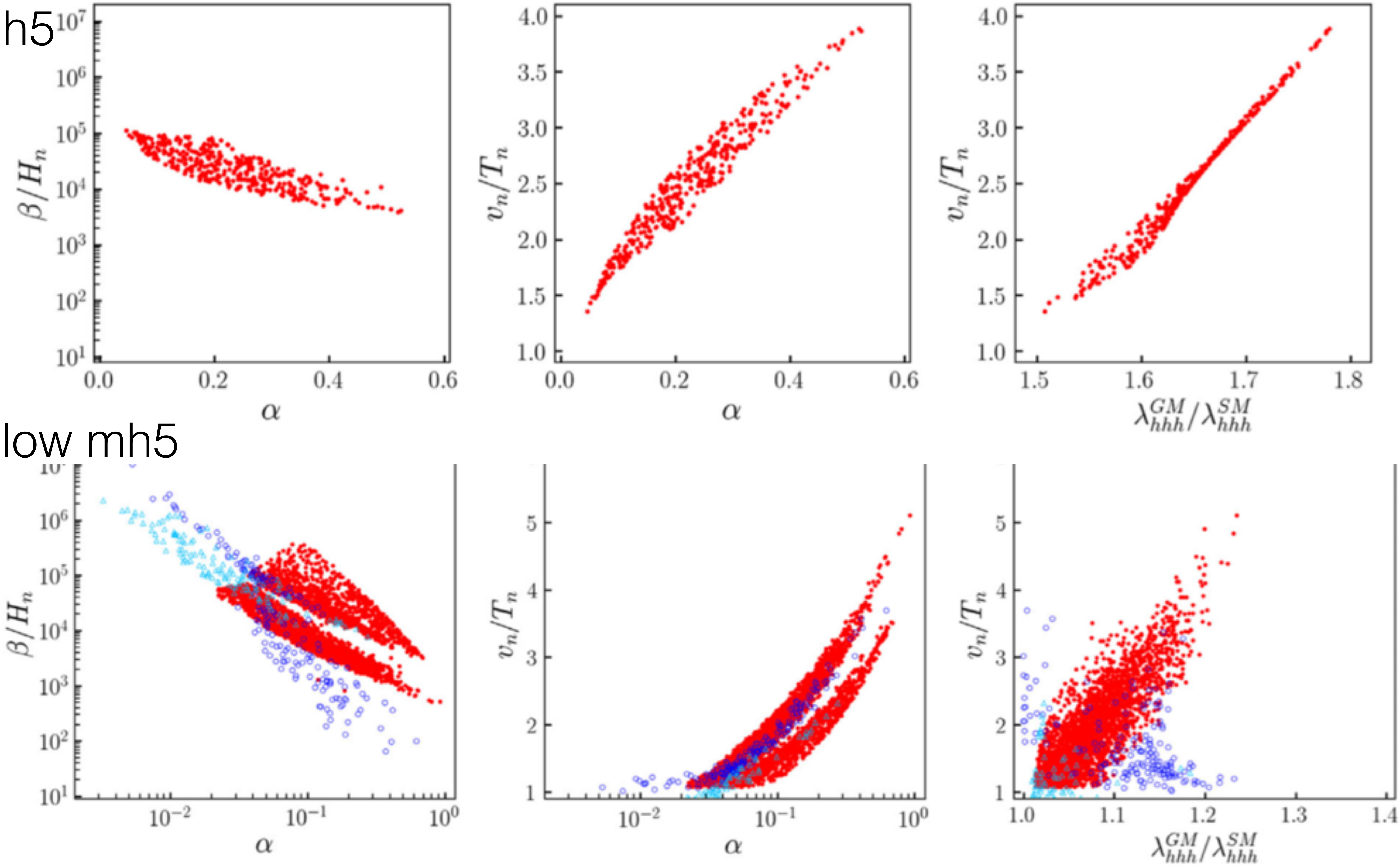
GW parameter and triple Higgs coupling

xSM



GW parameter and triple Higgs coupling

GM

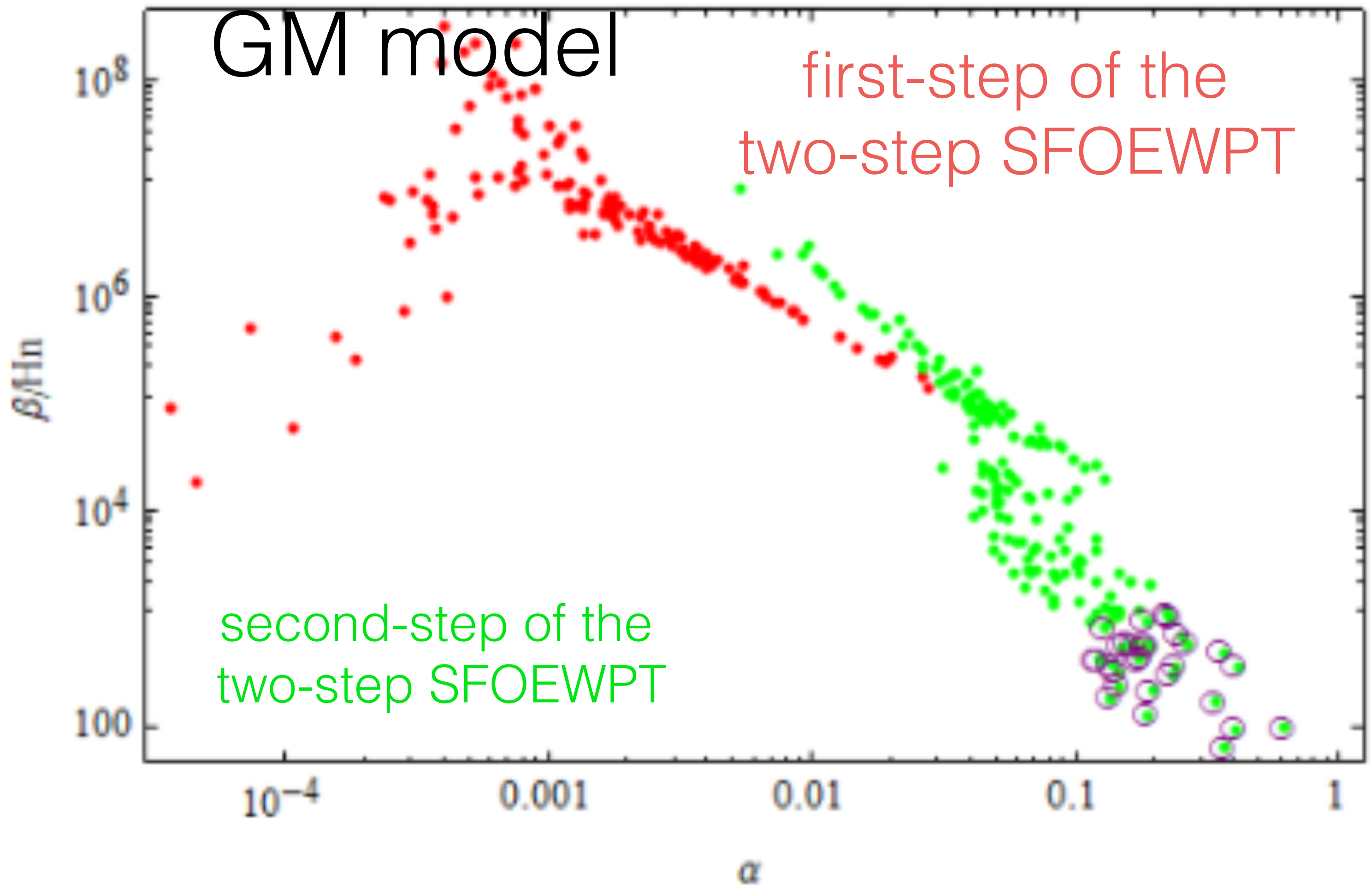


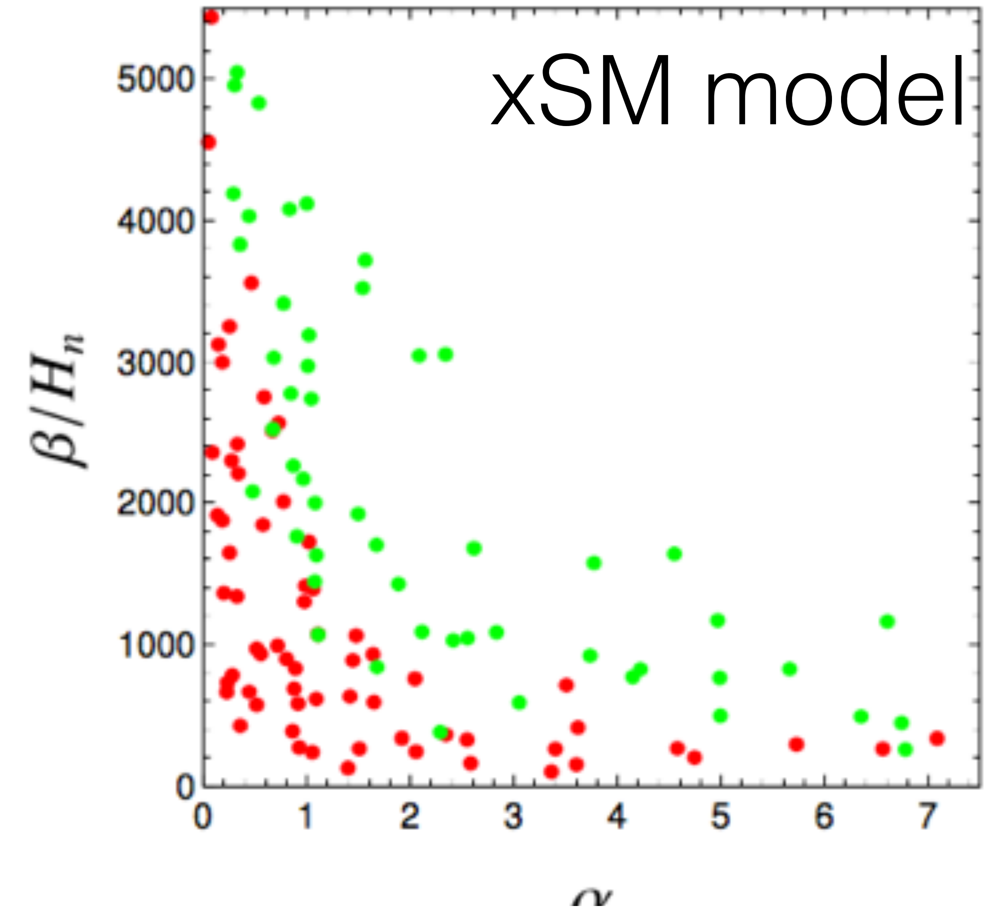
circles: two-step bubble nucleations (“bubble two-step”)

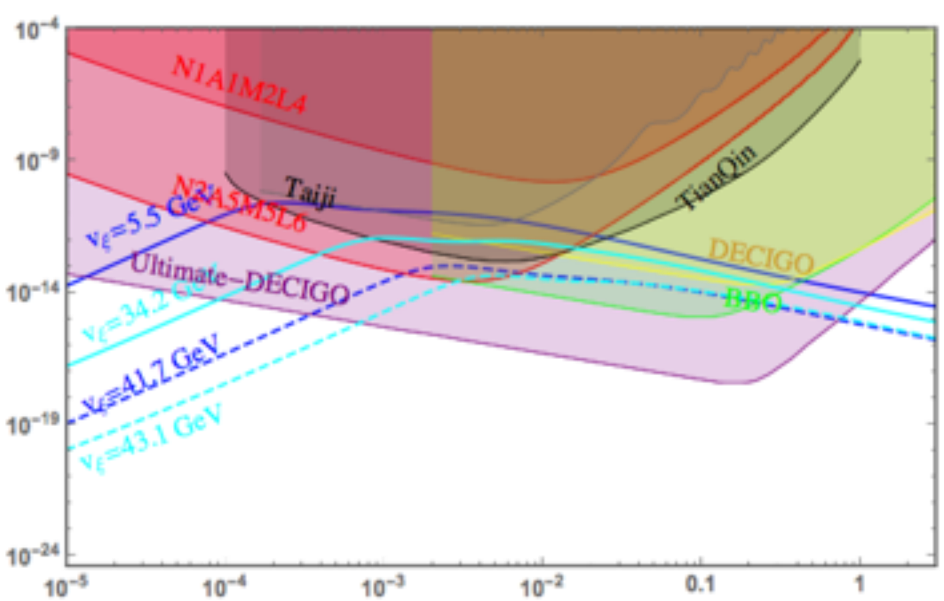
triangle points: one-step bubble nucleations (“bubble one-step”)

