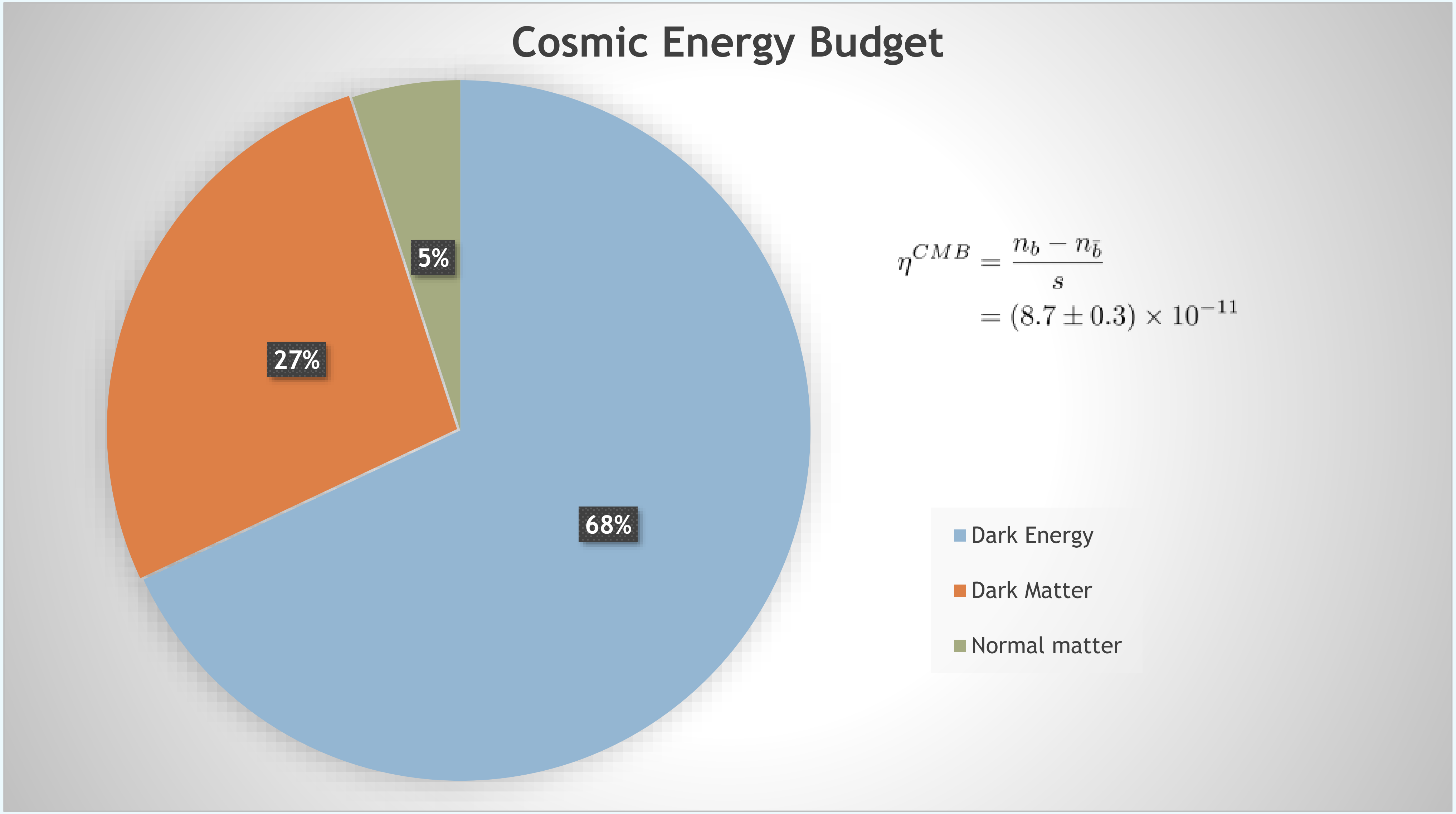
Probing the Complex Singlet Scalar Cosmology & Electroweak Phase Transition at the LHC

Wenxing Zhang (TDLI, SJTU) ,
Yizhou Cai, Michael Ramsey-Musolf, Lei Zhang

arXiv: 2303.03612，
2307.02187,
2307.01615

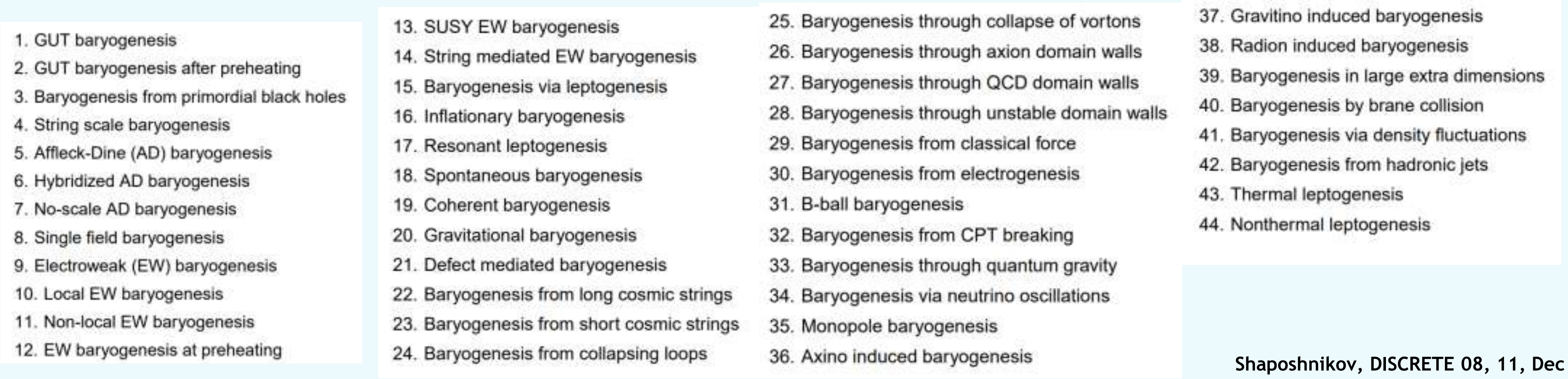


Cosmic Energy Budget

$$\eta^{CMB} = \frac{n_b - n_{\bar{b}}}{s} = (8.7 \pm 0.3) \times 10^{-11}$$

Bayon asymmetry of the Universe

44 different ways to creat baryons in the Universe



1. GUT baryogenesis
2. GUT baryogenesis after preheating
3. Baryogenesis from primordial black holes
4. String scale baryogenesis
5. Affleck-Dine (AD) baryogenesis
6. Hybridized AD baryogenesis
7. No-scale AD baryogenesis
8. Single field baryogenesis
9. Electroweak (EW) baryogenesis
10. Local EW baryogenesis
11. Non-local EW baryogenesis
12. EW baryogenesis at preheating
13. SUSY EW baryogenesis
14. String mediated EW baryogenesis
15. Baryogenesis via leptogenesis
16. Inflationary baryogenesis
17. Resonant leptogenesis
18. Spontaneous baryogenesis
19. Coherent baryogenesis
20. Gravitational baryogenesis
21. Defect mediated baryogenesis
22. Baryogenesis from long cosmic strings
23. Baryogenesis from short cosmic strings
24. Baryogenesis from collapsing loops
25. Baryogenesis through collapse of vortons
26. Baryogenesis through axion domain walls
27. Baryogenesis through QCD domain walls
28. Baryogenesis through unstable domain walls
29. Baryogenesis from classical force
30. Baryogenesis from electrogenesis
31. B-ball baryogenesis
32. Baryogenesis from CPT breaking
33. Baryogenesis through quantum gravity
34. Baryogenesis via neutrino oscillations
35. Monopole baryogenesis
36. Axino induced baryogenesis
37. Gravitino induced baryogenesis
38. Radion induced baryogenesis
39. Baryogenesis in large extra dimensions
40. Baryogenesis by brane collision
41. Baryogenesis via density fluctuations
42. Baryogenesis from hadronic jets
43. Thermal leptogenesis
44. Nonthermal leptogenesis

Shaposhnikov, DISCRETE 08, 11, Dec

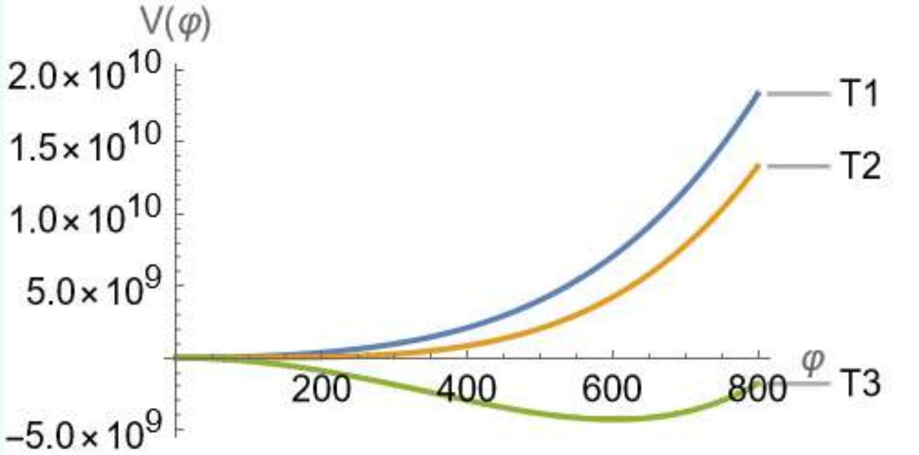
Sakharov conditions:

- Baryon number violating interactions. ☑
- C and CP violation. ☒
- Departure from thermal equilibrium. ☒ →

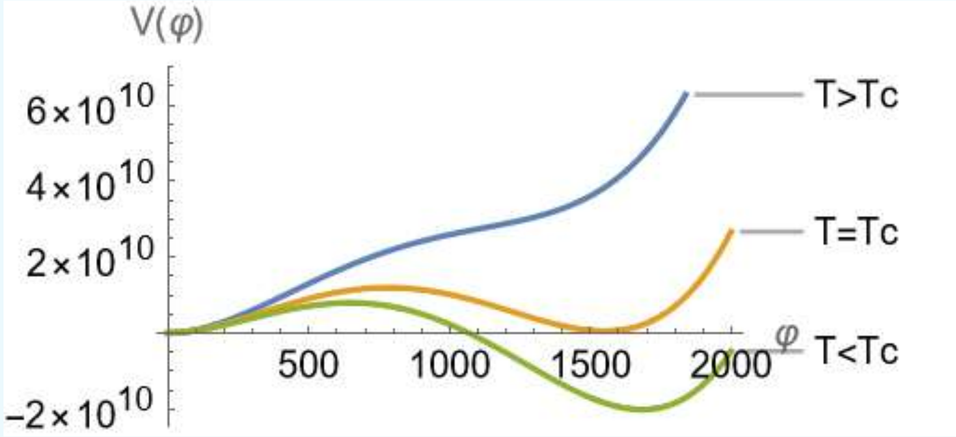
A.Sakharov JETP 5, 24 (1967)

