Complex scalar in light of dark matter, gravitational wave and future colliders

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work with Chen Ning, Wu Yongcheng, Bian Ligong
arXiv: 1911.05579

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Outline

- The motivation and model
- Dark matter, EW phase transition and GW
- Precision test at colliders
- Summary

Motivation

- Evidences beyond the SM

dark matter, baryon number asymmetry, neutrino oscillation…

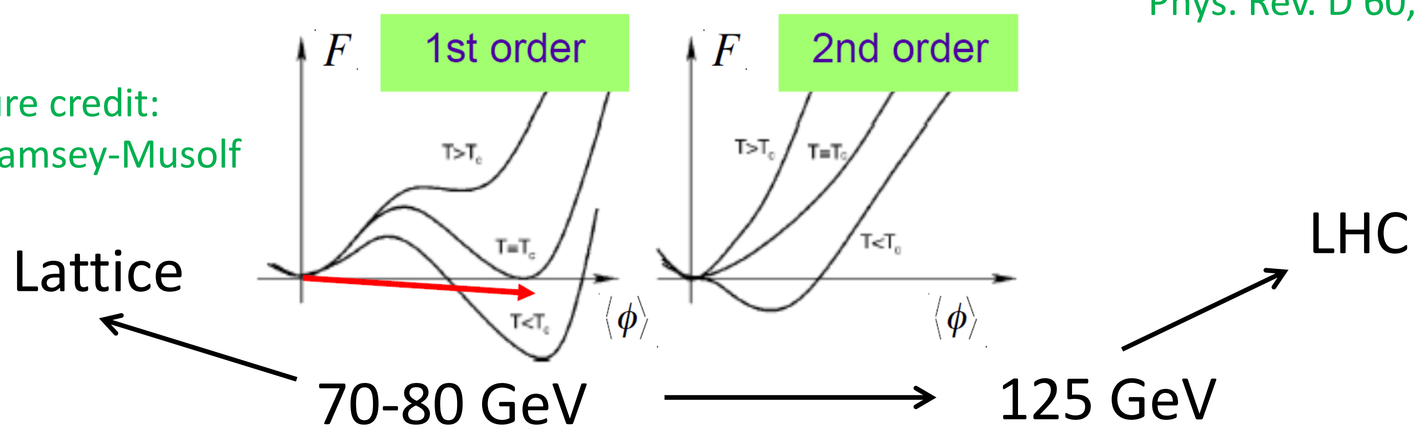
- Dark matter stabilized by discrete symmetry (e.g.Z2)
- EW Baryogenesis explaining BAU

✓ Sakharov's conditions (the 3rd) suggest strongly first order EW phase transition (SFOEWPT) Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967)

✓ The SM does not satisfy the SFOEWPT criterion $\varphi_c/T_c \gtrsim 1$

Phys. Rev. D 60, 013001 (1999)

picture credit:
M. Ramsey-Musolf



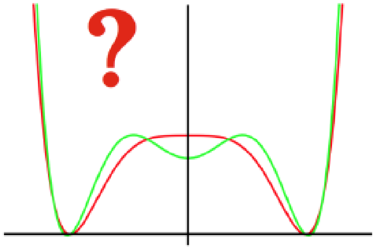
- The SM has to be extended
- DM and SFOEWPT can be realized in extended Higgs models (e.g. additional scalars)
- Vague Higgs potential: many possibilities

✓ Real singlet extension

✓ 2HDM/MSSM/NMSSM

✓ Type-II seesaw, Georgi-Macheck

✓ etc.



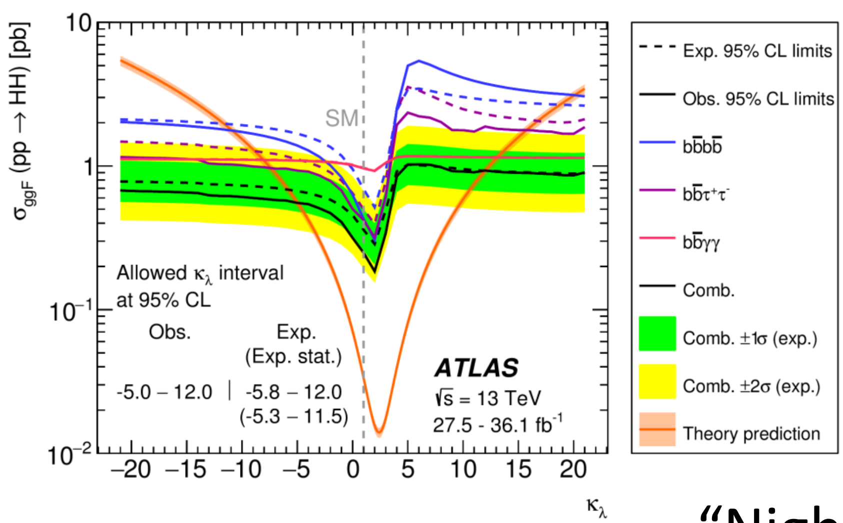
- For example: real singlet extension

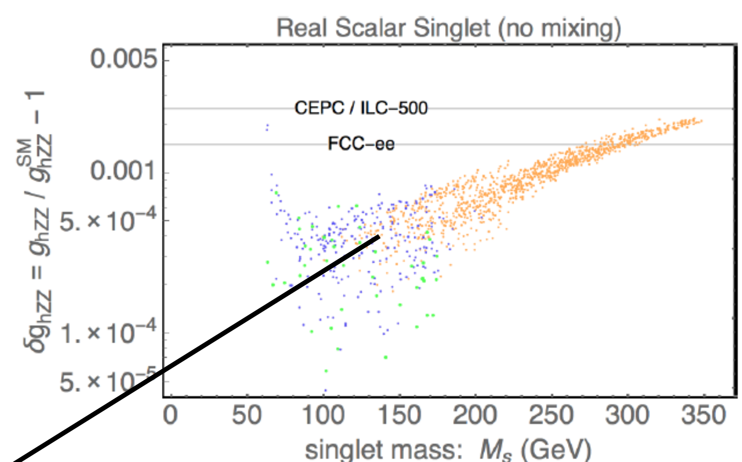
✓ DM requires Z2 symmetry (||SFOEWPT)

✓ The mixing between doublet and singlet is forbidden

✓ The deviations in the hZZ and hhh couplings induced at loop level

✓ Very challenging at colliders





“Nightmare”

P. Huang, A.J. Long, L.-T. Wang, arXiv: 1608.06619

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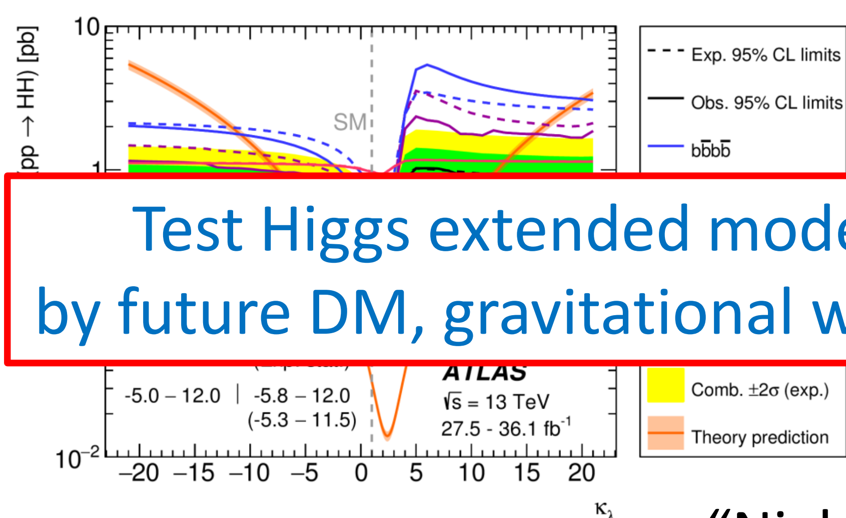

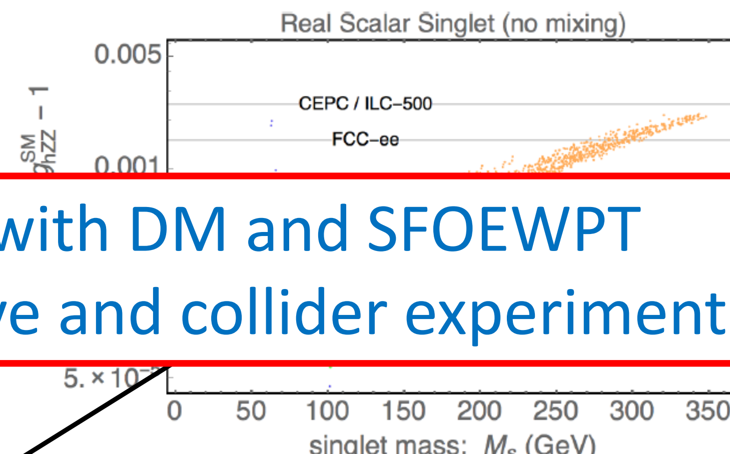

Test Higgs extended model with DM and SFOEWPT by future DM, gravitational wave and collider experiments