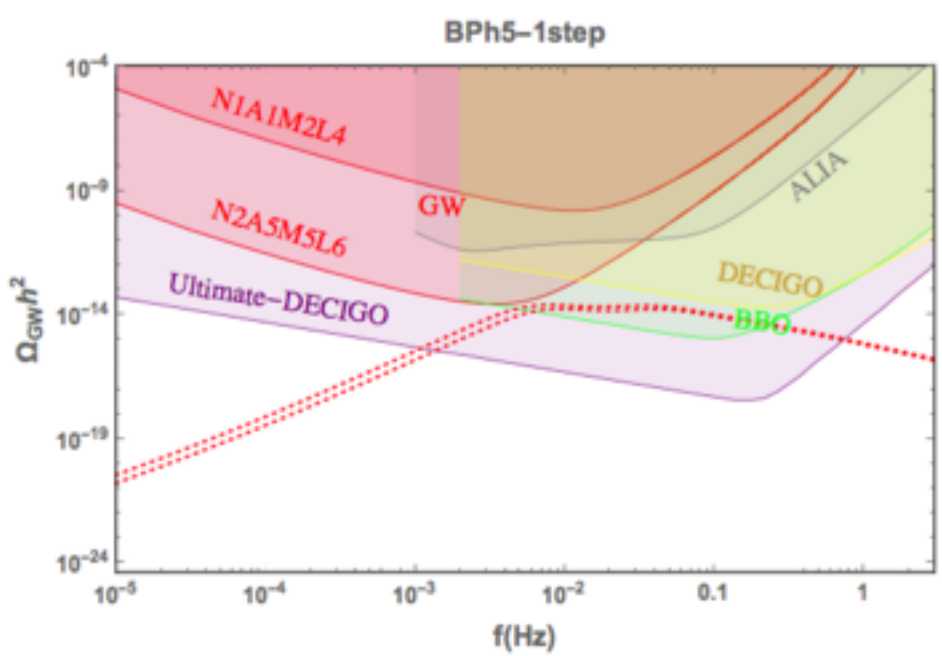
GW parameter

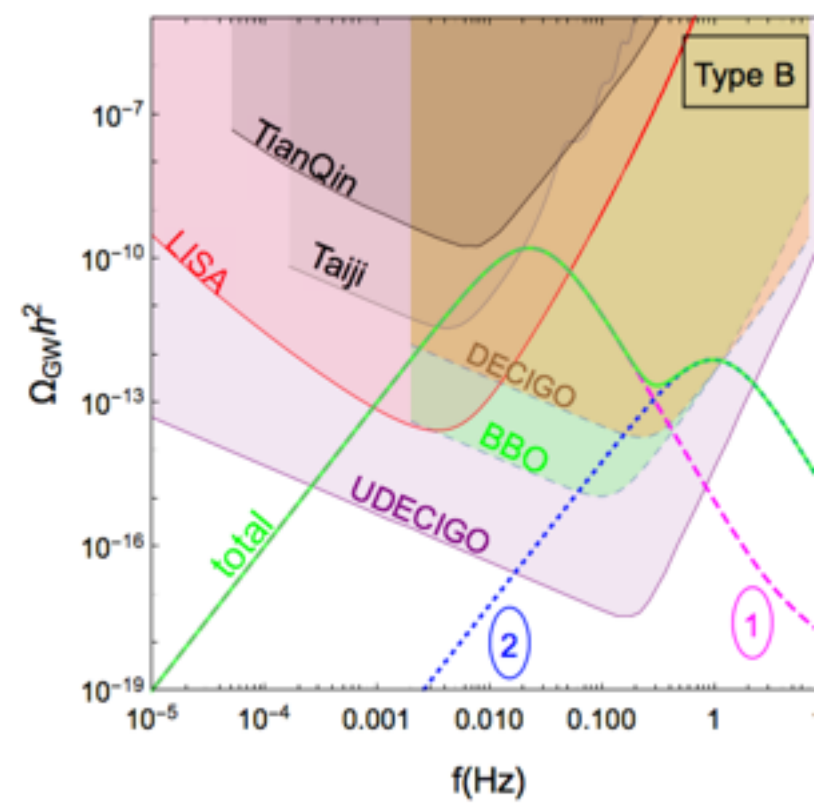
Two-step





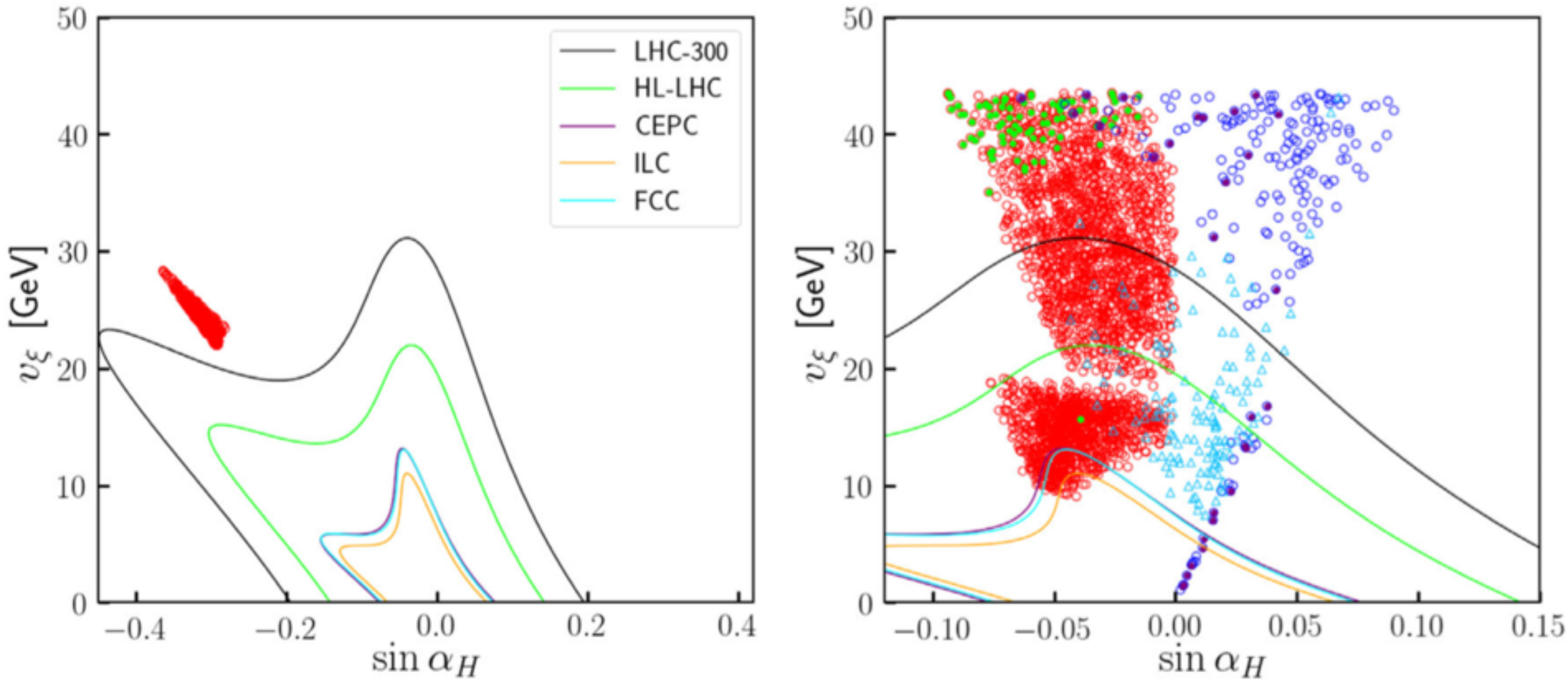






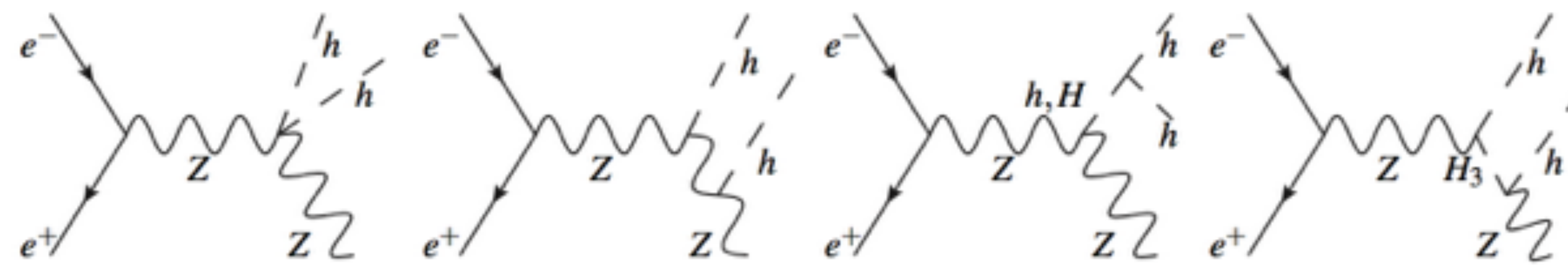
SFOEWPT viable points and future collider prospects

GM

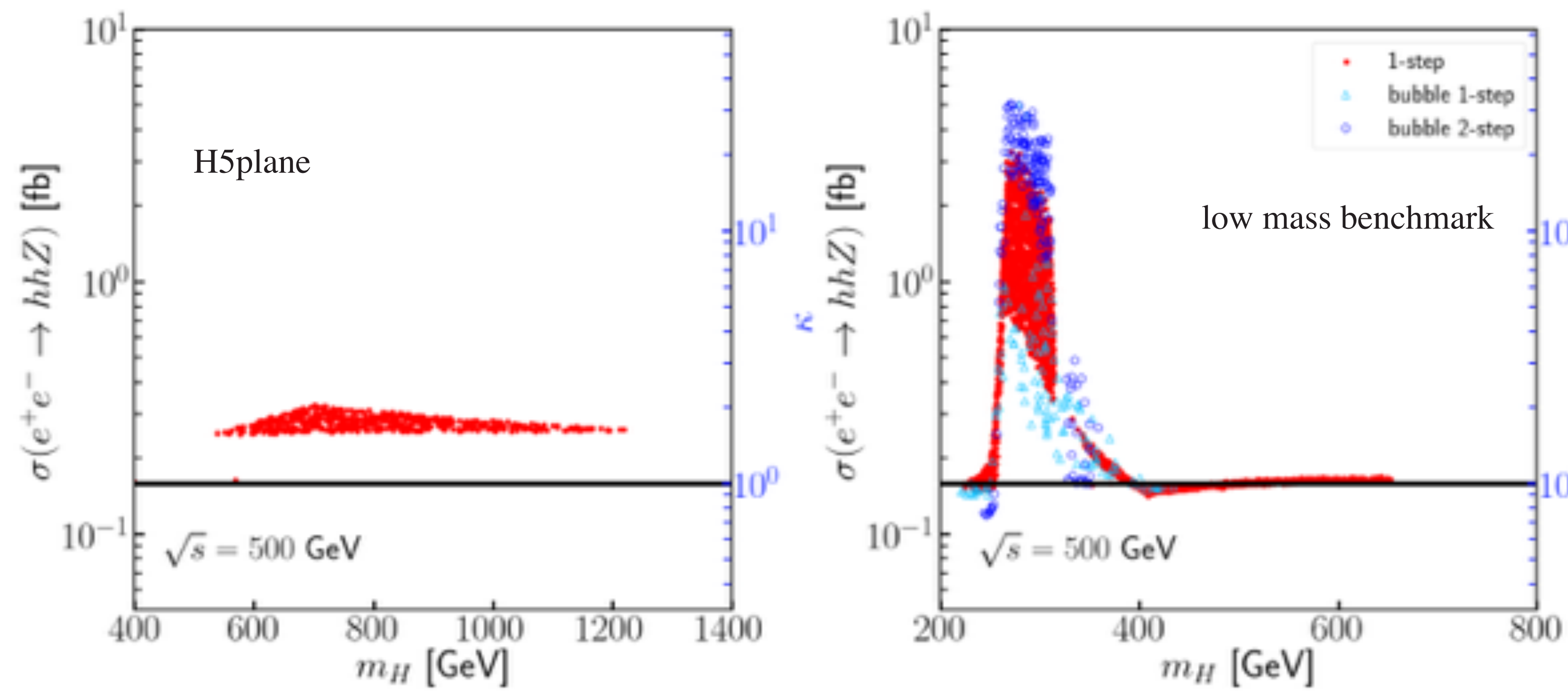


The SFOEWPT viable points with $v_n/T_n > 1$ in the $\sin\alpha_H - v_\xi$ plane for one-step (red) and two-step (blue) phase transition for H5plane (left panel) and low mass benchmark (right panel) scenario. In low mass benchmark, SNR > 10 with solid markers for one-step (green) and two-step (purple) cases.