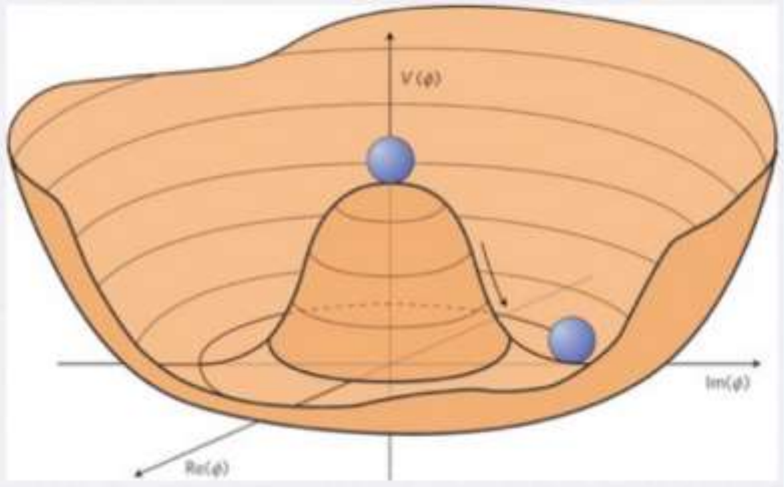
Sphaleron washout?
Strong First Order Electroweak Phase Transition **BSM**

Electroweak Phase Transition in the SM



First-order EWPT



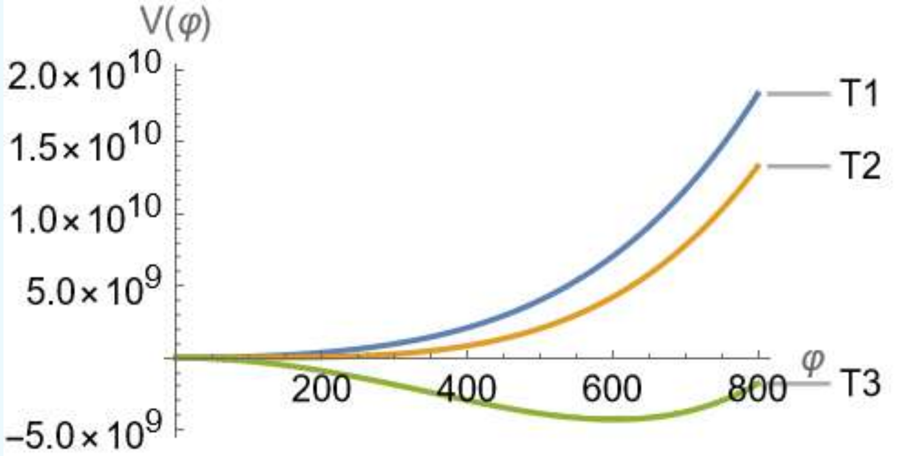


$$V_{eff}\left(\phi, T\right) \simeq D\left(T^2 - T_0^2\right)\phi^2 - ET\phi^3 + \frac{\bar{\lambda}}{4}\phi^4$$

$\longrightarrow$ Negative for $T < T_0$

SM: Crossover!

Electroweak Phase Transition in the SM



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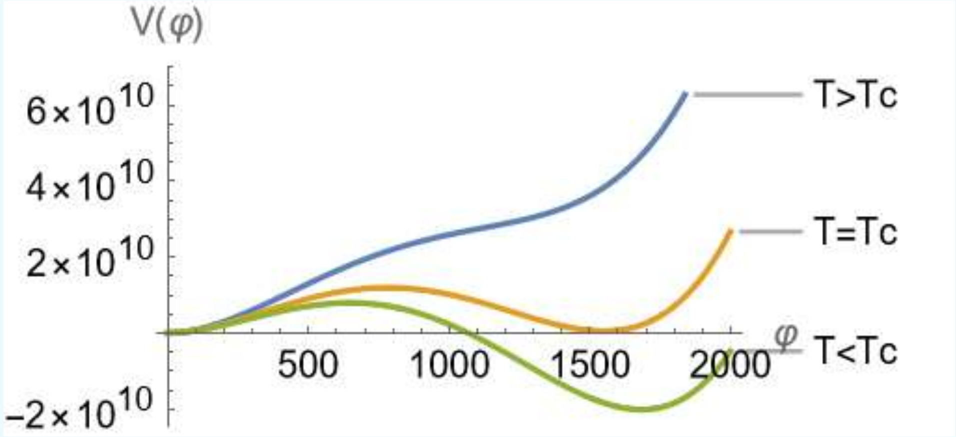
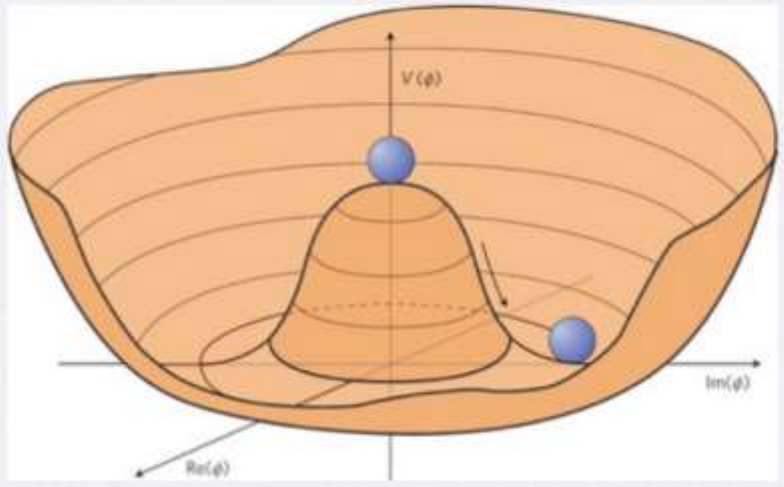




Generate barriers

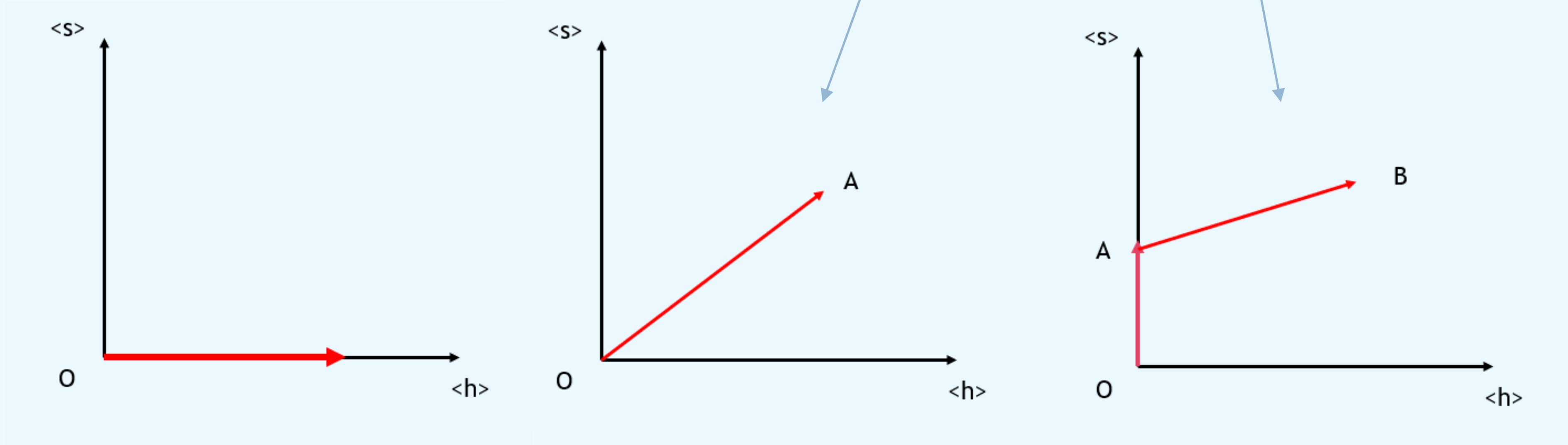
$$V_{eff}\left(\phi,T\right)\simeq D\left(T^2-T_0^2\right)\phi^2-ET\phi^3+\frac{\bar{\lambda}}{4}\phi^4$$

$\longrightarrow$ Negative for $T<T_0$

SM: Crossover!

SFOEWPT in BSM: Multi-step EWPT

$$V_0(H,S) = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \frac{a_1}{2}(H^\dagger H)S + \frac{a_2}{2}(H^\dagger H)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4,$$



a.

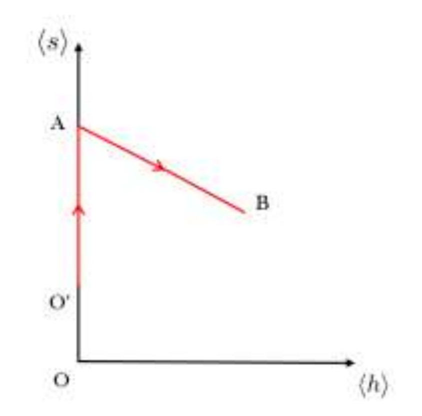
b.

c.

The cxSM

$$V_0(H,S) = \frac{\mu^2}{2}(H^\dagger H) + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + a_1 S + \frac{b_1}{4} S^2 + h.c..$$

$$S = x_0 + s + iA$$



One of the most simplest model in extended SM that generate multiple-step EWPT: the complex-singlet Standard Model(cxSM).

a. The cxSM can be a simplified model for many UV complete model that realise multiple-step SFOEWPT.

b. The cxSM provides both DM candidate and SFOEWPT.

Key-item to generate a barrier in FOEWPT: δ_2

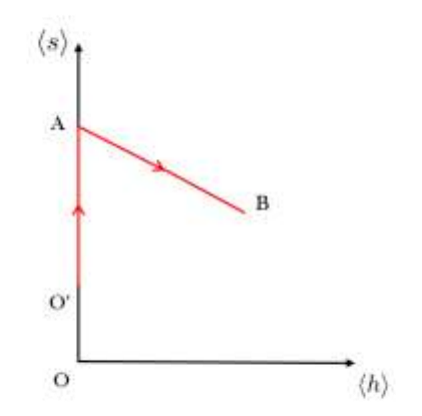
The cxSM

$$V_0(H,S) = \frac{\mu^2}{2}(H^\dagger H) + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + a_1 S + \frac{b_1}{4} S^2 + h.c..$$

$S = x_0 + s + iA$

CP-breaking phase $\phi_S \equiv \mathrm{Arg}(b_1 a_1^{*2})$
$\phi_S = 0$, CP-conserving

$$\mathcal{M}_h^2 \equiv \begin{pmatrix} M_{hh} & M_{hs} & M_{hA} \\ M_{sh} & M_{ss} & M_{sA} \\ M_{Ah} & M_{As} & M_{AA} \end{pmatrix} = \begin{pmatrix} \frac{1}{2}\lambda v_0^2 & \frac{\delta_2}{2} v_0 v_s & 0 \\ \frac{\delta_2}{2} v_0 v_s & \frac{1}{2} d_2 v_s^2 - \frac{\sqrt{2} a_1}{v_s} & 0 \\ 0 & 0 & -\frac{\sqrt{2} a_1}{v_s} - b_1 \end{pmatrix}$$



Key-item to generate a barrier in FOEWPT: δ_2

cxSM Constraints: Vaccum Stability

$$V_0(H,S) = \frac{\mu^2}{2}(H^\dagger H) + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 \\ + a_1 S + \frac{b_1}{4} S^2 + h.c..$$

- **Vaccum (v_0, x_0) is a stable minimum.**

$$\begin{vmatrix} \frac{\partial^2 V}{\partial v_0^2} & \frac{\partial^2 V}{\partial v_0 \partial x_0} \\ \frac{\partial^2 V}{\partial v_0 \partial x_0} & \frac{\partial^2 V}{\partial x_0^2} \end{vmatrix} > 0$$

- **The minimum (v_0, x_0) is global minimum.**
- **The potential is** *bounded from below.*

$$\begin{vmatrix} \lambda & \delta_2 \\ \delta_2 & d_2 \end{vmatrix} > 0$$

cxSM Constraints: Perturbation

$$
\begin{aligned}
V_0(H,S) =& \frac{\mu^2}{2}(H^\dagger H) + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2}H^\dagger H|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 \\
&+ a_1 S + \frac{b_1}{4}S^2 + h.c..
\end{aligned}
$$

