Revisiting the decoupling limit of the Georgi-Machacek model with a scalar singlet

Ref. JHEP10(2024)058

Authors: G. Belanger, J. Dutta R. M. Godbole, S. Kraml, M. Mitra, **RP**, A. Roy

Rojalin Padhan

Chung-Ang University, Seoul



OUT LINE

Model Review

Existing constraints

Dark Matter Phenomenology

Future prospects at HL-LHC

Summary

Georgi-Machacek (GM) Model

Exact nature of EW symmetry breaking:

[Georgi & Machacek] [Chanowitz & Golden]

Does any exotic scalar participate?

SM Higgs

$$\Phi = \begin{bmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{-} & \phi^{0} \end{bmatrix}$$

2 triplets Higgs in a Bi-triplet

$$X = \begin{bmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & -\xi^{-} & \chi^{0} \end{bmatrix}$$

Complex scalar Y=2

Real scalar Y=0

- **EW symmetry breaking:** $\langle \Phi \rangle = \frac{v_\phi}{\sqrt{2}} I_{2\times 2}, \quad \langle X \rangle = v_\chi I_{3\times 3}$
- $(SU(2)_L \times SU(2)_R \to SU(2)_V)$
- $\langle \xi^0 \rangle = \langle \chi^0 \rangle = v_\chi$, **necessary to ensure** $\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$, **Custodial** $SU(2)_V$ **at tree level**
- $v^2 = v_\phi^2 + 8v_\chi^2 \simeq 246\ GeV$
- **Contribution of triplets to EW symmetry breaking can be directly measured via** $\chi^{++}W^-W^-$ **coupling**

Scalar potential

$$
\begin{aligned}
V(\Phi, X) = & \frac{\mu_2^2}{2}\mathrm{Tr}\left[\Phi^\dagger\Phi\right] + \frac{\mu_3^2}{2}\mathrm{Tr}\left[X^\dagger X\right] + \lambda_1\left(\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\right)^2 \\
& + \lambda_2\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\mathrm{Tr}\left[X^\dagger X\right] + \lambda_3\mathrm{Tr}\left[X^\dagger X X^\dagger X\right] \\
& + \lambda_4\left(\mathrm{Tr}\left[X^\dagger X\right]\right)^2 - \lambda_5\mathrm{Tr}\left[\Phi^\dagger\tau^a\Phi\tau^b\right]\mathrm{Tr}\left[X^\dagger t^a X t^b\right] \\
& - M_1\mathrm{Tr}\left[\Phi^\dagger\tau^a\Phi\tau^b\right]\left(UXU^\dagger\right)_{ab} - M_2\mathrm{Tr}\left[X^\dagger t^a X t^b\right]\left(UXU^\dagger\right)_{ab}
\end{aligned}
$$

[Aoki & Kanemura]

[Chiang & Yagyu]

[Hartling, Kumar & Logan]

- **mixing between $SU(2)_L$ doublet and triplet:** $c_H \equiv \cos\theta_H = \dfrac{v_\phi}{v}, \quad s_H \equiv \sin\theta_H = \dfrac{2\sqrt{2}v_\chi}{v}$
- **10 physical scalars: Custodial fiveplet $\{H_5^{\pm\pm}, H_5^{\pm}, H_5^0\}$, triplet $\{H_3^{\pm}, H_3^0\}$, singlets $\{h, H\}$**
- **Mixing between two Custodial singlets:** $\sin_\alpha$
- **members in the same Custodial multiplet have same mass**

$$
M_{H_5}^2 = \frac{M_1}{4v_\chi}v_\phi^2 + 12M_2v_\chi + \frac{3}{2}\lambda_5 v_\phi^2 + 8\lambda_3 v_\chi^2, \qquad M_{H_3}^2 = \left(\frac{M_1}{4v_\chi} + \frac{\lambda_5}{2}\right)v^2
$$

$v_\chi \leq 1$ GeV (decoupling limit)

$$\lambda_2 = \frac{1}{6v^2 s_H c_H}\left[\frac{\sqrt{6}}{2} s_{2\alpha}(M_h^2 - M_H^2) + 3 s_H c_H (2M_{H_3}^2 - \widetilde{M_1^2})\right],$$

$$\lambda_3 = \frac{1}{v^2 s_H^2}\left[c_H^2(2\widetilde{M_1^2} - 3M_{H_3}^2) + M_{H_5}^2 - M^2\right],$$

$$\lambda_4 = \frac{1}{6v^2 s_H^2}\left[2M_H^2 c_\alpha^2 + 2M_h^2 s_\alpha^2 + 3M^2 - 2M_{H_5}^2 + 6c_H^2(M_{H_3}^2 - \widetilde{M_1^2})\right],$$

[Hartling, Kumar & Logan]

For $s_H \to 0$, $\lambda_{2,4}$ diverge, which can be avoided by $\sin_\alpha = 0$

[Chiang & Yagyu]

$$\lambda_1 = \frac{M_h^2}{8v^2 c_H^2}, \lambda_2 = \frac{M_{H_3}^2 + M_{H_5}^2 - M^2}{4v^2}, \lambda_3 = \frac{M_{H_5}^2 - M^2}{v^2},$$

$$\lambda_4 = \frac{M_{H_3}^2 - M_{H_5}^2 + M^2 + \overline{M}^2}{2v^2} \quad \lambda_5 = \frac{-(M_{H_3}^2 - M_{H_5}^2 + M^2)}{v^2}$$

$M^2 \equiv 3\sqrt{2} s_H v M_2$

- **Mass of CP-even BSM Higgs** *(no longer a free parameter)*

$$M_H^2 = \frac{1}{2}\left(3M_{H_3}^2 - M_{H_5}^2 + 3s_H^2 \overline{M}^2\right)$$

Extension of GM model

❖ DM Candidate

[Campbell,Godfrey, Logan & Poulin]

GM Model + Real singlet scalar (S)

→ *Z_2 symmetry ensure DM stability*

$$V(S) = \frac{\mu_S^2}{2} S^2 + \lambda_a S^2 \,\mathrm{Tr}\left(\Phi^\dagger \Phi\right) + \lambda_b S^2 \,\mathrm{Tr}\left[X^\dagger X\right] + \lambda_S S^4$$

Extra annihilation channels of DM into BSM scalar via λ_b

❖ Neutrino Mass

[Chiang & Yagyu]

Via LNV coupling of triplet scalar with $Y = 2$

$$\mathscr{L}_\nu = Y_\nu \bar{L}^c i\tau_2 \chi L + \mathrm{h.c.} \longrightarrow m_\nu = Y_\nu v_\chi$$

Y_ν allows interactions of fiveplet scalars with SM leptons which is absent in the original GM model

Theoretical constraints

❖**Perturbative unitarity** [Campbell,Godfrey, Logan & Poulin]

❖**Potential bounded from below**

❖$M_H \geq 130\ GeV$

❖ **Oblique parameters**

❖$\Gamma(H_i)/M_{H_i} \leq 0.5$

- *No strong bound from vacuum stability and oblique parameter*

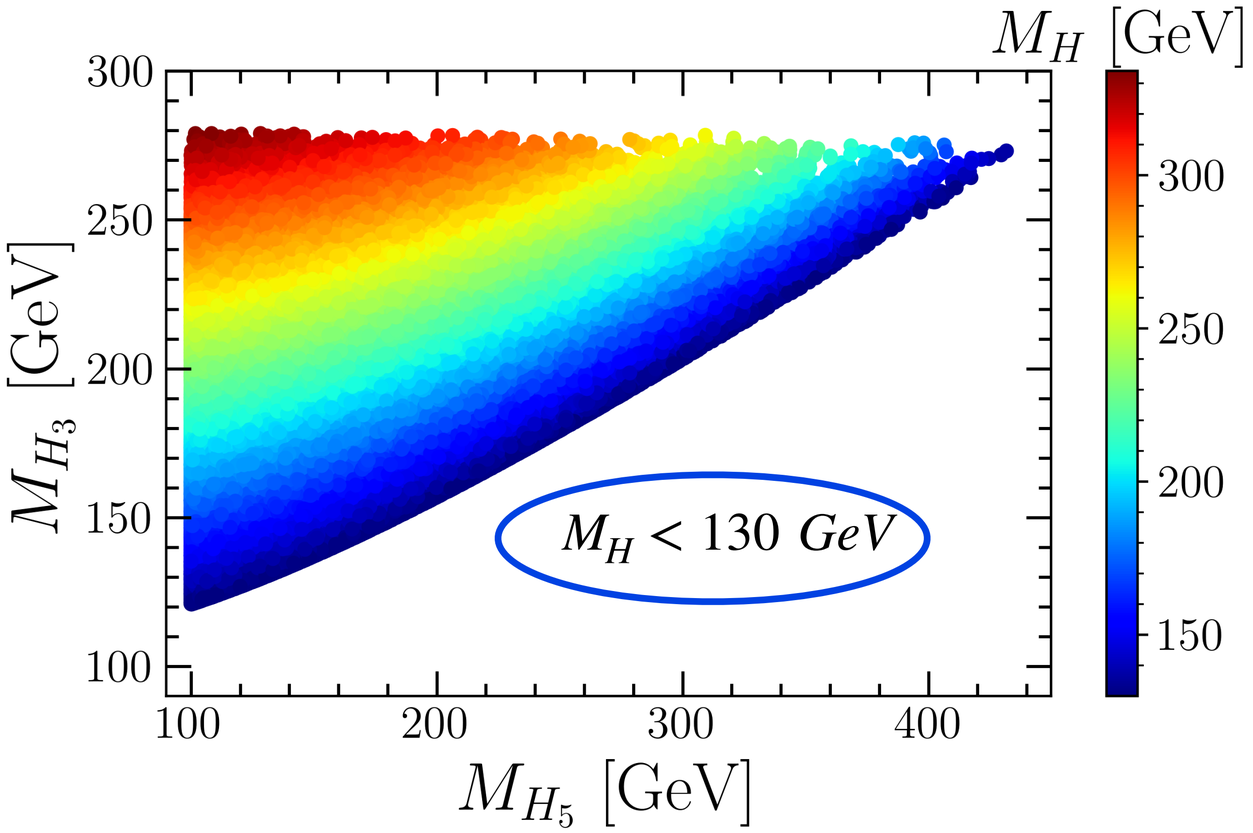
✓ All constraints are checked one-by-one in a cumulative manner