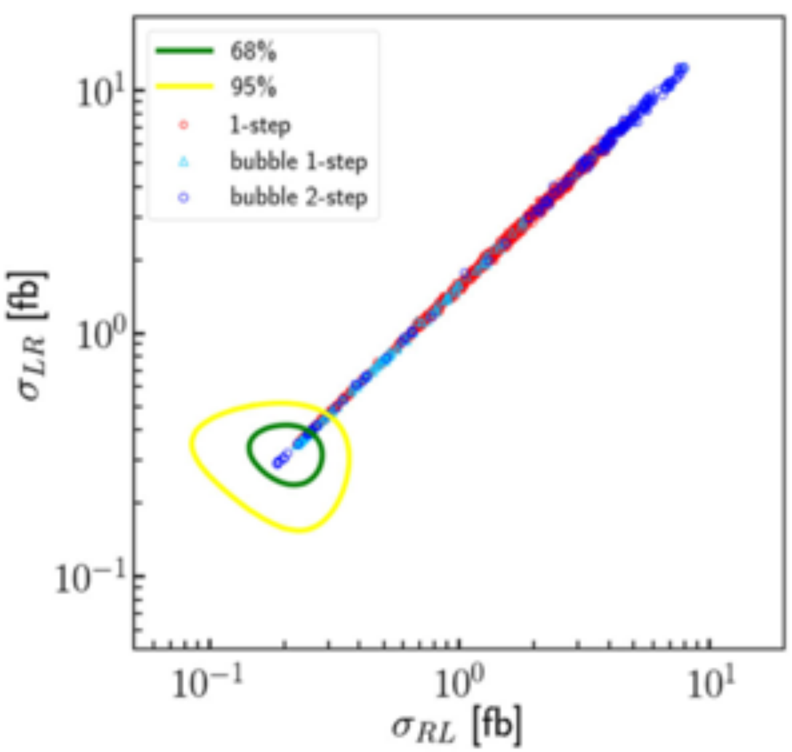
Lepton collider Search GM



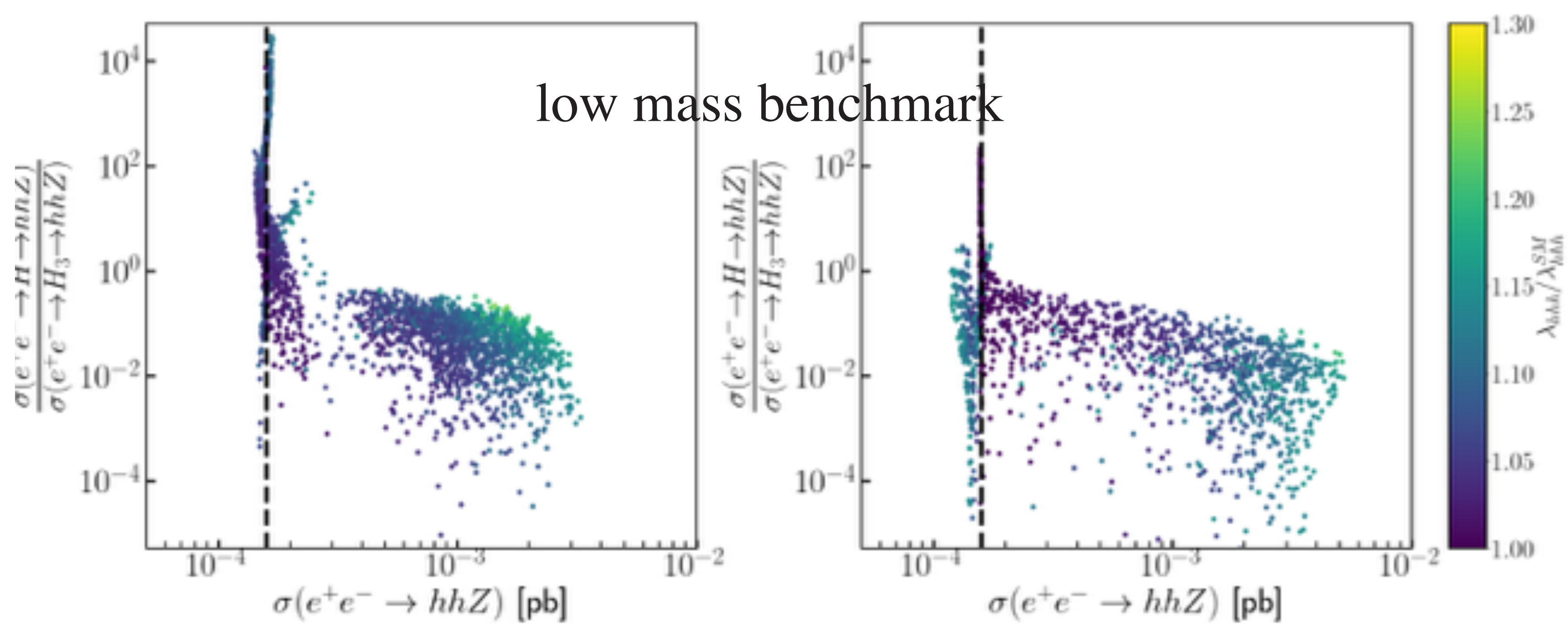
ILC/CEPC will have sensitivity for these SFOEWPT viable points.



$\kappa \equiv \frac{\sigma^{GM}}{\sigma^{SM}}$



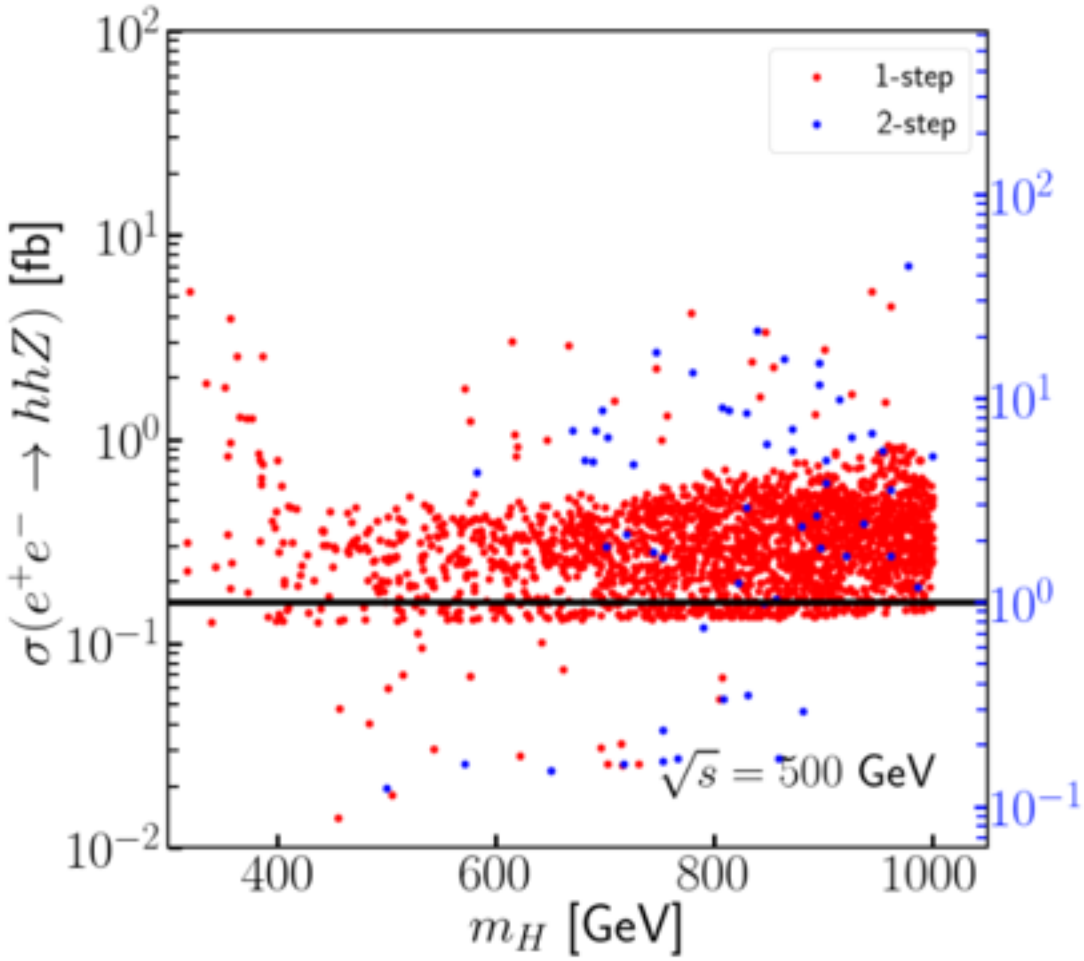
low mass benchmark

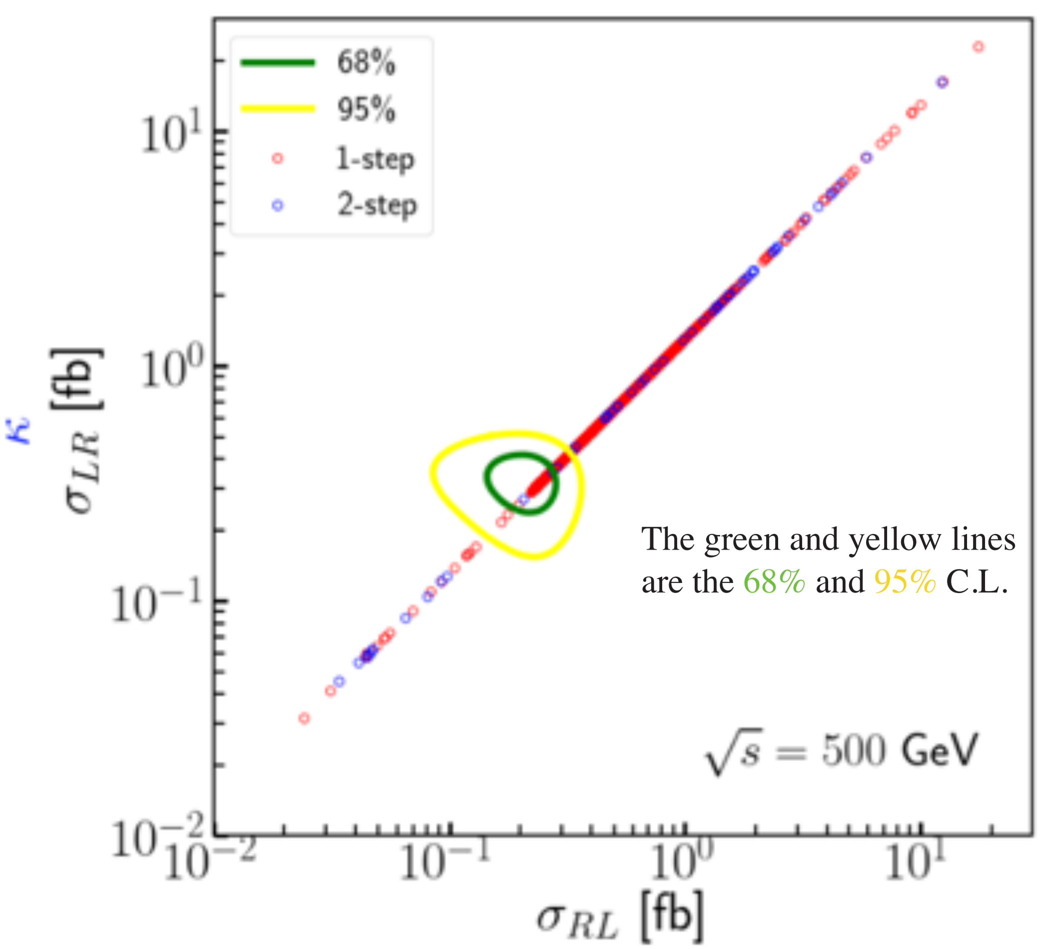


Lepton collider Search   xSM

$\sigma_{LR}(\sigma_{RL})$

denotes the cross section at beam polarization configurations of $(P_{e^+}, P_{e^-}) = (+1, -1)((-1, +1))$.