Input parameters: Dim-0, Dim-1, Dim-3 $\sin\theta, v_s, m_{h_2}, m_{h_1}, a_1$

EW effective theory: Normalisation Scale–10 TeV.

$$
\mathrm{d}X/\mathrm{d}\log\mu = \frac{1}{(4\pi)^2}\beta^{(1)}(X), \quad 0 \leq \frac{3\lambda}{2}, \frac{\delta_2}{2}, \frac{3d_2}{2} \leq 4\pi
$$

$$
\begin{aligned}
\beta^{(1)}(g_1) &= \frac{41}{10}g_1^3 \\
\beta^{(1)}(g_2) &= -\frac{19}{6}g_2^3 \\
\beta^{(1)}(g_3) &= -7g_3^3 \\
\beta^{(1)}(d_2) &= 2\delta_2^2 + 5d_2^2 \\
\beta^{(1)}(\lambda) &= 6\lambda^2 + \delta_2^2 - 3g_1^2\lambda - 9g_2^2\lambda + \frac{3}{2}g_1^4 + 3g_1^2g_2^2 + \frac{9}{2}g_2^4 \\
&\quad + 12\lambda|Y_t|^2 - 24|Y_t|^4 \\
\beta^{(1)}(\delta_2) &= 3\delta_2\lambda + 2\delta_2^2 + 2d_2\delta_2 - \frac{3}{2}\delta_2 g_1^2 - \frac{9}{2}\delta_2 g_2^2 + 6\delta_2|Y_t|^2 \\
\beta^{(1)}(d_2) &= 2\delta_2^2 + 5d_2^2 \\
\beta^{(1)}(Y_t) &= \frac{9}{2}Y_t|Y_t|^2 - \frac{17}{12}g_1^2Y_t - \frac{9}{4}g_2^2Y_t - 8g_3^2Y_t,
\end{aligned}
$$

cxSM Constraints: EWPO

$$\Delta\mathcal{O} = (\cos^2\theta - 1)\mathcal{O}^{\rm SM}(m_{h_1}) + \sin^2\theta\mathcal{O}^{\rm SM}(m_{h_2}) = \sin^2\theta\left[\mathcal{O}^{\rm SM}(m_{h_2}) - \mathcal{O}^{\rm SM}(m_{h_1})\right]$$

$$\begin{aligned} S - S_{SM} &= 0.04 \pm 0.11 \\ T - T_{SM} &= 0.09 \pm 0.14 \\ U - U_{SM} &= -0.02 \pm 0.11 \end{aligned}$$

$$\rho_{ij} = \begin{pmatrix} 1 & 0.92 & -0.68 \\ 0.92 & 1 & -0.87 \\ -0.68 & -0.87 & 1 \end{pmatrix} .$$

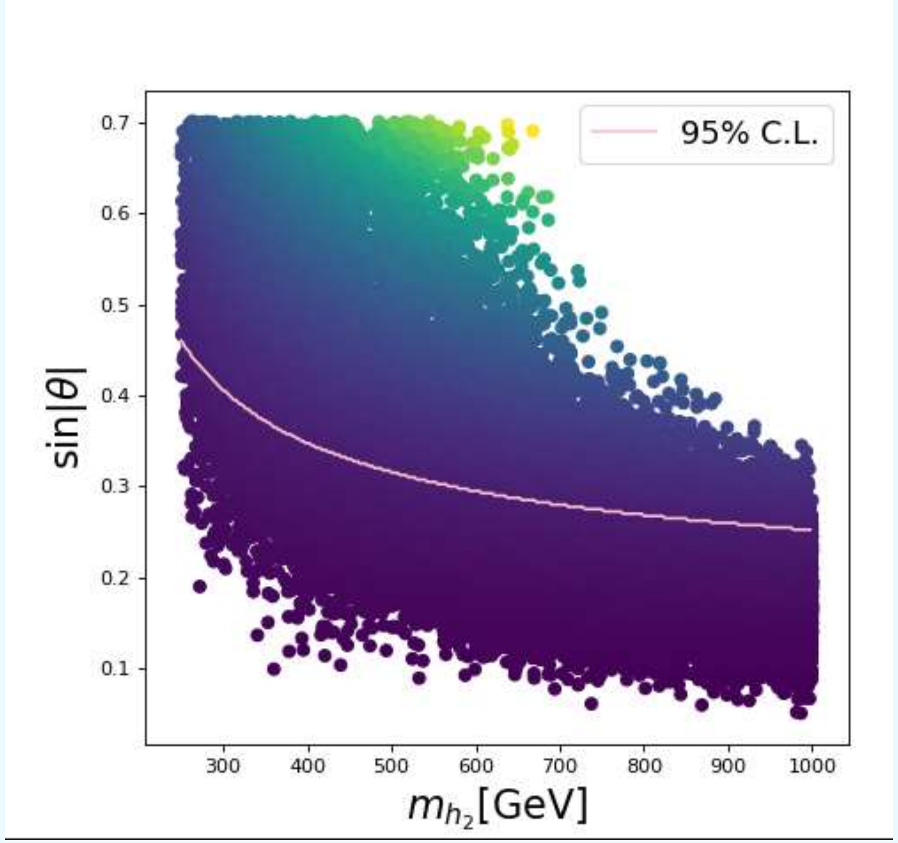
$$\chi^2 = (X - \hat{X})_i (\sigma^2)^{-1}_{ij} (X - \hat{X})_j < 5.99$$

→ **For 2 DoF, 95% C.L.**

Eur.Phys.J.C 78 (2018) 8

cxSM Constraints: EW Presion Observables

$$\Delta\mathcal{O} = (\cos^2\theta - 1)\mathcal{O}^{\mathrm{SM}}(m_{h_1}) + \sin^2\theta\mathcal{O}^{\mathrm{SM}}(m_{h_2}) = \sin^2\theta\left[\mathcal{O}^{\mathrm{SM}}(m_{h_2}) - \mathcal{O}^{\mathrm{SM}}(m_{h_1})\right]$$



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cxSM Constraints: W mass measurement

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$$\Delta S = 0.086 \pm 0.077,$$
$$\Delta T = 0.177 \pm 0.070$$

$$\rho_{ij} = \begin{pmatrix} 1 & 0.89 \\ 0.89 & 1 \end{pmatrix}.$$

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CDF, Science 376, 170 (2022).

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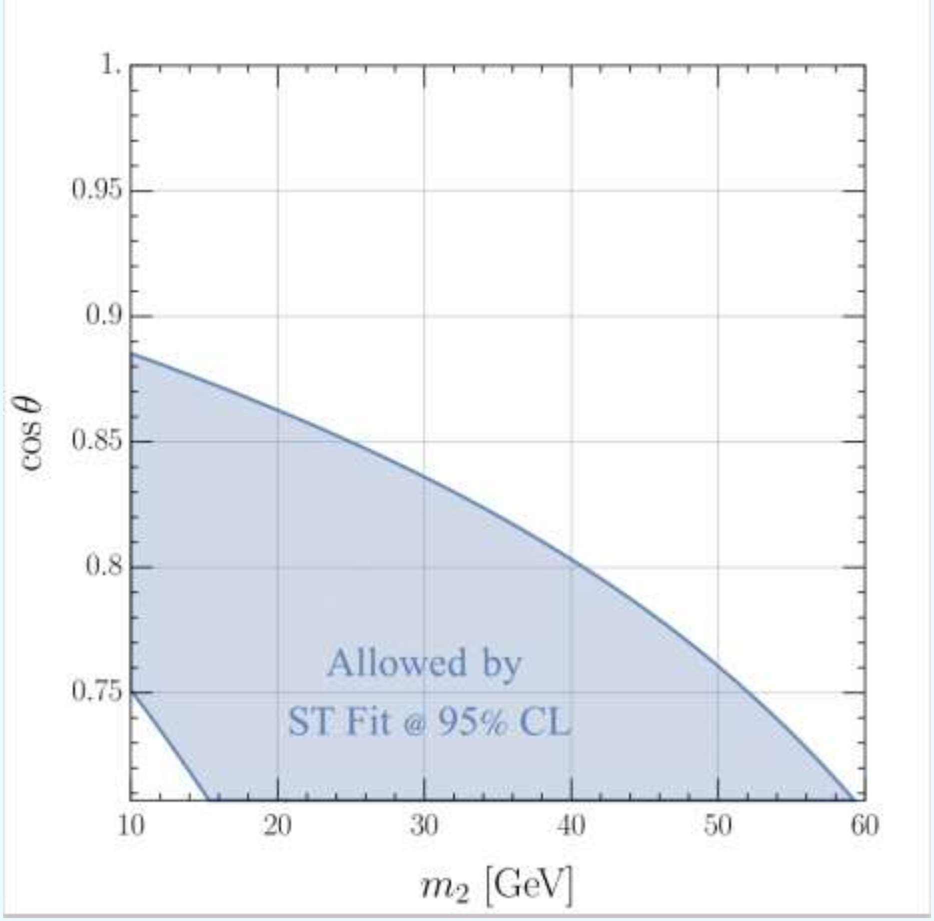

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CDF, Science 376, 170 (2022).

cxSM Constraints: Higgs Measurement

New physics may induce deviation in Higgs couplings. Therefore it modifies the Higgs signal strength in Higgs measurement.

Production mode	ggF+$b\bar{b}H$	VBF	WH	ZH	$t\bar{t}$H	tH
$\sum_f \mu_{i\to h_1\to ff}$	$1.03^{+0.07}_{-0.07}$	$1.10^{+0.13}_{-0.12}$	$1.16^{+0.23}_{-0.22}$	$0.96^{+0.22}_{-0.21}$	$0.74^{+0.24}_{-0.24}$	$6.61^{+4.24}_{-3.76}$

Nature 607, 52–59 (2022)

$$\mu_{pp\to h_1\to XX} = \frac{\sigma_{pp\to h_1}\ BR(h_1 \to XX)}{\sigma^{SM}_{pp\to h}\ BR(h\to XX)_{SM}} \simeq \cos^2\theta,$$

$$\chi^2 = \sum_{i,f} \frac{(\mu^{xSM}_{i\to h_1\to f} - \mu^{obs}_{i\to h_1\to f})^2}{\sigma^2_{\mu_{i\to h\to f}}}, \quad \Delta\chi^2 = \chi^2 - \chi^2_{min} < 3.841. \to$$ **For 1 DoF, 95% C.L.**

This set $\|\sin\theta\| < 0.2$.

DM in cxSM

$$V_0(H,S) = \frac{\mu^2}{2}(H^\dagger H) + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2}H^\dagger H|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4$$

$$+a_1 S + \frac{b_1}{4}S^2 + h.c..$$

$$S = x_0 + s + iA$$

CP-breaking phase $\phi_S \equiv \mathrm{Arg}(b_1 a_1^{*2})$

$\phi_S = 0$, **CP-conserving**

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$$h_1 = \cos\theta\ h + \sin\theta\ s,$$
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$$h_1 = \cos\theta\ h + \sin\theta\ s,$$
$$h_2 = -\sin\theta\ h + \cos\theta\ s.$$

$$g_{1AA} = \frac{\sqrt{2}a_1 + m_{h_1}^2 v_s}{2v_s^2}\sin\theta,$$

h_1**: SM-like Higgs with** $m_{h_1} = 125$ **GeV**
This induce Higgs invisible decay $h_1 \to AA$.

