EWPT, Higgs pheno and DM

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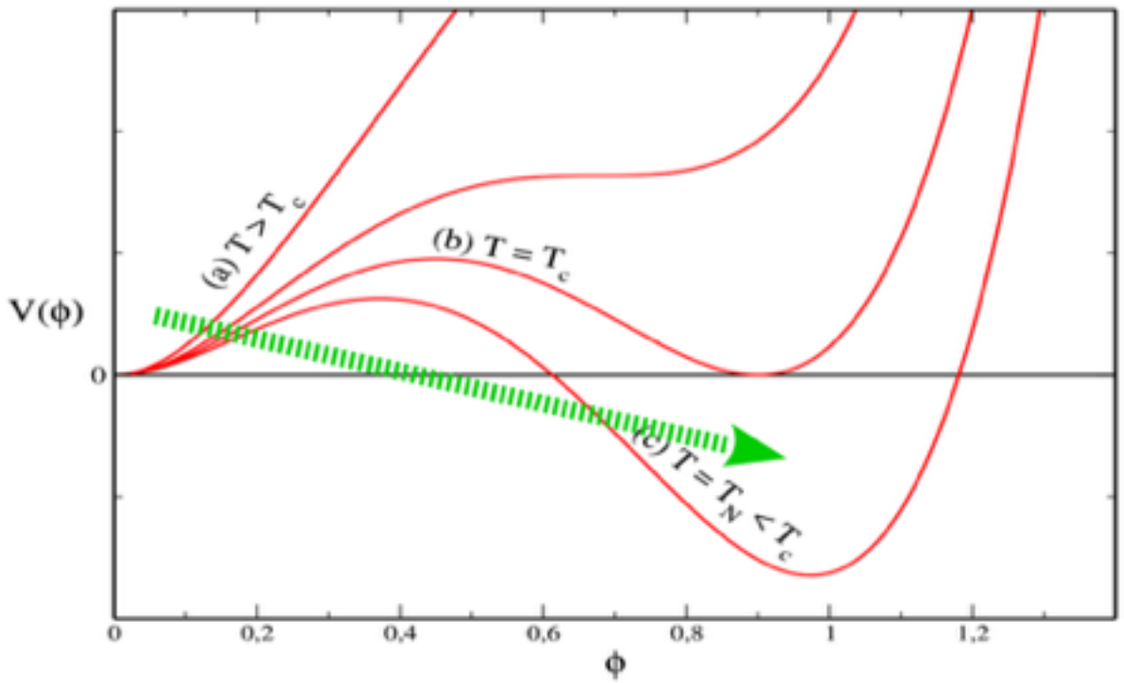
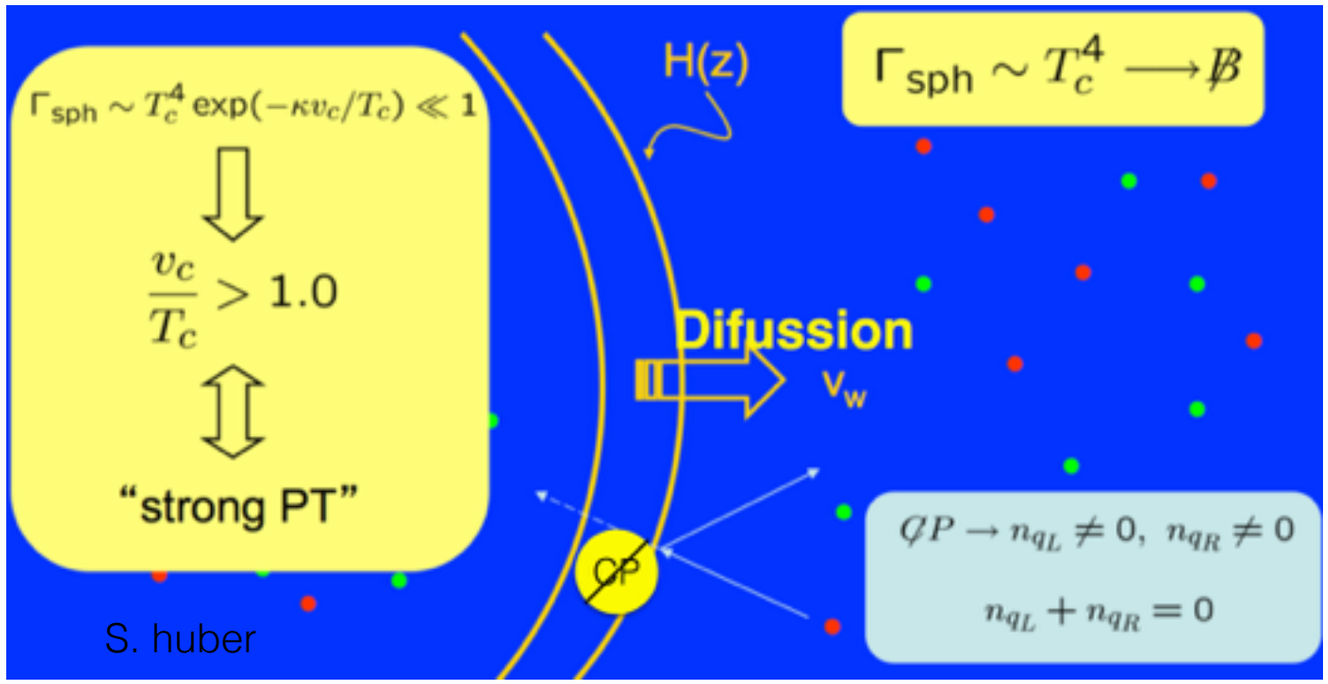
23rd LHC Mini-Workshop

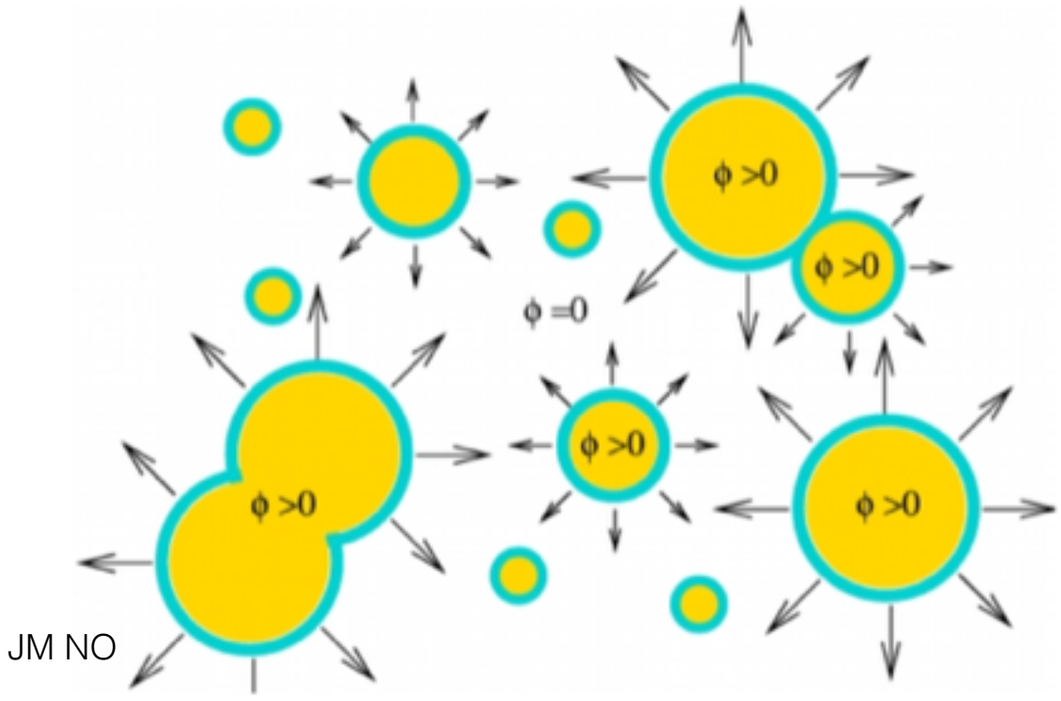
Why SFOEWPT

Tn~ 10^2 GeV

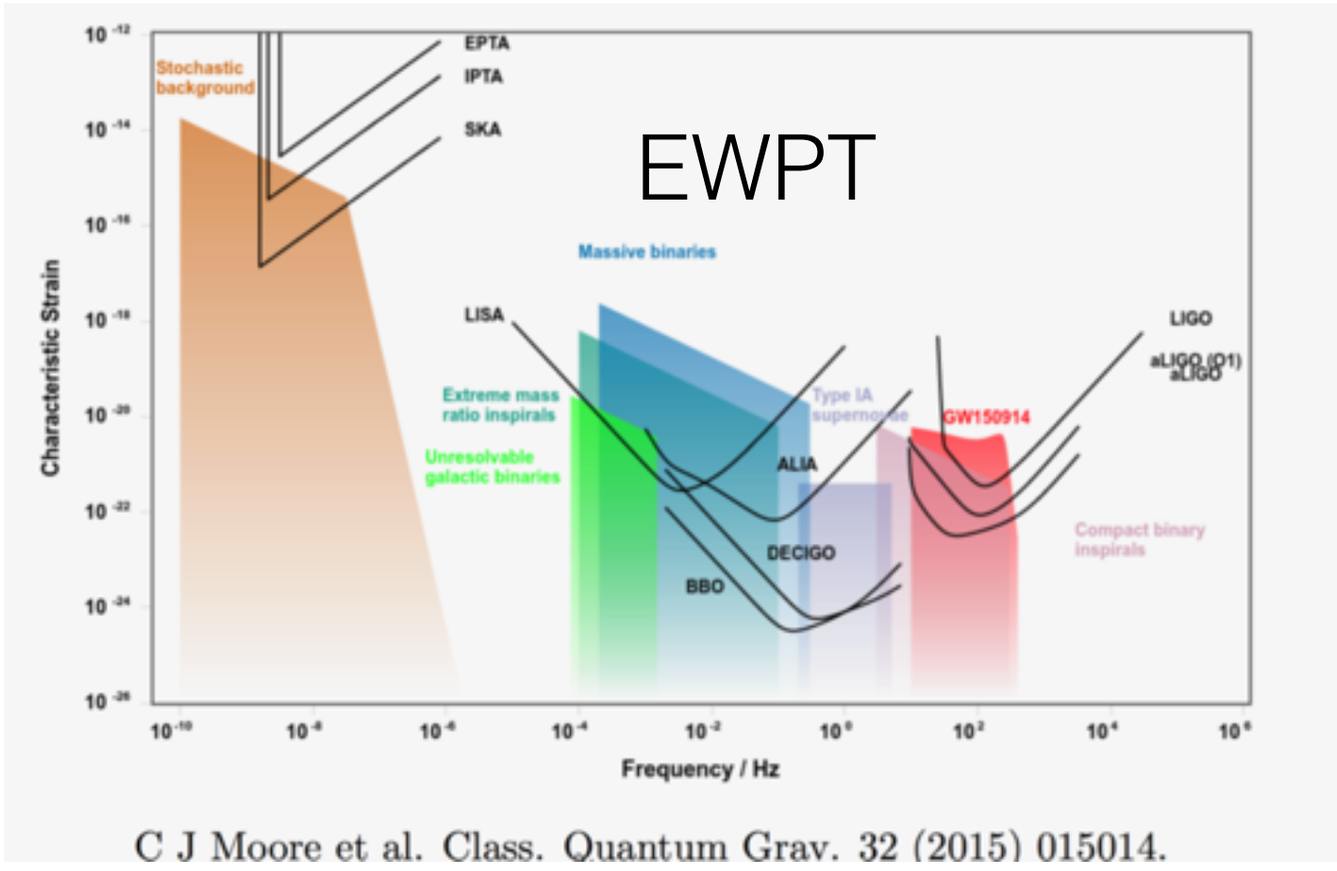
h







JM NO



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

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,…

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…

NMSSM

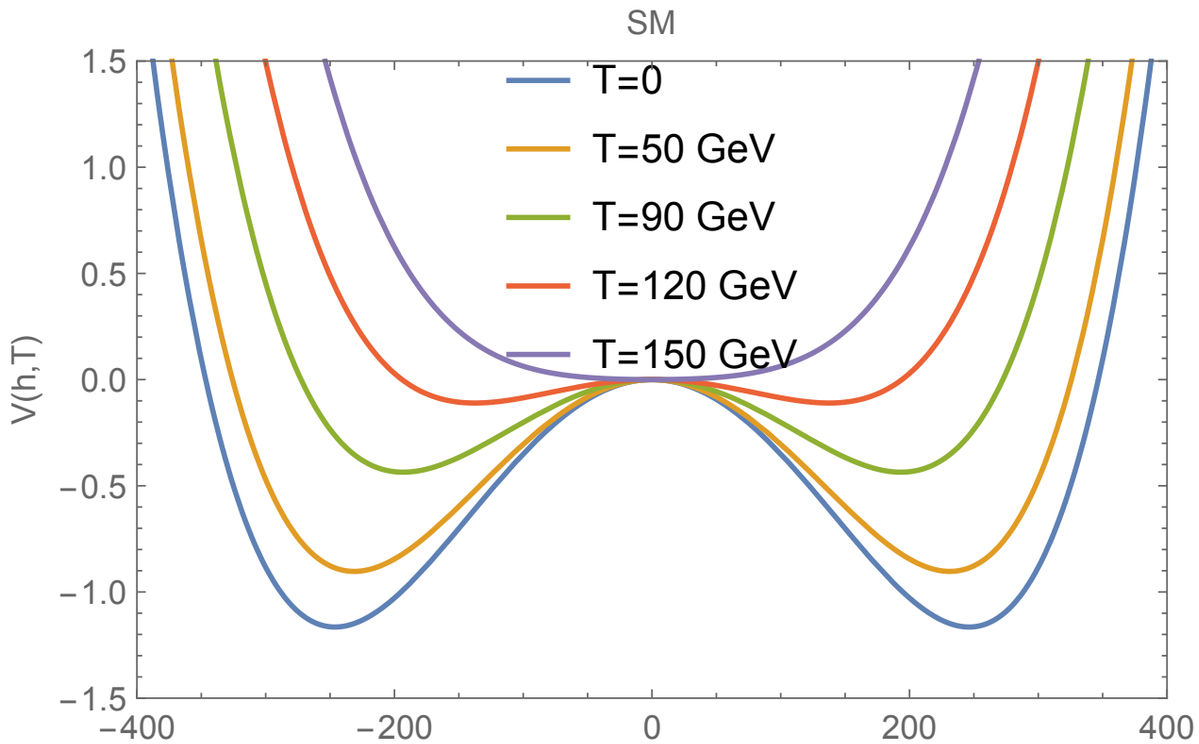
Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15, Bi, Bian, Huang, Shu, Yin 15, Bian, Guo, Shu 17…

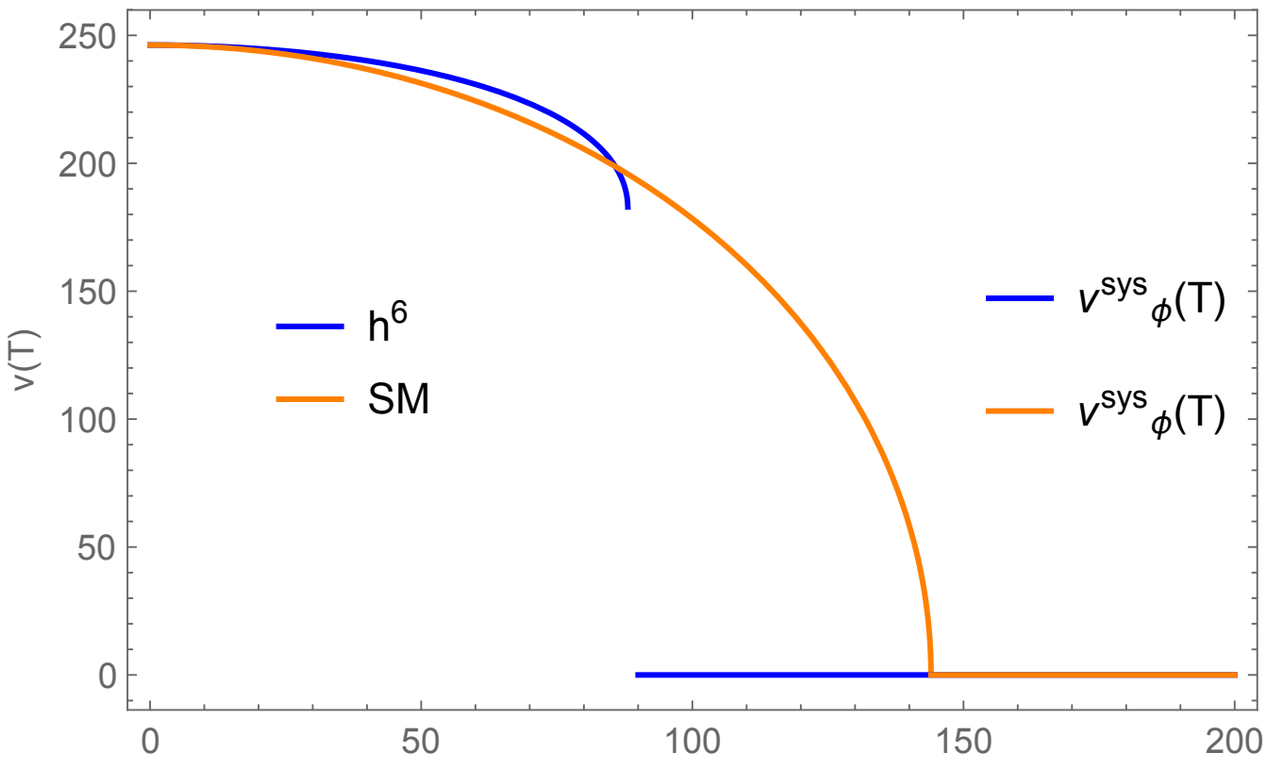
EFT Approach (h^6 and ??)