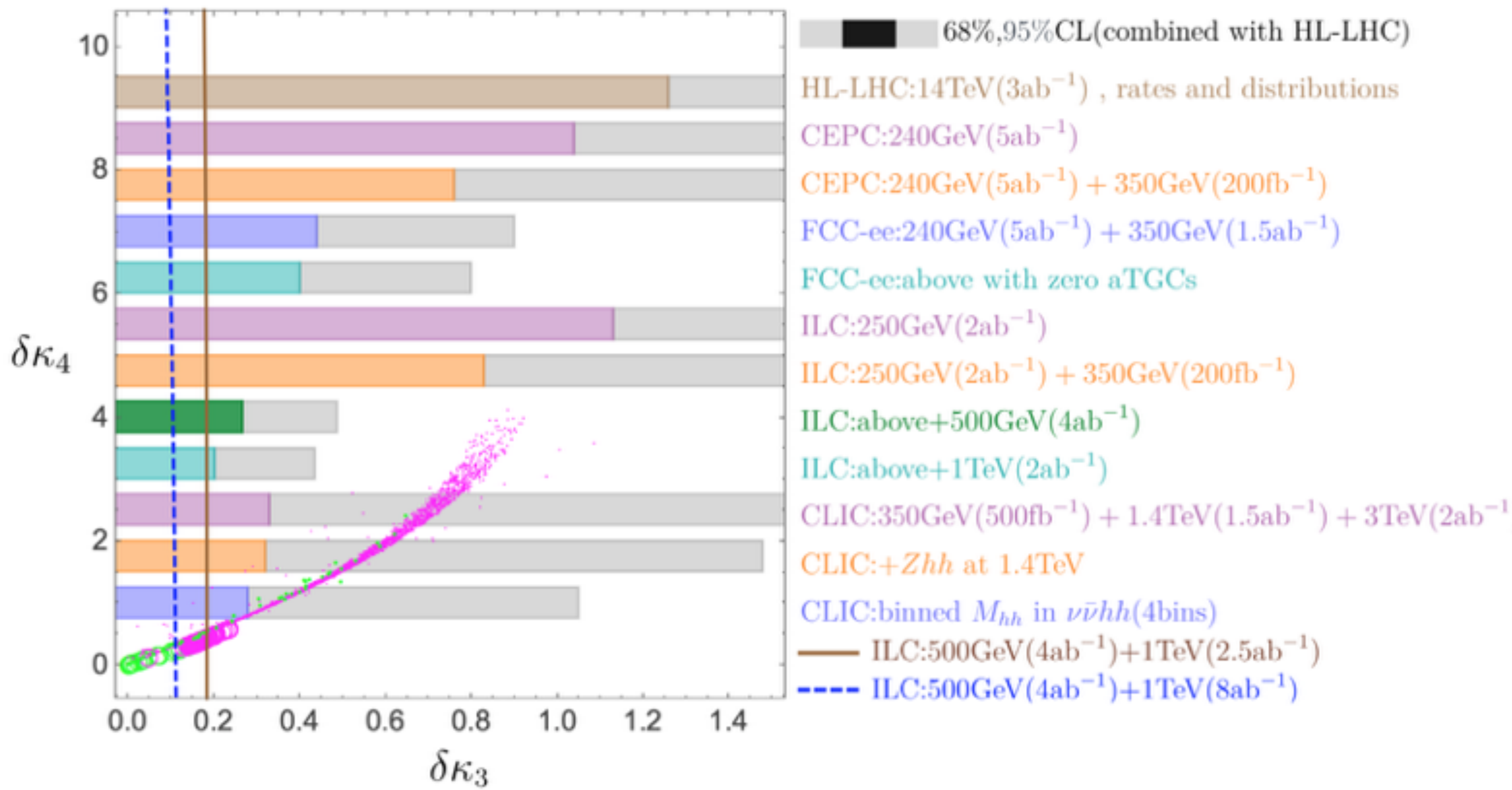




ILC/CEPC will exclude most one-step as well as two-step points in the xSM.

Collider & GW complementary search

SNR > 10 points for two-step and one-step SFOEWPT



Circles and the dotted points for the GM and xSM scenarios

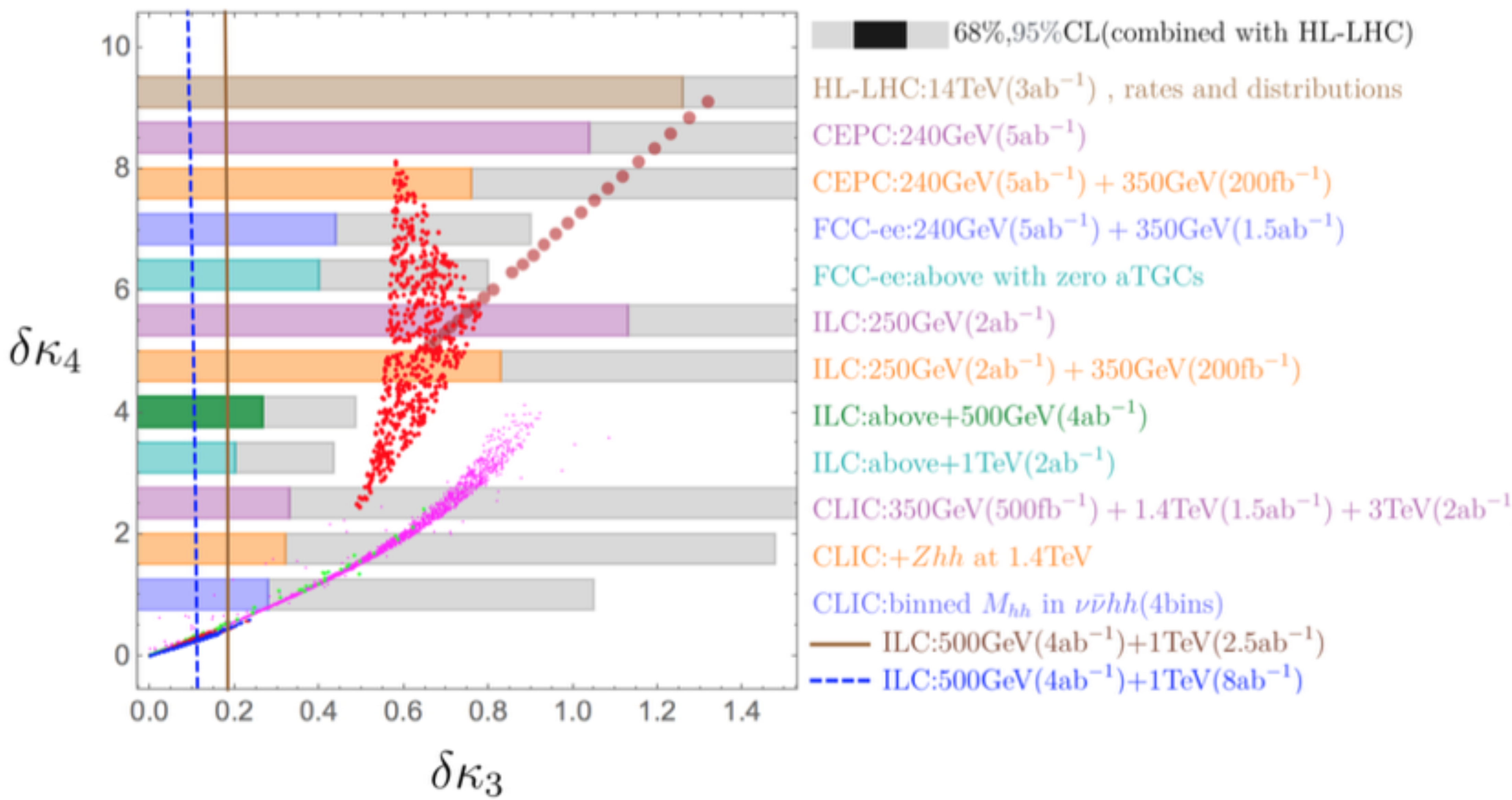
$$\delta\kappa_3^{\rm xSM} = \alpha_H^2\left[-\frac{3}{2}+\frac{2m_H^2-2b_3v_s-4b_4v_s^2}{m_h^2}\right]+\mathcal{O}(\alpha_H^3),$$

$$\delta\kappa_4^{\rm xSM} = \alpha_H^2\left[-3+\frac{5m_H^2-4b_3v_s-8b_4v_s^2}{m_h^2}\right]+\mathcal{O}(\alpha_H^3).$$

$$\delta\kappa_3^{GM} = -\alpha_H\frac{\sqrt{3}\mu_1 v}{2m_h^2}+\frac{\alpha_H v^2(4\alpha_H-\sqrt{6}\theta_H)(2\lambda_4+\lambda_5}{2m_h^2} - \frac{(3\alpha_H^2+\theta_H^2)}{2}+\mathcal{O}(\alpha_H^3,\theta_H^3),$$

$$\delta\kappa_4^{GM} = -2\alpha_H^2\left(1-\frac{2(2\lambda_4+\lambda_5)v^2}{m_h^2}\right)+\mathcal{O}(\alpha_H^3).$$