DM in cxSM: Higgs invisible decay

$$g_{1AA} = \frac{\sqrt{2}a_1 + m_{h_1}^2 v_s}{2v_s^2}\sin\theta,$$

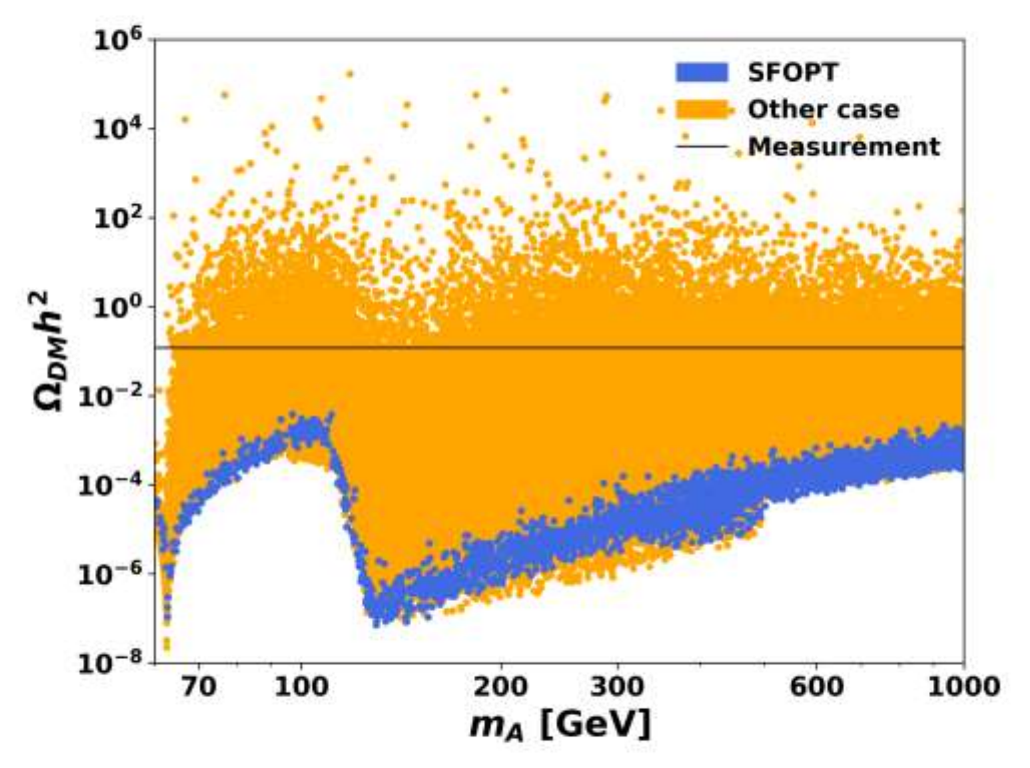
Redefine $a_1 = \gamma^3 m_{h_1}^3$, $v_s = \beta m_{h_1}$, $\gamma, \beta \sim \mathcal{O}(1)$, the invisible decay width can be expressed as

$$\begin{aligned}\Gamma_{h_1\to AA} &= \frac{g_{1AA}^2}{8\pi m_{h_1}}\sqrt{1-\frac{4m_A^2}{m_{h_1}^2}} \\ &= \frac{m_{h_1}}{8\pi}\left(\frac{\sqrt{2}\gamma^3+\beta}{2\beta^2}\right)^2\sqrt{1-\frac{4m_A^2}{m_{h_1}^2}}\ \sin^2\theta \\ &\sim \left(\frac{\sqrt{2}\gamma^3+\beta}{2\beta^2}\right)^2\sqrt{1-\frac{4m_A^2}{m_{h_1}^2}}\times\left(\frac{\sin\theta}{0.1}\right)^2\times 50\ [\mathrm{MeV}],\end{aligned}$$

$$\Gamma_{H\to inv}^{SM} \lesssim 4.1\ \mathbf{MeV}\times 13\% \simeq 0.4\ \mathbf{MeV}$$

➡ $62.5\mathbf{GeV} \le m_A \le 1\ \mathbf{TeV}$

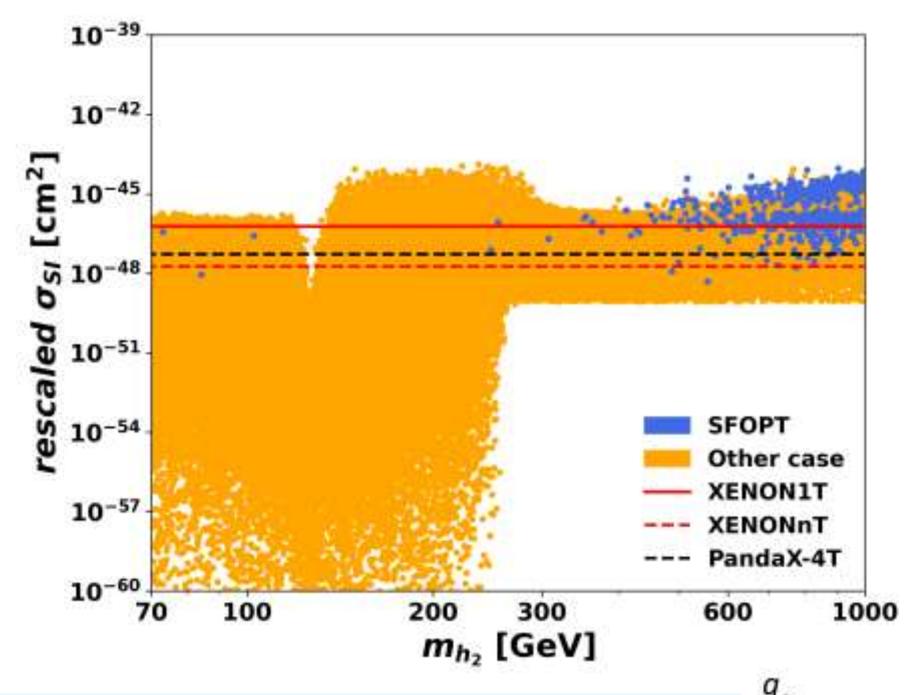
DM in cxSM: Relic Density



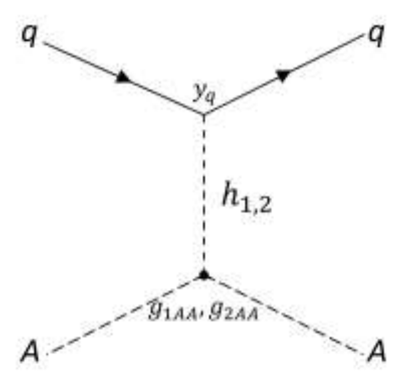
$$\Gamma^{SM}_{H\to inv} \lesssim 4.1 \ \textbf{MeV} \times 13\% \simeq 0.4 \ \textbf{MeV}$$

$$\Rightarrow \quad 62.5\textbf{GeV} \leq m_A \leq 1 \ \textbf{TeV}$$

DM in cxSM: Direct Detection



$m_A = 62.5\text{GeV}$



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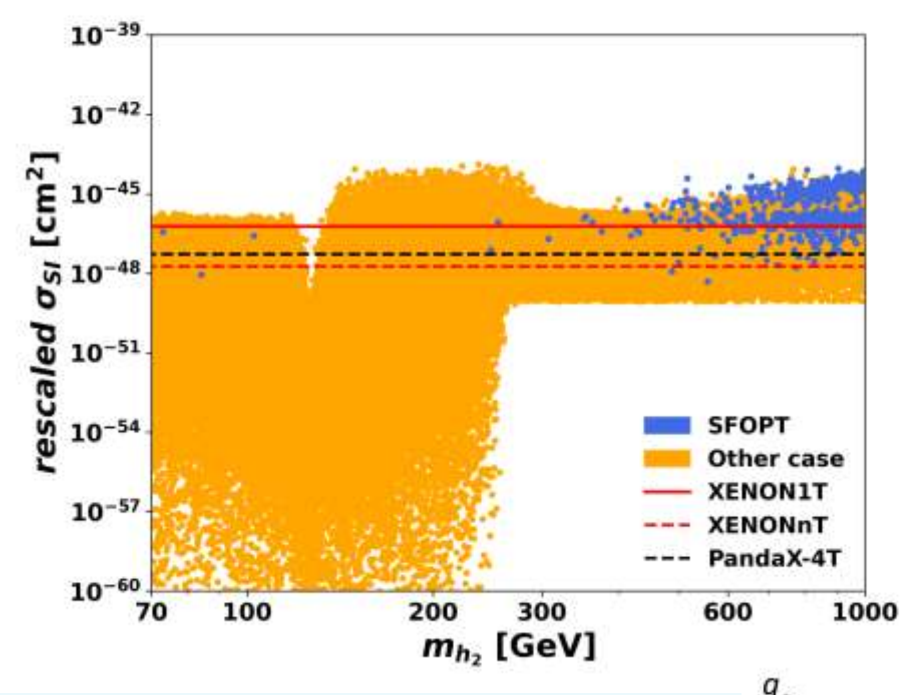

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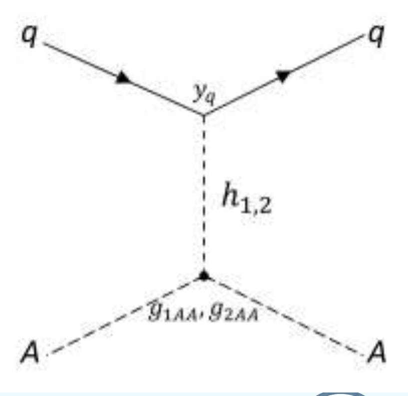
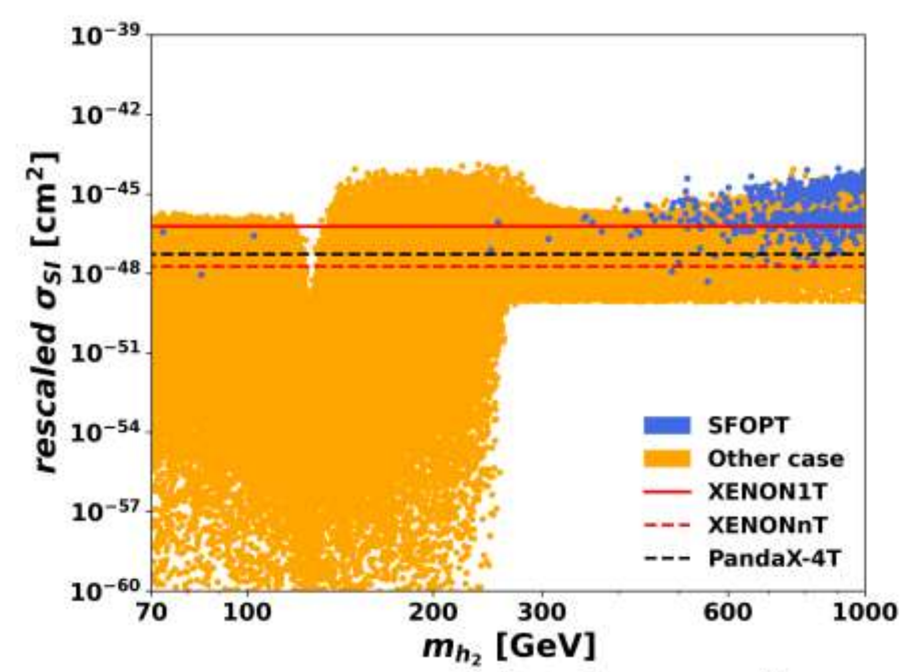


LHC: Well-studied di-Higgs channel.