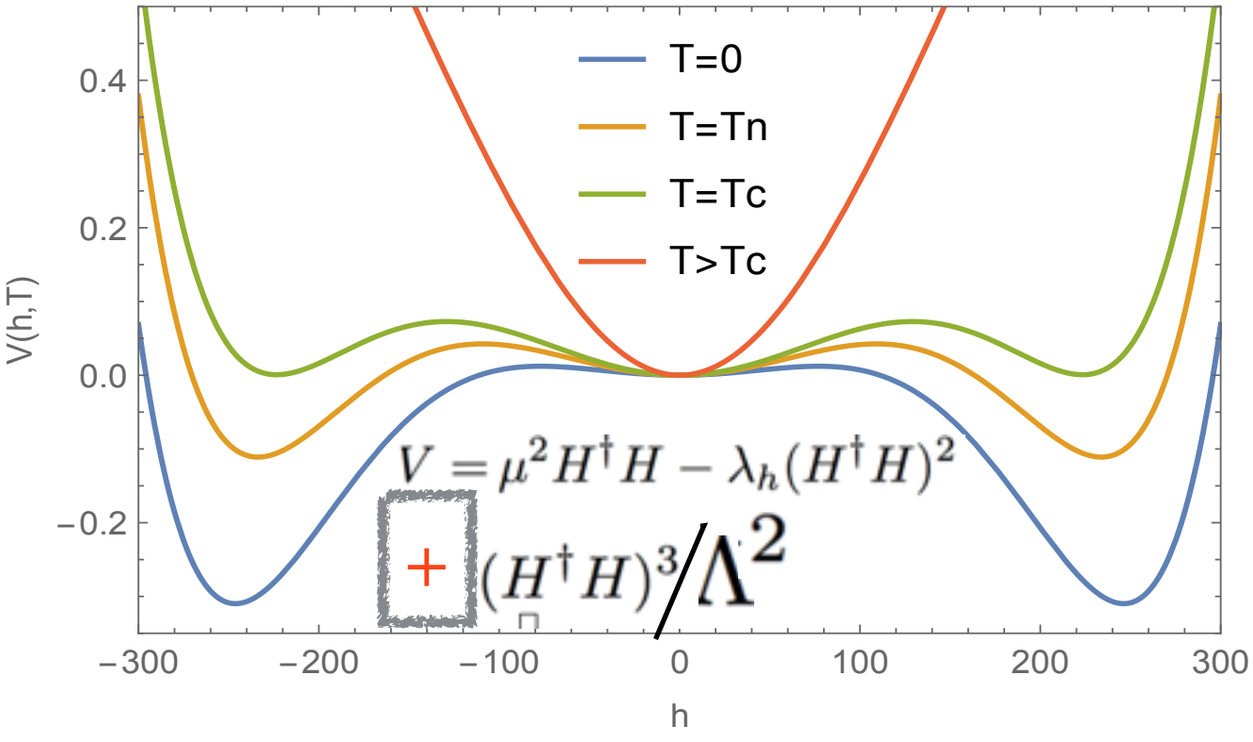
Grojean, Servant, Wells 05, Bodeker, Froome, Huber, Seniuch 05, Huang, Joglekar, Li, Wagner 15,Cai,Sasaki ,Wang17,Bian, Lee 190x.xxxxx,…

Higgs Potential Shape??? EFT or ???

First or second order





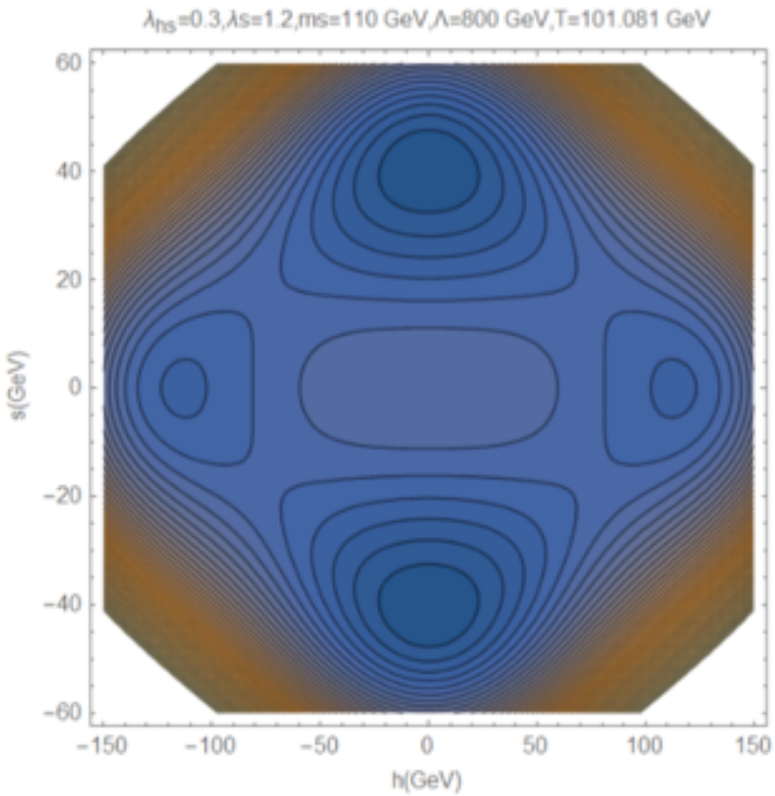


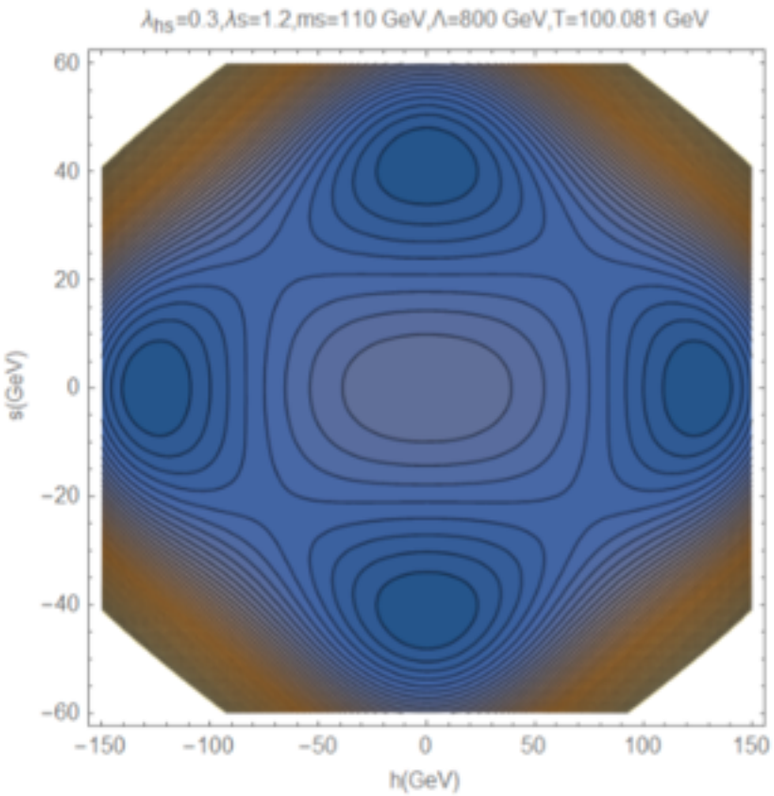
Grojean, Servant, Wells 05, P. Huang, Jokelar, Li, Wagner (2015)
F.P. Huang, Gu, Yin, Yu, Zhang (2015) F.P. Huang, Wan, Wang, Cai, Zhang (2016) Cao, F.P. Huang, Xie, & Zhang (2017)

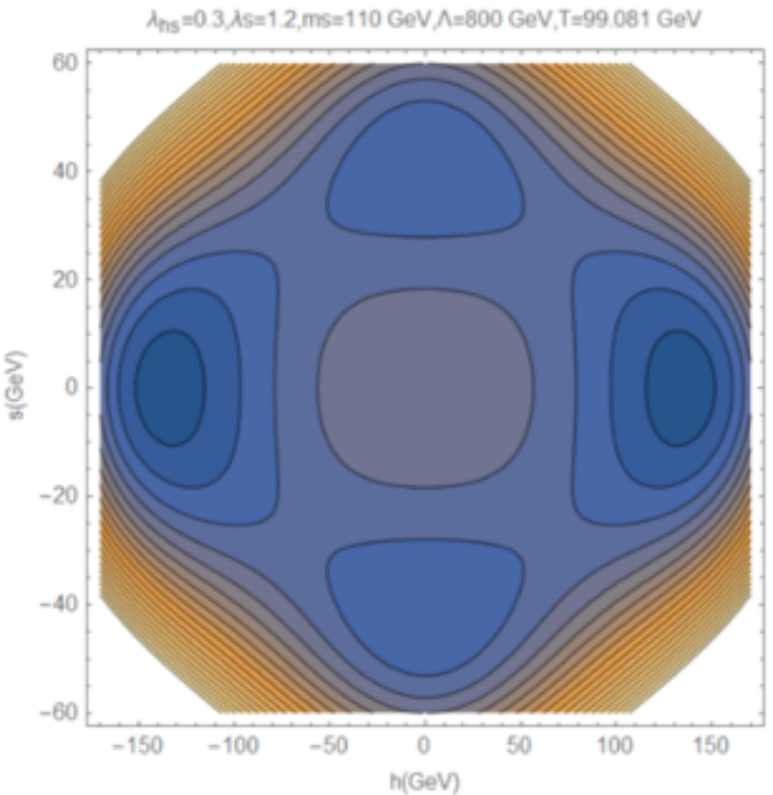
LHC say the quantum fluctuation (quadratic oscillation) around h=v with mh=126 GeV, not sensitive to the specifically potential shape