"Nightmare"

P. Huang, A.J. Long, L.-T. Wang, arXiv: 1608.06619

The complex scalar (S) extension

- The most general cxSM

V. Barger, P. Langacker, M. McCaskey, M. Ramsey-Musolf, G. Shaughnessy, arXiv: 0811.0393

$$
\begin{aligned}
V(\Phi\,,\mathbb{S}) = {} & \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 \\
& + \left(\frac{\delta_1}{4}|\Phi|^2\mathbb{S} + \frac{\delta_3}{4}|\Phi|^2\mathbb{S}^2 + c.c.\right) \\
& + \left(a_1\mathbb{S} + \frac{b_1}{4}\mathbb{S}^2 + \frac{c_1}{6}\mathbb{S}^3 + \frac{c_2}{6}\mathbb{S}|\mathbb{S}|^2 + \frac{d_1}{8}\mathbb{S}^4 + \frac{d_3}{8}\mathbb{S}^2|\mathbb{S}|^2 + c.c.\right)
\end{aligned}
$$

The complex scalar (S) extension

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- The most general cxSM

$$V(\Phi, \mathbb{S}) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{\delta_2}{2}|\Phi|^2|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{\delta_1}{4}|\Phi|^2\mathbb{S} + \frac{\delta_3}{4}|\Phi|^2\mathbb{S}^2 + c.c.\right) + \left(a_1\mathbb{S} + \frac{b_1}{4}\mathbb{S}^2 + \frac{c_1}{6}\mathbb{S}^3 + \frac{c_2}{6}\mathbb{S}|\mathbb{S}|^2 + \frac{d_1}{8}\mathbb{S}^4 + \frac{d_3}{8}\mathbb{S}^2|\mathbb{S}|^2 + c.c.\right)$$

- Imposing the global symmetries:

✓ Z2: eliminate odd powers of S

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$$+ \left(\frac{\delta_1}{4}|\Phi|^2\mathbb{S} + \frac{\delta_3}{4}|\Phi|^2\mathbb{S}^2 + c.c.\right)$$
$$+ \left(a_1\mathbb{S} + \frac{b_1}{4}\mathbb{S}^2 + \frac{c_1}{6}\mathbb{S}^3 + \frac{c_2}{6}\mathbb{S}|\mathbb{S}|^2 + \frac{d_1}{8}\mathbb{S}^4 + \frac{d_3}{8}\mathbb{S}^2|\mathbb{S}|^2 + c.c.\right)$$

- Imposing the global symmetries:

✓ Z2: eliminate odd powers of S

✓ U(1): eliminate all complex terms

- $\mathbb{S}$ =(S+iA)/sqrt(2), <S>=vs
- When vs=0, U(1) broken by b1, Z2 preserved

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

- ✓ Two not identical DM candidates, S and A
- ✓ S doesn't mix with H
- ✓ Z2 symmetric scenario

- When vs!=0, Z2 and U(1) spontaneously broken

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

- ✓ b1 term breaks U(1) and gives mass to the N-G A as DM
- ✓ a1 term explicitly breaks Z2
- ✓ S mixes with H
- ✓ Z2 breaking scenario

See also
M. Jiang, L. Bian, W. Huang, J. Shu, arXiv: 1502.07574;
C.-W. Chiang, M. Ramsey-Musolf, E. Senaha, arXiv: 1707.09960

Z2 symmetric cxSM

- mass spectrum

$$M_A^2 = \frac{\partial^2 V_0}{\partial A^2}\Big|_{h=v\,,S=0\,,A=0} = \frac{1}{4}\delta_2 v^2 - \frac{1}{2}(|b_1| - b_2)$$
$$M_h^2 = \frac{\partial^2 V_0}{\partial h^2}\Big|_{h=v\,,S=0\,,A=0} = 2\lambda v^2\,,$$
$$M_S^2 = \frac{\partial^2 V_0}{\partial S^2}\Big|_{h=v\,,S=0\,,A=0} = \frac{1}{4}\delta_2 v^2 + \frac{1}{2}(|b_1| + b_2)$$

- input parameters

$$65\,\mathrm{GeV} \le M_S \le 150\,\mathrm{GeV}\,, \quad 65\,\mathrm{GeV} \le M_A \le 2000\,\mathrm{GeV}$$
$$0 \le d_2 \le 20\,, \quad -20 \le \delta_2 \le 20\,.$$

- deviation of Higgs couplings induced at loop level
e.g. non-zero $\lambda_{hSS} = \lambda_{hAA}$ lead to Higgs self-energy
λ_{hhh} the same as SM

Z2 breaking cxSM

- mass spectrum

$$M_A^2 = \frac{\partial^2 V_0}{\partial A^2}\Big|_{h=v\,,S=v_s\,,A=0} = -|b_1| - \sqrt{2}\frac{a_1}{v_s}\,,$$

$$\mathcal{M}^2 = \begin{pmatrix} \mu_h^2 & \mu_{hs}^2 \\ \mu_{hs}^2 & \mu_s^2 \end{pmatrix}\,,$$

$$\mu_h^2 = \frac{\partial^2 V_0}{\partial h^2}\Big|_{h=v\,,S=v_s\,,A=0} = 2\lambda v^2\,,$$

$$\mu_s^2 = \frac{\partial^2 V_0}{\partial S^2}\Big|_{h=v\,,S=v_s\,,A=0} = \frac{d_2}{2}v_s^2 - \sqrt{2}\frac{a_1}{v_s}\,,$$

$$\mu_{hs}^2 = \frac{\partial^2 V_0}{\partial h \partial S}\Big|_{h=v\,,S=v_s\,,A=0} = \frac{\delta_2}{2}v v_s\,.$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

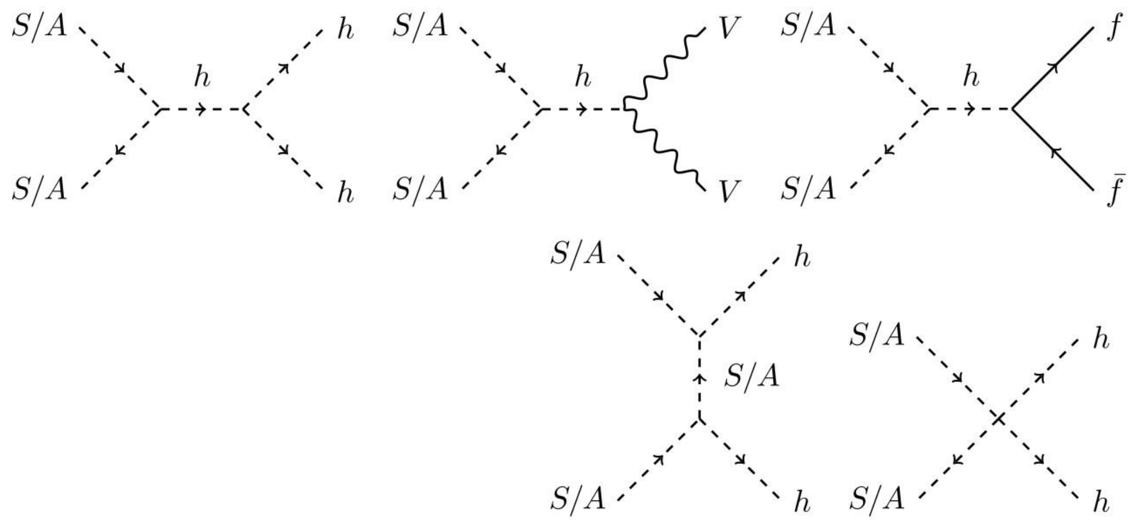
- input parameters

$$0 \le v_s \le 150\ \mathrm{GeV},\ \ 65\ \mathrm{GeV} \le M_2 \le 150\ \mathrm{GeV}\,,\ \ 65\ \mathrm{GeV} \le M_A \le 2000\ \mathrm{GeV}\,,$$
$$10^{-4} \le \theta \le 10^{-0.6},\ \ -(100\,\mathrm{GeV})^3 \le a_1 \le (100\,\mathrm{GeV})^3\,.$$