DM in cxSM: Direct Detection



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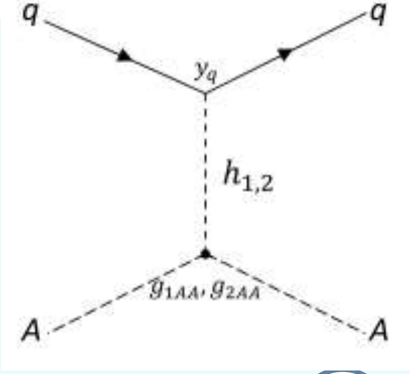
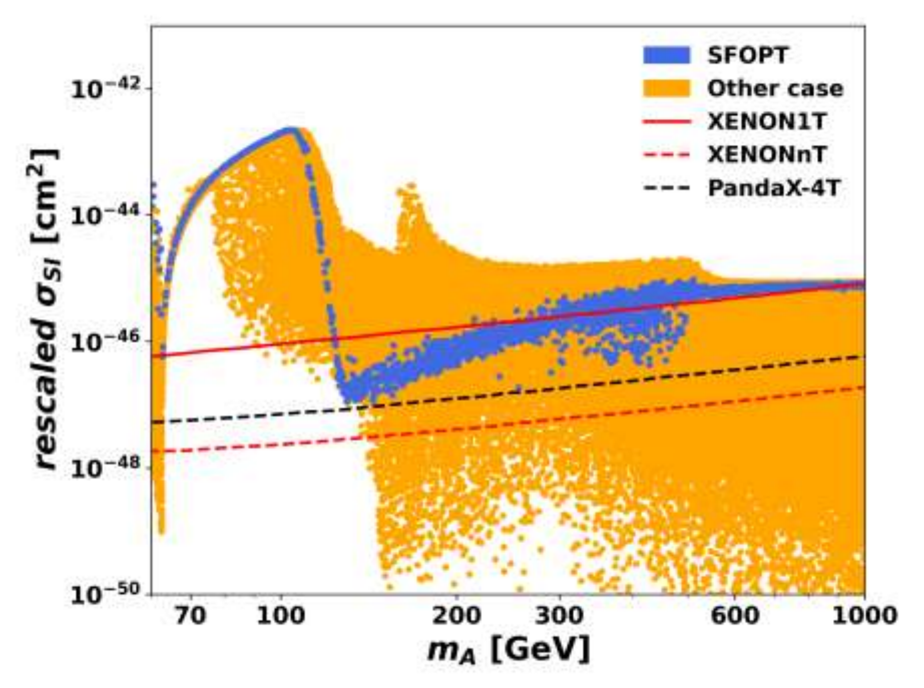
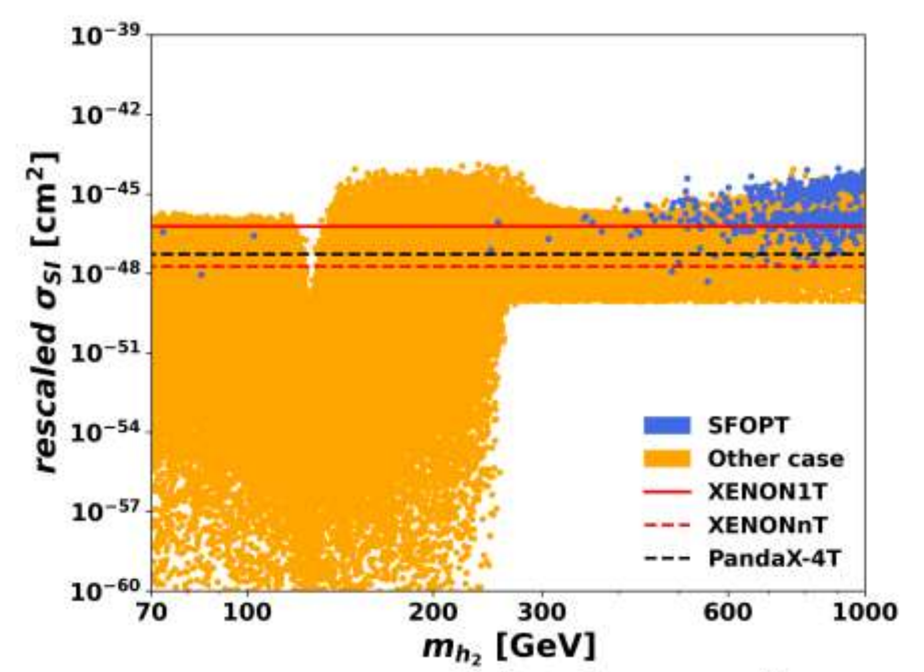


- $m_A = 62.5$ GeV: This case is almost excluded by the current DM direct detection. → LHC: Well-studied di-Higgs channel.

DM in cxSM: Direct Detection



$62.5\text{GeV} < m_A \leq 1\ \text{TeV}$



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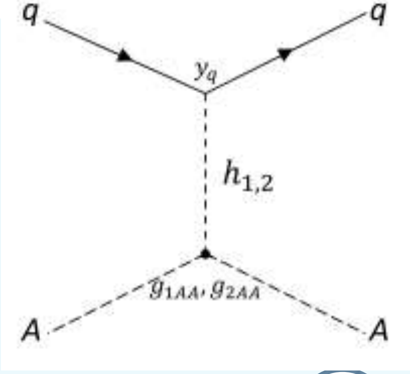

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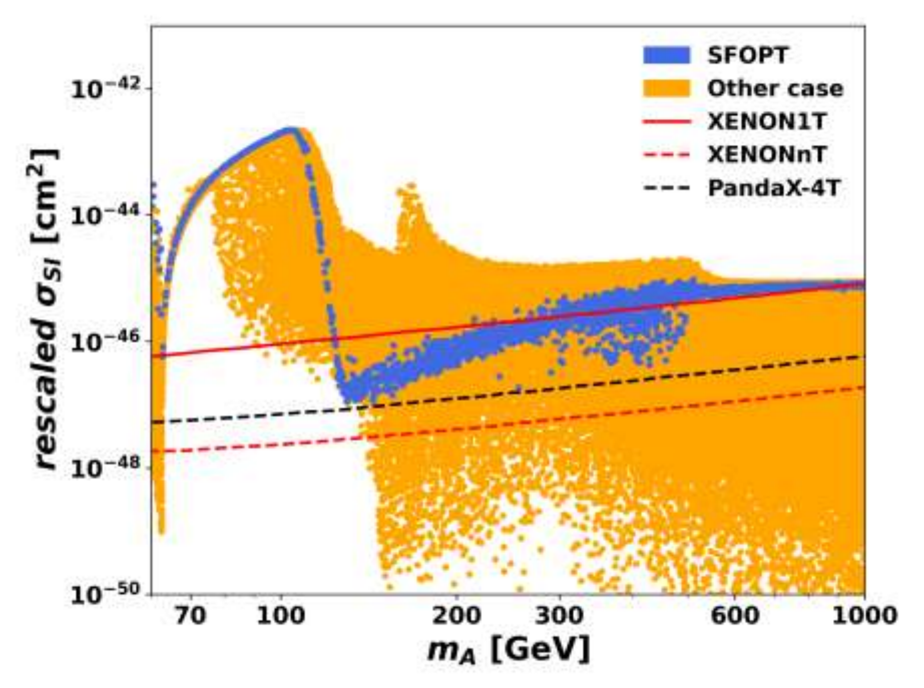
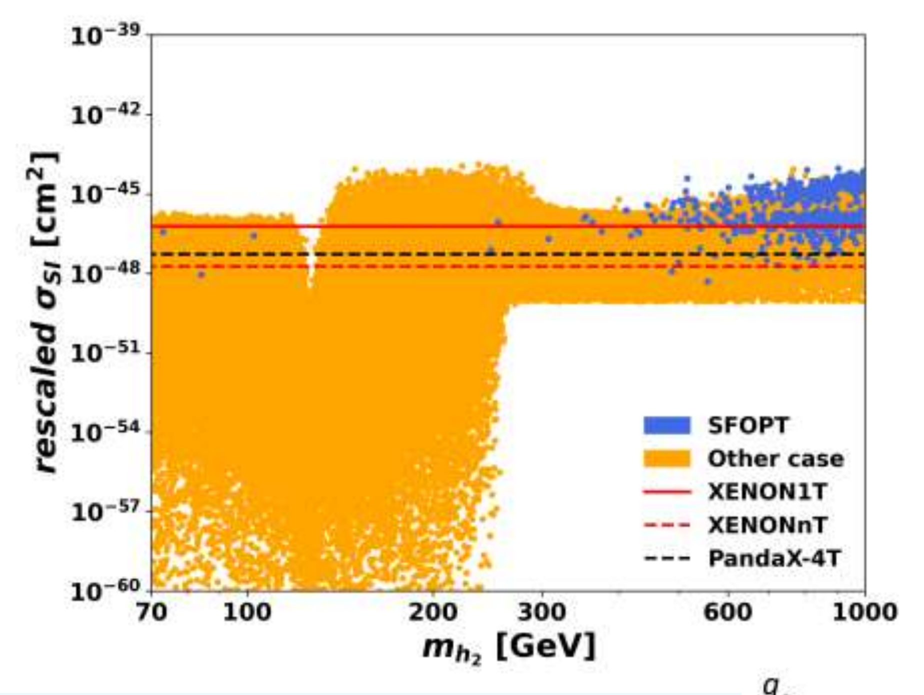
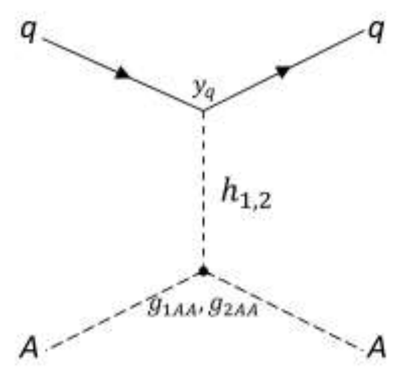


$62.5\text{GeV} < m_A \leq 1$ TeV



$m_A = 62.5\text{GeV}$



- $m_A = 62.5$ GeV: This case is almost excluded by the current DM direct detection.

→ LHC: Well-studied di-Higgs channel.

- $m_A > 62.5$ GeV: This case survives the current XENON1T constraints and can be mostly probed/exclued by the future XENONnT.

→ HL-LHC: New proposed channel.

cxSM: real singlet measurement at the (HL-)LHC

$$\mathcal{M}^2 = \begin{pmatrix} \frac{1}{2}\lambda v_0^2 & \frac{\delta_2}{2} v_0 v_s \\ \frac{\delta_2}{2} v_0 v_s & \frac{1}{2} d_2 v_s^2 - \frac{\sqrt{2} a_1}{v_s} \end{pmatrix} .$$

Di-Higgs	Ref.
$4b$	JHEP 01 (2019) 030, JHEP 08 (2018) 152
$bb\nu\bar{\nu}$	JHEP 04 (2019) 092, JHEP 01 (2018) 054
$bbl\nu l\bar{\nu}$	JHEP 01 (2018) 054
WW^*WW^*	JHEP 05 (2019) 124
$bb\tau\tau$	Phys.Rev.Lett. 122 (2019) 8, 089901, Phys.Lett.B 778 (2018) 101-127
$bb\gamma\gamma$	JHEP 11 (2018) 040, JHEP 11 (2018) 040
...	...

Di-Boson	Ref.
Semileptonic	Eur.Phys.J.C 80 (2020) 12, JHEP 03 (2018) 042
Hadronic	Phys.Lett.B 777 (2018) 91-113, JHEP 09 (2016) 173
Leptonic	Eur.Phys.J.C 78 (2018) 4, 293, Phys.Rev.D 98 (2018) 5 Eur.Phys.J.C 78 (2018) 1, 24
...	...

Di-Fermion	Ref.
$\tau\bar{\tau}$	Phys.Rev.Lett. 125 (2020) 5, JHEP 01 (2018) 055
$b\bar{b}$	Phys.Rev.D 102 (2020) 3
$t\bar{t}$	JHEP 07 (2023) 203
...	...