SFOEWPT

multistep 1. Z2 symmetry



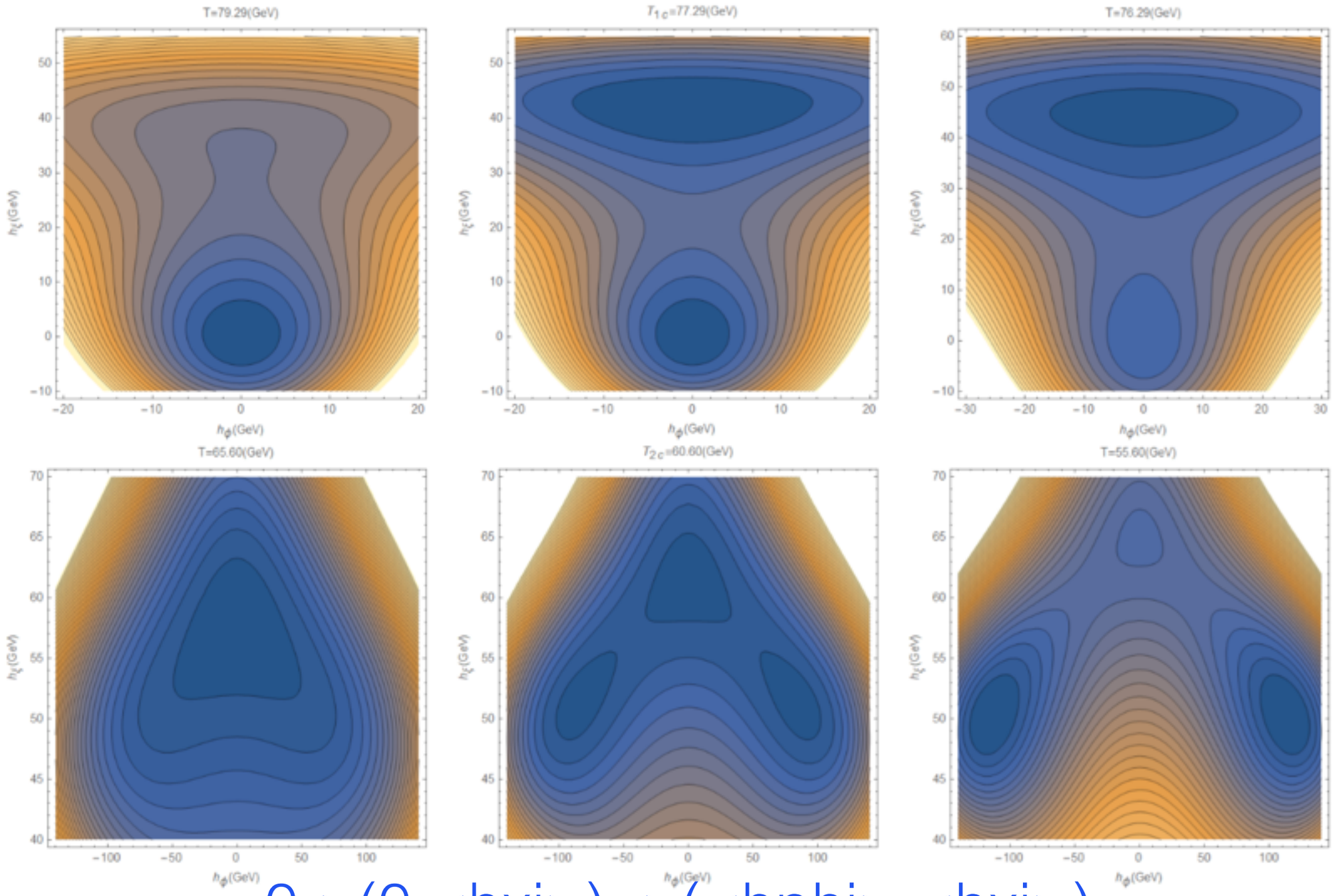




second order PT: Z2 → first order PT, EWSB

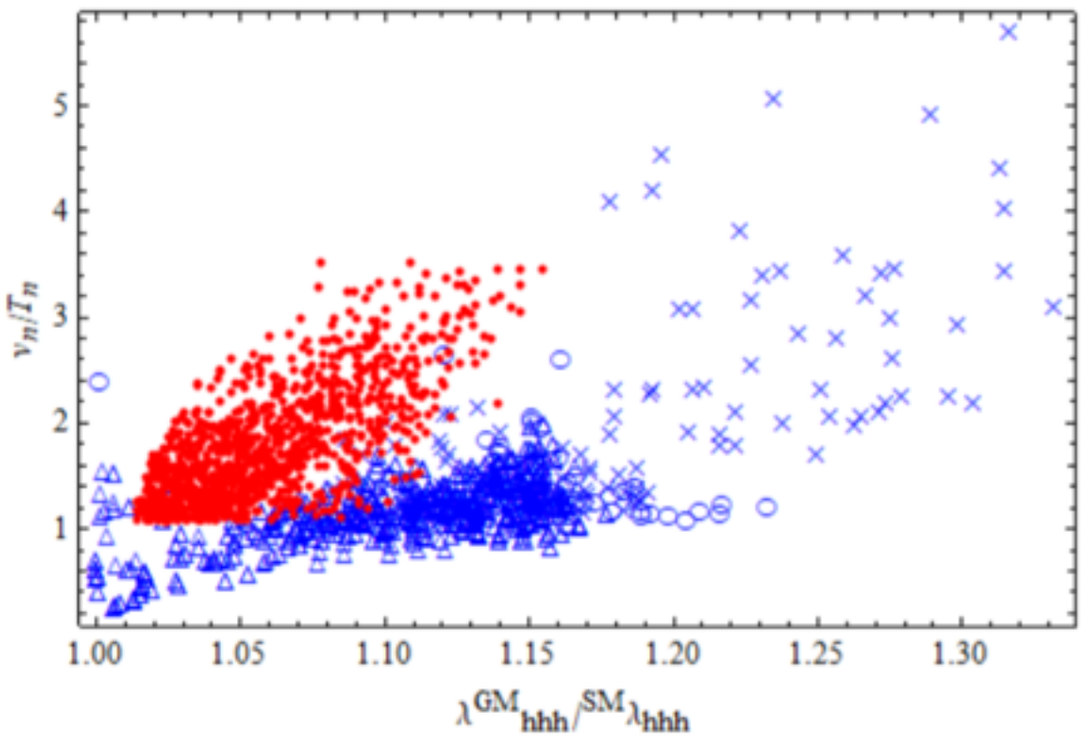
SFOEWPT

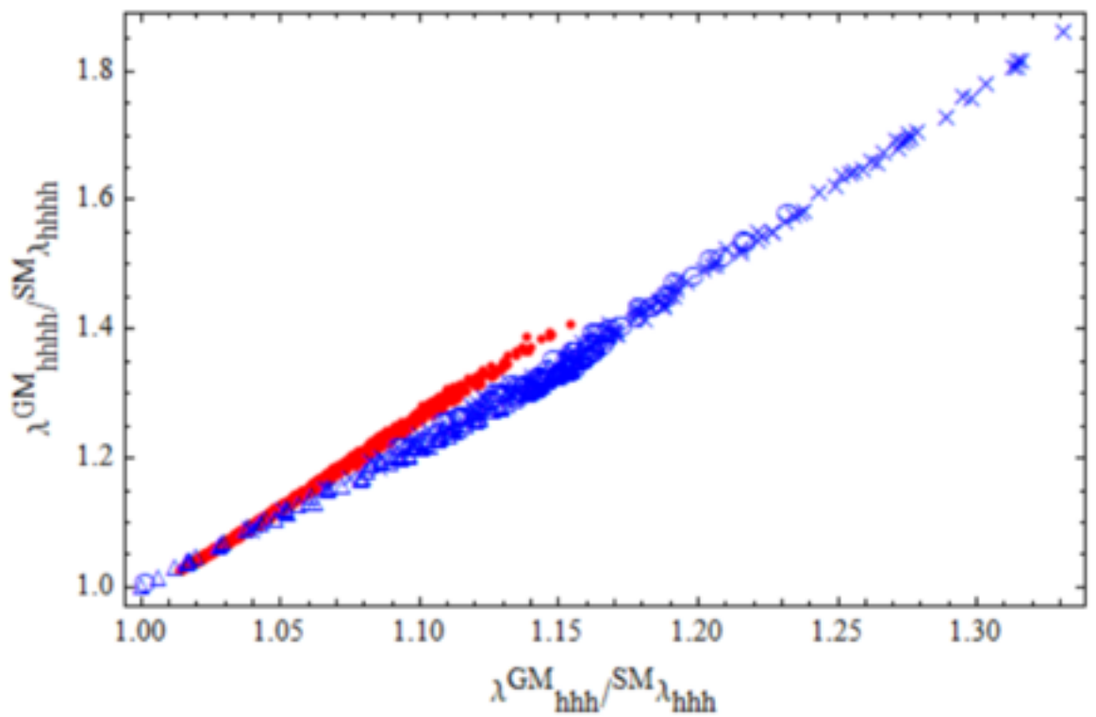
multistep 2. general with two fields

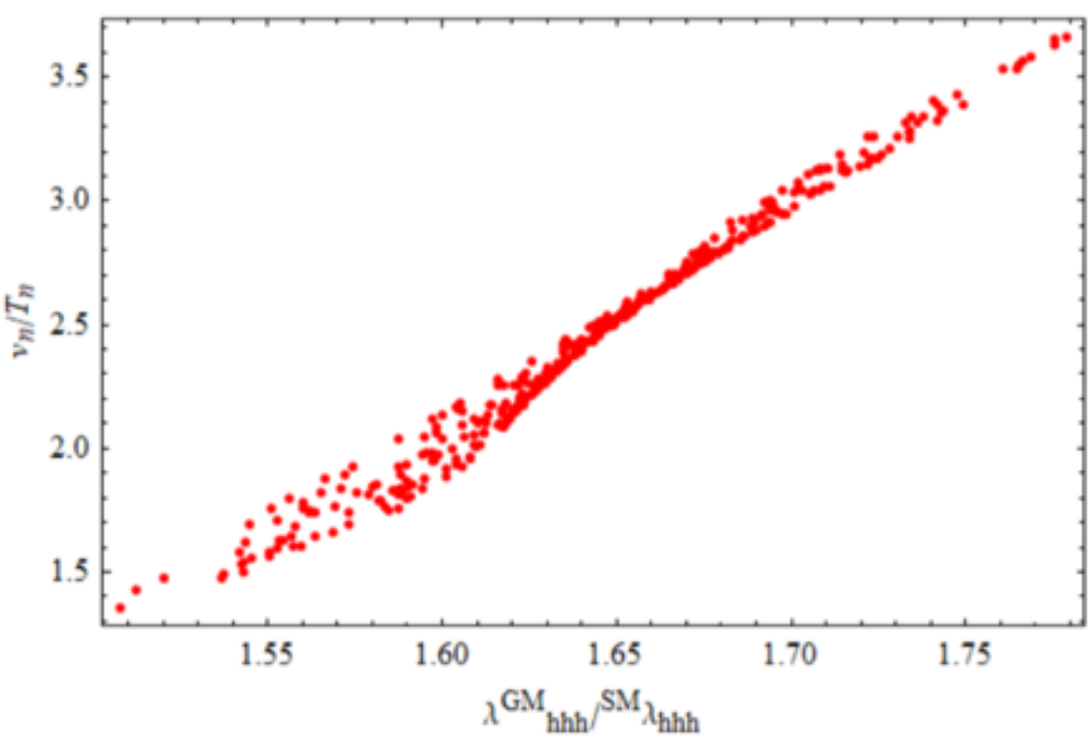


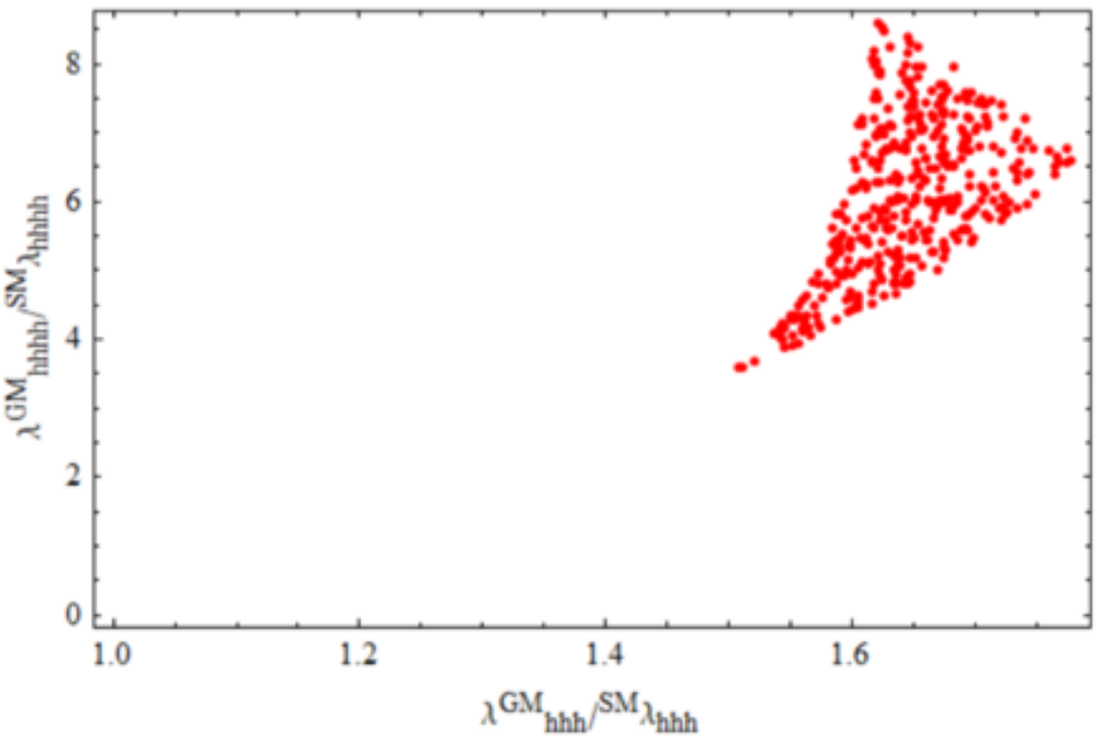
0->(0,<hxi>) ->(<hphi>,<hxi>)