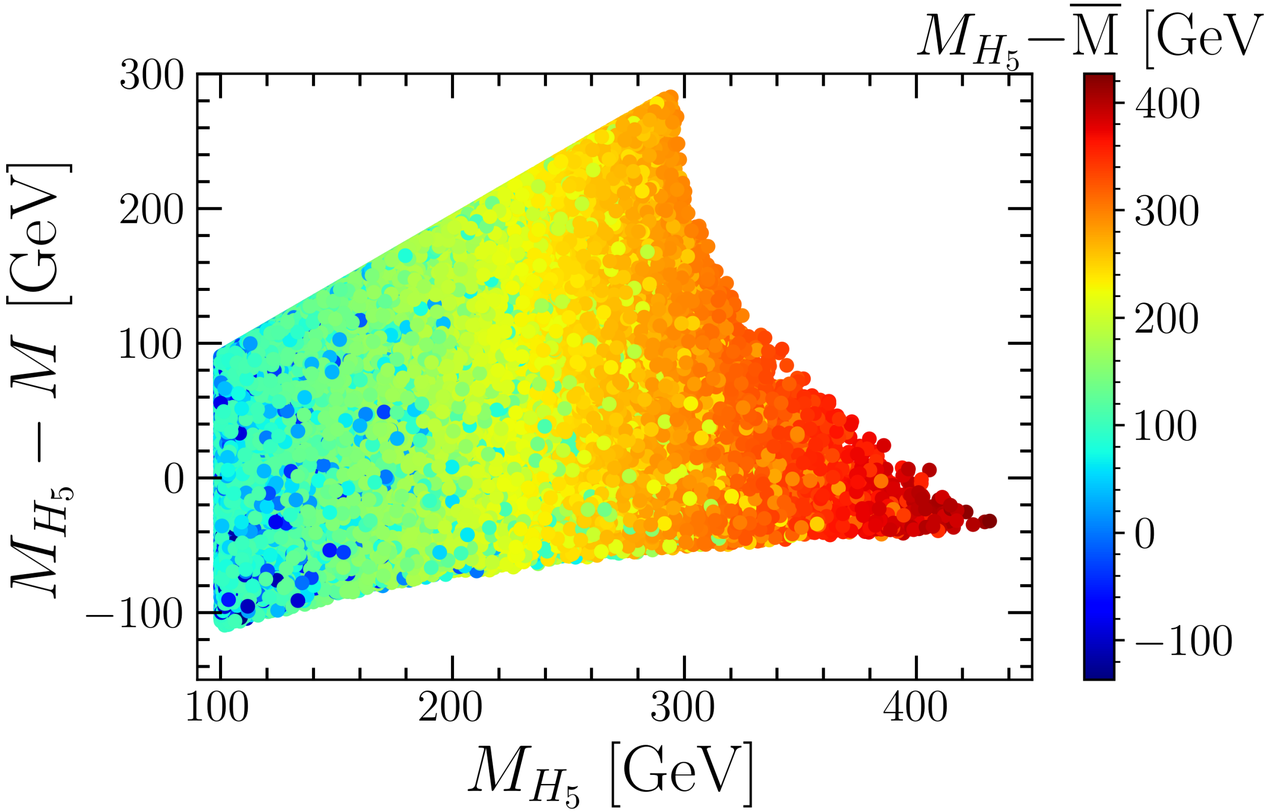
Free parameters

M_{H_3} [GeV]	$[10^2, 10^3]$	GM sector
M_{H_5} [GeV]	$[10^2, 10^3]$	
M [GeV]	$[10^1, 10^3]$	
$\overline{M}$ [GeV]	$[10^1, 10^6]$	
v_χ [GeV]	$[10^{-4}, 10^0]$	
$\lambda_a, \lambda_b, \lambda_S$	$[10^{-4}, 10^0]$	DM sector
M_S [GeV]	$[10^2, 10^3]$	

- $M_H > 130$ **GeV exclude a large region**
- **Perturbative unitarity set strong limit**

$\rightarrow M_{H_3} > 280$ GeV, $M_{H_5} > 435$ GeV





❖TeV scale scalar not allowed

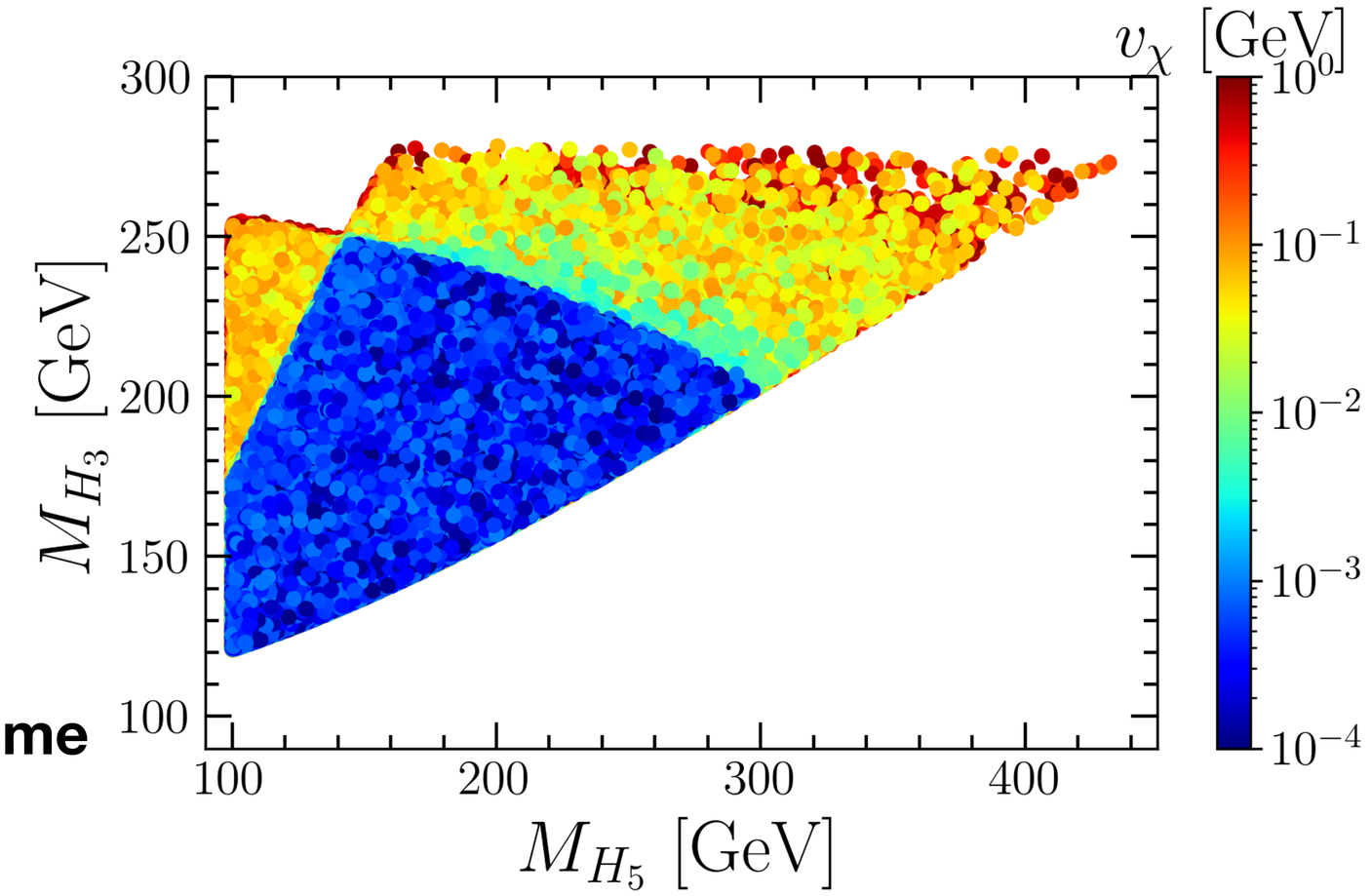
- **Trilinear scalar coupling has a term** M^2/v_χ

  → large Γ/M **for** H and H_5^0 **via**

  $H_i \to H_j H_j, H_i \to \gamma\gamma/Z\gamma$

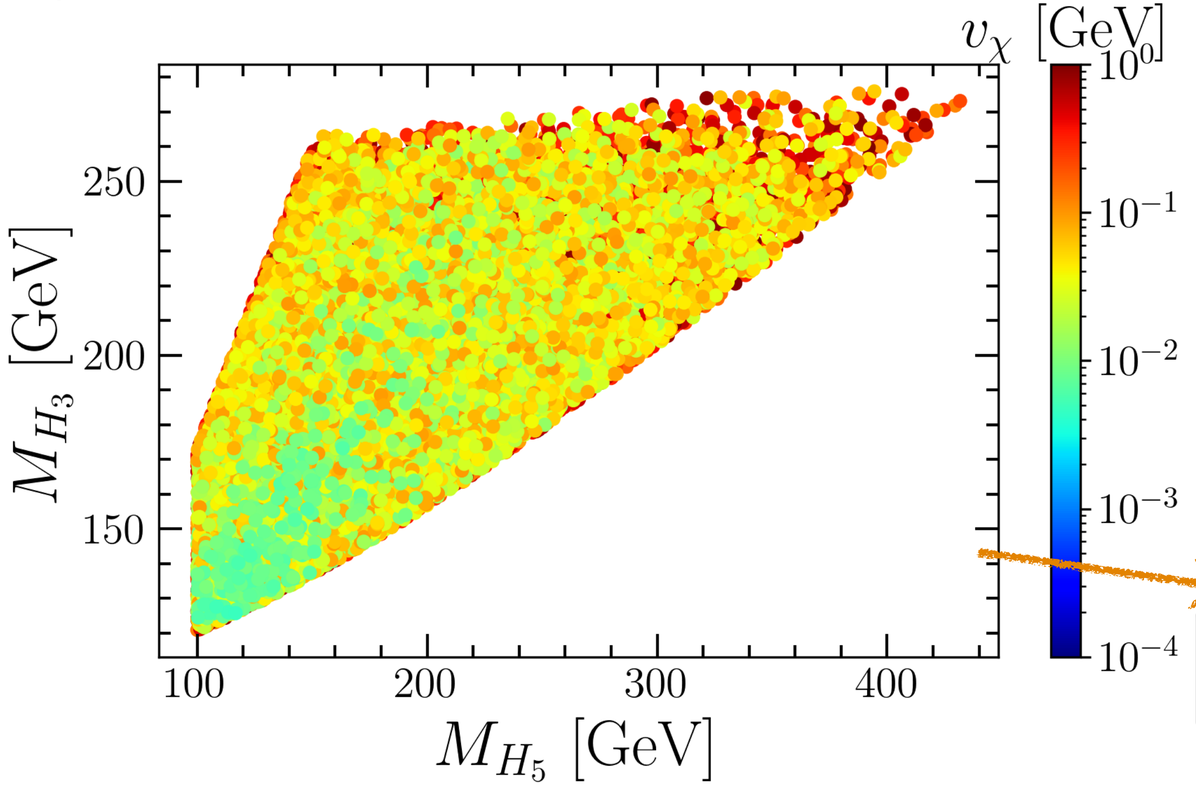
$$C_{H_5^{++}H_5^{--}H_5^0} = 2v_\chi \frac{(M_{H_5}^2 - M^2)}{v^2} - \frac{M^2}{12v_\chi}$$