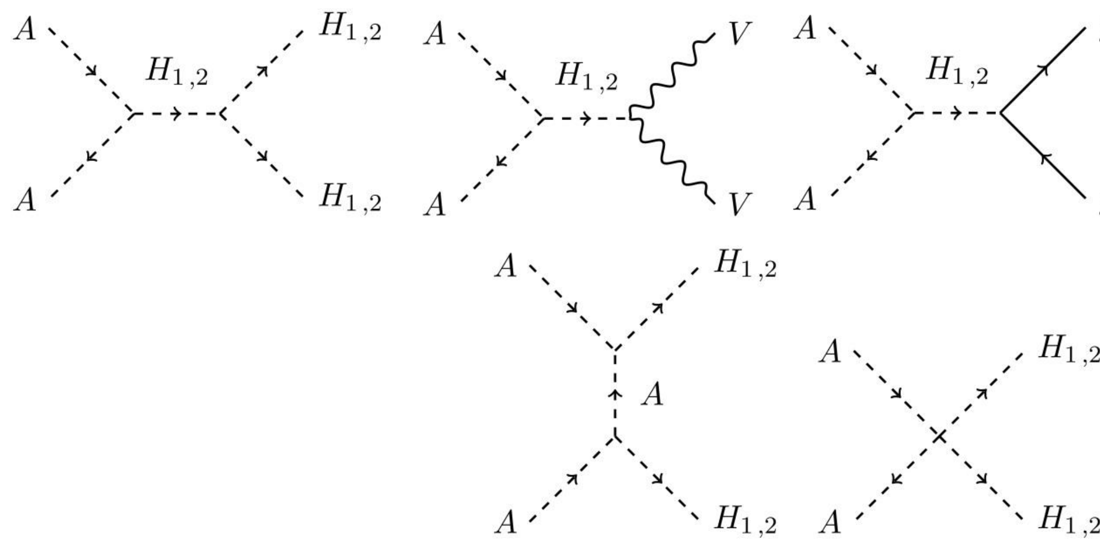
- h1ff/h1VV reduced by $cos\theta$ at tree level, cubic self-coupling λ_{111}……

Dark Matter annihilation

$\mathbb{Z}_2$



$\not{\mathbb{Z}}_2$



DM Direct Detection

- The SI scattering cross sections

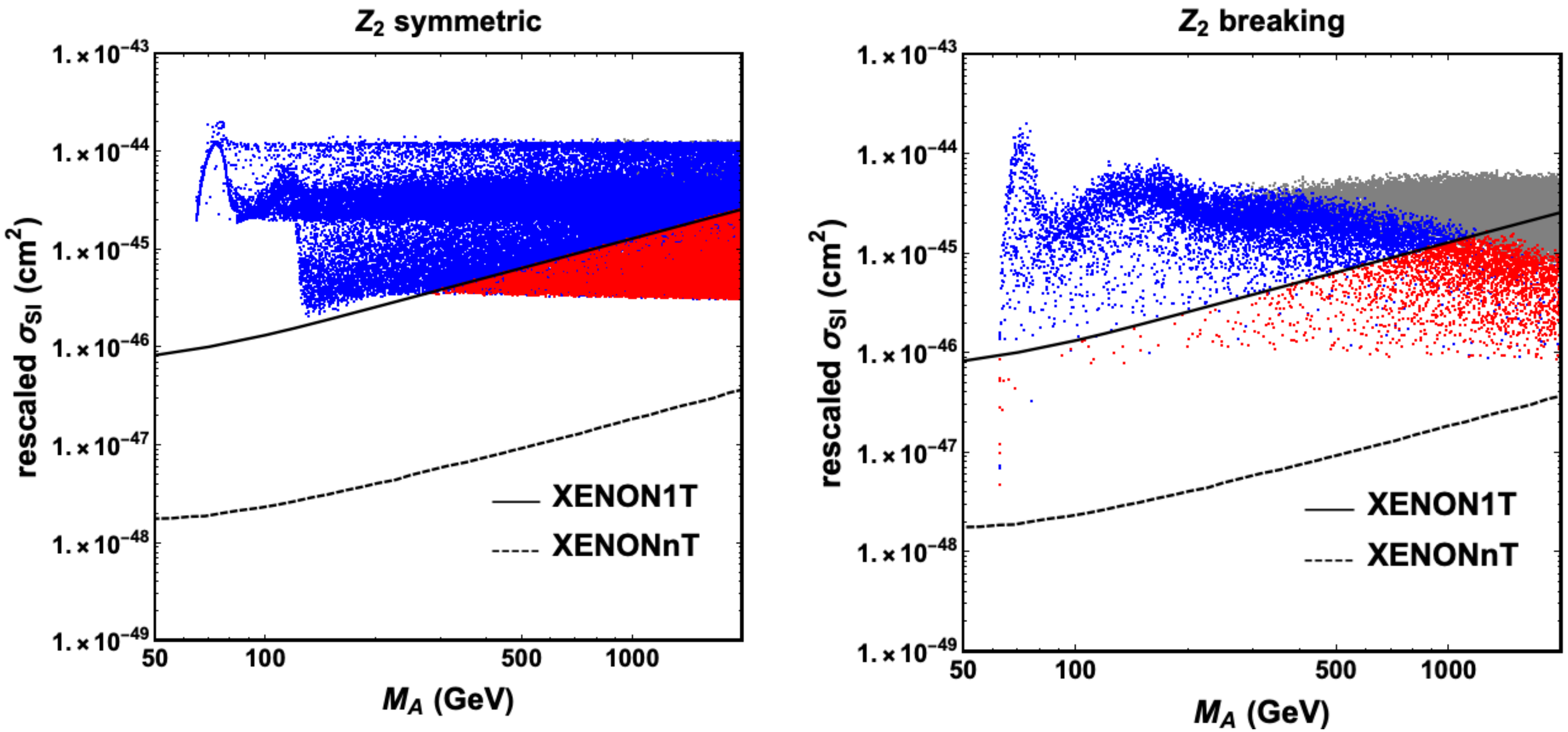
$$\sigma_{\rm SI}(\mathbb{Z}_2) = \frac{m_p^4}{2\pi v^2}\sum_{i=S,A}\frac{1}{(m_p+M_i)^2}\left(\frac{\lambda_{hii}}{M_h^2}\right)^2\left(f_{Tu}^{(p)}+f_{Td}^{(p)}+f_{Ts}^{(p)}+\frac{2}{9}f_{TG}^{(p)}\right)^2,$$

$$\sigma_{\rm SI}(\not{\mathbb{Z}}_2) = \frac{m_p^4}{2\pi v^2(m_p+M_A)^2}\left(\frac{\lambda_{1AA}\cos\theta}{M_1^2}-\frac{\lambda_{2AA}\sin\theta}{M_2^2}\right)^2 \times\left(f_{Tu}^{(p)}+f_{Td}^{(p)}+f_{Ts}^{(p)}+\frac{2}{9}f_{TG}^{(p)}\right)^2,$$

- Implemented by FeynRules and MicrOMEGAS
- Rescaled cross section

$$\sigma_{\rm SI}(\text{rescaled}) = \sigma_{\rm SI}\cdot\frac{\Omega_{\rm cxSM}h^2}{\Omega_{\rm DM}h^2}$$

DM constraints



- Blue: satisfy relic density
- Red: OK with relic density, DD and SFOEWPT

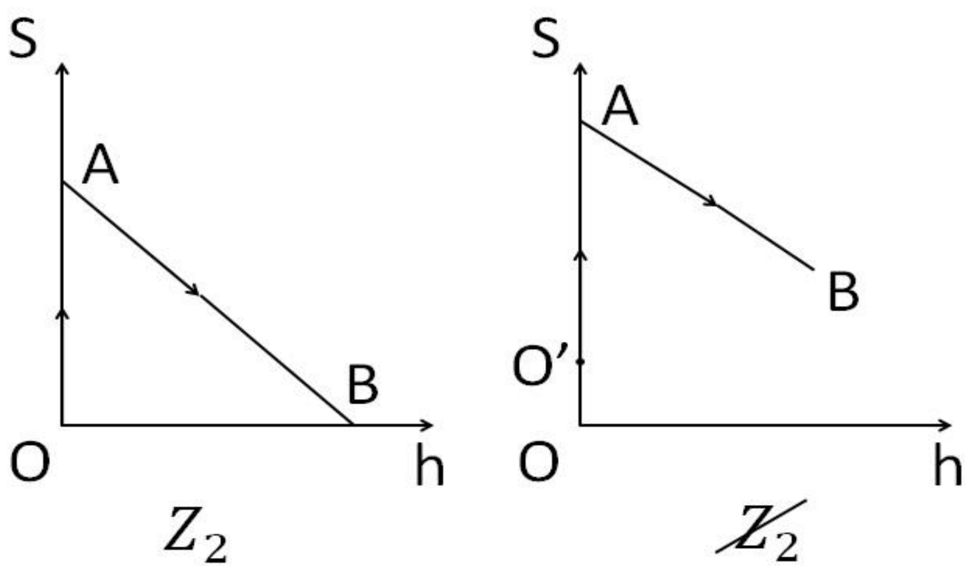
SFOEWPT

- High-T expanded effective potential

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

$$\Pi_h(T) = \Big(\frac{2m_W^2 + m_Z^2 + 2m_t^2}{4v^2} + \frac{\lambda}{2} + \frac{\delta_2}{24}\Big)T^2\,,$$