PT strength and Higgs triple and quartic couplings

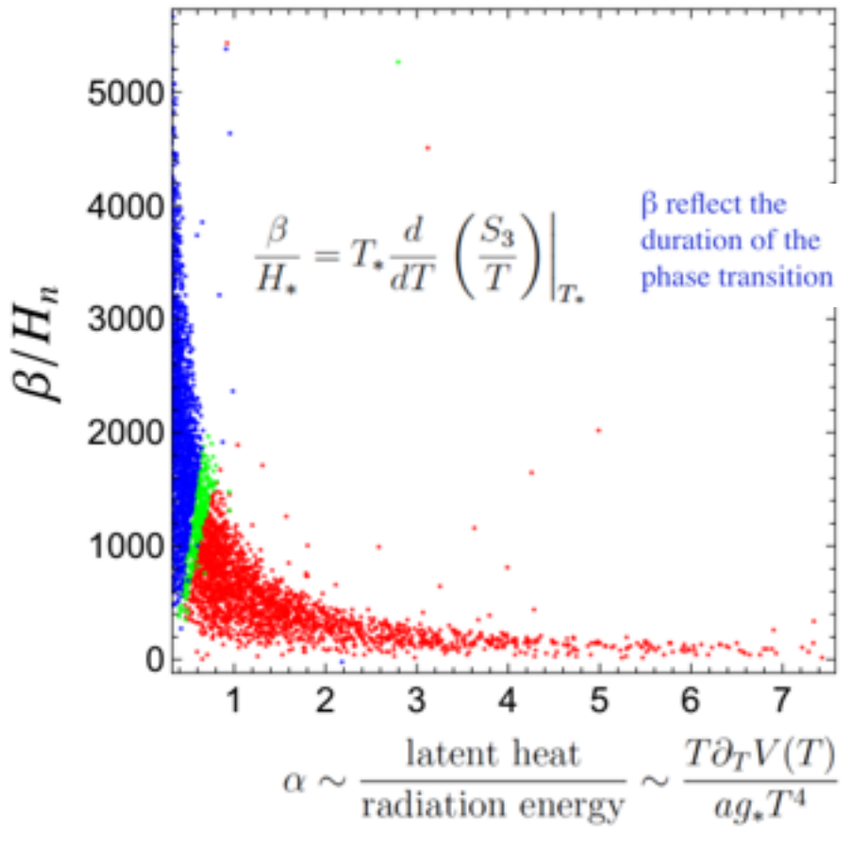


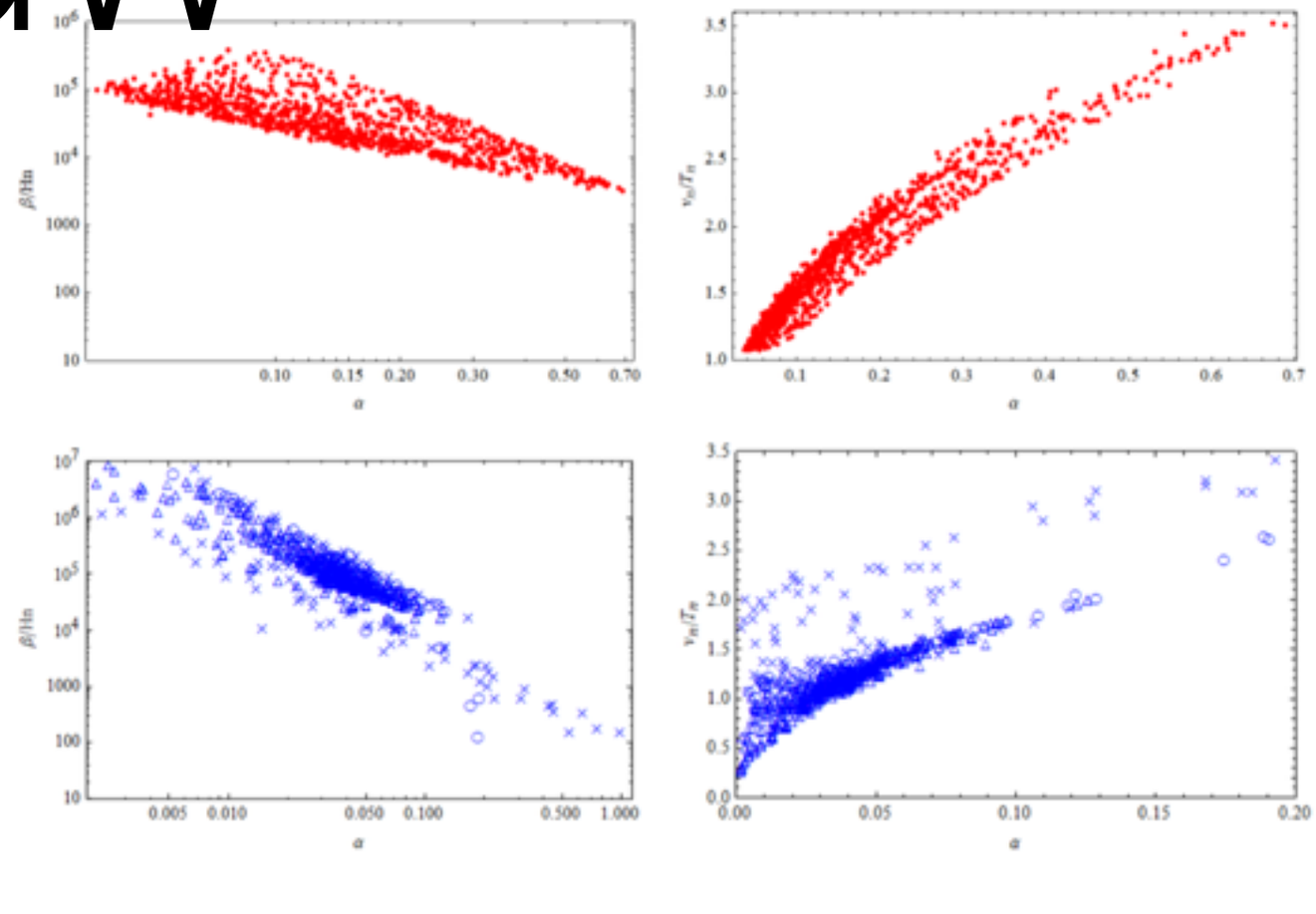


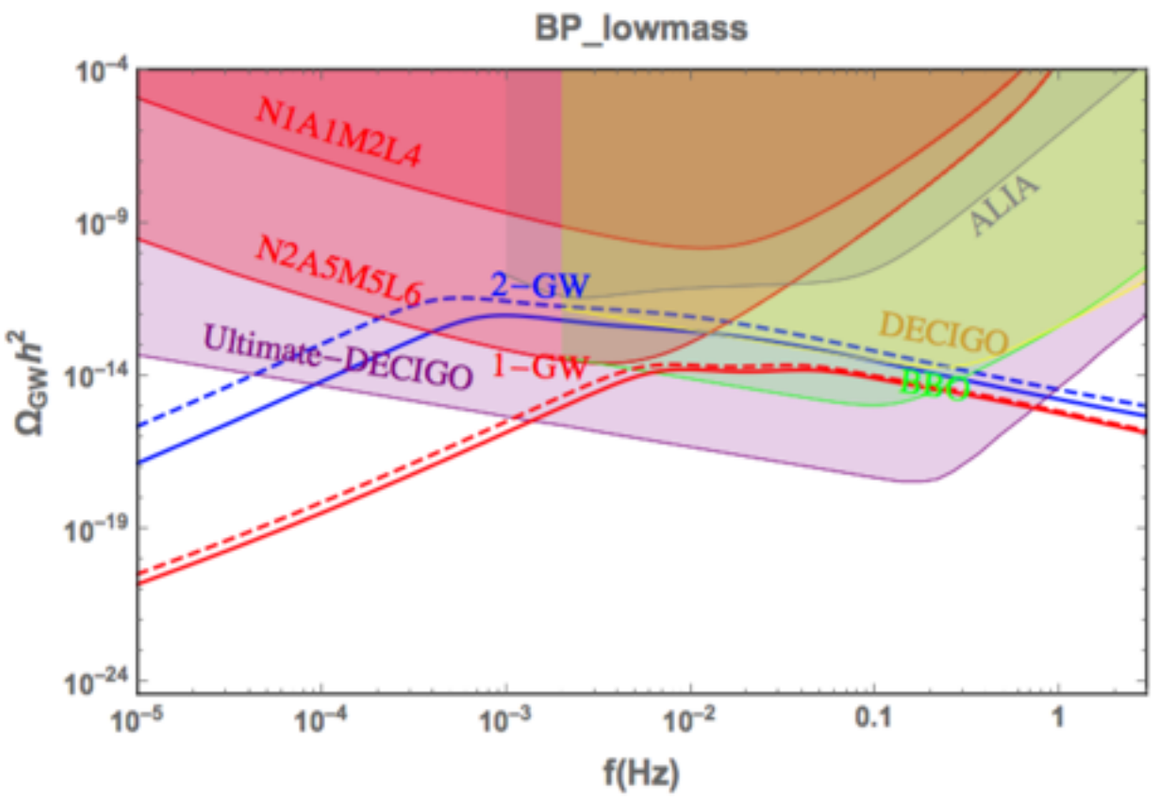


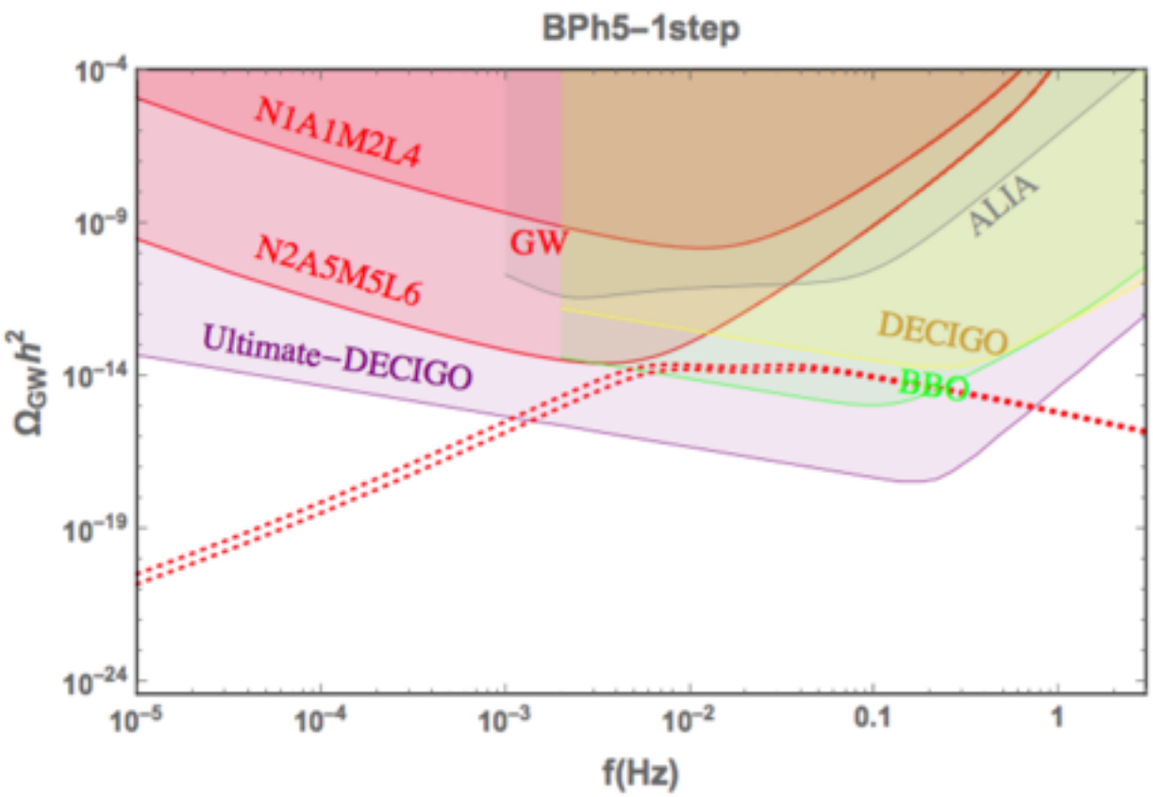


GW

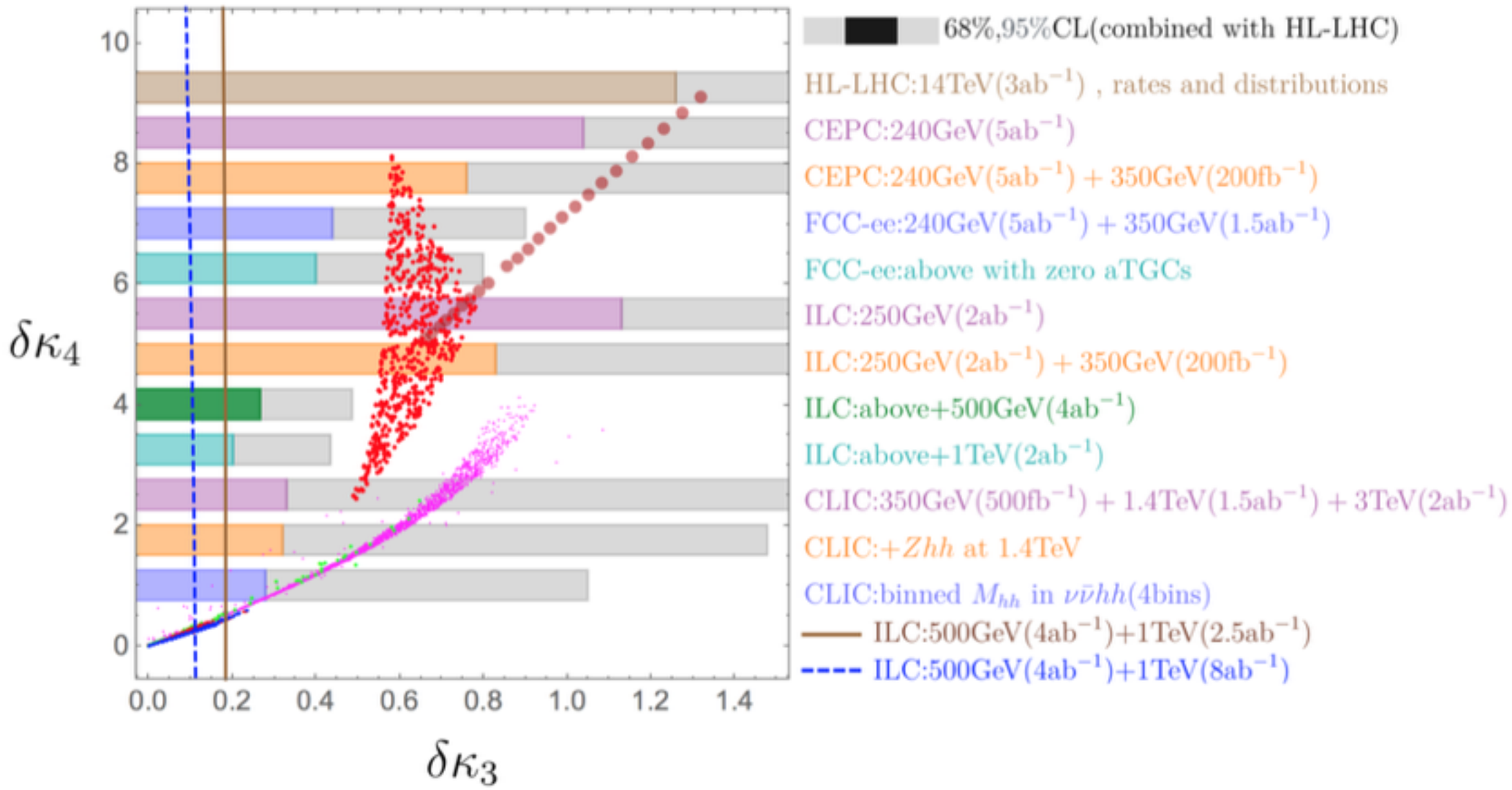

β/H_n
$\frac{\beta}{H_*} = T_* \frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T_*}$
β reflect the duration of the phase transition
$\alpha \sim \frac{\text{latent heat}}{\text{radiation energy}} \sim \frac{T\partial_T V(T)}{a g_* T^4}$


β/Hn
v_n/T_n
α

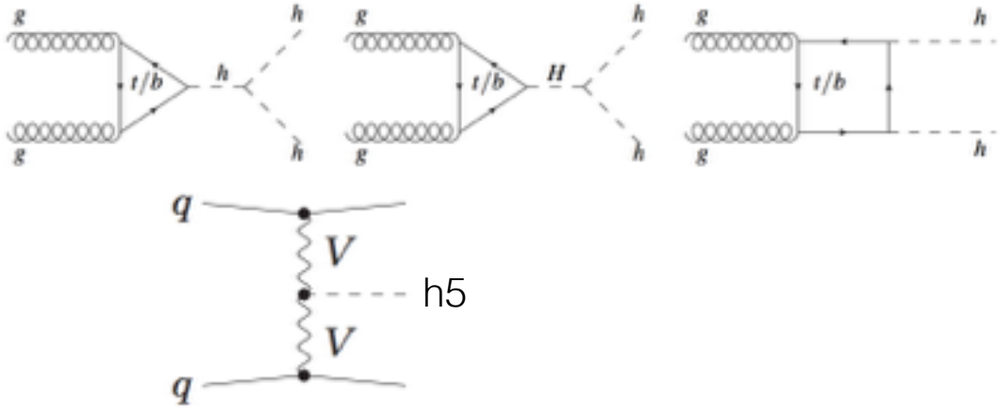

BP_lowmass
$\Omega_{GW}h^2$
f(Hz)
N1A1M2L4
N2A5M5L6
Ultimate−DECIGO
2−GW
1−GW
ALIA
DECIGO
BBO


BPh5−1step
$\Omega_{GW}h^2$
f(Hz)
N1A1M2L4
N2A5M5L6
Ultimate−DECIGO
GW
ALIA
DECIGO
BBO

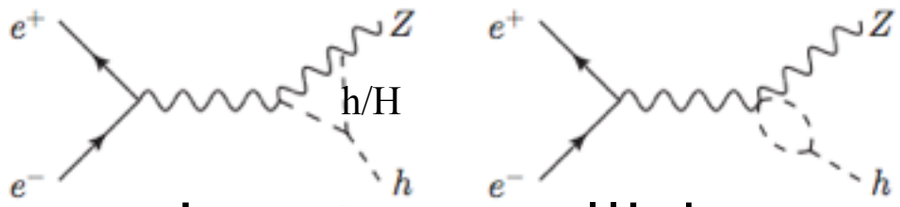
Triple and quartic Higgs coupling deviation, GW