- **Small** v_χ **or large** M **excluded in some parameter space**

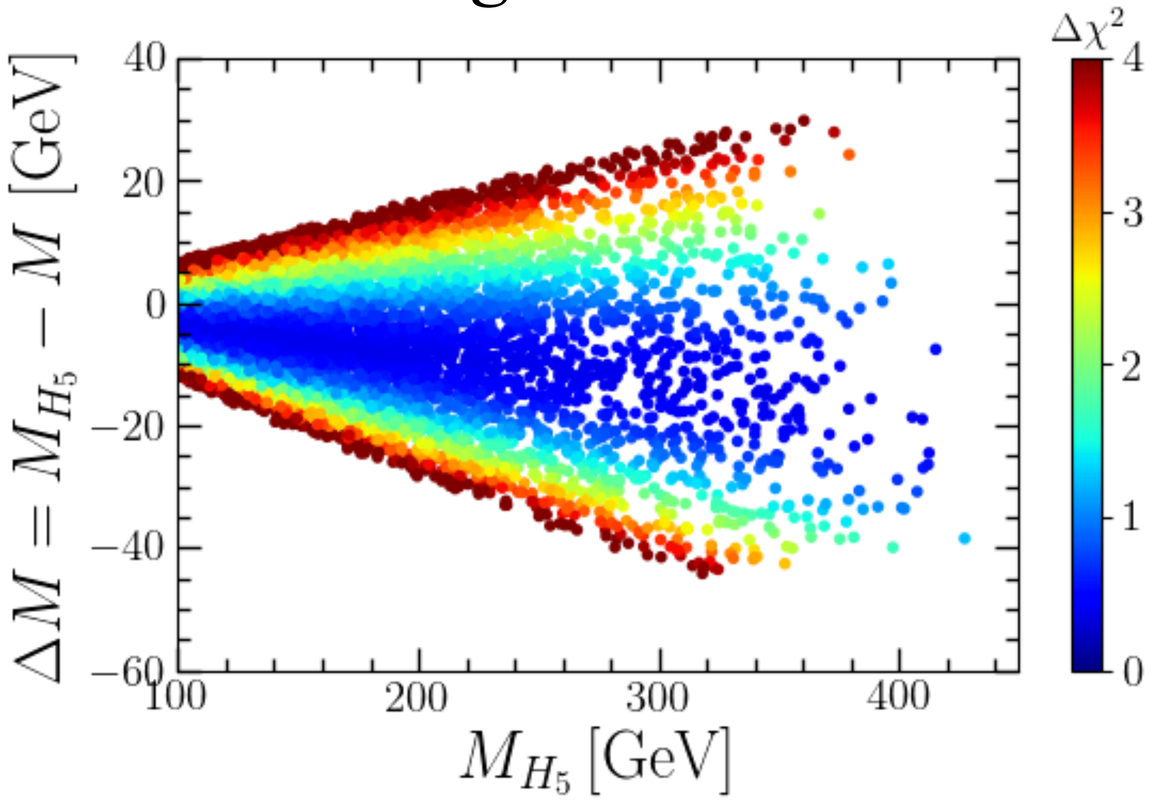


Exp. constraints : $h \to \gamma\gamma$

- $h \to \gamma\gamma$ **signal strength** $\mu_{\rm ATLAS} = 1.04^{+0.1}_{-0.09}$, $\mu_{\rm CMS} = 1.12 \pm 0.0$ [ATLAS] [CMS]
- $\mu_{h\to\gamma\gamma} = \dfrac{\sigma_h \times BR(h \to \gamma\gamma)}{\sigma_h^{SM} \times BR^{SM}(h \to \gamma\gamma)}$
- $H_5^{\pm\pm}, H_5^{\pm}, H_3^{\pm}$ **mediate** $h \to \gamma\gamma$ **via loop**
- $C_{H_5^+ H_5^- h} \sim (M_{H_5}^2 - M^2)$



Strong limit on ΔM



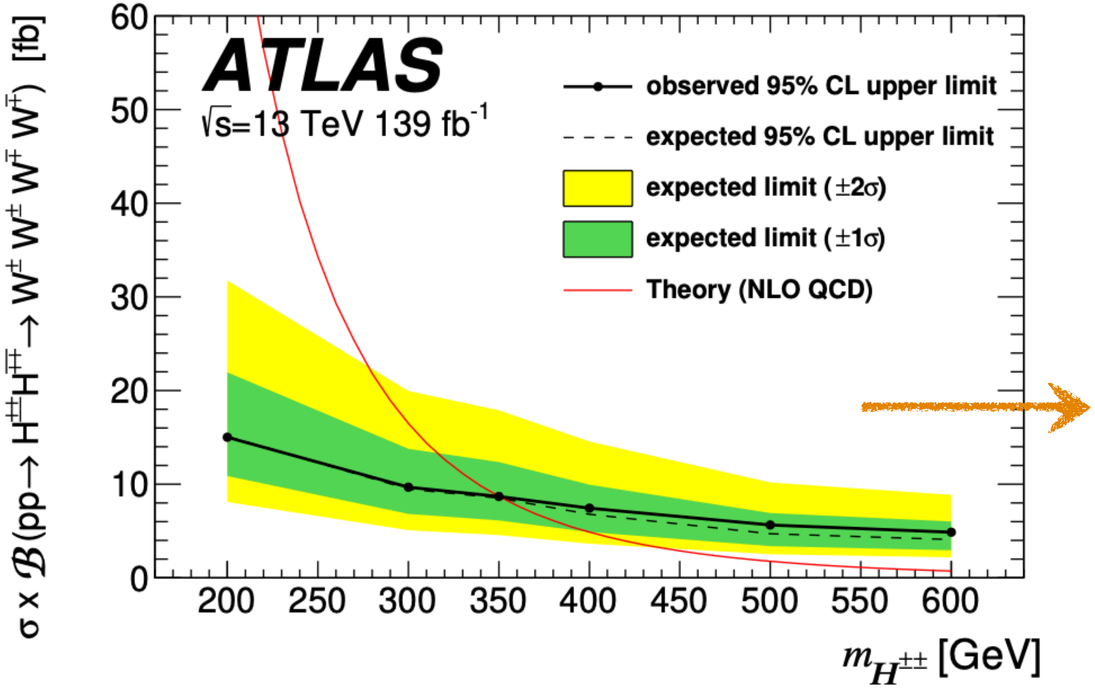
$v_\chi < 4.8 \times 10^{-3}$ GeV not allowed

Limit from $H_5^{\pm\pm} \to W^{\pm}W^{\pm}$ search

[ATLAS]