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



numerically calculated by CosmoTransitions

C.-W. Chiang, M. Ramsey-Musolf, E. Senaha, arXiv: 1707.09960

GW signals from EWPT

- Below Tc, the 2nd transition happens by tunneling process and true vacuum bubbles nucleate
- GW signal evaluated by critical bubble nucleation rate per unit time and per unit volume

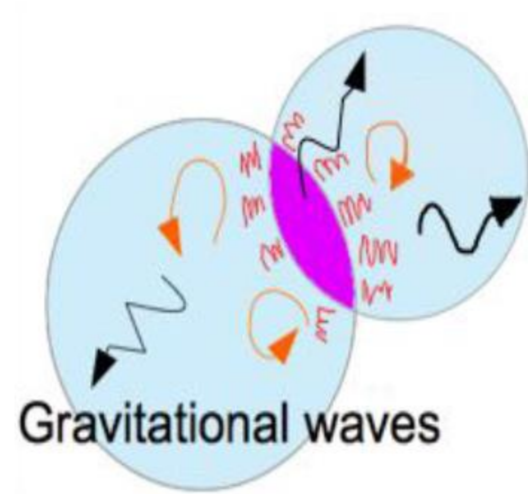
$$\Gamma \sim A(T) \exp(-S_3/T)$$

- GWs occur by collision of bubbles

✓ sound wave after bubble collision

✓ plasma turbulence

✓ collision of bubble walls



picture credit: K. Hashino

- For example: GW spectrum due to sound wave

$$\Omega_{\rm sw}(f)h^2 = 2.65\times10^{-6}\left(\frac{\beta}{H_n}\right)^{-1}\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}$$
$$\times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left[\frac{7}{4+3(f/f_{\rm sw})^2}\right]^{7/2},$$

LISA, arXiv: 1512.06239

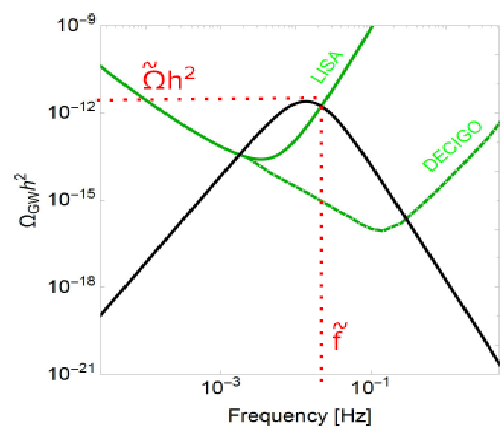
- Three parameters:

✓ Bubble nucleation temperature Tn

✓ Normalized latent heat released by EWPT $\alpha \equiv \frac{\rho_{\rm vac}}{\rho^*_{\rm rad}}$

✓ 1/(During time of the EWPT) $\frac{\beta}{H_n} \equiv T_n \frac{dS_3}{dT}\Big|_{T_n}$

- Depend on the model and determine the peak of frequency and spectrum



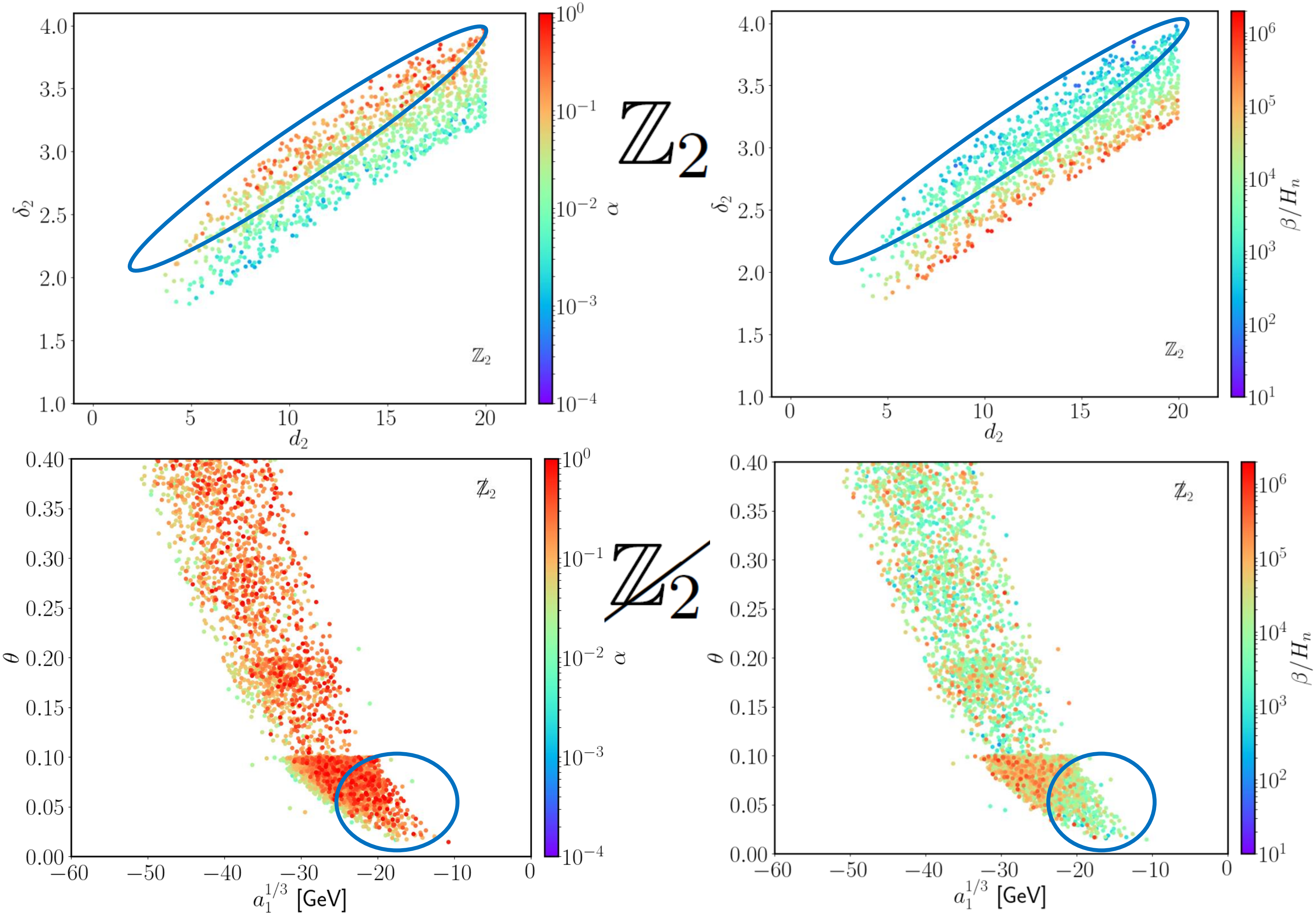
picture credit: K. Hashino

- The peak frequencies of the GW spectrum due to EWPT ~ 10^-4 – 10^-1 Hz
- The discovery prospect

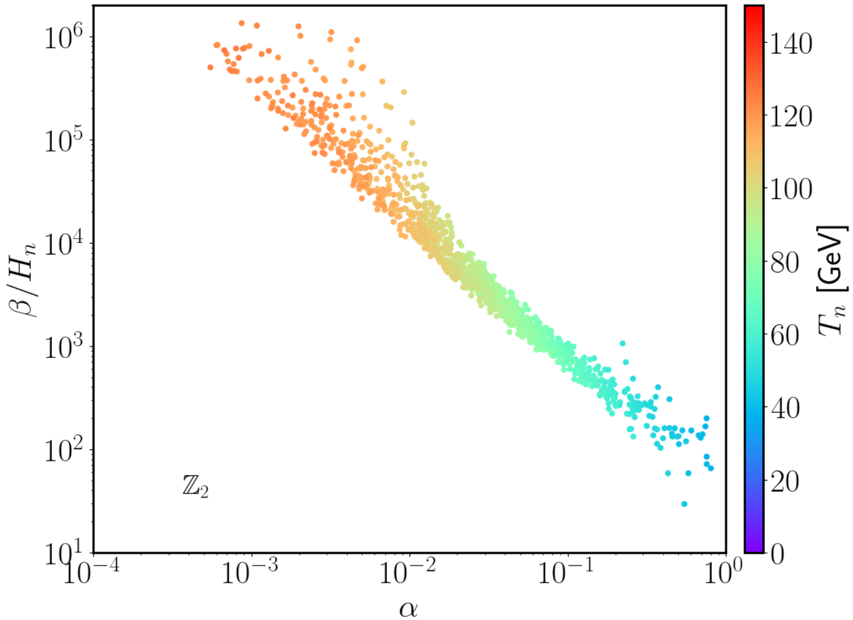
$$\mathrm{SNR} = \sqrt{\delta \times \mathcal{T} \int_{f_{\rm min}}^{f_{\rm max}} df \left[\frac{\Omega_{\rm GW}(f)h^2}{\Omega_{\rm exp}(f)h^2}\right]^2}$$