All channels are effective in probing the cxSM !

cxSM: real singlet measurement at the (HL-)LHC

$$\mathcal{M}^2 = \begin{pmatrix} \frac{1}{2}\lambda v_0^2 & \frac{\delta_2}{2} v_0 v_s \\ \frac{\delta_2}{2} v_0 v_s & \frac{1}{2} d_2 v_s^2 - \frac{\sqrt{2} a_1}{v_s} \end{pmatrix}.$$

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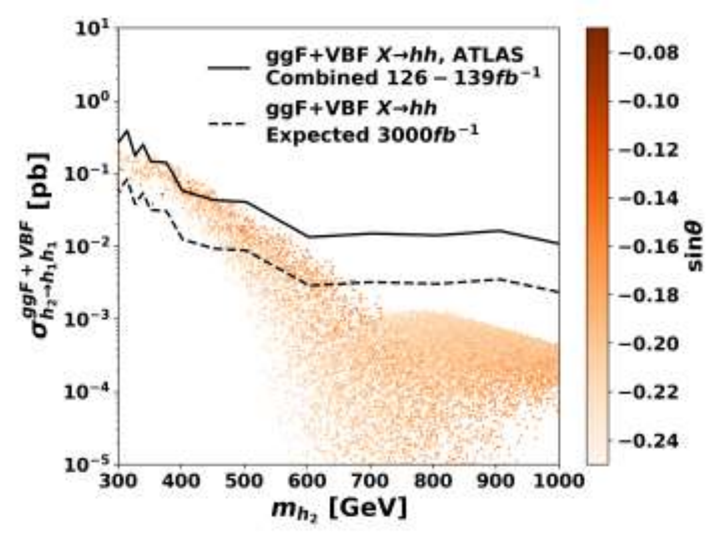
$\tau\bar{\tau}$	Phys.Rev.Lett. 125 (2020) 5, JHEP 01 (2018) 055
$b\bar{b}$	Phys.Rev.D 102 (2020) 3
$t\bar{t}$	JHEP 07 (2023) 203
...	...

If EWPT exists, why LHC haven't observed it?

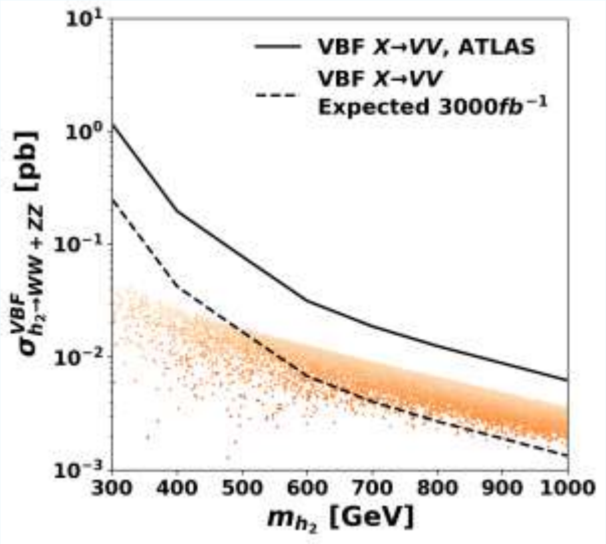
cxSM: real singlet measurement at the (HL-)LHC

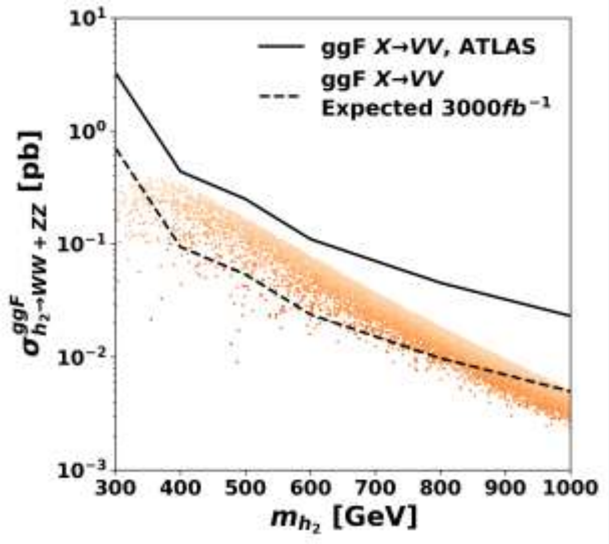


Di-Higgs: Cover significant portion in $m_{h_2} < 400$ GeV at 2σ C.L.

Well-studied

cxSM: real singlet measurement at the (HL-)LHC

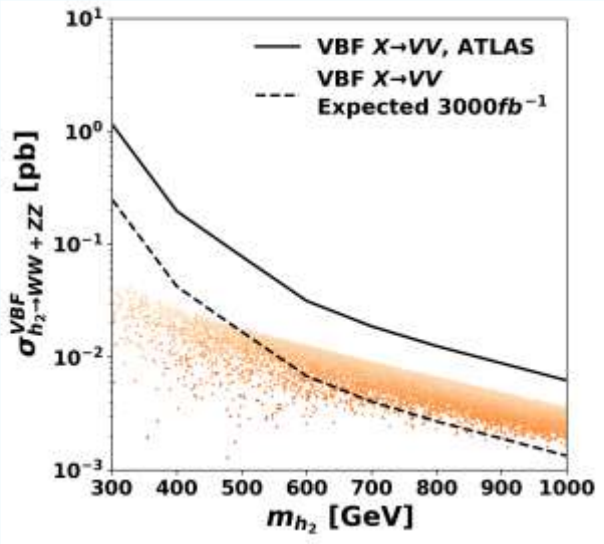


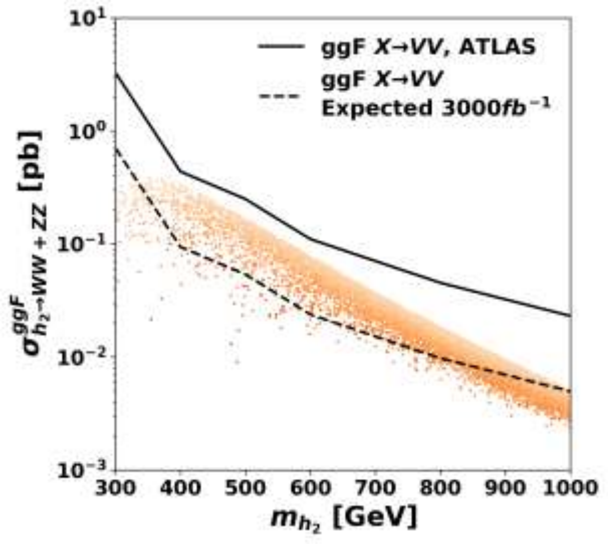


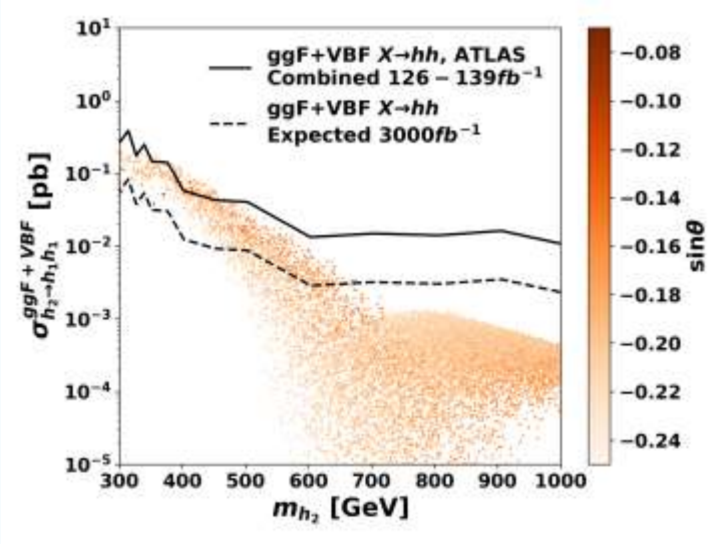
Di-Boson: Cover the whole space in $m_{h_2} > 600$ GeV at 2σ C.L.

Recently-studied

cxSM: real singlet measurement at the (HL-)LHC







Di-Boson: Cover the whole space in $m_{h_2} > 600$ GeV at 2σ C.L.

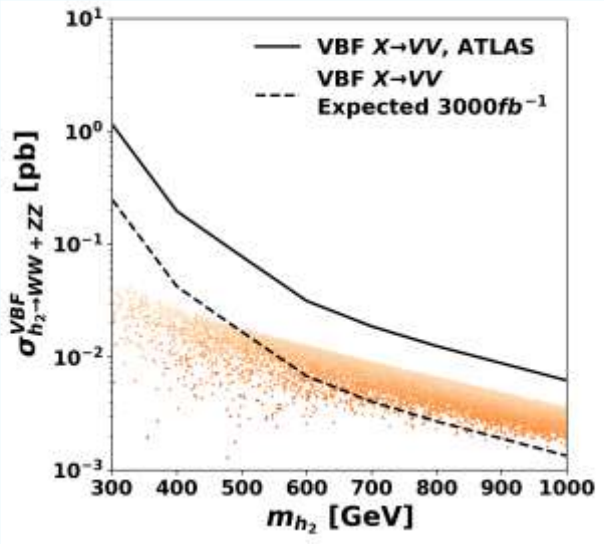
Recently-studied

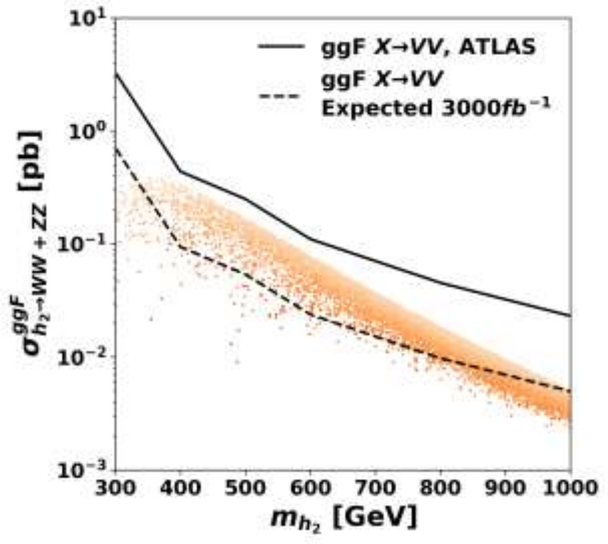
Di-Higgs: Cover significant portion in $m_{h_2} < 400$ GeV at 2σ C.L.