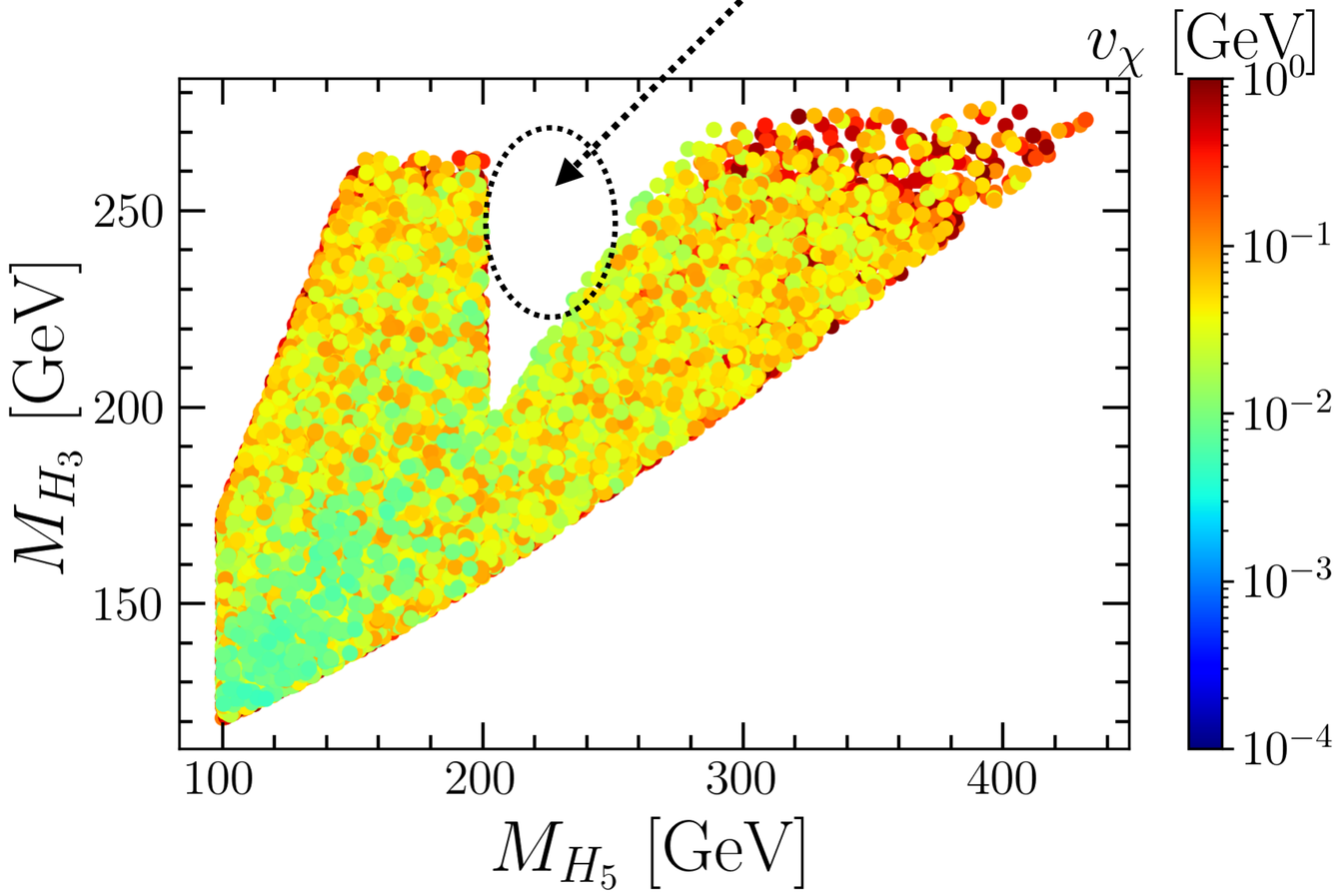
- **ATLAS search for**

$$pp \to H_5^{\pm\pm}H_5^{\mp\mp},\ H_5^{\pm\pm} \to W^{\pm}W^{\pm},\ W^{\pm} \to \ell^{\pm}\nu$$



$$Br(H_5^{\pm\pm} \to W^{\pm}W^{\pm}) \sim 1$$

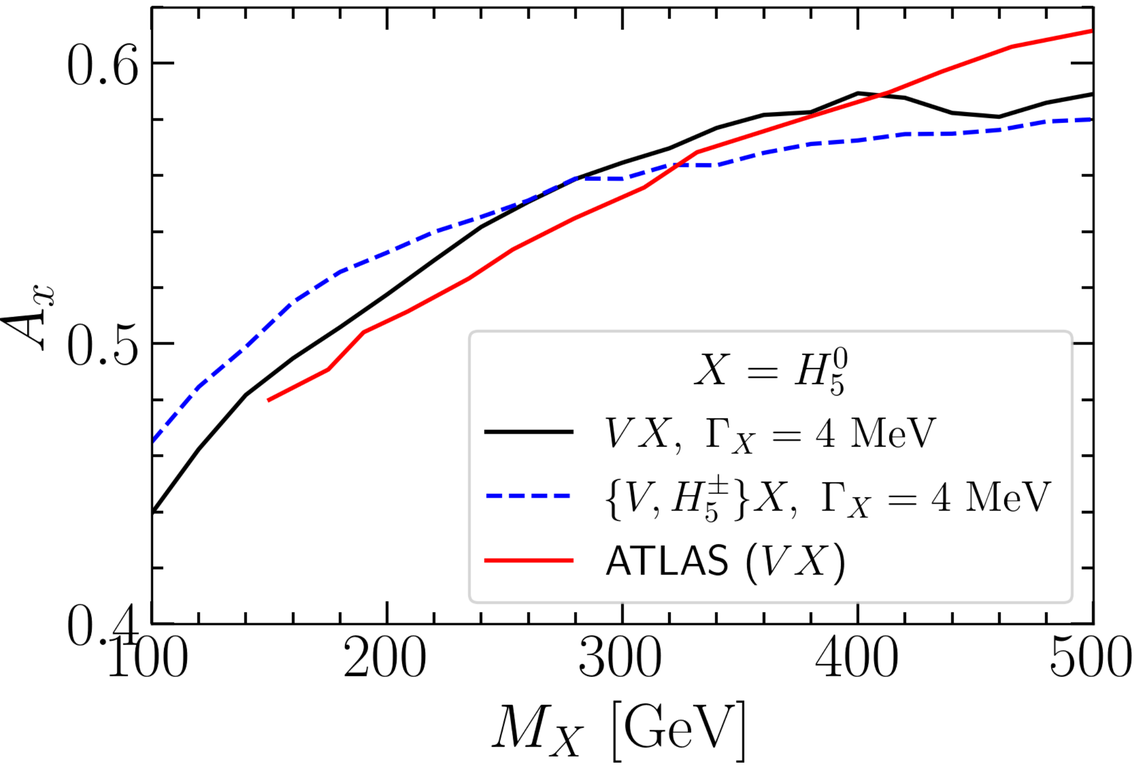
$H_5^{\pm\pm} \to W^{\pm}H_3^{\pm}/W^{\pm\star}H_3^{\pm}$ **closed or suppressed**

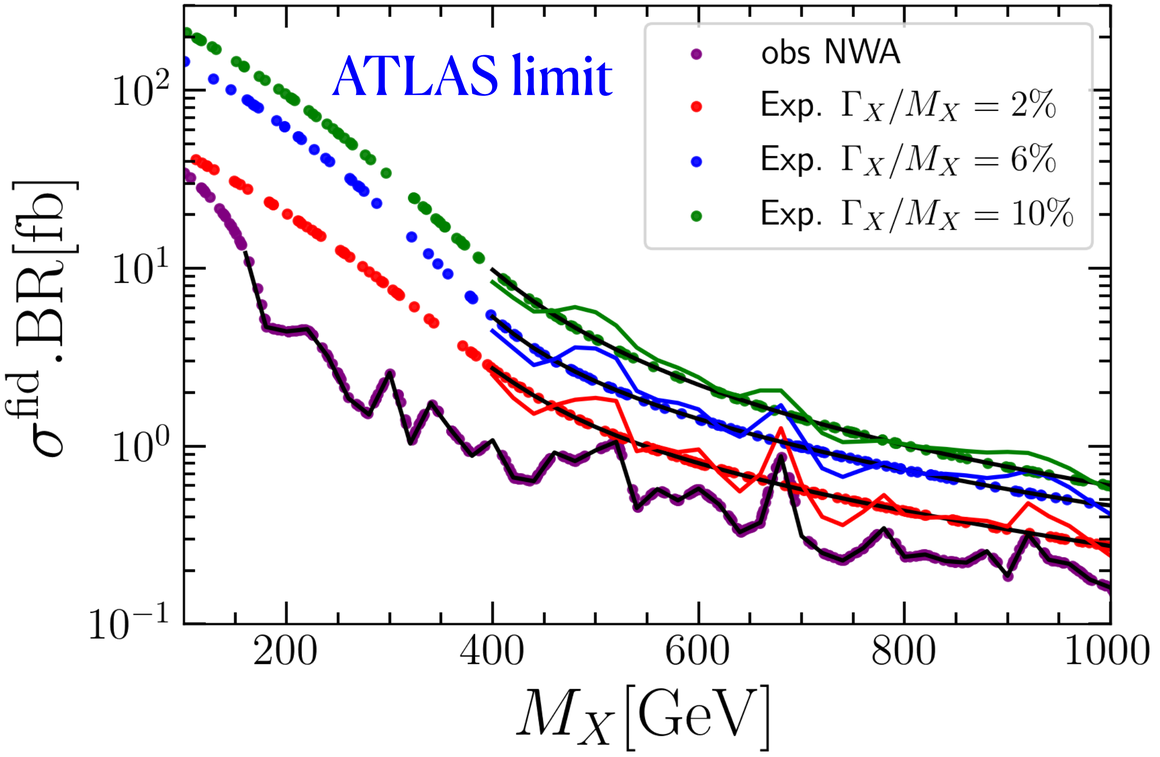


Limit from $H_5^0 \to \gamma\gamma$

- **ATLAS searched for spin-0 BSM resonances in the diphoton final state** [ATLAS]
- $pp \to H_5^0 + \{V, H_5^\pm, H_3^0, H_3^\pm\}$ **where** $H_5^0 H_5^\pm$ **is leading channel**
- $H_5^0 \to \gamma\gamma, H \to \gamma\gamma$ **via loop depend on** M^2/v_χ