- SNR>50 for LISA

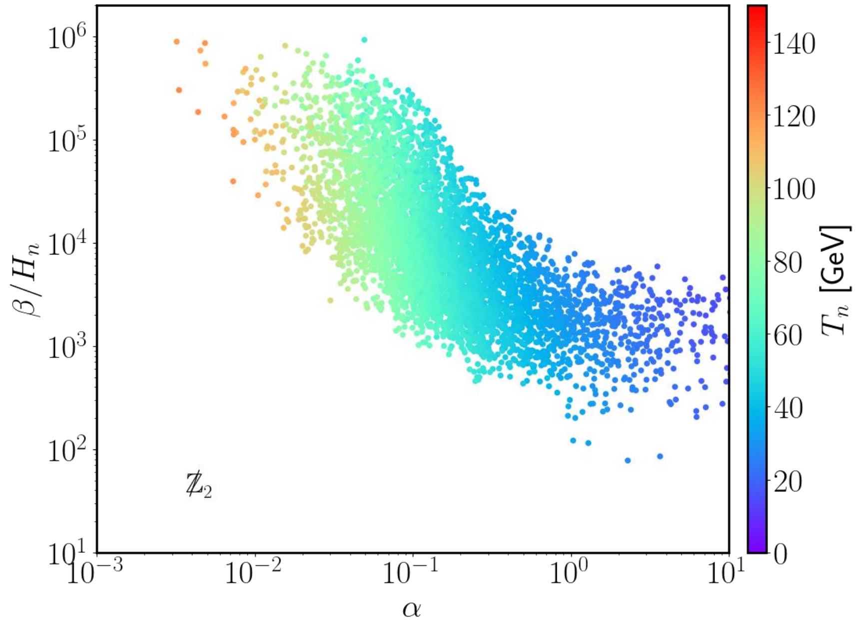
- larger alpha and smaller beta/Hn favored



$\mathbb{Z}_2$



$\not{\mathbb{Z}}_2$



- Lower Tn with stronger EWPT leads to larger alpha and smaller beta/Hn
- Z2 breaking case gives lower Tn

- Two benchmark points

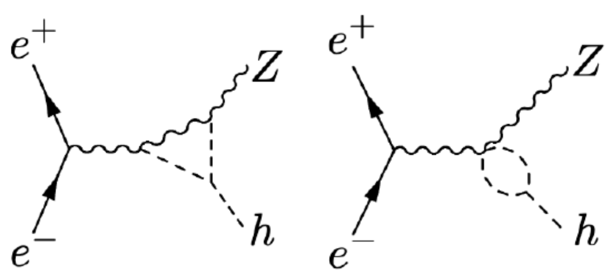
	$M_{S/2}$ [GeV]	M_A [GeV]	HL-LHC	e^+e^-	SNR (LISA)	α	β/H_n	T_n	v_n/T_n	v_w
$\mathbb{Z}_2$	129	950	$\times$	$\times$	4.9×10^4	0.11	737.47	67.12	3.08	0.78
$\mathbb{Z}_2$	99	963	$\times$	$\surd$	3.3×10^6	0.31	834.64	46.02	4.96	0.86

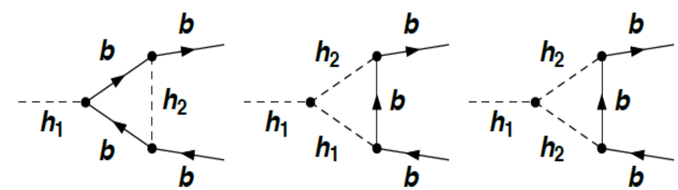
Precision test at e+e- colliders

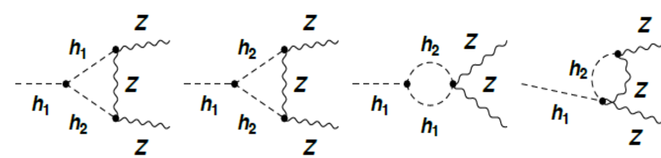
- Normalized Higgs couplings:

$$\kappa_{\rm loop}^{\rm cxSM} \equiv \frac{g_{\rm tree}^{\rm cxSM} + g_{\rm loop}^{\rm cxSM}}{g_{\rm tree}^{\rm SM} + g_{\rm loop}^{\rm SM}}$$