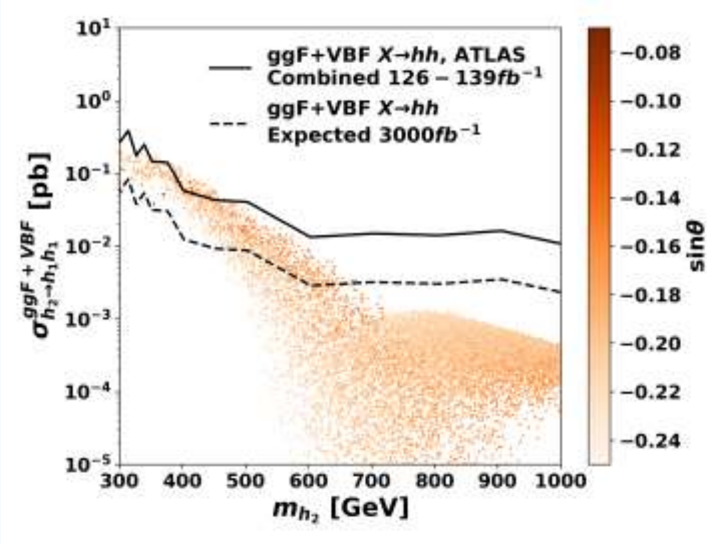
Well-studied

LHC Run2: Almost no exclusion ability!

cxSM: real singlet measurement at the (HL-)LHC





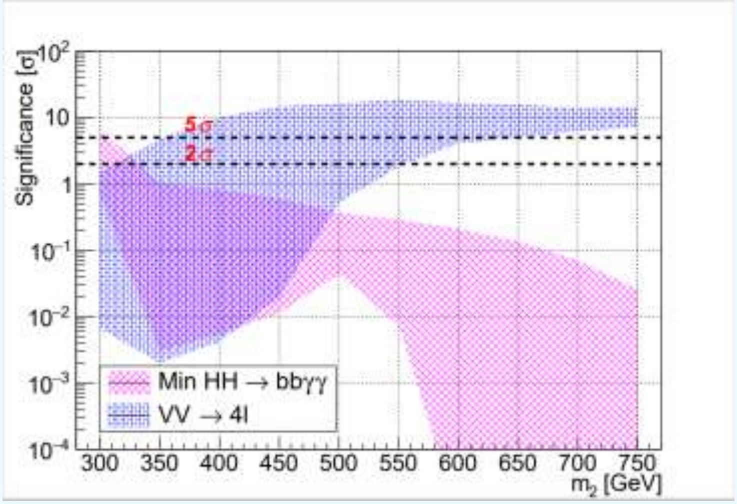


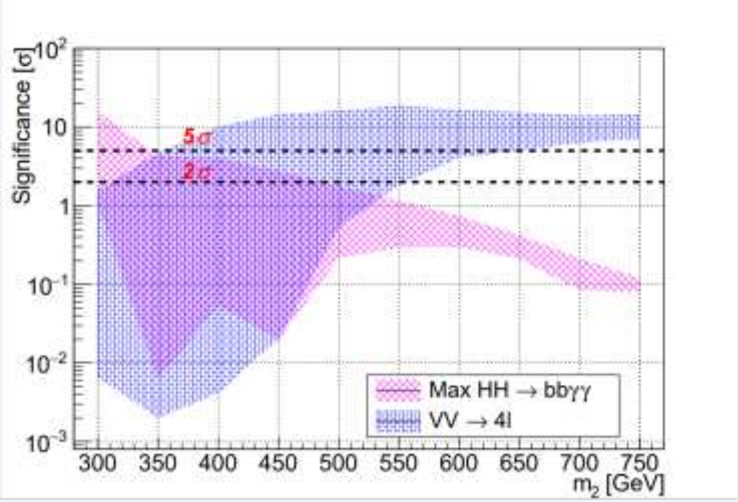
Model-independent phenomenon.

How about other model?
Are the results consistent?

cxSM: real singlet measurement at the (HL-)LHC

The real singlet standard model.





Di-Boson: Cover the whole space in $m_{h_2} > 600$ GeV at 5σ C.L.

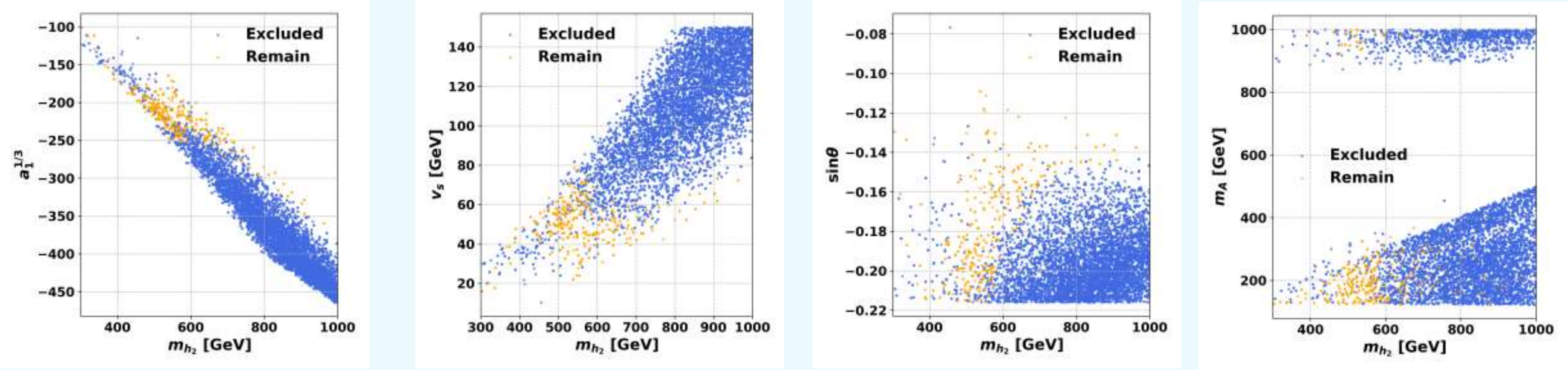
Recently-studied

Di-Higgs: Cover small portion in $m_{h_2} < 350$ GeV at 2σ C.L.

Well-studied

Consistent Result!

cxSM: real singlet measurement at the (HL-)LHC

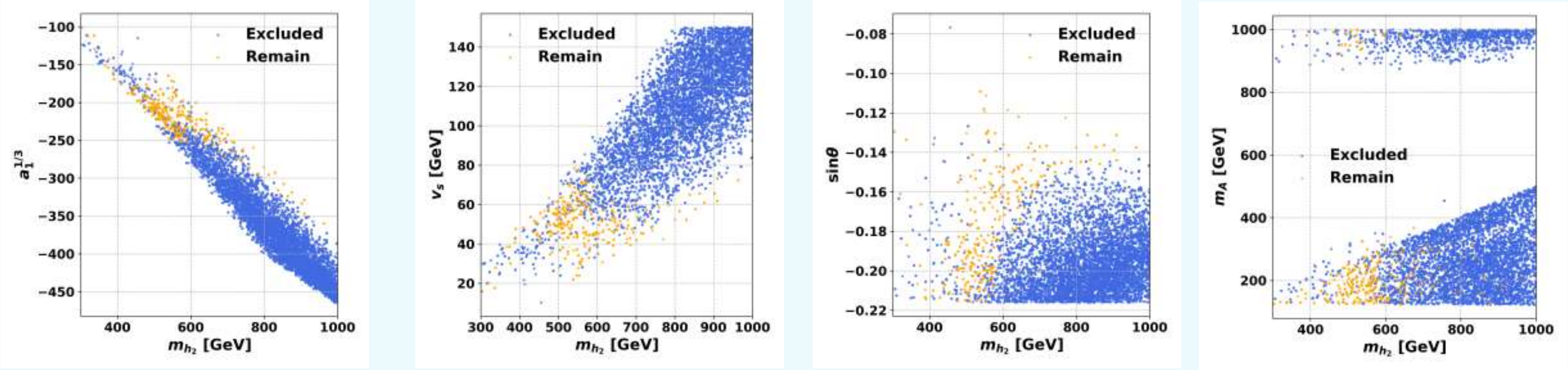


$$d_2 = \frac{2}{v_s^3}\left[m_{h_1}^2 v_s + (m_{h_2}^2 - m_{h_1}^2) v_s \cos^2\theta + \boxed{\sqrt{2}a_1}\right].$$

Linear-like relationship.

$$0 \leq d_2 \leq 8/3\pi$$

cxSM: real singlet measurement at the (HL-)LHC

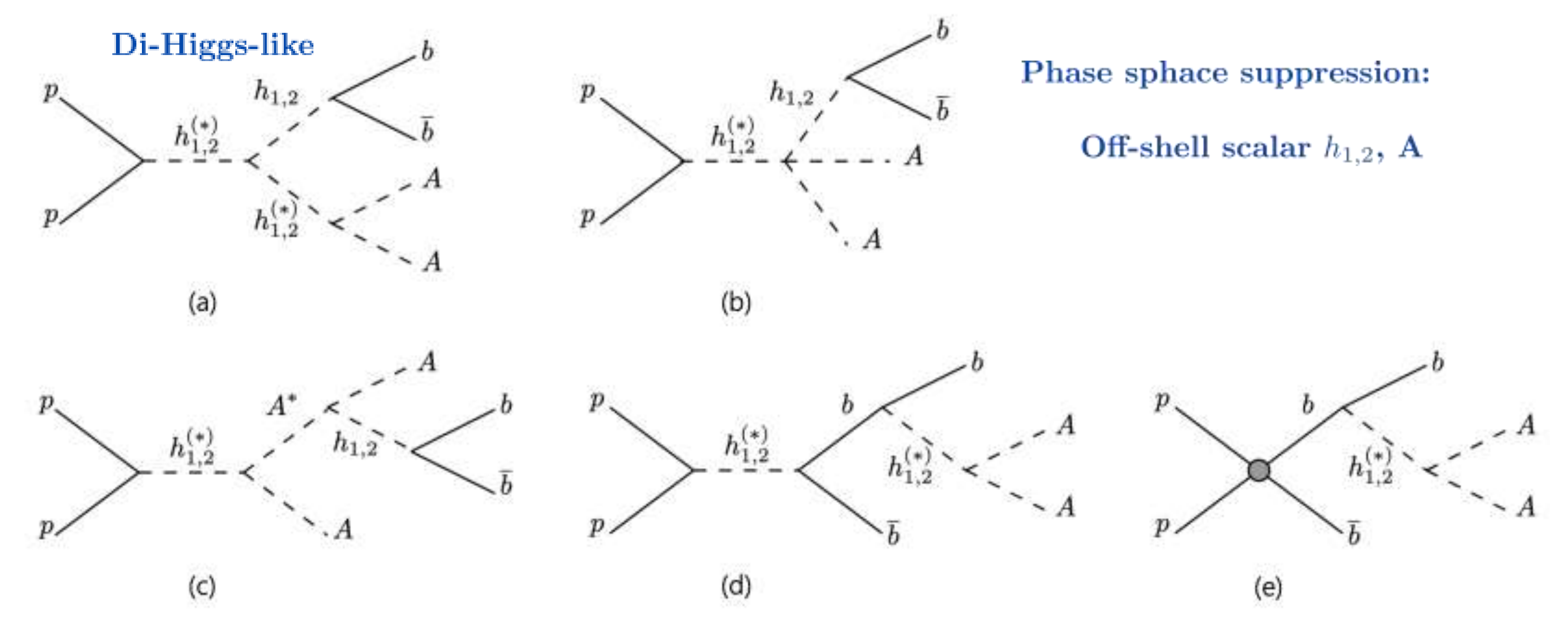


Heavy scalar resonance search cannot distinguish cxSM from xSM.

Heavy scalar resonance search cannot search for $m_{h_2} \sim 500$ GeV.

cxSM: Collider Searches via $b\bar{b}$+MET

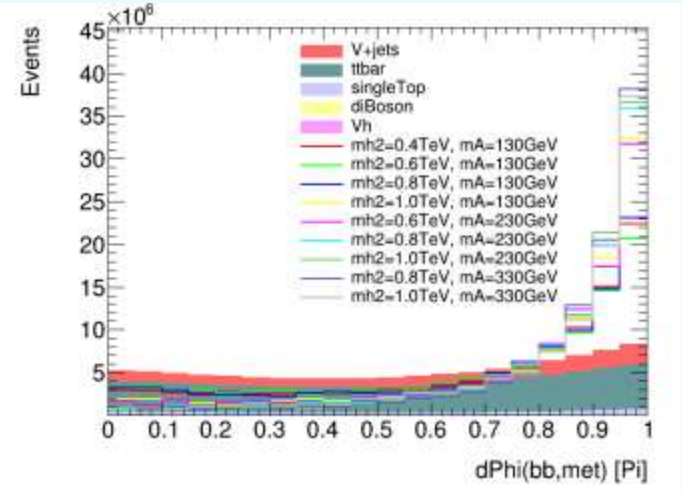
Can we distinguish cxSM from xSM? Whether the EWPT- and DM-viable cxSM can be probed by traditional heavy scalar resonance search?