Diphoton selection cut efficiency

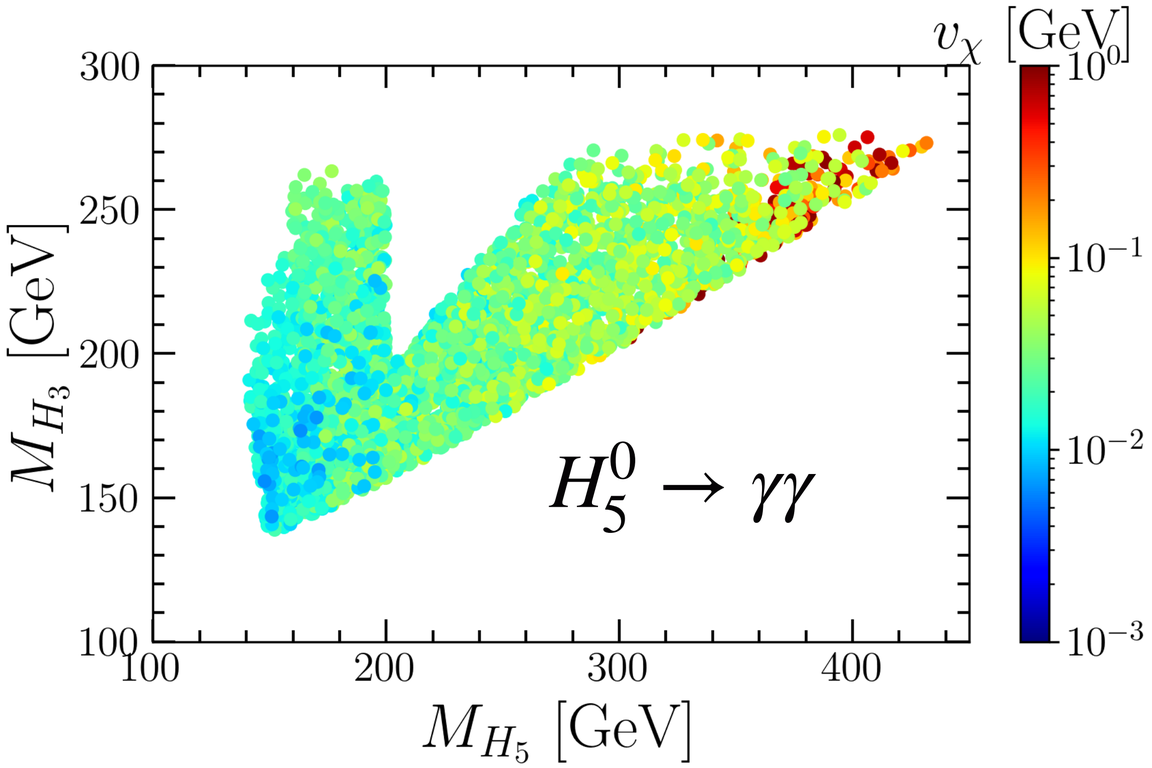


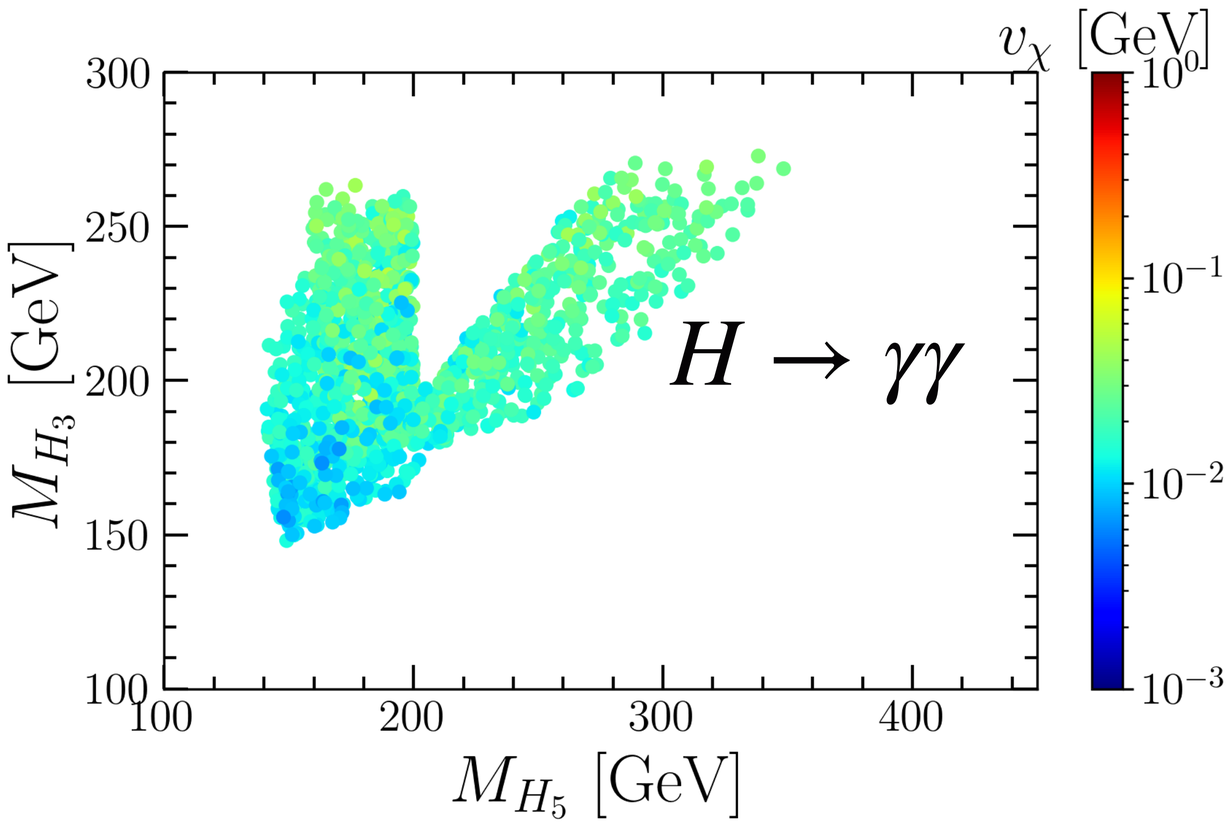


Observed limit is stronger for narrow resonance

[Tools used for simulation: FeynRules, MadGraph5, Pythia8]

Higher v_χ strongly constrained as H_5^0 (*or* H) is a narrow resonance for which obs. limit is stronger.





- $v_\chi > 0.05\ GeV$ **is excluded**

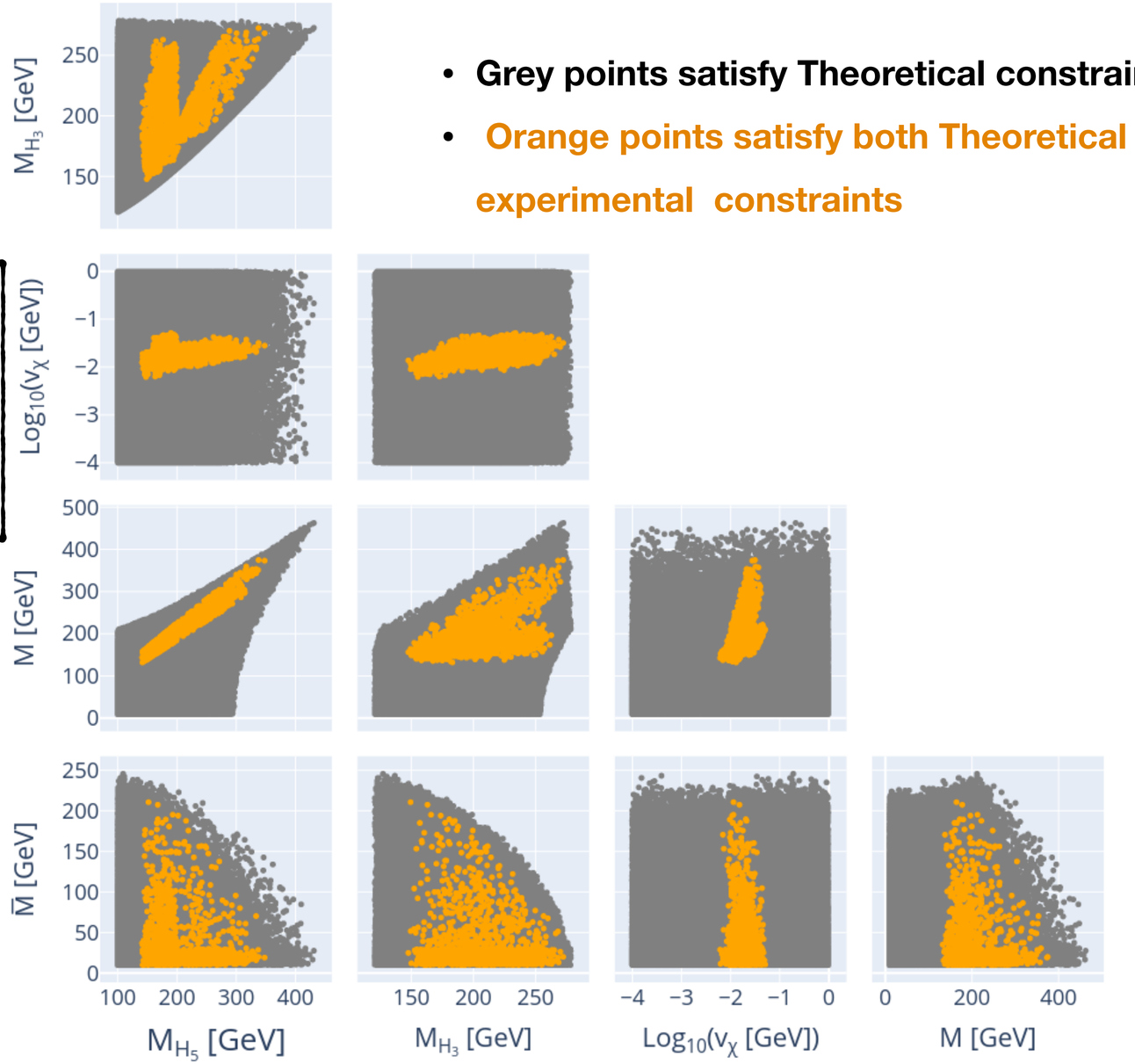
After all bounds

Final allowed range

- $M_{H_5} < 350\ GeV,\ 145 < M_H < 300\ GeV$
- $150\ GeV < M_{H_3} < 270\ GeV$
- $4.8 \times 10^{-3}\ GeV < v_\chi < 0.05\ GeV$

- *No bound on DM sector parameters at this stage*

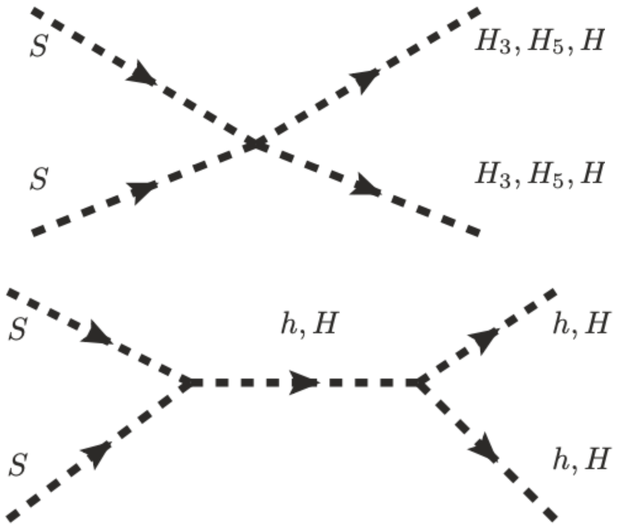
- **Grey points satisfy Theoretical constraints**
- **Orange points satisfy both Theoretical + experimental constraints**