- Signal strengths for each channel





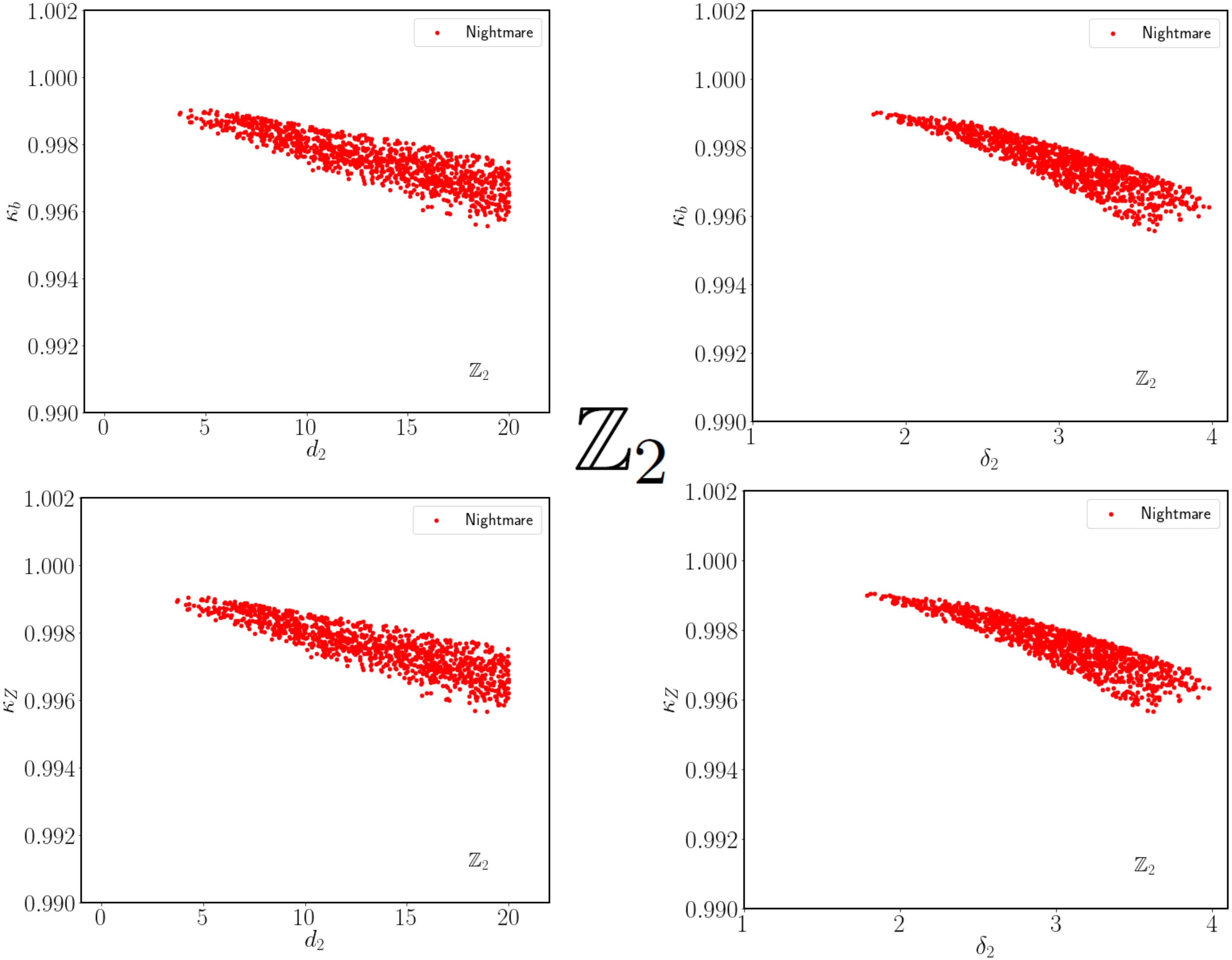


$$\mu_{i\to h\to f} \equiv \frac{\kappa_i^2 \kappa_f^2}{\kappa_{\rm width}}$$

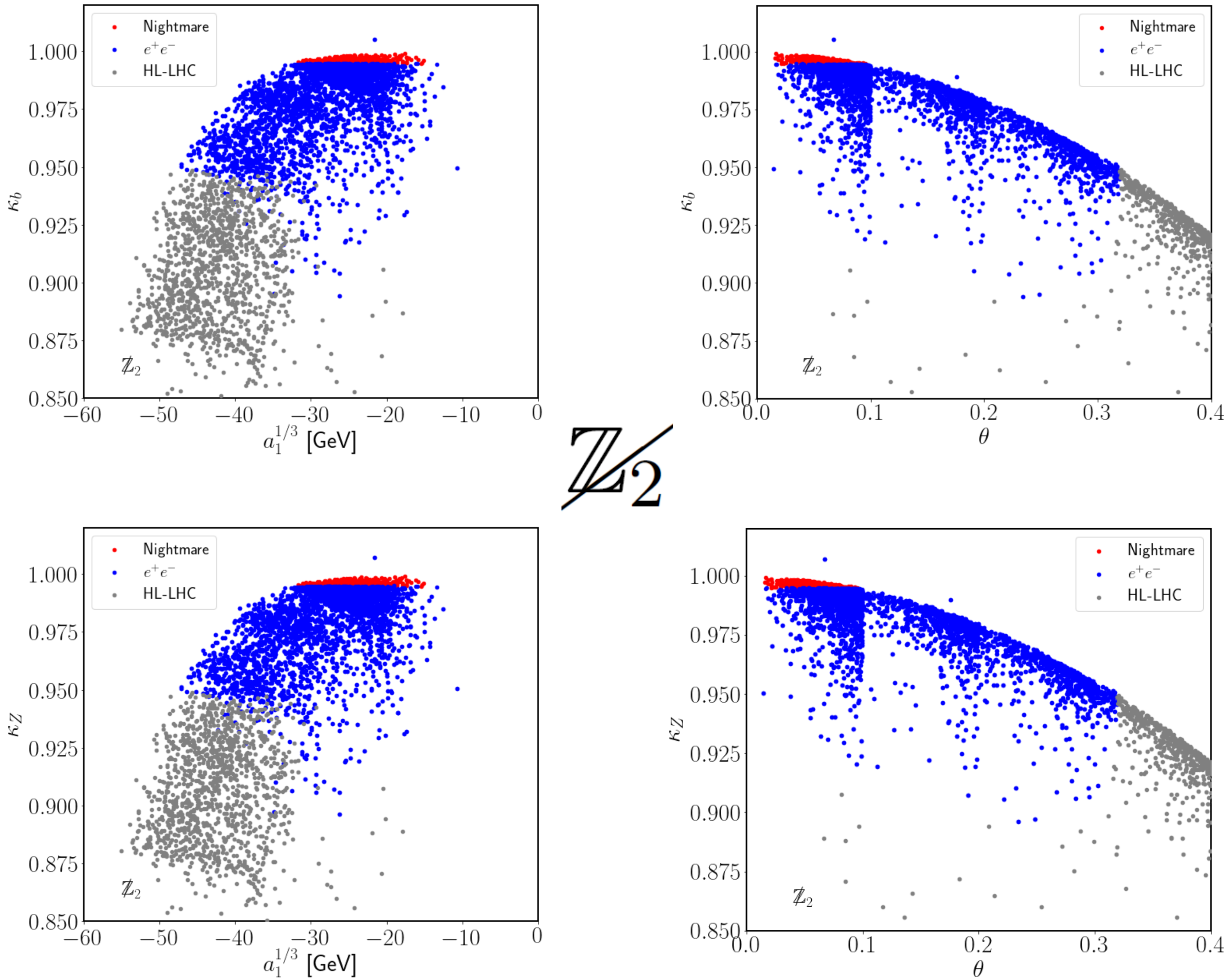
collider	CEPC	FCC-ee		
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV hZ 5 ab^{-1}	250 GeV hZ 5 ab^{-1}	365 GeV hZ ab^{-1}	365 GeV $h\nu\bar{\nu}$ ab^{-1}
$h \to b\bar{b}$	0.27%	0.3%	0.5%	0.9%
$h \to c\bar{c}$	3.3%	2.2%	6.5%	10%
$h \to gg$	1.3%	1.9%	3.5%	4.5%
$h \to WW^*$	1.0%	1.2%	2.6%	3%
$h \to \tau^+\tau^-$	0.8%	0.9%	1.8%	8%
$h \to ZZ^*$	5.1%	4.4%	12%	10%
$h \to \gamma\gamma$	6.8%	9.0%	18%	22%
$h \to \mu^+\mu^-$	17%	19%	40%	-

- chi2 fit for the Higgs signals:

$$\chi^2 \equiv \sum_i \frac{(\mu_i^{\rm cxSM} - \mu_i^{\rm obs})^2}{\sigma_{\mu_i}^2}$$

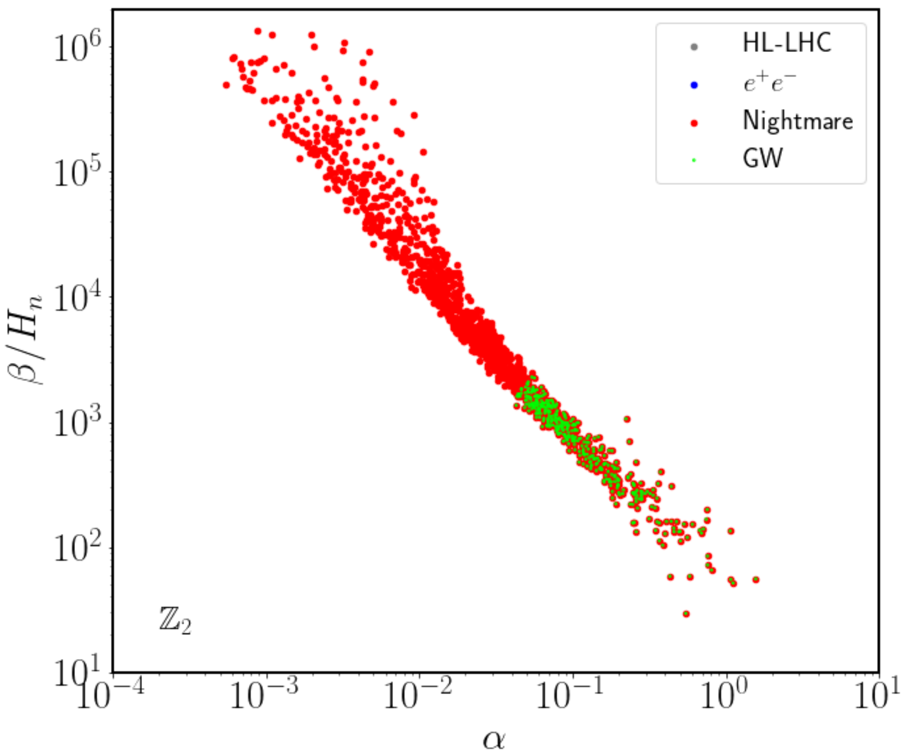


ℤ2
Nightmare
ℤ2
κb
d2
δ2
κZ
1.002
1.000
0.998
0.996
0.994
0.992
0.990
0
5
10
15
20
1
2
3
4