Collider & GW complementary search



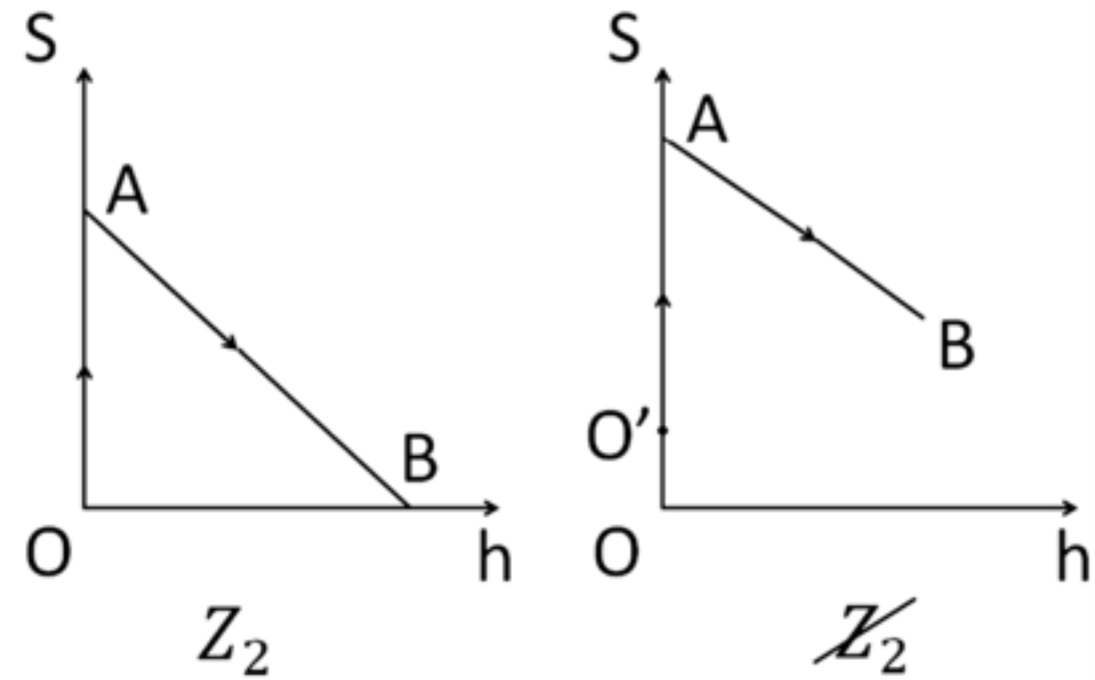
Blue: GM low mass; Red: GM h5; dark red: SMEFT; Pink and green: xSM one and two step

$$\delta\kappa_3^{h^6} = \frac{2v^4}{\Lambda^2 m_h^2}\,,\ \delta\kappa_4^{h^6} = \frac{12v^4}{\Lambda^2 m_h^2}$$

CxSM for 2-step

$$V(\Phi,\mathbb{S})_{\mathbb{Z}_2} = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \frac{b_1}{4}(\mathbb{S}^2 + \text{c.c.}). \quad (2)$$

$$V_0(h,S,A) = \frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{\delta_2}{8}h^2(S^2+A^2) + \frac{1}{4}(b_1+b_2)S^2 + \frac{1}{4}(b_2-b_1)A^2 + \frac{d_2}{16}(S^2+A^2)^2.$$



$$V(\Phi,\mathbb{S})_{\not{\mathbb{Z}}_2} = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(a_1\mathbb{S} + \frac{b_1}{4}\mathbb{S}^2 + \text{c.c.}\right). \quad (3)$$

$$V_0(h,S,A) = \frac{1}{2}\mu^2h^2 + \frac{\lambda}{4}h^4 + \frac{\delta_2}{8}h^2(S^2+A^2) + \sqrt{2}a_1S + \frac{b_1+b_2}{4}S^2 + \frac{d_2}{16}S^4 + \frac{-b_1+b_2}{4}A^2 + \frac{d_2}{16}A^4 + \frac{d_2}{8}S^2A^2. \quad ($$

$$V(h,S;T) = V_0(h,S,A=0) + \frac{1}{2}\Pi_h(T)h^2 + \frac{1}{2}\Pi_S(T)S^2, \quad (25a)$$

$$\Pi_h(T) = \left(\frac{2m_W^2 + m_Z^2 + 2m_t^2}{4v^2} + \frac{\lambda}{2} + \frac{\delta_2}{24}\right)T^2, \quad (25b)$$

$$\Pi_S(T) = \frac{1}{12}(\delta_2 + d_2)T^2, \quad (25c)$$

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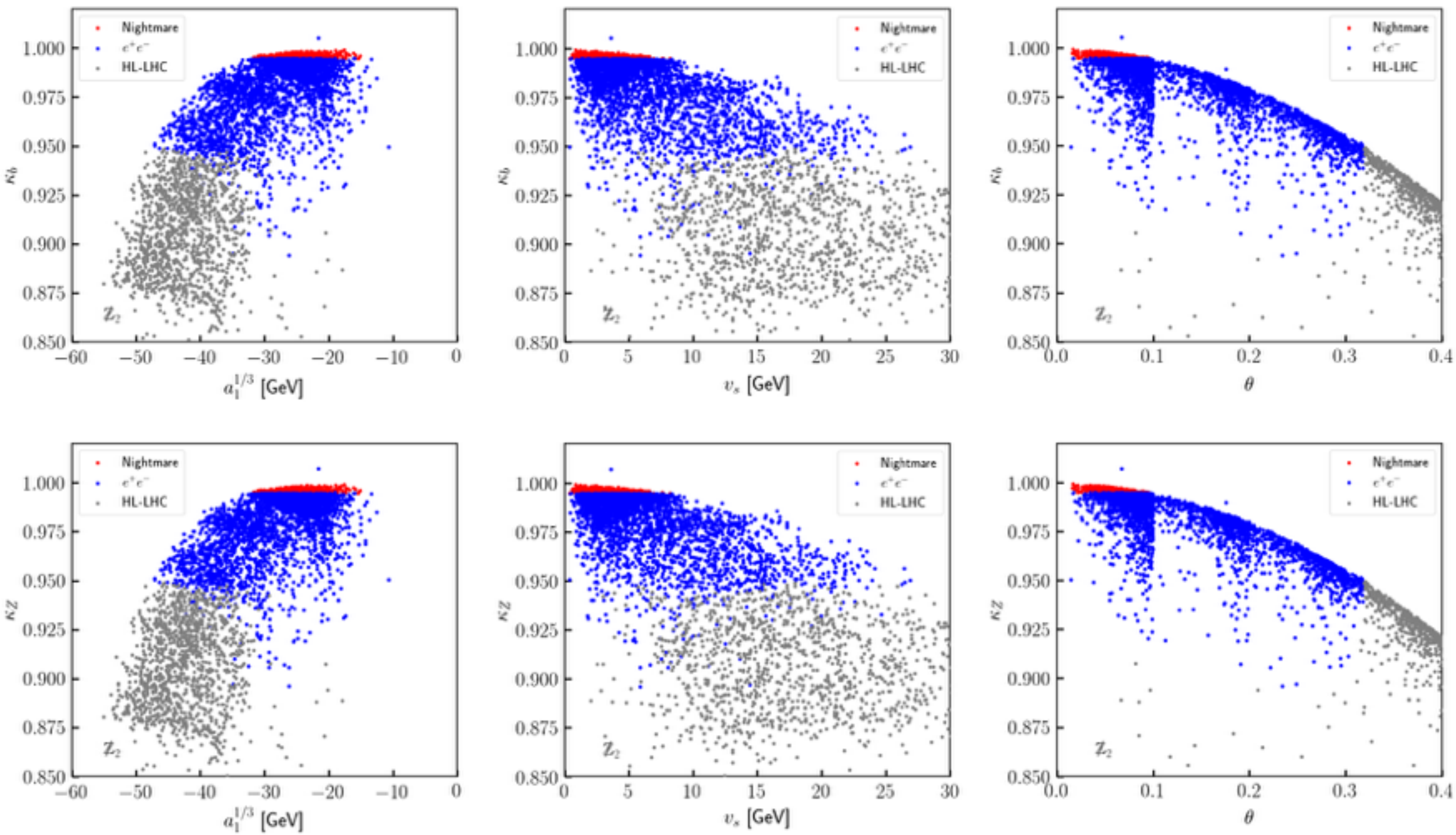
1ST EWPT and Collider search for CxSM



$$\kappa_V = \frac{\Gamma^1_{hVV}(m_V^2, m_h^2, q^2)_{\rm cxSM}}{\Gamma^1_{hVV}(m_V^2, m_h^2, q^2)_{\rm SM}},$$

$$\kappa_f = \frac{\Gamma^S_{hf\bar{f}}(m_f^2, m_f^2, q^2)_{\rm cxSM}}{\Gamma^1_{hf\bar{f}}(m_f^2, m_f^2, q^2)_{\rm SM}}.$$