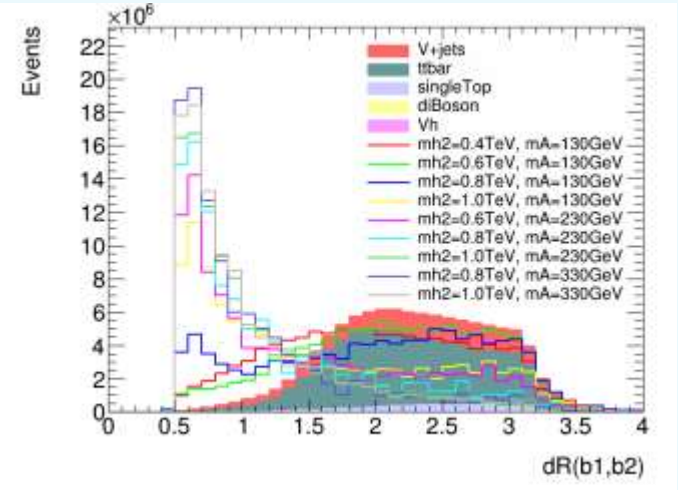


cxSM: Collider Searches via $b\bar{b}$+MET

	Process	σ (pb)	Generator
ttbar	$t\bar{t}$	493	Pythia8
single-top	tq	172	Pythia8
Vh	Wh	0.227	Pythia8
	Zh	0.0768	Pythia8
diboson	WZ	4.94	Pythia8
	ZZ	1.25	Pythia8
V+jets	$W+jets$	55.8	MG5_aMC
	$Z+jets$	218	MG5_aMC

m_A/GeV	130	130	130	130	230	230	230	330	330	430
m_{h_2}/GeV	400	600	800	1000	600	800	1000	800	1000	1000





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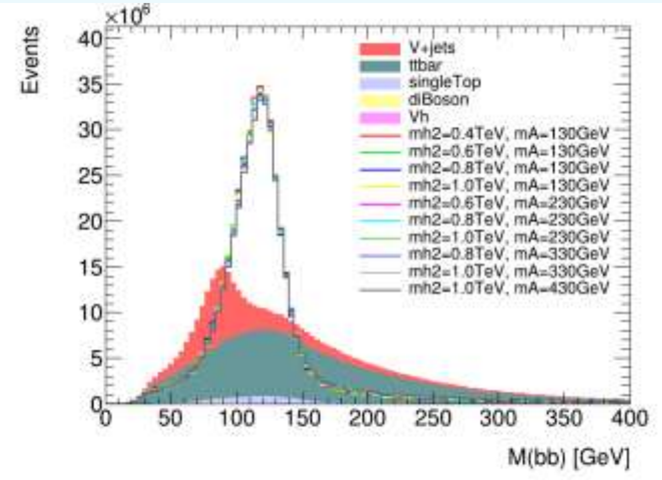
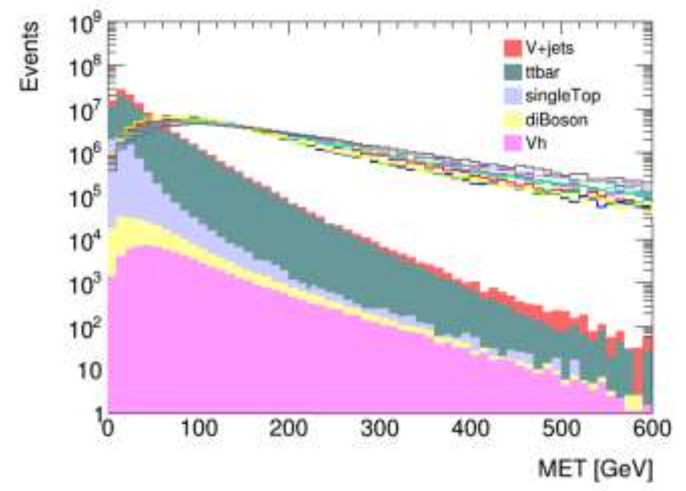
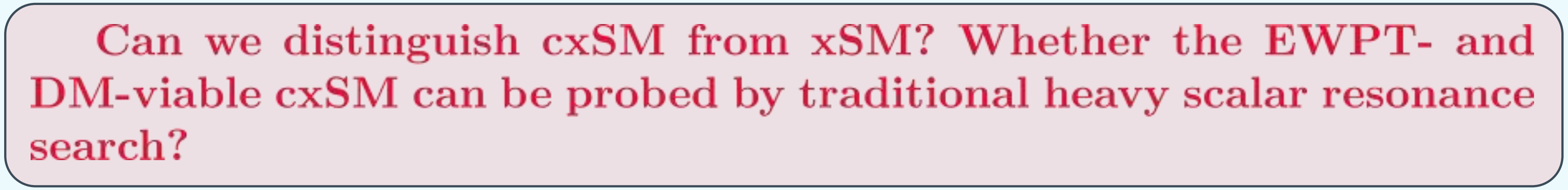




cxSM: Collider Searches via $b\bar{b}$+MET



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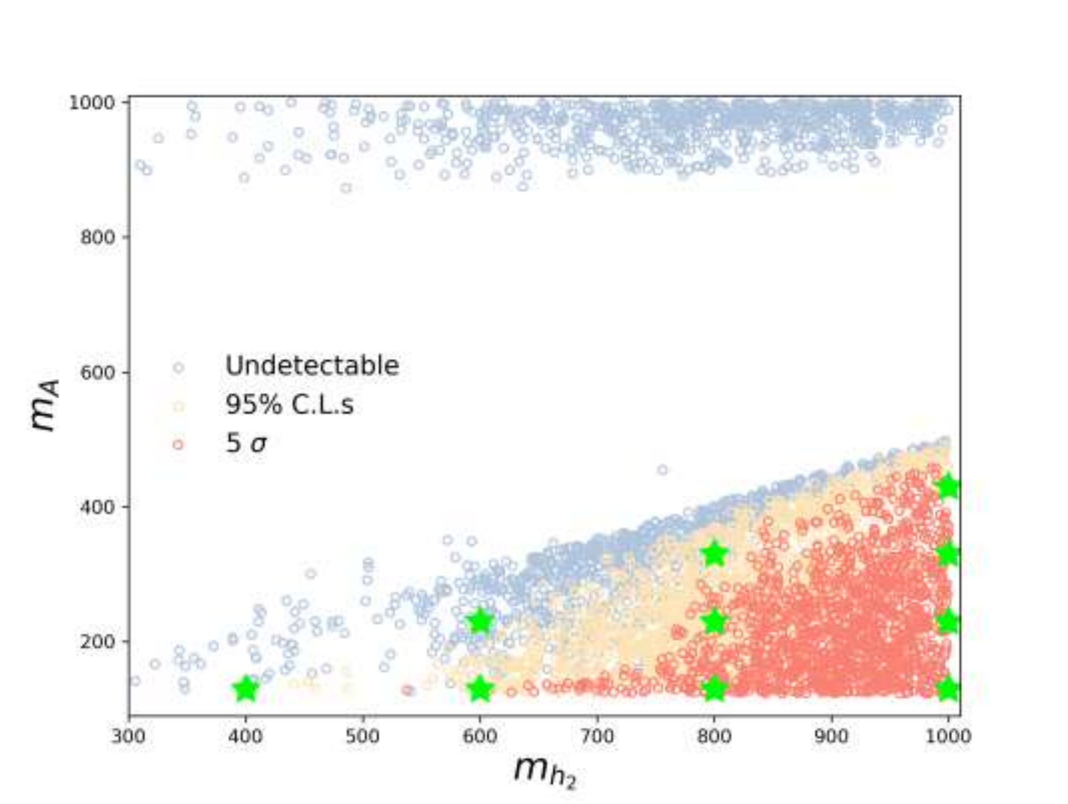

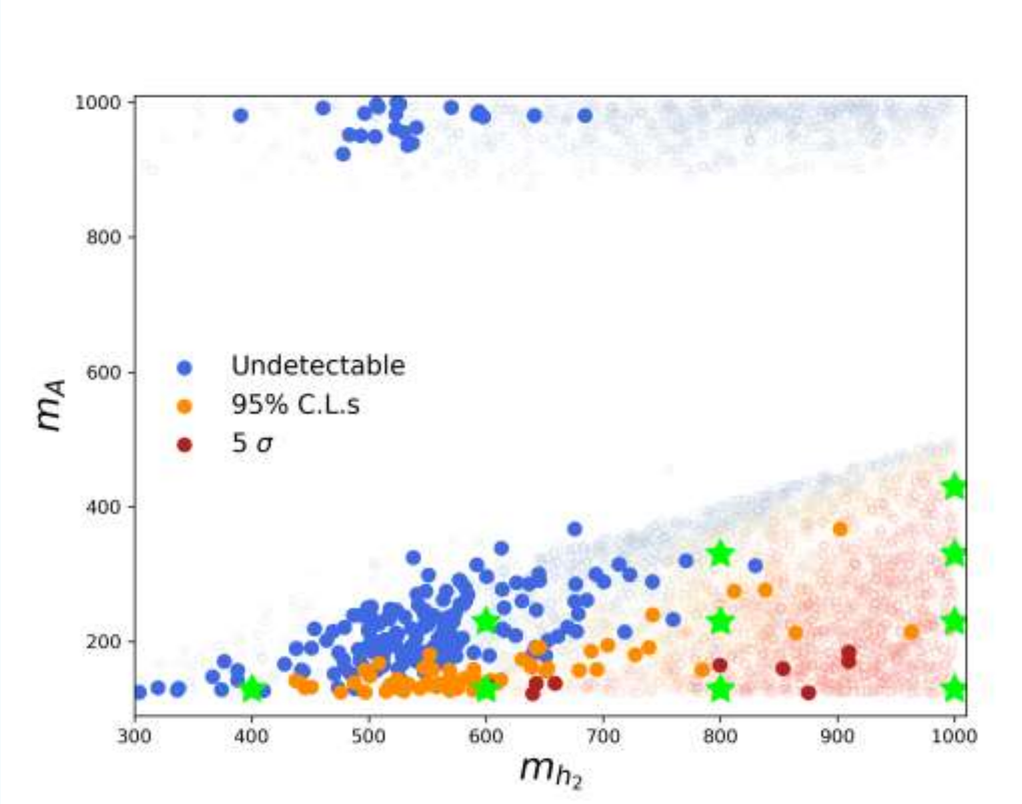

Summary

- In the SFOEWPT-viable scalar extended model, the heavy Higgs cannot be too heavy in order to generate a successful SFOEWPT.

- Heavy scalar resonance search can probe EWPT at colliders. The di-Higgs searches is powerful for smaller scalar mass($\sim 300 < m_{h_2} < 400$ GeV). **The recently studied powerful Channel, the di-boson channel, is possible to cover the heavy mass region ($m_{h_2} > 600$ GeV) at 5σ level.**

- For the h_2 between the effective region of di-Higgs and di-boson $m_{h_2} \sim 500$ GeV, a model-dependent phenomenon is needed.

- In the cxSM, the brand new search, $b\bar{b}$+MET is powerful in $m_{h_2} \sim 500$ GeV. Also, $b\bar{b}$+MET can differentiate cxSM from xSM.

- **What if no obvious excess observed at the HL-LHC?** –The answer may be: (1)Small mixing angle. We need Lattice to find these points. (2)Small singlet-like Higgs mass $m_{h_1} < 100$ GeV. We need lepton future colliders.