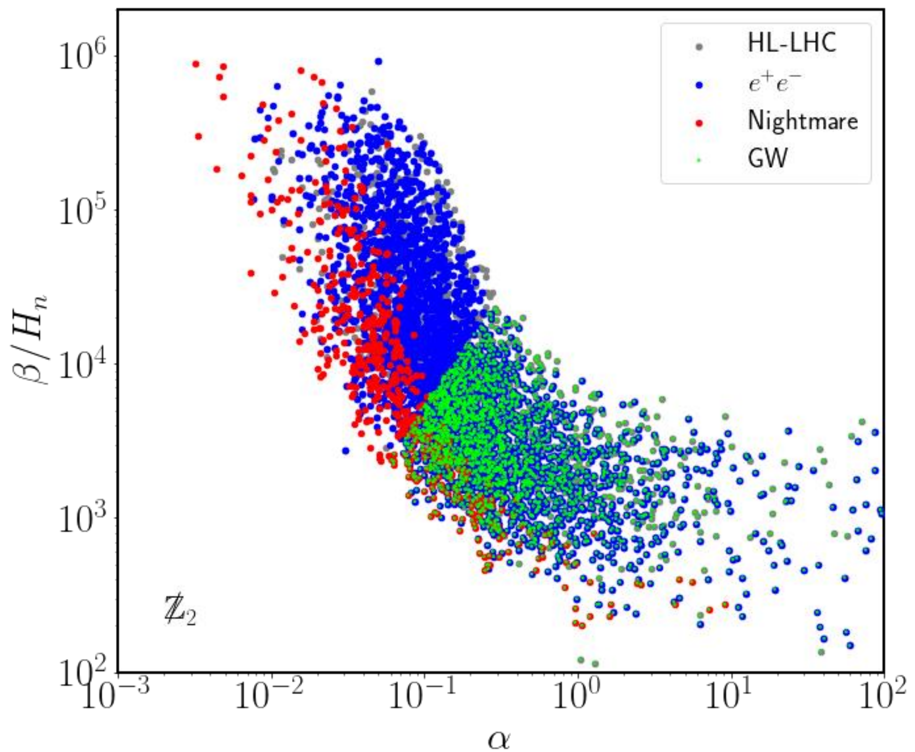


Nightmare
e^+e^-
HL-LHC
κ_b
κ_Z
$a_1^{1/3}$ [GeV]
θ
$\mathbb{Z}_2$

Combine e+e- and GW



$\mathbb{Z}_2$



$\not{\mathbb{Z}}_2$

Summary

- We study the cxSM with or without Z2 symmetry.
- DM constraints are imposed. The SFOEWPT and GW signals are evaluated.
- We implement the one-loop effects to the production and decay of 125 GeV Higgs at e+e- colliders.
- Z2 symmetric case: none can be probed at e+e-

  Z2 breaking case: a lot can be probed
- DM DD and GW signals are complementary to probe and distinguish the two cases.

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Thank You!

Backups

- Unitarity: $|\tilde{a}_0^i| \le 1$ for

$$a_0 = \frac{1}{16\pi}\begin{pmatrix} 4\lambda & \sqrt{2}\lambda & \sqrt{2}\lambda & \frac{\delta_2}{2\sqrt{2}} & \frac{\delta_2}{2\sqrt{2}} \\ \sqrt{2}\lambda & 3\lambda & \lambda & \frac{\delta_2}{4} & \frac{\delta_2}{4} \\ \sqrt{2}\lambda & \lambda & 3\lambda & \frac{\delta_2}{4} & \frac{\delta_2}{4} \\ \frac{\delta_2}{2\sqrt{2}} & \frac{\delta_2}{4} & \frac{\delta_2}{4} & \frac{3d_2}{4} & \frac{d_2}{4} \\ \frac{\delta_2}{2\sqrt{2}} & \frac{\delta_2}{4} & \frac{\delta_2}{4} & \frac{d_2}{4} & \frac{3d_2}{4} \end{pmatrix}$$

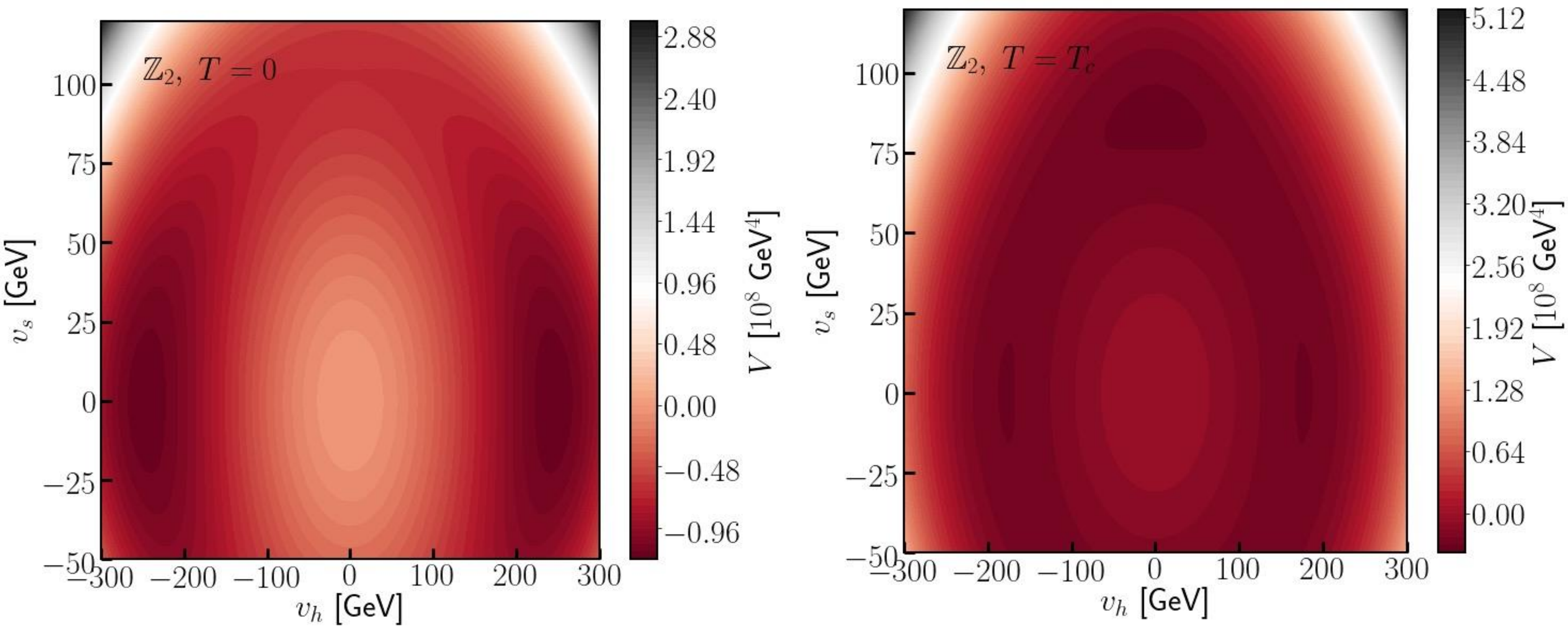
- Stability: $\lambda > 0\,,\ \ d_2 > 0\,,\ \ \lambda d_2 > \delta_2^2$

- Global min $A : \left.\frac{\partial V}{\partial S}\right|_{h=0\,,S=v_s} = 0,$

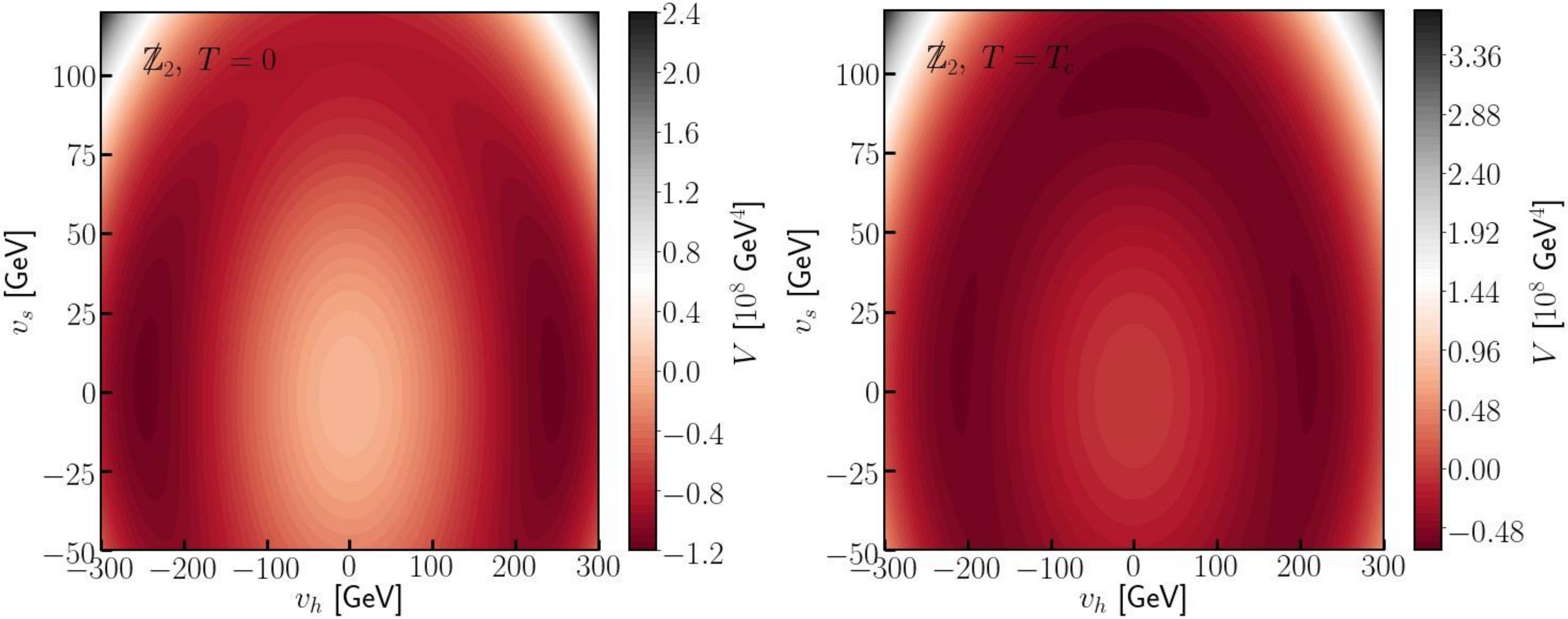
$$B : \left.\frac{\partial V}{\partial h}\right|_{h=v\,,S=0\,,A=0} = 0 \quad \mathbb{Z}_2$$

$$B : \left.\frac{\partial V}{\partial h}\right|_{h=v\,,S=v_s\,,A=0} = 0\,, \left.\frac{\partial V}{\partial S}\right|_{h=v\,,S=v_s\,,A=0} = 0 \quad \not\mathbb{Z}_2$$