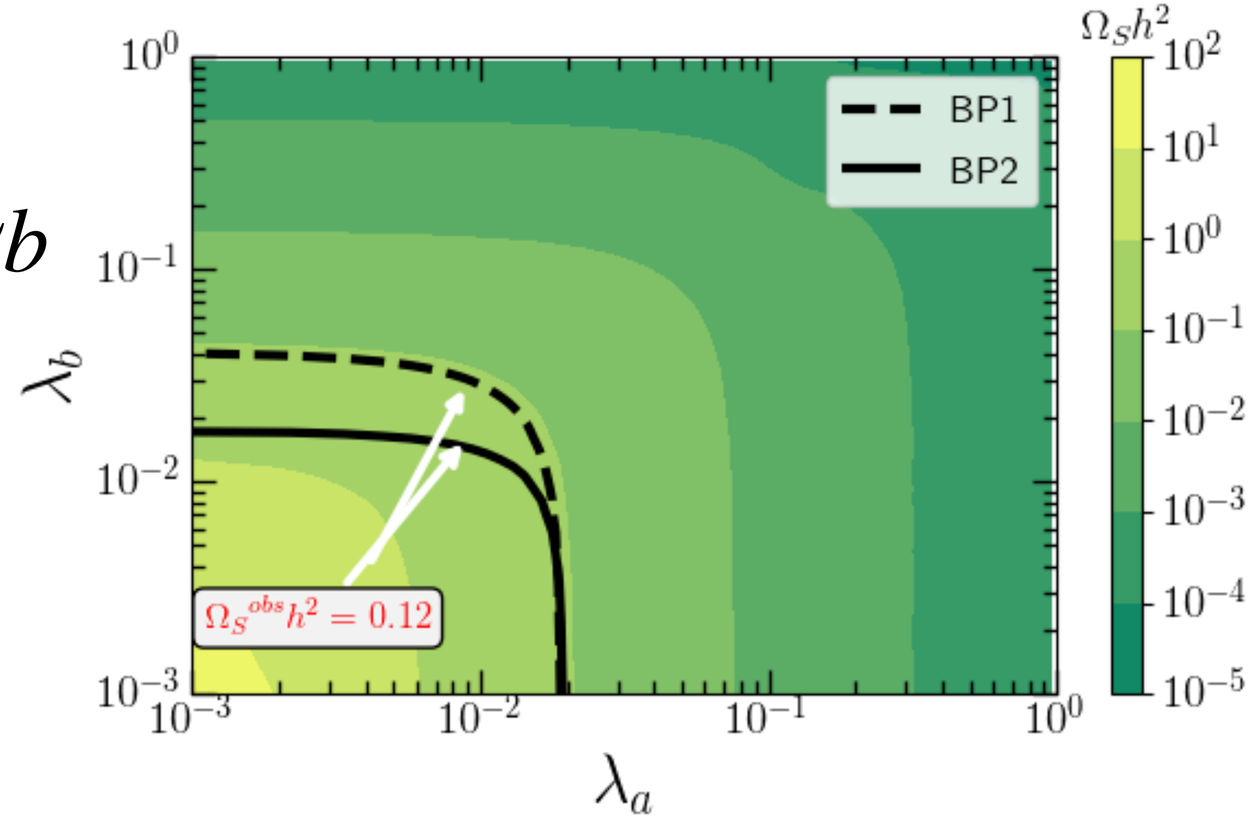


DM relic density

[Tools used for simulationFeynrule, micrOMEGAs,CalcHEP]

- $S\ S \rightarrow SM\ SM$ ---> λ_a
- $S\ S \rightarrow H_5\ H_5,\ H_3\ H_3,\ H\ H$ ---> λ_b





Benchmark point

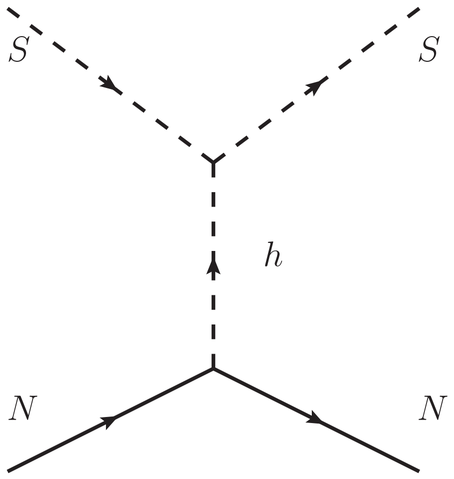
BP1: $M_{H_5} = 300\,\text{GeV},\ M_{H_3} = 254\,\text{GeV},\ M_H = 227\,\text{GeV},\ v_\chi = 0.036\,\text{GeV}$
$M = 335\,\text{GeV},\ \overline{M} = 43\,\text{GeV}$ and $M_S = 280\,\text{GeV}$

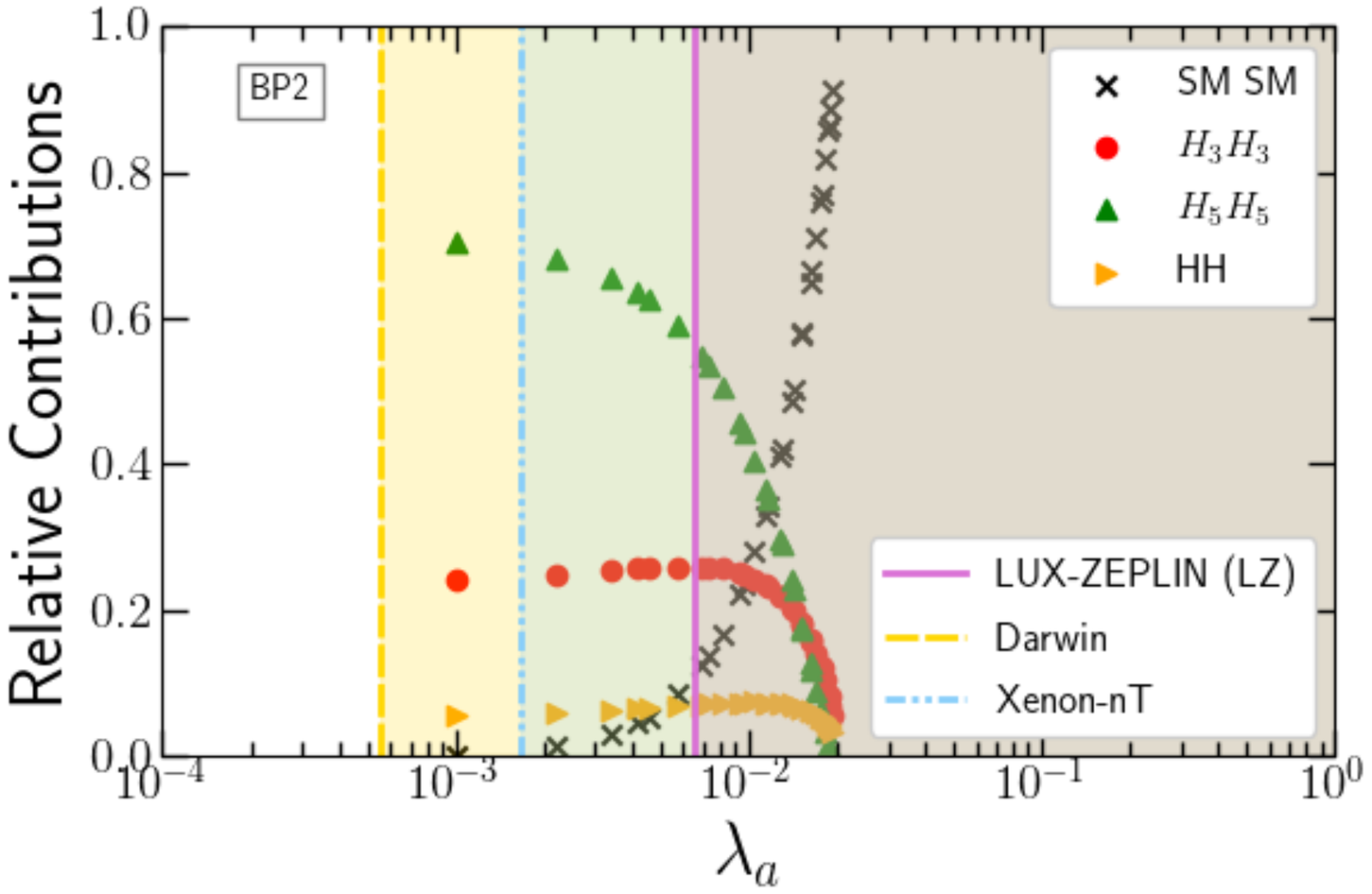
BP2: $M_{H_5} = 190\,\text{GeV},\ M_{H_3} = 234\,\text{GeV},\ M_H = 253\,\text{GeV},\ v_\chi = 0.05\,\text{GeV}$
$M = 210\,\text{GeV},\ \overline{M} = 10\,\text{GeV}$ and $M_S = 280\,\text{GeV}$

Direct detection

[PRL 131 (2023) 041002;*JCAP* 11 (2016) 017]

- λ_b **is tuned such that** $\Omega_S h^2 = 0.12$
- **For lower** λ_a**,** $S\ S \to H_5\ H_5,\ H_3\ H_3,\ H\ H$ **can have leading contribution**
- **No direct detection limit on** λ_b **as** $\sin_\alpha = 0$