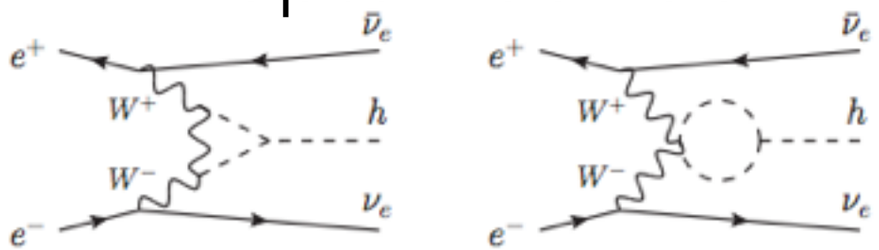
hadron collider

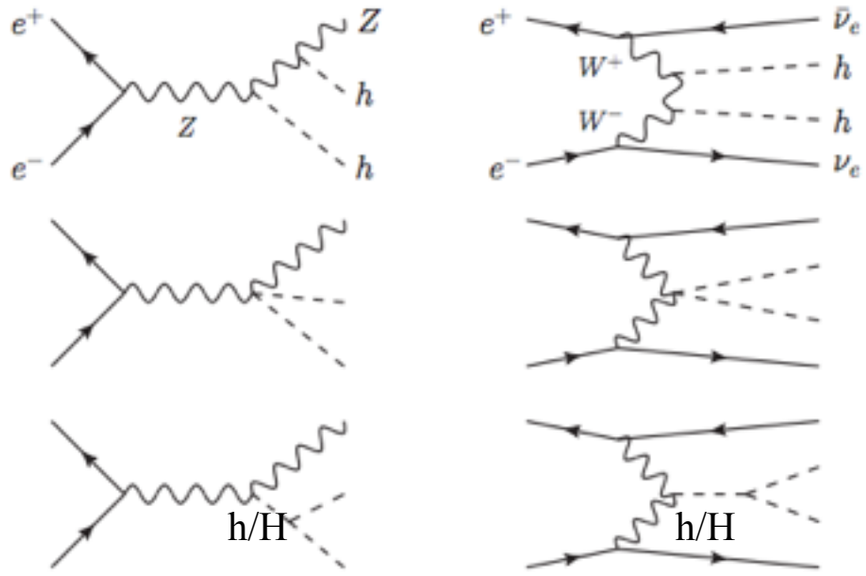


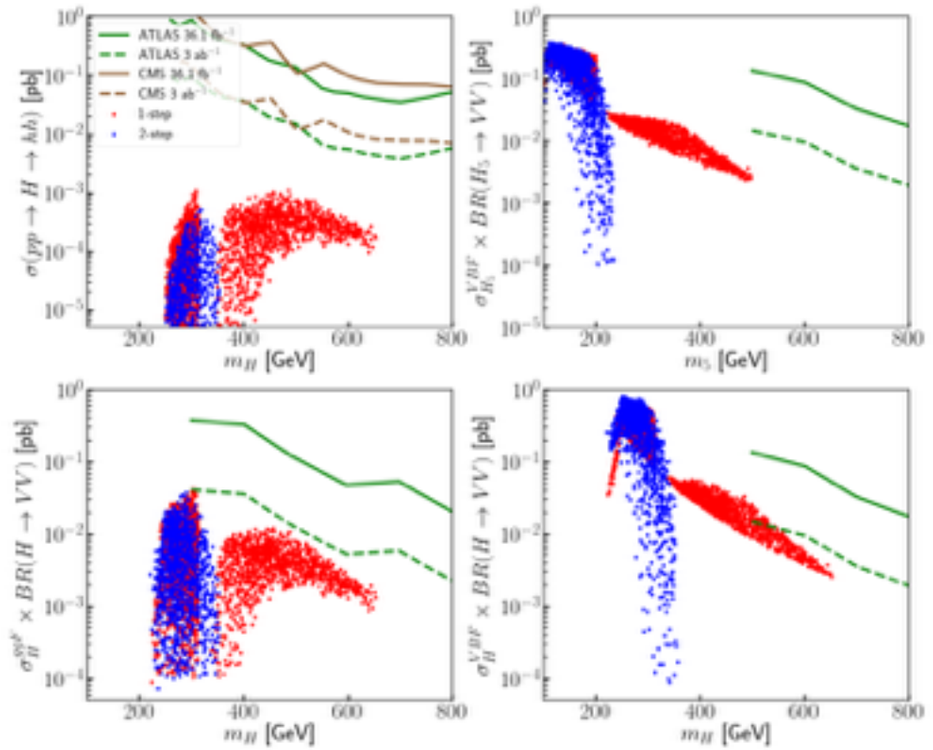
h5

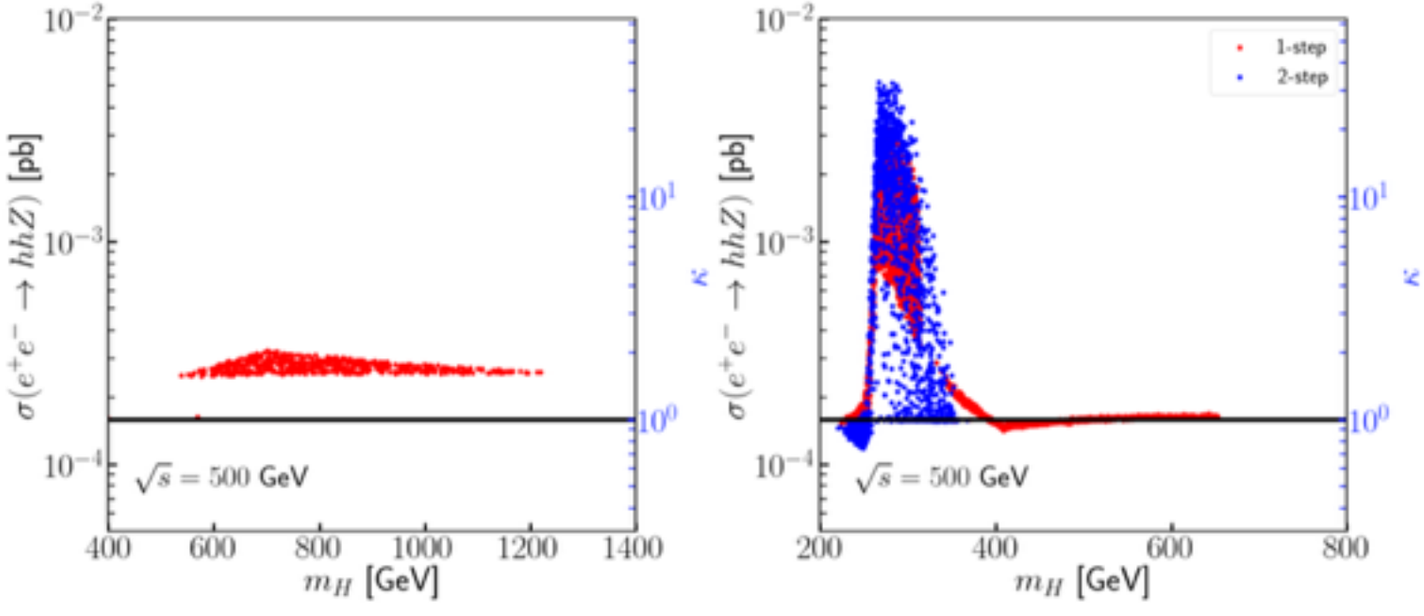


Lepton collider

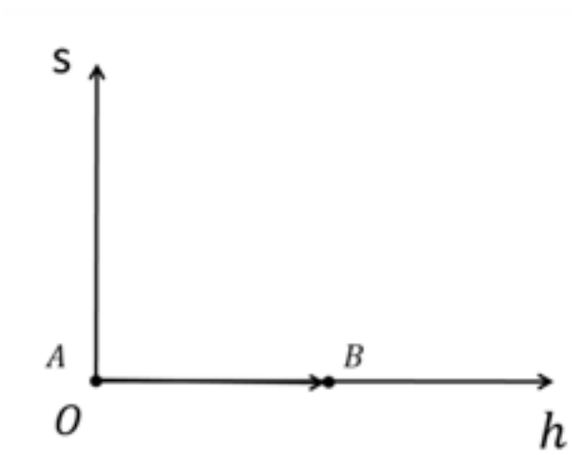


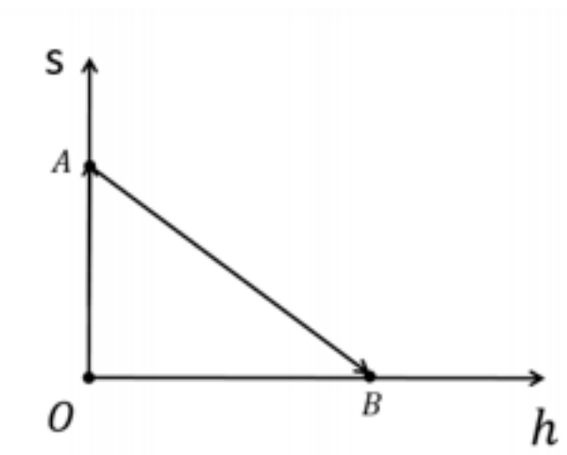


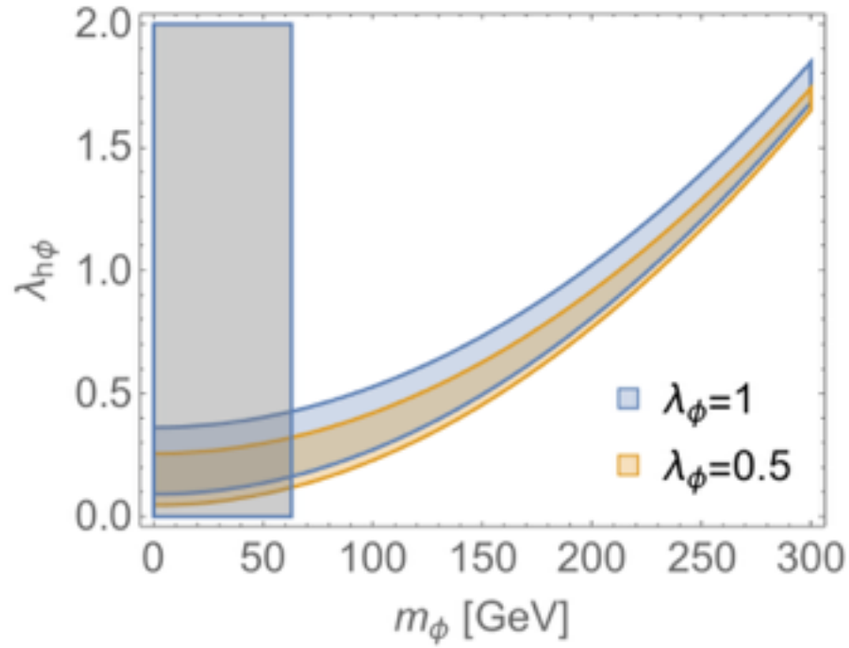




One-step/multi-step
With Z2



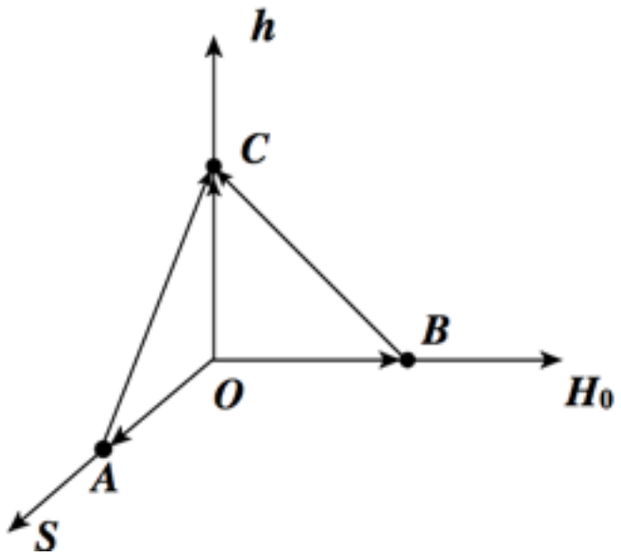




SM+real singlet:

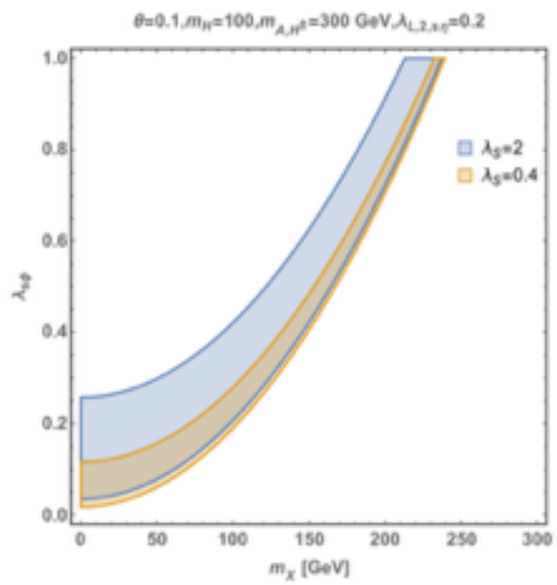
WIMP DM+Inflation, Cheng, Bian 18

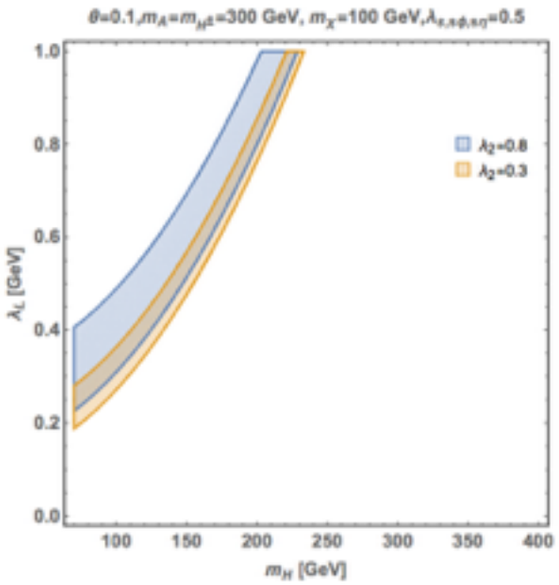
FIMP DM, Bian, Tang 18



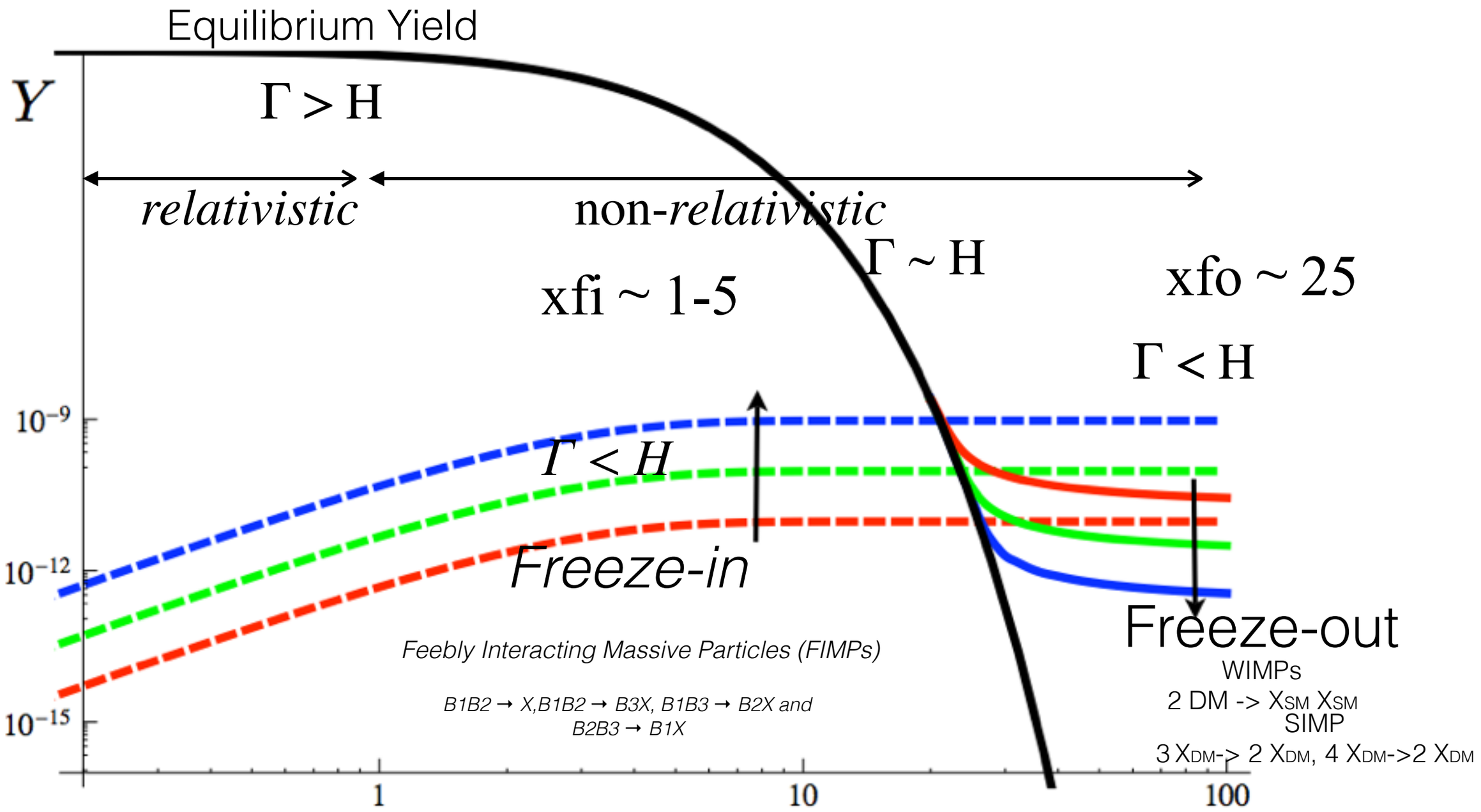
IDM+singlet

FIMP DM: Bian, Liu 18





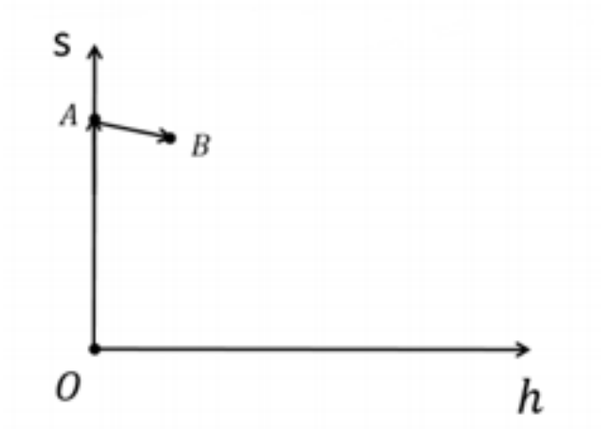
Freeze-in and Freeze-out



Tfi ~ mDM/xfi~10^2 GeV for mDM~ weak scale

Tfo ~ mDM/xfo~O(1) GeV for mDM~ weak scale

WIMP DM

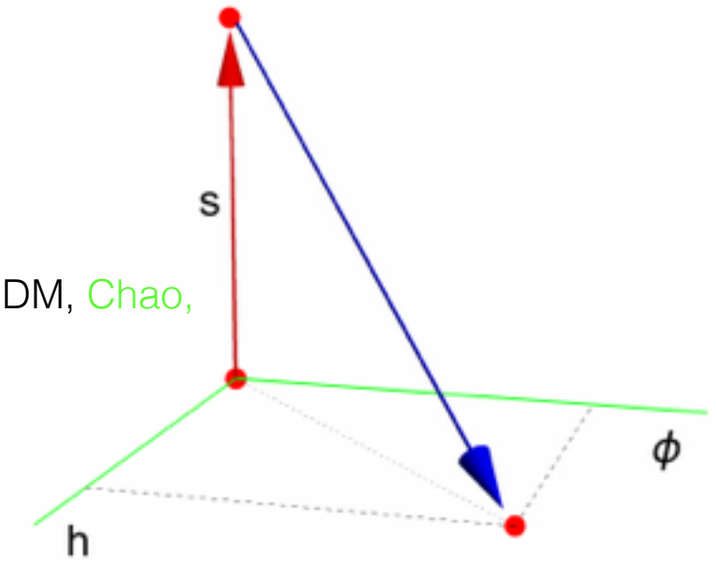


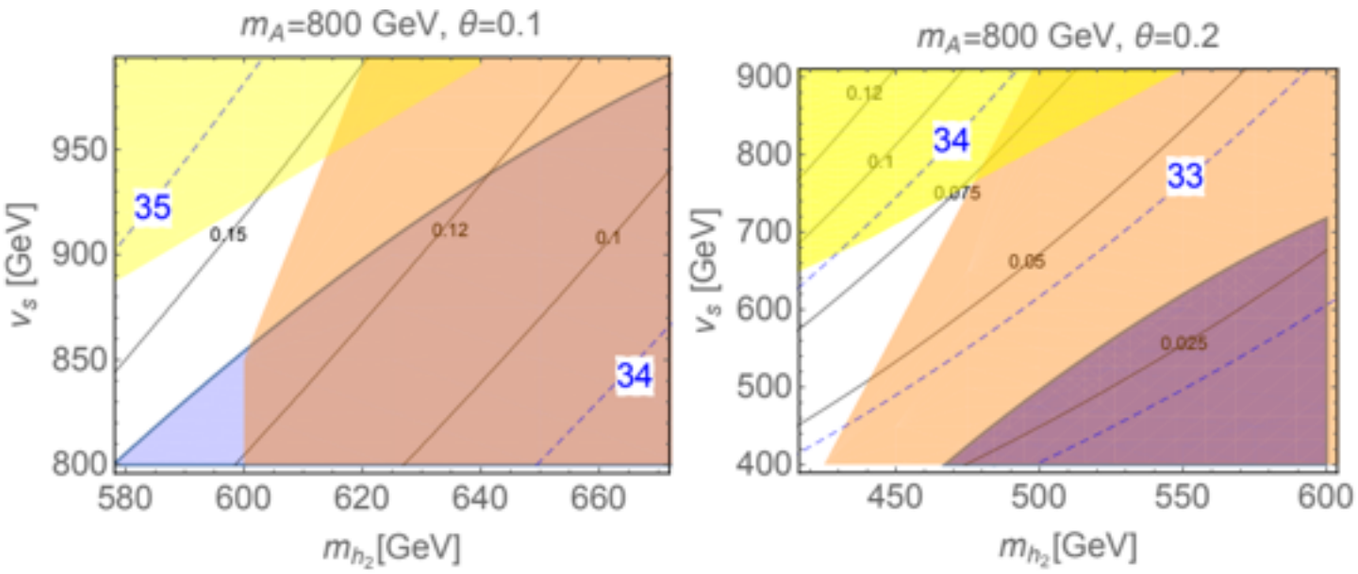
SM+complex singlet

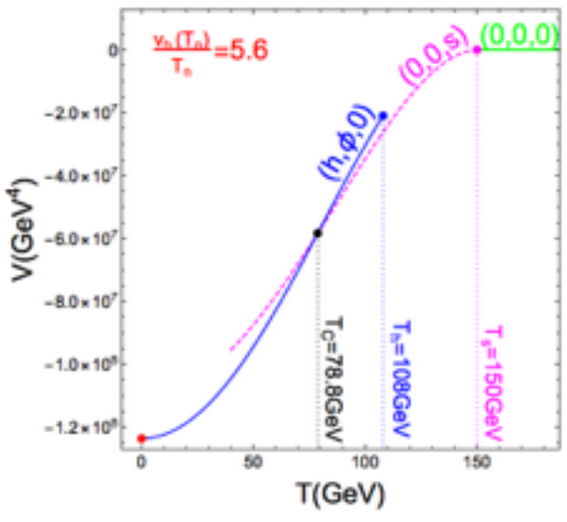
WIMP DM+Inflation, Cheng, Bian 18

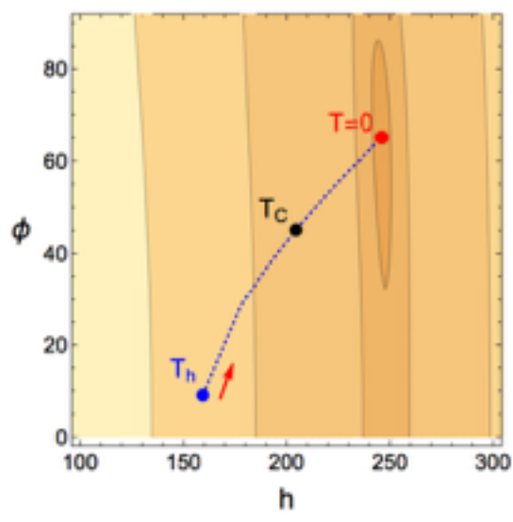
EWBG+sphaleron, Michael J. Ramsey-Musolf 17

SM+2 real scalars: WIMP DM, Chao, Guo, Shu 17



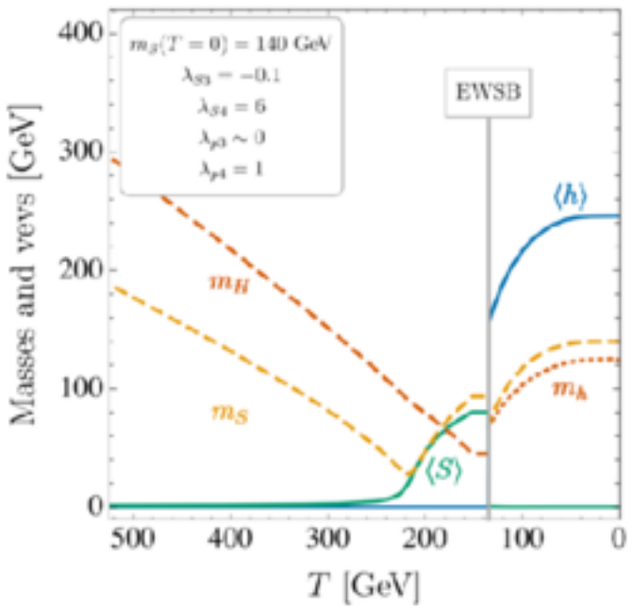


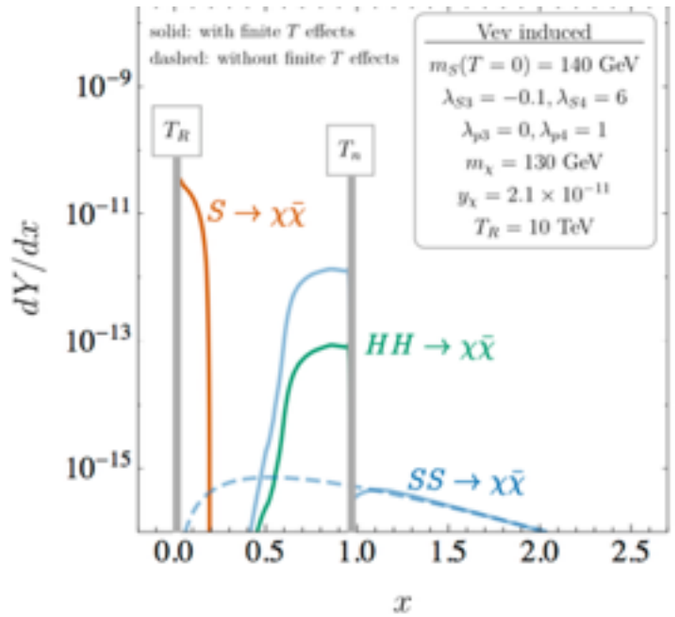


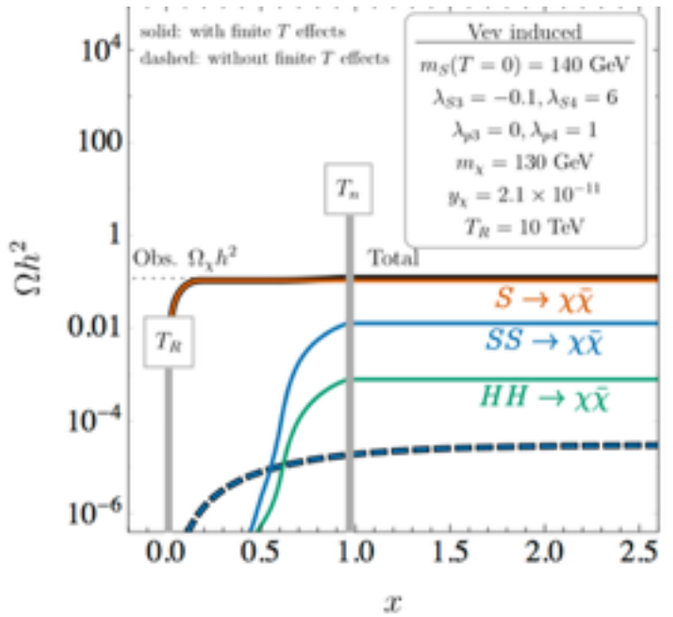


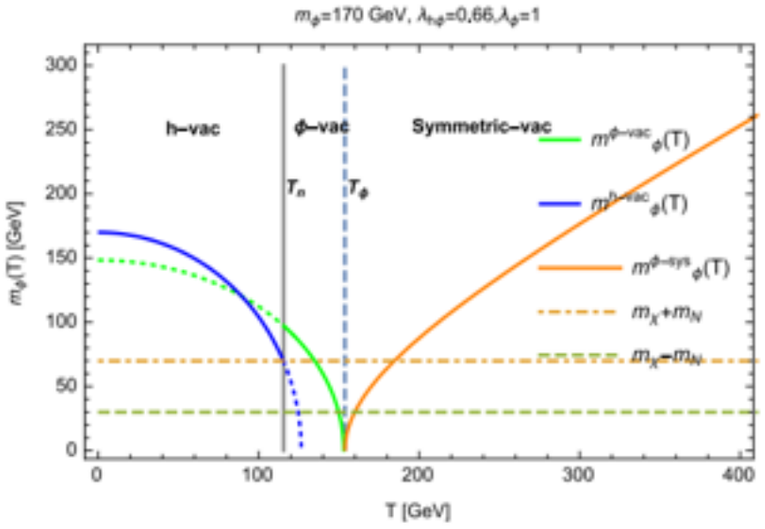
blue: Xenon1T; yellow: h(s) inflation;
orange: SFOEWPT

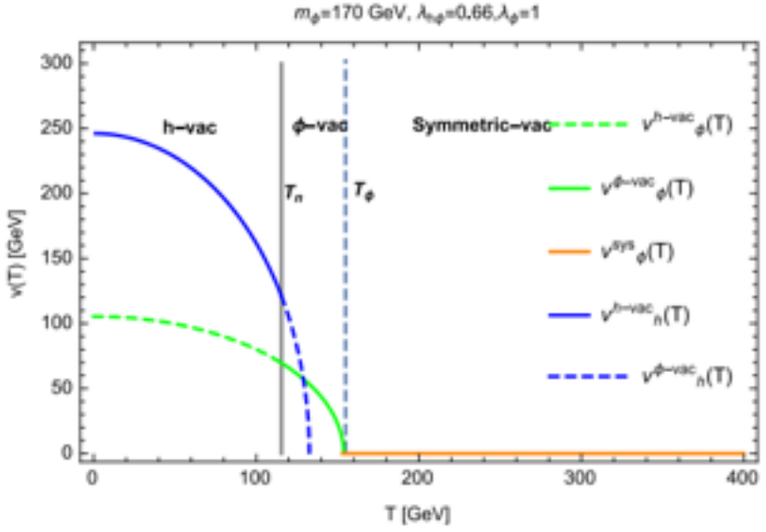
FIMP DM









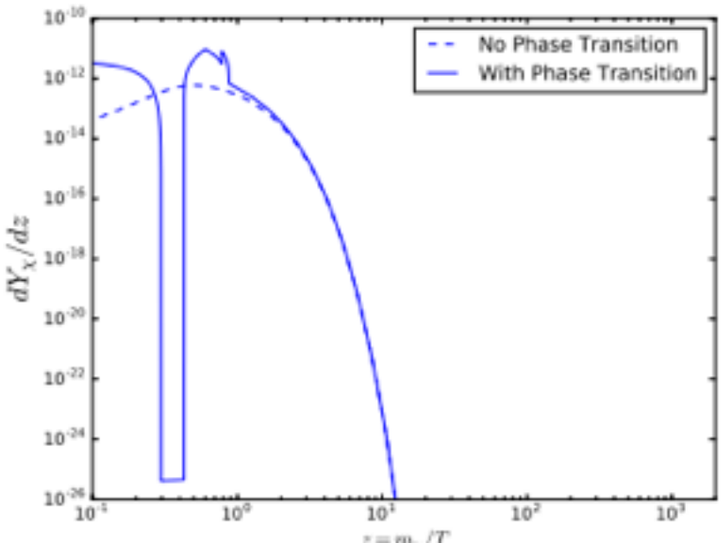


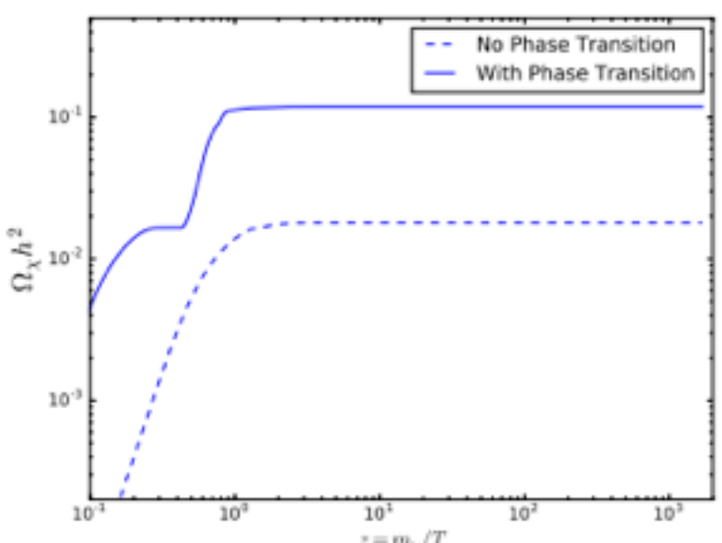
1712.03962,Michael J. Baker et al.