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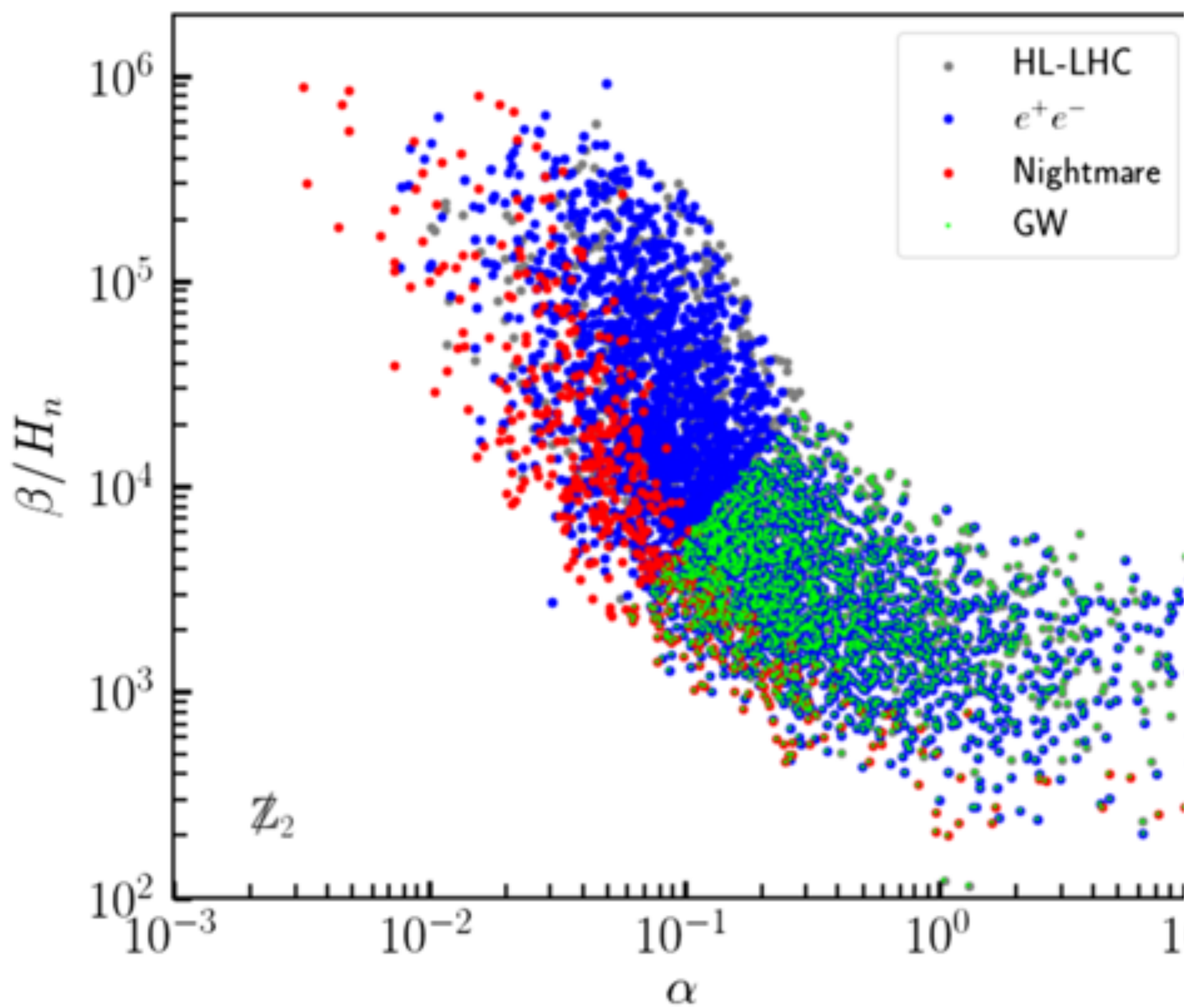
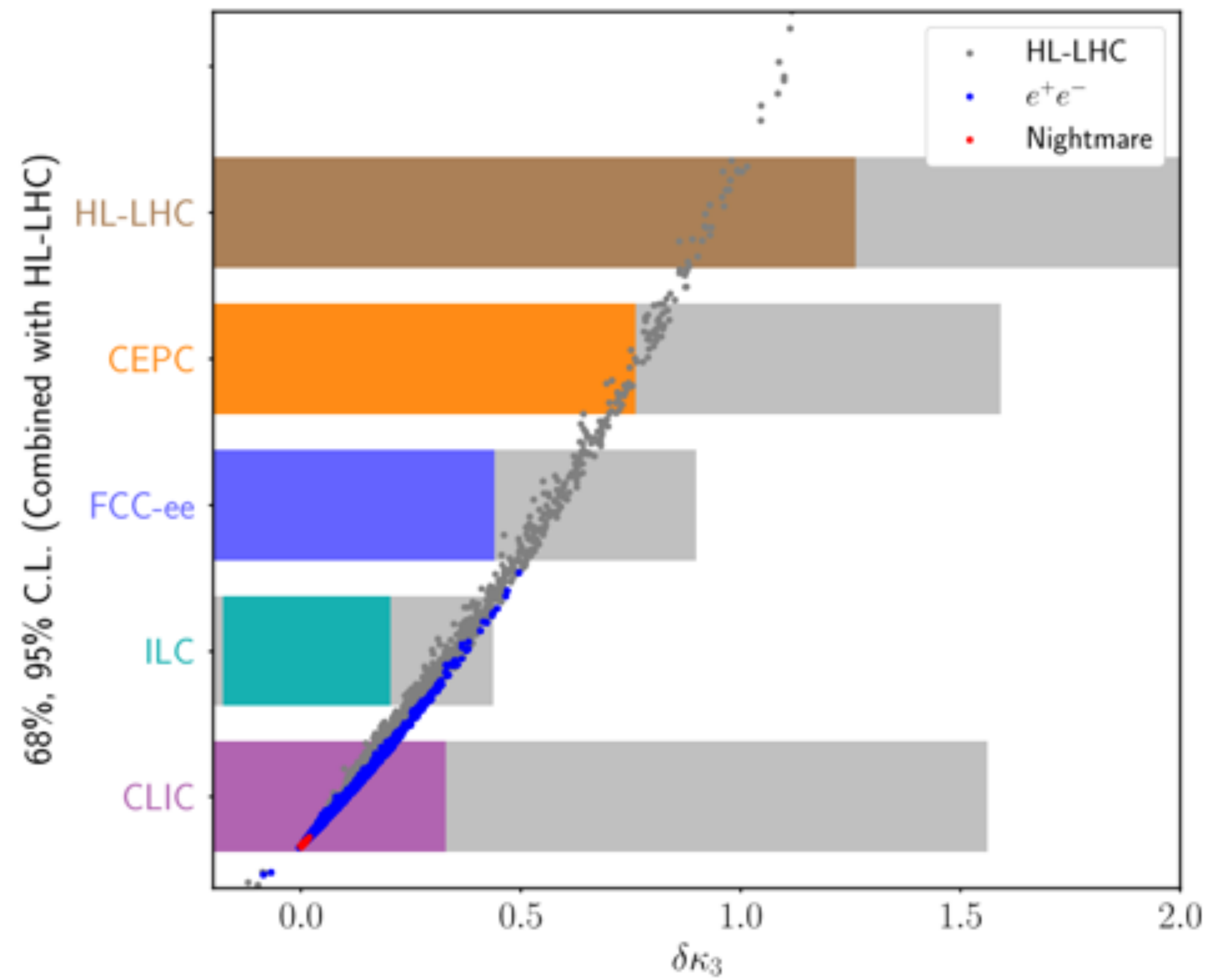
1ST EWPT and Collider search for CxSM

with GW at LISA SNR > 50





$$\lambda_{111} = \frac{s_\theta^3(\sqrt{2}a_1 + M_1^2 v_s)}{2v_s^2} + \frac{M_1^2 c_\theta^3}{2v}$$