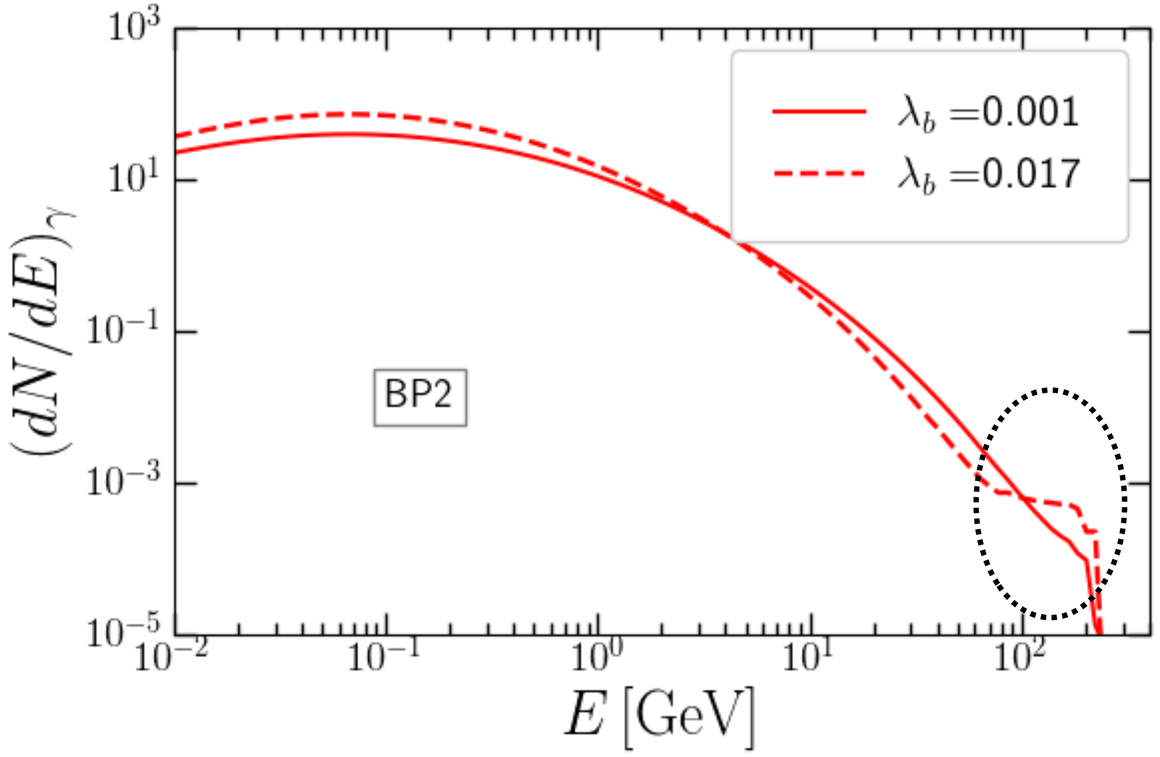


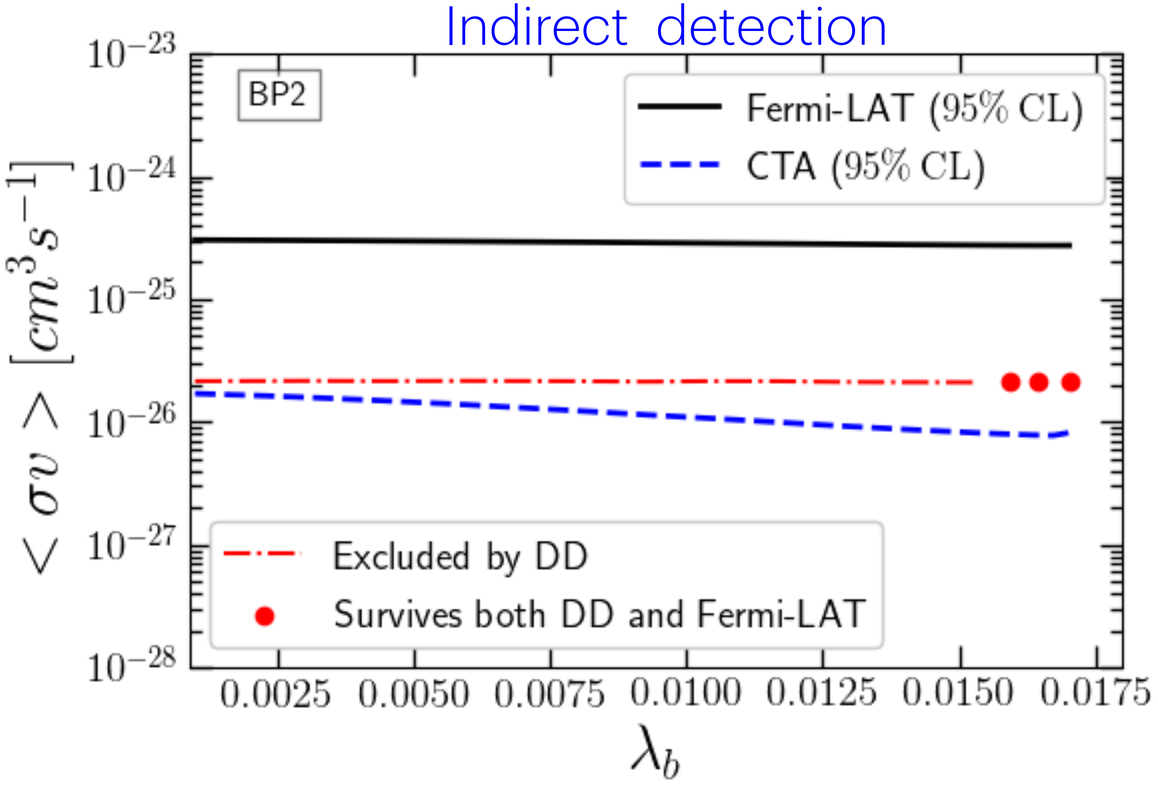
Indirect detection

[PRL 131 (2023) 041002;*JCAP* 11 (2016) 017]