Amplified effects: larger thermal masses before PT

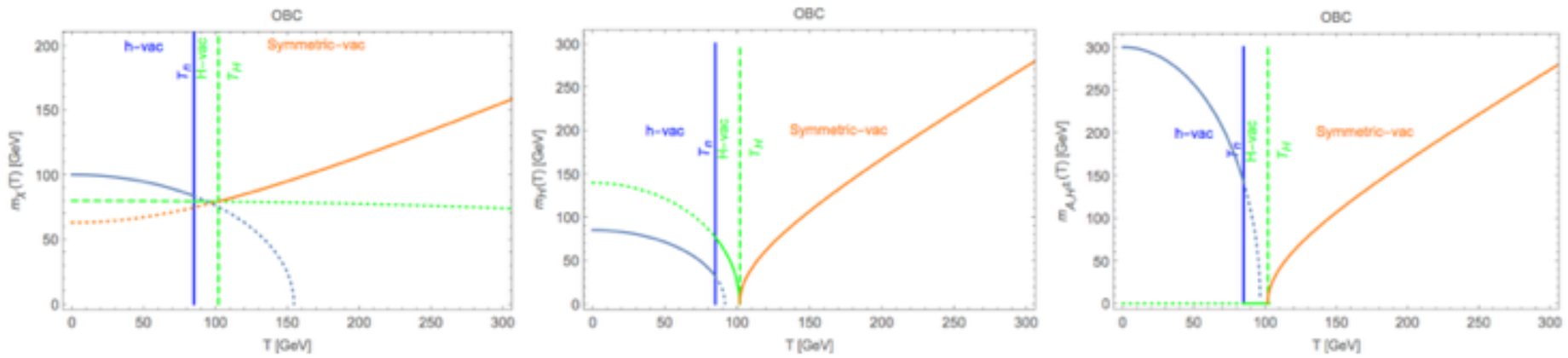
temporarily open of decay channel

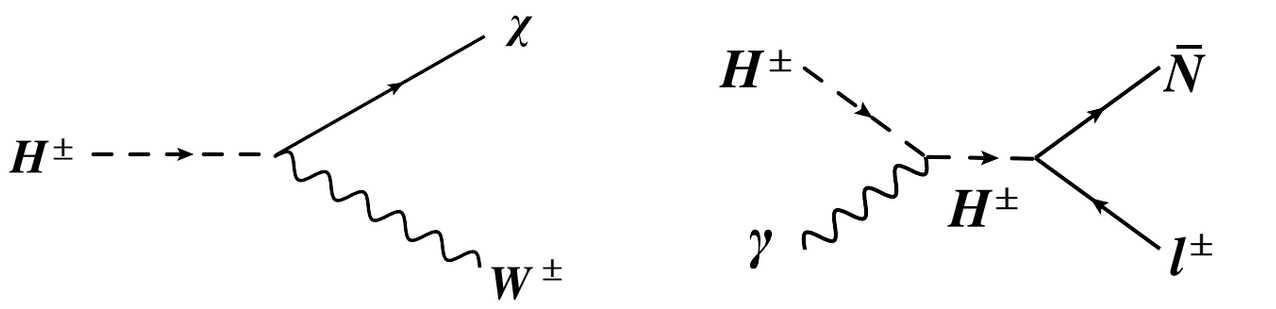
1810.03172, L.Bian, Y. Tang





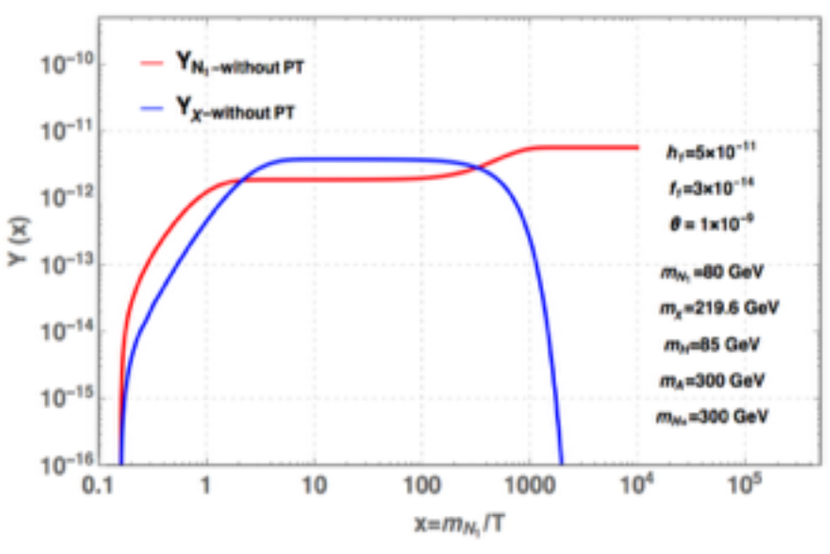
OBC pattern PT DDM-late decay

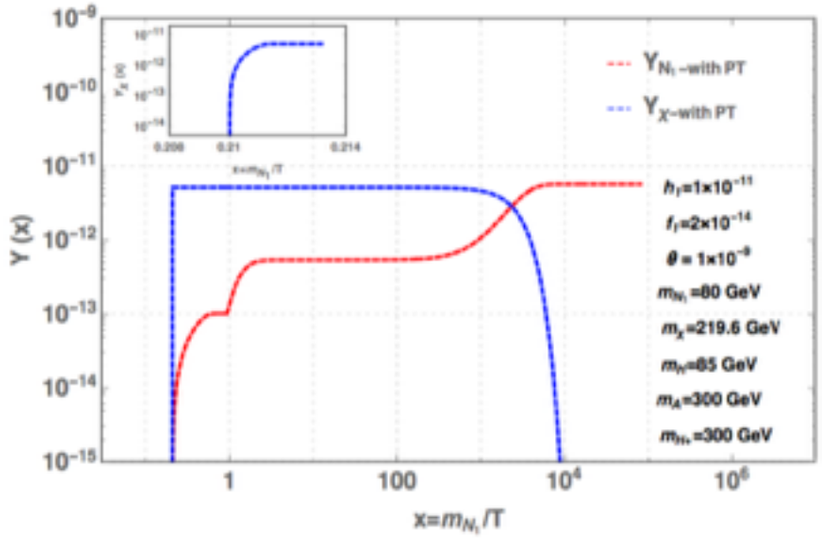


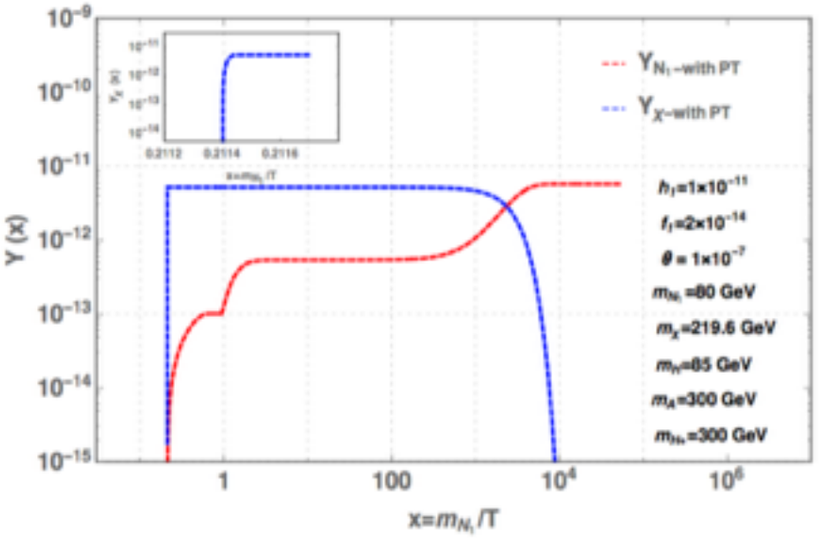


reduction effects: smaller thermal masses before PT

temporarily open of decay channel at high T







Possibilities

- Tell Potential Shape with collider and GW
- Dark matter with plasma effects
- Nonperturbative evaluation of EWPT and GW
- Sphaleron calculation and collider detect

Thanks

Bubble, Sphaleron and BAU

Instanton

$$\frac{\Gamma}{V} = A(T)e^{-S_3/T}$$

$$\frac{S_3(T_N)}{T_N} - \frac{3}{2}\ln\left(\frac{S_3(T_N)}{T_N}\right) = 152.59 - 2\ln g_*(T_N) - 4\ln\left(\frac{T_N}{100\ \text{GeV}}\right)$$

Bubble nucleation

S3 (TN)/TN ~140-150

Washout avoid

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

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

1708.03061

SM+S

$$E_{\text{sph}}[f,h,k] = \frac{4\pi v}{g_2}\int_0^\infty d\xi\left[4\left(\frac{df}{d\xi}\right)^2 + \frac{8}{\xi^2}(f-f^2)^2 + \frac{\xi^2}{2}\left(\frac{dh}{d\xi}\right)^2 + h^2(1-f)^2 + \frac{\xi^2}{2}\frac{v_S^2}{v^2}\left(\frac{dk}{d\xi}\right)^2 + \frac{\xi^2}{g_2^2 v^4}V_{\text{eff}}(h,k,T)\right]$$

$$V_{1\ell} = V_{\rm tree} + \Delta V_{1\ell}$$

$$\Delta V_{1\ell} = \Delta V_{1\ell,T=0} + V_{1\ell,T\neq 0} \ ,$$

$$\Delta V_{1\ell,T=0} = \sum_{i=h,\chi,W,Z,t} \frac{n_i\, m_i^2(h_c)}{64\pi^2} \left(\log \frac{m_i^4(h_c)}{v^2} - C_i \right) \ ,$$

$$V_{1\ell,T\neq 0} = \frac{n_t\, T^4}{2\pi^2} J_f\left(m_t^2(h_c)/T^2\right) + \sum_{i=h,\chi,W,Z} \frac{n_i\, T^4}{2\pi^2} J_b\left(m_i^2(h_c)/T^2\right)$$

the high-temperature expansion of J_b and J_f leading terms,

$J_b(x) \rightarrow \pi^2 x/12$ and $J_f(x) \rightarrow -\pi^2 x/24$

GWs

$$\alpha \sim \frac{\text{latent heat}}{\text{radiation energy}} \sim \frac{T\partial_T V(T)}{a g_* T^4}$$

$$v_b \simeq \frac{1/\sqrt{3} + \sqrt{\alpha^2 + 2\alpha/3}}{1+\alpha}\,, \qquad \kappa \simeq \frac{0.715\alpha + \frac{4}{27}\sqrt{3\alpha/2}}{1+0.715\alpha}$$

Bubble size $\langle R \rangle \sim v_b \tau \sim \frac{v_b}{\beta}$ $\qquad \frac{\beta}{H_*} = T_* \frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T_*}$

β reflect the duration of the phase transition

$$\Omega_{\rm col} h^2 = 1.67 \times 10^{-5} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \left(\frac{0.11 v_b^3}{0.42 + v_b^2}\right) \frac{3.8 (f/f_{\rm env})^{2.8}}{1 + 2.8 (f/f_{\rm env})^{3.8}}$$

envelop approximation

$$f_{\rm env} = 16.5 \times 10^{-6} \left(\frac{f_*}{H_*}\right) \left(\frac{T_*}{100{\rm GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6} {\rm Hz}$$

$$\Omega_{\rm sw} h^2 = 2.65 \times 10^{-6} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} v_b \left(\frac{f}{f_{\rm sw}}\right)^3 \left(\frac{7}{4 + 3(f/f_{\rm sw})^2}\right)^{7/2} \quad (5.6)$$

$$\Omega_{\rm turb} h^2 = 3.35 \times 10^{-4} \left(\frac{H_*}{\beta}\right) \left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{3/2} \left(\frac{100}{g_*}\right)^{1/3} v_b \frac{(f/f_{\rm turb})^3}{[1 + (f/f_{\rm turb})]^{11/3} (1 + 8\pi f/h_*)} \quad (5.7)$$

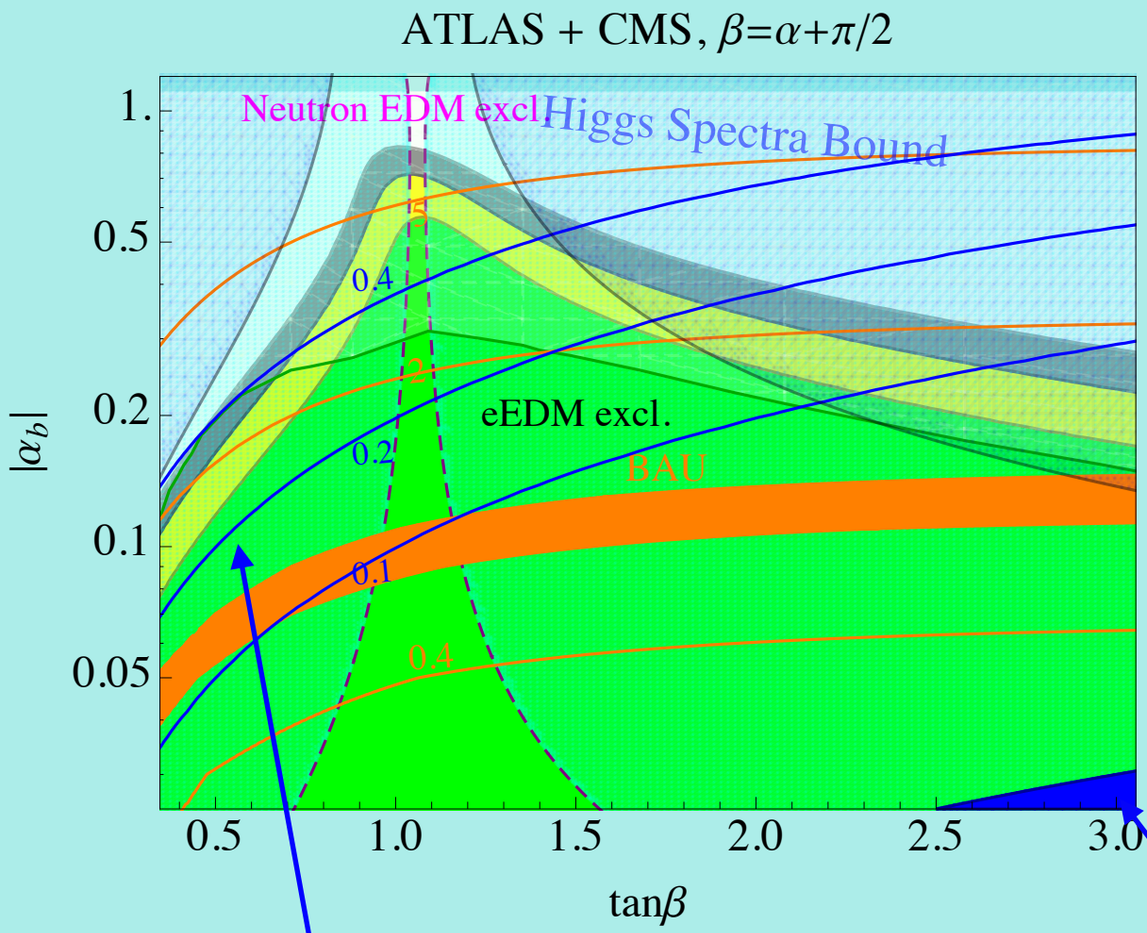
$\kappa_v \approx \alpha(0.73 + 0.083\sqrt{\alpha} + \alpha)^{-1}$ and $\kappa_{\rm turb} \approx 0.1\kappa_v$

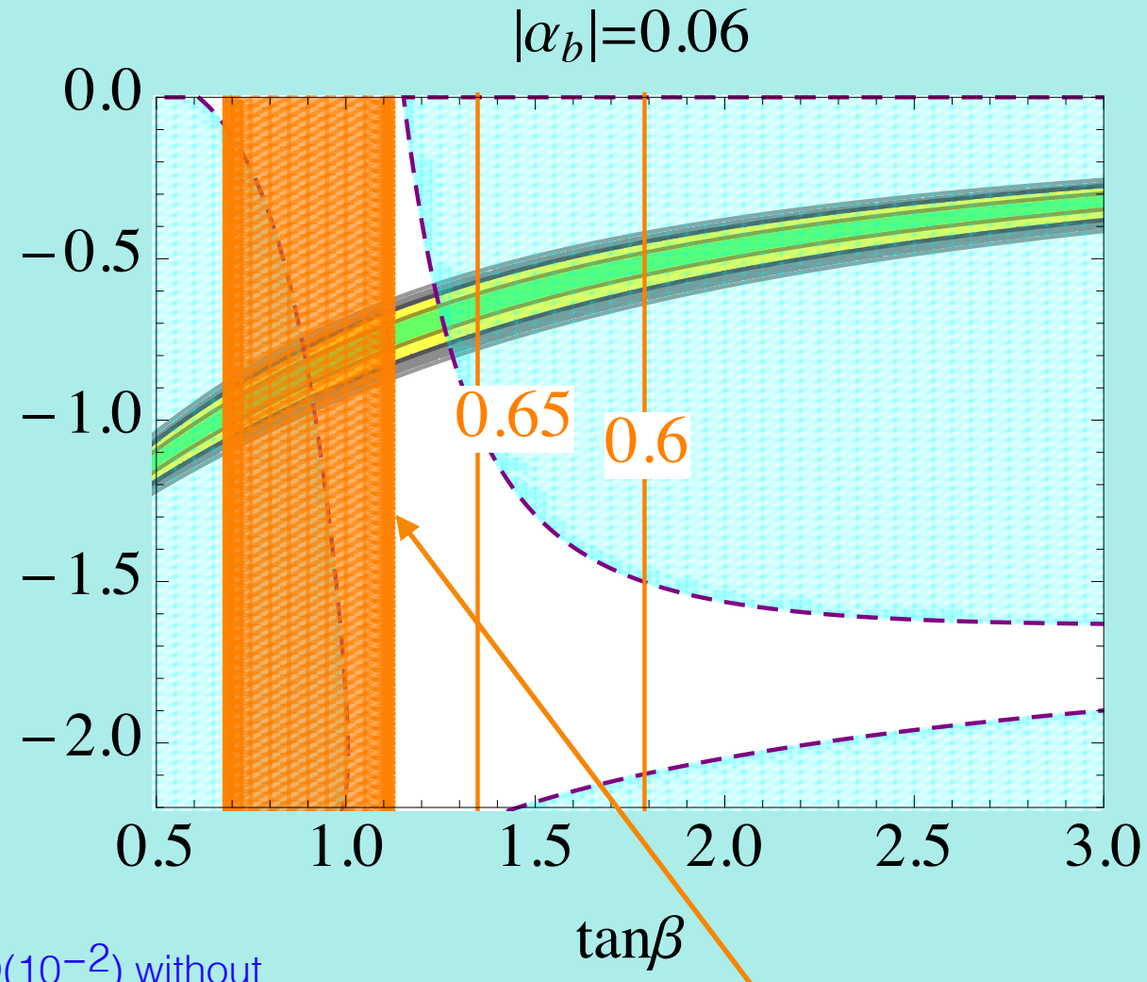
kv, kturb: the fraction of latent heat transformed into the bulk motion of the fluid for sound waves and MHD