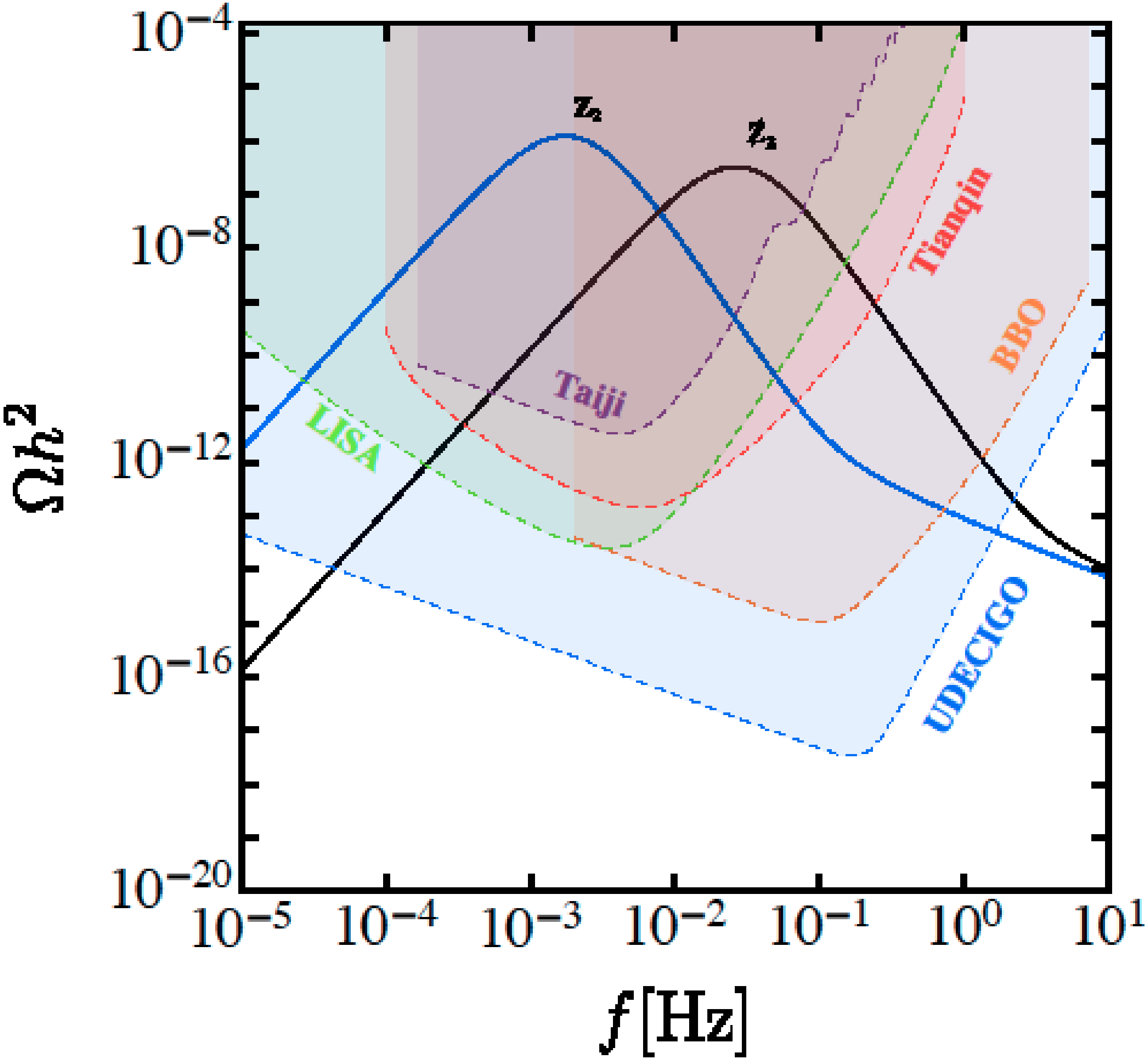
$$V(B) \le V(A)$$



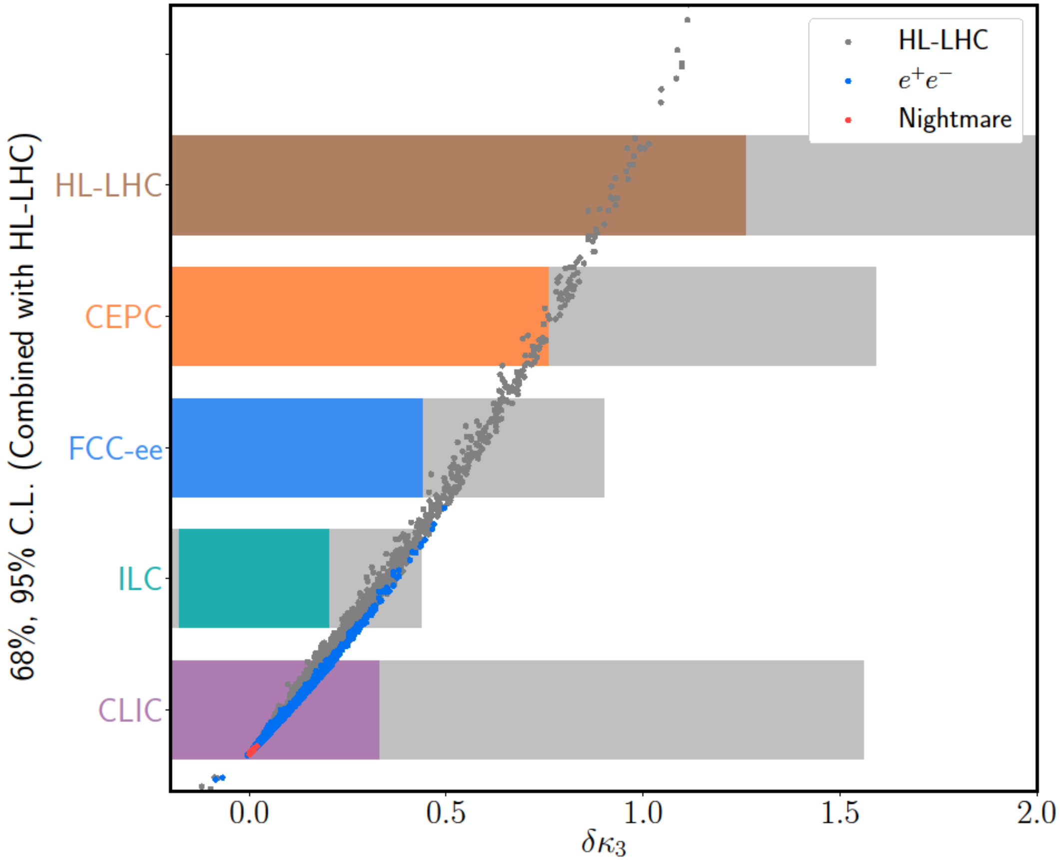
$\mathbb{Z}_2,\ T = 0$
v_s [GeV]
v_h [GeV]
V [10^8 GeV^4]
$\mathbb{Z}_2,\ T = T_c$



$\not{\mathbb{Z}}_2,\ T=0$
v_s [GeV]
v_h [GeV]
V [10^8 GeV^4]
$\not{\mathbb{Z}}_2,\ T=T_c$
v_s [GeV]
v_h [GeV]
V [10^8 GeV^4]



Ωh^2
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$f\,[\mathrm{Hz}]$
Taiji
LISA
Tianqin
BBO
UDECIGO


HL-LHC
e^+e^-
Nightmare
HL-LHC
CEPC
FCC-ee
ILC
CLIC
68%, 95% C.L. (Combined with HL-LHC)
0.0
0.5
1.0
1.5
2.0
$\delta\kappa_3$