$$S\ S \to H_5\ H_5,\ H_3\ H_3,\ H\ H\ ,\ H_5^0(or\ H) \to \gamma\gamma$$

offers high photon with energy > 100 GeV

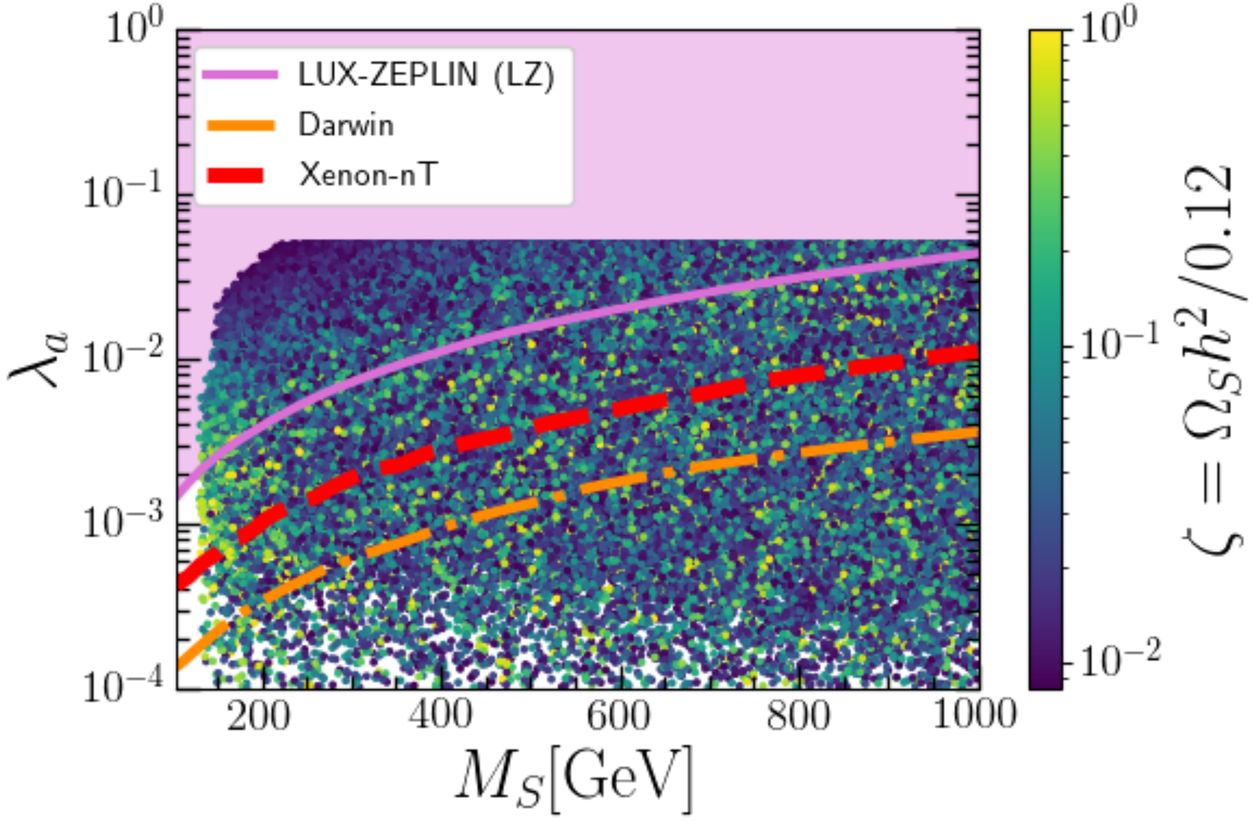




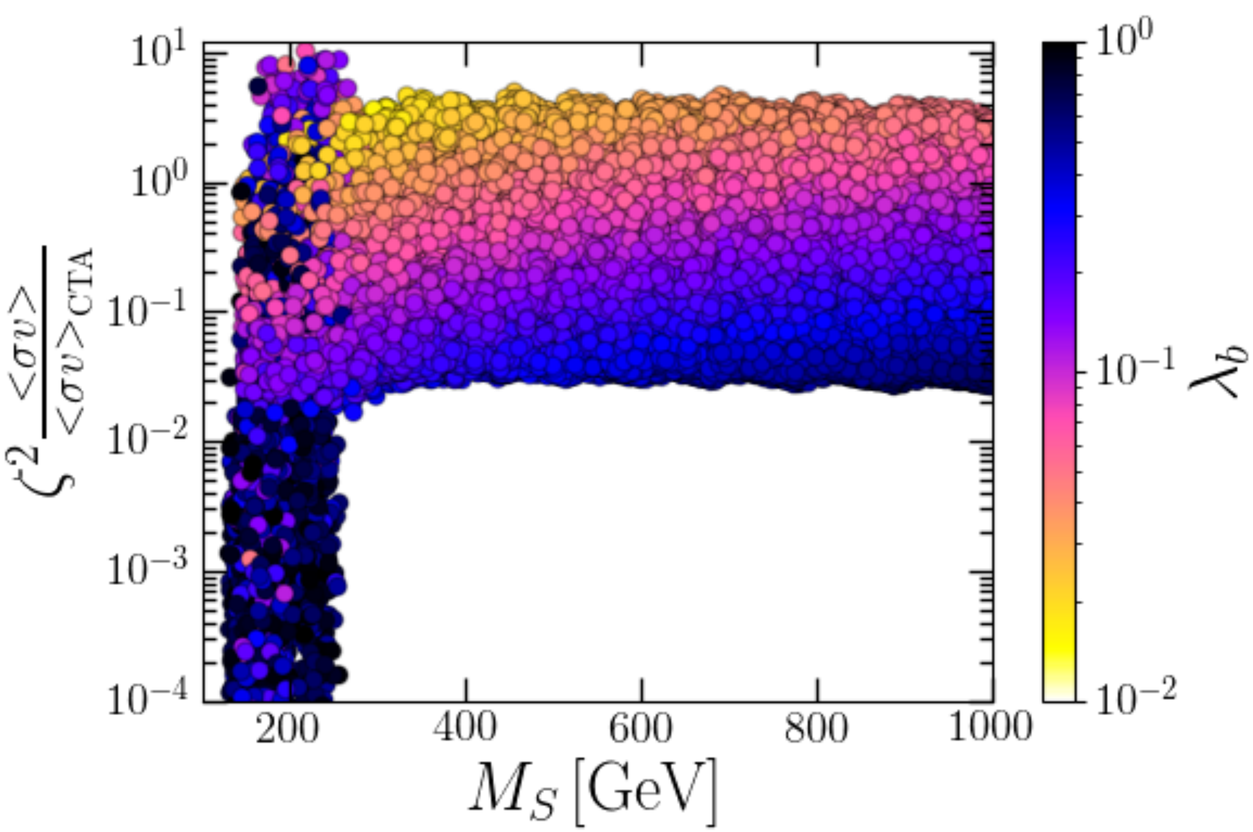
- **Lower λ_b (that corresponds to higher λ_a) excluded by DD**
- **No limit from Fermi-LAT (weaker limit for DM mass > 100 GeV)**
- **CTA may probe this benchmark**

Dark sector parameter scan

- *For all allowed* $\{M_{H_5}, M_{H_3}, M, v_\chi, \bar{M}\}$ *points another scan is performed over* $\{M_S, \lambda_a, \lambda_b, \lambda_S\}$
- *Future DD and ID experiments can probe entire range of DM mass.*
- *CTA may set strong limit on* λ_b



Sensitivity @CTA

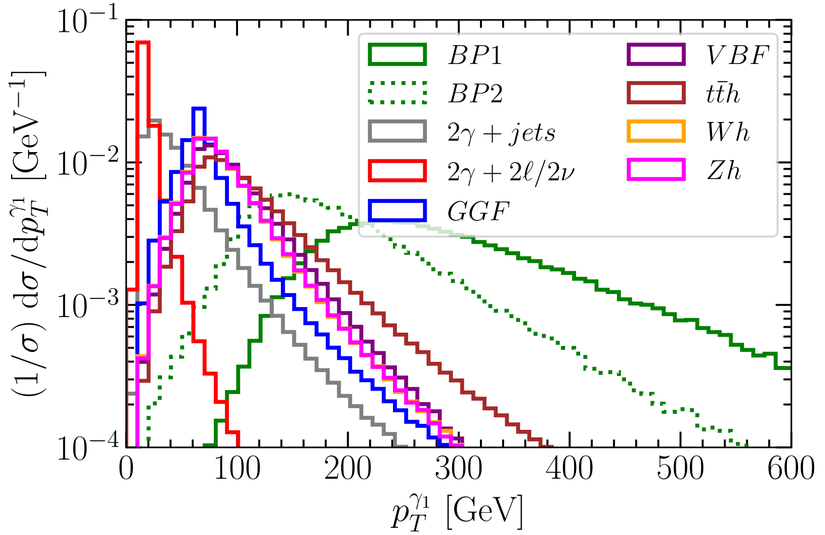


Diphoton signal @HL-LHC

$$pp \to H_5^0 + \{V, H_5^\pm, H_3^0, H_3^\pm\}, H_5^0 \to \gamma\gamma$$

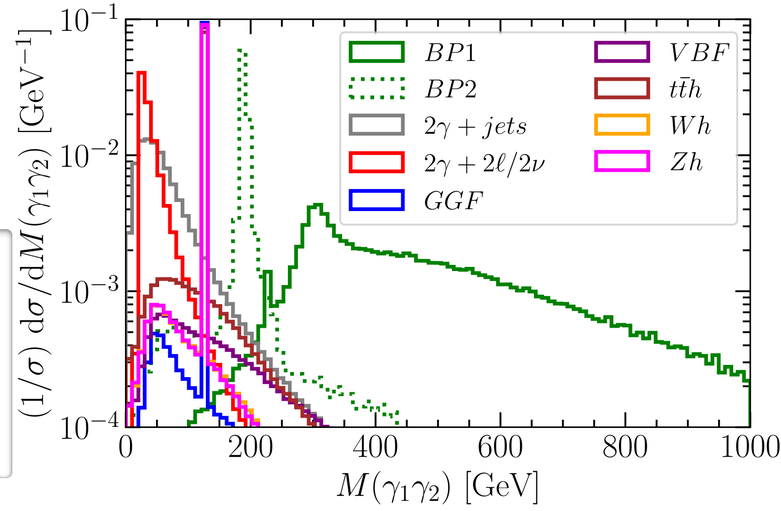
σ^s (pb)		σ^b (pb)						
BP1	BP2	GGF	VBF	Zh	Wh	$t\bar{t}h$	$\gamma\gamma + 2\ell(2\nu)$	$\gamma\gamma + jets$
0.0167	0.0976	49.6	4.26	0.9	1.5	0.6	156.8	128.34

Dominant background



Selection cuts

- $p_T^{\gamma_{1,2}} \geq 80{,}30\ GeV$
- $|M(\gamma_1\gamma_2) - M_{H_5}| = 20\ GeV$



Events with $\mathcal{L} = 3000/\text{fb}$, $\mathcal{S} = N^s/\sqrt{N^s + N^b + (N^b \delta b)^2}$	
BP1	BP2
$N^s = 5711,\ N^b = 1032684,\ \mathcal{S} = 0.55$	$N^s = 164434, N^b = 3758548, \mathcal{S} = 4.36$

HL-LHC can probe BP2

Summary

- **We study the collider and dark matter phenomenology of extended GM model in the decoupling limit.**
- **Unitarity constraints exclude TeV scale BSM scalars**
- $h \to \gamma\gamma$ **and** $H_5^0/H \to \gamma\gamma$ **set strong limit on triplet vev**
- **DM annihilation to the BSM Higgs play a crucial role to set relic density, while evading the strong DD limit.**
- $H_5^0/H \to \gamma\gamma$ **offers good sensitivity at CTA as well as at the HL-LHC.**

Thank You!

Scalar Spectrum

Custodial Multiplets

❖ **Fiveplet** $H_5^{++} = \chi^{++}$, $H_5^{+} = \frac{1}{\sqrt{2}}\left(\chi^{+} - \xi^{+}\right)$, $H_5^{0} = \sqrt{\frac{2}{3}}\,\xi^{0,r} - \sqrt{\frac{1}{3}}\,\chi^{0,r}$

❖ **Triplet** $H_3^{+} = -s_H\,\phi^{+} + \frac{1}{\sqrt{2}} c_H\left(\xi^{+} + \chi^{+}\right)$, $H_3^{0} = -s_H\,\phi^{0,i} + c_H\,\chi^{0,i}$

❖ **Singlet** $h = c_\alpha \phi^{0,r} - s_\alpha H_1^{0'}$, $H = s_\alpha \phi^{0,r} + c_\alpha H_1^{0'}$

s_α = CP-even Higgs mixing

SM- Higgs

$$c_H \equiv \cos\theta_H = \frac{v_\phi}{v}, \quad s_H \equiv \sin\theta_H = \frac{2\sqrt{2}v_\chi}{v}$$

$$H_1^{0'} = \sqrt{\frac{1}{3}}\,\xi^{0,r} + \sqrt{\frac{2}{3}}\,\chi^{0,r}$$

$$8\pi > \left|12\lambda_1 + 14\lambda_3 + 22\lambda_4 \pm \sqrt{(12\lambda_1 - 14\lambda_3 - 22\lambda_4)^2 + 144\lambda_2^2}\right|,$$

$$8\pi > \left|4\lambda_1 - 2\lambda_3 + 4\lambda_4 \pm \sqrt{(4\lambda_1 + 2\lambda_3 - 4\lambda_4)^2 + 4\lambda_5^2}\right|,$$

$$8\pi > |16\lambda_3 + 8\lambda_4|,$$

$$8\pi > |4\lambda_3 + 8\lambda_4|,$$

$$8\pi > |4\lambda_2 - \lambda_5|, \longrightarrow M_{H_3} < 870\ GeV$$

$$8\pi > |4\lambda_2 + 2\lambda_5|,$$

$$8\pi > |4\lambda_2 + 4\lambda_5|,$$

$$8\pi > |4\lambda_a|,$$

$$8\pi > |4\lambda_b|,$$

$$\lambda_S < \frac{1}{6}\left(4\pi + \frac{2\lambda_a^2(7\lambda_3 + 11\lambda_4 - \pi) + 9\lambda_b^2(3\lambda_1 - \pi) - 18\lambda_2\lambda_a\lambda_b}{2(7\lambda_3 + 11\lambda_4 - \pi)(3\lambda_1 - \pi) - 9\lambda_2^2}\right),$$

$$\lambda_S > \frac{1}{6}\left(-4\pi + \frac{2\lambda_a^2(7\lambda_3 + 11\lambda_4 + \pi) + 9\lambda_b^2(3\lambda_1 + \pi) - 18\lambda_2\lambda_a\lambda_b}{2(7\lambda_3 + 11\lambda_4 + \pi)(3\lambda_1 + \pi) - 9\lambda_2^2}\right).$$