$\delta\kappa_3 \equiv \lambda_{111}/\lambda_{hhh}(SM) - 1$

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Related interesting topics

1. Dark matter with phase transition

   1712.03962,Michael J. Baker et al.   1810.03172, L.Bian, Y. Tang   …

2. Leptogenesis with phase transition

   A. strumia, T. Hambye, …

3. Wall velocity

   T.Konstandin,G. Moore, J Kozaczuk, …

4. Nonperturbative evaluation of EWPT

   1711.09849, Anders Tranberg et al.
   PRL 113, 141602 (2014), Anders Tranberg et al. …

5. Sphaleron calculation and simulations

   Manton, Klinkhamer,L. Carson, L. Mclerran, G. D. Moore, Mark Hindmarsh, X.M.Zhang, L.Bian,…

6. Gravitational Waves simulation

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谢谢！

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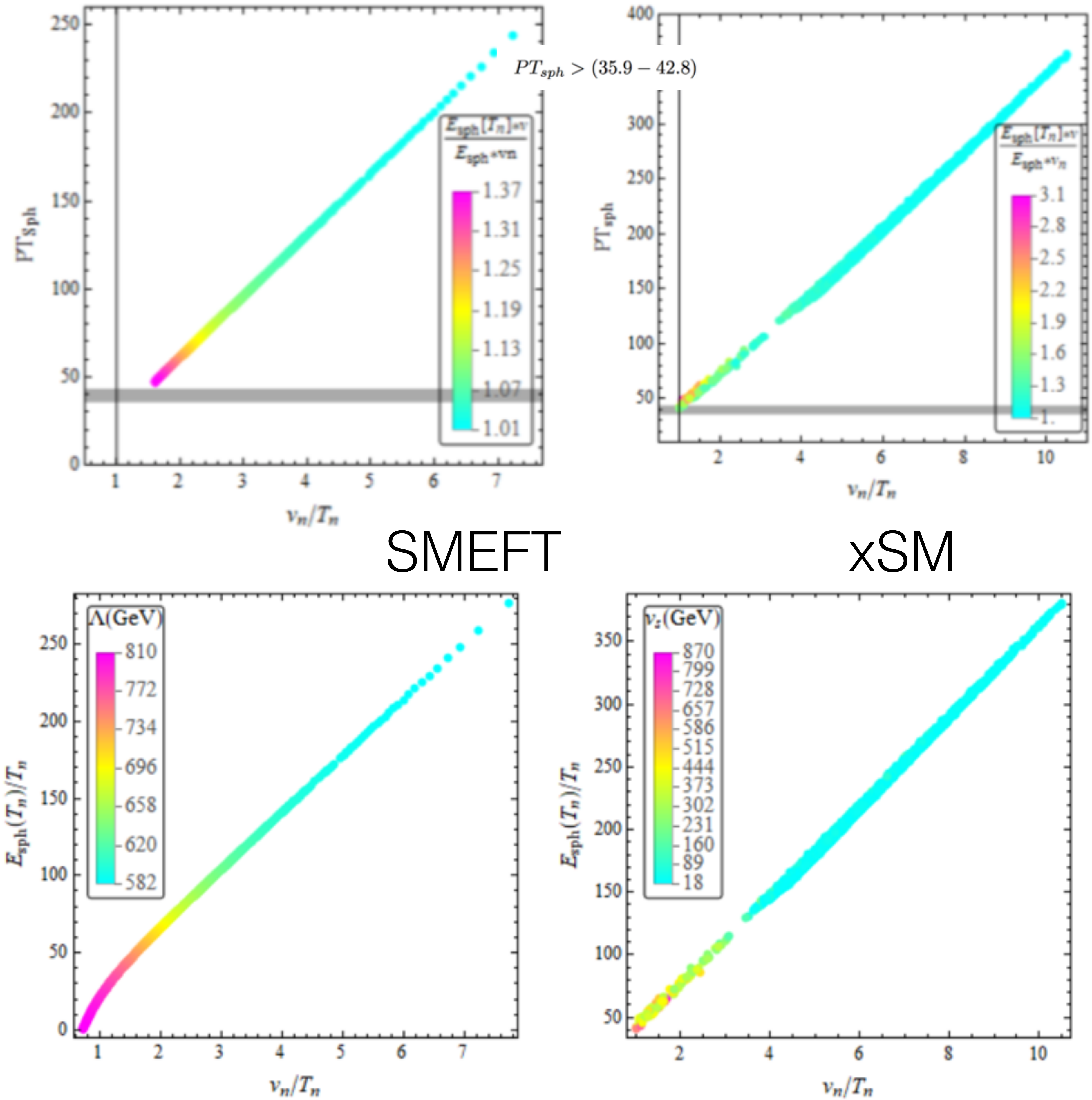
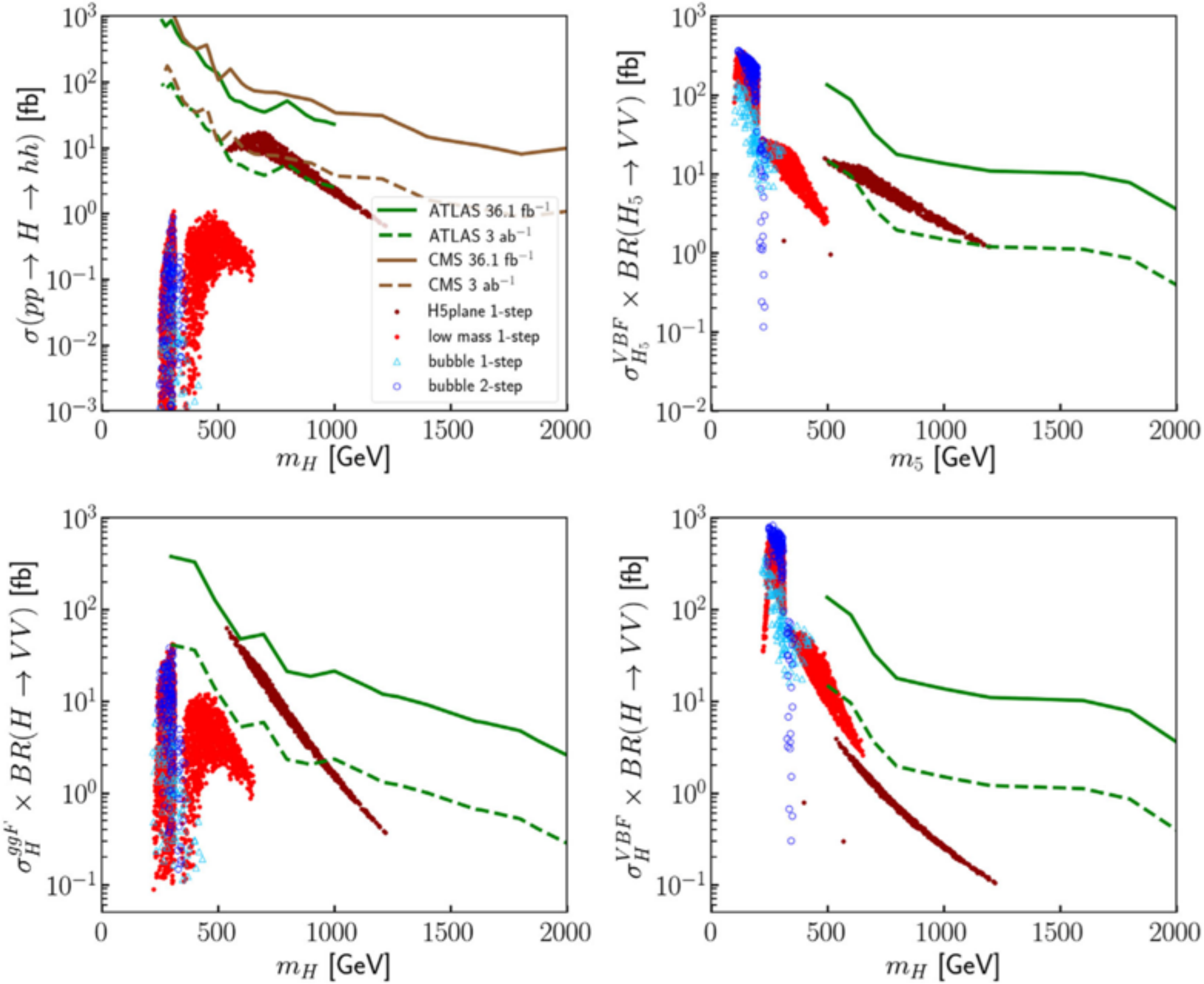
Sphaleron energy and SFOEWPT condition





$\sigma(pp \to H \to hh)$ [fb]
m_H [GeV]
ATLAS 36.1 fb^{-1}
ATLAS 3 ab^{-1}
CMS 36.1 fb^{-1}
CMS 3 ab^{-1}
H5plane 1-step
low mass 1-step
bubble 1-step
bubble 2-step
$\sigma^{VBF}_{H_5} \times BR(H_5 \to VV)$ [fb]
m_5 [GeV]
$\sigma^{ggF}_H \times BR(H \to VV)$ [fb]
m_H [GeV]
$\sigma^{VBF}_H \times BR(H \to VV)$ [fb]
m_H [GeV]