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

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

Type II 2HDM case (I)





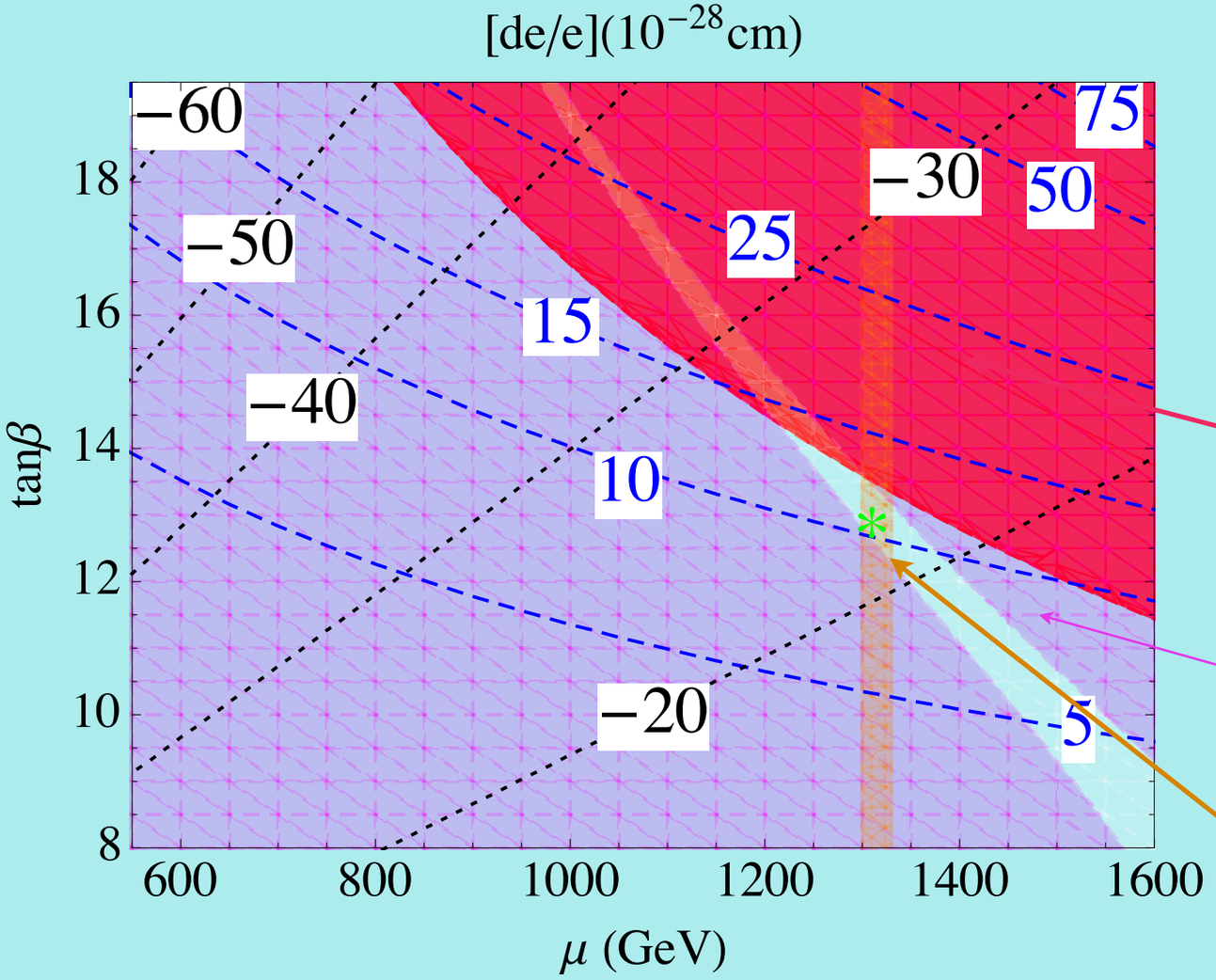
the CP-phase of the top Yukawa coupling tan θ_t .

the ACME constraint $|c\tilde{t}|<O(10^{-2})$ without cancellation(J. Brod, U. Haisch and J. Zupan, JHEP 1311, 180 (2013)

BAU

α, α_b: mixing angles between two CP-even Higgs, the light CP-even and the CP-odd Higgs

MSSM case

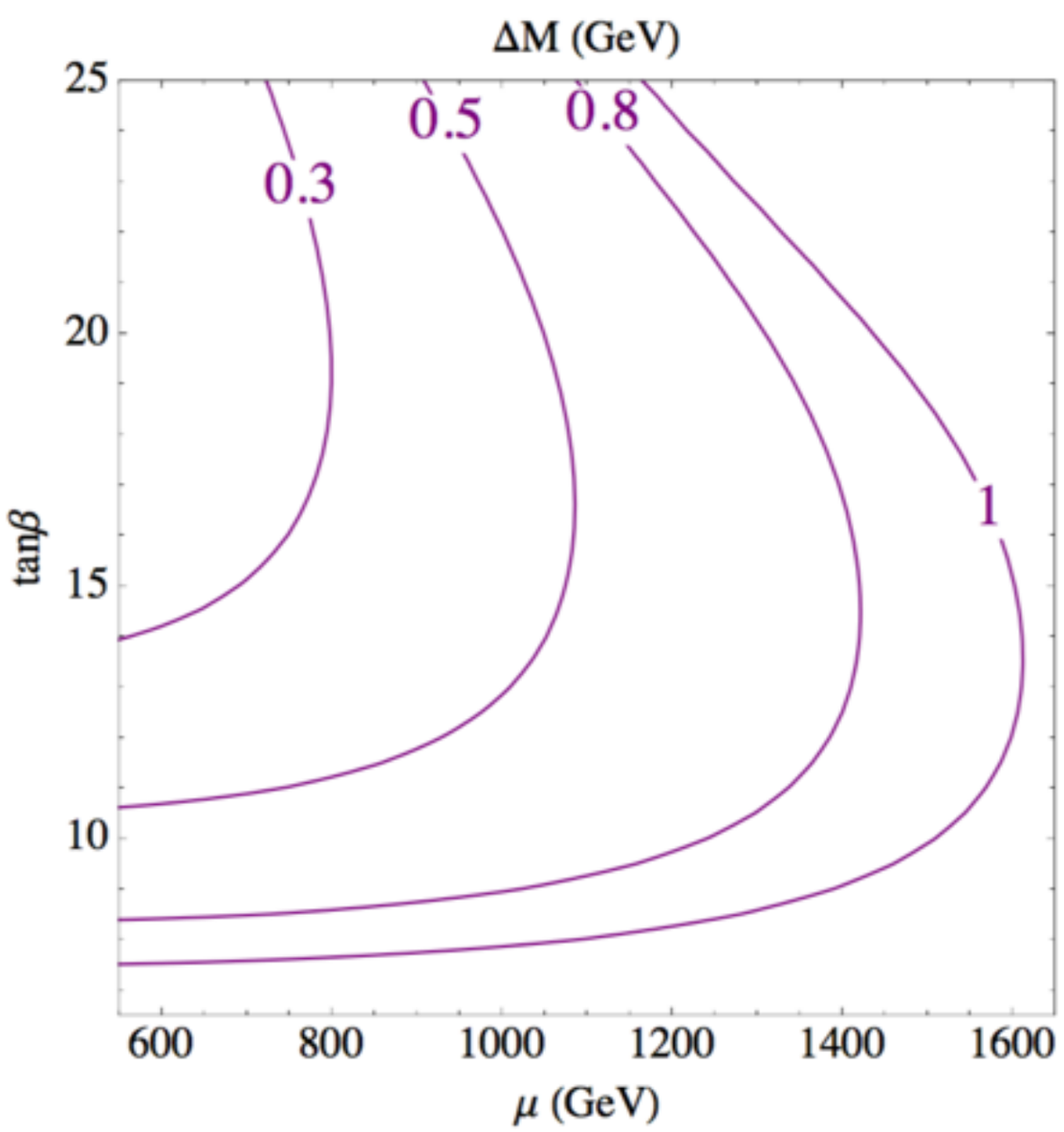


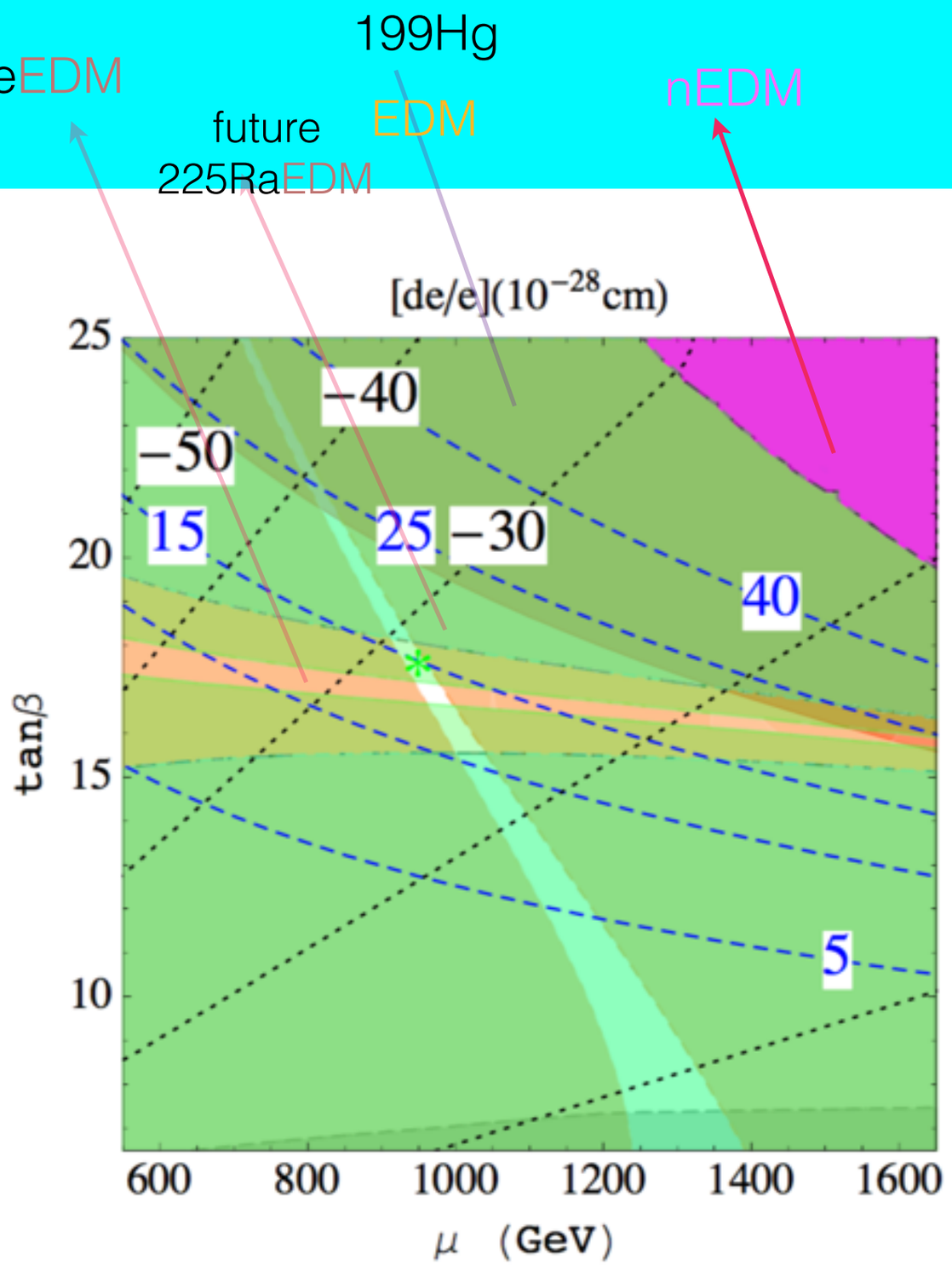
MSSM with
chargino & staus
Cancellation

Mercury exclusion

ACME exclusion

Preferred by EWBG





$\mathrm{Im}(\mu M_2^*) = \mathrm{Im}(\mu A_f^*) = 45^0.$

NMSSM case

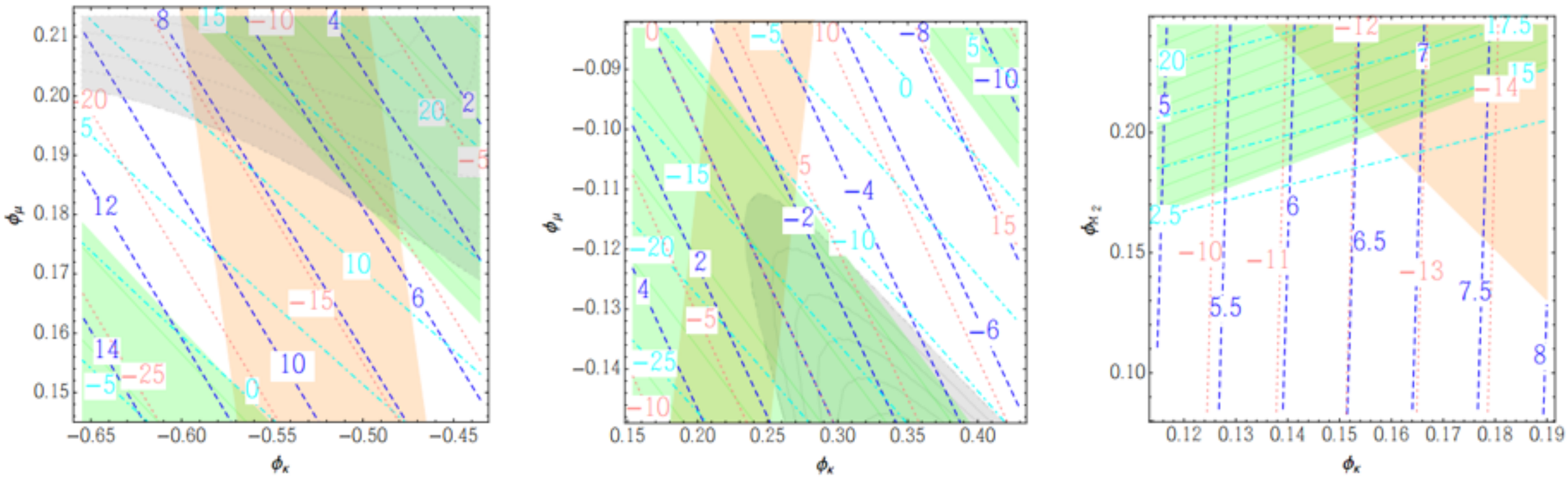


Figure 4. The combined plots of the eEDM and BAU in the plane $(\phi_\kappa, \phi_\mu(\phi_{M_2}))$ with $\phi_{M_2}(\phi_\mu) = 0$ for the scenario that H_2 is the SM-like Higgs in the CPV NMSSM. In both plots the green regions are excluded by the current eEDM experiments, the gray regions are excluded by requiring m_{H_2} to be close to 125 GeV while the orange regions are favored by the BAU results. For the contours, the blue, cyan and pink dashed lines represent the magnitudes of top quark, charginos and W boson loop contributions of the γH Barr-Zee diagrams of eEDM. The other parameters are chosen as in Table. 1.